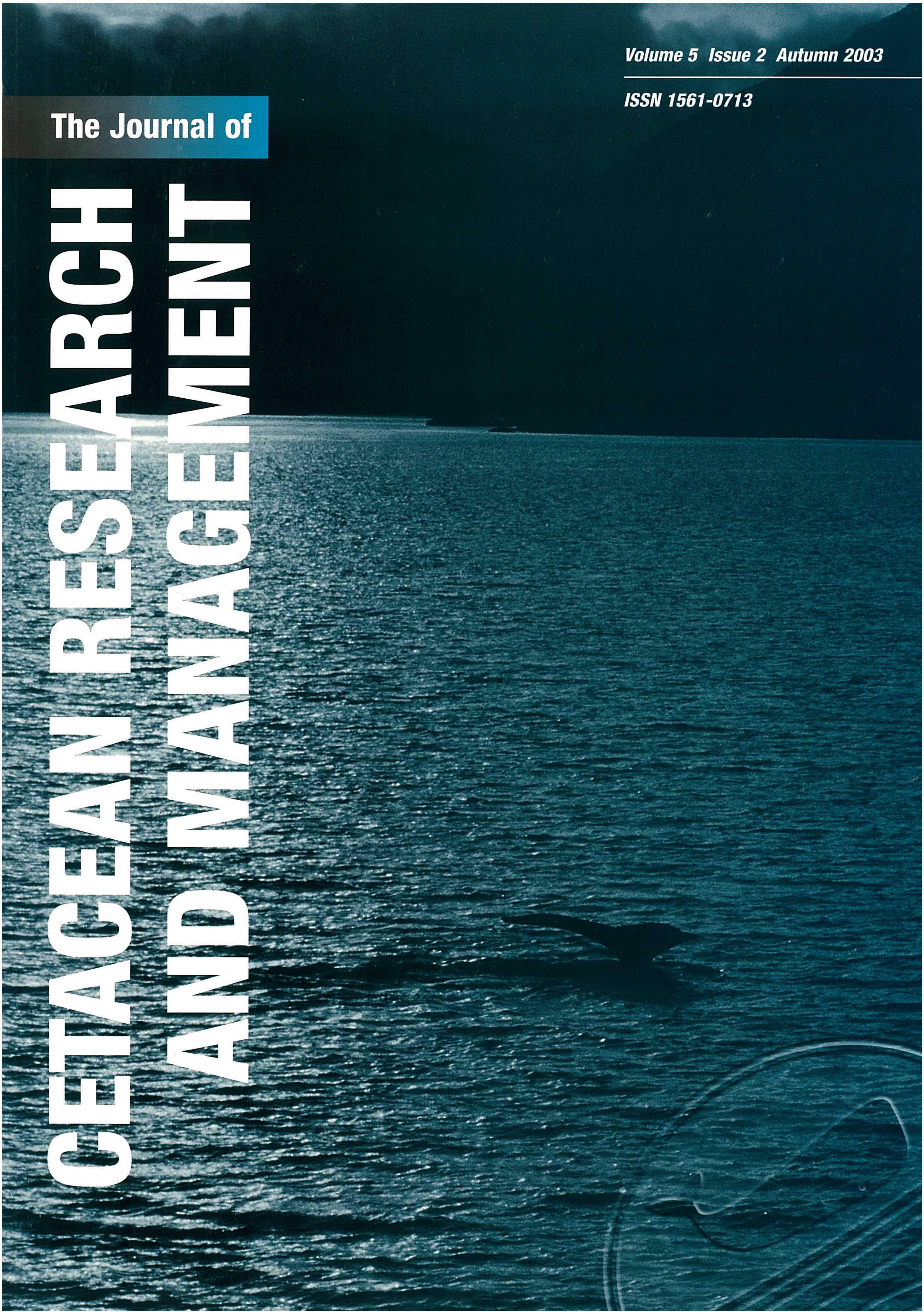
Volume 5 Issue 2 Autumn 2003

ISSN 1561-0713

The Journal of
CETACEAN RESEARCH AND MANAGEMENT



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Editorial

This issue of the Journal follows the 2003 meeting of the International Whaling Commission held in Berlin, Germany. Details of the Commission meeting will be published in the next *Annual Report of the International Whaling Commission.* The full report of the Scientific Committee will be published in spring 2004 as *J. Cetacean Res. Manage*. 6 (Suppl.). However, as is now traditional, here follows a summary of the work of the Scientific Committee at the recent annual meeting.

REVISED MANAGEMENT PROCEDURE

After the adoption of the moratorium on commercial whaling in 1982, the Committee spent over eight years developing the Revised Management Procedure (RMP) for baleen whales (IWC, 1999b). In brief, the RMP is a generic management procedure designed to estimate safe catch limits for commercial whaling of baleen whales. This was adopted some time ago by the Commission (IWC, 1993). However, the Commission has stated that it will not set catch limits for commercial whaling for any stocks until it has agreed and adopted a complete Revised Management Scheme (RMS). The RMS will also include a number of non-scientific matters, including inspection and enforcement. This has been the subject of a considerable amount of discussion within the Commission. A special task force led by the Chair of the Commission (Henrik Fischer) will operate during the year to see how to move to completion of the RMS.

Implementation Simulation Trials

Implementation Simulation Trials are trials that are carried out before using the RMP to calculate a catch limit and involve investigating the full range of plausible hypotheses related to a specific species and geographic area, particularly with respect to issues of stock structure.

The process of developing *Implementation Simulation Trials* is not the same as identifying the 'best' assessment for the species/region, but involves considering a set of alternative models to examine a broad range of uncertainties with a view to excluding variants of the RMP that show performance that is not sufficiently robust across the trials. Account needs to be taken of the plausibility of the various trial scenarios when evaluating RMP variants.

In the light of difficulties experienced in recent years, particularly with respect to the North Pacific region (common minke whales and Bryde's whales), the Committee has spent some time discussing the general question of how best to ensure that the process of carrying out *Implementations* (or *Implementation Reviews*) is efficient and prompt, whilst taking into account the available information. To achieve this it agreed that they should be conducted at discrete intervals, using the data available at one point in time. The process from *'pre-Implementation Assessment'* to initial *Implementation* and *Implementation Reviews* was formalised and clarified last year and a major review will be undertaken in 2004.

North Pacific common minke whales

The Committee has been working on *Implementation Simulation Trials* for this area since 1994; a special workshop was held prior to the Berlin meeting. The process has proven to be difficult for a number of reasons, including (1) harvesting is projected to take place on migration as well as on feeding grounds; (2) there is a seasonally-dependent overlap of management stocks; (3) continual updating of information on relatively complex population structure; (4) issues related to the plausibility of trials, particularly with respect to population structure; (5) complexity and time required to code and run trials; (6) lack of agreement on when to stop 'improving'. Completing this process was one of the major areas of work for the 2003 meeting.

The Committee considered four stock scenarios for the western North Pacific (ranging from 2-4 stocks with various boundaries and levels of mixing) and six management variants (allowing catches in different *Small Areas* and combinations of *Small Areas* and times of year). It also carried out trials with 1% and 4% MSYR and a variety of sensitivity investigations of a number of assumptions including numbers of bycaught animals, level of depletion of the non-target 'J-stock' etc.

There was disagreement within the Committee with respect to the plausibility of the various stock scenarios and this led to lack of consensus over the most appropriate management variant to recommend. Most members supported the management variant that performed best under all stock scenarios, whereas some supported the variant that performed best for the stock scenario that they believed was most plausible.

A full review of how best to implement the RMP in cases of uncertain stock structure will take place at next year's meeting.

North Pacific Bryde's whales

The Committee has made relatively slow progress on completing the *implementation* for western North Pacific Bryde's whales *inter alia* due to its heavy workload. While noting that it was in the *pre-implementation assessment* stage, the Committee noted the considerable work already undertaken and agreed that it should be possible to move faster towards *implementation* than would be the case for new situations. It will be an important topic at next year's meeting.

North Atlantic common minke whales

The Committee completed an *Implementation Review* of North Atlantic minke whales this year, taking into account new information on stock structure and abundance. The Committee recommended some changes to the *Small Area* boundaries for the eastern *Medium Area* and agreed that the *Catch-cascading* option at the *Medium Area* level remained the preferred management option.

Bycatches of large whales

The RMP estimates a limit for the number of non-natural removals, not simply a catch limit for commercial whaling. It is therefore important to estimate the numbers of whales removed from the population by indirect means including bycatches in fishing gear and ship strikes, for example.

The Scientific Committee began to consider this issue in some detail two years ago. It agreed that priority should be given to those areas where the RMP is likely to be implemented – such as the northwestern Pacific and the northeastern Atlantic. Four steps are required: (1) identification of the relevant fisheries; (2) description and categorisation of those fisheries to allow a sampling scheme to be devised; (3) identification of a suitable sampling strategy or strategies; and (4) design and implementation of the sampling scheme to enable estimation of the total bycatch.

The Committee has reviewed general methods for estimating bycatches. These fall under two headings: (1) those based on fisheries data and observer programmes; and (2) those based on genetic data. The former have been used successfully for several small cetacean populations. The Committee agreed that independent observer schemes are generally the most reliable means of estimating bycatch rates in a statistically rigorous manner, but that they may not always be practical and will require careful design.

Genetic approaches potentially represent a new way of estimating bycatches. The Committee has agreed that although genetic methods based on market samples may not be the primary approach to estimating bycatch, they could provide useful supplementary data that could not be obtained in another way. The use of market samples to provide absolute estimates should not be ruled out. However, it will require further developments in sampling design with input from experts with detailed knowledge of market sampling issues. A proposal for a workshop on that subject is being developed for consideration in 2004.

Work to further explore improved bycatch estimation methods for the two approaches noted above is continuing. Improved data reporting for large whale bycatches was also recommended.

DEVELOPMENT OF AN ABORIGINAL WHALING MANAGEMENT PROCEDURE

With the completion of the RMP, the Commission asked the Scientific Committee to begin the process of developing a new procedure for the management of aboriginal subsistence whaling. Such a procedure must take into account the different management objectives for such whaling when compared to commercial whaling. This is an iterative and ongoing effort. The Commission will establish an Aboriginal Whaling Scheme that comprises the scientific and logistical (e.g. inspection/observation) aspects of the management of all aboriginal fisheries. Within this, the scientific component might comprise some general aspects common to all fisheries (e.g. guidelines and requirements for surveys and for data c.f. the RMP) and an overall AWMP within which there will be common components and case-specific components.

At the 2002 meeting, the Committee completed its work with respect to the Bering-Chukchi-Beaufort Seas stock of bowhead whales. It agreed a *Strike Limit Algorithm (SLA)* for bowhead whales and the scientific aspects of a Scheme; this was adopted by the Commission. It noted that should the Commission decide, it would be possible to apply the *Bowhead SLA* at that meeting. Work continued intersessionally on gray whales and during the 2003 meeting. After a Workshop, the Committee hopes to be able to present a formal recommendation to the Commission for a *Strike Limit Algorithm* for gray whales in 2004. The situation for the Greenlandic fisheries for fin and minke whales is less promising. A considerable amount of research, especially concerning stock identity, is required and to this end, the Committee has developed a research programme in cooperation with Greenlandic scientists (see below).

ASSESSMENT OF STOCKS SUBJECT TO ABORIGINAL SUBSISTENCE WHALING

Aboriginal subsistence whaling is permitted for Denmark (Greenland, fin and minke whales), the Russian Federation (Siberia, gray and bowhead whales), St Vincent and The Grenadines (Bequia, humpback whales) and the USA (Alaska, bowhead and gray whales). It is the responsibility of the Committee to provide scientific advice on safe catch limits for such stocks and until the AWMP is completed then the Committee provides advice on a more *ad hoc* basis, carrying out major reviews according to the needs of the Commission in terms of establishing catch limits and the availability of data. It also carries out brief annual reviews of each stock.

The present catch limits had been set up to the 2002 season and so at the 2002 meeting, the Committee had to provide management advice for all of the stocks considered. The Commission sets catch limits based on the scientific advice and a ‘need’ statement from the countries involved.

Eastern gray whales

In 2002, the primary assessment carried out was for the eastern gray whale population (Issue 1 of volume 4 of the *Journal* was devoted to gray whale papers). New information on abundance, distribution, catches and ecology was presented. The population is believed to be close to carrying capacity. The Committee agreed that an annual take of up to 463 whales was acceptable; based on the submitted need statement, the Commission set a total for the 2003-6 seasons of 620 with a maximum of 140 in any one year.

Bering-Chukchi-Beaufort Seas stock of bowhead whales

In addition to the work on the *Bowhead SLA*, the Committee also examined the status of the Bering-Chukchi-Beaufort Seas stock of bowhead whales. New information in 2002 included a preliminary abundance estimate for 2001 of 9,860 (95%CI 7,700 – 12,600) giving a rate of increase between 1978 and 2002 of 3.3% (95%CI 2%, 4.7%). The Committee noted that irrespective of its work on the *Bowhead SLA*, the information here suggests that it is very likely that an annual catch of 102 whales will allow the stock to increase. A proposal to continue to include provision for such catches (up to 280 bowhead whales to be landed in the period 2003 – 2006, with no more than 68 whales struck in any year) failed to reach the necessary three-quarters majority in the Commission at the 2002 Annual Meeting but was agreed at a later Special Meeting. This year the Committee considered the work necessary to complete an in-depth assessment at the 2004 meeting. It agreed that the primary focus of the in-depth assessment should be: (a) the data required for the *Bowhead SLA*; and (b) examining whether the present situation is within the tested parameter space for that *SLA*. The latter effort will include consideration of such issues as stock identity and biological parameters. Previous assessment models can be used to investigate this, but it will not be necessary to determine the ‘best’ model or to calculate management-related quantities (in the time-consuming manner of previous assessments) as the *Bowhead SLA* will be used to provide management advice.

Minke and fin whales off West Greenland

Last year, at the Commission, the same catch limits as previously in force were agreed for the 2003-6 period, i.e. West Greenland minke whales – an annual limit of up to 175 strikes; East Greenland minke whales – an annual catch of up to 12 animals; West Greenland fin whales – an annual catch of up to 19 whales. The Committee had been unable to provide scientific advice on safe catch limits and once again this year, the Committee received little new information on stocks of minke and fin whales off West Greenland. It stressed that this inability to provide any advice on safe catch limits is a matter of great concern, particularly in the case of fin whales where the best available abundance estimate dates from 1987/88 and is only 1,096 (95% CI 520-2,100); that for West Greenland common minke whales dates from 1993 and is 8,371 (95% CI 2,400 – 16,900). The Committee strongly recommended that an abundance survey be carried out this year if at all possible.

The Committee also stressed that obtaining adequate information for management must be seen as of very high priority by both the national authorities and the Commission. Without this information, the Committee will not be able to provide safe management advice in accord with the Commission's management objectives, or develop a reliable *SLA* for many years, with potentially serious consequences for the status of the stocks involved.

Humpback whales off St Vincent and the Grenadines

Last year, after considerable debate in the Commission, a catch of up to 20 whales for the period 2003-7 was agreed (the Scientific Committee must review this in 2005). This year, the Committee repeated that it believes it is most plausible that eastern Caribbean humpbacks are part of the West Indies breeding population (abundance in 1992/93 – 11,570, 95%CI 10,100 – 13,200). However, it recommended further collection of relevant data to confirm this. It also agreed that catch limit set by the Commission would not harm the stock if it is part of the West Indies breeding population.

STOCK IDENTITY

Of general concern to the assessment of any cetaceans is the question of stock identity. Examination of this concept in the context of management plays an important role in much of the Committee's work, whether in the context of the RMP, AWMP or general conservation and management. In recognition of this, the Committee has established a Working Group to review theoretical and practical aspects of the stock concept in a management context. The Committee has noted that it is important, in any application of stock structure methods, to examine the sensitivity of conclusions to different *a priori* decisions about the definition of initial units, and as to which population structure hypotheses to examine.

A specialist workshop to examine the use of simulation testing to assess the performance of methods to identify population structure was held in January 2003 and discussed at the Berlin meeting. The workshop developed a suitable simulation framework to allow evaluation of genetic methods used in inferring population structure both in general terms (the issue is of great relevance to conservation and management outside the IWC) and from a specifically IWC viewpoint (particularly in an RMP/AWMP context).

It was recognised that such a complex project must proceed in an iterative fashion and the Workshop concentrated on specifying the various modular tasks needed for Phase I of the process (c.f. *Initial Exploration Trials* in the AWMP process), for which some results might be expected within a year, while also identifying the types of scenarios that would need to be covered in Phase II and beyond. The Workshop report will be published in *J. Cetacean Res. Manage*. 6 (Suppl.). Funding has been provided that will allow Phase I of the TOSSM project (Testing Of Spatial Structure Models) to be completed. The most challenging module is the development and validation of a program to simulate realistic genetic datasets. It is hoped that the first sets of simulated data will become available in February or March 2004. If so, some results for at least some methods may be available for consideration at next year's Scientific Committee meeting

COMPREHENSIVE ASSESSMENT OF WHALE STOCKS

The 'Comprehensive Assessment' of whale stocks

The development of the concept of the 'Comprehensive Assessment' is reviewed in Donovan (1989). It can be considered as an in-depth evaluation of the status of all whale stocks in the light of management objectives and procedures; this would include the examination of current stock size, recent population trends, carrying capacity and productivity. Clearly, it is not possible to 'comprehensively assess' all whale stocks simultaneously, and the Committee has been working in an iterative manner towards this, initially concentrating on stocks that have recently or are presently being subject to either commercial or aboriginal subsistence whaling. Some of these stocks have already been discussed in the sections on the RMP and AWMP.

Antarctic minke whales

The Committee has carried out annual surveys in the Antarctic (south of 60°S) since the late 1970s. The last agreed estimates for each of the six management Areas for minke whales (see Donovan, 1991) were for the period 1982/83 to 1989/90 (IWC, 1991). At the 2000 meeting, the Committee agreed that whilst these represented the best estimates for the years surveyed, they were no longer appropriate as estimates of current abundance. An initial analysis of available recent data had suggested that current estimates might be appreciably lower than the previous estimates (e.g. see Branch and Butterworth, 2001).

Subsequently, considerable time has been spent considering Antarctic minke whales with a view to obtaining final estimates of abundance and considering any trend in these. This has included a review of data collection methods (e.g. see Murase *et al.,* this issue) and analytical methodology. After considering many of the factors affecting abundance estimates, there is still evidence of a decline in the abundance *estimates*, although it is not clear how this reflects any *actual* change in minke abundance. Three hypotheses that might explain these results have been identified:

(1) a real change in minke abundance;
(2) changes in the proportion of the population present in the survey region at the time of the survey;
(3) changes in the survey process over time that compromise the comparability of estimates across years.

A considerable amount of work has been undertaken and further work is ongoing. It will again be a priority item for discussion at next year's meeting.

Southern Hemisphere blue whales

The Committee is beginning the process of reviewing the status of Southern Hemisphere blue whales. An important part of this work is to try to develop methods to identify pygmy blue whales from 'true' blue whales at sea (IWC, 1999a) and progress is being made on this. Work on genetic and acoustic differentiation techniques is continuing and there is considerable progress with morphological methods. The Committee has agreed on a number of issues that need to be resolved before it is in a position to carry out an assessment, which it believes should commence in 2006.

Southern Hemisphere humpback whales

Considerable progress has been made in recent years in working towards an assessment of humpback whales. Attention has focussed both on data from historic whaling operations and on newly acquired photo-identification, biopsy and sightings data. The Committee made a number of research recommendations to further progress towards an assessment. An intersessional group was established last year to review progress and determine whether it is feasible to set a deadline for the assessment to be completed. Further work was identified this year and progress will be reviewed in 2004.

North Atlantic right whales

The Committee has paid particular attention to the status of the North Atlantic right whale in the western North Atlantic in recent years (e.g. see special issue 2 of the Journal – *Right whales: worldwide status*). The Committee is extremely concerned about this population, which, whilst probably the only potentially viable population of this species, is in serious danger (*ca* 300 animals). By any management criteria applied by the IWC in terms of either commercial whaling or aboriginal subsistence whaling, there should be no direct anthropogenic removals from this stock.

This year, the Committee once again noted that individuals are continuing to die or become seriously injured as a result of becoming entangled in fishing gear or being struck by ships. It repeated that it is a matter of absolute urgency that every effort be made to reduce anthropogenic mortality in this population to zero. This is perhaps the only way in which its chances of survival can be directly improved. There is no need to wait for further research before implementing any currently available management actions that can reduce anthropogenic mortalities.

The Committee reviewed progress on a number of research and management recommendations concerning this stock.

Western North Pacific gray whales

This is one of the most endangered populations of great whales in the world. It numbers less than 100 animals (see the paper by Weller *et al.*, 2002) and there are a number of proposed oil and gas-related projects in and near its only known feeding ground. The Committee held a Workshop in October 2002 to review this further. The Workshop report will be published in *J. Cetacean Res. Manage.* 6 (Suppl.). Overall, the Workshop agreed with the conclusions of previous reviews on western gray whales. Specifically, that the population is very small, and suffers from a low number of reproductive females, low calf survival, male-biased sex ratio, dependence upon a restricted feeding area and apparent nutritional stress (as reflected in a large number of skinny whales). Other major potential concerns include behavioural reactions to noise (notably in light of increasing industrial activity in the area) and the threat of an oil spill off Sakhalin which could cover all or part of the Piltun area and thus potentially exclude animals from this feeding ground. The Workshop had noted that assessments of the potential impact of any single threat to the survival and reproduction of western gray whales were insufficient and had strongly recommended that risk assessments consider cumulative impact of multiple threats (from both natural and anthropogenic sources).

The Committee adopted the Workshop report and endorsed its recommendations, including the research and monitoring plan. In conclusion, the Committee strongly reiterated that it is a matter of absolute urgency that every effort is made to reduce anthropogenic mortality (including direct catches) and disturbance to zero to save western North Pacific gray whales from extinction.

EFFECTS OF ENVIRONMENTAL CHANGE ON CETACEANS

There is an increasing awareness that whales should not be considered in isolation but as part of the marine environment; detrimental changes to their habitat may pose a serious threat to whale stocks. The Committee has examined this issue in the context of the RMP and agreed that the RMP adequately addresses such concerns. However, it has also emphasised that the species most vulnerable to environmental threats might well be those reduced to levels at which the RMP, even if applied, would result in zero catches (IWC, 1994). Over a period of several years, the Committee has developed two multi-national, multi-disciplinary research proposals. One of these, POLLUTION 2000+ (Reijnders *et al.,* 1999) has two aims: to determine whether predictive and quantitative relationships exist between biomarkers (of exposure to and/or effect of PCBs) and PCB levels in certain tissues; and to validate/calibrate sampling and analytical techniques. The other, SOWER 2000 (IWC, 2000) is to examine the influence of temporal and spatial variability in the physical and biological Antarctic environment on the distribution, abundance and migration of whales. Progress reports on both of these programmes were considered at the 2003 meeting.

At the 2003 meeting, the Committee also held a special session on Southern Ocean climate change and cetaceans. In particular it considered two presentations, one summarising work on krill, its physical environment, competitors and predators, and emphasised major findings and current hypotheses. The other focussed on the US SO-GLOBEC programme, and described the integrated study of physical and biological oceanography, krill and krill predators, noting IWC collaboration with respect to cetaceans. The implications of this work (much of which occurs outside the normal timing of Antarctic cetacean research) for other aspects of the IWC's work (e.g. see the Antarctic minke whale section above) was noted.

The Committee has also begun to look at the issues surrounding fisheries and cetaceans. The main long-term objective of the Committee on this topic is to answer the question 'how are changes in abundance of cetaceans likely to be linked (in the short- and long-term) to changes in fishery catches?' A Workshop to address modelling-related issues related to the interactions between cetaceans and fisheries was held in July 2002. The report of the Workshop will be published in *J. Cetacean Res. Manage.* 6 (Suppl.). Its aim was to evaluate existing modelling approaches, including identifying their constraints and data requirements, in order to identify those approaches most likely to answer the above question. The Workshop reviewed all the available major modelling approaches that deal with top predators and multi-species fisheries interactions.

The Workshop concluded that despite recent advances, most multi-species models are still in the development phase. It therefore agreed that no single approach could be recommended at this stage to provide reliable information of value to consideration of cetacean dynamics in an ecosystem context. However, this does not necessarily rule out the possibility that useful inferences might be drawn if a number of different modelling approaches yield qualitatively similar results. The Workshop also agreed that despite these difficulties, the consideration of ecosystem interactions between fish stocks and cetaceans is a potentially important research topic.

The Committee endorsed the Workshop conclusion that for no system at present are we in the position, in terms of data availability and model development, to provide quantitative management advice on the impact of cetaceans on fisheries, or of fisheries on cetaceans. However, this does not rule out the possibility of providing qualitative advice if a number of different approaches yield qualitatively similar results. It also endorsed the conclusion that consideration of ecosystem interactions between fish stocks and cetaceans is a potentially important research topic in a general sense; however, there was disagreement as to whether further pursuit of this matter was likely to be helpful to the Committee in providing advice to the Commission regarding the management of whale populations.

SMALL CETACEANS

Despite disagreement within the Commission over the management responsibilities of the IWC with respect to small cetaceans, it has been agreed that the Scientific Committee can study and provide advice on them. As part of this programme, the Committee has reviewed the biology and status of a number of species and carried out major reviews of significant directed and incidental catches of small cetaceans (Bjørge *et al*., 1994).

In 2001, the Government of Japan had indicated that it would no longer co-operate with the Committee on small cetacean related matters. In 2002, the Committee referred to the great value of the information provided by the Government of Japan on the status of small cetaceans in previous years and respectfully requested that the Government of Japan reconsider its position on this matter and resume the valuable contribution of Japanese scientists to its work on small cetaceans. Unfortunately, this did not happen in 2003.

At the 2003 meeting, the Committee considered the status of small cetaceans in the Black Sea. The species of concern are the harbour porpoise (*Phocoena phocoena*), the short-beaked common dolphin (*Delphinus delphis*) and the common bottlenose dolphin (*Tursiops truncatus*). All three are found in the Turkish Straits System (TSS) but only harbour porpoises and bottlenose dolphins are present in the Azov Sea. There is relatively little information on current distribution. With respect to stock structure, it was agreed that the Black Sea harbour porpoises and bottlenose dolphins comprise separate stocks for management and conservation purposes. A similar but provisional conclusion was reached for common dolphins. A number of research recommendations to improve understanding of distribution and stock structure within the region were made. Similarly, the Committee recommended that systematic abundance surveys are required for all three species throughout their range. The Black Sea is one of the most highly modified marine ecosystems in the world and the habitats of cetaceans in this basin have been degraded by numerous human activities. However, for most of these, the effects on cetaceans in the region are unknown and the Committee recommended research into these.

Uncontrolled directed takes were the primary threat to cetaceans in the Black Sea until a ban was imposed in 1983. There is no evidence of continued directed takes. All three species are taken as bycatch, but incidental takes of harbour porpoises are of greatest concern. Illegal, unreported or unregulated (IUU) fisheries are widespread in the Black Sea and may have a significant bycatch. Further quantitative elaboration of bycatches for all species is important, particularly for the bottom-set gillnet fisheries for turbot. After the ban on directed harvest, removals of live bottlenose dolphins has continued and in view of the many other threats faced by this species in the Black Sea, it is recommended that any removals of live cetaceans be preceded by a rigorous assessment of the impacts of such removals.

In conclusion, the Committee was unable to fully evaluate the status of small cetaceans in the Black Sea due to a lack of information. It concluded, however, that all three species probably declined dramatically in the 20th century as a result of large directed catches; fisheries bycatch and habitat degradation pose the most significant current threats to these species.

The Committee also reviewed progress on previous recommendations it had made, particularly those concerning the critically endangered baiji and vaquita. The Committee received some information from China and welcomed the initiatives being taken. However, it reiterated that the prospects for the baiji remain extremely poor. The Committee was informed of some further research that suggested the vaquita's range may have contracted – fishing and bycatches continue. It reiterated its grave concern over the survival of this species. It noted that CIRVA (International Committee for the Recovery of the Vaquita) will meet later in 2003/4 and looked forward to receiving an update of progress.

The Committee reiterated its support for the ASCOBANS recovery plan for harbour porpoises in the Baltic which it hoped would be adopted and implemented by the ASCOBANS parties.

The Committee also reviewed progress on work on the reduction of bycatches in fishing gear. It expressed concern over the number of animals being taken in pelagic trawl fisheries in western Europe and recommended that independent observer programmes be established to document the extent of bycatches in pelagic trawl fisheries of all nations in this region where such programmes do not already exist.

The Committee repeated its concern over the catches and quotas for some stocks of white whales and narwhals, particularly in Greenland, east Hudson Bay and the Russian Arctic. Finally, the Committee repeated previous requests for all Governments to submit relevant information on direct and incidental catches of small cetaceans in their national progress reports and for improved information on stock identity and abundance.

Priority next year will be given to addressing the status of the franciscana (*Pontoporia blainvillei*).

SCIENTIFIC ASPECTS OF WHALEWATCHING

In 2000, the Committee had identified a number of areas for further research on possible long-term effects of whalewatching on whales and a number of possible data types that could be collected from whalewatching operations to assist in assessing their impact. The Committee developed this further at the 2003 meeting and will continue to work on data collection issues in the intersessional period.

The Committee also reviewed: whalewatching guidelines and regulations; and new information on dolphin feeding and 'swim-with' programmes. The Committee also welcomed the news that a whalewatching management workshop will be held in late 2003 or early 2004 in Cape Town, South Africa. It recommended that workshop participants should be geographically representative and include scientists, managers, conservation organisations, whalewatching operators and representatives from other disciplines, such as economics and social sciences. The Committee established an intersessional correspondence group to provide scientific advice for the organisation of the workshop

REVIEW AND COMMENT ON SCIENTIFIC PERMITS ISSUED FOR SCIENTIFIC RESEARCH

All proposed scientific permits have to be submitted for review by the Scientific Committee following guidelines issued by the Commission. However, in accordance with the Convention the ultimate responsibility for issuing them lies with the member nation.

Most of the discussion at the 2003 meeting centred on the proposal for a two-year feasibility study in Icelandic waters involving the taking of 100 common minke whales, 100 fin whales and 50 sei whales. The stated goal was to improve understanding of the biology and feeding ecology of important cetacean species in Icelandic waters for better management of living resources based on an ecosystem approach. It includes multiple specific objectives with different priorities for the different species. For common minke whales the primary specific objective is to increase the knowledge of the species' feeding ecology in Icelandic waters. For fin and sei whales the primary specific objective is the study of biological parameters during the apparent increase in population size in recent decades. These objectives are the basis for the proposed sample sizes. Other research objectives include studies of population structure, pollutants, parasites and pathogens, and the applicability of non-lethal methods.

There was considerable disagreement within the Committee over most aspects of this research programme, including objectives, methodology, sample sizes, likelihood of success, effect on stocks and the amount and quality of data that could be obtained using non-lethal research techniques.

The Committee also briefly considered the continuing programmes on Antarctic minke whales (last extensively reviewed in 1997 – IWC, 1998) and in the western North Pacific (150 common minke whales, 50 Bryde's whales, 50 sei whales and 10 sperm whales each year for an unspecified period). The latter was extensively reviewed last year.

WHALE SANCTUARIES

The Committee had been asked by the Commission to review the Southern Ocean Sanctuary (SOS) in 2004 and an intersessional working group had been appointed to develop a proposed framework to carry out the review. The Committee's discussions of sanctuaries in the past have been somewhat inconclusive, with attention being drawn to a number of general arguments both in favour of and against sanctuary proposals. This year discussions centred on consideration of existing criteria to review sanctuaries, the use and interpretation of the 'Precautionary Approach', the appropriateness of the use of simulation trials to evaluate sanctuaries and the introduction of the Marine Protected Area (MPA) concept. A number of detailed comments on the review process for the SOS were made and a mechanism to improve the review next year was developed.

DATA AVAILABILITY

The question of data availability is complex and sensitive. A balance must be struck between the needs of the Committee and the rights of the scientists who have invested considerable time and effort in collecting the data. To reach agreement on this has proved difficult in the past. A major achievement at the 2003 meeting was that consensus was reached on a protocol for data availability. The agreed protocol was based on the principles that:

(1) data represent a significant temporal and financial investment by scientists and research institutes – use of their data by others should be accompanied by appropriate safeguards;
(2) the right of first publication is a generally accepted scientific norm;
(3) if important management decisions are to be made, they should be based on a full scientific review of both data quality and analysis that can be independently verified.

G.P. Donovan
Editor

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The suitability of mandible growth layers in the common minke whale (*Balaenoptera acutorostrata*) for age determination

ERIK OLSEN, NILS ØIEN, ARILD LEITHE AND BJØRN BERGFLØDT

Division of Resource Ecology, Institute of Marine Research, PO Box 1870 Nordnes, N-5817 Bergen, Norway

Contact e-mail: eriko@imr.no

ABSTRACT

Ovaries from 82 female minke whales (30 from 1999 and 52 from 2001) caught in the North Atlantic were examined macroscopically and the number of *corpora lutea*, *c. albicatia* and *c. artretica* determined by two or three readers. From these whales and an additional 19 males (13 from 1999 and 6 from 2001), the number of GLGs in the buccal wall of the anterior part of both mandibles were counted. Mandible GLGs were counted by either examining digital images of haematoxylin stained 200-500μm segments, or from high-resolution X-ray images of 3mm thick unstained segments examined by two readers. The readers agreed completely when counting ovarian *corpora lutea*, but there was disagreement with the interpretation of *c. albicantia* and *c. artretica* in some ovaries. The average CV of the number of ovulations ($n_{c.lutea} + n_{c.albicantia}$) was 6%; when counting only *c. albicantia* the CV was 16.7%, and 64.9% when counting only *c. artretica*. The precision when counting mandible GLGs using the digital images was poor, with mean CV of 82%, compared to 41% using the X-ray images. There was poor agreement between the repeated readings of the X-ray images by each reader, as well as between the readers. Mean GLG count using either method did not correlate with the number of ovulations, and provided biologically unreasonable von Bertalanffy growth models. This study shows that there is some uncertainty when examining ovaries, although this is small compared to the variability and bias associated with counting mandible GLGs. New bone is deposited in the mandible in such a way that growth layers do not continuously accumulate, or cannot be distinguished using present technology and methods.

KEYWORDS: COMMON MINKE WHALE; ATLANTIC OCEAN; AGE DETERMINATION; REPRODUCTION; OVULATION

INTRODUCTION

Age determination of baleen whales is more difficult than ageing other mammals due to their lack of teeth. Many methods have been attempted, and most species are now routinely aged by counting annual Growth Layer Groups (GLGs) in the wax-like earplug (Purves, 1955; Kato *et al.*, 1991). However, earplugs seldom form in the North Atlantic common minke whales, *Balaenoptera acutorostrata* (Christensen, 1992) and there have been attempts to determine age by counting GLGs in the periosteal layer of the tympanic bulla (Christensen, 1981). However, bulla age estimates have low precision (Christensen, 1995) and are so heavily biased (Olsen, 2002) that these are of little practical use. In sperm whales, annual GLGs have been found in the mandibular walls (Laws, 1960), and these correlate well with the age estimate from counting GLGs in the teeth until the attainment of physical maturity (Nishiwaki *et al.*, 1961). A study of mandible GLGs in the white whale (*Delphinapterus leucas*) yielded similar results (Brodie, 1969). GLGs are found in the mandible of many other mammals and birds (Klevezal and Kleinenberg, 1967). Klevezal and Mitchell (1972) attempted to determine the age of fin (*Balaenoptera physalus*) and sei whales (*Balaenoptera borealis*) by counting mandibular laminations, but were unable to detect clear growth zones. However, this method had not been attempted on minke whales, and it was conceivable that in this short-lived species mandible GLGs were formed. In addition, during the three decades since the Klevezal and Mitchell (1972) study, technological advances in imaging and image analysis have provided new tools to identify possibly diffuse growth layers.

Beamish and McFarlane (1983) and later Campana (2001) stressed the need for validating possible ageing methods, preferably using animals of known age or by using mark-recapture experiments. Records of known-age animals are lacking for common minke whales and there has been no mark-recapture programme in place for the last 20 years. To test if mandibular GLGs are useful in ageing, an indirect approach was therefore required. Mandibular GLG counts were compared with body length, and for females, with the number of ovulations as determined by counting *corpora lutea* and *c. albicantia* in the ovaries[1]. Both indices increase with age, body length following a curvilinear growth with age, usually modelled by a growth equation (e.g. Gompertz or von Bertalanffy). Most mysticete species have been shown to have a regular ovulation and birth cycle, giving birth to one young every 1-3 years depending on species (Lockyer, 1984b). Mature female minke whales have a ~90% pregnancy rate (Jonsgård, 1951; Chrstensen, 1975; Larsen, 1984 and Olsen, 1997). It is also assumed that minke whales have a regular ovulation rate, as Laws (1958) observed in fin whales. These observations imply that the numbers of ovulations increase linearly with age after attainment of sexual maturity. Accordingly, unbiased and precise age estimates would be expected to follow these relationships when compared with body length or the number of ovulations. It was therefore important to investigate the precision of the indices, particularly the counting of ovarian *corpora*, which had not been done before. The aim was to quantify the precision of counting ovarian *corpora*, and use the *corpora* counts together with body length to test if mandible GLGs are useful for age determination of North Atlantic common minke whales.

MATERIALS AND METHODS

The samples used in this study were collected in 1999 (30 females; 13 males) and 2001 (52 females; 6 males) on commercial whaling vessels operating in the Norwegian Economic Zone along the coast of Northern Norway, Spitsbergen, the North Sea and the Norwegian Sea east of Jan Mayen. Standard body length was measured as the

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[1] In cetaceans, the corpus albicans generally persists on the ovaries throughout life (Perrin and Donovan, 1984).

distance in a straight line from the tip of the snout to the notch in the fluke. Ovaries were removed during flensing, labelled, and stored in 4% buffered formaldehyde for later laboratory examination. In the laboratory, excess connective tissue was removed and the ovaries cut into 3mm slices. Two or three persons trained and experienced in examining ovaries of cetaceans examined these independently without any accessory information. Each reader counted the number of *corpora lutea*, *c. albicantia* and *c. artretica* in each ovary. The number of times a female had ovulated was calculated as the sum of *c. lutea* and *c. albicantia* in each pair of ovaries, and is henceforth referred to as the number of ovulations. Variance between the readers when counting the different *corpora* and the variance of the numbers of ovulations was expressed as CV to facilitate comparison between individuals and with other studies.

Collection of mandibles

While the whale was flensed on deck, the mandibles were cut loose at the jaw joint and the anterior 50cm of both mandibles were cut off using a saw. Blubber, muscle and connective tissue were removed using a knife and the mandible sections were frozen on board at -23°C. The mandibles were thawed in the laboratory and segments were cut of the buccal (outer) wall of both mandibles 45cm posterior to the tip of the jaw using a dual-bladed saw. The segments cut from the 1999 samples were 200-500μm thick, while those from 2001 were 3mm thick. In a pilot-study of whale mandibles sampled in 1997 and 1998, what appeared to be GLGs were observed in the buccal wall of the mandible, and it was found that these were most clear in the area 40-50cm from the tip. Most of the mandible of baleen whales consists of a highly spongiose bone matrix filled with fat, with an outer edge of highly ossified bone also infused with fat. The segments from the 1999 whales were examined using visible light microscopy, while the segments from 2001 were examined using X-ray imaging. To increase the contrast of the segments examined using visible light, they were stained with haematoxylin. The high fat content of the bone prevented first attempts of staining the sections, but soaking the segment in concentrated HCl for about 30 seconds alleviated this. The segments were then rinsed in water, followed by ethanol and lastly stored in glycerin in small containers (they were too large to fit available microscope slides). One such segment was prepared from both mandibles of all whales (except for two whales where one of the mandibles was lost). For 13 whales sampled in 1999, four additional segments of the same thickness were prepared from each mandible to investigate if the same GLG pattern found in one segment could be detected in other segments cut within 5cm of the first. The mandibles collected in 2001 were to be analysed using X-ray techniques. X-ray imaging did not need staining or fat-removal, but a pilot-study had shown that the segments needed to be ~3mm thick to yield sufficient contrast when X-rayed. These segments were cut in the same manner as those for the visible light analysis, but stored in 4% buffered formaldehyde as this was thought to alter the chemical structure of the bone to the least extent.

Analysis of mandibles

Due to their size, it was difficult to examine the mandible segments in the limited field of view of the microscopes used. Instead, the segments were placed on a light table and a picture of each was taken using a *Nikon Coolpix* 990 digital camera. Pictures were taken at maximum resolution (2048 × 1536 pixels) in colour mode, and stored as TIFF (Tagged Image File Format) files for conservation of all image information. Each picture was later analysed using *ImagePro Plus* 4.0 software. In the image-analysis, an initial attempt was made to enhance the contrast and clarity of the pictures using several different filters and techniques. Eventually, the brightness and contrast of each colour channel (red, green and blue) were manipulated separately to achieve the best contrast of the GLGs (Fig. 1). Following image-enhancement, two readers cooperated in determining where the potential GLGs were placed in the segment, and marked and measured these using the software's tools. Prior to the analysis, all image files had been renamed by an independent observer to prevent the readers from using additional knowledge or recognising individual whales. The mean GLG count was calculated for all age estimates of the same whale.

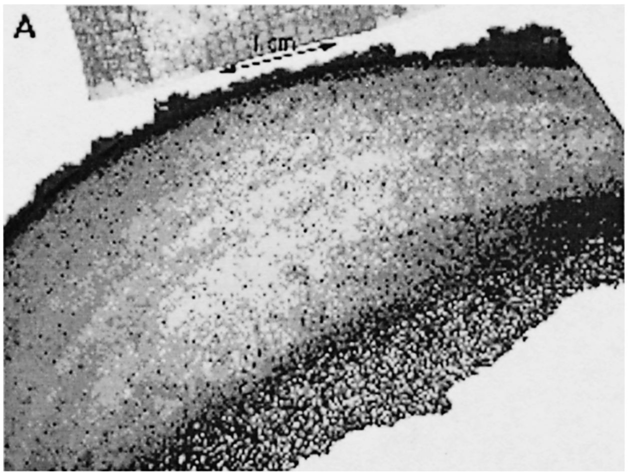

Fig. 1. Image of haematoxylin stained segment of the buccal mandible wall of a female minke whale. The colour balance has been manipulated to enhance the contrast of possible GLGs.

X-ray imaging

High resolution X-ray images of the 2001 sampled whales were taken using a human mammography X-ray apparatus (*Siemens Mammomat 3000*) at Haukeland University Hospital in Bergen, Norway. The pictures were taken using *Kodak* Min R 2000 X-ray film and, after some trial and error, the highest contrast was found at 25kV and 28mAs settings of the apparatus. Each segment was rinsed in water and images were taken at 2× magnification. Ordinary (higher intensity) X-ray technique as well as ultra-sound imaging were attempted, but the resolution of these was too low to discern any GLGs or fine structure in the mandible. Similar resolution was obtained when using mammography X-ray as when using visible light and digital camera (Fig. 2). The X-ray images were examined independently, twice by two readers to identify and count GLGs. Both readers were experienced in counting GLGs from other marine mammals, and made a subjective classification of the readability of each segment examined. Prior to the analysis, both readers and the first author examined 10 segments together to agree on criteria of how to interpret the observed structures in the mandibles.

Control of mandible aging using mandible and tooth from sperm whale

In April 1999 a male sperm whale (*Physeter macrocephalus*) stranded on a beach in Sola in southwestern Norway; sections of both the mandible and teeth of this animal were

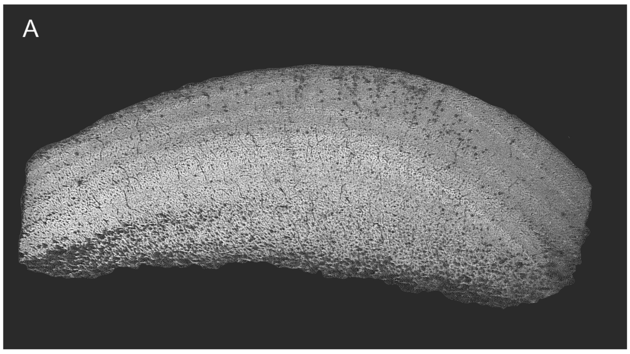

Fig. 2. Scanned X-ray (mammographic X-ray equipment) of buccal mandible wall from a female minke whale. The image was photographed at 25 kV and 28 mAs settings using *Kodak* X-ray film. Growth layers can be seen and followed through the length of the segment.

obtained. GLGs have previously been found in the mandible of sperm whales (Nishiwaki *et al*., 1961), and this sample allowed verification of whether the preparation and examination techniques used for this study were appropriate to identify the GLGs in the mandible. Three segments of the sperm whale mandible were prepared and stained in the same way as for the minke whale (Fig. 3); one tooth was cut longitudinally and the surface polished to verify whether the mandible GLG count corresponded with the tooth GLG count. Two readers independently examined the two sides of the tooth and mandible segments visually using a magnifying glass.

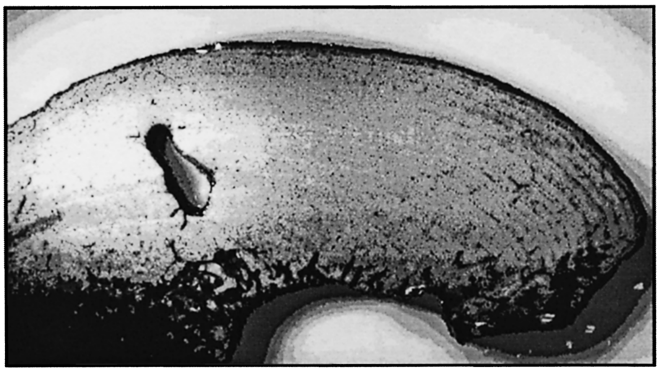

Fig. 3. Colour enhanced image of haematoxylin stained section of sperm whale mandible.

Statistical analysis

Precision of counting mandible GLGs was measured as the degree of agreement between successive readings of the same segment, or between different segments from the same animal. Precision could thus be assessed at two levels: the first at the individual reader level; and secondly between readers. In the visible light analysis the segments had been read only once, and only allowed analysis of precision between different segments, while the X-ray analysis allowed for both intra- and inter-reader analysis of precision. Possible bias of the mandible GLG count in relation to true age was examined by plotting the mean GLG count against the standard body length and number of ovulations. Body length would show a logistic growth with age levelling off around a sex-specific maximum body length, which was modelled with a von Bertalanffy growth equation:

$$Length = L_{MAX}[1 - e^{-k(age - t_0)}] \qquad (1)$$

L_{MAX} is the maximum body length, k is the growth rate, and t_0 is the age at length 0.

Linear least square regression models were fitted to the number of ovulation plots and the correlation together with the slope and intercept were examined to determine if mandible GLG counts were unbiased in relation to true age.

RESULTS

Ovary examinations

The largest group in the sample from 1999 and 2001 was females with 0 ovulations (Fig. 4) constituting > 20% of the sample. One female was estimated to have had 39 ovulations, but the majority of the sample had less than 15 ovulations. All readers agreed completely when classifying *c. lutea*, while the CV when counting *c. albicantia* was 16.7%, and 64.9% when classifying *c. artretica* (Table 1). There were some slight differences in CV between the right and left ovaries when classifying *c. artretica* and *c. albicantia*, but this was not significant. From Fig. 5 it appears there is an increase in CV with length, but there is large variability in CV for the larger (and older) whales. There was complete agreement amongst readers on the number of ovulations up to and including six ovulations, but with more ovulations, CV ranged from 0 to 44%, with a mean of 11% as compared to 6% for all females examined. This showed that as the *c. albicantia* became smaller and more numerous it was easier to misinterpret them. There seemed to be some misinterpretation of *c. albicantia* as *c. artretica* and vice versa, but in general it seemed that *c. artretica* were easily overlooked, probably due to their small size.

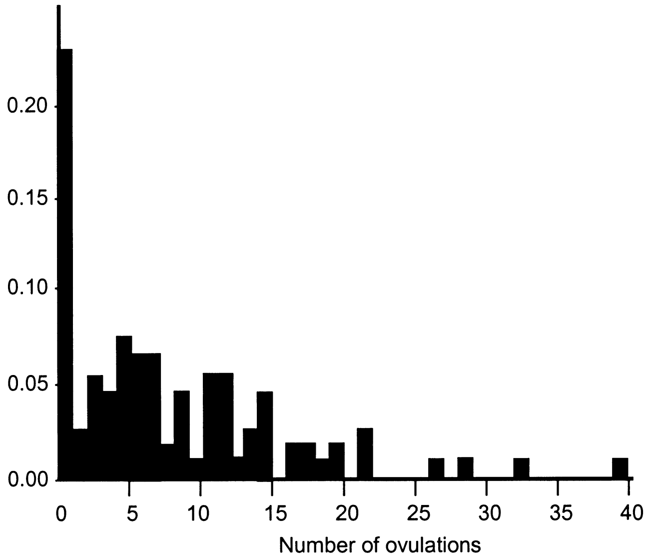

Fig. 4. Relative frequency of the number of ovulations of common minke whales caught in the North Atlantic in 1999 and 2001.

Table 1

CV of counting *corpora lutea*, *c. albicantia* and *c. artretica* in ovaries from minke whales caught in the North Sea and Norwegian Sea in 1999 and 2001. Each ovary was examined by two or three readers.

	C. lutea		*C. albicantia*		*C. artretica*		# Ovul.
	Right	Left	Right	Left	Right	Left	
All	0.0 %	0.0 %	14.8 %	18.7 %	70.6 %	61.9 %	7 %

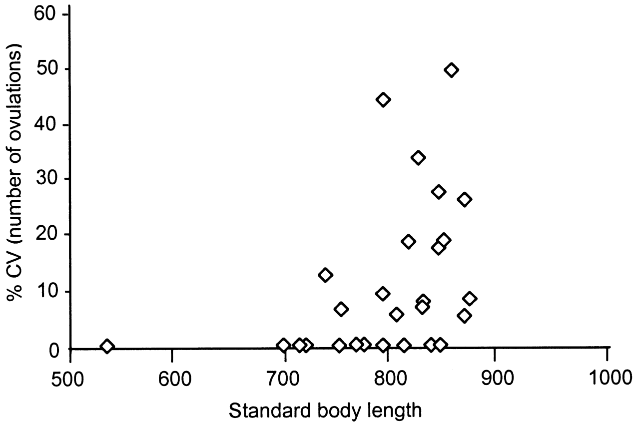

Fig. 5. CV of the number of ovulations versus standard body length.

Mandible GLGs

Mandible GLGs in the segments examined using visible light proved elusive and indistinct (Fig. 1) relative to those found in the sperm whale mandible (Fig. 3). The count of mandible GLGs (16) agreed with the tooth GLG count (16) by the three readers who examined these. Minke whale GLGs were by comparison indistinct and difficult to follow through even a small part of the segment. These difficulties resulted in high CVs of up to 165%, with an average of 82% (Table 2). There was no significant correlation between the mandible GLG count of the females and the number of ovulations, as is evident from Fig. 6. Similarly the plots of mandible GLG count versus body length (Figs 7a and b) showed a poor fit, and the model parameters for the fitted von Bertalanffy growth function indicated a maximum body length for males of 754cm, and 841cm for females. The poor fit was especially evident for the males (Fig. 7b) with very wide confidence intervals. The maximum body lengths estimated by the von Bertalanffy models were reasonable compared with the expected maximum body length from the 10% largest males and females caught from 1945 to 1994 (812cm for males and 826cm for females). However, the models would imply unrealistic lengths at birth (females: 643cm and males: 483cm), and juvenile growth rates, as well as a much larger difference in growth rate between the sexes than expected.

Interpretation of the X-ray images (Fig. 2) was easier and the GLGs observed were more distinct and easier to follow through the whole segment than in the visible light analysis. Although this increased the precision of the age estimates as compared with the visible light analysis, with CV of the GLG count averaging 41% (Table 3), it is still poor. From Fig. 8 it is evident that both readers had difficulties in interpreting the same segment in the same way in both readings. The correlation between the first and second reading was significant for both readers, but the slope of the regression line was different from the expected (1) in both cases. Neither was there any increase in deviation from the equivalence line with increasing GLG count. Fig. 9 shows that there was no relationship between the GLG count by reader B when reading the same segments as reader A. With knowledge of the poor precision and low agreement between the readers it was not surprising that a large bias was present. In the plot of GLG count versus the number of ovulations (Fig. 6) there is no correlation between the variables and a large variability in GLG count for a given number of ovulations. This variability was lower than for the visible light analysis, but still large. A von Bertalanffy growth model could not be fitted to the male data (Fig. 7b) as the sample only numbered six males. The fit to the female data was better than using the visible light GLG count, but the model parameters were biologically unrealistic with estimated length at birth of –3.43cm (1999) and 0.008cm

Table 2

Standard body length (L), numbers of ovulations with CV, number of age readings, mean GLG count with CV of 30 female and 13 male minke whales (*Balaenoptera acutorostrata*) sampled in the Spitsbergen (ES), Norwegian Sea (CM) and North Sea (EN) small management areas in 1999. GLG counts were made using visible light microscopy.

		Ovulations		Mandible		
Whale	L	Count	CV%	n	GLGs	CV%
Males						
K14	730	-	-	2	10.0	80
K18	769	-	-	2	10.0	40
K19	762	-	-	2	4.5	67
K20	730	-	-	2	7.5	40
K24	485	-	-	2	2.0	0
K25	840	-	-	2	4.5	111
K26	740	-	-	2	5.0	40
K29	832	-	-	1	9.0	
K31	820	-	-	2	1.5	67
K33	700	-	-	2	6.5	15
K35	845	-	-	2	3.5	86
N9	640	-	-	2	5.5	18
U1	701	-	-	2	7.0	29
Average	738	-	-		5.9	46
Females						
F1	620	Missing ovaries		3	7.0	0
F2	760	1.0	0	3	9.3	11
F7	760	0.0	0	3	8.0	65
F9	780	3.0	0	3	8.3	24
K1	857	12.0	0	1	4.0	
K2	840	8.7	6	2	11.0	36
K3	810	11.0	20	3	9.0	33
K4	885	14.3	8	6	11.8	107
K5	870	10.0	16	6	15.8	104
K6	776	3.0	0	6	5.7	101
K7	855	13.7	16	6	7.5	120
K8	801	10.0	61	8	6.6	161
K9	868	9.0	44	6	14.0	88
K10	845	5.0	0	6	11.0	73
K11	705	0.0	0	2	11.5	61
K12	802	11.7	40	6	10.0	118
K13	855	18.0	12	6	18.5	56
K15	858	4.0	0	6	7.8	118
K17	760	0.0	0	2	5.0	0
K21	675	0.0		2	8.0	75
K22	725	0.0	0	2	14.5	7
K23	726	0.0	0	3	5.0	69
K27	760	6.0	0	6	6.5	165
K28	835	10.0		6	8.2	108
K30	822	4.0		6	8.2	136
K34	788	6.0	0	6	7.0	70
N10	580	0.0		2	3.5	29
U2	593	0.0		2	5.5	91
U3	788	3.0		2	11.5	9
U4	822	2.0		2	7.5	13
Average	782	5.6	12		9.2	82

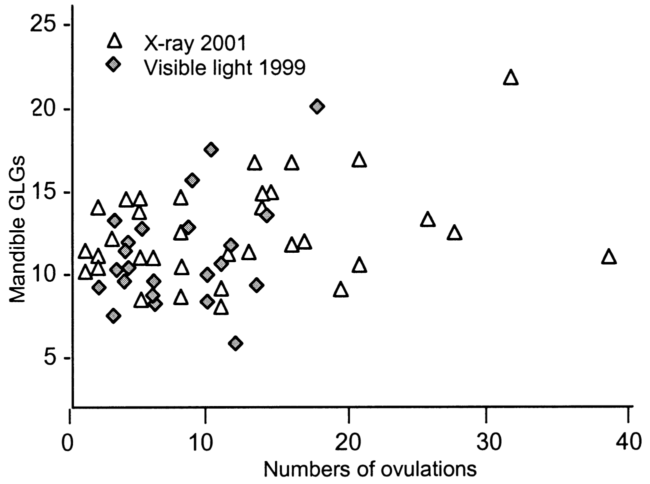

Fig. 6. Plot of ageing accuracy expressed as the relationship between the numbers of ovulations and mean mandible GLG count of females with one or more ovulations. Counts of GLGs using visible light microscopy (1999 samples) and mammographic X-ray (2001 samples) are shown.

(2001) (Table 4). Each GLG count was accompanied by a readability assessment of the segment in question. These were averaged across the readers and readings, and the combined 'quality' of a segment versus CV was plotted (Fig. 10). If the quality was related to precision, one would expect high quality segments to have a lower CV than low quality ones, and this was observed. However, little could be gained from this as the low-quality segments showed a wide spread in CV, including the CV range for the high-quality ones. Plotting only high-quality segments versus their number of ovulations or body length did not improve the correlation in Fig. 6. In addition, only 16.4% of the segments were given a combined quality score greater than 0, showing low subjective assessment of the possibility to correctly count GLGs in the mandible. Finally, the relationship between GLG count and the number of ovulations for each reader separately was evaluated, including only those segments with a CV (based on two readings by the same reader) of less than 15%. This resulted in significant positive correlation for the left mandible segments read by reader B (Fig. 11a), while for the right mandible of reader B (Fig. 11b) and both mandibles of reader A (Fig. 11c and d) the relationship was not significant. Reducing the CV criterion to 10% did not improve this result. Although Fig. 11a showed a significant positive correlation, the slope of the fitted regression line was only 0.52, implying an annual ovulation rate of 2.5 – much higher than expected for minke whales.

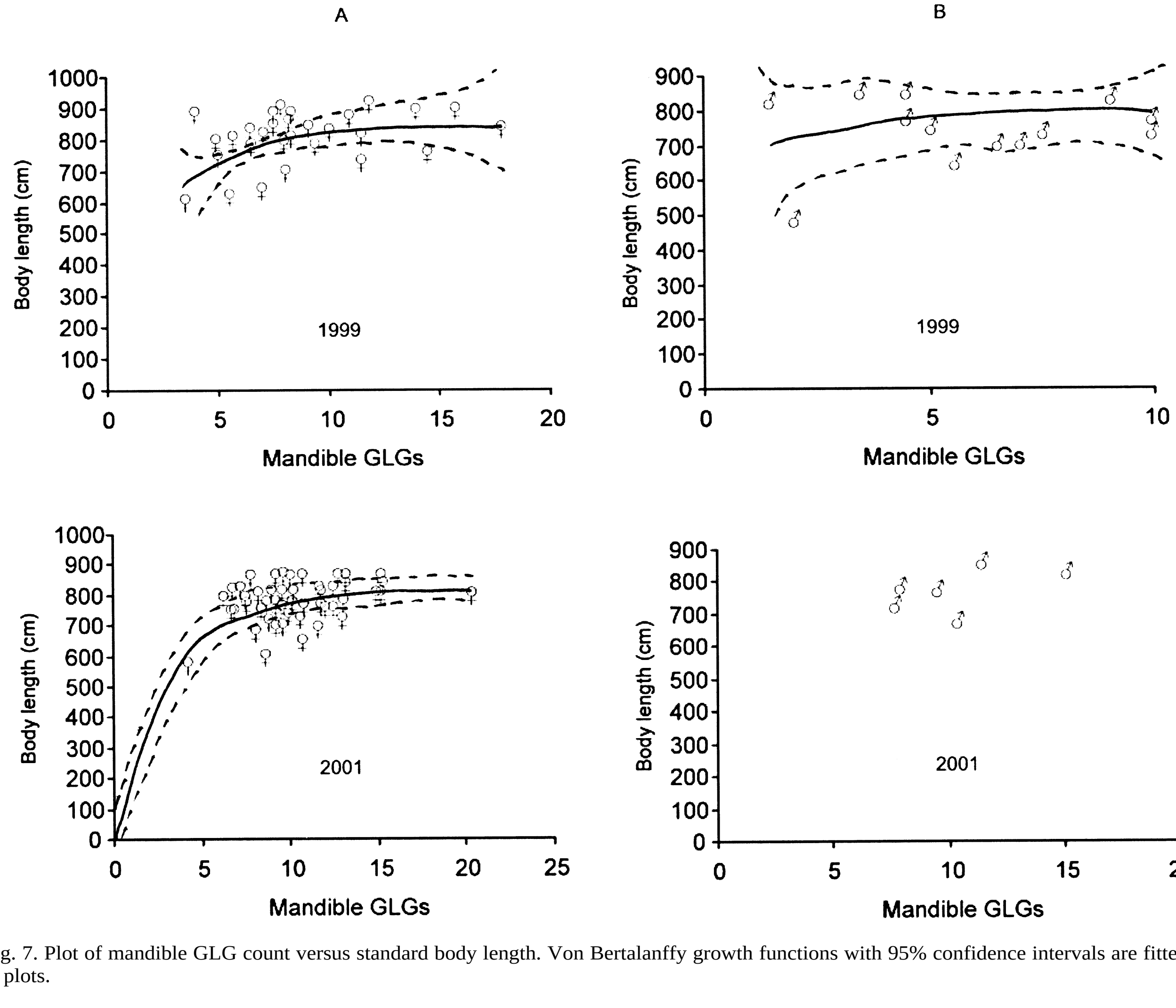

Fig. 7. Plot of mandible GLG count versus standard body length. Von Bertalanffy growth functions with 95% confidence intervals are fitted to the plots.

Table 3

Standard body length (L), numbers of ovulations with CV, number of age readings, mean GLG count with CV of 52 female and 6 male minke whales (*Balaenoptera acutorostrata*) sampled in the Spitzbergen (ES), Norwegian Sea (CM) and North Sea (EN) small management areas in 2001. GLG counts were made from high-resolution X-ray images.

		Ovulations		Mandible		
Whale	L	Count	CV%	n	GLGs	CV%
Males						
A17	670	-	-	8	10.4	36
A20	765	-	-	8	9.5	33
A25	720	-	-	8	7.8	20
A30	775	-	-	8	7.9	4
K17	816	-	-	8	15.1	81
K23	849	-	-	8	11.4	27
Mean	766				10.33	34
Females						
B1	760	6.0	-	7	6.6	87
B2	870	16.0	-	7	10.0	79
B3	830	8.0	-	8	6.9	108
B4	805	11.0	-	8	7.4	18
B5	870	13.0	-	8	9.6	41
B6	810	5.0	-	8	11.9	17
B7	760	5.0	-	8	6.8	13
B8	827	14.0	-	8	12.4	61
B9	793	4.0	-	8	9.9	40
B10	782	4.0	-	8	10.1	19
B11	697	0.0	-	8	8.0	53
B12	756	8.0	-	8	8.6	68
B13	825	17.0	-	7	10.1	55
B14	738	5.0	-	8	9.3	27
B15	794	4.0	-	8	9.5	30
B16	741	0.0	-	8	9.9	48
B17	803	2.0	-	7	8.4	54
B18	659	0.0	-	8	10.8	60
B19	822	26.0	-	8	11.6	44
B20	803	11.0	-	8	6.4	30
B21	591	0.0	-	8	4.3	53
A1	770	2.0	0	8	12.4	35
A2	720	1.0	0	8	9.6	11
A3	780	8.0	0	8	10.8	23
A4	760	11.5	6	8	9.5	73
A5	880	14.5	5	12	13.2	42
A6	730	3.0	0	8	8.6	20
A7	800	6.0	0	8	9.3	28
A8	765	2.0	0	8	9.3	20
A9	815	13.5	5	8	15.0	20
A10	740	3.0	-	8	10.4	40
A11	815	21.0	-	4	9.0	52
A12	765	1.0	-	8	8.4	52
A13	865	6.0	-	8	7.8	31
A14	870	4.0	-	8	12.8	25
A15	820	21.0	-	7	15.1	27
A16	845	14.0	-	8	13.1	24
A18	870	16.0	-	8	15.0	12
A19	845	10.0	-	8	15.1	27
A21	790	2.0	-	8	7.5	103
A22	780	14.0	-	8	11.9	25
A23	710	0.0	-	8	11.5	36
A24	805	6.0	-	8	7.4	66
A26	615	0.0	-	8	8.5	33
A27	805	32.0	-	8	20.4	27
A28	780	8.0	-	8	13.0	26
A29	740	5.0	-	8	12.9	31
A31	870	28.0	-	8	10.8	14
K18	775	5.0	0	8	12.1	34
K19	836	19.5	33	8	7.3	70
K20	783	4.0	0	8	8.6	26
K21	881	39.0	25	7	9.3	90
Mean	788	9.212	6		10.3	41

Table 4

Model parameters for von Bertalanffy growth model fitted to plots in Fig. 9.

	1999		2001	
Parameter	♂	♀	♂	♀
L_{MAX}	754	841	n.a.	809.7
k	0.42	0.22	n.a.	0.4096
t_0	-4.56	-3.93	n.a.	0.0080

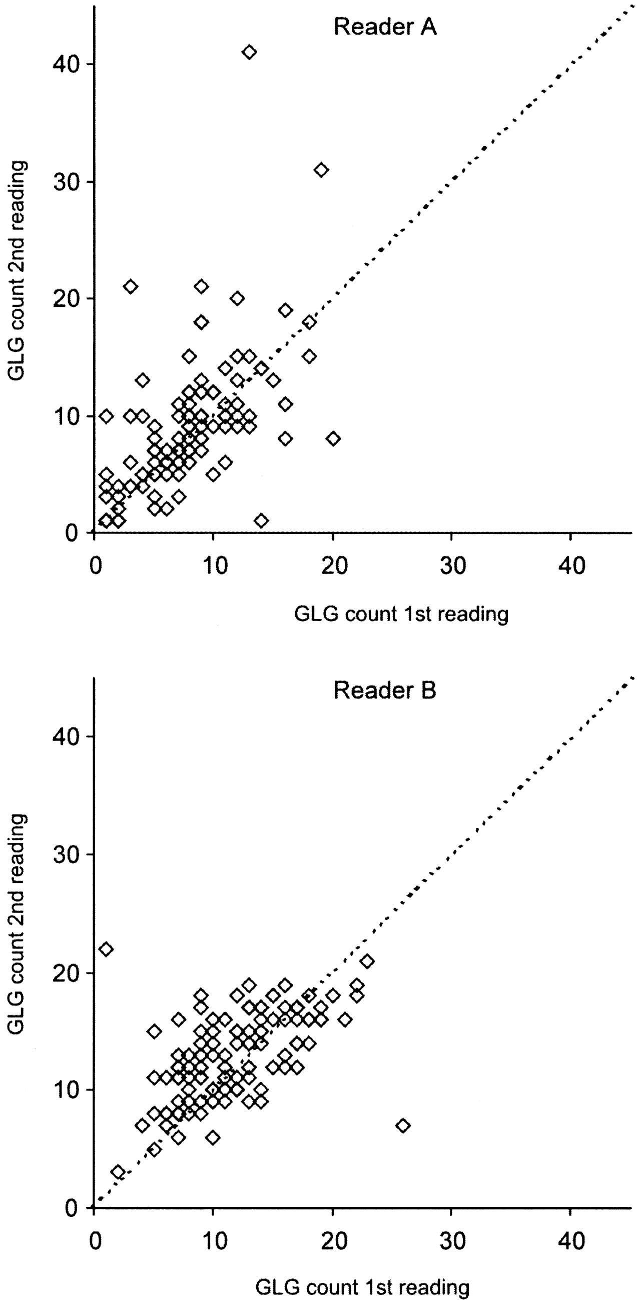

Fig. 8. Plot of intra-reader variation when counting mandible GLGs from X-ray images. The expected 1:1 equivalence line is shown.

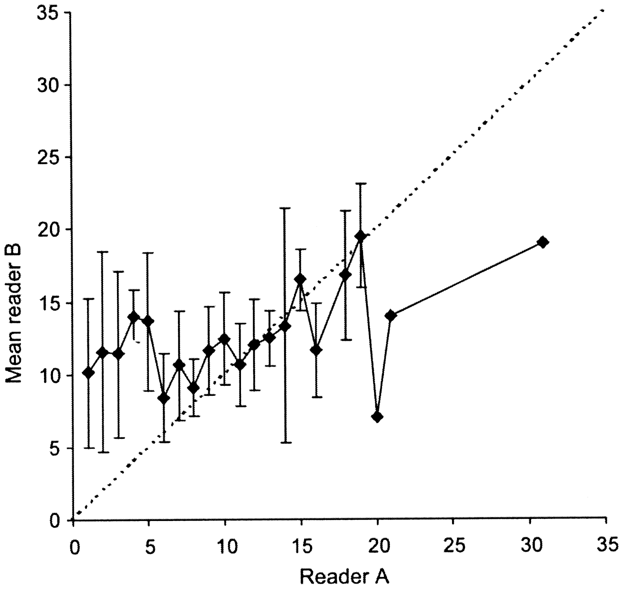

Fig. 9. Inter-reader bias plots of mandible GLG count by two readers. The *Y* axis represents the mean GLG count by reader B of all whales assigned age X by reader A. Error bars represent the standard deviation of the mean. The dotted line indicates the 1:1 equivalence line.

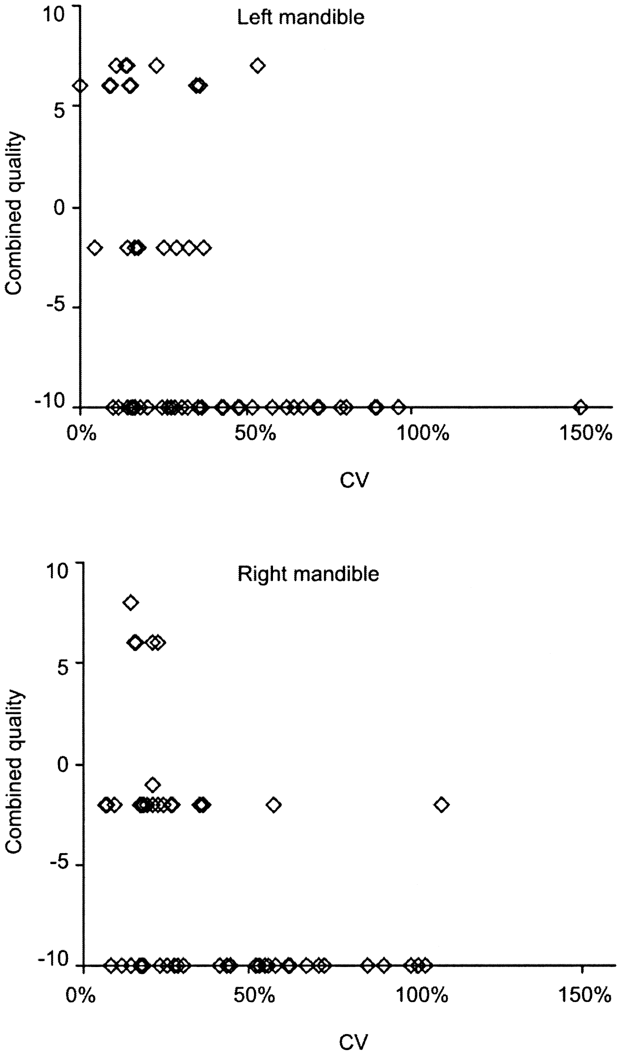

Fig. 10. The combined quality score of reader A and B for each segment from the left and right mandible plotted against the CV of the mean GLG count for each segment.

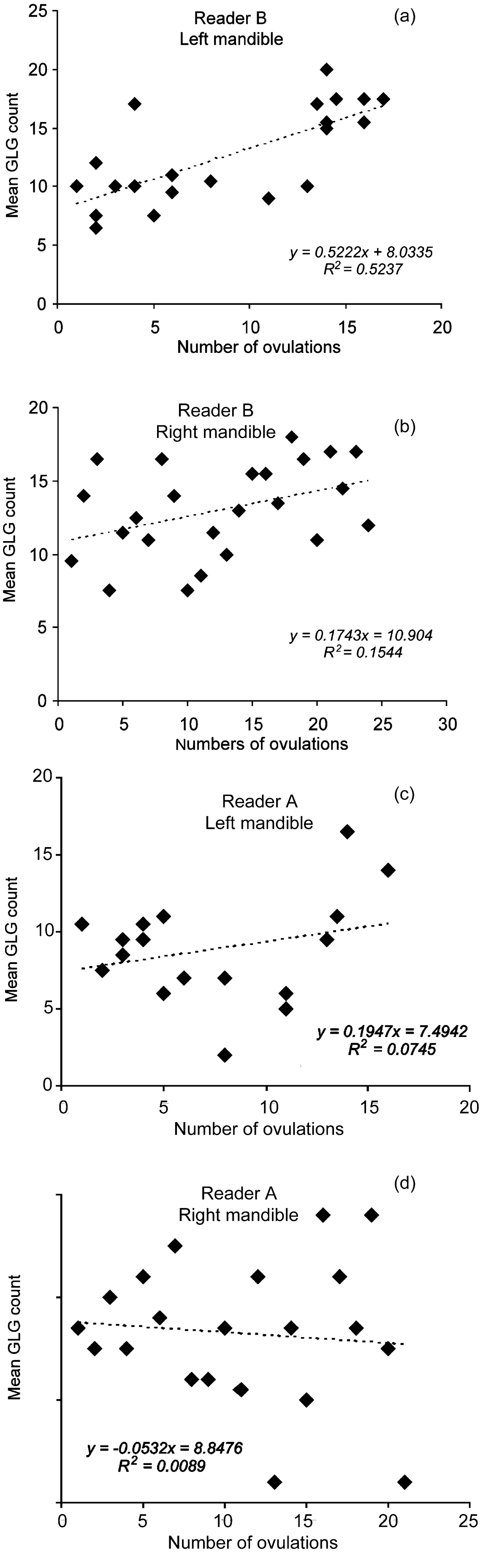

Fig. 11. The mean of two GLG counts of left (a) and right (b) mandible examined by reader B and left (c) and right (d) examined by reader A versus the numbers of ovulations. Only females with 1-19 ovulations and a CV < 15% were included.

DISCUSSION

The ovary reading experiment did reveal some variability in the way ovaries were interpreted by the readers. As expected, there was complete agreement for ovaries with few *corpora*, while variability increased with increase in total *corpora* count. A CV of 8% was found for the mature animals (excluding whales with 0 ovulations). Much of the reason for this variability appears to be caused by differences in how readers interpret small *corpus albicans* and *artreticum*, which are sometimes hard to distinguish and easy to overlook. The latter are usually smaller than *c. albicantia* (sometimes 1-2mm) and this is the most probable explanation for very high CV when counting them (Table 1). Larger *c. artretica* and *c. albicantia* can sometimes be confused with each other, as some *c. albicantia* have an orange colour, which is usually typical of *c. artretica*. However, the observed variability in corpora counts is too small to have any major implications on using the number of ovulations as an independent index of age in the comparison with GLG count. Estimated 95% confidence intervals averaged only ±2.4 *corpora* for the females where the readers did not agree on the *corpora* count. Thus the present study has shown the need for care when examining ovaries, as there is some error associated with counting *corpora*. However, this error is small, and of the same magnitude as that observed when ageing fish which are considered easy to age (e.g. haddock, *Melanogrammus aeglefinus*; Campana *et al*., 1995).

Using GLGs in the mandible of common minke whales proved to be more difficult and time-consuming than first anticipated. The sections could not be prepared or stained in a manner that brought forth the faint and elusive GLGs with acceptable clarity and distinctiveness. The experiments with the sperm whale mandible and tooth (Fig. 3) and with the harbour porpoise (*Phocoena phocoena*) teeth and mandibles (E. Olsen, unpublished results) indicated that the technique was not at fault. Rather, it appeared that common minke whales, like their larger cousins (fin, and sei whales, Klevezal and Kleinenberg, 1967) do not form GLGs in the mandibles that are clear and distinct under visible light. X-ray imaging of mandible segments gave higher contrast, and increased the readability of the GLGs, as was evident from the higher precision (low CV) of this method. From a practical perspective, X-ray imaging was simpler than the visible light analysis, as the segments used were thicker and thus easier to cut and required less treatment or staining than for the visible light analysis. The only other study using X-ray methods to elucidate GLGs was by Lockyer (1974), who attempted to use X-rays to image the earplug of sei whales with little success. In studies of GLGs in bone, it seems that X-ray methods are more appropriate and should be attempted as supplement to traditional visible light analysis. Mandible GLG counts had higher CVs than the CV of age estimates of sablefish (*Anoplopoma fimbria*; Heifetz *et al*., 1998) or Greenland halibut (*Reinhardtius hippoglossoides*; Bowering and Nedraas, 2001), two species of fish considered difficult to age.

The mandibles were thicker in larger animals, and the highly ossified buccal wall was thicker in larger than in small whales. In some minke whale mandibles, clear GLGs of two types were found. The first being narrow bands similar to those observed by Klevezal and Kleinenberg (1967) in the buccal wall of sei and fin whales. These were structurally similar to GLGs in the sperm whale and harbour porpoise mandibles examined. Also found were broader, less distinct bands using both X-ray imaging and visible light analysis. When observed, these GLGs could be followed through the whole segment, and were found within the whole highly ossified outer layer. Such wide GLGs were found either alone or together with a thin band of narrow GLGs in the outer wall. Interpretation of the observed structures was therefore difficult, and the GLG count of a segment was therefore the sum of all GLGs observed, narrow or broad. Had the GLG count been unbiased in relation to true age, one would have expected to see a linear increase in GLG count with the number of ovulations. In the case that one type of GLG was correlated with age, while the other could be considered random noise, one would still expect to find a correlation between the number of ovulations and GLG count. Such correlations were not found (Fig. 6, r^2 visible light = 0.175, r^2 X-ray = 0.134), irrespective of the method used to examine the segments.

Bone growth in the mandible is linked with absorption of bone tissue in the mandible canal (Nishiwaki *et al*., 1961) and with bone drift and compression of growth layers with increasing age (Brodie, 1969) as well as bone mobility during foetal growth and lactation. Nishiwaki *et al.* (1961) found mandibular GLGs to correlate with tooth GLGs up to 14 GLGs after which absorption seemed to equal formation of new GLGs. Bone absorption in minke whale mandibles does not necessarily start at 14 GLGs, but assuming this and an age at sexual maturity of ~8 years (Olsen, 1997), one would expect mandible GLGs and the numbers of ovulations to correlate up to 6 ovulations. However, the estimated correlation between GLG count and the number of ovulations was not significant for either examination method, in fact it was lower than when using the whole dataset. This poor fit could be explained by large variations in ovulation rate and age at sexual maturity, assumptions which are not fulfilled. Olsen (1997) found a pregnancy rate of 98% in the Northeastern Atlantic for the period 1972-1979, which would allow for some variability in ovulation rate from the hypothesised 1/yr, but far less than that needed to explain the lack of correlation in Fig. 6. Studies of Antarctic minke whales (*Balaenoptera bonaerensis*; Kato, 1983; Thomson *et al*., 1999) have not shown any short-term variability in the age at sexual maturity necessary to explain the variability in Fig. 6. Neither have there been any large-scale environmental changes in the North Atlantic which could explain a rapid increase in age at sexual maturity which would be necessary to explain the poor correlation observed. The modelled von Bertalanffy growth equations fitted to plots in Figs 7a-d yielded wide confidence intervals and biologically unrealistic parameter estimates. Fitting growth curves to such data where most animals were fully grown and few animals were sampled during the phase of most active growth limited the use of these analyses. There is some room for random error associated with the length data, but we find it highly unlikely that this is so large and biased that it could explain the poor fit of the length/GLG plots. We therefore interpret the poor fit as indicative of a large but unspecified bias in the mandible GLG count.

Lockyer (1984a) showed that there was disagreement between five readers for ~70% of a set of Antarctic minke whale earplugs examined, and Kato (1984) pointed out that 4% of all whole collected earplugs are classified as unreadable. Assigning a 'readability' criteria has been the standard procedure when reading earplugs, and a similar procedure was therefore attempted when reading the mandible segments. Introducing such a readability or quality criteria did not improve the analysis, as the GLG count of high quality segments did not have a better correlation with the number of ovulations or length than the rest of the dataset. In addition the high-quality segments constituted only 16% of all samples, which would imply that a large sample collection scheme would be needed to acquire a sufficient annual sample size for ageing.

While clearly there is continual growth in common minke whale mandibles, new bone is deposited in such a way that useful growth layers are not formed, or cannot be observed using the present technology and methods. The poor definition of mandibular GLGs in minke whales could possibly be attributed to the variable duration of the feeding season (Brodie, 1975), and the highly variable diet of North Atlantic common minke whales (Olsen and Holst, 2001).

ACKNOWLEDGEMENTS

This project was funded as part of Norwegian Research Council project number 127211/120. We wish to acknowledge the invaluable help given by Dr Audun Braathen and radiographer Tone Lønning at Haukeland Hospital in Bergen, Norway for allowing us access to the X-ray equipment and help with imaging. We also wish to thank Steinar Olsen for commenting on an earlier version of the manuscript.

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Date received: February 2002
Date accepted: April 2003

Organochlorine contaminants in cetaceans: how to facilitate interpretation and avoid errors when comparing datasets

Margaret M. Krahn*, Gina M. Ylitalo*, John E. Stein*, Alex Aguilar+ and Asuncion Borrell+

Contact e-mail: peggy.krahn@noaa.gov

ABSTRACT

This paper reviews current scientific literature to provide information for avoiding errors commonly made in comparing and interpreting datasets from laboratories measuring organochlorine contaminants in cetaceans. Before making comparisons and interpretations using heterogeneous datasets (e.g. those from different laboratories or those from different methods in the same laboratory), it is essential to consider specific information about the animals sampled (e.g. age, sex, reproductive status, body condition and health status), sampling procedures (e.g. necropsy of subsistence, stranded or bycaught individuals; remote or surgical biopsy), methods for measuring and conventions for expressing analytical results for lipids and contaminants (e.g. percent lipid, percent dry weight, contaminant concentration units, totals of contaminant groups such as PCB congeners) and quality assurance performance. Reformatting should be carried out, as necessary, to unify the datasets (e.g. into like units and weight basis) and allow a critical evaluation of the data to be made. As part of the data interpretation, caveats or limits in the comparability of the datasets (based on quality assurance results) should be provided. In addition, the biological relevance of the data must be considered in interpreting the datasets.

KEYWORDS: POLLUTANTS; POLLUTANT BURDEN; ORGANOCHLORINES; BIOPSY SAMPLING

INTRODUCTION

Levels of toxic contaminants in marine mammals at or near the top of the marine food web, as well as in their prey, are needed to provide important information on how contaminants are transferred between trophic levels and how contaminants affect biota at all trophic levels (AMAP, 1998; Reijnders *et al.*, 1999). Some marine mammals may be at risk from contaminants (even when environmental concentrations are relatively low) because of their biology, physiology or ecology. For example, the transfer of PCBs and DDTs from the female to their offspring is widely observed in marine mammals (Muir *et al.*, 1992; Aguilar and Borrell, 1994b; Norstrom and Muir, 1994; Lee *et al.*, 1996; Krahn *et al.*, 1997; Beckmen *et al.*, 1999). This transfer of a significant portion of the organochlorine (OC) contaminant burden from a female to her offspring, particularly during sensitive portions of the foetal and neonatal life cycle phases, could result in serious health problems. The offspring of primiparous females whose body burdens of contaminants are particularly high are especially vulnerable (Aguilar and Borrell, 1994b; Beckmen *et al.*, 1999; Ylitalo *et al.*, 2001). High concentrations of OCs have been associated with reproductive impairment, immunosuppression, alteration in bone development and growth, and increased susceptibility to disease (Brown, 1986; Reijnders, 1986; Olsson *et al.*, 1994; De Guise *et al.*, 1996; 1997; Kamrin and Ringer, 1996; Ross *et al.*, 1996; Zakharov *et al.*, 1997; Beckmen *et al.*, 1999), but direct cause-effect linkages remain unproven.

The assessment of differences and trends among populations and species, geographical regions and time periods is a central issue in evaluating the impact of OCs on marine mammals and is often required for determining the status of particular populations or their environment. This evaluation usually requires combining data from a variety of studies (both intra- and inter-laboratory) involving heterogeneous sample sets and dissimilar methods of analysis and interpretation. There are a number of confounding factors: sampling methods (e.g. necropsy of stranded or harvested individuals compared to biopsy techniques); analytical methods (e.g. use of different analytical methods or absence of quality assurance procedures); and biological factors (e.g. age, sex, reproductive status, nutritive condition) that can profoundly affect the ability to make a meaningful comparison. This review combines biological perspectives with the necessary knowledge of environmental chemistry to allow scientists to more readily and accurately compare data among studies.

CETACEAN SAMPLING METHODS

Necropsy sampling

Necropsy sampling is commonly used to process the carcasses of cetaceans harvested by subsistence hunters or for research, taken as ‘bycatch’ or found stranded. The systematic examination and collection of tissue samples during necropsy will not be described here, but details of the proper conduct of a necropsy can be found in papers such as Rowles *et al.* (2001). Record keeping is exceptionally important during necropsy and each sample should be identified with a unique sample number, animal identification number, a species code, a site code and the date. In addition, parameters such as length, weight and sex of the animal are recorded. Appropriate tissues should also be collected for ageing each animal (e.g. teeth of odontocetes or earplugs of mysticetes).

Thought should be given when sampling to the requirements (e.g. quality or freshness of the sample) for the analyses to be conducted. When samples originate from stranded or bycaught animals, the animals are most probably necropsied at unknown post-mortem times and this is likely to have an effect on contaminant and lipid levels in tissues (Aguilar *et al.*, 1999; Krahn *et al.*, 2001), as well as on

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* *Environmental Conservation Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Boulevard East, Seattle, WA 98112, USA.*

+ *Department of Animal Biology and Parc Cientific de Barcelona, Faculty of Biology, University of Barcelona, 08071 Barcelona, Spain.*

physical and biochemical indicators of exposure (e.g. hormones, immune parameters, enzyme induction). For example, if the carcass is exposed to sun or wind, lipid can be lost or decomposed and volatile contaminants can evaporate (Borrell and Aguilar, 1990; Krahn *et al.*, 2001). It is therefore recommended, whenever possible, to sample and analyse only reasonably fresh specimens. Investigation of the effects of post mortem times on measured pollutant levels is an important component of phase I of the POLLUTION 2000+ programme.

The age, and sometimes the sex composition, of stranded cetaceans can reflect a pattern of the specific mortality rate rather than the actual age and sex structure of the population. This occurs because neonates and senescent animals are more common among stranded animals than are juveniles and young adults. Moreover, the sex ratio or age-class composition of strandings can be affected by a number of factors, such as the occurrence of sex-specific disease or the geographical segregation of sexes or certain age groups (Sigurjónsson and Rorvik, 1983; Reijnders, 2003). A bias of this type may also occur in bycaught animals. For example, the data sets of dolphins killed by net entanglements usually show a severely skewed distribution, often with a higher representation of males and young individuals (Gearin *et al.*, 1994; Kinze, 1994; Silvani *et al.*, 1999). Comparisons between datasets should, whenever possible, ensure that the age and sex composition of the sub-samples are homogeneous. If this is not possible, comparisons should only be made between comparable groups (i.e. newborns, juveniles, adult males, adult females) or should be statistically adjusted. Since OC concentrations increase with age in males, the range of variability in this gender may be as high as six-fold (Aguilar *et al.*, 1999). If age of specimens cannot be determined, comparisons between female sub-samples are less likely to be affected by the heterogeneity in age structure.

Biopsy sampling

Biopsies are ‘non-destructive’ techniques for obtaining tissue samples from live, ‘free-ranging’ cetaceans (Fossi *et al.*, 1997). Biopsy samples are small sections (0.2-4g) of epidermis and underlying blubber. Samples can be obtained from smaller cetaceans (captured and released) using a biopsy punch or a surgical procedure. In addition, remote sampling of larger cetaceans can be conducted using a modified gun or crossbow to shoot a biopsy dart (5-9mm diameter and 20-100mm long) into the side of a free-ranging animal (Aguilar and Borrell, 1994a; Fossi *et al.*, 1997; Weller *et al.*, 1997). The sex of the animal sampled can be determined in the laboratory by PCR amplification of sex-specific DNA regions of the sex chromosomes (Bérubé and Palsbøll, 1996).

Biopsy sampling is often the primary means of obtaining samples from cetacean species that rarely strand, are not usually harvested or have been designated a protected species. In addition, these samples are easier to obtain on a sustained basis, provide better quality samples than those from stranded animals (because tissues, as well as certain contaminants and physiological parameters, degrade following death) and can be considered a reasonable representation of OC concentrations in the specimen sampled (Aguilar and Borrell, 1994a; Aguilar *et al.*, 1999). Unfortunately, there are limitations to this technique, particularly when biopsy darts are used. For example, most currently used darts are only able to extract epidermis and the outer layer of blubber from large whales. Researchers have demonstrated that the lipid content and composition differ between the outer and inner blubber layers in some species (Sigurjónsson and Rorvik, 1983; Aguilar and Borrell, 1991; Koopman *et al.*, 1996), so biopsy samples may not provide results identical to those of ‘full-thickness’ blubber samples in these species (see the discussion in the section ‘Blubber stratification’ below). A biopsy tip that avoids this limitation by sampling the whole blubber thickness in large whales has been designed (Lambertsen *et al.*, 1994), but has so far been used on very limited occasions because of its invasive nature.

The age of a cetacean cannot be determined from a biopsy sample alone and this information is important, because lipophilic contaminants can be accumulated throughout the entire life span of marine mammals. The sex and reproductive state of a cetacean are also significant, because females can transfer contaminants to offspring through gestation and lactation and therefore a stabilisation or a decrease in contaminant concentrations takes place (Aguilar *et al.*, 1999). Some techniques have been developed to determine sex from muscle and potentially other tissues, although they have not yet been widely applied to field studies (Yoshioka *et al.*, 1994). If, however, biopsy sampling is combined with photo-identification techniques and long-term tracking of animals (Smith *et al.*, 1999; Ylitalo *et al.*, 2001), both the sex and reproductive status of individuals can often be determined. Having this information greatly improves the ability to interpret data obtained from biopsy samples.

ANALYTICAL METHODS FOR DETERMINING CONTAMINANTS

Detailed methods

Detailed methods are employed to determine tissue concentrations of numerous individual OC contaminants (i.e. PCB congeners and pesticides) using a single analytical procedure. The multi-step procedure generally includes extraction, clean-up and instrumental determination of analytes. In the extraction step, each sample is weighed and then a solvent (e.g. dichloromethane or hexane) and a drying agent (e.g. sodium sulphate) are added and the mixture is ‘homogenised’, i.e. cut into very small pieces through use of an apparatus such as a ‘Tissumiser’ (Krahn *et al.*, 1988). Alternative extraction methods use a Soxhlet extractor (Schantz *et al.*, 1996) or an automated accelerated solvent extractor (Weichbrodt *et al.*, 2000) to extract the contaminants and lipid from tissue.

Since some endogenous components (e.g. lipid) are extracted along with the contaminants, a two-step clean-up process is generally used, because a single step is usually insufficient to remove all the interfering compounds. One step in sample clean-up is generally elution of the extract through a gravity-flow column of silica/alumina (Krahn *et al.*, 1988) or florisil (Muir *et al.*, 1988; 1990; Newman *et al.*, 1994; Stern *et al.*, 1994) to remove some of the endogenous materials. Size-exclusion chromatography (SEC) is often used as another step in removing co-extracted materials (Krahn *et al.*, 1988; Muir *et al.*, 1988; 1990; Stern *et al.*, 1994; Schantz *et al.*, 1996) and can be carried out before or after the gravity-flow column step. An alternative one-step clean-up method consists of treating the extract with an acid (e.g. sulfuric acid) which degrades the cellular material (Murphy, 1972; Smith *et al.*, 1990). This method is fast and effective, but has definite limitations. In particular, the acid degradation also oxidizes certain pesticides (e.g. aldrin, dieldrin, heptaclor, heptaclor epoxide) and these contaminants cannot be determined because their degradation products remain on the clean-up column. This method is of most use when the target compounds are acid resistant (e.g. PCBs, DDTs, hexachlorocyclohexanes (HCHs)).

Finally, gas chromatography (GC), an analytical technique that separates individual contaminants from each other, is used for resolving the contaminants (Wells *et al.*, 1993). In GC, compounds pass through the column (i.e. elute) at different rates. This allows the identification of various contaminants by their 'retention time' (time between injection and detection). Usually, the GC is equipped with either an electron capture detector (Krahn *et al.*, 1988; Muir *et al.*, 1988; 1990; Newman *et al.*, 1994; Stern *et al.*, 1994; Schantz *et al.*, 1996) or mass spectrometer (MS) detector (Reddy *et al.*, 1998) in order to measure the retention times and quantities of the compounds. In addition, if a MS detector is used, each compound is fragmented and these fragments form a pattern ('mass spectrum') that can be matched with an electronic library of spectra in order to identify the compound.

Detailed methods are advantageous because concentrations are provided for numerous individual OC contaminants and can be used with various statistical techniques (e.g. principal component analysis) to recognise variations in 'patterns' or 'fingerprints' of OCs in cetaceans from different stocks or geographical regions (Muir *et al.*, 1996; Krahn *et al.*, 1999). In addition, measuring concentrations of as many individual PCB congeners as feasible can increase the accuracy of 'total PCBs' (see 'Summed PCBs' below).

Rapid (screening) methods

A major challenge confronting environmental scientists is developing accurate and cost-effective analyses for measuring persistent contaminants in marine biota (Krahn *et al.*, 1994). Often, analytical time and costs can be greatly reduced by first employing rapid 'screening' methods to estimate contaminant concentrations (Krahn *et al.*, 1993; 1994). Based on the results of the screening analyses, a subset of samples can then be selected for detailed analyses (e.g. GC/MS) that can confirm the concentrations and identities of the contaminants. Screening methods often use high-performance liquid chromatography (HPLC) with ultraviolet photodiode array (PDA) (Krahn *et al.*, 1994; Ylitalo *et al.*, 2001) or fluorescence detection (Krahn *et al.*, 1993).

Rapid methods generally have fewer steps in the analytical procedure. Tissues are extracted using any of the methods described in 'Detailed methods' above. Next, a single clean-up step is used to remove endogenous materials and lipid, providing considerable savings in time and materials. For example, an extract can be chromatographed on a gravity-flow clean-up column, consisting of acidic, basic and neutral silica gel, to separate the analytes from interfering compounds in the tissue (Krahn *et al.*, 1994; Ylitalo *et al.*, 2001). Finally, the OCs are chromatographed on an HPLC column that separates the analytes according to their planarity and chlorination level and a UV photodiode array detector is used to measure the retention times, quantities and spectra of the compounds (Krahn *et al.*, 1994; Ylitalo *et al.*, 2001).

Although rapid methods are more cost-effective than detailed methods, they are generally limited to measuring fewer analytes than can be determined by GC/MS (Krahn *et al.*, 1994; Ylitalo *et al.*, 2001). However, this limitation can be overcome by reanalysing the extract prepared for the rapid method using GC/MS to measure additional analytes (Herman, pers. comm.). This GC/MS procedure does add some time and expense, but it still is cost-effective. The greatest drawback of rapid procedures that measure OCs is that certain pesticides (e.g. dieldrin and heptaclor epoxide) are degraded during the clean-up step.

Comparing results when analytical methods differ

There are procedures available to ensure that comparable data are obtained from two or more laboratories that use substantially different methods (or indeed similar methods). The first is to have each laboratory analyse splits of the same samples and then compare the results. Often, this approach is not reasonable (e.g. split samples may not be homogeneous) or possible (e.g. insufficient sample available). Furthermore, such analyses provide information on whether results are comparable among laboratories, but not on their accuracy. Ideally, each laboratory providing datasets should also provide related quality assurance information (see the section on 'Quality assurance procedures'). Then, quality assurance results (e.g. performance for analysing standard reference materials (SRMs) or results from Interlaboratory Comparison Exercises) can be assessed to determine each laboratory's accuracy. If the results from SRMs are similar among the laboratories, it is reasonable to assume that other data from these groups would also be comparable. However, this assumption should be made only for groups of similar analytes; thus, two laboratories may produce highly comparable PCB results for the SRM, but the determination of DDTs may differ substantially.

Conventions for summing groups of contaminants

The result of the analyses for certain OC groups are usually presented – not as the concentration of the individual chemicals – but as the sums of the various individual chemicals of a group (e.g. summing the PCB congeners to determine a 'total PCB' concentration). This is an important element to be taken into account when comparing sample sets analysed by laboratories using different procedures for calculating 'total' concentrations.

Summed PCBs

Summed PCBs (ΣPCBs or total PCBs) is the most difficult summed group to compare among studies, because there are many conventions for expressing this quantity. In the 1970s and 1980s, PCBs were commonly measured by comparing the pattern from a low resolution GC chromatogram to that of a commercial Aroclor product (e.g. 1254, 1260) and calculating how much Aroclor was present ('Aroclor equivalents'). When high resolution GC columns came into common usage in the 1980s, laboratories started measuring individual PCB congeners. Ideally, a laboratory should have the ability to measure all 209 PCB congeners individually and total their quantities to arrive at ΣPCBs. Unfortunately, it is exceptionally difficult to resolve the 209 PCB congeners by GC, unless a complicated 'multi-dimensional' GC technique is used (Schultz *et al.*, 1989). Furthermore, only recently have commercial standards been available for all PCB congeners. Thus, most laboratories routinely measure only a fraction of the total congeners (e.g. numbers of PCB congeners measured: 10 (AMAP, 1998), 88 (Muir *et al.*, 1996) or 136 (Ross *et al.*, 2000)), sum the congeners measured and then report the sum as ΣPCBs or 'total PCBs'. In most instances, the sum represents the major congeners (those present in largest quantities), but the total is still underestimated. Alternatively, the US National Status and

Trends Program recommended summing 17 particular PCB congeners and then multiplying this sum by 2 to provide a reasonable estimate of the total PCBs by measuring only a few congeners (Lauenstein *et al.*, 1993). However, this method tends to overestimate 'total PCBs' in marine mammals that are capable of metabolising PCB congeners, because the more recalcitrant PCBs are among the 17 measured. Thus, ΣPCBs is an estimate of total PCBs present in the sample and the degree of accuracy of ΣPCBs depends on the method used to calculate this sum.

Summed DDTs

Summed DDTs (ΣDDTs) is most often calculated by summing *o,p'*-DDD, *p,p'*-DDD, *o,p'*-DDE, *p,p'*-DDE, *o,p'*-DDT and *p,p'*-DDT. However, some investigators report the sum of *p,p'*-DDD, *p,p'*-DDE and *p,p'*-DDT instead, so care must be taken to determine which compounds are included in the total before comparisons are made. Unfortunately, some publications report only *p,p'*-DDE and others do not detail the exact method used to calculate ΣDDTs. However, *p,p'*-DDE occurs in the greatest proportion; thus, reporting only *p,p'*-DDE generally does not contribute to large errors when datasets are compared.

Summed chlordanes

Summed chlordanes (Σchlordanes) is usually calculated by summing *cis*-chlordane, *trans*-chlordane, oxychlordane, *cis*-nonachlor, *trans*-nonachlor, nonachlor III, heptachlor and heptachlor epoxide. However, some laboratories measure fewer chlordane-related compounds for Σchlordanes. Again, it is necessary to determine which compounds are included in the total before comparisons are made.

Summed HCHs

Technical HCH is a mixture of α-, β-, γ- (lindane) and ∂-HCH. Many laboratories do not determine all these isomers, so they report only two or three, usually α-HCH and γ-HCH, sometimes adding β-HCH. Thus, caution should be exercised when comparing sums of the HCHs.

Summed toxic equivalents

Exposure of marine mammals to and possible health risks from polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and other compounds that exhibit 'dioxin-like' toxicity (i.e. certain PCB congeners) can be measured by calculating 'toxic equivalents' (TEQs). TEQs are calculated according to an additive model of toxicity (Safe, 1990) in which the molar concentration of each dioxin-like congener is multiplied by the appropriate toxic equivalency factor (TEF; a measure of toxicity relative to that of 2,3,7,8-tetrachloro-dibenzo-*p*-dioxin) (Van den Berg *et al.*, 1998). The individual TEQs are then summed to determine ΣTEQs. Not all laboratories routinely measure PCDDs and PCDFs, so TEQs may be reported based on dioxin-like PCBs only. In marine mammal samples, concentrations of PCDDs and PCDFs are generally low, so the majority of the ΣTEQ contribution is from PCBs (often > 80%) (Ross *et al.*, 2000), so ΣTEQs derived from PCBs may be a reasonable measure of total TEQs in cetaceans. Because several different TEF schemes have been developed in the last decade, determining which set of TEFs each study used to calculate TEQs is very important. The TEFs established by Safe (1990) were revised in 1994 following international agreement at a workshop sponsored by the World Health Organisation-European Centre for Environment and Health (WHO-ECEH) and the International Programme on Chemical Safety (IPCS) (Ahlborg *et al.*, 1994). Subsequently, these TEFs were refined at an expert meeting organised by WHO in 1997 (Van den Berg *et al.*, 1998). Thus, publications before 1999 generally use the older TEFs. Therefore, care must be taken when comparing the older studies to those using newer TEFs, because some of the TEFs have been revised for several compounds and some formerly 'toxic' PCBs (congeners 170 and 180) have been withdrawn from the list.

ANALYTICAL METHODS FOR DETERMINING PERCENT LIPID

Gravimetric methods

There are a number of lipid extraction and analysis procedures available (Wells, 1993), but the method most often used as the 'gold standard' was reported by Bligh and Dyer (1959). This method involves extraction of the sample with chloroform and methanol in carefully controlled ratios. Another commonly used procedure measures the percent lipid in an aliquot of the extraction solvent used for contaminant determinations, quite often made using dichloromethane or hexane as solvents (Schantz *et al.*, 1993; Honeycutt *et al.*, 1995; Krahn *et al.*, 2001). The solvent is evaporated and the lipid is weighed. Because this technique extracts other endogenous material besides lipid, this is often called the 'total extractable' method. Researchers should be aware that different solvents are likely to produce different amounts of extractable material, which can markedly affect 'percent lipid' values (see below).

Instrumental method

A relatively recent innovation in lipid methods has been the use of a thin layer chromatography/flame ionisation detection (TLC/FID) micromethod (Iatroscan) in which total lipids, as well as lipid classes, can be determined concurrently (Parrish, 1987; 1998; Shantha, 1992; Krahn *et al.*, 2001). The advantages of this method include rapid analytical times, improved precision and accuracy and high sensitivities. There are some limitations to this method, such as the need for careful instrument calibration to achieve accurate quantitation (Crane *et al.*, 1983; Rao *et al.*, 1985; Shantha, 1992).

Comparing results when lipid methods differ

When percent lipid data are produced using different lipid methods, it is necessary to exercise care when comparing data presented as 'lipid weight' (see 'Lipid weight' discussion below). Solvents are particularly critical in this respect. For example, the chloroform-methanol mixture is more polar, and therefore able to extract a larger fraction of polar lipids (e.g. phospholipids), whereas hexane, a more neutral solvent, has a higher affinity for neutral lipids (e.g. triglycerides). For example, Randall *et al.* (1998) reported that a three- to five-fold variation in OC concentrations in fish muscle (lipid weight basis) is introduced using different lipid extraction methods. In general, lipid percentages determined by TLC/FID are lower than those determined using the 'total extractables' method. In one study, Delbeke *et al.* (1995) determined lipid in tissues of various marine species by both the 'total extractables' and TLC/FID methods. Although the lipid values determined by both methods were correlated, the lipid concentrations determined by TLC/FID were, on average, half as great as those determined by the gravimetric method. Another study (Krahn *et al.*, 2001), which measured percent lipid in blubber of gray whales (*Eschrichtius robustus*) by both the TLC/FID and ‘total extractables’ methods, found that the results were not statistically different.

CONCENTRATION UNITS COMMONLY USED IN CONTAMINANT ANALYSES

Before making a comparison of datasets from two or more sources, it is essential to establish that the concentration units used are the same for each dataset. If not, the numbers must be converted into like units (Table 1). Usually, an investigator will report the units that are conventionally used for the analytes measured or, alternatively, the units preferred by their laboratory. Investigators must provide units (e.g. ng/g wet weight) when entering numbers into text, tables and figures. Otherwise, the data cannot be properly interpreted, particularly if the units cannot be determined from information provided elsewhere in the document.

Three common formats for describing contaminant concentrations (wet, dry and lipid weight) are presented below. Investigators who report data using only one of these formats should be encouraged to provide enough additional information (i.e. percent lipid and/or percent dry weight), so that other researchers can recalculate the data in one of the other formats. This reformatting of data may be necessary so that data from two studies can be compared, or to allow a researcher to use the information for a purpose different from that of the original investigator (e.g. for use in human health risk assessments or for determining temporal or spatial trends). Again, it is critically important that every measurement reported have an associated set of units, including the designation ‘wet weight’, ‘dry weight’ or ‘lipid weight’. If this information is missing, no comparisons can be made with other data.

Wet weight

Contaminant concentrations are calculated by measuring the amount of a contaminant in a weighed portion of a tissue (as received, i.e. wet weight — sometimes called fresh weight). For example, if 50ng of hexachlorobenzene (HCB) is measured in a 2g tissue sample, the concentration of HCB would be reported as 50ng HCB/2g sample = 25ng/g, wet weight (w.w.).

The wet weight format is used in studies where the tissue is consumed (either by humans or other predators), as well as for other toxicological interpretations. It should be noted, however, that this format is particularly sensitive to tissue freshness because water — which is a main component in many tissues — is rapidly lost not only during decomposition, but also during freezer storage (where the potential for water loss increases as the storage temperature increases).

Dry weight

Contaminant concentrations can be calculated on a dry weight basis to offset the variability in concentrations caused by variations in water content of tissues. First, the dry weight of a tissue is determined by weighing a sample (as received, but a different portion from that used for contaminant determinations) and then the water is evaporated in a drying oven. The dried tissue is re-weighed and the percent dry weight is calculated as follows: Percent dry weight = weight of tissue after drying/weight of tissue (wet) × 100.

The dry weight of a contaminant is then calculated by dividing the wet weight concentration by the dry weight fraction (percent dry weight/100). For example, if the percent dry weight of the tissue in the first example is 20% then: 25ng/g HCB (wet weight)/0.20 (dry weight fraction) = 125ng/g, dry weight (d.w.).

Note that the dry weight determination is always conducted on a different portion of the sample from that used for contaminant determinations, because the heat used to dry the sample could result in loss of volatile analytes. The dry weight format is generally not used for blubber samples of marine mammals (because blubber has a low water content and can be difficult to dry), although it is often used for liver, kidney, muscle and other tissues, particularly when comparing contaminant concentrations among tissues. Note that some laboratories report ‘percent water’ in tissues and a calculation must be performed to obtain percent dry weight: percent dry weight = 100 – percent water.

Lipid weight

Lipid is extracted from a tissue, the solvent is removed and the remaining lipid is weighed (see the section ‘Analytical methods for determining percent lipid’). Lipid weight is then calculated by dividing the wet weight concentration of a contaminant by the lipid fraction (percent lipid/100).

For example, if the tissue sample in the example above contains 50% lipid, the concentration of HCB expressed in lipid weight would be: 25ng/g HCB (wet weight)/0.50 (lipid fraction) = 50ng/g, lipid weight (l.w.).

Lipid weight is often used to compare contaminant concentrations among different tissues in the same animal (see ‘Lipid normalisation’ below). In addition, comparisons of contaminant concentrations among different species or different studies are often made on a lipid weight basis to control for varying lipid content. This may be particularly useful when comparing specimens with dissimilar body condition or when analysing non-fresh samples. However, comparisons of different studies on a lipid weight basis should be made cautiously, because there are a number of analytical methods used to determine percent lipid and the lipid values can vary appreciably, depending on method selected (see ‘Comparing results when lipid methods differ’). In addition, some investigators believe (Hebert and Keenleyside, 1995) that contaminant concentrations should not be reported on a lipid weight basis unless these two

Table 1

Equivalencies for commonly used analytical units.

Equivalent units			Formulas for converting between units	Comments
ppm* (part per million)	μg/g ($\mu g_* g^{-1}$)	mg/kg ($mg_* kg^{-1}$)	# ppm = # ppb/1,000 = # ppt/1,000,000	Used for concentrations of organics and metals
ppb (part per billion)	ng/g ($ng_* g^{-1}$)	μg/kg ($\mu g_* kg^{-1}$)	# ppb = # ppm x 1,000 = # ppt/1,000	Most common units for concentrations of organics
ppt (part per trillion)	pg/g ($pg_* g^{-1}$)	ng/kg ($ng_* kg^{-1}$)	# ppt = # ppb x 1,000 = # ppm x 1,000,000	Used for toxic equivalents (TEQs)

*1 ppm = 1,000 ppb = 1,000,000 ppt.

factors are correlated (see the section on ‘Lipid normalisation’ below). Finally, when percent lipid information is not available, comparisons of contaminant data can still be made on a wet or dry weight basis.

LIPID ‘NORMALISATION’

Concentrations of lipophilic contaminants are often ‘adjusted’ for variation in tissue lipid content (see the section on ‘Lipid weight’ above). This adjustment is performed because it is assumed that lipophilic contaminants such as OCs accumulate in proportion to tissue lipid content. Lipid-adjusted (‘normalised’) data are used in a variety of applications, such as modelling biomagnification in food webs and examining differences in contaminant levels among tissues or species. Lipid normalisation is usually accomplished by dividing tissue contaminant concentrations by the corresponding lipid fraction to form a ratio (ratio approach; see the section ‘Lipid weight’ above) and it is assumed that this procedure eliminates the influence of lipid covariation. However, previous studies (Hebert and Keenleyside, 1995) have shown that this normalisation of contaminant concentrations to total lipid does not correct for variation in the lipid unless these factors are correlated. There is some evidence that contaminant concentrations do not correlate with total lipid when a marine mammal undergoes cyclic deposition and mobilisation of lipid stores, because the rates of mobilisation and deposition of pollutants are not identical to those of lipids (Aguilar, 1987). Moreover, even if the lipid content is similar among different tissues, their qualitative composition may markedly vary (see below). Even when contaminants and lipids are correlated, using the ratio approach to normalisation may lead to misleading conclusions and then an alternative normalisation approach (e.g. analysis of covariance) should be used (Hebert and Keenleyside, 1995).

The normalisation approach also has other limitations resulting from: (1) variations in lipid extraction and analysis procedures; (2) differences in contaminant partitioning among different lipid classes (e.g. neutral or polar); (3) very low lipid content of tissues; and (4) seasonal or physiological changes in lipid percentages or composition. Randall *et al.* (1998) reported that the three- to five-fold variation introduced by different lipid extraction methods may exceed any reduction in variation from lipid normalisation of contaminant concentrations (see the section ‘Comparing results when lipid methods differ’ above).

Various lipid classes have different affinities for PCBs (e.g. concentrations in brain are lower, partly due to high percent of phospholipids; Reijnders, 1986), with higher affinities observed for neutral (storage) lipids (de Boer, 1988). Thus, some researchers have begun to use certain lipid classes, rather than total lipid, in the study of pollutants in marine mammals. For example, Aguilar (1985) examined the relationship between the lipophilicity of various OCs and their distribution pattern among tissues and recommended triglycerides as the lipid class that best ‘matches’ the polarity of DDTs and PCB congeners most frequently occurring in cetaceans. In addition, Bergen *et al.* (2001) reported that the sum of PCBs in ribbed mussels was correlated to neutral lipids (‘triacyclglycerol’ = triglyceride) but not to total lipids, thus demonstrating that the current practice of normalising contaminant concentrations to total lipid may not be appropriate as a standard practice.

When low concentrations of lipids are present ($<5\%$), normalisation of OCs to lipid content results in a substantial increase in lipid weight concentrations compared to wet weight concentrations (20-fold increase for 5% lipid). Thus, lipid-normalised OC concentrations can be artificially inflated when lipid values are very low − for example, in blood where percent lipid generally ranges from 0.01-2.2% (50-10,000-fold increases from wet weight to lipid weight), because small errors in determination of percent lipid will have a large effect on concentrations expressed in lipid weight. Furthermore, when lipid percents are low, differences in analytical methods (e.g. gravimetric vs. TLC/FID) for lipids can result in very different lipid weight concentrations of OCs. In these instances, comparing datasets based on wet weight concentrations would be more accurate.

Investigators have found that OC concentrations differ among the blubber layers in certain cetacean species and this may be explained, in part, by different proportions of lipid classes (Sigurjónsson and Rorvik, 1983; Aguilar and Borrell, 1991; Koopman *et al.*, 1996) (see the section on ‘Blubber stratification’ below). Furthermore, lipid composition and distribution are influenced by seasonal or physiological changes. Some baleen whales increase their body weight (primarily through fat accumulation) by 50-100% between the beginning and the end of the feeding period (Lockyer and Brown, 1981). For example, the gray whales’ annual cycle of feeding, migration and reproduction causes marked changes in lipid content of blubber (Krahn *et al.*, 2001). Changes of this nature are expected to result in substantial variations in the lipid-contaminant relationship. Unfortunately, the resulting changes in contaminant concentrations can be misinterpreted (see ‘Lipid content and nutritive condition’).

QUALITY ASSURANCE PROCEDURES

The most important and relevant measures of data comparability, whether comparisons are made among datasets from several laboratories or between datasets from different analytical methods in the same laboratory, come from an assessment of each study’s Quality Assurance Programme. A comprehensive quality assurance plan (the foundation of a Quality Assurance Programme) is essential for producing and evaluating data (Topping, 1992; Wells *et al.*, 1993; Chidi Ibe and Kullenberg, 1995). The quality assurance plan is designed to monitor the performance of a laboratory’s analytical results and to provide rapid feedback so that corrective measures can be taken before data quality is compromised. In addition, the plan spells out procedures that will determine if reported data are sufficiently complete, accurate, comparable, representative, unbiased and precise. Many elements must be present in a quality assurance plan to assure that comparisons of the data produced by the study will be accurate and comparable to data from other studies. Typically, a laboratory’s protocols will include specification of the analytes to be determined, the minimum sensitivity of the analytical methods, and whenever possible, will specify the use of certified calibration solutions and standard/certified reference materials, as well as analysis of replicate samples and method blanks. In addition, a laboratory must continue to demonstrate its analytical proficiency through participation in refereed intercomparison exercises.

The quality of a chemical analysis is considered ‘assured’ when the analysis is performed in a technically competent manner by qualified personnel using appropriate methods and equipment. In addition, the precision and accuracy of the measurement must be within the expected ranges for the technique. Acceptable quality can vary by analyte, matrix, concentration level of analyte being measured (especially when levels are very high or near detection limits), analysis technique and quantitation method. The following quality control techniques should be applied to every set (generally 10-20 samples) of analyses, but these are not all the measures that are routinely applied to assure good quality (e.g. others are instrument calibration and maintenance, standard operating procedures that include field sampling procedures). Table 2 provides examples of the criteria from a laboratory's Quality Assurance Programme that are applied in evaluating laboratory performance.

Table 2

Selected Quality Assurance Programme criteria for evaluation of laboratory performance in analysing for OCs in tissue samples.

Surrogate/internal standards	60-130% recovery
Method blanks	One method blank should be analysed for every 20 samples. No more than 3 analytes in the method blanks are to exceed 3x the limit of detection.
Replicate samples	One sample should be analysed in duplicate for every 20 samples. The relative (percent) standard deviation between these two analyses must be < 25%.
Standard Reference Materials (SRMs)	One Standard Reference Material or appropriate control material must be analysed with each 20 samples. Concentrations of individual OC analytes must be within 30% of either end of the 95% confidence interval range of the certified values.
Spiked samples	60-130% recovery
Inter-laboratory comparisons	As defined by NIST, NRC, QUASIMEME or other certifying organisation; generally once a year.

Surrogate or internal standards are compounds that are not expected to be found in samples and are added in the beginning of the analysis to measure losses in laboratory processing procedures. The quantity of surrogate standard remaining at completion of the analysis is measured and compared to the amount originally added to determine the percent recovery. Percent recoveries of surrogate standards are evaluated in accordance with laboratory criteria.

Method blanks provide a check on the quality of the reagents and solvents and reflect any system contamination. The blank is an empty sample container to which all of the reagents, chemicals, or solvents used in an analysis are added and then the blank is processed in the same manner as the rest of the samples.

Replicate samples are analysed to provide a measure of the precision for the methods used by analysing two separate sub-samples. Most often, sub-sampling occurs following homogenisation of the samples, particularly when the sample to be analysed is a composite (from two or more animals). Replicate analyses are evaluated in accordance with laboratory criteria.

Standard or Certified Reference Materials (SRMs/CRMs) are analysed to provide evidence that the analytical method works with the naturally incorporated analyte and that the results are comparable to those obtained by a certifying organisation (e.g. National Institute of Standards and Technology (NIST, USA), National Research Council (NRC, Canada) or Quality Assurance of Information for Marine Environmental Monitoring in Europe (QUASIMEME)). Reference materials are pre-homogenised samples that are certified to contain a stated amount of analyte. Great care is taken by the certifying organisation in the homogenising step, because it is critical that each sub-sample of the SRM/CRM is identical in concentrations of contaminants. Furthermore, a laboratory should choose an SRM/CRM with tissue characteristics as close to the samples to be analysed as possible. For example, NIST whale blubber SRM 1945 should be used with cetacean samples and NIST mussel SRM 1974b with invertebrate analyses. SRMs/CRMs are evaluated in accordance with the precision and accuracy that would be expected for the amount of analyte present and with the known error in the certification.

Spiked matrices are analysed to provide a measure of the accuracy of the methods used when no reference materials are available for specific analytes. After a sample is homogenised, two separate sub-samples are taken; one is processed as a sample and a known quantity of analyte is added to the other sub-sample before analysis. Recoveries of the spiked analytes are determined and evaluated in accordance with laboratory criteria.

Interlaboratory comparisons on at least an annual basis, i.e. participation in a refereed interlaboratory comparison, is essential (Chidi Ibe and Kullenberg, 1995; Davies and Wells, 1997). In this intercomparison, each laboratory analyses a portion of the same 'blind' sample and the results are compared by the organiser of the exercise — generally one of the certifying organisations (e.g. NIST or QUASIMEME) listed under 'Standard Reference Materials' (above). If any significant differences occur from the 'consensus value' (typically, the mean of all participating laboratories, excluding outliers), corrective action should be initiated by laboratories who do not meet the criteria.

BIOLOGICAL FACTORS TO CONSIDER WHEN COMPARING DATA

Age, sex and reproductive status

Age, sex and reproductive status are important factors to be taken into account when making intra- and interspecies comparisons of OCs in cetaceans (Aguilar *et al.*, 1999). Bioaccumulative contaminants, such as many OCs, would be expected to increase progressively with age in individual animals. However, the rate of increase tends to level off in older individuals as a result of reduced daily feeding, as well as increased metabolism and excretion rates when OCs accumulate (Aguilar *et al.*, 1999). In most of the studies reviewed by Aguilar *et al.* (1999), a positive correlation was found between age and OC concentrations in male cetaceans, indicating bioaccumulation of these contaminants. Similarly, OC concentrations increased with age in male white whales from the Arctic (Krahn *et al.*, 1999) and in male harbour porpoises (*Phocoena phocoena*) from Scandinavia (Kleivane *et al.*, 1995). In contrast, no similar correlation was found between age and OC concentrations in adult female cetaceans, because transfer of contaminants from mother to offspring during gestation and lactation affect OC concentrations in tissues of reproductive females (Aguilar *et al.*, 1999). Studies of mother-calf pairs have shown that significant quantities of lipid-soluble contaminants can be transferred to the young via lactation (Aguilar and Borrell, 1994b; Ridgway and Reddy, 1995) and the amount of contaminants transferred is directly related to the duration of lactation (Aguilar *et al.*, 1999). This transfer was also demonstrated in juvenile killer whales — especially in first-recruited animals, which were found to contain much higher concentrations of PCBs and DDTs in blubber than were found in their mothers (2.8-28 times and 3.2-54 times, respectively) (Ylitalo *et al.*, 2001). This initial contaminant dose can be further concentrated as the weaned whale metabolises fat to provide energy, resulting in unusually high OC concentrations in young animals. For the mother, this transfer represents a loss of contaminants, evidenced by the fact that actively reproducing females have notably lower OC concentrations than those in mature males and in some instances, tissue concentrations may even decrease with age (Aguilar *et al.*, 1999).

Health status

Information on the health status of cetaceans is important for interpreting observed tissue pollutant levels. For example, diseases affecting hepatic and renal functions are likely to affect OC metabolism or excretion, and could result in increased accumulation (Aguilar *et al.*, 1999). However, this should not be considered a rule, because some diseases may also activate hepatic enzymatic activity and this would eventually result in increased metabolism of pollutants and consequently in reduced OC burdens (Aguilar *et al.*, 1999). Furthermore, reduced reproduction in females limits pollutant transfer during gestation and lactation, thereby altering the usual age-related decrease in OC concentrations in maternal tissues. For example, in reproductively impaired populations of white whales and ringed seals (*Phoca hispida*), it has been difficult to establish whether abnormally high OC levels observed in adult females were a consequence of the reduced reproductive activity (caused by other factors) or, actually, the cause of impaired reproduction (Helle *et al.*, 1983; 1990; Martineau *et al.*, 1987). One plausible hypothesis suggests a synergistic process – elevated OC concentrations can result in reproductive failure and then as a result of reproductive failure, OC levels increase further. Some diseases may also cause reproductive failure (e.g. abortions). An example of an infectious agent of this nature is *Brucella*, which has been recently reported as widespread among marine mammals (Miller *et al.*, 1999; Nielsen *et al.*, 2001). In individuals affected by this disease, the pollutant transfer associated with gestation and lactation does not take place and consequently, OC concentrations in the female increase abnormally. Thus, it is important that the health status of cetaceans is assessed and then considered when datasets are evaluated.

Lipid content and nutritive condition

Due to the lipophilic (hydrophobic) nature of OCs, their dynamics in marine food webs is closely related to the dynamics of lipids in marine organisms. Concentrations of OCs in organisms are correlated with OC levels in lipids of prey that they consume and by the efficiency of lipid absorption (AMAP, 1998). Fat comprises a large proportion of the body mass of many cetaceans and is consolidated as a blubber layer. In species that have seasonal migratory and feeding regimes (e.g. most baleen whales), lipid content may vary throughout the year; seasonal fluctuations in condition do not appear to be as large in odontocetes as in mysticetes (Aguilar *et al.*, 1999).

Data to assess overall body condition of the specimens sampled (e.g. body girth, body mass and/or blubber thickness at selected body sites) should be collected and examined in connection with the OC concentrations observed. The lipid content of the tissues surveyed, which is routinely determined during the analyses for OCs, is also a significant variable to use in this respect. Lipid content and thickness of blubber can be indicative of the nutritive condition of marine mammals (Sigurjónsson and Rorvik, 1983) and nutritive status can have dramatic effects on OC concentrations. When animals lose weight (i.e. lipid is mobilised and metabolised) due to migration, food shortage, reproductive activity, disease or other stresses, two processes are possible: either contaminants remain in the blubber or are redistributed to vital organs such as the central nervous system (Henrikson *et al.*, 1996). Aguilar *et al.* (1999) reported that the actual process is probably somewhere between these extremes. The total amount of many OCs increases in body tissues as lipid is metabolised, but are not as high as would be predicted if all the contaminants were concentrated in the remaining lipid. This increase of OCs in tissues following depletion of lipid stores has been observed in a number of species. For example, PCB concentrations (lipid basis) in Mediterranean striped dolphins (*Stenella coeruleoalba*) were negatively correlated to lipid content, indicating a build-up of contaminants in dolphins in poor nutritive condition (Aguilar *et al.*, 1999). Thus, it is important when comparing contaminant concentrations in cetaceans to consider nutritive status, as well as to compare animals of similar status, e.g. males or juveniles during a single season.

Blubber stratification

As noted above, collecting biopsies from the blubber of free-ranging cetaceans through surgical or punch biopsies on captured/released small cetaceans and through remote biopsy darting of larger cetaceans, is becoming more frequent as part of an effort to develop non-destructive techniques for contaminant monitoring. There are only a few studies that have tested whether these small samples are representative of the contamination in the entire blubber layer (Aguilar and Borrell, 1991; Gauthier *et al.*, 1997). Examination of this is an important component of the POLLUTION 2000+ research programme. Unfortunately, studies that assess differences among blubber layers do not provide unequivocal answers. Among the odontocetes, Koopman *et al.* (1996) found that vertical stratification was evident between the inner and outer blubber layers in harbour porpoises, suggesting that the inner blubber layer is more active metabolically than the outer layer in terms of lipid deposition and mobilisation and thus that stratification could affect contaminant distribution. Another study (Tilbury *et al.*, 1997) found no differences in lipid content among three blubber layers in harbour porpoises, but the study included just three animals. In addition, distribution of lipid-normalised OCs in the blubber layers was inconsistent among the animals studied. Two of the animals had significantly higher OC concentrations in the inner layer nearest the muscle than in the other two layers and the third showed no differences among layers.

Baleen whales are much larger than most odontocetes and their blubber is more markedly layered. In addition, the intensity of feeding varies seasonally for many baleen whales, so that the lipid reserves in blubber vary throughout the year. Two studies of blubber stratification in baleen whales have led to different conclusions. Aguilar and Borrell (1991) have found that the lipid content of blubber differs among the three layers in balaenopterid whales and that this may result in differential distribution of lipophilic contaminants. They studied the stratification of OCs in the blubber of 89 fin whales (*Balaenoptera physalus*) and 23 sei whales (*B. borealis*) and found significantly higher OC concentrations in the outer layer compared to the inner layer of blubber in both species (Aguilar and Borrell, 1991). They concluded that blubber samples collected from cetaceans for pollutant analyses should include all layers in order to be representative of an individual animal's pollutant load. In contrast, Gauthier *et al.* (1997) found no statistically significant differences in lipid-normalised OCs among the outer, middle or inner blubber layers in balaenopterid whales: minke (*B. acutorostrata*) and blue (*B. musculus*). However, this study was limited to only three minke whales and one blue whale, so no statistical conclusions could be drawn due to the reduced sample size.

As a result of these inconsistent findings for stratification of lipid classes or OC distributions, it will be necessary to determine whether stratification is species-specific and if it changes seasonally. Surgical biopsies should take a full-thickness sample of blubber whenever possible. In addition, designing biopsy darts to sample deeper into the blubber strata may help obtain more representative biopsy samples (Lambertsen *et al.*, 1994; Gauthier *et al.*, 1997), although this technique has the potential for producing a higher impact on the sampled individual.

ACKNOWLEDGMENTS

The authors from the Northwest Fisheries Science Center were supported, in part, by the National Marine Fisheries Service's Marine Mammal Health and Stranding Response Program. Aguilar and Borrell were partially supported by projects by the Comisión Interministerial para la Ciencia y Tecnología-CICYT (project AMB99-0640) and the European Community project LIFE00NAT/E/7303.

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Date received: December 2001.
Date accepted: July 2002.

J. CETACEAN RES. MANAGE. 5(2):115–124, 2003

Regional differences in fatty acid composition in common minke whales (*Balaenoptera acutorostrata*) from the North Atlantic

P. MØLLER*, E.W. BORN+, R. DIETZ#, T. HAUG¥, D.E. RUZZANTE** AND N. ØIEN++

Contact e-mail: pem@DMU.dk

ABSTRACT

Variation in fatty acid (FA) composition of blubber collected in 1998 from 170 common minke whales (*Balaenoptera acutorostrata*) was used to study population structure in the North Atlantic. Samples from seven IWC management units were analysed: West Greenland (‘WG’, *n* = 69); East Greenland (‘CG’, *n* = 3); Jan Mayen (‘CM’, *n* = 24); Svalbard (‘ES’, *n* = 16); the Barents Sea (‘EB’, *n* = 30); Vestfjorden/Lofoten (‘EC’, *n* = 7); and the North Sea (‘EN’, *n* = 21). FA analyses were conducted on both deep and superficial blubber with a one-step extraction and esterification method followed by gas-chromatography. The 43 FAs identified comprised 93-99% of total FAs. CART and MANOVA analyses on FA signatures in both blubber sections suggested a ‘3-geographic Regions model’ where the regions were Greenland (WG, CG), the Northeast Atlantic (CM, ES, EB, EC) and the North Sea (EN). This is in general agreement with a genetic study on the same samples and suggests that differences in FA signatures can be used for studying population structure in minke whales. Potential variation in FA signatures caused by internal and environmental factors needs to be better understood. It is recommended that future studies of blubber FA signatures in minke whales include samples from their entire North Atlantic range (including Canadian and Icelandic waters). Samples should be collected from a pre-specified body site to rule out possible internal variation and during a narrow time-window in the same year to rule out seasonal exchange between areas.

KEYWORDS: COMMON MINKE WHALE; STOCK STRUCTURE; POPULATION; FATTY ACIDS; GREENLAND; NORTH ATLANTIC; NORTH SEA

INTRODUCTION

The common minke whale (*Balaenoptera acutorostrata*) is the smallest and most abundant of the baleen whales in the North Atlantic (e.g. Stewart and Leatherwood, 1985; Donovan, 1991a; b). During summer, minke whales are distributed from the east coast of Canada to the North Sea, and as far northeast as the Svalbard-Barents Sea region (Fig. 1). This species is exploited by Greenlandic subsistence hunters in coastal Greenland waters (IWC, 2003, pp.68-70) and by Norwegian whalers along the Norwegian coast and offshore in the North East Atlantic region and the North Sea (e.g. Grønvik, 1998). Determining sustainable harvest levels for minke whales in these areas requires an understanding of the population structure and the ability to identify the exploited units demographically.

In 1977, the International Whaling Commission (IWC) divided the North Atlantic minke whale population into four management stocks: (1) West Greenland; (2) Central North Atlantic; (3) NE North Atlantic; and (4) Canadian East Coast (Donovan, 1991b). However, the evidence for some of these was ‘somewhat scanty’ and there have been a number of suggestions for changes and improvements (e.g. Larsen and Øien, 1988; Bakke *et al.*, 1996; Palsboll *et al.*, 1997). With the development of the Revised Management Procedure, the Committee re-evaluated the evidence and divided the North Atlantic into 10 ‘*Small Areas*’[1] (IWC, 1993; 1994) (Fig. 1).

In the North Atlantic and elsewhere, genetic data have proved equivocal information on stock structure (e.g. IWC, 2004) and it is important that information from a variety of techniques is examined (e.g. Donovan, 1991b). Other studies have applied various techniques including comparison of catch composition (e.g. Larsen and Øien, 1988), morphological differences (Christensen *et al.*, 1990) and reproductive parameters (Olsen, 1997), but have not provided a definite answer to this question. However, new analytical tools that reflect changes over a shorter time-scale compared to genetics may assist in the understanding of the population structure of North Atlantic minke whales. One such tool is the composition of fatty acids (FAs) in depot fats such as the blubber of marine mammals. Examples where FAs have been used as a tool to discriminate between

[1] The formal definition is that ‘*Small Areas* are disjoint areas small enough to contain whales from only one biological stock, or be such that if whales from different biological stocks are present in the *Small Area*, catching operations would not be able to harvest them in proportions substantially different to their proportions in the *Small Area*’. They are thus management units and do not have to have boundaries that coincide with biological stocks. *Medium Areas* ‘correspond to known or suspected ranges of distinct biological stocks’. (IWC, 1999).

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* *Roskilde University, Department of Chemistry and Life Sciences, P.O. Box 260, DK-4000 Roskilde, Denmark.* Present Address: *National Environmental Research Institute, Department of Arctic Environment, P.O. Box 358, DK-4000 Roskilde, Denmark.*
+ *Greenland Institute of Natural Resources, P.O. Box 570, DK-3900 Nuuk, Greenland.*
# *National Environmental Research Institute, Department of Arctic Environment, P.O. Box 358, DK-4000 Roskilde, Denmark.*
¥ *Institute of Marine Research, Tromsó Branch, P.O. Box 6404, N-9294 Tromsó, Norway.*
** *Danish Institute for Fisheries Research, Department of Inland Fisheries, DK-8600 Silkeborg, Denmark.* Present Address: *Dalhousie University, Department of Biology, Halifax, Nova Scotia B3H 4J1, Canada.*
++ *Institute of Marine Research, Marine Mammals Division, P.O. Box 1870, Nordnes, N-5817 Bergen, Norway.*

populations include: ringed seals, *Phoca hispida* (Käkelä *et al.*, 1993); harp seals, *Phoca groenlandica* (Grahl-Nielsen *et al.*, 1993); harbour seals, *Phoca vitulina* (Smith *et al.*, 1996; Iverson *et al.*, 1997); and harbour porpoises, *Phocoena phocoena* (Møller *et al.*, 2003). In addition, Olsen and Grahl-Nielsen (2002) were able to differentiate between minke whales from the Norwegian Sea and the North Sea using differences in FA signatures in blubber.

In marine mammals the dietary FAs are represented mainly by long chain mono-unsaturated (e.g. C18:1n-7/n-9, C20:1n-9/n-11, C22:1n-9/n-11) and poly-unsaturated fatty acids (e.g. C18:3n-3, 18:4n-3, 20:4n-6, C20:5n-3, C22:5n-3, 22:6n-3) (e.g. Ackman *et al.*, 1975; West *et al.*, 1979; Koopman *et al.*, 1996; Iverson *et al.*, 1997; Smith *et al.*, 1997; Walton *et al.*, 2000).

Previous genetic studies compared minke whales collected in different years, making it difficult to distinguish between spatial and potential temporal differentiation (IWC, 1998). To eliminate some of these uncertainties, this study used minke whales caught during a single whaling season in seven of 10 IWC '*Small Areas*' in the North Atlantic. To date, the samples have been analysed for regional differences in signatures of elements and stable isotopes (Born *et al.*, 2003), organochlorines (Hobbs *et al.*, 2002), genetics (Andersen *et al.*, 2003) and caesium-137 (Born *et al.*, 2002).

This paper provides an analysis of the fatty acids in the deep and superficial blubber from 170 minke whales sampled in 1998 in West Greenland, the northeastern Atlantic and the North Sea with the objective of elucidating population structure. Information is presented on the FAs identified, and on the regional variation in the composition of the FAs in minke whales. Preliminary analyses were presented by Møller *et al.* (2000).

MATERIALS AND METHODS

Field sampling

Blubber samples were collected from 6 May until 31 October 1998 from 170 minke whales taken during directed catches by Greenlandic and Norwegian whalers in the North Atlantic region (Fig. 1): West Greenland ('WG', $n = 37$); East Greenland ('CG' $n = 3$); Jan Mayen ('CM', $n = 24$); Svalbard ('ES', $n = 16$); the Barents Sea ('EB', $n = 30$); Vestfjorden/Lofoten ('EC', $n = 7$); and the North Sea ('EN', $n = 21$). Within the same period additional samples were collected in Greenland from 32 minke whales. These samples, for which exact information on site and date was not available, were grouped together with the three animals from CG to form a mixed CG and WG group, from here on referred to as 'GR' ($n = 35$).

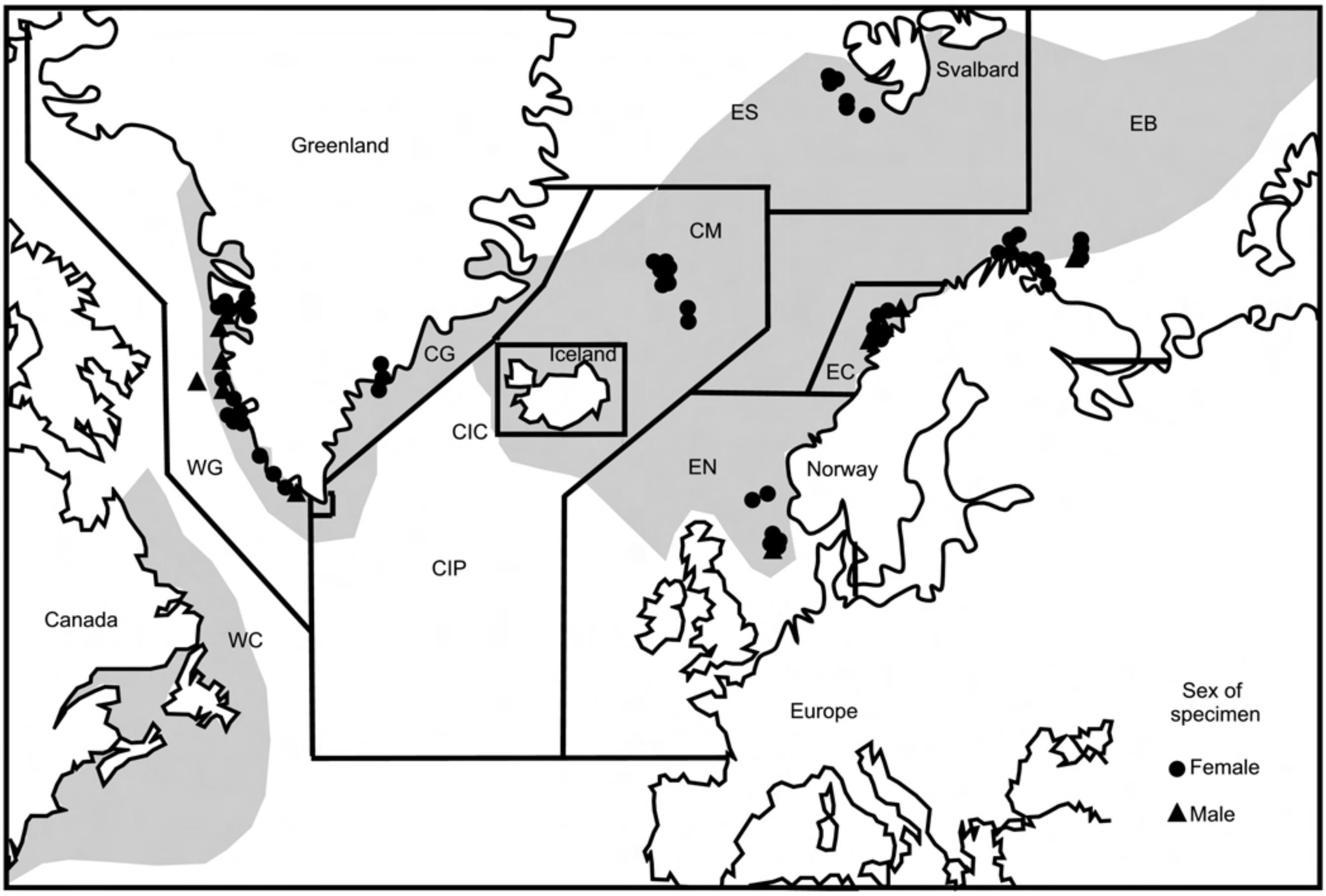

Fig. 1. Map showing the boundaries of the IWC '*Small Areas*' and the location of sampling of tissues from a total of 170 minke whales in 1998. The approximate summer range of minke whales (Stewart and Leatherwood, 1985; Donovan, 1991a; b) is indicated in grey. The areas west of 57°W (i.e. the central parts of Davis Strait and the Canadian East Coast waters) have not been surveyed systematically and therefore it is not known whether or not the distribution of minke whales is continuous between western Greenland and Canada.] Key = WC (West Canada); WG (West Greenland); CG (Central Greenland); CIC (Central Island Coastal); CIP (Central Iceland Pelagic); CM (Central Jan Mayen); ES (East Svalbard); EB (East Barents Sea); EC (East Coastal); EN (East North Sea).

Samples for analyses were taken only if sub-samples included skin or muscle for correct orientation. This selection procedure resulted in deep blubber samples from 154 animals and superficial blubber samples from 164 animals representing 170 animals. Both the deep and superficial blubber were sampled from 148 minke whales.

A deep blubber core including skin and muscle was collected from each whale and stored at −20°C. The sex of each individual was determined genetically (Andersen *et al.*, 2003). The overall percentage of females in the samples was 79% ranging between 50% (EC) and 100% (CG).

Sample preparation and fatty acid methyl-esters

In September 1999, sub-samples representing the centre core of an entire blubber profile were transferred to polyethylene plastic bags where air was evacuated and samples stored at −80°C until analysis. For analysis, sub-samples were thawed and placed on oil-free paper where a 2-3mm thick blubber layer was dissected from (a) immediately under the skin, and (b) adjacent to the muscle core.

Following this procedure, the individual layers were transferred to thick-walled glass tubes to be sealed with screw-caps fitted with a silicone-PTFE cap-membrane. Lipids were extracted and FAs trans-esterified to produce FA methyl-esters (FAME) using a one-step method (Sukhija and Palmquist, 1988) as modified by Møller (1999). FAMEs were stored in air-sealed GC-vials at −80°C until the identification-analysis could be performed (0-5 days). To avoid auto-oxidation of unsaturated FAs, all chemicals and headspace volumes were de-aerated using purified argon gas.

To avoid loss of particular volatile short-chained FAs (e.g. isovaleric acid) the use of FA butyl-esters (FABE) instead of the commonly used FAME has been recommended. However, analyses on blubber FABE in minke whales have shown no presence of such volatile FAs (P.M., unpublished data) and for convenience FAME (referred to as FAs in the following) were therefore chosen for this study.

FA analysis

The FAs were analysed and identified using a *Hewlett Packard* 5890 gas-chromatograph equipped with a split/splitless FID detector. A 30 × 0.25mm internal diameter column coated with 50% cyanopropyl polysiloxane (0.247mm film thickness; J&W DB-23; Folsom California) was used. Helium was used as the inert carrier gas at a constant flow of 1.2ml/min. Injection- and detection-temperatures were set at 250°C and the initial column temperature at 65°C. Two minutes after sample injection the temperature was increased from 65°C to 165°C at 20°C/min and held for 0.4min. The temperature was then increased to 210°C at 2°C/min, held for 1min, and then finally increased to 240°C at 30°C/min and held for 1min. The entire program took 32.9min to complete. The Hewlett Packard ChemStation software (HP 3363 Series II ChemStation) performed integration of chromatograms. Identification of most individual FAs was performed using methyl-ester standard mixes FIM-FAME-7 and PUFA-3 (Matreya, Inc.). FAs of the n-11 and n-9 type were identified using an oil-extract from harbour porpoise blubber of known composition. The integrated area peaks were converted to FA percentage by weight (mass percentage of total FAs) using theoretical correction factors (Craske and Bannon, 1988; Møller, 1999). Standards were run before and after sample-sequences to calibrate the retention times and to monitor the condition of the column. Individual FAs have been named according to the short-hand IUPAC nomenclature: C(#carbon):(#double bonds)n-x, where x is the location of the double bond nearest the terminal methyl group.

Data analysis

Classification and Regression Tree analysis (CART), ANOVA and MANOVA available in *S-plus*© (version 4.5, Mathsoft, Inc.) were used to investigate patterns in the FA signatures among: (a) IWC '*Small Areas*'; and (b) major regions i.e. Greenland (CG, WG), the NE Atlantic region (CM, ES, EB and EC pooled) and the North Sea (EN) (Fig. 1). In contrast to ANOVA and MANOVA, CART multivariate analysis (Clark and Pregibon, 1992; Venables and Ripley, 1994) is non-parametric and has no restriction as to the number of variables allowed in the model. Therefore the total array of FAs was tested when using CART. The CART technique has previously been applied to the analysis of FA signatures containing more than 60 variables (FAs) per observation (Iverson *et al.*, 1997; Smith *et al.*, 1997). An initial CART analysis revealed similar patterns for males and females and the two genders were therefore pooled in subsequent analyses of spatial differences. The deep blubber and the superficial blubber were analysed separately. Prior to analysis, the data were arcsin transformed to meet the assumption of normality and homoscedasticity. For construction of the classification trees, two stopping criteria were used to determine branches: (1) a change in deviation of less than 1% of the root node deviation; or (2) when the minimum number of observations at a node was less than 10.

A '3-Region model' and a '2-Region model' as suggested by the CART analysis was tested further by use of multivariable analyses of variance (MANOVA; Wilks λ) including a total of 18 FAs. Furthermore, analyses of variance (ANOVA) were conducted to indicate the probable importance of individual FAs included in the MANOVA. These 18 FAs were those responsible for the major splits picked up by the CART analyses and other FAs of dietary origin.

RESULTS

The 43 FAs identified in this study made up 93-99% of total FAs in the blubber of the minke whales. Of these FAs, the following 16 were generally represented by > 1% on weight basis: 14:0, 16:0, 16:1n-7, 18:0, 18:1n-11, 18:1n-9, 18:1n-7, 18:2n-6, 18:3n-3, 18:4n-3, 20:1n-11, 20:1n-9, 20:5n-3, 22:1n-11, 22:5n-3, 22:6n-3 (Table 1).

Regional differences based on CART analyses

Deep blubber signatures

Based on the FAs in the deep blubber, the overall percentage of misclassification of individuals to area was 17% (i.e. 26 misclassified of 154 analysed, 26/154). The model selected 19 of 43 FAs for the construction of a classification tree with 19 terminal nodes (Fig. 2). At the root C20:1n-7 formed an initial split into a NE Atlantic-North Sea group (3/69, 3 misclassified of 69 classified) and a NE Atlantic-Greenland group (0/85). Only 3 out of 64 Greenland animals were misclassified to the NE Atlantic-North Sea group. In addition, all 20 North Sea animals were found in this group where all but one could successfully be categorised in a clean terminal node (0/19). Within the NE Atlantic-Greenland group C18:4n-1 distinguished between NE Atlantic (9/32) and Greenland animals (1/53). In the Greenland group the one misclassified animal was from the neighbouring Jan Mayen area (CM). In both NE Atlantic sub-groups, Jan

Table 1

Fatty acid composition (average mass (%) ± standard deviation) of the deep and the superficial blubber of minke whales representing the three regions, Greenland, the North Eastern Atlantic and the North Sea.

Fatty acid	Greenland		North Eastern Atlantic		North Sea	
	Deep	Superficial	Deep	Superficial	Deep	Superficial
C10:0	0.01 ± 0.01	0.00 ± 0.00	0.00 ± 0.01	0.00 ± 0.00	0.02 ± 0.01	0.00 ± 0.00
C12:0	0.14 ± 0.05	0.09 ± 0.03	0.08 ± 0.03	0.07 ± 0.01	0.12 ± 0.02	0.07 ± 0.01
C13:0	0.03 ± 0.01	0.01 ± 0.02	0.03 ± 0.01	0.02 ± 0.01	0.04 ± 0.01	0.01 ± 0.02
C14:0	4.80 ± 0.56	4.21 ± 0.45	5.54 ± 0.74	4.15 ± 0.37	4.99 ± 0.54	4.37 ± 0.51
C14:1n-7	0.22 ± 0.10	0.08 ± 0.02	0.22 ± 0.15	0.06 ± 0.02	0.14 ± 0.05	0.09 ± 0.04
C14:1n-5	0.22 ± 0.05	0.72 ± 0.30	0.17 ± 0.05	0.92 ± 0.19	0.17 ± 0.01	0.99 ± 0.38
C15:0	0.27 ± 0.08	0.29 ± 0.05	0.32 ± 0.06	0.31 ± 0.08	0.30 ± 0.05	0.28 ± 0.10
C15:1n-5	0.06 ± 0.05	0.09 ± 0.04	0.02 ± 0.07	0.09 ± 0.03	0.11 ± 0.06	0.09 ± 0.03
C16:0	10.73 ± 2.18	8.71 ± 2.18	14.46 ± 2.45	8.49 ± 1.34	10.32 ± 2.12	7.28 ± 1.34
C16:1n-7	7.78 ± 2.46	13.45 ± 2.63	6.88 ± 2.51	13.06 ± 2.21	5.61 ± 2.33	10.66 ± 1.79
C16:2n-4	0.44 ± 0.13	0.54 ± 0.10	0.38 ± 0.11	0.36 ± 0.10	0.34 ± 0.09	0.35 ± 0.08
C17:0	0.42 ± 0.25	0.27 ± 0.08	0.51 ± 0.31	0.20 ± 0.12	0.31 ± 0.12	0.25 ± 0.11
C16:3n-4	0.29 ± 0.15	0.34 ± 0.12	0.33 ± 0.10	0.48 ± 0.13	0.39 ± 0.08	0.47 ± 0.14
C17:1n-7	0.04 ± 0.03	0.20 ± 0.10	0.10 ± 0.06	0.12 ± 0.11	0.05 ± 0.04	0.17 ± 0.10
C16:4n-1	0.42 ± 0.25	0.18 ± 0.11	0.18 ± 0.11	0.10 ± 0.20	0.39 ± 0.15	0.14 ± 0.15
C18:0	2.45 ± 0.68	1.84 ± 0.44	2.54 ± 0.77	1.77 ± 0.33	2.75 ± 0.59	1.84 ± 0.46
C18:1n-11	1.54 ± 0.74	2.60 ± 0.94	0.82 ± 0.64	2.15 ± 0.61	1.61 ± 0.63	2.70 ± 0.83
C18:1n-9	13.80 ± 3.44	18.31 ± 2.84	21.35 ± 4.44	22.16 ± 2.23	11.22 ± 2.73	18.63 ± 2.03
C18:1n-7	3.71 ± 1.14	4.52 ± 0.95	5.19 ± 1.76	4.86 ± 0.99	1.84 ± 0.23	2.93 ± 0.63
C18:2n-6	1.33 ± 0.28	1.64 ± 0.25	1.28 ± 0.35	1.93 ± 0.20	2.16 ± 0.43	2.34 ± 0.35
C18:2n-4	0.12 ± 0.04	0.09 ± 0.05	0.07 ± 0.04	0.08 ± 0.05	0.09 ± 0.04	0.05 ± 0.05
C18:3n-6	0.10 ± 0.03	0.02 ± 0.05	0.12 ± 0.04	0.10 ± 0.09	0.10 ± 0.07	0.06 ± 0.07
C18:3n-4	0.14 ± 0.04	0.65 ± 0.16	0.10 ± 0.05	0.95 ± 0.21	0.12 ± 0.03	1.40 ± 0.24
C18:3n-3	0.52 ± 0.14	0.95 ± 0.38	0.66 ± 0.21	1.03 ± 0.20	1.11 ± 0.39	1.47 ± 0.28
C18:4n-3	1.60 ± 0.58	0.33 ± 0.13	1.81 ± 0.67	0.22 ± 0.18	2.32 ± 0.69	0.18 ± 0.07
C18:4n-1	0.24 ± 0.11	0.00 ± 0.00	0.10 ± 0.06	0.01 ± 0.03	0.20 ± 0.07	0.00 ± 0.00
C20:0	0.16 ± 0.06	0.08 ± 0.08	0.18 ± 0.08	0.11 ± 0.06	0.24 ± 0.06	0.11 ± 0.07
C20:1n-11	1.80 ± 1.19	2.62 ± 0.88	1.14 ± 1.00	2.32 ± 0.70	2.37 ± 1.07	3.03 ± 0.81
C20:1n-9	11.42 ± 3.84	10.91 ± 3.30	7.45 ± 4.19	9.26 ± 2.84	10.97 ± 3.14	10.44 ± 2.57
C20:1n-7	0.73 ± 0.93	0.50 ± 0.15	0.33 ± 0.12	0.35 ± 0.06	0.23 ± 0.05	0.25 ± 0.04
C20:2n-6	0.33 ± 0.09	0.30 ± 0.07	0.34 ± 0.10	0.32 ± 0.05	0.36 ± 0.05	0.39 ± 0.05
C20:3n-6	0.11 ± 0.10	0.05 ± 0.07	0.10 ± 0.04	0.08 ± 0.06	0.10 ± 0.05	0.06 ± 0.05
C20:4n-6	0.29 ± 0.11	0.36 ± 0.10	0.30 ± 0.10	0.37 ± 0.10	0.40 ± 0.12	0.42 ± 0.10
C20:3n-3	0.07 ± 0.02	0.01 ± 0.03	0.09 ± 0.04	0.07 ± 0.05	0.10 ± 0.05	0.10 ± 0.08
C20:4n-3	0.89 ± 0.21	0.98 ± 0.26	0.84 ± 0.21	1.19 ± 0.22	1.12 ± 0.26	1.37 ± 0.27
C20:5n-3	6.29 ± 2.85	4.59 ± 1.60	5.50 ± 1.47	4.00 ± 1.24	5.61 ± 2.26	3.45 ± 1.20
C22:0	0.04 ± 0.02	0.00 ± 0.01	0.02 ± 0.03	0.01 ± 0.01	0.02 ± 0.03	0.01 ± 0.01
C22:1n-11	9.08 ± 3.47	7.37 ± 3.04	7.30 ± 4.39	6.20 ± 2.43	12.72 ± 3.64	10.18 ± 3.47
C22:1n-9	1.01 ± 0.35	0.90 ± 1.00	0.56 ± 0.37	0.58 ± 0.16	0.83 ± 0.19	0.60 ± 0.12
C22:2n-6	0.40 ± 0.16	0.24 ± 0.10	0.40 ± 0.17	0.26 ± 0.08	0.54 ± 0.14	0.27 ± 0.11
C22:5n-3	2.82 ± 0.65	2.64 ± 0.62	2.30 ± 0.65	2.55 ± 0.61	2.68 ± 0.46	2.38 ± 0.74
C22:6n-3	6.75 ± 1.59	5.01 ± 2.00	5.37 ± 2.03	4.79 ± 1.88	8.06 ± 2.45	5.79 ± 2.25
C24:1n-9	0.41 ± 0.18	0.19 ± 0.10	0.31 ± 0.21	0.17 ± 0.08	0.79 ± 0.15	0.20 ± 0.12
Ident. FA	93.97 ± 0.95	96.87 ± 0.60	95.80 ± 1.15	96.34 ± 0.97	93.94 ± 1.06	95.90 ± 1.10
Not ident. FA	6.03 ± 0.95	3.13 ± 0.60	4.20 ± 1.15	3.66 ± 0.97	6.06 ± 1.06	4.10 ± 1.10
Sample size	64	71	70	74	20	19

Mayen and Greenland animals (GR and WG) intermingled while a lumping of Vestfjorden/Lofoten (EC) and Svalbard (ES) was apparent. The whales from the Barents Sea (EB) showed a more pronounced isolation from the rest of the NE Atlantic (i.e. 0/16 and 1/7). Approximately half of the Jan Mayen animals were isolated from the rest of the NE Atlantic and lumped together with the North Sea animals.

Superficial blubber signatures

The CART analysis based on FAs in the superficial blubber resulted in a slightly higher rate of misclassifications (22.0%, 36 misclassified of 164) (Fig. 3) than found for the deep blubber. The model selected 19 FAs to produce a total of 20 terminal nodes. At the root node, C18:3n-4 distinguished between animals from Greenland and the NE Atlantic-North Sea with a misclassification rate of 12.2% (20/164). All of the 19 North Sea animals were along the NE Atlantic-North Sea branch where 17 were categorised correctly into a terminal North Sea (EN) node. The only misclassification at this node represented an animal from the neighbouring Vestfjorden/Lofoten (EC) area. Similarities between Jan Mayen (CM) and Greenland animals were observed as indicated by a general intermingling between animals from these two areas (Fig. 3).

Conclusion

The FA signatures of both the deep and the superficial blubber indicated: (1) that North Sea minke whales differed from those sampled in the northeastern Atlantic (i.e. Jan Mayen, Svalbard, Barents Sea and Vestfjorden/Lofoten) and

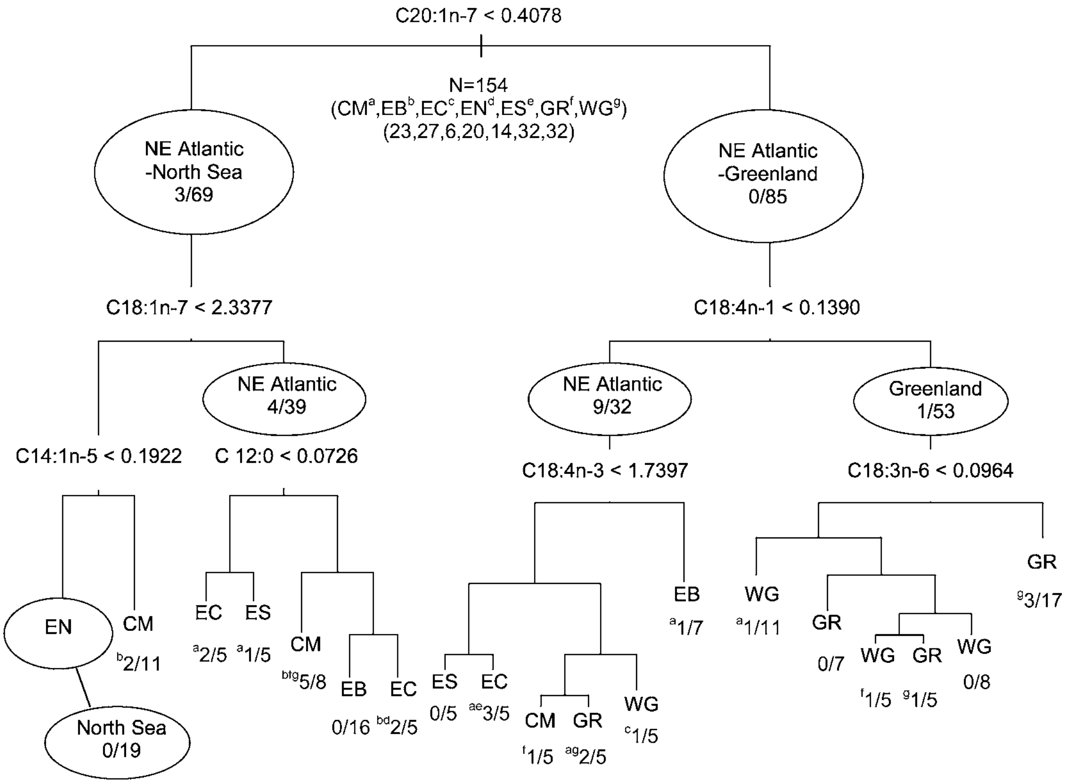

Fig. 2. Classification of 154 minke whales according to IWC '*Small Areas*' in the North Atlantic using CART analyses on fatty acid (FA) signatures of the deep blubber. Overall misclassification rate = 17% (26/154). Fractions represent the number of misclassified individuals over the total number of individuals classified in a given category. Letters in superscript refer to the 'origin' of misclassified individuals where individual codes (i.e. a to g) are indicated at the root node. Only FAs responsible for the major branches have been included in the figure.

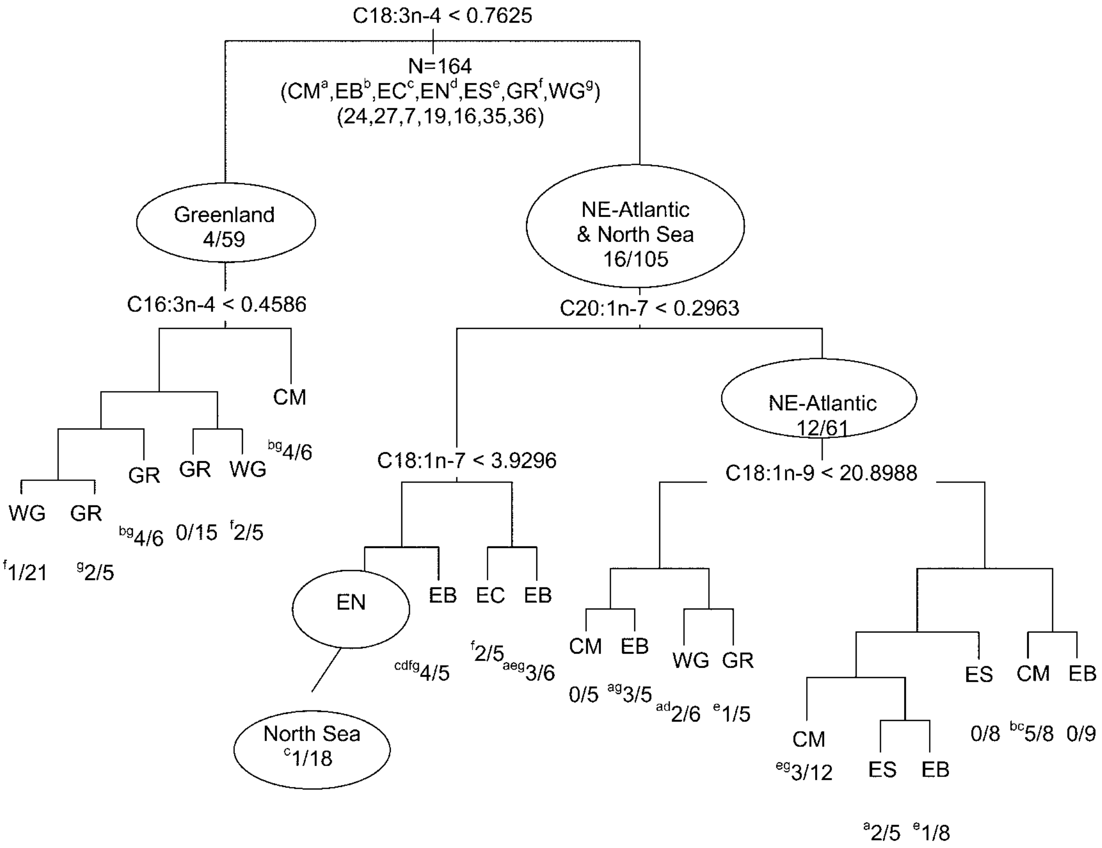

Fig. 3. Classification of 164 minke whales according to IWC '*Small Areas*' in the North Atlantic using CART analyses on fatty acid (FA) signatures of the superficial blubber. Overall misclassification rate = 22% (36/164). Fractions represent the number of misclassified individuals over the total number of individuals classified in a given category. Letters in superscript refer to the 'origin' of misclassified individuals where individual codes (i.e. a to g) are indicated at the root node. Only FAs responsible for the major branches have been included in the figure.

Greenland; and (2) that animals from Greenland waters differed from NE Atlantic minke whales; (3) a similarity between CM and Greenland; and (4) minke whales from the Barents Sea appeared to be somewhat different from the rest of the NE Atlantic. Although the FAs responsible for the tree construction differed between blubber layers, the complexity and overall topography of the trees did not.

Regional differences based on MANOVA and ANOVA

Eighteen principal FAs were included in the analyses of regional differences using MANOVA (Fig. 4). The FA composition of both the deep and the superficial blubber layers differed significantly among (a) IWC '*Small Areas*'; and (b) among three regions in a '3-Region model' (i.e. all-Greenland versus NE Atlantic versus Eastern North Sea) ($p < 0.0001$, Table 2). However, the largest *F*-value resulted from the analysis of the '3-Region model'. Furthermore, a MANOVA on Eastern North Sea versus NE Atlantic supported the 3-Region model ($p < 0.0001$) (Table 2). The ANOVAs performed on the 18 individual FAs that were included in the MANOVA test of the '3-Region model' showed that six FAs in the deep blubber and seven in the superficial blubber were responsible for the significant differences in FA signatures among areas (Fig. 4). In three cases, the same FAs found both in the outer and inner blubber were involved in these differences.

DISCUSSION

Location of the tissue samples

In no instances, except for the North Sea, were the same FAs picked up by the tree functions from both the deep and the superficial blubber layer. This emphasises that the two layers likely represent different metabolic histories. The blubber layer of the North Atlantic minke whale is stratified in such a way that the FA composition in the superficial layer differs from that in the deep blubber (Fehn, 1996; Møller *et al.*, 2000; Olsen and Grahl-Nielsen, 2002). A similar stratification has been described for several other marine mammals (West *et al.*, 1979; Lockyer *et al.*, 1984; Fredheim *et al.*, 1995; Käkelä and Hyvärinen, 1996; Koopman *et al.*, 1996; Møller *et al.*, 2002). These studies suggest that the superficial blubber layer is a region for storage of relatively endogenous FAs with its main function being insulation. In contrast, the deep blubber layer has a higher degree of unsaturation and is thought to be metabolically more active.

The attempts to distinguish among all IWC '*Small Areas*' resulted in relatively high percentages of misclassification both for the deep and the superficial blubber layer (17% and 22%, respectively). However, included in these percentages are misclassified animals from the mixed Greenland group (GR) representing 3 East Greenland animals and 32 Greenland animals with no exact information on sampling area (i.e. CG or WG). Animals from this group could in fact represent 'false' misclassifications. Consequently, a clear distinction between samples from the different IWC '*Small Areas*' was not possible, although given that '*Small Areas*' are not intended to correspond to separate biological stocks, this is not surprising. However, the classification trees constructed on the deep and the superficial blubber both indicated that whales sampled in Greenland differed from those from the NE Atlantic-North Sea region (Figs 2 and 3). In addition, CART analyses indicated that minke whales from the North Sea area (EN) differed from the NE-Atlantic minke whales. The MANOVA supported the existence of both a '2-Region model' (Greenland versus NE

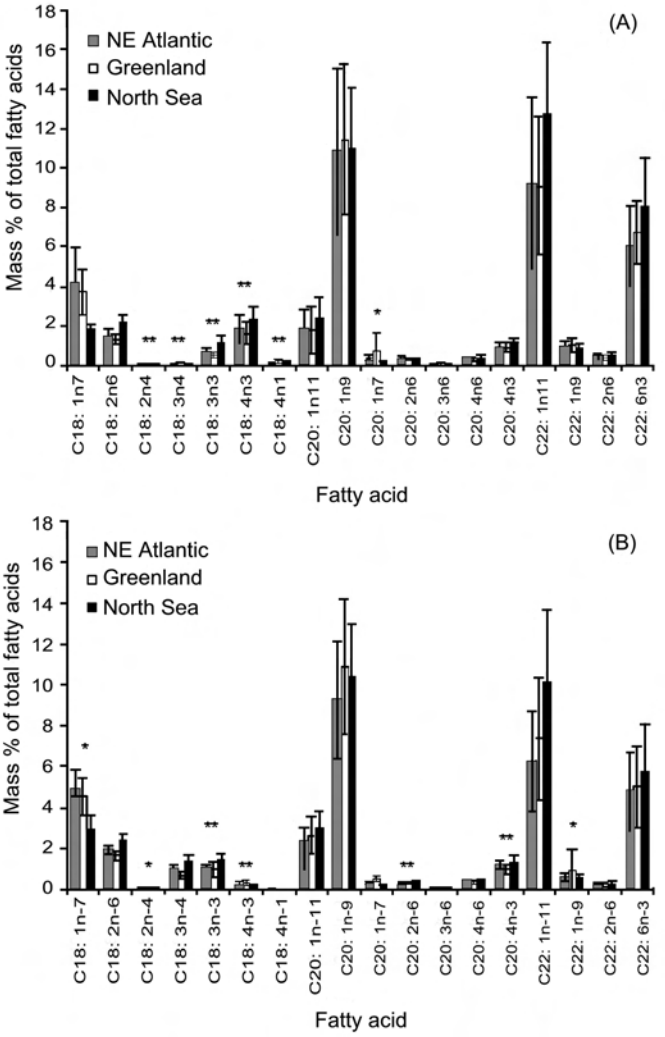

Fig. 4. Results of ANOVAs performed on 18 fatty acids in blubber of minke whales that were sampled in the North Atlantic region during 1998. Bars and lines represent the mean and standard deviation, respectively, by major region (NE Atlantic, Greenland, North Sea) as identified from the CART analyses. (A) deep blubber; (B) superficial blubber (* = $p < 0.01$, ** = $p < 0.001$).

Table 2

MANOVA analysis for the effect of areas on the concentration of 18 fatty acids in the blubber of minke whales from the North Atlantic (1998). (A) = deep blubber and (B) = superficial blubber.

Variable	Df	Pillai	Approx F	Num df	Denom df	P-value
(A)						
IWC small areas*	1	0.534	8.589	18	135	< 0.0001
3 areas**	1	0.731	20.373	18	135	< 0.0001
Residuals	152					
Eastern North Sea vs NE Atlantic	1	0.702	9.27	18	71	< 0.0001
Residuals	88					
(B)						
IWC small areas*	1	0.418	5.716	18	143	< 0.0001
3 areas**	1	0.699	18.438	18	143	< 0.0001
Residuals	160					
Eastern North Sea vs NE Atlantic	1	0.683	8.731	18	73	< 0.0001
Residuals	90					

*Six groups representing IWC small areas and one which represents animals from two IWC small areas (i.e. West and East Greenland). **Greenland vs North East Atlantic vs Eastern North Sea.

Atlantic-North Sea) and a '3-Region model' (Greenland vs. NE Atlantic vs the North Sea) model. However, larger *F*-values were obtained from testing the '3-Region model' for both blubber layers thereby favouring this model over the '2-Region model'. This effectively is in accord with IWC '*Medium Area*' assumptions of three biological stocks (IWC, 2004). The MANOVA also indicated that there were significant differences among some IWC '*Small Areas*'. However, because a total of 43 FAs were included in the construction of classification trees, the CART analyses are thought to be relatively more powerful than the MANOVA in separating among whales sampled in different areas. Differences in FA signatures in this study may have been influenced by the fact that samples may have been taken from different parts of the body of the whale. Differences in blubber FA composition between two dorsal sites (30cm in front of and 30cm behind the dorsal fin) have been reported for North Atlantic minke whales (Olsen and Grahl-Nielsen, 2002). However, this difference was much smaller than the difference in FA signatures between the deep and superficial layer (Olsen and Grahl-Nielsen, 2002). No information is available about the exact sites from where the samples were taken and therefore the potential influence of the uncertainty associated with the sampling method is difficult to assess. There is no indication that large (> 7m) and small (< 7m) whales feed on different food items (Haug *et al*., 2002), but differences according to sexual maturity have been identified in harbour porpoise (Møller, 1999) and may also influence the results of this study to some degree. However, the fact that the findings in this study resemble those obtained in a genetic study using the same samples (Anderson *et al*., 2002) indicates that the FA technique is useful irrespective of sexual status and the location of the blubber sample on the whale.

Animal movements

The lack of clear differences among regions could to some extent be explained by some animals moving rapidly among feeding grounds. Minke whales are capable of relatively high swimming speeds (i.e. 7-12km/h, Blix and Folkow, 1995; Folkow, in litt., 27 April 2000). Therefore, a directed movement between even distant areas within the range of this study may take a minke whale only a few weeks. Hence, a whale may have fed in one area to be sampled not much later in another area. Furthermore, the actual lag-time between the dietary intake of the FAs and their deposition as a signal in the blubber is not known.

Despite the fact that the composition of FAs in the depot fats of marine mammals is influenced by the composition of the diet (e.g. Ackman, 1980), finding a FA composition in a predator identical to that of its diet is unusual (Iverson *et al*., 1995). This can be explained by an animal's ability to *de novo* synthesise and selectively metabolise, absorb and deposit FAs (Enser, 1984; Sargeant *et al*., 1988). It is a combination of dietary fats and endogenous synthesis that influences the blubber FA signature. Even though the diet of North Atlantic minke whales has been shown to vary considerably between geographic regions and periods (e.g. Haug *et al*., 2002; Sigurjónsson and Galan, 1990; Lydersen *et al*., 1991), it is a combination of internal and environmental factors that influences the composition of the blubber.

Additional sampling areas

Ideally, samples of minke whales from neighbouring Canadian (WC) and Icelandic (CIP and CIC, *cf*. Fig. 1) waters should have been included in this study. However, minke whales are currently not harvested by Canada or Iceland. Further work on differences in FA signatures to incorporate minke whales from the entire North Atlantic range of this species is recommended. Samples from areas where minke whales are not harvested may in the future be obtained from biopsies taken from free-roaming whales. Knowledge of the metabolism of the blubber, the turnover rate of FAs, and the effect of e.g. physiological state and reproductive status of the individual may significantly advance the feasible use of FA signatures as a tool in population studies.

The influence of foraging

Blubber FA signatures may reflect major and sometimes even minor differences in the diet (e.g. Iverson *et al*., 1997; Møller *et al*., 2003). Within the range covered by this study, there are major differences in food available to and consequently eaten by minke whales. Minke whales concentrate on traditional summer feeding grounds (Solvik, 1976; Harwood, 1990) where they feed in shallow shelf areas in association with highly productive frontal regimes (Mann and Lazier, 1991). In the Northern Hemisphere no single organism forms a predominant food supply in the minke whale diet. The complex oceanography and bathymetry of the North Atlantic (Mackintosh, 1965) can in part explain this heterogeneity. Minke whales differ markedly among the regions within the range of this study with respect to diet (Folkow *et al*., 2000; Neve, 2000; Olsen and Holst, 2001; Haug *et al*., 2002). Capelin (*Mallotus villosus*) is an important food for minke whales in West Greenland waters whereas polar cod (*Boreogadus saida*) seems to be of relatively greater importance in eastern Greenland (Neve, 2000). Generally, the minke whale food composition in Greenland waters resembles that reported for Icelandic nearshore waters where capelin and sand eel (*Ammodytes* sp.) made up *ca* 56% and krill (mainly *Thysanoessa* sp.) *ca* 35% of the food on weighted frequency basis (Sigurjónsson *et al*., 2000).

Studies of minke whale diet in the Northeast Atlantic over the period 1992-1999 showed that the food comprised of relatively few species and that the dietary composition varied considerably both in space and time, presumably due to geographic differences in the distribution and abundance of potential prey (Haug *et al*., 2002). In general, the whales find capelin and herring (*Clupea harengus*) and, occasionally, krill more preferably than other prey, which usually comprised of gadoid fish (cod, *Gadus morhua*; saithe, *Pollachius virens* and haddock, *Melanogrammus aeglefinus*). In the northeastern Atlantic, regional differences in stomach contents were found. Consumption of herring was almost exclusively confined to the Vestfjorden/Lofoten (EC) and the Barents Sea (EB) areas whereas consumption of krill was most pronounced in the Svalbard (ES) area (Folkow *et al*., 2000). In the latter area, capelin was important prior to the collapse of the Barents Sea capelin stock in 1992-1993 (Haug *et al*., 2002). In 1999, herring was a predominant food item in the Norwegian Sea whereas sand eel dominated (86.6% by weight) the minke whale food in the North Sea. In this latter area, mackerel (*Scomber scombrus*) made up 9.3% and other fish (e.g. herring) the remainder of food items (Olsen and Holst, 2001). These diets (stomach contents) are very different from those in Greenland waters where cod (*Gadus* sp.) has only been reported in a limited number of stomachs and herring in none (cf. Neve, 2000). The cod stock in Greenland during the 1990s has been very small (Anon., 2001) and herring, mackerel, saithe and haddock are almost absent (H.

Hovgård, Danish Fisheries Institute, DFU, pers. comm., 2001).

Although minke whales are euryphagous, and despite the fact that there are both inter-annual and inter-seasonal variation in their food, it is clear that their overall food selection is determined by prominent regional differences in the distribution and abundance of various prey types. Likely, these regional differences in prey availability are recorded as differences in signatures of FAs in the blubber of the minke whales. We believe that differerences in the foraging ecology of minke whales among regions is recorded in the blubber layers. The deep layer likely provides a record of a more recent history in contrast to an older history recorded in the superficial blubber. However, there are no comparable data on regional differences in FAs in the fish species or in other prey of minke whales to allow for a thorough discussion on the trophic importance of the signatures found in the minke whales (e.g. Dietz *et al.*, 1998).

Comparison with other studies

Only one other study exists on regional differences in blubber FA signatures in North Atlantic baleen whales. Olsen (2002) used FAs to differentiate between minke whales sampled in the North Sea and the Norwegian Sea in 1999. The findings by Olsen (2002) supported the results of Møller *et al*. (2002) and this study, that minke whales from the North Sea constitute a group that is different from those summering further north in the NE Atlantic region.

The present study indicates the existence of population sub-structuring in North Atlantic minke whales on a large geographical scale. This is in accordance with other studies using the same material from 1998 but applying different analytical techniques. Genetic analyses, which included both mitochondrial and nuclear DNA suggested the existence of four genetically distinct subpopulations: (1) West Greenland; (2) East Greenland and Jan Mayen; (3) North East Atlantic (Svalbard, Barents Sea Vestfjorden/Lofoten); and (4) the North Sea (2002). Andersen *et al.* (2002) had access to a larger sample from East Greenland than the present study, which only included three samples from this region. This is the likely explanation for Andersen *et al.*'s (2002) finding that CG constitutes a separate unit.

A regional comparison of PCBs and organochlorine (OC) pesticides showed that minke whales from the Barents Sea (EB) had significantly higher concentrations of ΣPCBs than those from the Vestfjorden/Lofoten, the North Sea and Svalbard, as well as significantly higher ΣDDT concentrations compared to West Greenland animals (Hobbs *et al.*, 2002). The similarities and differences in concentrations suggested that minke whales from West Greenland and East Greenland represent one group of whales, distinct from both the Jan Mayen minke whales and those from other IWC defined stocks within the range covered by the present study. However, principal component analysis using proportions of OCs did not reveal any major differences among groups. With the exception of the Barents Sea and West Greenland, there was a general similarity in mean levels and proportions of OC contaminants among minke whales in the northeastern Atlantic suggesting that the minke whales are quite mobile and may feed in multiple areas.

Multivariate and principal component analyses of signatures of stable isotopes of Pb, C and N and 19 other elements in muscle, kidney, liver and baleen of the minke whales that were sampled in 1998 suggested the existence of sub-structuring of the minke whale population within the explored geographical range. In particular, minke whales in West Greenland, the North Sea and the Vestfjorden/Lofoten areas appeared to be different from those in other areas (Born, *et al.*, 2003). Finally, Born *et al.* (2002) found the highest caesium-137 concentration in minke whales from the North Sea, and that the mean Cs-137 levels in minke whales from Svalbard and the North Sea differed significantly from mean levels in the other areas. This difference supports the indications from other studies that groups of minke whales are resident for some time at their feeding grounds in the North Atlantic and may occur in separate stocks during summer.

ACKNOWLEDGEMENTS

The present project has received financial support from the Danish Environmental Protection Agency as part of the environmental support programme Dancea – Danish Cooperation for Environment in the Arctic. The authors are solely responsible for all results and conclusions presented in the report, and do not necessary reflect the position of the Danish Environmental Protection Agency. The Greenland Institute of Natural Resources and the Danish National Environmental Research Institute also funded this study.

We wish to thank the Greenland and Norwegian fishermen and hunters and others who helped collecting the samples. The cooperation during the sampling phase with the Directorate of Fisheries (Nuuk) and KNAPK (Association of Greenland Hunters and Fishermen) is greatly acknowledged. Thanks to Sofie Jeremiassen and Kirsten Rydahl (Greenland Institute of Natural Resources) and to Sigga Joensen, Else Marie Nielsen and Maja Kirkegaard (Danish Environmental Research Institute, Roskilde) for various help during the sampling and preparation of the samples. We gratefully acknowledge the constructive criticism offered by Dr Sara J. Iverson (Dalhousie University, Nova Scotia, Canada) and an anonymous reviewer.

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Date received: September 2000.
Date accepted: December 2002.

Migration of a humpback whale (*Megaptera novaeangliae*) between the Cape Verde Islands and Iceland

B. JANN[*], J. ALLEN[+], M. CARRILLO[#], S. HANQUET[$], S.K. KATONA[+], A.R. MARTIN[**], R.R. REEVES[++], R. SETON[+], P.T. STEVICK[+] AND F.W. WENZEL[##]

Contact e-mail: Frederick.Wenzel@noaa.gov

ABSTRACT

The movements of individual humpback whales (*Megaptera novaeangliae)* can be tracked by matching photographs of the distinctive markings on the ventral sides of their tail flukes. During the winter-spring seasons of 1990, 1991, 1995, 1996, 1999, 2000, 2001 and 2002 a total of 42 individual humpbacks were identified by fluke photographs from the waters of the Cape Verde Islands. These were compared with photographs taken elsewhere in the North Atlantic. One match was made with a whale previously photographed in the Denmark Strait off Iceland, providing the first direct evidence of a link between the humpbacks in tropical waters of the eastern North Atlantic and a high-latitude feeding ground. This finding is consistent with the mitochondrial DNA evidence of at least two distinct breeding populations of humpback whales in the North Atlantic. The presence of cows with young calves as well as singers during the humpback mating and calving season implies that waters surrounding the Cape Verde archipelago constitute a breeding and calving ground for an eastern North Atlantic population of humpback whales.

KEYWORDS: HUMPBACK WHALE; REPRODUCTION; HABITAT; ATLANTIC OCEAN; BREEDING GROUNDS; PHOTO-ID; MIGRATION; FEEDING GROUNDS

INTRODUCTION

The population of humpback whales (*Megaptera novaeangliae*) in the North Atlantic Ocean is one of the best-studied populations of large whales in the world (see review in IWC, 2002; 2003). Since the 1970s, extensive photo-identification effort has yielded much information on population structure and migratory movements (Katona and Whitehead, 1981; Katona and Beard, 1990; Clapham and Mead, 1999; Smith *et al.*, 1999). Genetic tagging has also been used to determine connections between whales in different areas of the North Atlantic (Palsbøll *et al.*, 1995; 1997; Larsen *et al.*, 1996; Valsecchi *et al.*, 1997).

It is clear from previous studies that humpback whales feed during the summer in a number of relatively discrete grounds, including: Gulf of Maine; Newfoundland/Labrador; Gulf of St Lawrence; Greenland; Iceland; and Norway. Fidelity to these summer feeding areas is strong and apparently maternally directed; genetic analyses suggest that it is maintained on an evolutionary timescale (Larsen *et al.*, 1996; Palsbøll *et al.*, 1997). Despite the low level of movement between the various feeding grounds, photo-identification and genotyping has shown that some individuals from all of the identified high-latitude areas migrate long distances (in some instances more than 8,000km) to common winter breeding grounds in the West Indies (Martin *et al.*, 1984; Stevick *et al.*, 1998; 1999b; 2003) where they mix spatially and genetically. The great majority of humpback whales in the North Atlantic appear to use West Indies wintering areas, with large concentrations in the northern Antilles, especially on or near Silver Bank (Winn *et al.*, 1975; Clapham and Mead, 1999; Smith *et al.*, 1999).

During the 19th century, American open-boat whalers rarely reported taking humpbacks in the northern Antilles. Instead, their humpback whaling effort focused on portions of the southeastern Caribbean and on the Cape Verde Islands (Mitchell and Reeves, 1983; Reeves *et al.*, 2001; 2002; Reeves and Smith, 2002). Today, densities of humpbacks in these two historic breeding areas are comparatively low (Jann and Wenzel, 2001; Swartz *et al.*, 2003). A photographic match was made recently between the southeastern Caribbean and Fyllas Bank off West Greenland (Stevick *et al.*, 1999a), suggesting that at least some of the whales that winter in the southern portion of the West Indies have migratory habits similar to those of the whales that winter in the northern Antilles. The summer feeding range of the humpback whales that winter in the Cape Verde Islands has remained uncertain.

This paper reports the first match of an individually identified humpback whale from the Cape Verde Islands to a northern feeding ground (Iceland), and discusses the implications for population structure.

METHODS AND MATERIALS

Study area

The Cape Verde Islands are situated in the eastern North Atlantic between 14°48’-17°22’N and 22°44’-25°22’W, 460-830km west of Senegal, West Africa (Hazevoet, 1995). The ten islands and several islets are of volcanic origin, with steep shores, arising from a marine bottom more than 3,000m deep. Only the islands of Maio, Boavista and Sal have a continental platform, while the northwestern islands of Sao Vicente, Santa Lucia, Branco and Raso have limited

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[*] *Swiss Whale Society, via Nolgio 3, CH-6900 Massagno, Switzerland.*
[+] *College of the Atlantic, 105 Eden St., Bar Harbor, Maine 04609, USA.*
[#] *La Laguna, Tenerife, Canaries, Spain.*
[$] *Los Cristianos, Tenerife, Canaries, Spain.*
[**] *British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 OET, UK.*
[++] *Okapi Wildlife Associates, 27 Chandler Lane, Hudson, Quebec, Canada, J0P 1H0.*
[##] *National Marine Fisheries Service, Northeast Fisheries Science Center, 166 Water St., Woods Hole, MA 02543, USA.*

amounts of water less than 100m deep (Fig.1). Most research effort since 1990 has been in the eastern sector of the archipelago around the islands of Sal, Boavista and Maio.

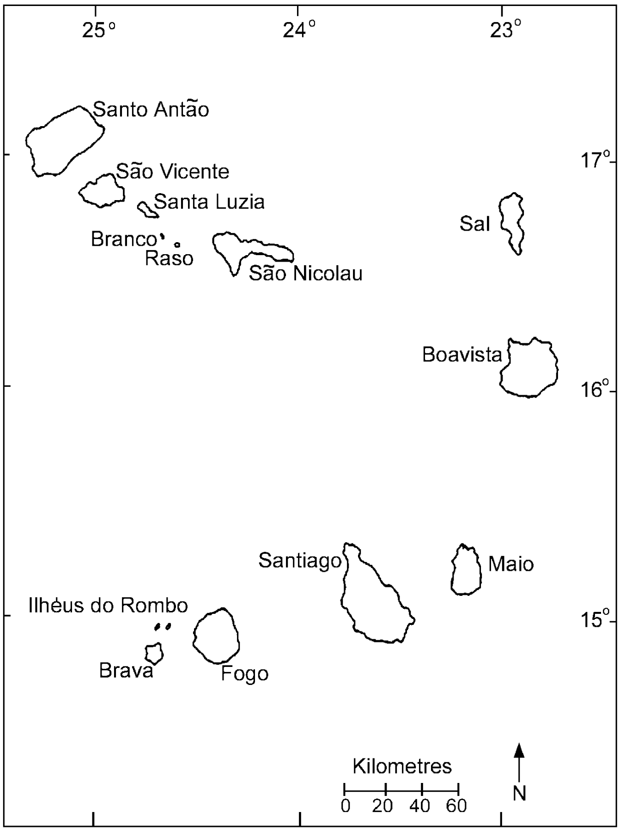

Fig. 1. Map of the Cape Verde Islands, as in Hazevoet (1995), with permission of the author.

These waters are known for strong trade winds, rough seas and sand storms, often making navigation around the islands difficult and hazardous and producing less than ideal conditions for mariners and whale researchers. This helps explain the low number of fluke photographs and limited amount of information on cetaceans from this region (Reiner *et al.*, 1996; Hazevoet and Wenzel, 2000; Jann and Wenzel, 2001; Jann *et al.*, 2002).

Data collection

Searches for humpback whales in the Cape Verde Islands were conducted from February to May in 1990, 1991, 1995 and 1996 aboard a 5m inflatable boat around the islands of Sal and Boavista (Reiner *et al.*, 1996; Hazevoet and Wenzel, 2000). The searches in 1999 (26 February – 8 April) were made from a 50m steel-hulled motor ship; in 2000 (27-29 February, 30 March – 4 April) and 2001 (31 March – 2 May) from a 37m schooner; and in 2002 (22 March – 2 May) from a 20m sailboat. During 2000-2002, a 5m inflatable boat was deployed from the larger vessels when humpbacks were observed and sea state permitted. More humpback fluke photographs were obtained in the 1999-2002 seasons than in previous years, presumably because of the advantages associated with using larger vessels in the types of sea-state conditions that prevail in these waters.

For each cetacean sighting, the time, GPS position, group size and composition, and behaviour were noted. Photographs were taken for identification purposes and acoustic recordings were made during approaches to humpback whales. The photographs were taken with a 35mm single lens reflex camera equipped with a 75-300mm zoom lens using 400 ASA black and white and/or colour print film.

Photo comparison

There are two major projects involving individual identification of humpback whales that include geographical coverage over much of the North Atlantic Ocean: the North Atlantic Humpback Whale Catalogue (NAHWC) and the collection from the Years of the North Atlantic Humpback Whale (YoNAH) project. Both humpback catalogues (NAHWC and YoNAH) are maintained at Allied Whale, College of the Atlantic, 105 Eden St., Bar Harbor, Maine 04609, USA.

The NAHWC is a central curator facility for photographs of humpback whales from throughout the North Atlantic Ocean. Photographs date from 1952 to 2002, though few are available from years prior to 1978. The NAHWC project is collaborative and photographs have been submitted by more than 350 contributors. Photographs have been obtained opportunistically, so temporal and spatial coverage is highly variable. Most photographs were taken on the western North Atlantic feeding grounds (Tables 1 and 2).

Table 1

Numbers of identified individuals in the two photograph collections (as of 31 December 2002) to which the Cape Verde Islands photographs were compared. Individuals identified in both a feeding and breeding region are included only in the number for the feeding region and not also in that for the breeding region. Western and eastern feeding areas are divided at the longitude just east of Cape Farewell, Greenland (40W longitude). No photographic matches have been found between the western and eastern feeding areas.

Collection	NAHWC	YoNAH
Feeding grounds, western	3,431	1,398
Feeding grounds, eastern	158	260
West Indies	1,647	1,324
Cape Verde Islands	42	0
Non-feeding/breeding regions: US coast south of Cape Cod, Bermuda and Mediterranean	122	0
Total	5,400	2,982

Table 2

Numbers of individuals in the NAHWC and the YoNAH collections identified in both a feeding and a breeding ground.

	West Indies	Cape Verde Is.
NAHWC		
Feeding grounds, western	564	0
Feeding grounds, eastern	15	1
YoNAH		
Feeding grounds, western	163	0
Feeding grounds, eastern	21	0

The YoNAH project, an extensive study of humpback whales in the North Atlantic, was conducted during 1992 and 1993. It did not include the waters of the Cape Verde Islands, the Irish Sea and other parts of the eastern North Atlantic. As part of that study, identification photographs were obtained in all of the known major feeding grounds and in the West Indies, using standardised protocols. Due to logistical considerations, sampling intensity in Icelandic and Norwegian waters, while considerably greater than during any previous effort, was less than that in the western North

Atlantic feeding areas (i.e. Greenland, eastern Canada and northeastern United States (Gulf of Maine) (Smith *et al.*, 1999). No YoNAH sampling was conducted in the Cape Verde Islands (Tables 1 and 2).

Since 1994, it has not been possible to manually compare all photographs within the (growing) NAHWC with the YoNAH catalogue. While the YoNAH collection has not been systematically compared to the NAHWC, due to resource and time limitations, nearly 800 individual humpback whales have been identified in both collections (J. Allen, unpublished data). All identification photographs from the Cape Verde Islands were compared to both the NAHWC and the YoNAH collections using methods described by Katona and Whitehead (1981), Katona and Beard (1990) and Smith *et al.* (1999).

RESULTS

Photographic match

A total of 42 individual humpback whales have been identified thus far in the Cape Verde Islands. The first Cape Verde fluke photographs were obtained in 1991 ($n = 2$), and numbers thereafter were 1 in 1995, 22 in 1999, 1 in 2001 and 16 in 2002. No individual has been identified in more than one year.

A single individual, NAHWC#4504, photographed on 10 March 1999 in the Bay of Sal Rei, Boavista, at 16°02’N, 23°02’W, had previously been photographed in the Denmark Strait west of Iceland, at 65°16’N, 27°30’W, in July 1982 (Fig. 2a-2b). No other photographic re-identifications of this animal were recorded during the 18 years between the 1982 and 1999 sightings.

Fig. 2a and 2b. Fluke photographs of NAHWC#4504, from the Denmark Strait west of Iceland at 65°16’N, 27°30’W in July of 1982 and again photographed on March 10 1999 in the Bay of Sal Rei, Boavista, Cape Verde Islands at 16°02’N, 23°02’W.

Presence of mother-calf pairs

Mother-calf pairs of humpback whales have been observed at the Cape Verde Islands as early as 23 February (in Baia de Mordeira, Sal, in 1995 and in the Bay of Sal Rei, Boavista, in 2002) and as late as 5 June (at Punta Preta, Sal; Robert Mannink, pers. comm.). A calf was defined as: $<$5m in total length; often of grey body colouration; and remaining most of the time within one body length of the female (see Clapham *et al.*, 1999; Clapham and Mead, 1999). Most observed calves had floppy dorsal fins and foetal folds on the sides of the body. Some had wrinkles reminiscent of a pickle. Nearly all encounters with mother-calf pairs were in waters $<$15m deep (see Smultea, 1994).

Presence of singers

Humpback whale songs have been described in detail by many authors (see Payne and Guinee, 1983; Payne and McVay, 1971; Winn and Winn, 1978; Noad *et al.*, 2000). Winn *et al.* (1981) compared humpback whale songs between the West Indies and the Cape Verde Islands. The small sample size from the Cape Verde Islands ($n = 1$ individual) and a couple of hours of recordings (13 songs) were compared to 10 songs from a probable 7 individuals from the West Indies. Winn *et al.* (1981) stated that by aligning similar themes it was clear that the thematic composition of the Cape Verde Island song format followed that of the West Indies songs, the only differences being in the number of ‘groans’ emitted within each theme and minor variations in phase structure. Winn *et al.* (1981), based on their sample size of one, stated that the songs from the Cape Verde Islands and the West Indies were ‘essentially equivalent’.

Humpback whale songs have been recorded during every field season, between February and May, especially around the islands of Sal and Boavista (Reiner *et al.*, 1996; Carrillo *et al.*, 1999; Hazevoet and Wenzel, 2000; Jann and Wenzel, 2001). The earliest song recording was on 17 February (1990) (Reiner *et al.*, 1996) and the latest was on 12 May (1996) (Hazevoet and Wenzel, 2000). It is assumed that by mid-May most humpbacks have started their northward migration to the feeding grounds. Unfortunately, to date no additional song comparisons have been undertaken to evaluate the validity of the conclusions of Winn *et al.* (1981) with regard to intra-ocean variability.

DISCUSSION

Over the years, several authors have suggested the existence of two breeding stocks of humpback whales in the North Atlantic, one along the western and another along the eastern margin of the basin, separated roughly at Cape Farewell, Greenland (Ingebrigtsen, 1929; Kellogg, 1929). However, the degree of separation, overlap and limits of the two proposed stocks have often been discussed and questioned (Mitchell and Reeves, 1983; Palsbøll *et al.*, 1995; 1997; Larsen *et al.*, 1996; Valsecchi *et al.*, 1997; Smith *et al.*, 1999; Stevick *et al.*, 1999b; IWC, 2002).

Two spatially distinct tropical regions of the North Atlantic are known to have been used traditionally by humpback whales during the winter calving/breeding season − one in the West Indies (assuming a continuous distribution from the Greater Antilles to Venezuela) and one in the Cape Verde Islands. The recent sightings of mothers with young calves, recordings of humpback songs, and observations of surface-active groups establish that the waters around the Cape Verde Islands are currently used as a breeding and calving habitat during the boreal winter and spring.

The photographic match with Iceland is the first evidence of a feeding-ground destination for humpback whales from the Cape Verde Islands. As animals photo-identified off Iceland have also been observed in the West Indies (Martin *et al.*, 1984; Smith *et al.*, 1999; Stevick *et al.*, 2003), this match is consistent with the hypothesis that there is overlap on the feeding grounds between animals from the West Indies and Cape Verde Islands. Moreover, the failure to match any of the photo-identified animals from the Cape Verde Islands with those on western feeding grounds or on the West Indies breeding ground is consistent with the hypothesis that humpbacks from the Cape Verde Islands constitute a distinct breeding population that feeds preferentially or exclusively in eastern feeding areas. Such a model is supported by the existence of mitochondrial DNA differences between eastern and western feeding areas (Palsbøll *et al.*, 1995; 1997; Larsen *et al.*, 1996; Valsecchi *et al.*, 1997).

It is difficult to interpret effort for the NAHWC by region and years. The NAHWC humpback fluke catalogue has grown enormously over the last 30 years, and YoNAH was a limited two-year study (1992 and 1993). However, the low match rate (1) strongly suggests that most of the whales that winter in the Cape Verde Islands use one or more eastern North Atlantic summer feeding area where there has been little or no recent sampling effort. When one considers how limited the photo-identification effort has been in the eastern feeding areas over the last 20 years, it is not particularly surprising that only one match has been made with a Cape Verde Islands fluke photograph, or that there has been an 18-year interval between the photographs of that individual.

CONCLUSIONS

Research effort in the Cape Verde Islands has been modest in comparison to that in the West Indies and many other parts of the western North Atlantic (Reiner *et al.*, 1996; Carrillo *et al.*, 1999; Hazevoet and Wenzel, 2000; Jann and Wenzel, 2001). The first long-distance match, reported in this paper, should stimulate increased photo-identification effort not only in the Cape Verde Islands, but also at sites along the likely migratory route to the north (e.g. Canary Islands, Madeira) and on potential eastern North Atlantic feeding grounds (e.g. the Irish Sea). It should also give impetus to intensified efforts to obtain biopsies and song recordings from whales in Cape Verdean waters for comparative genetic and acoustic analyses. From a local perspective, it is desirable to improve understanding of habitat use patterns, residency times and site fidelity of individual humpbacks within the Cape Verde archipelago, and to determine whether numbers are increasing in this part of the species' range as they have been elsewhere in the North Atlantic (Sigurjónsson and Gunnlaugsson, 1990; Barlow and Clapham, 1997; Smith *et al.*, 1999).

ACKNOWLEDGMENTS

We wish to acknowledge the Captains and crews of the ships *Holland*, *Corvette* and *Sodade*, especially Luis and Carlos Albrecht, Captain Luis A. Lopez, Captain Kees Roll, Captain Robert Mannink, Sonia Elsy Merino, The Instituto Nacional de Desenvolvimento da Pesca (INDP), and the volunteers who made this research possible through their very often enthusiastic participation, in particular Doris Vetsch and Walter Heckenthaler. Partial funding support for the 2002 cruise and the photograph matching at the College of the Atlantic was through the International Whaling Commission. In previous years, funding support was provided by the Whale and Dolphin Conservation Society (UK) and Cetacean Society International (USA). A number of friends and reviewers greatly assisted us with earlier drafts of this manuscript. Special thanks to Tim Smith, Phil Clapham, Per Palsbøll, Phil Hammond, Kees Hazevoet, Melissa Alexander, Gwilym Jones, Northeastern University, David Senn, Karl Zbinden, Daniel Zbinden, Chris Schlegel and Durant Hembree for their years of encouragement regarding humpback whale research in the eastern North Atlantic, especially at the Cape Verde Islands and Iceland. We thank Finn Larsen and one anonymous reviewer for comments and suggestions which improved this manuscript.

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Date received: March 2003.
Date accepted: July 2003.

Three forms of killer whales (*Orcinus orca*) in Antarctic waters

ROBERT L. PITMAN[*] AND PAUL ENSOR[+]

Contact e-mail: Robert.Pitman@noaa.gov

ABSTRACT

This paper provides field descriptions and biological observations of three different forms of killer whale (*Orcinus orca*) that occur in Antarctica based on field observations and a review of available photographs. Identifications were based on the relative size and orientation of the white eyepatch and the presence or absence of a dorsal cape. Type A (presumably the nominate form) has a medium-sized eyepatch oriented parallel to the body axis, no dorsal cape, it occurs mainly off-shore in ice-free water, has a circumpolar distribution and apparently preys mainly upon Antarctic minke whales (*Balaenoptera bonaerensis*). Type B also has an eyepatch oriented parallel to the body axis, but the eyepatch is at least twice as large as in Type A, it has a dorsal cape, mainly inhabits inshore waters, regularly occurs in pack-ice, is distributed around the continent and is regularly sighted in the Antarctic Peninsula area. Although it may also prey upon Antarctic minke whales and possibly humpback whales (*Megaptera novaeangliae*), seals seem to be the most important prey item. Type C has a small, forward-slanted eyepatch, a dorsal cape, inhabits inshore waters and lives mainly in the pack-ice; it occurs mostly off East Antarctica, and to date it has been recorded feeding only on Antarctic toothfish (*Dissostichus mawsoni*). Type C appears to be referable to *Orcinus glacialis* as described by Berzin and Vladimirov (1983). Although similar ecological specialisations have been reported for sympatric killer whale populations in the Northeast Pacific (i.e. an inshore mammal-eater, an inshore fish-eater and an offshore form), the extent of morphological divergence, habitat segregation and, perhaps, reproductive isolation, appears to be more pronounced among Antarctic populations. Although under a Biological Species Concept these forms appear to warrant separate species status, it will be important to show that this interpretation is consistent with results of molecular genetic analyses and additional morphological studies.

KEYWORDS: KILLER WHALE; ANTARCTICA; COLOURATION; DISTRIBUTION; TAXONOMY

INTRODUCTION

Killer whales (*Orcinus orca*) are generally considered to constitute a single species with a cosmopolitan distribution in the world ocean (Rice, 1998). However, during the late 1970s, several different groups of researchers independently concluded that, based on differences in morphology, ecology and acoustic repertoire, there were recognisably different forms of killer whales in Antarctica.

Mikhalev *et al.* (1981) used catch data from killer whales taken opportunistically by the Soviet whaling fleet in Antarctica during 18 seasons between 1961/62 and 1978/79, and reported what they thought was sufficient evidence to describe a new species – *Orcinus nanus*. During the following season (1979-80), Soviet whalers specifically targeted killer whales in Antarctica and took 916 (Berzin and Vladimirov, 1983). Based on catch data from that season, Berzin and Vladimirov (1982; 1983) described another new species of killer whale – *Orcinus glacialis*. Although the purported new species in each case was described as a 'dwarf' form (*ca.* 1-1.5m smaller than the nominate form), it is not clear from the descriptions if they were describing the same or different species (Rice, 1998). For example, when fluke sizes of the new forms were compared to *O. orca*, *O. nanus* reportedly had relatively larger flukes (at least in females; Mikhalev *et al.*, 1981), while those of *O. glacialis* were 40% smaller (Berzin and Vladimirov, 1983).

There were some additional problems with the Antarctic killer whale descriptions. Mikhalev *et al.* (1981) provided few descriptive details and did not designate a holotype specimen, making *O. nanus* a *nomen nudum* (IWC, 1982). Berzin and Vladimirov (1983) provided much more descriptive detail and designated a holotype specimen and five paratypes for *O. glacialis*, but their specimens were deposited at the Pacific Research Institute of Fisheries and Oceanography, TINRO, Vladivostok, and apparently all of them have been subsequently discarded (R.L. Brownell, pers. comm.).

Berzin and Vladimirov (1983) cited a number of other biological and morphological features to support their claim for a separate species. According to them, *O. glacialis* lived in the pack-ice (at least during the summer) and fed mainly on fish, while the typical form (*O. orca*) foraged in ice-free waters and preyed mainly upon marine mammals, especially Antarctic minke whales (*Balaenoptera bonaerensis*). Although the nominate form was black and white, the smaller form was often yellowish, which the authors attributed to diatom infestation. Berzin and Vladimirov (1983) also described differences in skull morphology and relative appendage size, and reported that tooth size alone could reliably distinguish adults of the two species, with a tooth from *O. glacialis* being half as long and one quarter the mass of a comparable tooth from *O. orca*.

In the late 1970s, US researchers reported that killer whales inhabiting the pack-ice near McMurdo Sound in the Ross Sea had distinctive colour patterns and vocalisations (Jehl *et al.*, 1980; Thomas *et al.*, 1981; Awbrey *et al.*, 1982; Evans *et al.*, 1982). In addition to a yellowish colouration (also attributed to an 'algal concentration'), the McMurdo whales had a discernable dorsal cape and eyepatches of variable shape and size. Given that the Soviet scientists did not discuss size and shape of the eyepatch or mention the presence of a dorsal cape in their descriptions, and the American scientists did not examine any carcasses, it has not been possible to determine if the McMurdo whales might be the same as either of the species described in the Soviet papers.

More recently, Miyazaki (1992) reported 18 killer whale sightings made during a cetacean survey in the Ross Sea in 1980-81. Although based on estimated body length, dorsal

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[*] *Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla, CA 92037, USA.*
[+] *Governors Bay, Lyttelton RD1, New Zealand.*

fin size and colouration (yellow versus white), he speculated that there might be several populations of killer whales in the Ross Sea, but expressed doubt about the validity of *Orcinus glacialis* as a separate species.

To date, the lack of specimen material, coupled with the inadequate descriptions, has left most cetologists skeptical of the evidence for more than one species of killer whale in Antarctica (IWC, 1982; Miyazaki, 1992; Rice, 1998; Dahlheim and Heyning, 1999). In a preliminary effort to clarify the taxonomic status of Antarctic killer whales, this study considers field observations and reviews literature and available photographs. Based on colour patterning, habitat selection and prey preferences, evidence indicates there are at least three field-identifiable forms of killer whales in Antarctica. This paper provides field descriptions of these forms, along with some biological observations and discusses their status relative to the two previously described killer whale species from Antarctica.

METHODS AND RESULTS

Published and unpublished photographs of killer whales from Antarctica (i.e. waters south of 60°S) were reviewed, and records of Antarctic-type killer whales north of 60°S were also compiled. The terminology used for colour pattern elements follows Perrin (1972) and Dahlheim and Heyning (1999).

Three distinct forms of killer whales were identified in Antarctica (Types A, B and C), based mainly on the size and shape of the eyepatch (Fig. 1). The presence of a dorsal cape (Figs 1c and 1f) was also important in identifying two of the types (B and C). Although other morphological characters, such as tooth size, may prove to be more useful for specimens in hand, the features discussed here are mainly relevant to field observers.

Descriptions

The typical form of *O. orca* in Antarctica is relatively large, black and white (rarely with a yellow tinge), and looks like the familiar killer whale seen worldwide (Type A: Figs 1a-b). It is apparently the largest of the Antarctic killer whales with reported lengths of up to 9.0m for males and 7.7m for females (Mikhalev *et al.*, 1981). It lacks a visible dorsal cape and the eyepatch is of medium size, generally oval, with the long axis roughly parallel to the body axis. Although numerous unpublished photos of Type A in

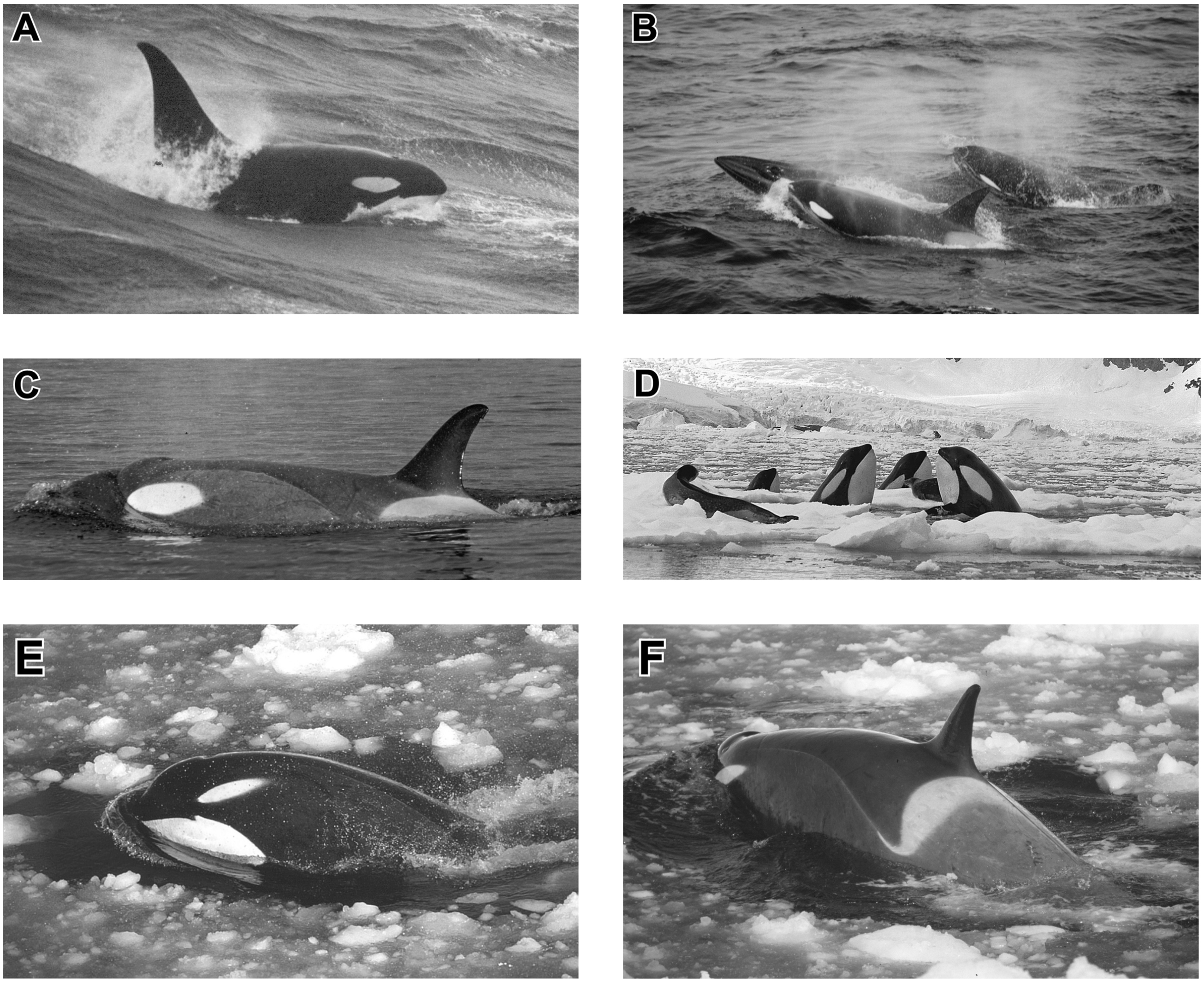

Fig. 1. Three forms of killer whales that occur in Antarctica (see text for description of Types): (a) Type A — showing medium-sized, horizontally-oriented eyepatch and no cape, K. Sekiguchi photo, 2 February 2002, 66°03'S, 150°01'E; (b) Type A — attacking an Antarctic minke whale, R. Rowlett photo, 13 January 1985, 65° 00'S, 117° 00'E; (c) Type B — showing large, horizontally-oriented eyepatch and cape, I. Visser photo, 23 December 2001, 64°54'S, 62°52'W; (d) Type B — spyhopping, next to a leopard seal (left), and a Weddell seal on ice floes, O. Carlsson photo, 14 January 2000, 64°14'S, 64°10'W; (e) Type C — showing small, slanted eyepatch, R. Pitman photo, 20 Jan 2002, 77°39'S, 165°54'E; (f) Type C — showing slanted eyepatch and cape, R. Pitman photo, 20 Jan 2002, 77°39'S, 165°54'E.

Antarctica were found (Table 1), the only published photographs of this type in Antarctic waters were found in Miyazaki (1992, pp.57-58, School No. 4).

The other two forms (Type B: Figs 1c-d; Type C: Figs 1e-f) both have dorsal capes that are visible when lighting conditions are favourable. They are two-toned-gray and white, instead of black and white, often with a strong yellow cast apparently due to a diatom film on the body. In both forms, a dark gray dorsal cape is set off against a medium-gray lateral field. At sea, the dorsal surface of Type A appears as black behind the saddle as it is in front of it, so that the dorsum usually appears all black with a pale saddle. In the caped forms, the paler lateral field merges over the back immediately behind the saddle, making that area noticeably lighter than in front of the saddle (e.g. Dahlheim and Heyning, 1999, p.288; Visser, 1999).

In both of the caped forms, the anterior end of the cape begins at the forward tip of the white eyepatch and arches well above the eyepatch as it passes posteriad (Type B: Fig. 1c; Type C: Fig. 1f). The cape is narrow forward, and widens mid-body as it dips down adjacent to the dorsal fin. Posterior to the dorsal fin, the cape sweeps upward and becomes confluent with the trailing edge of the saddle, so that the saddle appears to be derived from the cape (Fig. 1f). The lower part of the saddle projects forward as a thin taper, sometimes extending far forward as a narrow outline of the cape (Fig. 1f).

Although killer whales in Antarctica have often been reported to be yellowish (e.g. Evans *et al.*, 1982; Berzin and Vladimirov, 1983; Shiriahi, 2002), yellow colouration appears to occur only on the caped forms (Type B: Taylor, 1957; RLP, pers. obs.; Type C: Wu, 2002; RLP, pers. obs.). In addition to colouring the white areas yellow, a heavy concentration of diatoms will cause black areas to appear brown (Shiriahi, 2002; RLP, pers. obs.).

The two caped forms are readily distinguishable in the field. Type B has a very large, white eyepatch (at least twice as large as in Type A), oriented parallel to the body axis (Figs 1c-d). Type C has a much smaller eyepatch than Type B and it angles downward in the front (Figs 1e-f). A useful way to distinguish between the two caped forms is to imagine a line running through the long axis of the eyepatch and compare that to the horizontal black border that runs from the gape to the flipper. In Types A and B, the axis runs more or less parallel to the flipper-to-gape line, but in Type C, the forward end of the patch points down at a *ca*. 45° angle (see Evans *et al.*, 1982; Visser and Mäkeläinen, 2000).

Published photos of Type B killer whales can be found in Taylor (1957, Plate 1, Figs 3-4), Porter (1978, p.77), Smith *et al.* (1981), Bonner (1998, p.132), Miyazaki (1992, p.58, middle right and bottom right; p.59, bottom), Todd (1993, p.161, bottom left), Heimlich-Boran and Heimlich-Boran (1994, p.14), Miyashita *et al.* (1995, p.127), Rowell (1995, p.71), Monteath (1996, p.135), Carwardine *et al.* (1998, p.5), Dahlheim and Heyning (1999, p.288), Lanting *et al.* (1999, p.249), Visser (1999), Stone (2001, p.40) and Shirihai (2002, p.28).

Published photos of Type C killer whales can be found in Evans *et al.* (1982, Fig. 2), Payne and Crawford (1989, Plate 40, Fig. 4), Martin (1990, p.120), Gill and Thiele (1997), Carwardine *et al.* (1998, p.187), Lundgren and Carlsson (2001, pp.23-24), McGonigal and Woodworth (2001, p.273), Nybakken (2001, p.105), Shirihai (2002, pp.333, 336 and 462) and Wu (2002).

Specific data on body lengths of Type B and C animals are not available because it is not known which types were included in the Soviet catch data. It is clear however that at least one, and probably both of these are smaller than Type A killer whales. Mikhalev *et al.* (1981) reported that adult females of 'regular' killer whales (Type A) taken by Soviet whalers reached 7.5-7.8m, but '*Orcinus nanus*' females reached only 6.4-6.5m. Since the latter was taken in high latitudes of Area 1 in Antarctica (120°W-60°W), an area where we found Type B to be common but no Type C (see below), we suspect that Type B could be a dwarf form. Miyazaki (1992) also reported that individuals in their School No. 10-A (Type B) were smaller than individuals in School No. 4 (Type A), and adult males of the former had relatively smaller dorsal fins. The only other information on the relative size of Type B is from Visser (1999) who reported that individuals in a herd she observed in New Zealand were *larger* than the resident killer whales from that area. From our experience in the field, Type B appears smaller than Type A. Berzin and Vladimirov (1983) reported that male '*O. glacialis*' (probably Type C; see Discussion) averaged 112cm shorter than 'white' killer whales (Type A), and that females were 64cm shorter.

Distribution and Movements

Killer whales are known to occur throughout Antarctic waters (Kasamatsu and Joyce, 1995). However, because previous workers did not distinguish between the three forms described here, practically nothing is known about their relative distributions or movements. Possible exceptions to this come from Berzin and Vladimirov (1983), who reported that *O. glacialis* (probably Type C – see Discussion) was commonly encountered from at least 60°E to 141°40'E and might have a circumpolar distribution, and Visser (1999), who reported a 'possible Antarctic killer whale' sighting (Type B, see Table 1) from New Zealand.

It was possible to classify 101 sightings of Antarctic killer whales to type that had at least general location information and 96 that had specific coordinates (Table 1). Fig. 2 shows plots, by type and location, of all the identified sightings compiled (two additional sightings in Table 1, 1 Type B and 1 Type C, occurred north of 40°S and were not included in the plots). Type A killer whales (Fig. 2a, $n = 32$) were circumpolar in Antarctica. An apparent concentration of sightings just west of the Ross Sea is an artefact of a recent cruise there by PE after he was able to correctly identify killer whales to type. Type B (Fig. 2b, $n = 47$) also had a circumpolar distribution but appeared to be especially common in the Antarctic Peninsula area. The apparent concentration of Type B sightings there is due to the many photos available from the numerous cruise ships that regularly visit that area. Type C (Fig. 2c, $n = 17$) may also have a circumpolar distribution but as yet it has not been recorded in the Antarctic Peninsula area; most of the sightings were from East Antarctica, especially the Ross Sea.

There is also relatively little specific information on seasonal movements of these forms in Antarctic waters. Many killer whales apparently leave Antarctica during the austral winter and migrate to lower latitudes (Mikhalev *et al.*, 1981; Kasamatsu and Joyce, 1995), although there has been very little survey work conducted in the Antarctic in the austral winter (Gill and Thiele, 1997). Type A apparently migrates from lower latitudes to Antarctic waters during the austral summer in pursuit of its main prey, Antarctic minke whale, and then moves north again when the minke whales migrate in the autumn (Budylenko, 1981; Mikhalev *et al.*, 1981; Berzin and Vladimirov, 1983; Kasamatsu and Joyce, 1995). To date, there are no verified records of Type A killer whales overwintering in Antarctica.

Table 1

Sightings of three different types of killer whales in Antarctic and adjacent waters (see text for description of Types).

Type	Date	Location	Herd size	Source	Comments
A	16 Jan 1981	64° 33’S, 162° 06’E	14	Miyazaki (1992), p. 57-58, School No. 4	
A	3 Jan 1982	59° 33’S, 44° 10’W	14	R. Rowlett, photo	
A	14 Jan 1983	67° 40’S, 74° 33’W	35	R. Rowlett, photo	
A	23 Jan 1983	69° 03’S, 96° 31’W	?	Photo courtesy R. Reeves	
A	13 Jan 1985	65° 00’S, 117° 00’E	21	R. Rowlett, photo	Attacking a minke whale
A	6 Feb 1986	69° 40’S, 170° 40’W	12	R. Rowlett, photo	
A	5 Jan 1988	62° 34’S, 39° 23’E	18	R. Rowlett, photo	
A	5 Jan 1989	64° 21’S, 62° 38’W	?	F. Todd, photo	
A	27 Dec 1996	63° 16’S, 53° 53’W	15-20	K. Robertson, photo	
A	26 Jan 1998	60° 09’S, 45° 29’E	10	P. Ensor, photo	
A	21 Feb 1999	62° 56’S, 128° 57’E	21	P. Ensor, photo	
A	21 Feb 1999	63° 52’S, 124° 40’E	35?	K. Sekiguchi, video	5 ‘small, yellow’ individuals reportedly in this scattered school
A	8 Feb 2001	71° 21’S, 175° 40’E	14	C. Olavarría, photo	
A	2 Feb 2002	66° 04’S, 150° 01’E	14	K. Sekiguchi, photo	2 groups of 7 animals each
A	26 Dec 2002	64° 12’S, 174° 03’E	10	P. Ensor, pers. obs.	
A	31 Dec 2002	67° 48’S, 178° 34’W	15	P. Ensor, pers. obs.	
A	31 Dec 2002	67° 45’S, 178° 30’W	18	P. Ensor, pers. obs.	
A	31 Dec 2002	67° 44’S, 178° 30’W	?	P. Ensor, pers. obs.	
A	31 Dec 2002	67° 40’S, 178° 27’W	12	P. Ensor, pers. obs.	
A	31 Dec 2002	67° 15’S, 177° 57’W	38	P. Ensor, pers. obs.	
A	6 Jan 2003	61° 23’S, 63° 16’W	5	R. Pitman, pers. obs.	
A	6 Jan 2003	63° 09’S, 61° 50’W	8	R. Pitman, pers. obs.	
A	16 Jan 2003	61° 29’S, 173° 26’W	5	K. Matsuoka, pers. comm.	
A	18 Jan 2003	60° 31’S, 171° 32’E	3	P. Ensor, pers. obs.	
A	24 Jan 2003	63° 18’S, 167° 20’E	8	P. Ensor, pers. obs.	
A	24 Jan 2003	63° 47’S, 167° 42’E	35	P. Ensor, pers. obs.	
A	29 Jan 2003	64° 20’S, 150° 23’E	10	S. Rankin, photo	
A	30 Jan 2003	64° 40’S, 63° 00’W	5	R. Pitman, pers. obs.	
A	12 Feb 2003	62° 10’S, 157° 39’E	3	K. Matsuoka, pers. comm.	
A	16 Feb 2003	67° 14’S, 160° 04’E	1	K. Matsuoka, pers. comm.	
A	16 Feb 2003	67° 40’S, 161° 56’E	9	F. Ugarte, photo	
A	3 Mar 2003	60° 58’S, 53° 46’W	6	R. Pitman, pers. obs.	
B	13-16 Aug 1955	63° 52’S, 58° 08’W	?	Taylor (1957), Plate 1, Figs 3-4	In a polynya in winter
B	Feb 1979	64° 54’S, 62° 52’W	?	D. Larsen, photos, courtesy I. Visser	
B	12 Nov 1979	64° 53’S, 62° 53’W	7	Smith *et al.* (1981)	Apparently took a crabeater seal off an ice floe
B	Jan 1981	51° 41’S, 57° 51’W	?	D. Larsen, photos, courtesy I. Visser	Falkland Islands
B	5 Jan 1981	65° 23’S, 137° 50’E	4	J. Joyce, photo	
B	25 Jan 1981	75° 46’S, 169° 07’E	min. 12	Miyazaki (1992)	
B	28 Jan 1981	63° 51’S, 53° 49’W	?	R. Rowlett, photo	
B	1 Feb 1981	75° 48’S, 168° 36'W	18	Miyazaki (1992), p. 59, bottom	
B	28 Dec 1981	64° 06’S, 54° 04'W	5	J. Joyce, photo	
B	9 Jan 1982	63° 14’S, 37° 23’W	20	R. Rowlett, photo	
B	31 Jan 1982	69° 36’S, 11° 00’W	6	R. Rowlett, photo	In pack-ice
B	Feb 1982	62° 10’S, 58° 24’W	?	F. Todd, photo	
B	15 Dec 1985	65° 12’S, 64° 08’W	4	Heimlich-Boran and Heimlich-Boran (1994), p. 14; M. Webber, pers. comm.	Spy-hopping in pack-ice
B	31 Jan 1987	69° 44’S, 03° 53’W	15	J. Joyce, photo	
B	15 Jan 1988	64° 58’S, 63° 30’W	22	M. Webber, photo	
B	24 Jan 1988	69° 12’S, 01° 54’E	8	K. Matsuoka, photo	
B	7 Jan 1989	63° 52’S, 86° 12’E	2	K. Matsuoka, photo	
B	23 Jan 1990	‘off the Antarctic Peninsula’	?	Dahlheim and Heyning (1999), Fig. 3; J. Heyning, pers. comm.	
B	1992	64° 52’S, 62° 53’W	5	Rowell (1995), p.71	
B	?	64° 52’S, 62° 53’W	?	Monteath (1996), p. 135	
B	1 May 1997	35° 09'S, 174° 08'E	8	Visser (1999)	Bay of Islands, New Zealand
B	1 Jan 1999	63° 31’S, 56° 47’W	6	I. Visser, pers. comm.	
B	14 Jan 1999	64° 37’S, 54° 56’E	31	K. Matsuoka, photo	
B	14 Jan 2000	65° 14’S, 64° 10’W	7	O. Carlsson, photo	Spyhopping around a Weddell seal on an ice floe
B	5 Feb 2000	62° 55’S, 61° 42’W	10	R. Pitman, pers. obs.	Travelling alongside 8 Antarctic minke whales
B	11 Feb 2000	63° 41’S, 61° 36’W	5	R. Hucke-Gaete, photo	
B	Jan 2001	63° 18’S, 56° 40’W	10	T. Dennis, photo	
B	15 Feb 2001	63° 37’S, 56° 43’W	5	S. Todd, photo	Chased a crabeater seal that got away; then attacked(?) a Gentoo penguin
B	20 Feb 2001	72° 02'S, 170° 04'E	30	Stone (2001), p. 40 lower; C. Olavarría, pers. comm.	In pack-ice

cont.

Table 1 continued

B	2 Mar 2001	65° 07’S, 64° 02’W	?	M. Pope, video	In pack-ice; tipped a crabeater seal off an ice floe
B	23 Mar 2001	63° 26’S, 61° 12’W	8	Photos courtesy D. Thiele	Followed 3 humpback whales (2 adults; 1 calf)
B	5 April 2001	67° 15’S, 67° 29’W	30	Photos courtesy D. Thiele	
B	19 Dec 2001	74° 25’S, 176° 19’E	3	R. Pitman, pers. obs.	
B	22 Dec 2001	64° 41’S, 62° 38’W	15	I. Visser, photo	
B	23 Dec 2001	64° 54’S, 62° 52’W	12	I. Visser, photo	
B	Feb 2002	63° 35’S, 57° 20’W	12	T. Dennis, photo	In pack-ice
B	Feb/Mar 2002	64° 47’S, 63° 30’W	?	M. Pope, photo	
B	23 Feb 2002	62° 43’S, 59° 50’W	12 (+11?)	Shirihai (2002), p. 28; M. Jorgensen, pers. comm.	1, possibly 2 herds apparently attacking a lone humpback whale
B	29 Dec 2002	64° 41’S, 62° 58’W	15	R. Pitman, pers. obs.	Feeding on a southern elephant seal
B	6 Jan 2003	63° 47’S, 57° 18’W	7	R. Pitman, pers. obs.	
B	6 Jan 2003	64° 09’S, 56° 52’W	12	R. Pitman, pers. obs.	Spy-hopping among loose ice floes
B	6 Jan 2003	64° 18’S, 57° 00’W	6	R. Pitman, pers. obs.	
B	29 Jan 2003	63° 34’S, 56° 22’W	13	R. Pitman, pers. obs.	
B	8 Feb 2003	64° 45’S, 62° 58’W	15	M. Jorgensen, pers. comm.	Attacking humpback calf with cow
B	14 Feb 2003	65° 04’S, 63° 58’W	18	T. Pusser, pers. comm.	Harassing (attacking?) 4 humpback whales
B	16 Feb 2003	67° 20’S, 160° 20’E	5	F. Ugarte, photo	Travelling along pack-ice edge
B	19 Feb 2003	67° 06’S, 66° 34’W	9	R. Pitman, pers. obs.	
B	19 Feb 2003	67° 04’S, 66° 45’W	20	R. Pitman, pers. obs.	
C	Nov-Dec 1973	McMurdo, Ross Sea	?	F. Todd, photo	
C	1975-76	McMurdo Sound	?	Porter (1978)	
C	31 Dec 1980	66° 00’S, 147° 18’E	28	P. Best, photo	In 2 sub-groups
C	3 Jan 1981	66° 32’S, 140° 46’E	150	J. Joyce, photo	
C	6 Jan 1981	65° 04’S, 133° 32’E	50-60	Payne and Crawford (1989), plate 40, fig. 4; P. Best, pers. comm.	In 5 sub-groups; possibly attacking humpback whales
C	30 Jan 1981	73° 50’S, 179° 19’W	78	J. Joyce, photo	At ice-edge
C	2 Feb 1981	76° 18’S, 175° 10’W	13	R. Rowlett, photo	
C	10 Feb 1985	66° 54’S, 70° 28’E	45	R. Rowlett, photo	
C	Jan 1990	69° 37’S, 14° 45’E	?	S. Lundgren, photo	Attacked(?) photographer; see text
C	19-20 Jan 1991	Ross Island, Ross Sea	?	F. Todd, photo	
C	10 Aug 1995	65° 42’S, 139° 56’E	40+	Gill and Thiele (1997)	In pack-ice
C	19 Jan 1999	64° 45’S, 72° 45’E	16	K. Matsuoka, photo	
C	Jan 2000	Off Dry Valleys, Ross Sea	?	F. Todd, photo	
C	Jan 2001	ca 76° 00’S, 26° 34’W	?	British Antarctic Survey, photo	In a lead
C	24 Jan 2001	35° 58’S, 174° 40’E	35-40	I. Visser, photo	In New Zealand
C	23 Dec 2001	76° 05’S, 172° 24’E	55	R. Pitman, pers. obs.	
C	6 Jan 2002	77°38'S, 165°51'E	15-20	J. Cato, photo	In a lead
C	12 Jan 2002	77°36'S, 165°41'E	35	R. Pitman, pers. obs.	In pack-ice
C	16 Jan 2002	77°24'S, 165°01'E	10	R. Pitman, pers. obs.	In pack-ice
C	30 Jan 2002	66°05'S, 141°10'E	75	P. Olson, photo	
C	9 Feb 2002	65°58'S, 141°22'E	30	J. Cotton, photo	

The migratory status of Type B and C killer whales is currently unknown. They could be year-round residents because at least some of the prey that they are known to feed on (see below) are non-migratory. There is at least one winter record of Type B killer whales in Antarctica: Taylor (1957) reported 60 killer whales ‘trapped’ in a polynya off the Graham Land coast in August 1955 and his photos show at least three Type B whales (Taylor, 1957: Plate 1, figs 3-4; the whales shown in his fig. 7 are of indeterminate type). Two records were found of Type B killer whales north of Antarctic waters that may be indicative of migratory movements; these include a group photographed in the Falkland Islands in February 1979, and a group photographed off New Zealand in May 1997 (Table 1).

The only specific evidence of Type C killer whales overwintering in Antarctica comes from Gill and Thiele (1997), who reported a group of at least 40 killer whales well inside the sea ice, 100km north of the Adelie Land coast in August 1995; their accompanying photograph shows a pair of Type C whales. There is one, possibly two, records of this form occurring north of Antarctic waters: a mass stranding of 17 whales in New Zealand in May 1955 was possibly this type (Baker, 1983; see also Visser and Mäkeläinen, 2000) and a group photographed off New Zealand in January 2001 was clearly this type (Visser, pers. comm.; Table 1).

RLP saw a pair of killer whales (an adult male and a female or sub-adult) each with an obvious cape pattern at 28°31’S, 145°46’W, *ca*. 350km south of Tahiti on 2 March 2001. Although the type (i.e. B or C) could not be verified at the time, it seems likely that at least one of the caped forms ranges into the tropics.

In summary, all three killer whale types occur in Antarctica during the austral summer. Type A apparently migrates to lower latitudes during the winter and there is some indication that Type B could also be migratory. Type B and C whales, but not Type A, have been found wintering in the pack-ice. It may be that the caped forms, because they inhabit the pack-ice and polynyas during the summer, are more likely to become trapped in advancing winter ice and perhaps forced to overwinter, or it could be that either form is normally a year-round resident in Antarctica.

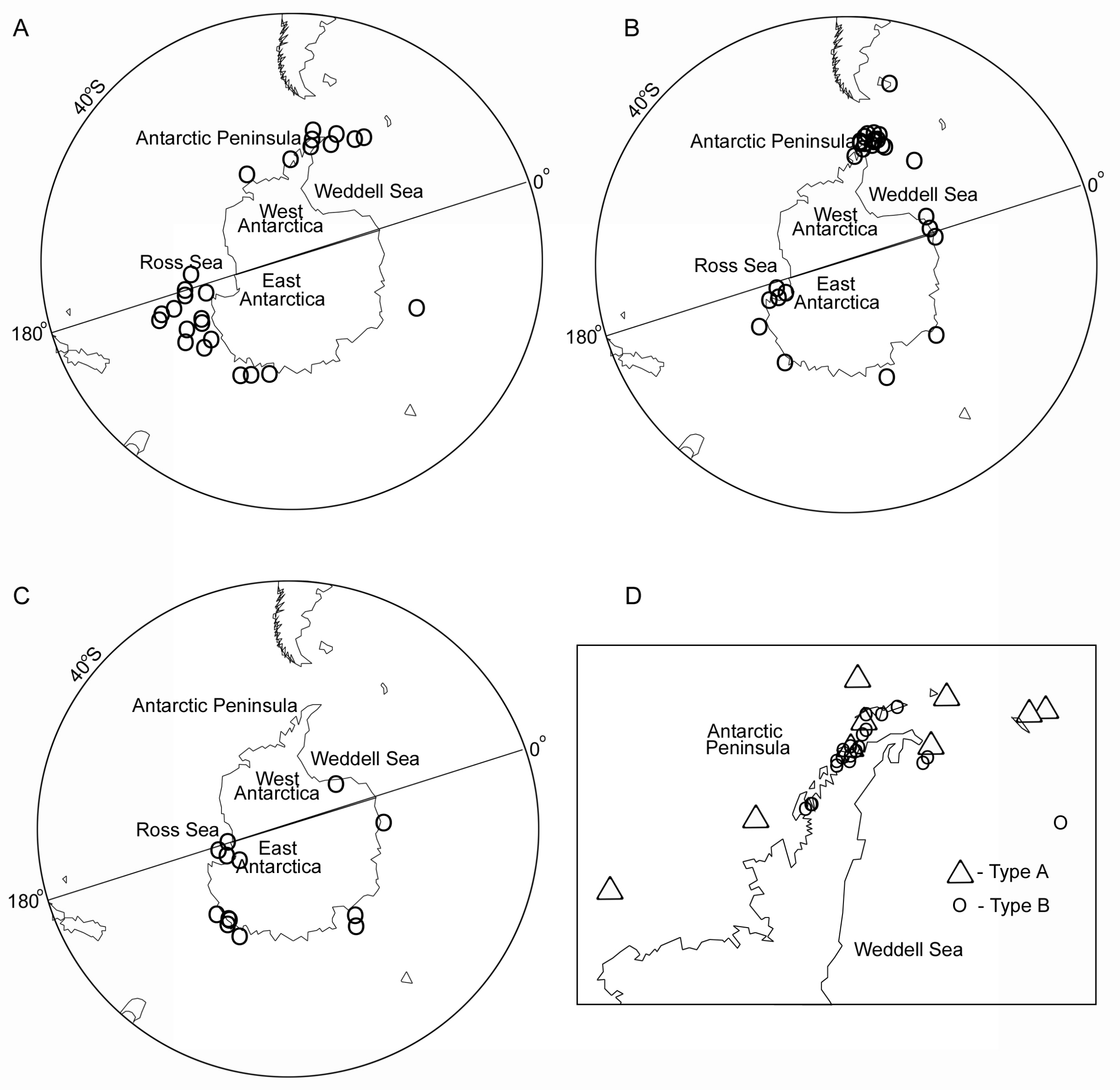

Fig. 2. Sighting locations of three forms of killer whales in Antarctica: (a) Type A; (b) Type B; (c) Type C; (d) Details of habitat preferences of types A and B in Antarctic Peninsula area (see text for description of Types).

Habitat

The observations indicate some clear habitat preferences among the three forms based on the amount of ice present. We found Type A only in open water, as did Berzin and Vladimirov (1983). Type B occasionally occurred in open water but was most often seen travelling among loose sea ice and regularly spyhopping next to individual floes, apparently looking for seals (see below). Fig. 2d shows a more detailed view of killer whale distribution around the Antarctic Peninsula and clearly indicates the preference of Type A for open water and Type B for nearshore habitat. Type C penetrated further into the ice than Type B and regularly occurred in dense pack-ice, along leads in fast ice and in polynyas. This form was often seen spyhopping also, but it appeared to be mostly interested in surveying for open water.

Biological observations

Group size

According to Berzin and Vladimirov (1983), the larger, offshore killer whale (presumably Type A) was usually found in groups of 10-15 animals, while groups of the ice-inhabiting form(s) ranged up to 150-200 animals. (Berzin and Vladimirov did not distinguish between B and C types but they were likely referring to Type C; see below). Ivashin (1981) put the school size of the smaller, yellow form as ‘up to 150-300 whales’. Table 1 shows the data compiled on group sizes: Type A had an average group size of 13.6 individuals (range = 1-38; $n = 28$); Type B, 11.8 (range 2-31; $n = 37$) and Type C, 46.1 (range 10-150; $n = 14$).

Feeding

Specific information on prey preferences of Antarctic killer whales is relatively sparse but suggests that dietary specialisation occurs among the three forms, at least in Antarctic waters. Type A apparently feeds mainly on Antarctic minke whales (Berzin and Vladimirov, 1983; Fig. 1a; see also Yukhov *et al.*, 1975). Type B often spyhops among ice floes where seals are hauled out (Fig. 1d) and pinnipeds appear to be an important prey item (Table 1). This is supported by some observations that suggest that Type B killer whales have developed some sophisticated behaviours for taking seals off ice floes. Smith *et al.* (1981) reported on the hunting behaviour of a pod of killer whales in the Peninsula area and their accompanying photo shows they were Type B. The whales were spyhopping among loose ice when they spotted a crabeater seal (*Lobodon carcinophagus*) on a floe. The whales moved 100m away, then charged at the floe at high speed. They turned abruptly in front of the floe sending a large wave over it that swept the seal into the water. The seal was not seen again and was presumably taken by the whales.

O. Carlsson (pers. comm.) reported that a group of Type B killer whales in the Peninsula area charged an ice floe five times with a Weddell seal (*Leptonychotes weddellii*) on it, washing the seal off with a wave each time. The whales swam off without harming the seal and Carlsson thought it might have been a training session for the two calves that were present. W. Fraser (pers. comm.) observed a different foraging tactic near Palmer Station, Anvers Island (the type of killer whale was not specified but was presumably Type B). The whales approached a leopard seal (*Hydrurga leptonyx*) on an ice floe and an adult male whale tilted up one side of the floe with his head and spilled the seal into the water where the rest of the group were waiting.

Type B may also prey upon whales but clear evidence is lacking (Table 1). RLP observed a pod chasing a group of minke whales, possibly attacking them. Another Type B group closely followed three humpbacks whales (*Megaptera novaeangliae*), including a calf, for 30min, and another group harassed, and probably attacked, a group of four humpbacks. Type B has also been reported attacking Gentoo penguins (*Pygocelis papua*; Table 1), but it is not known to what extent any of these forms feed on penguins in Antarctica.

Type C apparently feeds mainly on fish (Berzin and Vladimirov, 1983) and has been photographed carrying large Antarctic toothfish (*Dissostichus mawsoni*) on at least two occasions (Thomas *et al.*, 1981; Wu, 2002). There are unconfirmed reports that suggest that they may feed on other prey also. Various personnel at McMurdo Station, Ross Sea, have reported that they have seen killer whales attacking both penguins and seals just off the base there on several occasions. Although it is not known which type of killer whales were involved (or even if these were really attacks), Type C is by far the most common form in the McMurdo area and would be the most likely candidate. S. Lundgren (pers. comm.) reported that a killer whale near the Cape Lazarev Ice Shelf lunged out of a lead and pinned him against the ice briefly before sliding back into the water. His photo shows that the whale was a Type C and its behaviour suggests that this form may also take prey (i.e. penguins or seals) off the ice.

DISCUSSION

Based on field observations and a review of available photographs, three distinct forms of killer whales were identified in Antarctic waters (Types A, B and C). Available evidence on colour patterning, group size, body size, habitat, geographical distribution and food habits, suggests that Type A is referable to *O. orca*. Type B has apparently not been specifically noted previously and, to our knowledge, has no taxonomic standing. (Although, based on what is currently known about the distribution of Type B and the collection/sighting localities of '*Orcinus nanus*' [Mikhalev *et al.*, 1981], there is some limited circumstantial evidence to suggest that they might be the same.) Based on the preliminary distribution information, Type C is the most common pagophilic form in the Indian Ocean sector where most of the Soviet Antarctic whaling was conducted during the 1979-80 season, it has a larger average group size than the other two mammal-eating forms, it is known to eat fish and is therefore probably the type that Berzin and Vladimirov (1983) described as *O. glacialis*. Since types B and C are both pack-ice-inhabiting forms that are often coloured yellow, it is possible that specimens of both types were combined in the descriptions of either Mikhalev *et al.* (1981) or Berzin and Vladimirov (1983); this is especially true if (as seems likely) both are confirmed as 'dwarf' forms. These issues will not be resolved until specimens become available, and perhaps not even then.

The three different types of killer whales all appear to have distinct habitat and diet preferences, colour patterning and average group sizes. Clear geographic and habitat segregation was identified with an offshore, circumpolar form (Type A), and two nearshore, pagophilic forms that also appear to have distinct habitat preferences: Type B ranges around the continent in the loose pack-ice but is particularly common in the Antarctic Peninsula area; Type C occurs most of the way around the continent along the edges of the fast ice and in dense pack-ice, but is as yet unrecorded from the Peninsula area.

There is also strong evidence for dietary specialisation among the three types: Type A takes mainly Antarctic minke whales; Type B regularly takes pinnipeds, but perhaps whales and penguins also; Type C appears to prey mainly on fish. Berzin and Vladimirov (1983) reported the stomach contents of 785 killer whales taken by the Soviet fleet in 1979/80, a sample that included 156 'white' (= *O. orca*; Type A) and 629 'yellow' (= *O. glacialis*; Type C?) individuals. The main prey items they found (in frequency of occurrence) were: *O. orca* - 3.2% fish, 89.7% marine mammals, 7.1% squid; *O. glacialis* – 98.5% fish, 0.4% marine mammals, 1.1% squid. Mikhalev *et al.* (1981) also reported relatively infrequent mixing of prey types in Antarctic killer whale stomachs. (Here again, the possible presence of an unrecognised third type of killer whale in either of the two Soviet studies and the fact that the pack-ice forms (B and C) are not always coloured yellow, make the results of those studies difficult to interpret.) A potential implication of dietary specialisation (and perhaps size disparity) among the three forms is an incidence of 'cannibalism' in southern killer whales reported by Shevchenko (1975) that may have been a case of a larger, mammal-eating form (A or B) preying upon a smaller form (B or C).

Most interesting is the apparent evolutionary parallel between the killer whale community of Antarctica and that of the northeastern Pacific. The North Pacific community is also substructured by dietary specialisation, with a nearshore, mammal-eating form (often referred to as 'transients') living in close proximity to a nearshore, fish-eating form ('residents') (Bigg *et al.*, 1987; Baird, 2000). The larger group size of Type C killer whales relative to A and B types is also consistent with the pattern of herd size versus prey preferences found in the Northeast Pacific, where the mammal-eating form typically ranges from 1-7 individuals per herd and the fish-eating form ranges from 5-50 individuals (Bigg *et al.*, 1987). Possible causal links between diet and herd size are discussed by Baird and Whitehead (2000). A third form of killer whale in the North Pacific ('offshores') is rarely encountered in nearshore waters and has unknown prey preferences.

Despite the similarities between these two communities, the different forms of Antarctic killer whales appear to be more divergent from one another than the Northeast Pacific forms. For example, the Antarctic forms are more distinct morphologically with respect to colour patterning, length and probably other anatomical features, as well as in parameters relating to reproduction (size and age of first reproduction, seasonality, testis size, etc.) (Mikhalev *et al.*, 1981; Berzin and Vladimirov, 1983; this study). We suspect that the presence and differential use of sea ice in Antarctica could have been a major factor in spurring this divergence, by promoting specialised foraging adaptations and contributing to more complete habitat segregation. By contrast, in the Northeast Pacific at least the two nearshore killer whale trophotypes share much of the same habitat (Baird, 2000). As further evidence of reproductive isolation among the Antarctic forms, no mixing of types within herds was found (nor by Berzin and Vladimirov, 1983), nor were any photographs found that clearly showed eyepatches of individual whales that were not unambiguously assignable to type (i.e. no apparent intergrades).

A recent investigation of killer whale genetics found relatively little diversity among killer whales worldwide (Hoelzel *et al.*, 2002), but the only Antarctica sample available for that study was from a single Type A animal (Olavarría, pers. comm.). This study found that there are three morphologically distinct types of killer whales in Antarctica that do not appear to mingle in schools or hybridise, although they have overlapping geographic ranges. This suggests that isolating mechanisms are already in effect and, under a Biological Species Concept (Mayr, 1969), they may each warrant separate species status. Evidence from molecular genetic analyses and additional morphological studies will be important in verifying this interpretation.

Killer whales are common top predators in Antarctica; in order to understand their role in the Antarctic ecosystem it will be necessary to clarify the taxonomic relationships, further identify the ecological traits, and determine the relative abundance of the three forms described here.

ACKNOWLEDGMENTS

The International Whaling Commission and the Institute of Cetacean Research, Tokyo, allowed the authors to use unpublished sightings data from whale survey cruises in Antarctic waters; we thank them for their cooperation. The National Science Foundation (US) allowed the senior author to conduct an important part of this research onboard the US Coast Guard Icebreaker *Polar Star* in Antarctica; Captain Dave MacKenzie (USCG) was especially supportive of our onboard activities. The Abercrombie and Kent Foundation allowed the senior author to conduct research while onboard the cruise ship MS *Explorer*; we thank V. Underwood, T. Dennis and K. Crosbie for use of ship time for this project. This study would not have been possible without the cooperation of many of our colleagues and we are indebted to the following people for providing us with their unpublished photographs and data on Antarctic killer whales: J. Bannister, P. Best, O. Carlsson, J. Cato, J. Cotton, T. Dennis, W. Fraser, D. Hembree, R. Hucke-Gaete, S. Imberti, M. Jorgensen, G. Joyce, D. Larsen, S. Leatherwood, S. Lundgren, F. Marques, J. Mastro, K. Matsuoka, C. Olavarría, P. Olson, M. Pope, T. Pusser, S. Rankin, R. Reeves, K. Robertson, R. Rowlett, K. Sekiguchi, D. Thiele, F. Todd, S. Todd, F. Ugarte, I. Visser, M. Webber, R. Williams, N. Wu and the British Antarctic Survey. R. Baird, R. Brownell, J. Heyning, R. LeDuc and W. Perrin improved this paper with their comments. B. Ballenger, K. Clement and J. Wilson assisted with fieldwork; J. Fluty drafted Fig. 2.

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Date received: December 2002.
Date accepted: July 2003.

J. CETACEAN RES. MANAGE. 5(2):141–147, 2003

Abundance and sighting patterns of bottlenose dolphins (*Tursiops truncatus*) at four northwest Atlantic coastal sites

CARA M. GUBBINS*, MARTHAJANE CALDWELL+#, SUSAN G. BARCO++, KEITH RITTMASTER**, NAN BOWLES** AND VICTORIA THAYER¥

Contact e-mail: *caragubbins@hotmail.com*

ABSTRACT

Researchers and managers studying Atlantic coastal bottlenose dolphins along the east coast of the United States have been working on the hypothesis that there are two units within the population. One unit migrates seasonally along the northwest Atlantic coast (moving north during summer and south during autumn and winter), while the other remains in local inshore waters year-round. As part of independent, on-going studies begun in the late 1980s and mid-1990s, the occurrence of dolphins was compared among four separate sites (Virginia, North Carolina, South Carolina and Florida) in 1997. The goals of the study were to test the current working hypothesis of one migrating stock of dolphins using data on abundance, distribution and sighting patterns and to calculate a minimum estimate of the population size of northwest Atlantic coastal bottlenose dolphins at the four sites. Dolphins were consistently present in Virginia from April to October and year-round in North Carolina, South Carolina and Florida. In total, 7,830 dolphins were counted and 2,839 identifications were made. Monthly dolphin counts and water temperatures were positively correlated at the Virginia, South Carolina and Florida sites. After adjusting for effort, monthly dolphin counts were significantly different among the four sites but new identification rates were not. The monthly resighting rates were significantly higher in Florida than at the other sites. Based on mark-recapture analysis, it was estimated that 2,392 coastal bottlenose dolphins were present at the four sites in 1997. This estimate is similar to published abundance estimates for dolphins along the entire US Atlantic coast (2,482). These results support the hypothesis of multiple population units with distinct movement patterns and suggest that published abundance estimates for coastal bottlenose dolphins are greatly underestimated.

KEYWORDS: ABUNDANCE ESTIMATE; ATLANTIC OCEAN; BOTTLENOSE DOLPHIN; DISTRIBUTION; MARK-RECAPTURE; MOVEMENTS; PHOTO-ID

INTRODUCTION

Although bottlenose dolphins (*Tursiops truncatus*) are distributed along the Atlantic coast of the United States from the Florida Keys to New York, distribution and abundance change seasonally between northern Florida and New York (Kenney, 1990; Wang *et al.*, 1994). During the summer, dolphins are distributed throughout this range and abundance is greatest between North Carolina and New Jersey. In the autumn, the distribution of dolphins begins to shift south and by winter abundance is greatest between Cape Hatteras, North Carolina and northern Florida (Wang *et al.*, 1994). This shift in abundance suggests that at least some coastal animals migrate south to winter at the southern end of their range somewhere between Cape Hatteras and central Florida (Wang *et al.*, 1994). Against this background of seasonal movements, there is evidence that some individuals move little over the course of the year, particularly in the more southern parts of this range (Wang *et al.*, 1994; Gubbins, 2002a; b). These resident dolphins may comprise distinct population units that should be managed independently of migratory dolphins (CeTAP, 1982; Wang *et al.*, 1994; Hohn, 1997; Barco *et al.*, 1999a).

Attention was drawn to the question of population structure and movement patterns by analysis of stranding patterns associated with a mass mortality event. Between June 1987 and March 1988, more than 740 dead bottlenose dolphins washed ashore from New Jersey to Florida (Scott *et al.*, 1988; Wang *et al.*, 1994; Mead and Potter, 1995). Two agents were associated with the event: brevitoxin originating from a red tide (Geraci, 1989) and a morbillivirus (Lipscomb *et al.*, 1994; Duignan *et al.*, 1996). Carcasses were recovered from North Carolina, Virginia and New York in June 1987, from Virginia, New York and New Jersey in July, and from North Carolina between August and November. In December, carcasses were found in South Carolina, Georgia and Florida but by January 1988, and through February, carcasses were recovered only in Florida. Carcasses were recovered in Florida, Georgia, South Carolina and North Carolina during March 1988.

Based on stranding data from the 1987-88 die-off and abundance data from aerial surveys, Scott *et al.* (1988) hypothesised that a single migratory stock of bottlenose dolphins ranged seasonally from Long Island, New York to central Florida. This hypothesis, known as the ‘single stock’ hypothesis, has been the working paradigm for researchers and managers along the east coast of the United States (Waring *et al.*, 2000, pp.141-149). However, due to the dearth of published data on the behavioural ecology of Atlantic bottlenose dolphins, this hypothesis excludes inshore dolphins and has not been formally tested.

Stranding data were also used to estimate a potential stock decline of 53% due to the die-off (Scott *et al.*, 1988). Consequently, this stock was officially classified as depleted under the US Marine Mammal Protection Act of 1972 (Wang *et al.*, 1994). As the agency responsible for implementation of the Marine Mammal Protection Act, the US National Marine Fisheries Service was required to develop a conservation plan for the coastal migratory stock. However, limited data on dolphin movement patterns and abundance has hampered development of a plan and, thus, management of the depleted migratory stock. Only five

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* *Program in Ecology, Evolution and Conservation Biology, University of Nevada, Reno, NV 89557-0015, USA.*
+ *Department of Biology, University of Miami, Coral Gables, FL 33149, USA.*
# *Department of Marine Science, Savannah State University, PO Box 20467, Savannah, Georgia 31404, USA.*
++ *Virginia Marine Science Museum Stranding Program, 717 General Booth Boulevard, Virginia Beach, Virginia 23451, USA.*
** *North Carolina Maritime Museum, 315 Front Street, Beaufort, NC 28516, USA.*
¥ *Duke University Marine Laboratory, 315 Duke Marine Lab Road, Beaufort, NC 28516, USA.*

studies on the behavioural ecology of these bottlenose dolphins (Blaylock, 1988; Jacobs *et al.*, 1993; Barco *et al.*, 1999b; Gubbins, 2002a; b) have been published. Furthermore, none of these address large-scale movement patterns of dolphins. The paucity of published research is a hindrance to better understanding the consequences of the 1987-88 mortality event, the population biology of these animals and the development of a management plan for the depleted migratory stock.

In response to the 1987-88 die-off and the lack of data relevant to movement, status and risk questions, the Atlantic Coastal Dolphin Cooperative was formed in 1993. The goal of the cooperative was to share information, compare sightings among areas and provide data that would elucidate the population biology of coastal Atlantic bottlenose dolphins. As members of the Atlantic Coastal Dolphin Cooperative, the authors of this paper collaboratively analysed data collected during 1997 from the four independent sites. The first goal was to compare local abundance, distribution and sighting patterns between the four sites and to combine the data to examine large-scale movement patterns of population units in order to test the Scott *et al.* (1988) single stock hypothesis. The second goal was to calculate a minimum estimate of the population size of northwest Atlantic coastal bottlenose dolphins based on photo-identification rates at the four sites.

MATERIALS AND METHODS

Coastal bottlenose dolphins were defined as those animals using inshore and alongshore waters (Wells *et al.*, 1999). Data collected during 1997 at four sites along the Atlantic coast of the United States were analysed (Fig. 1). These data were collected as part of independent research projects in: Virginia Beach, Virginia from 1989 to present; Beaufort, North Carolina from 1985 to present; Hilton Head, South Carolina from 1994-1998; and Jacksonville, Florida from 1994-1997. In 1997, data were collected from March-October in Virginia Beach, February-December in Hilton Head, and January-December in Beaufort and Jacksonville. The research goals at each study site were similar, resulting in similar data collection methods and compatible data.

At each site, small powerboats were used on standard transects to survey each study area; hours on survey in the field were recorded as a measure of effort. A survey team consisted of a vessel operator, a data recorder and one or two photographers. The vessel maintained a cruising speed of 30-40km h^{-1} until dolphins were encountered, at which time the boat slowed down and the time of initial observation was recorded. The boat then moved parallel to the group, and the location, number of dolphins and number of young of the year were recorded. A dolphin group was defined as a collection of individuals that were estimated to be within 100m of each other while being observed. Once location, number and group composition data were recorded, attempts were made to photograph the dorsal fin of each member of the group.

Unique nicks, marks and scars on dorsal fins were used to identify individual dolphins (Würsig and Jefferson, 1990). Using standard protocols, dorsal fin photos were compared to independent catalogues of fin photos of known dolphins at each site in order to confirm sightings of identifiable individuals (Urian and Wells, 1996). For each site, the total number of dolphins observed and identified per hour surveyed was calculated for each month. For each dolphin identified, it was determined whether the observation was the initial sighting in 1997 (new) or a subsequent sighting (resight). The number of new and resighted dolphins per survey hour recorded each month was calculated for all four sites. Data were not normally distributed, therefore all data were transformed by adding 0.5 and then taking the square root (Zar, 1999).

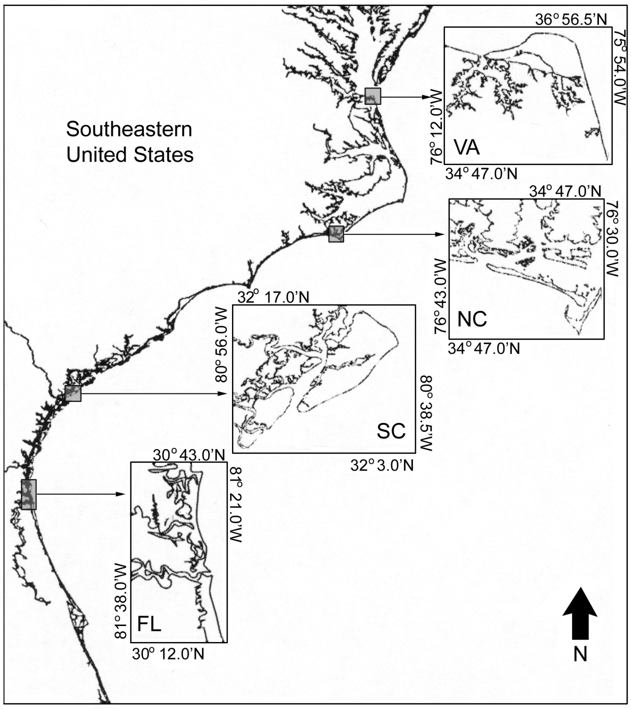

Fig. 1. Four study sites at Virginia Beach, Virginia; Beaufort, North Carolina; Hilton Head, South Carolina; and Jacksonville, Florida. The Virginia Beach site was exposed ocean coastline while the other three sites combined exposed ocean coast and inshore tidal rivers.

Stranding patterns during the die-off suggested that one population unit of coastal dolphins was migrating seasonally along the northwest Atlantic coast (moving north during summer and south during autumn and winter). Based on this, a seasonal influx of dolphins was expected at the northern study sites and a concomitant decrease in abundance expected at the southern sites. Specifically, it was predicted that abundance and water temperature would be positively correlated in Virginia Beach and negatively correlated in Beaufort, Hilton Head and Jacksonville. To test this prediction, two types of analyses were performed. First, a simple linear regression was used to test for a correlation between mean monthly sea surface water temperature and the number of dolphins observed per survey hour per month within each site (Statistix; Analytical Software, 2000). Water temperatures were either measured directly during surveys (Jacksonville) or obtained from National Oceanic and Atmospheric Administration weather stations for the dates surveyed from the website *www.noaa.gov* (Virginia Beach, Beaufort, Hilton Head). Second, a two-way analysis of variance was used to test for differences among the four sites in the number of dolphins observed per survey hour for the six months that dolphins were observed at all sites (May to October). Both analyses were then repeated using the number of new dolphins identified per hour per month and the number of resighted dolphins per hour per month.

With the CAPTURE program (Otis *et al.*, 1978), Chao *et al.*'s (1992) M_{th} model was used to estimate population size at each site. Wilson *et al.* (1999) suggest that the M_{th} model, which allows capture probability to vary by time and individuals, is the most appropriate model for bottlenose dolphin populations given the behaviour of this species. Local abundance was calculated at each of the four sites using sighting records of all individuals identified from May to October. By restricting the analysis to this six-month time period, the possibility of violating the model's assumptions of geographic closure and mark retention (Wilson *et al.*, 1999) was reduced. To estimate the minimum number of dolphins using the northwest Atlantic coast between Jacksonville and Virginia Beach in 1997, the May to October mark-recapture data were combined. In this analysis, it was assumed that the dolphins using the northwest Atlantic comprised one closed population.

RESULTS

During 917 survey hours in 1997, 7,830 dolphins were counted; 1,138 individual dolphins were identified a total of 2,839 times (Table 1). Each site had a unique abundance pattern (Fig. 2). In Virginia Beach (VA), dolphins were present from May through October, with the highest counts in July and September. In Beaufort (NC), dolphins were seen consistently year round, with the lowest abundance records in April and June. In Hilton Head (SC), dolphin abundance was lowest from February to April and two peaks were recorded in May and July. Jacksonville (FL) had oscillating abundance year round, with lows in January and December and a high peak in July.

As expected, dolphin abundance in Virginia Beach was positively correlated with water temperature ($R^2 = 0.89$, $p < 0.001$). Dolphins were not observed in Virginia Beach when water temperature was less than 16°C (Fig. 2). Contrary to the prediction, a positive correlation between water temperature and dolphin abundance was found in Hilton Head and Jacksonville ($R^2 = 0.48$, $p = 0.02$ and $R^2 = 0.43$, $p = 0.03$, respectively) and no significant correlation in Beaufort ($R^2 = 0.18$, $p = 0.19$). In accordance with the prediction, there was a significant effect of site on dolphins observed per hour surveyed per month from May-October ($f = 4.46$, df = 3, $p = 0.01$, Fig. 2). Significantly more dolphins were observed per hour per month in Virginia Beach than in Beaufort and Jacksonville (after Bonferroni correction $p = 0.025$ and $p = 0.016$, respectively). However, there was no difference between Virginia Beach and Hilton Head or between Beaufort, Hilton Head and Jacksonville.

The number of new dolphins identified per survey hour per month was only correlated with water temperature in Virginia Beach ($R^2 = 0.74$, $p < 0.007$, Fig. 2). After square root transformation these data violated the assumption of homogeneity of variance, therefore a non-parametric Kruskal-Wallace one-way ANOVA was used rather than a parametric two-way ANOVA. From May-October, there was no significant difference in the number of new dolphins identified per survey hour per month among the four sites ($u = 5.46$, $p = 0.14$, Fig. 2).

The number of resighted dolphins per survey hour per month was positively correlated with water temperature in Virginia Beach and Jacksonville ($R^2 = 0.71$, $p = 0.001$ and $R^2 = 0.77$, $p = 0.0003$, respectively, Fig. 2). A significant difference among the four sites was found in the number of dolphins resighted per hour surveyed each month from May through October ($f = 10.87$, df = 3, $p < 0.0001$, Fig. 2). Significantly more dolphins were resighted per hour in Jacksonville than in any other site (after Bonferroni correction, $p < 0.003$).

The percentage of identified dolphins sighted only once was variable among the four sites (Virginia Beach = 72%, Beaufort = 59%, Hilton Head = 64% and Jacksonville = 44%). The frequency at which individual dolphins were resighted varied among the sites (Fig. 3). No identified dolphins were sighted more than nine times in Virginia Beach, Beaufort and Hilton Head, while 17% of dolphins identified in Jacksonville were sighted between 9-16 times. The mean number of sightings for individual dolphins identified in Jacksonville (mean = 6.6) was over 1.8 times greater than those for the other three sites (Virginia Beach: mean = 2.8; Beaufort: mean = 3.6; Hilton Head: mean = 3.0; Fig. 3).

The population estimates and confidence intervals obtained for each of the four sites using the M_{th} model and data from May-October are presented in Table 2. Combining data from all four sites resulted in a minimum population estimate for the northwest Atlantic coast of 2,392 dolphins, only 59 dolphins less than when the estimates from each site are summed (2,451).

DISCUSSION

The 'single stock' hypothesis has not been formally tested and, until now, data were not available to do so. The hypothesis is not consistent with the results of this study using data on three aspects of the behavioural ecology of coastal dolphins: abundance, distribution and sighting patterns.

The single stock hypothesis predicts that abundance and distribution will change along the coast as the year progresses. Specifically, it predicts an increase in abundance at increasingly more northern sites until late summer. However, in this study, abundance increased at all four of the sites between May and October, peaking at the same time (in July) at Virginia Beach, Hilton Head and Jacksonville. Further, the predicted autumn southern shifts in abundance and distribution were not apparent – all three of these same sites showed a decrease in abundance in the autumn. Water

Table 1

Summary of data collection effort and results. The rates of identifying new dolphins were similar among the four study sites, but significantly more dolphins were counted per survey hour in Virginia Beach, Virginia (VA) (F = 4.46, df = 3, P = 0.01) and resighted in Jacksonville, Florida (FL) (F = 10.9, df = 3, P = <0.0001, Bonferroni adjusted). NC = Beaufort, North Carolina; SC = Hilton Head, South Carolina.

Site	Effort (months surveyed)	Effort (survey hours)	Dolphins observed	Total dolphin identifications	Individual dolphins identified	Number of individuals resighted (% of total)	Dolphins observed per survey hour	New dolphins per survey hour	Dolphins resighted per survey hour
VA	8	105	2,147	513	337	176 (52)	10.0	1.3	0.8
NC	12	273	1,869	480	233	96 (41)	6.9	0.9	0.9
SC	11	206	1,729	399	234	84 (36)	7.2	1.0	0.7
FL	12	333	2,085	1,447	334	188 (56)	5.9	1.0	3.1
Total	43	917	7,830	2,839	1,138	544 (48)			

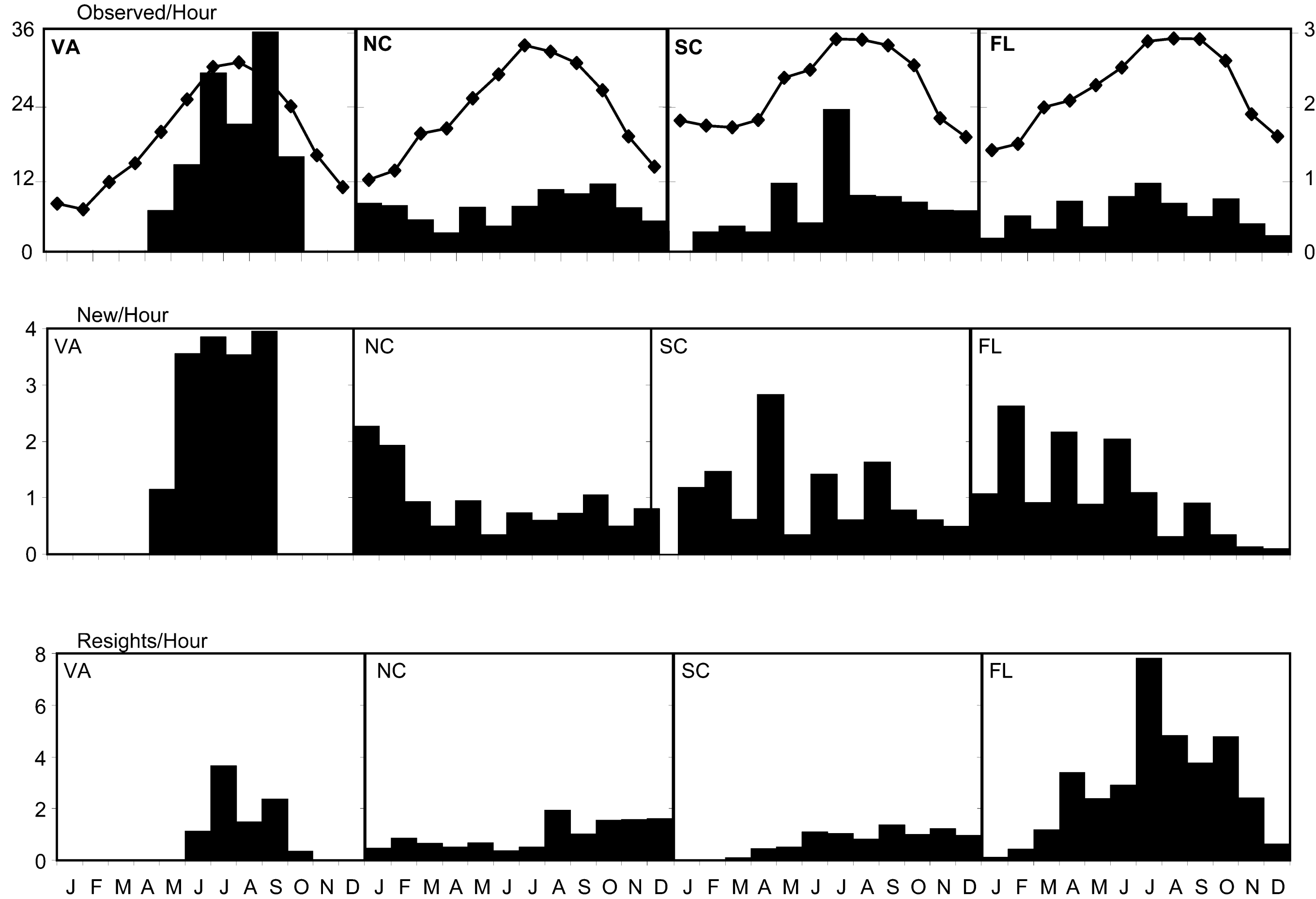

Fig. 2. Comparison of the total numbers of dolphins counted (observed), identified (new) and re-identified (resighted) per survey hour for each site. Sea surface water temperature from 0-30^{0}C is shown on the right Y-axis in the observed/hour row and the number of dolphins counted per survey hour is on the left Y-axis of all rows. Dolphin abundance was positively correlated with water temperature at Virginia Beach (VA), Hilton Head (SC) and Jacksonville (FL), but there was no correlation in Beaufort (NC). Although there was no significant difference in the rate at which new dolphins were identified among sites, significantly more dolphins were counted per survey hour at Virginia Beach ($f = 4.46$, df = 3, $p = 0.01$) and significantly more known dolphins were resighted per survey hour at Jacksonville ($f = 10.9$, df = 3, $p < 0.0001$, Bonferroni adjusted).

temperature was positively correlated with dolphin abundance in Virginia Beach, Hilton Head and Jacksonville: more dolphins were encountered at these sites when the water temperature exceeded 16°C.

Distribution was related between sites in the northern end of the study but not coast-wide or in the south. Abundance was lowest in Beaufort when it was highest in Virginia Beach. Detailed examination of sightings of individuals at both sites indicates that there is north-south movement of some dolphins between Virginia Beach and Beaufort: 120 dolphins have been photographed in both sites (Barco and Swingle, 1996; Barco *et al.*, 1997; Rittmaster and Thayer, 1998). In contrast, only two dolphins have been sighted in both Hilton Head and Jacksonville (Urian *et al.*, 1999) and there was no relationship between sighting or abundance patterns between these two sites in 1997. Similarly, none of the data suggest any relationship in changing abundance patterns between Hilton Head or Jacksonville and the two sites farther north.

Contrary to single stock predictions, sighting rates of new dolphins were not significantly different among the four sites between May and October. Sighting patterns of new and previously observed individuals suggest short-term use of Virginia Beach during the summer. In Beaufort, the highest identification rate of new dolphins occurred in January and February while resighting rates were highest from August to December, suggesting that dolphins were moving out of Beaufort mid-year and back into Beaufort during the end of the year. These patterns coincide with the shifts in abundance between Virginia Beach and Beaufort noted above, further supporting seasonal movement between these two sites. Contrary to single stock predictions, few new dolphins were identified and relatively few known dolphins were resighted during autumn and winter months in Hilton Head and Jacksonville. While Hilton Head and Jacksonville populations included individual dolphins present year-round as well as seasonally, the seasonal patterns of resights were different from those predicted by the single stock hypothesis. Specifically, dolphins in Hilton Head were present for short periods of time during the summer and dolphins in Jacksonville were summer rather than winter residents. These residency and movement patterns are supported by multiple-year sighting data at each site (Rittmaster and Thayer, 1998; Barco *et al.*, 1999a; Gubbins, 2000; Caldwell, 2001).

Our results provide support for an alternative hypothesis that there are multiple population units of coastal dolphins with distinct movement patterns (Hohn, 1997). This is a likely scenario since the data (and additional unpublished data) show a relationship in dolphin movement patterns between Virginia Beach and Beaufort but no relationships among Beaufort, Hilton Head and Jacksonville or Virginia Beach, Hilton Head and Jacksonville. These patterns indicate that at least three independent population units: Virginia Beach/Beaufort, Hilton Head and Jacksonville. A second alternative hypothesis is that there is seasonal

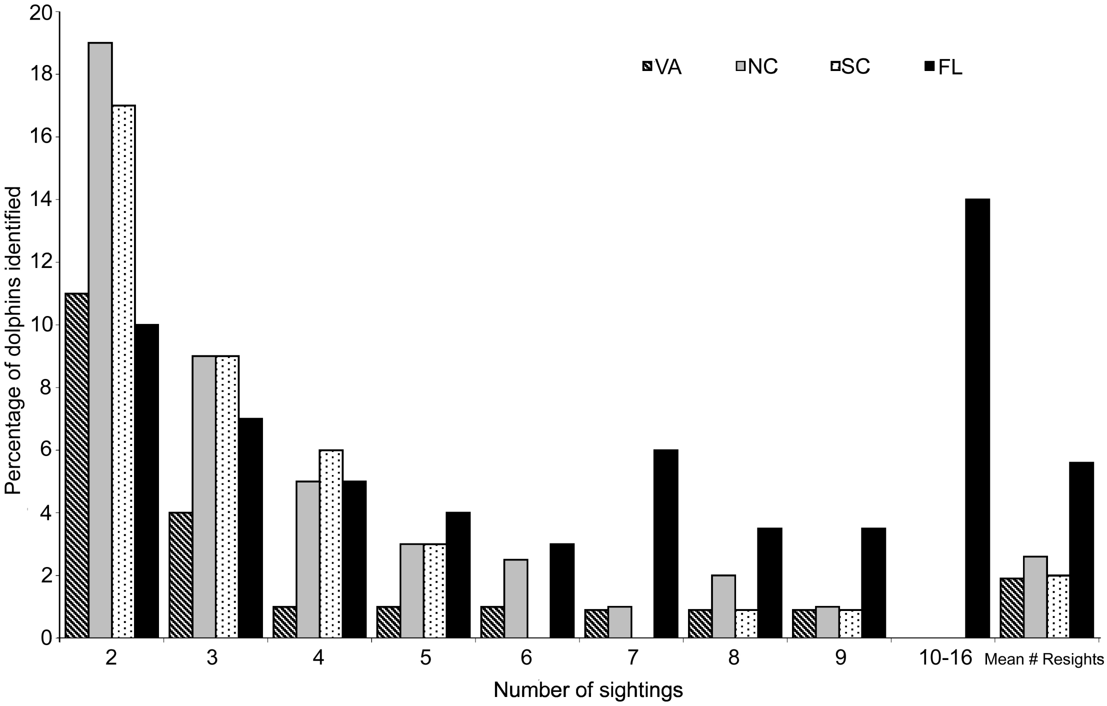

Fig. 3. Sighting frequencies of identified dolphins expressed as the percentage of identified dolphins sighted one or more times at each site. Sighting frequencies were similar in Virginia Beach (VA) and Hilton Head (SC), higher in Beaufort (NC) and highest in Jacksonville (FL).

Table 2

Abundance estimates for each site and for all four sites combined. The estimate for the four sites is as much as eight times larger than previous estimates for dolphins along the entire east coast. Estimates were calculated using the program CAPTURE. M_{th} estimate is the estimate of the population for each site. Estimated prob. of capture was automatically calculated. 'Number captured' represents the number of individual dolphins identified. 'Total captures' is the number of times all dolphins were identified, including first identifications and subsequent resightings. Study areas are Virginia Beach (VA), Beaufort (NC), Hilton Head (SC) and Jacksonville (FL).

Study area	M_{th} estimate	Lower CI	Upper CI	SE	Estimated prob. of capture	Number captured	Total captures
VA	1,001	786	1,318	134.10	0.085	337	412
NC	513	405	680	69.09	0.154	205	299
SC	525	399	728	82.26	0.051	233	262
FL	412	374	468	23.69	0.392	333	719
Sum of estimations for all four sites	2,451						
Estimation of all four sites together	2,392	2,158	2,673	131.1909	0.2095	1,240	1,692
Difference	59						

longitudinal movement offshore in the winter and inshore during the summer months. The monthly abundance data coupled with no resights between southern and northern sites and only two between southern sites suggest that this might occur in Hilton Head and Jacksonville and may contribute to the high summer abundance in Virginia Beach.

One caveat inherent in this and all similar collaborative field studies is that there are gaps in areas surveyed. The four study areas were separated by hundreds of kilometres of coastline. When not observed in one study area, dolphins could simply have moved to adjacent coastal areas with no survey effort. Expansion of this format, by including more coastal sites closer together and incorporating offshore photo-identification surveys, would help test the alternative hypotheses presented here. Such additional data would help managers more accurately determine the existence and ranging patterns of distinct population units of coastal dolphins and estimate the population size of all coastal dolphins, including those in inshore waterways. A cooperative photo-identification effort of 21 independent research sites (including those here) from Jacksonville, Florida to Cape May, New Jersey is currently underway (Urian *et al.*, 1999). Results from this collaboration should help elucidate stock structure of coastal dolphins throughout their known range. To date there has been no survey effort offshore to test the seasonal longitudinal movement hypothesis and this seems a fruitful area for future research since most coastal studies take place within a few kilometres of the shoreline.

Due in large part to data gaps, published stock assessments of *Tursiops* along the Atlantic coast of the United States group all animals into a single coastal stock (Waring *et al.*, 2000, pp.141-149). Informally, however, it is widely accepted among researchers and managers that this population is comprised of multiple stocks most likely containing year-round and seasonal residents as well as transient dolphins. The data and analyses in this paper are the first to formally test this hypothesis and the results support this informal contention. Between northern Florida and Virginia, multiple population units of coastal dolphins were found with differing movement patterns.

The second goal of this study was to calculate a minimum estimate of the population size of northwest Atlantic coastal bottlenose dolphins. The estimate of 2,392 dolphins was as high as or higher than previous abundance estimates for dolphins along the entire US Atlantic coast. Kenney (1990) estimated that the population of coastal and offshore bottlenose dolphins off the northeastern USA was between 10,000 and 13,000 individuals in the early 1980s. Kenney (1990) further proposed that the inshore (coastal) stock comprised 3-4% of the total population, leading to an estimate of 300-400 coastal dolphins. The most recent estimate of abundance for the coastal population (2,482) was simply a count of the number of dolphins sighted during aerial surveys along the coast (Waring *et al.*, 2000, pp.141-149).

Previous estimates were based on aerial or ship-transect surveys conducted in oceanic waters and none have been based on photo-identification or included estuarine waters (CeTAP, 1982; Kenney, 1990; Waring *et al.*, 2000, pp.141-149). Line transect methods can be used to estimate dolphin density, and therefore abundance (Wilson *et al.*, 1997). However, cetaceans are wide-ranging and spend much of their time underwater, making this type of sampling difficult to implement (Wilson *et al.*, 1999). Several additional problems are associated with aerial and ship-transect surveys. Dolphin behaviour is often related to coastal topography and aerial and shipboard observers can miss submerged animals as they survey at a pre-determined, constant speed (Wilson *et al.*, 1997). Further, observers cannot differentiate offshore dolphins from coastal dolphins on sight in areas where both occur, such as the northwest Atlantic Ocean. These considerations, coupled with the highly variable group size of bottlenose dolphins (Wells *et al.*, 1980), can lead to estimates of abundance with poor precision (Wilson *et al.*, 1999). Mark-recapture methods use data on the number of animals marked and their proportion represented in subsequent samples to estimate population parameters including abundance (Seber, 1982). Mark-recapture techniques can provide unbiased estimates of population size that are more precise than those derived from line-transect sampling (Calambokidis *et al.*, 1990; Fairfield, 1990; Read *et al.*, 2001).

The combined population estimate of 2,392 dolphins, which represents an absolute minimum 'best' coastal estimate, is comparable to the recent estimate of 2,482 dolphins reported by Waring *et al.* (2000, pp.141-149). The estimate from this study is eight times greater than Kenney's (1990) coast-wide estimate based on aerial survey data from the Cetacean and Turtle Assessment Program (CeTAP, 1982). The differences between the four-site estimate and the two coast-wide estimates are even more important when one considers the fact that the study sites here encompass less than 300km of the > 2,000km of coastline available to Atlantic bottlenose dolphins. Further, during previous and subsequent years of research following the same data collection and photo-identification protocols, more individual dolphins have been identified at all four sites than the 1,138 identified in 1997 reported in this paper (Virginia Beach: 1,000; Beaufort: 1,300; Hilton Head: 503; Jacksonville: 905; total: 3,708; unpublished data). After accounting for the two dolphins identified at both Hilton Head and Jacksonville and 120 dolphins identified at both Virginia Beach and Beaufort, this study identified a total of 3,694 individual dolphins in the four study areas. This number does not include the unmarked juveniles and calves in the populations. Assuming a 10% calving rate, this number jumps to over 4,000 individuals. Finally, Waring *et al.*'s (2000, pp.141-149) estimate did not include dolphins using bays, sounds and estuaries. The study sites in Beaufort, Hilton Head and Jacksonville included coastal and inshore waters and the mark-recapture estimate in this paper is likely more representative of the actual abundance of dolphins in the study sites than Waring *et al.*'s (2000, pp.141-149) estimate based on transect data collected during alongshore surveys. The results in this paper imply that a much larger number of individual dolphins are utilising the coastal waters of the northwest Atlantic than are currently considered.

[Authors' note: At meetings of the '*Tursiops* Take Reduction Team in the mid-Atlantic and southeast US' in July and August 2001, new information was presented on stock structure and abundance estimates for coastal *Tursiops*. These data will be published in the US Atlantic and Gulf of Mexico Marine Mammal Stock Assessments 2002.]

ACKNOWLEDGEMENTS

We are grateful to the many volunteers who assisted us in the field and in analysing fin photos, particularly A. Groth (Virginia Beach) and C. Eckland (Hilton Head). In 1997, SGB was supported by a grant from National Marine Fisheries Service to the Virginia Marine Science Museum Stranding Program and to D.A. Pabst and B. McLellan of the University of North Carolina at Wilmington. Many volunteers and the staff of the Museum, particularly Stranding Program curator W.M. Swingle, supported the Virginia Beach research. The Beaufort team is grateful to the Friends of the Museum/North Carolina Maritime Museum and the National Marine Fisheries Service Beaufort Lab for providing much-needed equipment, supplies, logistical support, and dedicated students and volunteers. K. Merrels has spent countless hours in the darkroom and photo catalogues helping organise the Beaufort individual recognition data. John Russell contributed many hours of his time, boat driving expertise, and funds to this project. L. Barker, C. Jones and C. Spangler provided valuable help, inspiration and critical feedback. The Worthington Foundation, University of Nevada Reno Ecology, Evolution and Conservation Biology Program, University of Nevada Reno Biology Department and Mystic Aquarium provided field support for CMG. CMG was partially supported by fellowships and awards from the University of Nevada Reno Graduate School, Graduate Student Association, Biology Department, and Ecology, Evolution and Conservation Biology Program, and Mystic Aquarium. Many volunteers and the staff of Mystic Aquarium, particularly Director of Research and Veterinary Services, D. St Aubin, supported the Hilton Head research. MjC was supported by a grant from National Marine Fisheries Service to the University of Miami. MjC is grateful to the University of Miami for logistical support and Drs Gaines, Wells, Searcy, Hughes and Green for advice. Mayport Marine and a host of volunteers, especially J. Nangle and L. Reynolds, kept the Jacksonville project afloat. This research was conducted under National Marine Fisheries Service General Authorisations Number 9 (Virginia Beach), Number 2 (Hilton Head), Number 738 (Jacksonville) and National

Marine Fisheries Service research permit #779-1339 (Beaufort). Fin photographs of dolphins identified in Hilton Head (South Carolina) and in Jacksonville (Florida) and in Virginia Beach (Virginia) and Beaufort (North Carolina) were matched by K. Urian, curator of the Mid-Atlantic Bottlenose Dolphin Catalogue. E. Beever and J. Lewis kindly reviewed an earlier draft of this manuscript. Two anonymous reviewers provided helpful comments that improved this manuscript.

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Date received: August 2001.
Date accepted: January 2003.

A note on using satellite telemetry to document the use of San Ignacio Lagoon by gray whales (*Eschrichtius robustus*) during their reproductive season

BRUCE R. MATE*, BARBARA A. LAGERQUIST* AND JORGE URBAN-RAMIREZ+

Contact e-mail: bruce.mate@oregonstate.edu

ABSTRACT

In February 1996, 12 gray whales (*Eschrichtius robustus*), consisting of six animals without calves and six females with calves, were instrumented with Argos satellite-monitored radio tags in San Ignacio Lagoon, Baja California Sur, Mexico. San Ignacio is one of only three major breeding and calving lagoons located along the Pacific Baja Coast. Tracking periods ranged from 1.5 to 20.8 days. Mothers stayed in the lagoon longer than animals without calves and made repeated excursions to and from the lagoon. The experiment took place at a time of year when the number of animals without calves usually declines, which likely influenced the residence time of these animals in the lagoon. The question of residence time and turnover of both animals with and without calves is important in establishing how many whales actually use the lagoon during the winter reproductive season.

KEYWORDS: GRAY WHALE; SATELLITE TAGGING; TELEMETRY; MOVEMENTS; DISTRIBUTION; BREEDING GROUNDS

INTRODUCTION

The Eastern stock of gray whales migrates to winter areas on the Pacific coast of Baja California, Mexico from summer feeding grounds in the northern Bering, Chukchi and Beaufort Seas, and to a lesser extent from waters off Southeast Alaska, British Columbia, Washington, Oregon and northern California (e.g. Rice and Wolman, 1971; Swartz, 1986). Three lagoons of Baja California have long been recognised as important breeding and calving areas for gray whales: Laguna Ojo de Liebre (Scammon's Lagoon); San Ignacio Lagoon; and Magdalena Bay (Scammon, 1874).

San Ignacio Lagoon (26°43'N, 113°16'W) is the smallest of these (Fig. 1). It was declared a whale refuge by Presidential decree in late 1970 and became part of the Vizcaino Biosphere Reserve in 1988. The northern two-thirds (upper and middle) of the lagoon are set aside as a sanctuary. Tourist and fishing activities are prohibited in the sanctuary during the breeding and calving season. The lower third of the lagoon, however, is a popular and regulated whalewatching destination. San Ignacio Lagoon was also the site of a proposed salt-production facility. The effects of such activities on gray whales in the lagoon were unknown (Urbán-R *et al.*, 1997) and part of the motivation for this study.

Previous aerial (Gilmore, 1960; Hubbs and Hubbs, 1967; Gard, 1974; 1978; Rice *et al.*, 1981; Mizroch *et al.*, 1984) and boat surveys (Swartz and Jones, 1980; 1981; Jones and Swartz, 1984) of San Ignacio Lagoon suggest the population of gray whales at any one time is a fraction of the total population. Data from recent boat surveys revealed a maximum combined count (both animals with and without calves) of 207 gray whales in the lagoon in the first week of March 1996 (Urbán-R *et al.*, 1997). The population estimate for that same winter was 22,263 (CV = 0.0925) whales (Hobbs *et al.*, 1996). Evidence from photographic identification studies, shore-based observations of the main entry channel to the lagoon and radio-tagging studies suggests a considerable turnover in the lagoon population (Jones and Swartz, 1984; Mate and Harvey, 1984). Photographic evidence has also confirmed that two whales moved from one breeding lagoon to another in the same season (Jones and Swartz, 1984). The extent of this type of interchange between lagoons is unknown. Without a good understanding of the amount of exchange and the turnover rates, it is impossible to accurately estimate the number of animals using a particular lagoon (Mate and Harvey, 1984).

The purpose of this study was to examine the movements of gray whales tagged in San Ignacio Lagoon, to try to obtain some insight into lagoon residency, the extent of movements in and out of the lagoon, and interchange between other breeding lagoons.

METHODS

From 8 to 16 February 1996, 12 Argos (satellite-monitored) radio tags were attached to gray whales in San Ignacio Lagoon. Two tag types were used. One type consisted of a *Telonics* ST-10 Argos transmitter in a cylindrical housing identical to that used on humpback (Mate *et al.*, 1998) and blue whales (Mate *et al.*, 1999). These tags (17cm long by 2.5cm in diameter) provided the location information discussed here as well as percentage of time the whale spent at the surface (not discussed). The other tag was a *Telonics* ST-6 Argos transmitter with a Wildlife Computers controller board in a larger cylinder identical to that used on blue whales (Mate *et al.*, 1999). In addition to the location information, these larger tags (19cm long by 5cm in

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* *Oregon State University, Fisheries & Wildlife, Coastal Oregon Marine Experiment Station, Hatfield Marine Science Center, Newport, Oregon 97365, USA.*

+ *Departamento de Biologia Marina, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., México.*

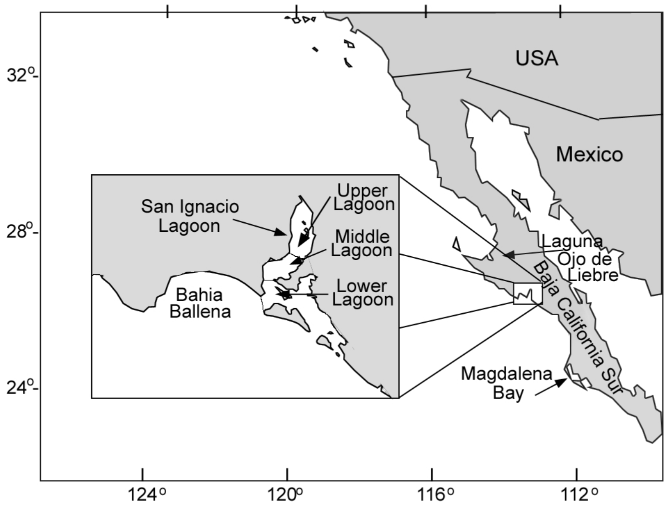

Fig. 1. Study area of the 1996 gray whale tagging effort in San Ignacio Lagoon.

diameter) transmitted data summarising the whale's dive habits (not presented in this manuscript). Both types were attached to the whale's back with two subdermal anchors, each consisting of a stainless steel rod with a cutting tip and backward-facing barbs to hold them in the blubber layer. Tags were applied close to the mid-dorsum (1.5-6m behind the blowhole) with a *Barnett* compound crossbow (68kg). Whales were approached from behind and to one side at a vessel speed similar or slower than the whale's speed of travel. Once within deployment range (2-6m), vessel speed was increased to slightly greater than the whale's so as to catch up and position the tag in the desired location. In cases where whales were 'resting' at the surface, the boat approached at just above idle with as little change in engine pitch as possible. The tags transmitted every 10s ($n = 2$) or 20s ($n = 10$) when the tag was above water during alternate 6h periods (0900 to 1500, and 2100 to 0300 GMT).

The tags were monitored by Argos Data Collection and Location Service receivers on two NOAA TIROS-N weather satellites in sun-synchronous polar orbits. At the latitude of San Ignacio Lagoon, each satellite passes over the region 7–8 times/day. With the programmed duty cycle (12h/d), it was possible to acquire data from up to 10 orbits/d. Surfacing was determined when the tag's conductivity switch was above the surface of the water.

Locations were calculated by Argos from Doppler shift data when multiple messages were received during the 7 to 16 minutes of a satellite's passage overhead. It was not possible to determine the accuracy of locations when less than three messages were acquired within a single orbit (location quality $\leqslant 0$). Screening criteria were used to edit these locations by allowing an 11.5km error radius around them (Mate *et al.*, 1997). Distances and speeds were then calculated between edited locations. Locations were eliminated if speeds between adjacent locations were > 15km/h for < 1h, > 10km/h for > 1h, or were located on land > 11.5km from the nearest shoreline. Overall speeds were calculated by dividing a whale's total distance travelled between locations by the total time between tagging location and last location received. As such, these speeds represent minimums. It is important to emphasise that the lines connecting locations do not imply the route taken by the whale, but merely the chronological order of locations.

Given the error radius, it was impossible to determine whether locations of < 0 quality within 11.5km of the lagoon entrance were actually inside or outside the lagoon. Therefore, only locations of quality > 0 (good quality) were used for inside vs. outside lagoon comparisons.

RESULTS

Six females with calves, hereafter referred to as 'mothers' (whales M-1 through M-6; estimated length $\overline{X} = 12.4$m), and six other whales (estimated length $\overline{X} = 11.5$m), hereafter referred to as 'singles' (whales S-1 through S-6; Table 1) were tagged. The sex of only one of the six singles could be positively determined. The single whales consisted of two solitary whales, one whale from each of three different pairs, and a male in a mating group of 4–5 individuals pursuing a mother with a calf. Since it was late in the calving season, it is extremely unlikely that any of the single whales became mothers.

Table 1

Tag identity, tagging date, duration of operation, sex, estimated size and group composition of 12 gray whales instrumented with Argos satellite-monitored radio tags in San Ignacio Lagoon, Baja California Sur, Mexico, February to March 1996.

Tag #	Tagging date	Days of attachment	Sex	Length (m)	Group composition
S-1	8 Feb 96	15.0	Unknown	10	Singleton
S-2	8 Feb 96	3.5	Male	13	Three escorts with mother/calf
S-3	10 Feb 96	2.7	Unknown	11	Singleton
S-4	11 Feb 96	8.1	Unknown	12	Two adults
M-1	13 Feb 96	2.3	Female	12.5	Mother with calf
M-2	13 Feb 96	20.8	Female	12	Mother with calf
M-3	13 Feb 96	1.4	Female	--	Mother with calf
S-5	14 Feb 96	3.1	Unknown	11	Two adults
S-6	14 Feb 96	1.5	Unknown	12	Two adults
M-4	14 Feb 96	12.7	Female	12.5	Mother with calf
M-5	14 Feb 96	1.4	Female	13	Mother with calf
M-6	16 Feb 96	9.1	Female	12	Mother with calf

Whales exhibited no strong reactions to the tagging process, and the mild reactions that were observed were short-lived. The majority consisted of an exaggerated fluke beat upon tagging ($n = 7$). In four other cases the animals dived quickly upon tagging. One whale exhibited no reaction to the tagging process.

There was no significant difference in mean tracking period between singles ($\overline{X} = 5.6 + 5.11$d) and mothers ($\overline{X} = 9.1 + 8.17$d; t-test $p = 0.41$). Locations were received for 11 of the 12 tagged whales (6 singles and 5 mothers; Table 2). The total number of locations received per day did not differ significantly between singles ($\overline{X} = 2.9 + 2.1$) and mothers ($\overline{X} = 2.3 + 1.7$; t-test $p = 0.65$). Sample sizes were too small to warrant statistical comparisons of tracking periods or number of locations between the two tag types (only two large tags), however the values for the larger tags were within the ranges for the smaller tags.

The fastest overall speed (5.1km/h, 123km/d) was obtained for a single whale (S-1) that began its northward migration two days after tagging (Mate and Urban-Ramirez, 2003). One other single whale (S-4) also began its northward migration, but did not provide enough locations to allow us to determine exactly when it left the lagoon area. Its first location after tagging was five days later (16 Feb) and 399km northwest (minimum of 3.5km/h, 83km/d). Whales S-1, S-4 and S-5 (4.1km/h, 99km.d), moving north beyond Bahía Ballena, had the top three highest speeds for all whales.

Table 2

Location data derived from satellite-monitored radio tags on single and mother gray whales in and around San Ignacio Lagoon, Baja California Sur, Mexico, February to March 1996.

Whale ID (tag type)	Number of locations[a]	Total days tracked	Locations[a] per day	Distance (km)	Days from first to last location[a]	Speed (km/day)	Number of locations of >0 quality
Singles							
S-1 (ST10)	37	15.0	2.5	1779	14.5	123	5
S-2 (ST10)	6	3.5	1.7	52	3.5	15	1
S-3 (ST10)	6	2.7	2.2	68	2.7	25	0
S-4 (ST10)	3	8.1	0.4	537	6.5	83	0
S-5 (ST6)	20	3.1	6.4	306	3.1	99	3
S-6 (ST6)	6	1.5	4.0	77	1.5	51	1
Mean (SD)	13 (13.2)	5.6 (5.11)	2.9 (2.11)	470 (668.7)	5.3 (4.80)	66 (42.6)	1.7 (2.0)
Mothers							
M-1 (ST10)	0	2.3[c]	--	--	--	--	--
M-2 (ST10)	78	20.8	3.8	642	20.8	31	23
M-3 (ST10)	3	1.4	2.1	68	0.9	76	0
M-4 (ST10)	42	12.7	3.3	521	12.7	41	2
M-5 (ST10)[b]	1	1.5	0.7	7	1.2	6	0
M-6 (ST10)[b]	38	9.1	4.2	287	8.8	33	10
Mean (SD)	32 (31.8)	9.1 (8.17)	2.8 (1.42)	305 (276.4)	8.9 (8.36)	37 (25.2)	7.0 (9.8)

[a] Locations of any quality that met our editing criteria. [b] These two tags had a 10s repetition rate, all others had a 20s repetition rate. [c] Transmissions were received for 2.3 days, but no locations were provided.

Only seven whales (4 singles and 3 mothers) had locations of qualities >0 (Figs 2-3). The median percentage of total locations that were of good quality did not differ significantly between singles (15.8%) and mothers (26.0%; Mann-Whitney W-test $p = 0.59$). These seven whales were the only animals considered for inside vs outside lagoon comparisons, however samples sizes were too small to warrant statistical comparisons.

Two single whales provided good quality locations for longer than two days: S-1 (Mate and Urban-Ramirez, 2003; Fig. 2a) and S-5 (Fig. 2c). Whale S-1 was tagged just outside the mouth of the lagoon and did not enter the lagoon, beginning its migration north two days after tagging (10 Feb). Whale S-5 left the lagoon within 17.8h after tagging (15 Feb) and did not re-enter. The other two single whales did not leave the lagoon, but their tracking periods (between good quality locations) were extremely short (2.6h and 29.1h, respectively, Figs 2b, 2c), with only one good quality post-tagging location each. Both of these latter locations were in the lower portion of the lagoon, near the lagoon entrance.

All three mothers with location qualities >0 made at least one excursion to and from the lagoon during their tracking periods, travelling into adjacent Bahía Ballena (Fig. 3). When only one location was received on either end of an excursion (one location outside the lagoon followed by one location inside and so on), the time spent inside vs outside the lagoon during the excursion could not be accurately determined. This was the case for M-4 (Fig. 3b), for which only two good post-tagging locations were received. Whale M-4 left the lagoon sometime in the 76.1h following tagging, and then re-entered the lagoon sometime in the next seven days. Her last location was in the middle portion of the lagoon (on 25 Feb).

When two or more successive locations were inside or outside the lagoon, the minimum time spent in that area could be determined. Whale M-2 stayed in the lagoon for 2.3 days after tagging, followed by a departure from the lagoon sometime in the next 1.3 days. In the next 3.7 days she re-entered and left the lagoon again, after which she spent a minimum of 7.7h outside the lagoon, before re-entering for a third time. The remainder of M-2's tracking period (between good locations) was spent in the lagoon (17.6d, last location on 2 Mar). Thirteen percent of M-2's good locations were spent in the upper portion of the lagoon, 35% in the middle portion, 39% in the lower portion and 13% outside the lagoon.

Whale M-6 left the lagoon only once, following a 3.3 day period in the lagoon after tagging. This excursion took place sometime in the next 18.8h. Whale M-6 then re-entered the lagoon sometime in the next 4.8h, where she remained for the duration of her tracking period (4.0d, last location on 25 Feb). Thirty percent of her good quality locations were in the middle portion of the lagoon, 60% in the lower and 10% outside the lagoon.

DISCUSSION

This preliminary study demonstrates the feasibility of monitoring gray whale movements by satellite, and provides some confirmation to previous studies' findings that single whales depart from the lagoon before females with calves (mothers). Jones and Swartz (1984) found single whales departing from San Ignacio Lagoon approximately one month before mother-calf pairs. They also report a mean residence time of 11 weeks for singles with the mean day of residency ranging from 1-16 Feb. The study here does not accurately address the issue of residence time, as tagging was not done at the beginning of the season and it was not known how long whales had already been in the lagoon. The two single whales that began their northward migrations left the lagoon area (including Bahía Ballena) within 2-5 days of tagging (tagged 8 and 11 Feb).

Overall speeds were highest for single whales moving north beyond the lagoon area. This may reflect actual differences in speed of travel, but more likely reflects the nature of the speed calculation. Total distance between locations is used to calculate overall speed. For animals moving in a more or less straight line, the measured distance more accurately reflects true distances covered, and thus travel speeds. For animals moving in a non-linear fashion, as

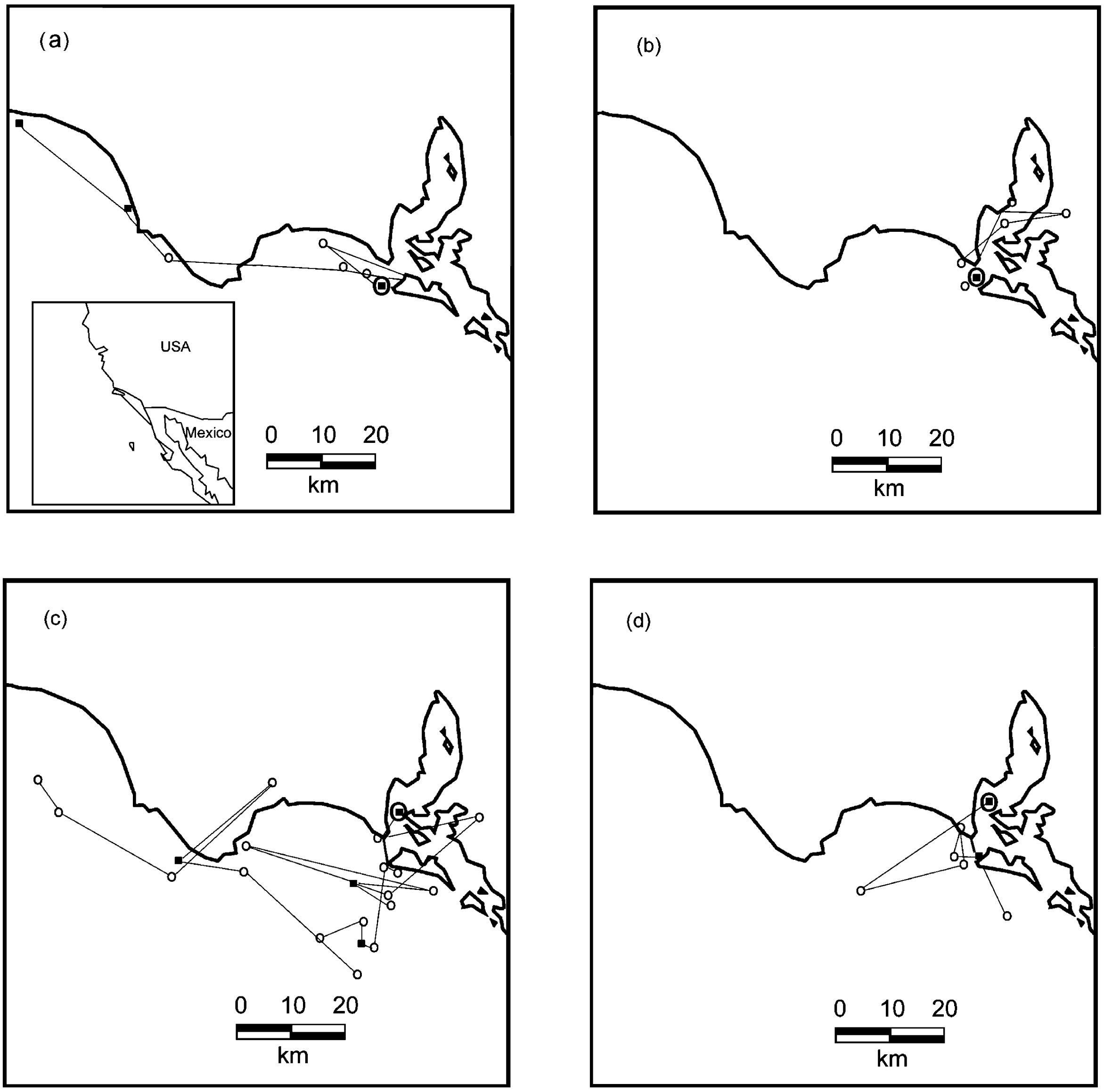

Fig. 2. Satellite-acquired locations of 4 single gray whales tagged in San Ignacio Lagoon, Feb 1996: (a) whale S-1, showing inset of full migration (details in Mate and Urban-Ramirez, 2003); (b) whale S-2; (c) whale S-5; and (d) whale S-6. Locations for whales S-3 and S-4 are not depicted as too few locations passed editing criteria. ⦿ represents the tagging location for each whale. ○ represents locations of $\leqslant 0$ quality that met our editing criteria. □ represents locations of >0 quality.

with clustered movements in a small area, total distance between locations is underestimated, as are speeds.

The distribution pattern was quite different between single whales and mothers, with 100% of locations for single whales being either in the lower portion of the lagoon or outside the lagoon (not including the two that began their northward migration), but only 57% of locations for mothers being in these same areas. In their surveys within San Ignacio Lagoon, Jones and Swartz (1984) noted a preference by single whales for the lower lagoon region, and also use of the entrance to the lagoon. A preference by single animals for lagoon entrances has also been reported for Laguna Ojo de Liebre and Magdalena Bay (Gilmore, 1960). The predominant activity in these areas is courtship and mating (Gilmore, 1960; Samaras, 1974; Norris *et al.*, 1983; Jones and Swartz, 1984). Jones and Swartz (1984) have suggested that the deeper waters of the lower lagoon (2-4 times deeper than the middle and upper lagoon) may be more conducive to sexual behaviour. Several factors may contribute to these activities in the lower lagoon, including an increase in the likelihood of encountering other single whales moving in and out of the lagoon and mothers with calves spending a greater percentage of their time farther up lagoon, possibly to avoid mating. While mothers may leave the lagoon briefly, the activities of tagged whales (mothers) were most concentrated in the lower two-thirds of the lagoon, which is consistent with survey results from the same time of year (Jones and Swartz, 1984). Jones and Swartz (1984) felt that mothers with calves may actively avoid courting groups of whales due to the disruptive and potentially harmful nature of mating aggregations. Thus their use of the more inner portions of the lagoon while singles are still around is not unexpected. The use of the entrance area and adjacent Bahía Ballena by single whales, as well as the back and forth movement of mothers, emphasises the importance of surveying both inside and outside the lagoon when determining abundance.

While these results provide some minimum residence time information and lagoon utilisation by individual gray whales, they must be treated with caution. The sample sizes are small, and not representative of the whole population. Tagging mid-season biases the estimates of residence times

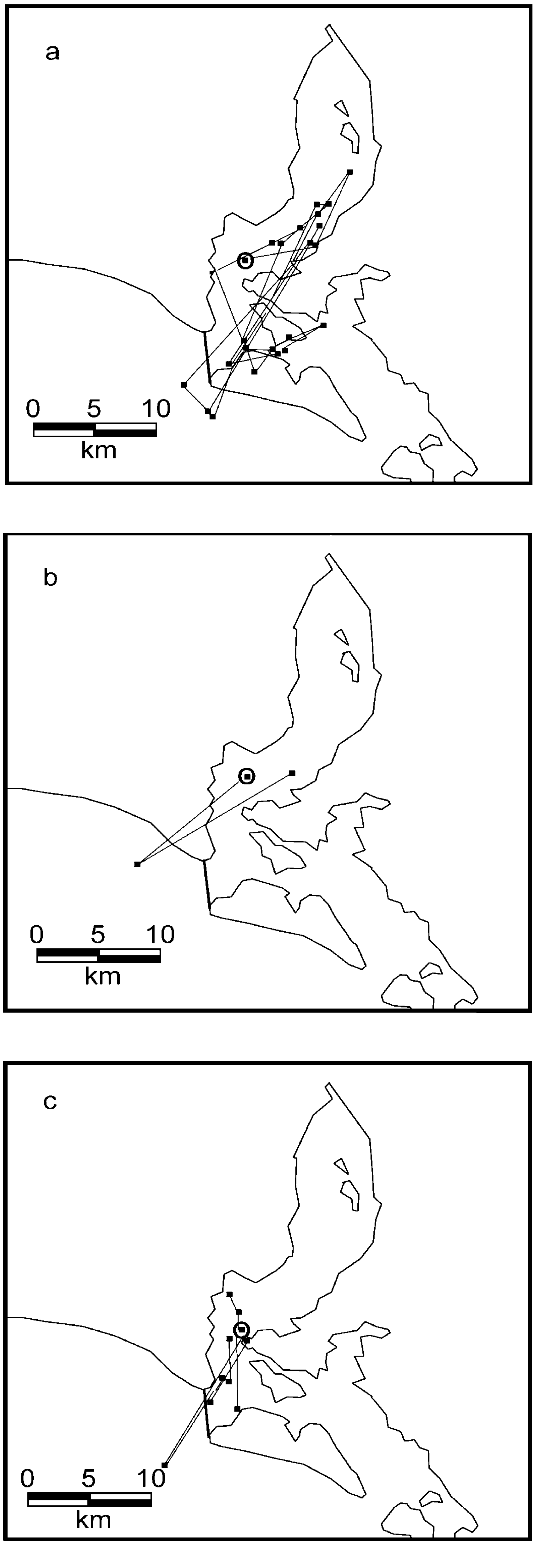

Fig. 3. Satellite-acquired locations of 3 mother/calf gray whale pairs tagged in San Ignacio Lagoon, Feb 1996: (a) whale M-2; (b) whale M-4 and (c) whale M-6. Locations for whales M-3 and M-5 are not depicted as too few locations passed editing criteria. ⊙ represents the tagging location for each whale. Only locations of >0 quality are shown.

downward, as many whales may have been there for some time already and others would soon be leaving the lagoon. Also, tag attachment was quite short, again biasing residence time downward. Finally, the conservative criteria of only using good quality locations for examining movement into or out of the lagoon may have resulted in an underestimate of these movements. A good example of this is the single whale S-6 (Fig. 2d). Only one good post-tagging location was received, suggesting the animal stayed in the lagoon following tagging. If lesser quality locations were considered, there would be little argument that this animal had indeed left the lagoon, as four lesser quality locations in a row were outside the lagoon entrance, one of which was further from the entrance than our 11.5km error radius.

Future studies would benefit from increasing the transmission capability of all tags from 20s to 10s, which would result in more messages received per satellite pass, contributing to higher numbers of good quality locations. Benefits would also be gained by tagging a larger number of whales, earlier in the reproductive season and with longer-lasting tags. The latter can be achieved with the use of smaller, implantable tags, reducing their vulnerability to hydrodynamic drag or being scraped off during courtship and normal intimate mother/calf behaviour. Longer-term tracking could reveal the extent to which whales use other reproductive and/or offshore areas during the same winter. Tagging earlier in the reproductive season would provide better estimates of the duration of lagoon residency and other seasonal movements. It may also be important to tag animals in offshore areas, as the majority of gray whales (other than cow/calf pairs) may spend the winter outside lagoons (Mizroch *et al.*, 1984).

Even with such short periods of attachment, we believe satellite-monitored tags provide an improvement in range and confidence over conventional VHF/HF tags (Mate and Harvey, 1984) in resolving questions of whale movement, both within lagoon reproductive areas and offshore.

ACKNOWLEDGEMENTS

We thank Dr. Roderick Mesecar for tag construction, Mercedes Guerrero for field assistance, Martha Winsor for statistics and graphics, and Veryl Barry and Carol DeLancey for manuscript preparation. This project was carried out under a permit issued by the Mexican Department de Pesca. It was funded by the Office of Naval Research, Grant #N000149610608 and by donors to the Endowed Marine Mammal Program of Oregon State University. This paper is dedicated to the memory of Dr. Ken Norris, whose interests in gray whales and migrations included radio-tagging experiments in Baja, and who encouraged both Mate and Urban-Ramirez at various times throughout their careers.

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Date received: September 2002.
Date accepted: July 2003.

A note on the route and speed of a gray whale on its northern migration from Mexico to central California, tracked by satellite-monitored radio tag

BRUCE R. MATE[*] AND JORGE URBAN-RAMIREZ[+]

Contact e-mail: bruce.mate@oregonstate.edu

ABSTRACT

A gray whale (*Eschrichtius robustus*) tracked with an Argos satellite-monitored radio tag travelled 1,794km during the northbound migration season from San Ignacio Lagoon (SIL), Baja California Sur, Mexico to north of San Francisco from 8–23 February 1996. The migration route was predominately nearshore and in water <100m deep, with 75% of the Argos-acquired locations averaging 7.3 ± 1.22km from shore. Distances >20km from shore and water depths >100m were encountered only when the whale crossed Vizcaino Bay or through the Channel Islands. During migration, the whale maintained an average speed of 5.6km h^{-1}, suggesting a coastal migration of 49 days from SIL to the Bering Sea.

INTRODUCTION

Scammon (1874) was the first to recognise gray whales as long-distance migrants when he found Alaskan hunting implements in gray whales harvested in Mexico. Gray whales feed predominately in the Bering Sea during the summer and autumn and migrate in winter to selected Pacific lagoons in Baja Mexico to breed and calve (Rice and Wolman, 1971; Swartz, 1986). Their reputation as a nearshore species during these migrations has enabled researchers using shore-based counts during daylight hours to examine the numbers and timing of both the northbound and southbound migrations (Reilly, 1984; Buckland and Breiwick, 2002). While a few estimates of travel speeds have been made for individual whales over short distances (<10km) from shore-based theodolite measurements (Perryman *et al.*, 1999), or by following VHF radio-tagged individuals by boat for up to a few hours (Swartz *et al.*, 1987), little has been determined about the route and speed of individuals over longer distances. This study used a satellite-monitored radio tag to identify the route and speed of a gray whale migrating north from the winter breeding and calving area in San Ignacio Lagoon, Baja California Sur, Mexico.

METHODS

On 8 February 1996, a lone adult gray whale of unknown sex (10m long) was tagged in San Ignacio Lagoon (26°43’N, 113°16’W) with an Argos (satellite-monitored) radio tag. The Argos Data Collection and Location Service (ADCLS) was used to acquire whale locations based on Doppler-shifted messages received by the polar-orbiting NOAA TIROS-N weather satellites (Argos, 1984). The tag, attachments and method of deployment were identical to those used on humpback whales (Mate *et al.*, 1998) and blue whales (Mate *et al.*, 1999).

The tag was applied to the whale’s dorsum 34cm to the left of the midline and about 4m behind the blowhole. The tag was programmed to transmit every 20 seconds when its conductivity switch was above water during alternate 6h periods (0900 to 1500, and 2100 to 0300 GMT).

Distances and speeds were calculated along the straight line between consecutive whale locations, except for a few segments, which were modified to deviate around coastal promontories whenever straight lines crossed them. All locations were subjected to editing criteria, which allowed an 11.5km error radius around each location and eliminated those locations which resulted in speeds >10km h^{-1}. Experiments (Mate *et al.*, 1997 and Mate *et al.*, 1999), determined that an 11.5km error radius would encompass two standard deviations (95%) of all Argos Class 0 locations from their true location. Means are reported with standard errors.

RESULTS

A total of 41 Argos locations were recorded during the next 14.5 days, 36 of which (Fig. 1) met the editing criteria (2.5 locations per day). The whale stayed in San Ignacio Lagoon and the adjoining nearshore region of Bahía Ballenas for only two days before migrating north. There was no evidence that the whale stopped at Laguna Ojo de Liebre, another breeding and calving area *en route*, as it moved north.

Overall, the whale travelled at least 1,794km to an area north of San Francisco, California (38°17’N, 123°10’W) at a minimum average speed of 5.2km h^{-1}. After leaving Bahía Ballenas, the overall average distance travelled per day was 134km (5.6km h^{-1}), while the average of speeds calculated from distances and times between locations was 5.7 ± 0.3km h^{-1} ($n = 31$). There was no significant difference found between average speeds of 5.6 ± 5.3km h^{-1} ($n = 18$) for night and 5.7 ± 2.6km h^{-1} ($n = 19$) for the day (t-test, $p = 0.94$).

Locations were an average of 21 ± 4.6km ($n = 36$) from shore. However, only nine locations were >20km from shore. The latter occurred as the whale crossed Vizcaino Bay ($n = 3$) and through the California Channel Islands ($n = 6$). The average distance of the other 27 locations from shore

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[*] *Oregon State University, Marine Mammal Program, Hatfield Marine Science Center, 2030 SE Marine Science Drive, Newport, Oregon 97365 USA.*

[+] *Departamento de Biologia Marina, Universidad Autónoma de Baja California Sur, La Paz, B.C.S., 23081 México.*

was 7.3 + 1.22 km. Six of the locations in the Channel Island area were in water between 100 and 1,800m deep ($\overline{X} = 948 \pm 310.8$m). The remaining 30 locations occurred in water < 100m deep ($\overline{X} = 39 \pm 4.9$m).

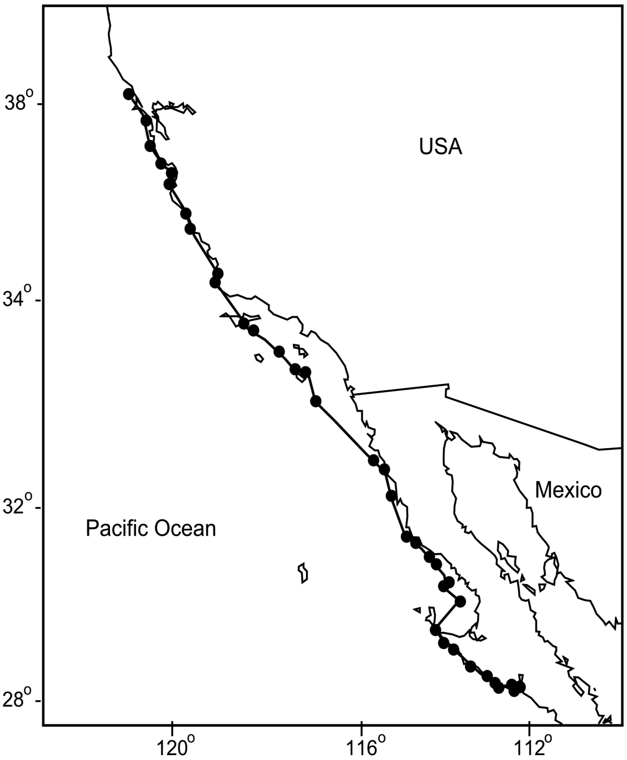

Fig. 1. The track of a satellite-monitored radio-tagged gray whale as it migrated north from San Ignacio Lagoon to central California between 8 and 23 February 1996.

DISCUSSION

The gray whale is the only baleen whale with a conspicuously nearshore migration along much of its route, but how it navigates is still uncertain. The tagged whale in this study did not follow a specific depth contour or maintain a specific distance from shore. We speculate that gray whales may migrate in part by passively listening to simple acoustic cues. By merely keeping the sound of the surf to their right side, northbound migrants from Mexico could reach Unimak Pass, Alaska (the eastern end of the Aleutian Islands), to enter the population's main feeding area, the shallow Bering Sea Shelf. Rice and Wolman (1971) described gray whales taking the most direct route when crossing bights or coastal indentations, such as the Channel Islands and Vizcaino Bay. Listening to surf sounds of the outer California Channel Islands may also explain how some gray whales navigate through this area. There has been speculation that gray whales in southern California now migrate farther offshore than in the past, due to increased harassment from nearshore vessel noise. It is not possible to address that issue in this paper, but we suggest a route between the outer Channel Islands is direct and makes good energetic sense regardless of human activities. During the spring migration northward in 2000 and 2001, gray whales were observed in the western Santa Barbara Channel occasionally feeding on surface swarms of krill, alongside feeding blue and humpback whales (Le Boeuf *et al.*, 2000). Krill aggregations are not common nearshore in the Southern California Bight, but are quite regular along the northwestern parts of the westerly Channel Islands (Fiedler *et al.*, 1998).

The northward migration of gray whales is divided into two parts: single animals (males and adult females without calves) depart Mexico first, followed 4-6 weeks later by females with calves (Herzing and Mate, 1984; Poole, 1984). The tagged whale's departure from the lagoon in early February is consistent with the mid-February decline of single whales in San Ignacio Lagoon observed by Jones and Swartz (1984).

The distances between locations reported here are minimum estimates of the actual distance travelled and thus also minimum estimates of the whale's swimming speed. The average migration speed of this animal (5.6km h^{-1}) is faster than the speed of a gray whale tagged with a VHF radio transmitter in 1979 moving from San Diego to Coos Bay, Oregon (3.5km h^{-1}) but very close to its average speed of 5.3km h^{-1} (assuming a nearshore route) from Oregon to Unimak Pass, Alaska (Mate and Harvey, 1984). The speed of the northbound tagged whale is only slightly less than the 6km h^{-1} estimated for southbound whales tracked with VHF radio tags for up to 13.5h and 81k off the central California coast (Swartz *et al.*, 1987). If the satellite-monitored whale had maintained its average speed as it continued north, it would have reached the central Oregon coast by 1 March. The northbound migration in Oregon starts in mid-February, and 25% of the single whale population has typically passed north by 1 March (Herzing and Mate, 1984). Presuming a coastal route, the tagged whale could have reached Unimak Pass (3,700km from Oregon) by 28 March (49 days after tagging), when early migrant gray whales are usually observed (Rugh, 1984). Whales could save time and energy if they cut across the Gulf of Alaska, but it is not known if this occurs and seems doubtful from shore-based observations in Alaska.

The data suggest a consistent migration speed. The motivation, and hence the speed, of individual whales to get to the feeding grounds might differ depending upon their age, sex, reproductive status and energy stores. While some migrant whales stop to mate or feed for short periods along the California and Oregon coasts, most do not (Herzing and Mate, 1984). Observations of feeding are not common along the Oregon coast until May, well after the March/April peak of single migrants (Sumich, 1986).

This is the first detailed description of the route and rate of speed for an individual gray whale during its northbound migration. The data support the long-standing belief that gray whales are nearshore migrators. Since they travel so close to shore, the population may be at some risk from catastrophic anthropogenic events (such as an *Exxon Valdez*-sized oil spill) along their migration route. Thus, whilst eastern gray whales have fully recovered from exploitation (IWC, 2003), they are still potentially at risk from industrial developments and accidents. However, as gray whales are no longer listed under the United States Endangered Species Act (ESA), developers do not presently need to take gray whales into consideration when drafting Environmental Impact Statements (EIS) for proposed activities in gray whale habitat. It may be appropriate for a mechanism to be developed (e.g. a new category of 'in jeopardy' be added to the existing ESA terminology of 'threatened' and 'endangered'), which would require developers to address special risks associated with gray whales (or other 'numerically recovered' species) in an EIS describing a proposed project, when significant risk to the entire population is feasible.

ACKNOWLEDGEMENTS

We thank Dr. Roderick Mesecar for tag construction, Barbara Lagerquist and Mercedes Guerrero for field assistance, Martha Winsor for statistics and graphics, and Veryl Barry and Carol DeLancey for manuscript preparation. This project was carried out under a permit issued by the Mexican Ministry of Environment, Natural Resources and Fisheries, and the El Vizcaino Biosphera Reserve. It was funded by the Office of Naval Research, Grant #N000149610608 and by donors to the Endowed Marine Mammal Program of Oregon State University. This paper is dedicated to the memory of Dr. Ken Norris, whose interests in gray whales and migrations included radio-tagging experiments in Baja, and who encouraged both authors at various times throughout their careers.

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Date received: September 2002.
Date accepted: March 2003.

Distance measurements using binoculars from ships at sea: accuracy, precision and effects of refraction

DOUGLAS KINZEY*+ AND TIM GERRODETTE*

Contact e-mail: dkinzey@u.washington.edu

ABSTRACT

The distances to 1,576 targets between 0.3 and 10.4km from two ships were measured using the reticle scale in 25× binoculars during cetacean surveys in the eastern tropical Pacific Ocean. Distances were measured under a range of conditions representing the environmental variability in three years of field surveys. Alternative formulae for calculating distance from optical devices were applied to the reticle measurements and compared to distances measured by radar. Reticles in 25× binoculars provided unbiased measurements to about a third of the way to the horizon, or from 0-4km for the 10.5m platform heights used for the study. Between 4 and 8km (approximately one-third to two-thirds of the distance to the horizon), distances tended to be slightly underestimated, reaching a maximum bias at the most distant targets of 6% for one ship and 16% for the other. Distances beyond about two-thirds of the way to the horizon were not measurable because the angles were too small. The negative bias in measurements of distances from 4-8km was due to refraction of light and other factors. Refraction had less of an effect than expected for a temperature gradient based on a standard atmosphere, suggesting a mean gradient for the eastern tropical Pacific of $-0.02°C\ m^{-1}$ in the first 10m above the sea surface rather than the standard value of $-0.0065°C\ m^{-1}$. Correcting the measurements for refraction improved their accuracy, eliminating the bias for one ship and reducing it for the other. Adjusting for refraction should improve measurements of distance using theodolites or photographic/video imaging as well as measurements using binoculars. An additional regression-based correction suggested that the remaining negative bias for one ship was a complex interaction of Beaufort Sea state, swell height and wind speed. Precision of distance measurements decreased multiplicatively with target distance. Including errors due to bias, the multiplicative standard error was 12%, or a 95% confidence interval from 0.8-1.2km for a target at 1km and from 6.5-9.9km for a target at 8km. Compared with other methods of measuring distance to marine mammals at sea, measurements using binocular reticles are more precise than distances estimated by eye, less precise than distances measured with photographic imaging, and useful over a larger range.

KEYWORDS: TELEMETRY; SURVEY-VESSEL; PACIFIC OCEAN; MODELLING

INTRODUCTION

The distances to marine mammals from a point of observation are fundamental data for estimating abundance using line-transect methods (Buckland *et al.*, 2001), and for some studies of cetacean behaviour (DeNardo *et al.*, 2001; Heckel *et al.*, 2001; Leaper and Gordon, 2001; Frankel and Clark, 2002) and ecology (Fiedler *et al.*, 1998). The distance between a cetacean and an observer can be calculated from the observer's eye-height and the vertical angle between the mammal and a reference line, typically the horizon or shoreline (Lerczak and Hobbs, 1998). This angle is often measured optically using a theodolite, the reticle scale in a binocular or a video/photographic image, and is converted to radial distance using a formula based on spherical geometry (Gordon, 1990; Lerczak and Hobbs, 1998). The measurement can be improved by correcting for refraction (Leaper and Gordon, 2001).

Errors in the estimation of distance in line-transect analyses have been considered by Schweder (1997), Alpízar-Jara *et al.* (1998) and Chen (1998). Underestimation of distance leads to overestimation of abundance and vice versa. Errors in distance measurement can lead to underestimation of abundance even if errors are unbiased (Chen, 1998).

On ship surveys conducted by the Southwest Fisheries Science Center (SWFSC), the angle between a mammal sighting and the horizon is measured using a reticle scale in 25× binoculars (Kinzey and Gerrodette, 2001). This paper examines 1,576 binocular measurements vs radar measurements of distances between 0.3 and 10.4km from two ships for evidence of bias or inaccuracies using reticles. This study compares alternative equations for calculating distance, reports the accuracy and precision obtainable using reticle-based measurements under a range of environmental conditions and introduces: (1) local versus average corrections for the effects of refraction; and (2) additional ship-specific corrections for using reticles in 25× binoculars under field survey conditions. The accuracy and precision of distance measurements obtainable with reticles under field conditions are compared with the accuracy and precision obtainable using naked eye estimates (Schweder, 1997) or using video/photographic images (Gordon, 2001).

METHODS

Converting reticle values to distances

Kinzey and Gerrodette (2001) provide factors to convert reticle values to vertical angles. Lerczak and Hobbs (1998) provide formulae for converting vertical angles to radial distances. Alternative formulae that give equal numerical results for converting angles to distances are given in Gordon (1990), Jaramillo-Legorreta *et al.* (1999) and Buckland *et al.* (2001, p.257).

Two vertical angles are required when binocular reticles are used to measure the distance to a sighting: (1) the angle from a reference line down to the sighting; and (2) an upper angle from the reference line to the horizontal tangent. The first is measured with reticles and the second is calculated from observer height. Both angles, in radians, are summed to calculate distance, D_a, to the sighting in kilometres[1]

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[1] The following equation is slightly modified from the form in which it is presented in Gordon (1990) and Lerczak and Hobbs (1998). We thank J.L. Laake, Alaska Fisheries Science Center, for an earlier version of this modified form.

* *NOAA, NMFS, Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, CA 92037, USA.*
+ Current address: *School of Aquatic and Fishery Sciences, University of Washington, 1122 NE Boat St, Seattle, WA 98105, USA.*

as follows:

$$D_a = h_e * \sin(\theta + \alpha) - \sqrt{R_E^2 - (h_e * \cos(\theta + \alpha))^2} \qquad (1)$$

where:

θ = angle below the horizon to the sighting, in radians;
α = angle above the horizon to the horizontal tangent = atan $(\sqrt{2R_E h + h^2} / R_E)$, in radians;
h = eye height above sea level, in km;
R_E = radius of earth (= 6,371km);
h_e = $R_E + h$.

θ is referred to as the target angle and α as the above-horizon angle. These angles are also known as 'dip short of the horizon' and 'dip of the visible horizon', respectively (Bowditch, 1995). The distance to the horizon is given by the term $\sqrt{2R_E h + h^2}$ in the definition of α.

Equation 1 can be used to calculate distances from any angle-based device, including theodolites (measuring $\theta + \alpha$ as a single term) or video/photographic images (Gordon, 2001; Leaper and Gordon, 2001). Formulae that produce different numerical results from equation 1 are given in Smith (1982), Buckland *et al.* (1993, p.325), and Bowditch (1995, p.340) (Table 1). Both the Smith (1982) and Buckland *et al.* (1993) formulae use the simplifying assumption of straight-line distance between the sighting and the observation platform rather than accounting for the curvature of the earth (Lerczak and Hobbs, 1998). The Bowditch (1995) formula in Table 1 is an empirically-derived formula used by mariners that accounts for average, worldwide refractive conditions to calculate the dip short of the horizon for an object at known distance.

The 25× binoculars used in this study have no measurable differences in the accuracy of angle measurements among different binoculars (SWFSC 'old style'; Kinzey and Gerrodette, 2001). Each reticle spans 0.0771° (0.00135 radians). The scale is marked to every 0.2 reticles between 0 and 2 reticles and to every half reticle from 2 to 20. The angle between a mammal sighting and the horizon is measured by placing the uppermost reticle line on the horizon and counting the reticles down to the sighting.

Correction for refraction

Equation 1 assumes that light travels in straight lines. It does not account for possible bending due to environmental conditions that can cause refraction (Lerczak and Hobbs, 1998). However, light rays curve when passing obliquely through an atmospheric density gradient (Fleagle and Businger, 1980; Leaper and Gordon, 2001). Light travels faster at lower density and so bends toward higher density when it encounters a gradient. Atmospheric density typically decreases with height (Fleagle and Businger, 1980), which results in a decrease in the perceived angle between a distant object at sea level and the horizontal tangent when the light arrives at an observer. The object is perceived higher relative to the observer than it is based on geometry. This refraction effect is greatest at the horizon, so that although both above-horizon and target angles decrease as a result of refraction, the relative angle between the object and the horizon increases. These combined effects on the target and above-horizon angles result in underestimation of the object's distance when a geometry-based formula such as equation 1 is used.

Equation 1 can be corrected for refraction by using air temperature, air pressure and the vertical gradient in air temperature between target and observer to adjust both the above-horizon and target angles (Leaper and Gordon, 2001). The correction involves calculating the radius of the arc of the refracted ray of light, which is then used to calculate a corrected angle of dip and angle below the horizon. The first empirical term is atmospheric density, A (kg m^{-3}):

$$A = \frac{p\beta}{T} \qquad (2)$$

where:

p = atmospheric pressure in Pa (= 100mb = 100kg m^{-1} s^{-2});
T = air temperature in degrees Kelvin;
β = reciprocal of specific gas constant = 0.00348m^{-2} s^{2} degrees^{-1}.

Atmospheric density is then combined with the temperature gradient to calculate a 'radius of curvature', r, of the refracted ray in meters:

$$\frac{1}{r} = \frac{\varepsilon A}{(1+\varepsilon A)T}\left(\frac{\Delta T}{\Delta h} + g\beta\right) \qquad (3)$$

where:

ε = (refractive index of air − 1)/ air density at sea level = 0.000227m^{3} kg^{-1} for a standard atmosphere at 0°C;
$\frac{\Delta T}{\Delta h}$ = change of temperature with change in height of the light ray = –0.0065^{0}K m^{-1} for a standard atmosphere;
g = gravitational constant = 9.81m s^{-2}.

The $1/r$ value is then used to calculate refraction-corrected horizon and target angles for equation 1, α_c and θ_c, as follows:

$$\alpha_c = \text{atan}\sqrt{2h_m\left(\frac{1}{1000R_E} - \frac{1}{r}\right)} \qquad (4)$$

Table 1

Alternative angle-distance formulae: D_a = distance in kilometres, h = observer eye height in metres above sea level, R_E = radius of earth (= 6,371km), $h_e = h + R_E$, θ = angle from horizon to target in radians, α = angle above horizon to horizontal tangent in radians. The Bowditch (1995) equation was modified from its original form expressing angle in terms of distance by rearranging terms. For the Bowditch formula, observer height (h_f) is in feet, k_1 = 6,076.1 and k_2 = 8,268.

Reference	Formula
Lerczak and Hobbs (1998) (Eq.1)	$D_\text{a} = h_e$*sin$(\theta+\alpha)$ - sqrt[R_E^2 - $(h_e$*cos$(\theta+\alpha))^2$]
Smith (1982)	D_a = 1.852*(h/1852)*tan(atan(89.173/sqrt(h/1852))-θ)
Buckland *et al.* (1993)	D_a = (0.001h)/tan(acos(R_E/(R_E+(0.001h)))+θ)
Bowditch (1995)	D_a =1.852{tan($\theta+\alpha$)k_1k_2 - sqrt[(-tan($\theta+\alpha$)$k_1k_2)^2$-4$h_fk_1k_2$]}/(2k_1)

and

$$\theta_c \approx \theta + \frac{1000D}{2r} \tag{5}$$

where D = true distance, h_m = observer height in metres above sea surface, and all other terms are defined as for equations 2 and 3 above. These corrected angles can then be used in equation 1 to calculate a corrected distance, D_c, from D_a. Under normal survey conditions, the true distance (D) to the target in equation 5 will be unknown, but it can be initially approximated using D_a from equation 1 to calculate θ_c in equation 5, then substituting θ_c for θ in equation 1 to calculate a new D_a and iteratively repeating this process until D_a converges to D_c. This distance, D_c, is the distance corrected for refraction.

Equation 3 uses the standard temperature gradient of –0.0065°K m^{-1}, which assumes standard atmospheric conditions in the bottom kilometre of the atmosphere (Fleagle and Businger, 1980; Leaper and Gordon, 2001). This is a simplification of the actual situation, where the temperature gradient in the bottom metres of the atmosphere is rarely constant (Fraser and Mach, 1974). The mean gradient along the path the light ray travelled may differ from the standard one, and can be calculated from the observed refraction when true distance to the sighted object is known (Fraser, 1979; Lehn, 1983). Although either positive or negative gradients, indicating increasing or decreasing temperature with height, respectively, are possible near sea level, the typical pattern is decreasing temperature with height as noted above. Equation 3 produces no change in distances calculated from equation 1 at a temperature gradient of approximately –0.034°K m^{-1}, the gradient at which the decreasing temperature with height balances the effect of decreasing pressure to produce a constant density of air (refraction increases as temperature decreases and pressure increases). When air density is constant, no refraction occurs. Refraction will cause underestimates of distance from equation 1 as gradient becomes more positive from –0.034, and overestimates of distance for gradients more negative. As described below, the temperature gradient $\Delta T / \Delta h$ was estimated by fitting equation 3 to the data.

The ε term in equation 3 is based on the refractive index of air of 1.000293 and a density of 1.292kg m^{-3} for a standard atmosphere at 0°C (Lehn, 1983). This term is necessary to weight the measured density by the ratio of the refractive index to refraction calculated at 0°C, and assumes a linear relationship between the index and air density.

Field methods: Distance measurements with reticles and radar

A total of 1,576 measurements of the distances to targets from two ships were made using the reticles in 25× binoculars under a variety of sighting conditions, and paired with radar measurements to the same targets. The reticle measurements were recorded by the regular mammal observers during testing periods on shipboard surveys in the eastern tropical Pacific Ocean in July-December during 1990, 1992 and 1993. 662 of these were made from the NOAA[2] Ship *McArthur* and 914 measurements were made from the NOAA Ship *David Starr Jordan*. Twenty-nine additional measurements made on one day, and 6 that were estimated at less than 0.1 reticles (the normal minimum value used on our surveys) were non-standard or otherwise anomalous and were eliminated from the analysis. These excluded values did not qualitatively affect the results.

Targets ranged between 0.33 and 10.35km from the ships. Within this range, 278 different distances, averaging 0.04km apart, were measured with reticles during the study. The target was generally the waterline of a small boat with a radar target set out for the purpose, but occasionally buoys or other floating objects visible to radar were used. A range of distances between the ship and target was measured during a single testing period by moving either the target (small boat) or the ship (for non-boat targets). To reduce intra- and inter-individual correlations in measurements, observers did not watch the target as it moved to a new position, and did not discuss their measurements with each other. Once the target and ship were in position, three simultaneous measurements with reticles were generally made by different observers together with a single radar measurement to the target. Measurements were made by 24 observers, 16 of whom recorded measurements from both ships and 8 recorded measurements from only one ship. Air temperatures, air pressures, wind speed, sea surface temperature and swell heights associated with the measurements were obtained from the ship deck logs. Ship, Beaufort Sea state and a relative motion code (upswell, downswell, trough) were also recorded.

Binocular heights were fixed, and measured above waterline with a plumb bob while the vessels were at the dock. Observer eye-height above sea level was 10.4m (horizon distance = 11.5km) for the *McArthur*, and 10.7m (horizon = 11.7km) for the *Jordan*. The farthest measurements that could be made using equation 1 at the finest resolution level of 0.1 reticle below the horizon given these platform heights were 7.8 and 8.0km for the *McArthur* and *Jordan*, respectively.

For an object at the farthest measurable distance (0.1 reticle) the target angle, θ (equation 1), is 0.000135 radians. The above-horizon angle (α) for a 10.4m high platform is 0.00181 radians. Although equation 1 is the most geometrically accurate formula for angles of this small magnitude (Buckland *et al.*, 2001), these near-horizon angles are also those for which refraction effects are expected to be greatest (Leaper and Gordon, 2001).

To test accuracy, reticle values were converted to distances using the alternative formulae in Table 1 and compared to distances measured with radar. To evaluate the effects of refraction, the accuracy obtained by correcting reticle measurements for refraction using equations 2-5 was compared to uncorrected equation 1.

Several methods of estimating the terms in the refraction equations were assessed. Refraction corrections using the local air temperature and pressures at the time the reticle measurements were made were compared to those calculated using an average 1/r value. As an alternative to the standard temperature gradient, $\Delta T / \Delta h$ in equation 3 was allowed to be an adjustable variable, with the criterion of minimum logarithmic mean squared error (MSE) between distances from reticles and radar (minimum s_2^2 from equation 8 below) determining the most likely gradient present during each series of measurements taken with the same air temperature and pressure on one day. This produced an estimate of the temperature gradient for each day and an average gradient for the time and region that could be compared to the use of the standard gradient. The results obtained using these various methods for estimating refraction were evaluated on the basis of their data needs and practicality for field studies.

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[2] US Department of Commerce, National Atmospheric and Oceanographic Administration.

Calculating precision, bias and accuracy

The variability of 25× measurements of distances corrected and uncorrected for refraction and other factors was assessed in two ways, one that included bias (accuracy) and one that did not (measurement error). Accuracy was calculated using the difference between distances from reticles and radar. Manufacturer specifications indicated that distances from the radar were accurate to within 0.9% or 8m, whichever was greater. Measurement error from reticles was based on the variability of repeated measures to a single target without reference to the true (radar) distance.

Variance of calculated distance D_* increased with true distance D. Log (D_*/D) was approximately normally distributed, indicating that errors were multiplicative rather than additive. A multiplicative standard error for D_* was exp(σ)-1, and an approximate 95% confidence interval was [D/P,DP] where:

$$P = \exp(1.96 * \sigma) \qquad (6)$$

and

σ = standard deviation of the logarithm of distance, estimated by s_1 or s_2 as described below.

Three or more reticle measurements were made to 502 separate targets. The standard deviation of measurement error, s_1, was estimated as:

$$s_1 = \left(\sum_{i=1}^{502} \left[\frac{n\sum_j d_{\mathrm{a},j}{}^2 - (\sum_j d_{\mathrm{a},j})^2}{n(n-1)} \right] / 502\right)^{1/2} \qquad (7)$$

where:

n = the number of repeated measurements to a single target (range 3 to 6); and

$d_{\mathrm{a},j}$ = $ln(D_\mathrm{a})$ for the jth observation, $j = 1, \ldots,$ n.

This calculation of precision indicates the variability of repeated measurements to a target, but not any systematic bias that would cause the mean of those measurements to differ from the true distance. The quantity s_1 will overestimate the accuracy of reticle measurements of distance to the extent that systematic errors result in E(D_a) not equalling D. It represents the maximum precision potentially attainable using unbiased reticle measurements in 25× binoculars at sea, given the variability observed in simultaneous, replicated field measurements.

The second method of estimating σ in equation 6 incorporated bias as well as variability to estimate accuracy. In this method, σ was represented by the root mean squared error between logarithms of distances from reticles and radar, s_2, where:

$$s_2(\text{including bias}) = \sqrt{\frac{\sum (d_{2,k} - d_k)^2}{m}} \qquad (8)$$

and

m = total number of paired reticle and radar measurements;

$d_{2,k}$ = logarithm of distance from reticles (d_a or its corrected values, d_c, see below) for the k^{th} measurement, $k = 1, \ldots, m$; and

d_k = logarithm of distance from radar for the k^{th} measurement.

In equation 8, s_2 is calculated using an independent measurement (radar) of the true distance to estimate error in place of a (possibly biased) model estimate. The difference between the two estimates of variability in equations 7 and 8 is an indication of the amount of total variability in reticle measurements that could be due to a biased rather than random component.

In addition to its use calculating confidence intervals in equation 6, the square of s_2 is a measure of the goodness of fit of distances from reticles to radar. Lack of pattern in the residuals of the mean squared errors of logarithms indicated they were a superior measure of this fit compared to mean squared error of unlogged distances, for which residuals increased with distance from the ship.

Correcting distances for bias additional to refraction

Nine variables representing ship motion or other factors potentially influencing measurements using reticles were recorded in addition to the air temperatures and pressures used in the correction for refraction. These included sea surface temperature, year, ship and six factors influencing the motion or average height of the observation platform or target. Sea surface temperature was recorded to test its possible role in refraction. Year and ship effects were examined to see whether additional explanatory factors may have been present but not modelled. These nine variables were coded as: vessel (categorical variable: 1 = *Jordan*, 0 = *McArthur*); Beaufort sea state (continuous: recorded as integers 1-5); ship motion 1 (categorical: 1 = trough, 0 = downswell, 0 = upswell); ship motion 2 (categorical: 1 = upswell, 0 = downswell, 0 = trough); swell height (continuous: in feet); wind speed (continuous: in knots); sea surface temperature (continuous: in °C); year90 (categorical: 1 = 1990, 0 = 1992, 0 = 1993); and year92 (categorical: 0 = 1990, 1 = 1992, 0 = 1993).

The possible affects of these predictors on reticle measurements after correcting for refraction were modelled in two ways using least-squares regression. In each case, predictors were retained or discarded in the final models based on the small-sample Akaiki Information Criterion (AIC$_\mathrm{c}$ – Burnham and Anderson, 1998).

In the first set of regressions, the ratio of distance from (refraction-corrected) reticles to radar was the dependent variable predicted by combinations of the nine factors, their squares and pairwise interactions. Thus, the model for the ratio D_c/D of distance from refraction-corrected reticles (D_c) to distance from radar (D), was:

$$D_c/D = \mathbf{bx} + \varepsilon \qquad (9)$$

where:

bx = the product of the transposed vector of regression coefficients times the vector of predictor variables selected by AIC$_\mathrm{c}$; and

ε = a normally distributed variable with mean 0 and variance σ^2_ε.

In the second set of regressions, the logarithm of distance from reticles was the dependent variable and the logarithm of distance from radar, its square and pairwise interactions, were additional predictor variables. This model for the logarithm of distance from refraction-corrected reticles (d_c) was:

$$d_\mathrm{c} = \mathbf{bx} + \mathbf{b}_\mathrm{r}\mathbf{d}_\mathrm{r} + \varepsilon \qquad (10)$$

where:

bx = the product of the vectors of coefficients and predictor variables (potentially different from those in equation 9), other than factors including radar distance, selected by AIC_c; and

$\mathbf{b}_r\mathbf{d}_r$ = the product of the vectors of coefficients and predictor variables that include the logarithm of radar distance, its square, or interactions.

In the regressions represented by equation 10, true (radar) distance was one of ten possible factors explaining the variability in refraction-corrected distances from reticles. Including true distance as one of the predictors of the reticle value allowed the model to minimise additional variation in reticle measurements due to the other influences once distance was accounted for. In both sets of regressions, the possible combinations of potential predictor variables, pairwise interaction terms and factors squared, were many. Potential variables were added and discarded in stepwise up and stepwise down exploratory fashion, examining hundreds of models, but not all potential combinations were exhaustively explored.

Once a best model (minimum AIC_c) was selected for each of equations 9 and 10, rearrangement of terms to solve for true distance from the initial distance from reticles, independent variables and regression coefficients provided a correction for bias beyond the effects of refraction. This yielded two estimates by equations 9 and 10 of distance from reticle measurements corrected for bias. For equation 9, the model for corrected distance from reticles, D_m, was calculated in a simple rearrangement of the distance from refraction-corrected reticles, D_c, and the associated regression variables and coefficients, as:

$$D_m = D_c/(\mathbf{bx}) \tag{11}$$

with all variables defined as for equation 9.

For equation 10 the final rearrangement involved logarithmic transformations, and so required one additional adjustment to correct for bias in calculating antilogs. This adjustment was based on the property that if the logarithm of x is normally distributed with mean μ and variance σ^2, the expected value of x is $\exp(\mu+\sigma^2/2)$. Thus, the corrected distance from reticles, D_m, based on d_c in equation 10, was:

$$D_{m(k)} = E(X_k) = \exp\left[\frac{\mathrm{bx}_k - s^2/2}{\prod_{i=1}^{j} b_{r,i}}\right] \tag{12}$$

for the $k = 1$ to m paired reticle and radar measurements, where:

b = the vector of regression coefficients for the model under consideration, excluding $\mathbf{b}_r$ (equation 10);

x = the vector of (non-distance) explanatory factors for the model;

$b_{r,i}$ = the j regression coefficient(s) for factors including radar distance, its squares and interactions (coefficients for the $\mathbf{d}_r$ in equation 10);

and s^2 was calculated as:

$$s^2 = \frac{\sum_{i=1}^{m}[d_{c(k)} - (\mathrm{bx}_k)]^2}{m - df} \tag{13}$$

where:

df = dimension of $\mathbf{b}$ + 1 = the number of coefficients + 1;

k = 1 to m paired reticle and radar measurements (from equation 12) and all other variables are as defined for equation 10.

The calculation of s^2 in equation 13 differs from the squares of s_1 in equation 7 or s_2 in equation 8 in that the value in equation 13 is the deviation from a predicted value based on a model, while the earlier methods of calculating variance did not depend on modelled values. The value in equation 13 was used to correct for bias in calculating antilogs in equation 12, and in calculating an AIC_c for ranking the regression models. The final evaluation of goodness of fit of all the methods of calculating the reticle measurement, D_*, where $D_* = D_a$ or D_c or D_m, was based on minimising s_2, the deviation of D_* from radar, rather than minimising the variance of a model.

RESULTS

Accuracy and precision of distances measured with reticles

Reticle readings fell rapidly with increasing distance to the target (Fig. 1). The reticle values assigned to the targets ranged from 20.5 reticles for the closest to 0.1 reticles for those near the horizon. Thus, in a practical sense, distances could be measured using reticles in 25× binoculars to two-thirds of the way to the horizon, or about 8km. Distances farther than this could not be measured because the angles were too small. Equation 1 provided the best fit of reticles against radar among the formulae tested (Fig. 2). The biases evident in the fits of the Smith (1982; Fig. 2a) and Buckland *et al.* (1993; Fig. 2b) formulae match those discussed from a theoretical perspective in Lerczak and Hobbs (1998). The Bowditch (1995) formula underestimated distances (Fig. 2c).

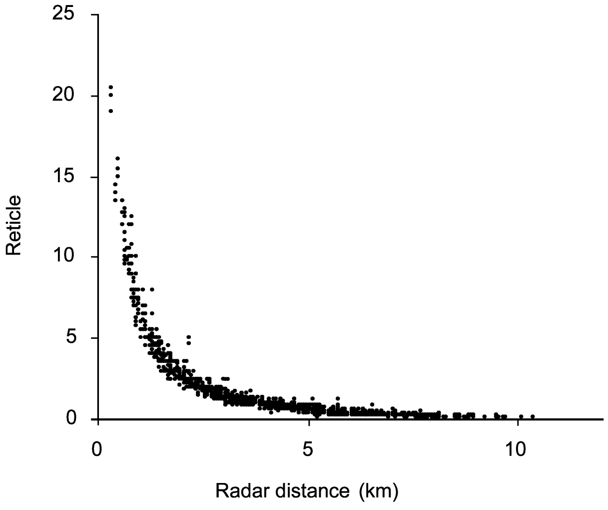
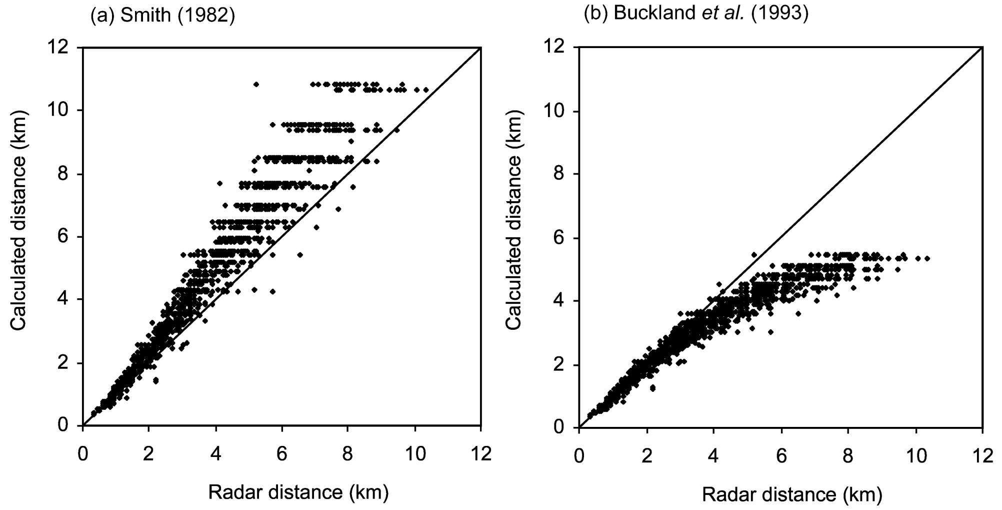
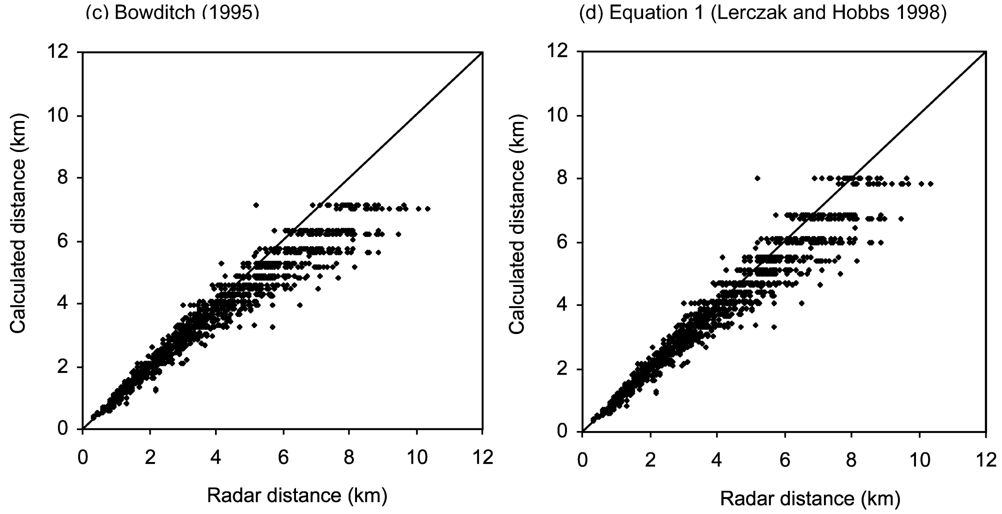


Fig. 1. Distribution of 25× binocular reticle values assigned by observers to targets versus the distances from radar in km to the targets.

Confidence intervals based on estimating σ by equation 8 (accuracy) were wider than those using equation 7 (measurement error). The measurement error (s_1), or


(a) Smith (1982)

(b) Buckland *et al.* (1993)


(c) Bowditch (1995)

(d) Equation 1 (Lerczak and Hobbs 1998)

Fig. 2. Distances calculated from reticles using the formulae in Table 1 versus radar. Diagonal lines indicate 1:1 relationship for unbiased reticle measurements of distance. Banding at large distances is due to the discrete values of reticles.

precision of replicate measurements of distance from equation 1 to a single target, was 0.0866 for both ships combined, a multiplicative standard error of 9.0%. This value corresponds to a 95% confidence interval from 0.8-1.2km for a target at 1km, and from 6.8-9.5km for a target at 8km (equation 6). Measurements from the *Jordan* were more precise than those from the *McArthur* (s_1 = 0.0834 vs 0.0909, respectively).

Table 2 lists the mean squared errors, or the variability including bias (calculated as the square of s_2), of the various methods of correcting distances from equation 1 compared to radar. The MSE of the uncorrected distances from equation 1 for the combined dataset was 0.0151 (Method #1 — Table 2), a multiplicative standard error of 13.1%. The uncorrected *Jordan* measurements were closer to radar (MSE = 0.0100) than those from the *McArthur* (MSE = 0.0220).

Although equation 1 produced distances from reticles that agreed well with radar on average, there was a slight tendency to underestimate distances to targets near the horizon (Fig. 2d). For the farthest targets, both ships combined, distance was underestimated by about 10%. A difference between ships was apparent (Figs 3 and 4), with reticle measurements made from the *Jordan* underestimating the distance to targets between 7.5 and 8.5km by 6% on average, or about 0.5km, and measurements from the *McArthur* underestimating these distances by 16%, or about 1.3km. This difference between the ships was unexpected, and suggests either variable refractive effects at the times the measurements were made, or differences between ships other than refraction, as examined below.

Correcting distances from reticles based on refraction

All methods of correcting for refraction improved the mean fit of distances from reticles to distances from radar when the measurements from both ships were combined (reduced the MSEs for the adjusted measurements, Table 2). Using locally measured temperatures and pressures with the standard temperature gradient of –0.0065°C m^{-1} produced an MSE for the combined ships of 0.0125 (Method #7 — Table 2), 83% of the variability for the uncorrected distances. Differences between alternative methods of estimating the terms in the refraction equations were less than the difference between uncorrected equation 1 and the corresponding value from any of the refraction-correction methods.

Air temperatures and pressures during the measurements covered similar ranges on each ship (Table 3). Temperatures were between 15.7 and 31.5°C and pressures were between 100.8 and 101.9 kPa. These values are typical for the eastern tropical Pacific from July to December (da Silva *et al.*, 1994). Air temperatures averaged 25.4°C on the *McArthur* and 25.5°C on the *Jordan*. Air pressure averaged 101.24 kPa on both ships.

Table 2

Accuracy achieved using equation 1 and its corrections (D_*). Results of six methods of calculating distance from reticles are each reported in three ways: once representing the two ships combined, and once for each ship individually. The adjustment terms for air temperature, pressure, and temperature gradient in equations 2-5 were as indicated for each method. Air temperatures and pressures were either those recorded during the measurements ('local') or averaged over the entire study ('average'). Relative reduction in variance is indicated as the ratio between the MSE from the previous column's correction Method (#s 4-18) over the uncorrected MSE (Method #s 1-3) for the same ship(s). Reduced bias is indicated as the ratio of the mean corrected distance from reticles ($D_* = D_a$, D_c, or D_m) over the mean distance from radar (D) approaches 1. NA = not applicable.

Method #	D_*	Distance equations	Air temp/ press	Temp gradient (°C m^{-1})	Ship(s)	MSE (s_2^2)	Relative reduction in variance	Mean D_* / D
1	D_a	Eq. 1	NA	NA	Both	0.0151	NA	0.957
2	"	"	"	"	*Jordan*	0.0100	NA	0.975
3	"	"	"	"	*McArthur*	0.0220	NA	0.932
4	D_c	Eq. 1, 2-5	Average	-0.0065	Both	0.0124	0.82	0.999
5	"	"	"	"	*Jordan*	0.0095	0.94	1.018
6	"	"	"	"	*McArthur*	0.0165	0.75	0.971
7	D_c	Eq. 1, 2-5	Local	-0.0065	Both	0.0125	0.83	0.997
8	"	"	"	"	*Jordan*	0.0095	0.94	0.997
9	"	"	"	"	*McArthur*	0.0165	0.75	0.950
10	D_c	Eq. 1, 2-5	Local	-0.02	Both	0.0132	0.88	0.997
11	"	"	"	"	*Jordan*	0.0093	0.92	0.997
12	"	"	"	"	*McArthur*	0.0188	0.85	0.950
13	D_c	Eq. 1, 2-5	Average	-0.02	Both	0.0132	0.88	0.997
14	"	"	"	"	*Jordan*	0.0092	0.92	0.996
15	"	"	"	"	*McArthur*	0.0187	0.85	0.951
16	D_m	Eq. 1, 2-5, 14	Average	-0.02	Both	0.0119	0.79	0.997
17	"	"	"	"	*Jordan*	0.0096	0.96	0.997
18	"	"	"	"	*McArthur*	0.0152	0.69	0.998

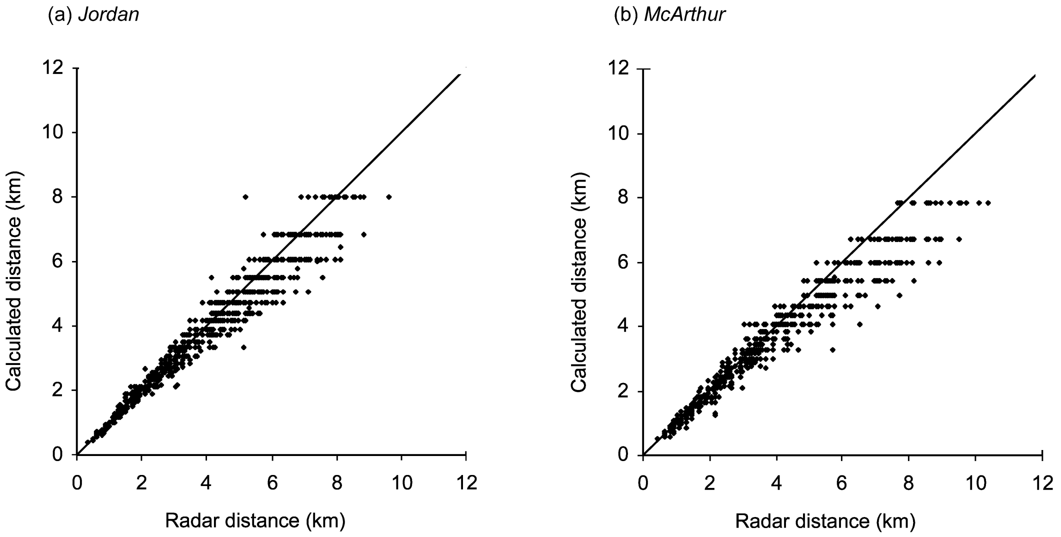


Fig. 3. Differences between ships in the fit of distances calculated from equation 1 (D_a) to radar (D). Uncorrected for refraction or other factors.

Refraction effects were insufficient to account for all of the underestimates of target distances using locally measured air temperatures and pressures with the standard temperature gradient for the *McArthur* measurements. Extreme air temperatures below 0°C, or pressures above 200 kPa (the normal maximum air pressure at sea level worldwide is 104.0 kPa, averaging 101.3 kPa – Fleagle and Businger, 1980), would be required with the standard temperature gradient to produce refractive effects from equations 1-5 sufficient to explain underestimates of the size recorded. The ratio of corrected distance to radar distance using local temperatures and pressures with the standard gradient was 0.950 for the *McArthur* (D_*/D from Method # 9, Table 2), a 5% underestimate on average (note that the bias was nonlinear and so was less than 5% for close targets and more than this for far targets). The *Jordan* ratio of 0.997 was very close to 1, indicating unbiased measurements of distance using reticles for targets at all distances from 0.3-8km from this ship once refraction was accounted for.

Since air temperatures and pressures recorded from the *McArthur* were far from what would be required to produce underestimates of the size observed, the only term left to explain the difference between ships if it was the result of refraction was the temperature gradient, ΔT / Δh. The locally-measured air temperatures and pressures produced 1/r values between 2.38×10^{-8} and 2.67×10^{-8} when combined with the standard temperature gradient. The transformed dip values, α_c, using these ranges were between

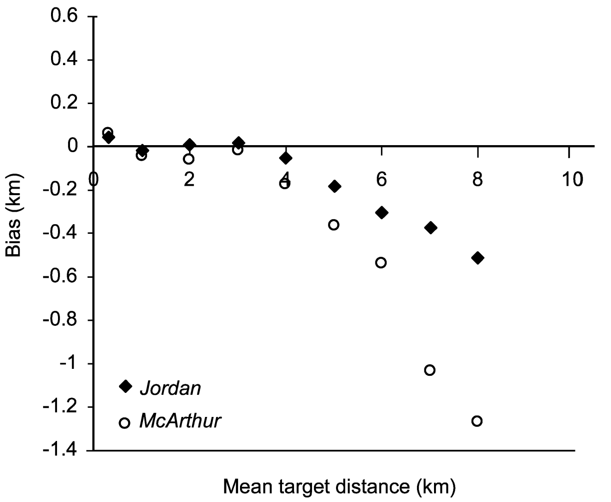


Fig. 4. Bias as a function of distance. Mean differences (bias) between distances measured with reticles (equation 1) and by radar. Measurements are grouped in 1km intervals around each of km 1 to 8, and from 0 to 0.5km, separately for the two ships.

0.00165 and 0.00169 radians. The target angles, θ_c, were increased relative to θ by approximately 10^{-8} radians. The effects of these small angular increases on the calculated distance were most evident for targets near the horizon.

Table 3

Number (N) of paired radar and reticle measurements of distance to targets taken at the given date, water temperature, air temperature, air pressure and ship. Temperature gradients were estimated by fitting $\Delta T/\Delta h$ in equation 3 to minimise the differences in distances from reticles and radar (s_2). Sorted by $\Delta T/\Delta h$ for each ship.

Date yymmdd	N	Water temp °C	Air temp °C	Air press kPa	Fitted $\Delta T/\Delta h$ °C m^{-1}
David Starr Jordan					
900922	55	24.6	21.5	101.29	-0.049
930910	54	20.6	20	101.13	-0.047
930817	53	30	31.5	101.08	-0.046
930731	46	18.1	19	101.74	-0.04
930910	61	20.5	20.2	101.72	-0.039
931017	39	30.5	30	100.87	-0.036
930922	13	19.2	19.5	101.40	-0.031
900825	56	29.5	29.2	101.20	-0.031
900928	63	29.2	27.5	100.80	-0.023
930922	63	19.1	21.5	101.38	-0.021
931017	54	30.2	29.8	100.80	-0.013
930817	60	30.1	30	101.10	-0.009
921009	70	26.7	24.5	101.18	-0.008
920825	114	30.1	29.8	101.20	0.008
920819	23	29.9	28.1	101.18	0.01
930731	90	18.3	20.8	101.75	0.029
McArthur					
901119	42	23.6	26.2	101.38	-0.051
920825	53	31.4	31.1	101.11	-0.014
930728	47	26.3	21	101.50	-0.004
900808	83	26.5	27	101.26	0.001
901119	30	23.6	25	101.29	0.002
900915	39	24.8	24.2	101.31	0.006
901124	102	24.4	26.1	101.16	0.009
920825	53	31	30.9	101.05	0.011
901124	23	24.3	24	101.28	0.012
930821	54	12.5	15.7	101.91	0.013
900821	48	28.3	30.2	100.97	0.024
901119	16	23.6	26.5	101.32	0.034
900821	60	28.3	29	100.84	0.045
900905	12	27.9	26.9	100.99	0.052

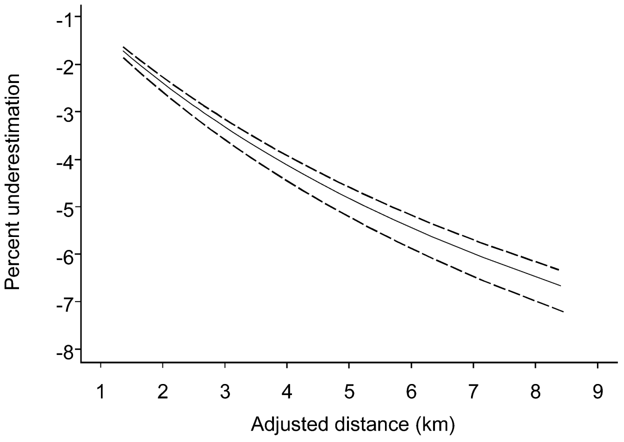


Fig. 5. Sensitivity of the underestimate of distance due to the ranges of air temperatures and pressures measured in this study. The vertical axis represents $1 - D_a/D_c$. The solid line was calculated using average temperatures (25.2°C) and pressures (101.24 kPa). The dashed lines indicate the high and low values around this average due to the range of air temperatures and pressures recorded. All calculations used the standard temperature gradient.

Fig. 5 shows the effect this range of $1/r$ values had on correcting distances from reticles for refraction from a 10.4m platform. By 8km, the uncorrected distance from equation 1 varied between about 93% and 94% of the corrected value. The approximately 1% difference attributable to local conditions suggested a standard correction based on average conditions would provide most of the improvement obtainable using local temperatures and pressures (see also Leaper and Gordon, 2001).

Using the average 1/r value of 2.48×10^{-8}, calculated from mean temperature and pressure and the standard temperature gradient (-0.0065°C m^{-1}) from both ships reduced the MSE to 0.0124 for the combined measurements (Method #4 — Table 2), a greater apparent improvement than achieved using local measurements of temperature and pressure. This apparent improvement using averaged rather than locally measured values appeared to be a spurious overcorrection of the underestimate from the *McArthur* due to inaccuracies associated with the use of the standard temperature gradient as discussed below. The *Jordan* ratio of corrected to uncorrected distances indicated a slight overcorrection when average temperatures and pressures were combined with the standard gradient for the refraction adjustment (D_c/D = 101.8%, Method #5 — Table 2). The use of the standard temperature gradient as an average value for the eastern tropical Pacific appears to overestimate the bias due to refraction, as follows.

Fitting the temperature gradient: Average vs standard

Temperature gradients in this study were fitted from observed refractive effects rather than directly measured. Two questions concerning the temperature gradient in equation 3 were: (1) how likely does the standard value of –0.0065°C m^{-1} appear to be a mean value for the gradient in the eastern tropical Pacific given the measurements made during the study; and (2) could different values of this parameter at the times of measurement explain the difference in the bias of reticle measurements observed between the ships?

Sixteen series of measurements were made from the *Jordan* during a single period under the same temperature and pressure (made over 11 different days in 3 years) and 14 such series were made from the *McArthur* (8 days in 3 years). The number of measurements in a series varied from 12 to 114 (Table 3). Estimating the local value of the $\Delta T / \Delta h$ term in equation 3 by allowing it to be an adjustable variable selected to minimise s_2 produced daily temperature/height gradients ranging from –0.05-0.03°C m^{-1} for the *Jordan* and from –0.05-0.05°C m^{-1} for the *McArthur* (Table 3). Although these ranges were similar, 11 of the 14 *McArthur* fittings produced positive temperature gradients, while only 2 of the 16 *Jordan* gradients were positive. The average gradient from the *Jordan* was –0.02°C m^{-1}, while the *McArthur* average was 0.01. The 95% confidence interval for the temperature gradient from the *Jordan* measurements, –0.0107 to –0.0333°C m^{-1}, did not include the standard value of –0.0065. The confidence interval for the gradient from the *McArthur* was much wider, 0.0233 to –0.0334, and included the standard value.

The estimated gradients fit this way would be different for the two ships if refractive conditions were different at the times of measurement, or if non-refractive biases were also present that were inadvertently incorporated into the fittings. In evaluating the use of the standard vs a fitted temperature gradient in parameterising the refraction terms, the possibility of bias other than refraction needs to be considered. If reticle measurements underestimated distances from factors in addition to refraction, fitting the gradient term to these measurements would produce a positive bias in the estimated gradient, overfitting additional error than just the portion due to refraction.

This method of calculating the local temperature gradient would not be feasible under normal survey conditions, when the true distances would not be known and so the local gradient could not be estimated for each sighting. Under normal circumstances an average gradient (either calculated for the region or using the standard value) would need to be used.

There are three lines of evidence against different temperature gradients being the explanation for the differences in bias between the ships. First is the similarity between ships in the environmental variables that it was possible to measure directly (Table 3). Second is the greater variability remaining in the *McArthur* measurements compared to those from the *Jordan* even after allowing gradient to be a free variable. Third is that negative gradients are more common than positive gradients. Together these suggest the *Jordan* mean gradient of –0.02°C m^{-1} is probably a better value for the average rate of change in air temperature in the first 10m above the sea surface in the eastern tropical Pacific in July-December than either the *McArthur* value, or the –0.0065°C m^{-1} value based on a standard atmosphere.

Using a temperature gradient of –0.02°C m^{-1} with the mean measured temperature and pressure resulted in a smaller adjustment to distances from reticles than the standard gradient. Correcting the reticle measurements for refraction using average temperature (25.2°) and pressure (101.24 kPa) and the fitted gradient (–0.02°C m^{-1}) produced a mean ratio of refraction-corrected distance from reticles to radar (D_c/D) of 0.996 for the *Jordan* (Method #14 – Table 2), close to a 1 to 1 relationship on average. Using local measurements of air temperature and pressure with either the standard or fitted gradient improved this *Jordan* ratio slightly, to 0.997 (Table 2). For the *McArthur* the mean ratio after correcting for refraction using average air temperatures and pressures and the (*Jordan*) fitted gradient was 0.951, indicating a continued underestimate of distances from this ship. The distance underestimates from the *McArthur* were apparent for targets farther than 4 or 5 kilometres, while the *Jordan* measurements appeared unbiased after correcting for refraction (Fig. 6).

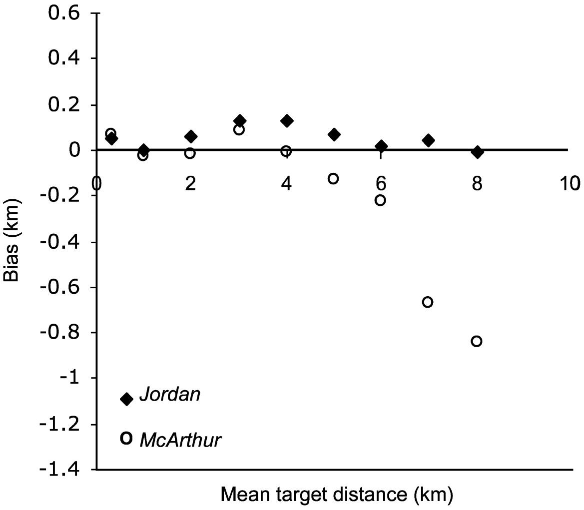


Fig. 6. Bias following correction for refraction. Mean difference by ship between distance from refraction-corrected reticles (D_c) and radar for targets grouped in 1 km intervals. Corrections used average temperature (25.2°C) and pressure (101.24 kPa) and the fitted temperature gradient (–0.02 °C m^{-1}) to adjust the reticle measurements (Methods #14 and #15 in Table 2).

Regression models: Ship, Beaufort, swell and interaction effects

All ratio models based on equation 9 displayed a nonlinear relationship in the errors with target distance. Target distances tended to be overestimated at middle ranges and underestimated at far ranges. This suggested predicting distance from reticles with radar distance as one of the independent factors, rather than assuming the ratio was constant as in the ratio models (i.e. equation 10 rather than equation 9). The best model, selected based on minimum AIC_c, for the logarithm of refraction-corrected distance from reticles, d_c, (equation 10) was:

$$d_c = b_0 + b_1(\mathrm{fv})^2 + b_2\mathrm{sv} + b_3\mathrm{f}^2 + b_4\mathrm{fv} + b_5\mathrm{y} + b_6\mathrm{w} + b_7\mathrm{w}^2 + b_8 d + b_9 d^2 \qquad (14)$$

where:

f = Beaufort sea state;
v = vessel (1 = *Jordan*, 0 = *McArthur*);
s = swell height in feet;
y = 1 for year 1990, 0 otherwise;
w = wind speed in knots;
d = logarithm of distance, D, from radar;
and b_0 to b_9 are reported in Table 4.

Rearrangement of this model using the quadratic equation to solve for the refraction- and regression-adjusted distance, D_m, produced the correction:

$$\mathrm{Dm} = \exp(\frac{-b_6{}^{-1} - \sqrt{b_6{}^{-2} - 4b_5{}^{-1}c}}{2b_5{}^{-1}} \qquad (15)$$

where:

$$\mathrm{c} = - \left[\frac{d_c - b_0 + b_1(\mathrm{fv})^2 + b_2\mathrm{wv} + b_3\mathrm{f}^2 + b_4\mathrm{fv} + b_5\mathrm{y} + b_6\mathrm{w} + b_7\mathrm{w}^2 - s^2/2}{b_8 b_9} \right]$$

Table 4

Coefficients for empirical regression model (eq. 14) predicting logarithm of refraction-corrected reticles (d_c) from logarithm of distance (d), or rearranged (eq. 15) to predict model distance (D_m) from refraction-corrected reticles.

Coefficients	Factors	Values
b_0		-0.01625
b_1	(Beaufort*vessel)^2	0.01293
b_2	swell*vessel	0.009993
b_3	Beaufort^2	-0.005584
b_4	Beaufort*vessel	-0.03681
b_5	year90	0.06335
b_6	wind	0.009259
b_7	wind^2	-0.0003381
b_8	d	1.045
b_9	d^2	-0.04616

with s^2 as defined in equation 13. This model had the lowest MSE for the combined ships, 0.0119, of any of the corrections in Table 2, with a multiplicative standard error of 11.5%. The ratio of distances from the best model to radar (D_m/D) was 0.997 over all target distances, and the downward bias remaining in the refraction-only corrected *McArthur* measurements (Fig. 6) was removed (Fig. 7).

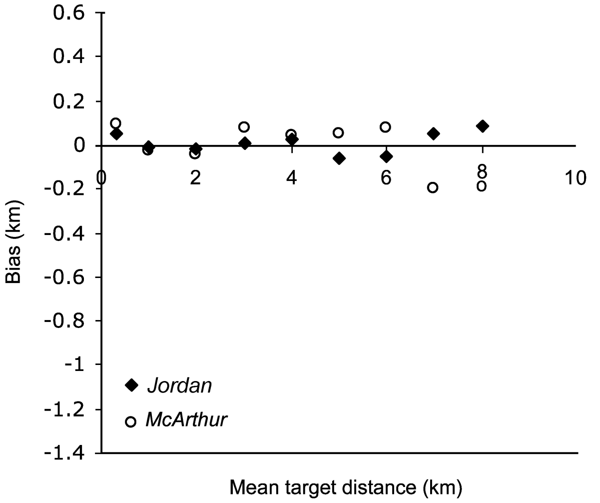


Fig. 7. Bias following correction by regression modelling (equation 15). Mean difference by ship between distance from regression-corrected reticles (D_m) and radar for targets grouped in 1km intervals. Reticles were corrected for refraction using average temperatures and pressures and the fitted gradient before modelling additional, ship-specific factors (equation 14) and solving for empirically-corrected distance (equation 15).

The six factors in equation 14 interact in a complex, nonlinear fashion to produce reticle values from the true distance combined with three factors affecting ship motion (Beaufort, swell height and wind speed), and two categorical variables, one representing ship, and the other a year effect in 1990. The inclusion of the latter two variables indicated that a complete explanation of the difference in measurement bias either included more factors or had a different structure than the models considered in this study. The empirical model distinguished between some of the important and unimportant factors and was useful in a predictive sense. It indicated that relative to the *Jordan*, the *McArthur* bias increased with Beaufort, swell height and wind speed. Water temperatures and the ship's course relative to the swell direction (categorical motion codes ship motion 1 and ship motion 2) were not important in reducing the variance of the estimates.

Table 5 and Fig. 8 summarise the precision and accuracy for the three methods of calculating distance considered in this paper. Reticle measurements from both ships were grouped into eight sets or blocks. Each block was composed of all radar measurements within a 1km interval, centred on integer distances from 1-8km. The 95% confidence interval (equations 6 and 8) and mean bias (D^*/D) of distance from reticles against radar was calculated for each of the blocks. The product of each confidence limit and mean bias illustrates the improvements obtained using the corrections.

The results from uncorrected equation 1 included all the sources of bias and variability that were present during the tests. These had little effect on the precision and accuracy for targets closer than about 4km. Beyond 4km, the confidence intervals widened and there was a tendency to underestimate distance. The refraction and empirical regression corrections in Fig. 8 show the improvements achieved in measurements of radial distance using the methods discussed in this study. The 95% confidence intervals improved both in terms of precision and reduced bias.

DISCUSSION

Accuracy and precision

This study identified the accuracy with which distances can be measured from ships using the reticles in 25× binoculars, provided empirical support for the theoretically derived equation 1 over alternative equations, and explored the effect of refraction on distance measurements in the eastern tropical Pacific Ocean in July-December. It also quantified small differences between two ships in the precision and bias of these measurements.

In light of these findings, the first questions a researcher using angle-based measurements of distance should ask are (1) how far from the sighting platform will the sightings be and (2) what level of accuracy is required to meet the research objectives? The underestimate of distances from uncorrected reticle measurements effectively disappeared for objects closer than about 4km, or a third of the way to the horizon, for both ships in the study. For measurements closer than this the practical effect of the corrections would be negligible, and distances computed with equation 1 should suffice. This is true of most of the radial sighting distances obtained during SWFSC field surveys. Researchers measuring distances nearer the horizon with optical devices who require accuracy better than the 6-16% mean underestimate for targets at 0.1 reticles may want to consider the types of corrections discussed here, however.

The accuracy and precision of distances measured at sea for biological studies has been assessed in two other studies at shorter distances (0-2km) than tested in this study (0-8km). Using video and still cameras, Gordon (2001) reported accuracy as absolute mean percentage error from 2.6-6.4%. This included error due to the independent measurement of range by non-differential GPS or laser range-finding binoculars. Percentage error over a similar range of distances in this study was 8.2%. Video and photographic methods are currently limited in range by image quality (Leaper and Gordon, 2001). Distance measurements made by eye over a range of 0-2km had a negative bias of 9% at close distances and less bias at 2km (Schweder, 1997). The multiplicative standard error of

Table 5

Precision and accuracy at eight distances using three methods of computing distance. Bias (D_*/D), multiplicative standard error ($SE_* = (\exp(s_{2*})-1)$), lower (L_*) and upper (U_*) 95% confidence limits are shown at each distance for each method. The three methods, indicated by subscripts, are: *a* = without correction for refraction (eq. 1), *c* = with correction for refraction (eqs. 2-5), and *m* = with empirical regression correction for other factors (eq. 15). *n* = number of measurements within each distance category.

Midpoint of radar distances (*D*)	*n*	Uncorrected reticles (*a*)				Refraction-corrected (*c*)				Regression-corrected (*m*)			
		D_a/D	SE_a	L_a	U_a	D_c/D	SE_c	L_c	U_c	D_m/D	SE_m	L_m	U_m
1	148	1.04	12.8	0.8	1.3	1.05	12.7	0.8	1.3	1.05	11.6	0.8	1.3
2	209	0.99	12.0	1.6	2.5	1.00	12.0	1.6	2.5	0.98	12.1	1.6	2.5
3	245	1.00	9.8	2.5	3.6	1.02	10.0	2.5	3.7	1.01	9.9	2.5	3.6
4	249	0.98	10.3	3.2	4.7	1.00	10.0	3.3	4.8	1.01	10.1	3.3	4.9
5	234	0.96	12.0	3.8	6.0	0.98	11.1	4.0	6.0	1.00	11.2	4.1	6.2
6	205	0.93	13.0	4.4	7.1	0.96	11.6	4.6	7.1	1.00	11.0	4.9	7.4
7	136	0.91	16.0	4.8	8.5	0.94	14.1	5.1	8.5	0.99	11.5	5.6	8.6
8	88	0.87	18.8	5.0	9.8	0.90	16.4	5.4	9.7	0.98	12.3	6.2	9.8
Means		0.96	13.1			0.98	12.2			1.00	11.2		

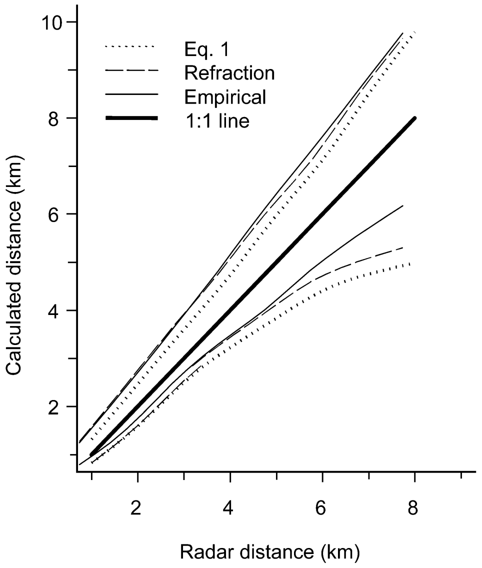


Fig. 8. 95% confidence intervals for measurements of distance using reticles, from Table 5. The 1:1 line indicates measurements without variance or bias.

distances estimated by eye (36%) was three times the value for distances measured by binocular reticles in this study (12%).

Refraction

Effects of refraction in measuring distance were responsible for small but measurable underestimates of distances beyond about one third the distance to the horizon. Corrections to account for refraction removed the downward bias from one ship but not the other. The corrections for refraction incorporated either the locally-measured or mean air temperature, air pressure and temperature gradient into a single term, 1/*r*, which was then used to modify the two angles associated with each sighting. In the typical circumstance of decreasing air density with height, both angles were somewhat reduced relative to their geometrically expected values in the absence of refraction.

Refraction in the study region appeared to be less than predicted from the temperature gradient based on a standard atmosphere. The standard gradient is a worldwide average and includes polar, terrestrial and other areas where the average rate of change in temperature with height above the earth's surface might differ from the study region. The mean gradient calculated by empirically fitting the $\Delta T / \Delta h$ term in this study was more negative than the standard one, indicating a stronger decrease in temperature with height in the first 10m above sea surface in the study area than the standard value. This stronger gradient produced less refraction by reducing the change in air density with height, relative to the standard gradient. Refraction accounted for about half of the underestimate of distance (approximately 5%) for the farthest measurements in this study.

Refraction effects would be greater than in the eastern tropical Pacific in regions of colder air temperatures, higher pressures and/or a less negative temperature gradient. Leaper and Gordon (2001) calculate an underestimate of about 10% for measurements made to 12km at air temperature 0°C, pressure 100.0 kPa, and temperature gradient of 0°C m^{-1}. A positive temperature gradient above the sea surface would cause even more of an underestimate.

Extreme gradients of air temperature produced numerically undefined results in equations 2-5. Gradients between about –0.519 and 0.027°C m^{-1} produced defined solutions with the average temperature and pressure recorded in the eastern tropical Pacific. For more extreme combinations of air temperature, pressure and air temperature gradient, the refraction solutions became unstable, reversing direction with changing gradient as the limits were approached before becoming undefined. For instance, the solution was undefined at a gradient of –0.520, reduced the distance to 77% of its uncorrected value at a gradient of –0.519, had no affect on distance when gradient was approximately –0.514, and increased the distance to 148% of the uncorrected value when the gradient was –0.423. From –0.423 to –0.034 the effect again decreased to zero and then increased as the gradient became less negative than –0.033. Analogous behaviour in the physical system may correspond to mirage or other visual distortions (Fraser and Mach, 1974; Fleagle and Businger, 1980).

The maximum underestimate produced by the refraction equations, other than near the limits of the range of gradients that produce extreme and unstable numerical results as described above, was about 13%. For example, distances at 0.1 reticle from a 10.4m platform were reduced by this much at air temperature 0°C, pressure 1012 hPa and a $\Delta T / \Delta h$ of +0.01°C m^{-1}. Changing any of the three environmental terms in either direction caused less of an underestimate.

The correction for refraction warrants consideration anytime distance measurements are to be made near the horizon with an angle-based optical device if mean accuracy better than about 5-13% (the range of adjustments obtainable from equations 2-5 using realistic temperatures, pressures and gradients) is desired. Refraction will be greatest in cold air temperatures with a positive gradient near the surface. Researchers conducting studies under such conditions could use equations 2-5 with the standard gradient to estimate the likely magnitude of refraction expected for the region. If this suggests inaccuracies due to refraction larger than acceptable for the research objectives, field measurements to estimate local temperature gradients may be warranted. Optical measurements of distance could be calibrated against targets of known distance. For a stationary platform such as a theodolite on a clifftop, local refractive conditions might be checked regularly against a buoy or similar target. For shipboard measurements, a calibration system using radar or similar range-finding equipment would likely need to be used.

Swell, Beaufort, wind and ship effects

The regression modelling was to clarify and explain any additional features affecting reticle measurements from ships at sea beyond the effects of refraction. Reticle measurements from the *McArthur* underestimated distances more than expected from refraction alone. This was the largest portion of the underestimate from both ships combined, both before and after refraction had been accounted for. The regression model suggested that biasing factors in the underestimate of distances remaining after correcting for refraction were a complex interaction among Beaufort Sea state, swell height, wind speed and ship. There was also a small year effect, with 1990 differing from 1992 and 1993. None of these effects were large individually. The average difference between the distance predicted by the empirical regression model and that calculated from reticles corrected for refraction only was 0.15km. The average difference due to the year effect was less than 0.001km.

The presence of both year and ship effects in the empirical model is an indication that the physical factors included in the modelling and/or the model structures considered did not completely explain the underestimate of far distances from the combined ships. The year effect was small, but the difference between the ships that appeared as three interaction terms in the empirical model suggests that the results of the regression modelling should not be automatically applied to new, uncalibrated platforms. New platforms would require additional field measurements to targets at far distances to determine whether bias beyond the effects of refraction is present.

The *McArthur* was the more active of the two ships under similar sea conditions. If differences in ship responsiveness resulted in observers reading reticles differently as ship motion increased, for instance tending to read more at the top of a swell on the *McArthur* than on the *Jordan*, the effective height on the *McArthur* would increase and the results observed in the data would be obtained. Gordon (2001) discusses the opposite effect of ship rolling or heeling, which will result in distances being overestimated. This heeling effect was not apparent in the data used here, however.

As a check on the ‘effective height’ of the ships, platform height was used as an adjustable variable minimizing s_2 (equation 8) for each ship, using average temperatures and pressures and the fitted gradient. For the *Jordan* this produced a fitted height of 10.8m, close to the measured 10.7. For the *McArthur*, a minimum s_2 of 0.1256 was obtained at a height of 11.2m, compared to the s_2 of 0.1369 for these values with the measured height of 10.4m. Using the standard gradient, the fitted heights were 10.5m and 10.9m for the *Jordan* and *McArthur*, respectively. The reason for the 0.5 to 0.8m difference between effective height and measured height on the *McArthur* is unclear, but could be due to differences in ship responsiveness to sea state or some other unmeasured variable. Even with the empirical height adjustment, measurements on the *McArthur* were more variable than those on the *Jordan*.

Barlow *et al.* (2001) examined factors affecting the perpendicular sighting distances (= radial distance × sine of the horizontal angle from the ship’s trackline) to marine mammals from the two ships used in this study. Their results were interpreted in terms of whether or not particular species were seen with distance from the trackline under different sighting conditions. The effect of sighting conditions on perceived (radial) sighting distances in this study even after a target was located suggests another possible avenue by which perpendicular distances could be influenced. This effect would be the same regardless of species, but would differ by ship.

Barlow *et al.* (2001) found both swell and Beaufort sea state to be important factors affecting the perpendicular sighting distances of marine mammal sightings from the two ships, but did not find a ship effect. As sightings are made closer to the ship’s trackline, differences in radial distance become smaller on an absolute scale relative to perpendicular distance (sightings on the trackline are all 0km perpendicular, regardless of radial distance). This would decrease the effect of differences in radial distance.

ACKNOWLEDGEMENTS

We thank the observers who made the reticle measurements, and the officers and crew of the NOAA Ships *McArthur* and *David Starr Jordan* for providing radar distances to the targets, conducting the small boat operations, and overall professional support. Daniel Fink produced and edited the initial database from the field measurements. We would also like to thank Russell Leaper and Jonathan Gordon for discussion of the refraction calculations. The manuscript was improved following suggestions by Karin Forney, Rod Hobbs, André Punt and an anonymous reviewer. The analysis portion of this study was made possible through funding by the International Dolphin Conservation Program Act to the Southwest Fisheries Science Center.

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Date received: April 2003.
Date accepted: July 2003.

Overview of minke whale sightings surveys conducted on IWC/IDCR and SOWER Antarctic cruises from 1978/79 to 2000/01

KOJI MATSUOKA*, PAUL ENSOR+, TAKASHI HAKAMADA*, HIROYUKI SHIMADA#, SHIGETOSHI NISHIWAKI*, FUJIO KASAMATSU** AND HIDEHIRO KATO#

Contact e-mail: matsuoka@cetacean.jp

ABSTRACT

The IWC Southern Hemisphere minke whale assessment cruises (IDCR and SOWER) have been conducted since 1978/79 in the Antarctic regions of all six IWC management Areas for baleen whales (covering all, or more recently, part, of one Area each season). During the 23-year history of the programme to 2000/01, a total search distance on primary effort of 70,340 n.miles has been achieved during 2,448 ship-days in the Antarctic. A total of 6,027 primary minke whale school sightings were recorded. Over the years, there have been two major and some minor modifications to the survey design as a result of the development of survey procedures. These developments represent the best possible compromise between statistical needs and logistics. This paper outlines the most significant modifications that have occurred to the research equipment, protocols and data collection. Some preliminary results are also included. From 1985/86, the beginning of the second circumpolar set of cruises, the programme (initially a combination of Discovery marking and sightings) became essentially a dedicated line-transect systematic sightings cruise only. Modification of the survey design from the third circumpolar set of cruises (from 1991/92), to cover the whole region south of 60°S in the Antarctic resulted in a change in emphasis of the latitudinal coverage, especially in Areas I, II, III and V; the implications of this are discussed. The paper also describes: guidelines for the identification of minke whales; methods used for assessment of duplicate status in passing mode with independent observer; the protocol used for conducting the estimated angle and distance experiment; and methods used for determining the southern boundary of the research area (ice-edge). The programme has also enabled collection of biopsy, photo-identification, oceanographic and acoustic samples, and can be adapted to research programmes in other parts of the world. It is concluded that the programme has developed and established standard sighting procedures and has also improved the precision of whale identification standards in the Southern Ocean.

KEYWORDS: MONITORING; POPULATION ASSESSMENT; SURVEY-VESSEL; ANTARCTIC; ANTARCTIC MINKE WHALE; DWARF MINKE WHALE; SOWER

INTRODUCTION

This paper presents an overview of the minke whale (primarily the Antarctic minke whale *Balaenoptera bonaerensis*, with some dwarf minke whales, *B. acutorostrata*) sighting surveys component of the International Whaling Commission/International Decades of Cetacean Research (IWC/IDCR; 1978/79 until 1995/96) and IWC/Southern Ocean Whale and Ecosystem Research (IWC/SOWER; since 1996/97 – see review in IWC, 1997) austral summer Antarctic cruises, noting changes across years. With the start of the SOWER programme, a blue whale research component was added but all of the Antarctic cruises have been primarily minke whale assessment cruises designed for abundance estimation (Butterworth *et al.*, 1994). The first circumpolar series, hereafter CPI (i.e. all six management Areas covered longitudinally) was between 1978/79 and 1983/84, CPII was between 1984/85 and 1990/91, while CPIII is currently incomplete (from 1991/92). During the early years, there was a major change in emphasis of the cruises, with a shift from marking to sightings surveys. The sightings survey methodology underwent early development and standardisation phases during which many experiments were conducted and the current survey procedures were developed.

This paper does not attempt to provide a comprehensive description of all aspects of this research programme Details of the Soviet vessel activities (ice-edge mapping etc.), oceanographic survey (Shimada *et al.*, 1997) and the blue whale research (IWC, 1997), are not covered in this summary. The survey procedures, experimental design and the equipment developed and used during the first 10 cruises (1978/79 to 1987/88) are summarised in Joyce *et al.* (1988). After the first 10 years, the survey protocol became largely routine with no major changes but some refinement.

One motivation for the development of this paper is the observation that although the full third circumpolar set of cruises is not yet complete, the indications are that the abundance estimates for the set will be appreciably lower than those for the earlier surveys (IWC, 2001; Branch and Butterworth, 2001b). As part of ongoing efforts to determine whether this represents a real change in abundance or is a consequence of some other factors, this paper therefore describes some of the key areas where changes in protocol and data recording have been made.

SURVEY ITEM

Research area

First two circumpolar series (1978/79 to 1983/84, 1985/86 to1990/91)

One of the IWC Antarctic Management Areas (Fig. 1, see Donovan, 1991) was surveyed during each cruise in CPI and CPII. In each Area, longitudinal coverage took precedence over latitudinal coverage. The northern boundary of each Area was established around 60°S-61°S in Areas IV and VI, and at 62-65°S in Areas I and III, and 58-59°S in Areas II and V (Fig. 2a-f).

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* *The Institute of Cetacean Research, 4-5, Toyomi, Chuo, Tokyo 104-0055, Japan.*
+ *Governors Bay, Lyttelton RD1, New Zealand.*
# *National Research Institute of Far Seas Fisheries, 5-7-1, Orido, Shimizu, Shizuoka 424-8633, Japan.*
** *Formerly of: Marine Ecology Research Institute, 3-29 Jinbo, Kanda, Chiyoda, Tokyo 101, Japan. Deceased 22 July 2001.*

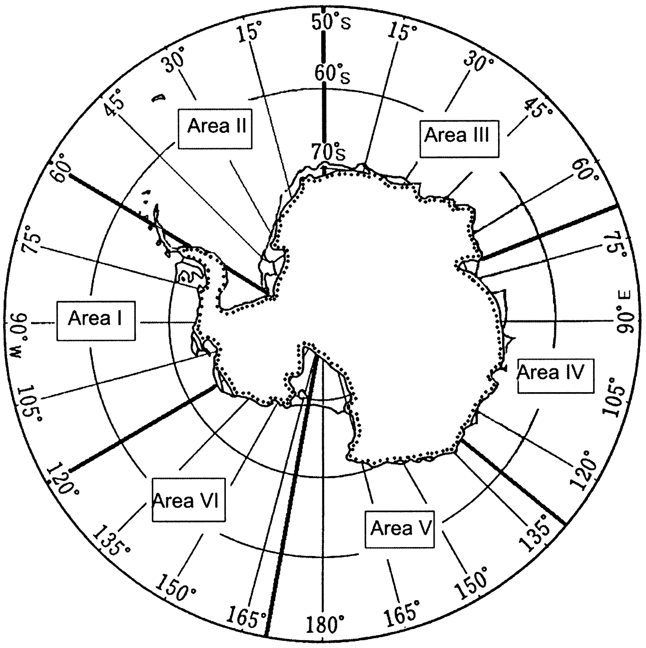

Fig.1. The IWC Antarctic Areas for the management of baleen whale species (except Bryde's whale).

Third circumpolar series (1991/92 to the present)
During CPIII, on all cruises since the 1991/92 cruise, priority has been given to latitudinal coverage (from the ice-edge to 60°S) instead of longitudinal coverage (i.e. there was additional coverage of northern waters compared with the first two circumpolar cruises). As a consequence of this modification (the aim was to correct for the bias of animals between 60°S and the northern boundary of earlier surveys), there has been an expansion in the width of the southern stratum (Fig. 2a-f).

Research vessels

Over the years, a total of eight vessels have been involved in the cruises. Six of the ships equipped with sighting platforms were provided by the Government of Japan: *Kyo Maru 27* (K27); *Toshi Maru 11* (T11); *Toshi Maru 16* and *18* (T16 and T18); and the *Shonan Maru* and *Shonan Maru 2* (SM1 and SM2). Two vessels were provided to the programme by the USSR: the *Vdumchivy 34* (V34) and the *Vderzhanny 36* (V36). One Soviet vessel was predominantly used for research in the vicinity of the ice-edge and to map the ice-edge between 1980/81 and 1986/87. SM1 and SM2 have been engaged in this programme for over 20 years consecutively (i.e. since 1981/82) and most of the sightings data has come from these vessels. A summary of ship deployment for each cruise is presented in Table 1. The specifications of the Japanese research vessels are shown in Appendix 1. Photographs of the research vessels are shown in Appendix 2.

Transit survey and homeports

On each cruise, a systematic sightings survey was conducted from homeport to Antarctic research area and vice versa using the same methodology as on the cruises. 'Closing' mode was used unless a schedule problem occurred in which case 'passing' mode was substituted (see below for definitions). The pre- and post-cruise meetings were held in the homeports and the ships re-fuelled and re-provisioned. In some cases, the Soviet research vessel met with a Soviet ship for fuel and supplies. The cruises have used a total of 10 homeports in 7 nations (Table 1).

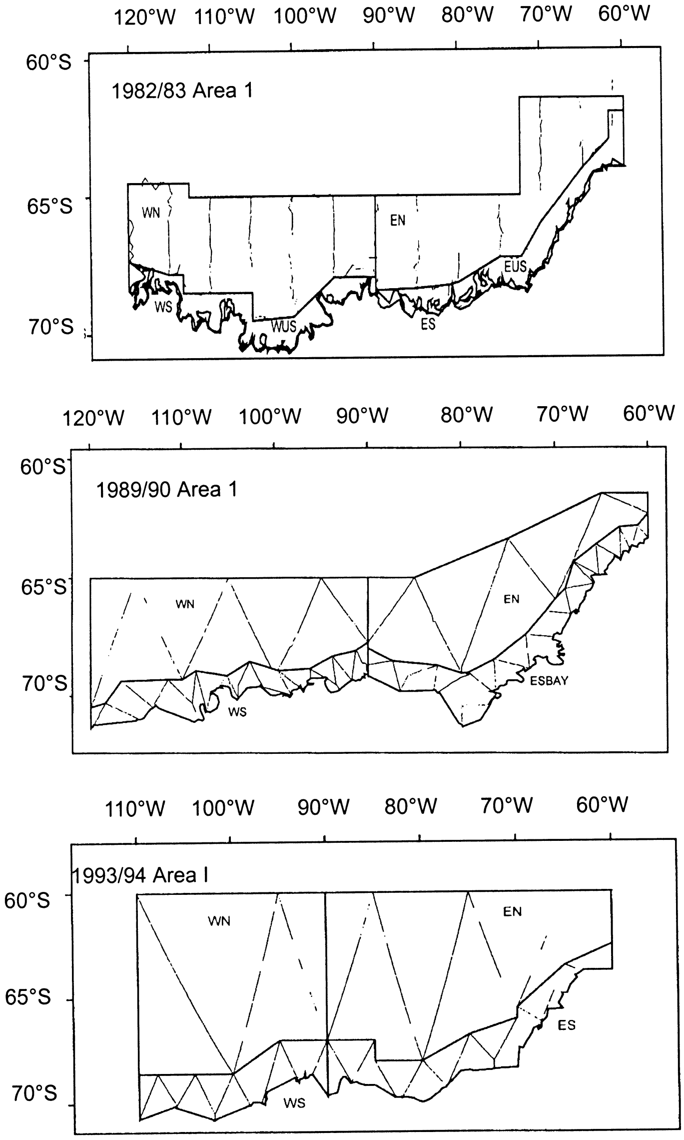

Fig. 2a. Strata surveyed in Area I throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b).

Research periods

Table 2 shows the overall schedule for each cruise, comprising the schedule of the Antarctic research (minke component only) and the transits. Table 2 also shows the number of research days in each calendar month per cruise. The minke whale research component of the 1994/95 cruise, and all subsequent cruises, was delayed by a period of two or three weeks compared with the previous cruises. The aim of this was to facilitate cruise track construction by increasing the likelihood of the ice-edge receding prior to the survey to form a compact edge at a position more readily determined.

Change of the positioning (navigation) system

Prior to 1981/82, all vessels employed celestial navigation as the principal technique for determining position in the Antarctic. The Navy Navigation Satellite System (NNSS) was installed on the Japanese vessels from the 1981/82 cruise. From 1991/92, Global Positioning System (GPS) equipment was used on both research vessels. Each of these changes improved the accuracy of the positional data recorded during the research activities. From 1993/94, latitude and longitude on the sightings and effort data forms

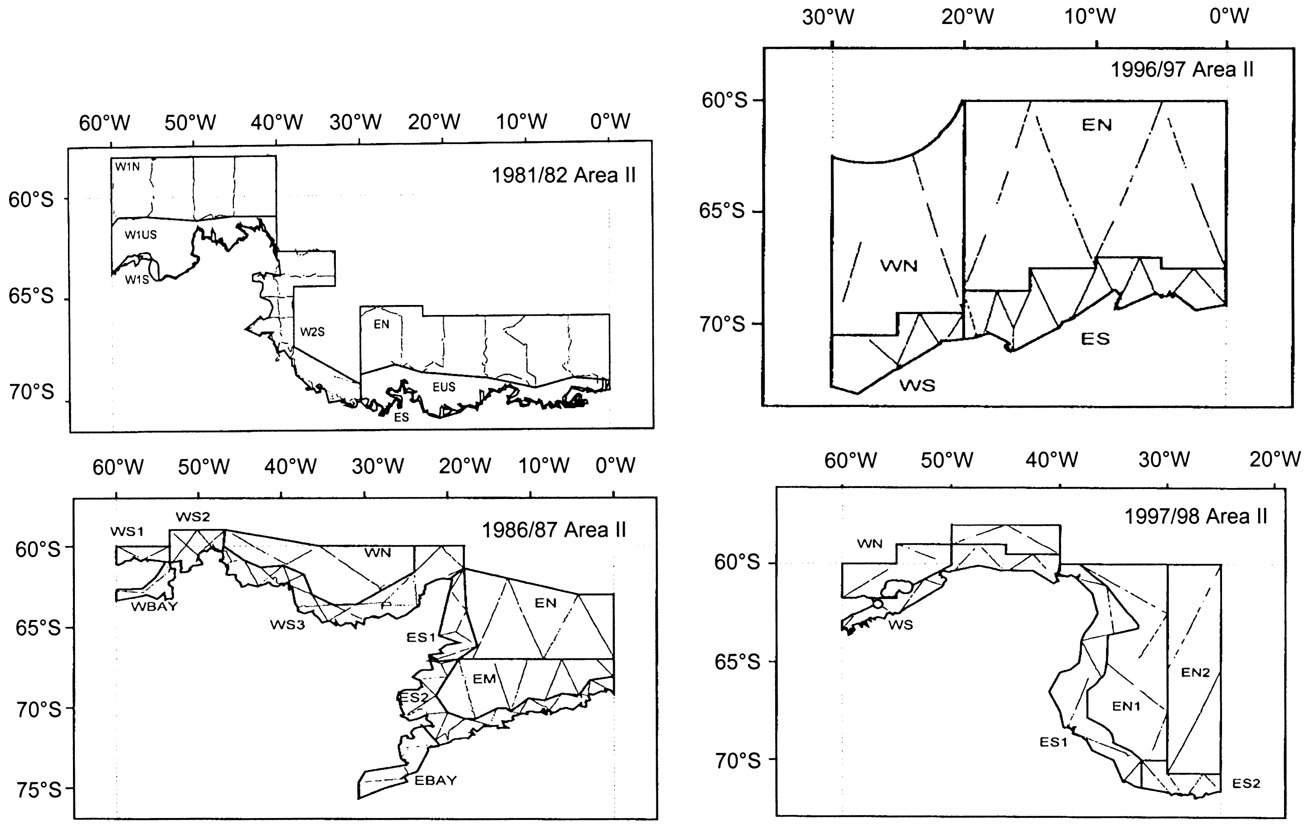

Fig. 2b. Strata surveyed in Area II throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b). In the 3rd circumpolar survey for this Area was conducted by 1996/97 and 1997/98 cruises.

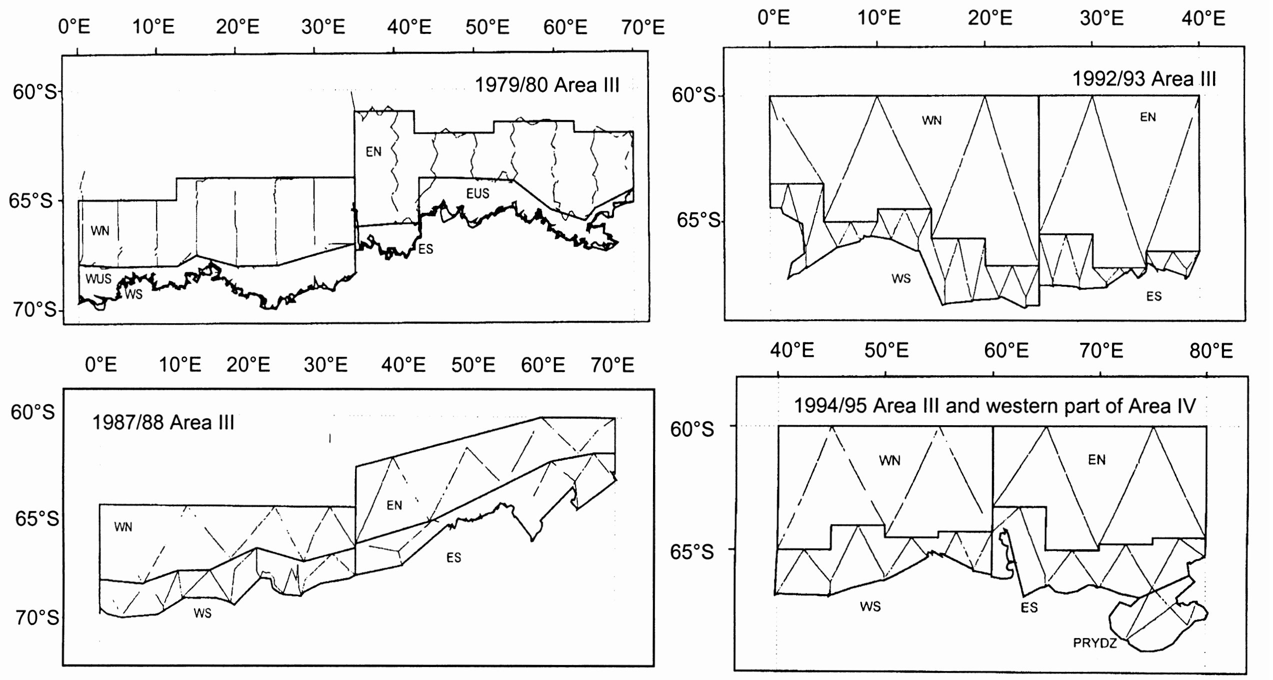

Fig. 2c. Strata surveyed in Area III throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b). In the 3rd circumpolar survey for this Area was conducted by 1992/93 and 1994/95 cruises.

were recorded to the nearest one hundredth of a minute (instead of to the nearest minute). Additionally, the advent of GPS navigation coupled with the VDU (Visual Display Unit) track recorder, greatly enhanced the accuracy and ease of establishing the 3 n.mile bound on either side of the trackline (see Survey Protocol section) and the accuracy of positions recorded during such activities as chasing, returning to the trackline and during ice navigation etc. The precision of the GPS navigation also eliminated the need for 'major position shifts' (corrections to the positions), which had occurred on the earlier cruises and been recorded on the weather and effort data records.

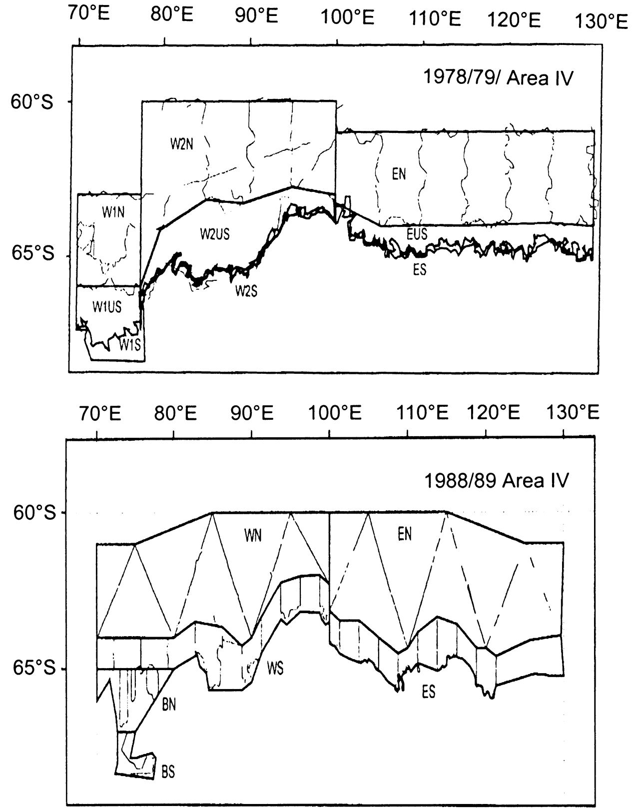

Fig. 2d. Strata surveyed in Area IV throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b).

Measurements of angles and distances

As is well-known (e.g. Hiby and Hammond, 1989), the radial distance from the observer to the sighting, and the angle between the heading of the vessel and the sighting of the animal, are important measurements in line transect surveys. Together they are used to estimate the perpendicular distance from the cruise track to the sighting, essential information for distance-based estimation methods (Buckland *et al.*, 1993). Experiments to determine the reliability of distance and angle estimates are discussed below.

Use of reticle binoculars

Initially, all distances were estimated by eye. Reticle binoculars were developed and applied to estimate the distance between ship and whales from 1981/82. They have been used routinely (after considerable experimentation and development beginning in 1981/82) by observers in the top barrels and the Primary observers on the upper (front) bridge of the Japanese vessels since 1984/85 (Joyce *et al.*, 1988). Reticle binoculars were made available for the independent observer platform (IOP) from 1987/88. Since 1998/99, reticle binoculars have also used by the researchers on the upper bridge. The advantage of using reticle binoculars has recently been quantified by Kinzey and Gerrodette (2003).

Installation of angle boards

Angles were initially estimated by eye, using tape marks placed on the wind protection screen in all platforms as an aid. Angle boards, used in conjunction with a pointer on the binocular holder, were introduced to the top barrel and for use by the captain on the 1983/84 cruise (Joyce *et al.*, 1988)[1]. Angle boards were used routinely in the IOP from 1987/88. From the 1997/98 cruise, additional angle boards with pointers were installed on the front bridge; on SM1, they were available for the three researchers and the engineer, whilst on SM2, they were available for the three researchers, the engineer and the helmsman (the other primary observer). Improved pointers on the binocular holders were installed in 1998/99. New angle boards were installed in the IOP and for all upper bridge observers when the vessels were subsequently modified (SM1 prior to the 1998/99 cruise and SM2 prior to the 1999/2000 cruise).

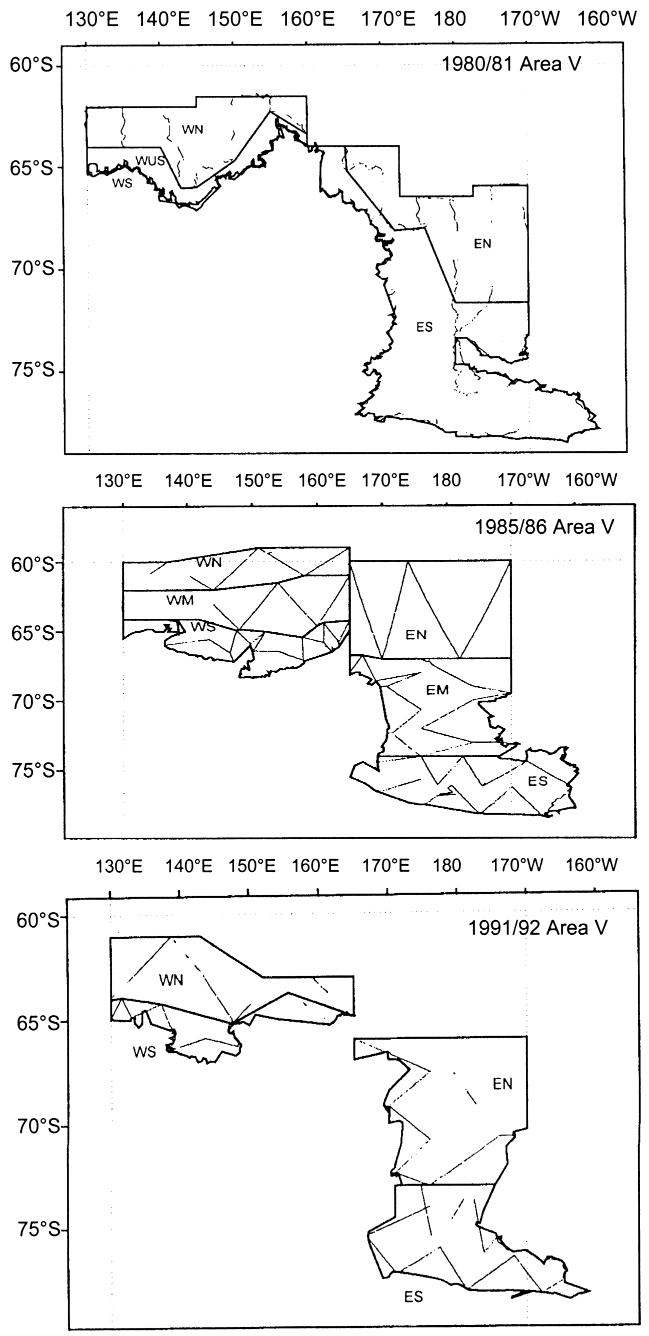

Fig. 2e. Strata surveyed in Area V throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b).

Rebuilding of upper bridge and the IOP

IOPs were initially installed on SM1 and SM2 for the 1985/86 cruise; these could accommodate one person. These remained essentially the same until extensive modifications were made to the SM1 in time for the 1998/99 cruise. The wheelhouse and front bridge were removed and replaced with an upper bridge and a new IOP. The new IOP was larger

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[1] Tape marks continued to be used as a back-up for several years.

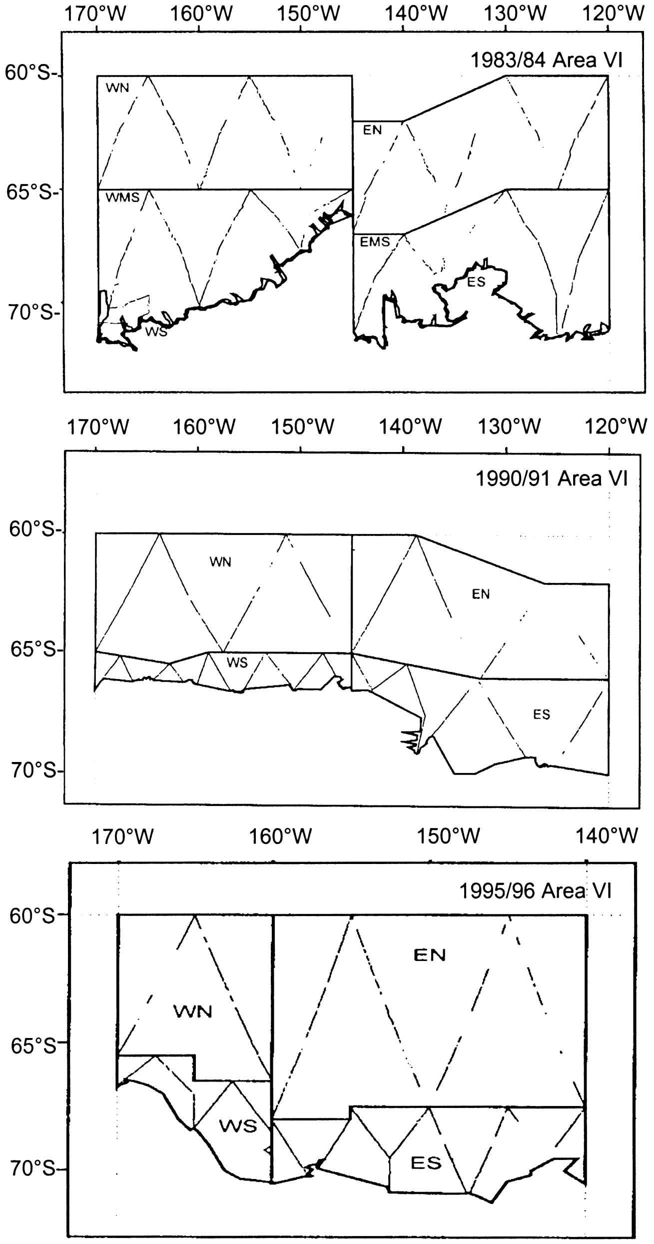

Figure 2f. Strata surveyed in Area VI throughout circumpolar sets from 1978/79 to 1997/98 (after Branch and Butterworth, 2001b).

with the potential to accommodate three observers, although there was no change to the standard procedure of using one observer in this platform. The heights above sea level of the IOP and upper bridge were not changed by the modifications. The new upper bridge and IOP had better wind protection and 360° visibility. At the same time, an identical new IOP was installed on the SM2. The following year (prior to the 1999/2000 cruise), the SM2 was extensively modified; the wheelhouse and front bridge were removed and replaced with an upper bridge such that it is now identical to the SM1.

Digital anemometers

From the 1996/97 cruise, digital anemometers were installed in the wheelhouse of the SM1 and SM2 (Ensor *et al.*, 1997). The new anemometers indicate true wind speed and direction. The previous anemometers had measured relative wind speed (from which the true wind speed was calculated by vector analysis). This modification has facilitated data recording by the vessels officers.

Data entry

Since the 1987/88 cruise, weather and effort data records have been entered onto computer files during the cruise. For the 1990/91 cruise, new programs were developed and these facilitated the routine entry of these data in addition to input of sightings and boundary/ice-edge data. The current data entry and utility programs (the Moon-Joyce Data form[2] and Plot programs) provide data entry, validation, summary and plotting capabilities. The data are usually entered each evening, after the end of the research day.

SURVEY PROCEDURE

Stratification, cruise track design and coverage

The areas surveyed by each cruise are outlined in Figs 2a-f, together with the tracklines followed while on primary searching effort. It is clear that the survey design for the first five cruises differs from that in later cruises.

First circumpolar series (1978/79 to 1983/84)

During the first circumpolar series of cruises (except for the 1983/84 cruise), one vessel followed the ice-edge closely (the 'S' stratum), while another vessel alternated between latitudinal and longitudinal legs (the 'N' stratum), typically 60 n.miles or more north of the pack ice. An unsurveyed area ('US') generally remained between the 'S' and 'N' strata. The S stratum generally covered an area twice that between the ice-edge and the vessel's trackline. From the 1983/84 cruise, vessels off the ice-edge followed the zigzag cruise track design that was used in subsequent cruises (Branch and Butterworth, 2001a).

Second circumpolar series (1984/85 to 1990/91)

The research areas were typically divided into four strata (East-North, East- South, West-North and West-South). Exceptions occurred when there were bays in the South strata. The 1984/85 cruise was experimental (Joyce *et al.*, 1988). A zigzag cruise track design within each stratum was used in CPII. A square trackline design was adopted in 1988/89 but only in the southern strata. Details of the cruise track design, including construction of waypoints were reported in the appendix of each planning report (IWC, 1988; 1989; 1990; 1991)[3]. New survey procedures were introduced in 1984/85 when part of the survey was conducted in Passing mode, and in 1986/87 Passing mode with independent observer was introduced and covered half of the planned tracklines; see Survey mode section).

Third circumpolar series (from 1991/92 to the present)

From the 1992/93 cruise onwards, the research area (and the cruise track construction) was divided into sectors of 10° longitude. Each sector was divided into two strata (Southern and Northern). The Southern Stratum extended from the estimated ice-edge (or the 100 fathom line if this extends beyond the ice-edge) to the southern boundary of the Northern Stratum. The Northern Stratum extended from the northern boundary of the Southern Stratum to the northern boundary of the research area (60°S). The boundary between the Northern and Southern strata in each sector was a line of fixed latitude. The position of the Interstratum Boundary was intended to achieve a Southern Stratum width of approximately 60-90 n.miles. The northern waypoints were placed on the Interstratum Boundary. Details of the cruise

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[2] *Moon Joyce Resources, 11740 Exeter Ave. NE, Seattle, WA 98125, USA.*

[3] Planning reports are available from the IWC Secretariat.

Table 1

Summary of the cruises from 1978/79 to 200/01 (Area, Vessel and home port). Abbreviations: SM2 = *Shonanmaru No.2*, T16 = *Toshimaru No.16*, T18 = *Toshimaru No.18*, K27 = *Kyomaru No.27*, V34 = *Vdumchivyi No.34*, V36 = *Vyderzhanny No.36*, * = experiment cruise.

			Longitudinal coverage					
CP	Cruise	Area	Range	Degrees	Latitudinal range (average)	Research vessel	Departure home port	Arrival home port
CP I	1978/79	IV	70E-130E	60	ice-61S	T16,T18	Fremantle	Fremantle
	1979/80	III	0-70E	70	ice-63S	K27,T11	Cape Town	Cape Town
	1980/81	V	130E-170W	60	ice-62S	K27,T11,V34	Wellington	Wellington
	1981/82	II	60W-0	60	ice-63S	SM1,SM2,V34	Buenos Aires	Cape Town
	1982/83	I	120W-60W	60	ice-64S	SM1,SM2,V34	Ushuaia	Wellington
	1983/84	VI	170W-120W	50	ice-61S	SM1,SM2,K27,V34	Wellington	Wellington
CP II	1984/85*	IV	70E-130E	60	ice-61S	SM1,SM2,K27,V34	Fremantle	Fremantle
	1985/86	V	130E-170W	60	ice-60S	SM1,SM2,K27,V36	Wellington	Wellington
	1986/87	II	60W-0	60	ice-62S	SM1,SM2,K27,V34	Ushuaia	Port Luis
	1987/88	III	0-70E	70	ice-63S	SM1,SM2	Fremantle	Port Luis
	1988/89	IV	70E-130E	60	ice-61S	SM1,SM2	Fremantle	Fremantle
	1989/90	I	120W-60W	60	ice-64S	SM1,SM2	Ushuaia	Wellington
	1990/91	VI	170W-120W	50	ice-61S	SM1,SM2	Wellington	Wellington
CP III	1991/92	V	130E-170W	60	ice-63S	SM1,SM2	Wellington	Wellington
	1992/93	III W	0-40E	40	ice-60S	SM1,SM2	Cape Town	Fremantle
	1993/94	I	110W-60W	30	ice-60S	SM1,SM2	Wellington	Valparaiso
	1994/95	III E, IV W	40E-80E	40	ice-60S	SM1,SM2	Cape Town	Fremantle
	1995/96	VI W	170W-140W	30	ice-60S	SM1,SM2	Hobart	Wellington
	1996/97	II E	30W-0	30	ice-60S	SM1,SM2	Cape Town	Cape Town
	1997/98	II W	60W-25W	35	ice-60S	SM1,SM2	Punta Arenas	Cape Town
	1998/99	IV	80E-130E	50	ice-60S	SM1,SM2	Cape Town	Hobart
	1999/00	I E, II W	80W-55W	25	ice-60S	SM1,SM2	Valparaiso	Punta Arenas
	2000/01	VI E, I W	140W-110W	30	ice-60S	SM1,SM2	Wellington	Papeete

Table 2

Summary of the cruises from 1978/79 to 2000/01. * = for the minke whale component.

		Research period		Number of research days							Area[a]	
				Transit			Antarctic					
Cruise	Area	Home port to home port	Antarctic*	to	from	Total	Dec.	Jan.	Feb.	Total	No. of strata[b]	(n.mile^2)
CP I												
1978/79	IV	12/12/78 - 14/02/79	28/12/78 - 07/02/79	16	7	23	4	31	7	42	9	427,496
1979/80	III	20/12/79 - 21/02/80	27/12/79 - 14/02/80	7	7	14	5	31	14	50	6	493,908
1980/81	V	17/12/80 - 12/02/81	22/12/80 - 06/02/81	5	6	11	10	31	6	47	5	480,280
1981/82	II	19/12/81 - 14/02/82	27/12/81 - 06/02/82	8	8	16	5	31	6	42	7	398,021
1982/83	I	30/12/82 - 26/02/83	02/01/83 - 15/02/83	3	11	14	-	30	15	45	6	372,005
1983/84	VI	29/12/83 - 01/03/84	04/01/84 - 19/02/84	6	11	17	-	28	19	47	6	725,179
CP II												
1984/85	IV	21/12/84 - 01/03/85	29/12/84 - 19/02/85	8	10	18	3	31	19	53	6	-
1985/86	V	18/12/85 - 24/02/86	22/12/85 - 18/02/86	4	6	10	10	31	18	59	6	963,468
1986/87	II	27/12/86 - 20/02/87	28/12/86 - 04/02/87	1	16	17	4	31	4	39	10	495,208
1987/88	III	11/12/87 - 08/02/88	20/12/87 - 25/01/88	9	14	23	12	25	-	37	4	479,730
1988/89	IV	21/12/88 - 20/02/89	29/12/88 - 11/02/89	8	9	17	3	31	11	45	6	577,099
1989/90	I	26/12/89 - 19/02/90	28/12/89 - 10/02/90	2	9	11	4	31	10	45	4	429,512
1990/91	VI	29/12/90 - 23/02/91	03/01/91 - 11/02/91	5	12	17	-	29	11	40	4	557,424
CP III												
1991/92	V	21/12/91 - 17/02/92	31/12/91 - 08/02/92	10	9	19	1	31	8	40	4	443,845
1992/93	III W	17/12/92 - 16/02/93	25/12/92 - 04/02/93	8	12	20	7	31	4	42	4	445,316
1993/94	I	23/12/93 - 21/02/94	03/01/94 - 14/02/94	11	7	18	-	29	14	43	4	667,776
1994/95	III E, IV W	05/01/95 - 06/03/95	13/01/95 - 25/02/95	8	9	17	-	19	25	44	5	428,564
1995/96	VI W	06/01/96 - 04/03/96	14/01/96 - 21/02/96	8	12	20	-	18	21	39	4	446,418
1996/97	II E	07/01/97 - 26/02/97	16/01/97 - 14/02/97	9	12	21	-	16	14	30	4	445,715
1997/98	II W	14/01/98 - 26/02/98	18/01/98 - 14/02/98	4	12	16	-	14	14	28	6	306,981
1998/99	IV	31/12/98 - 01/03/99	20/01/99 - 22/02/99	20	7	27	-	12	22	34	4	387,581
1999/00	I E, II W	06/01/00 - 18/02/00	15/01/00 - 13/02/00	9	5	14	-	17	13	30	4	-
2000/01	VI E, I W	05/01/01 - 05/03/01	16/01/01 - 22/02/01	11	11	22	-	16	22	38	4	-

[a] 1978/79-1997/98, Branch and Butterworth (2001); 1998/99-2000/01, Ensor *et al.*, (1999, 2000, 2001). [b] Cruise reports.

track design including construction of waypoints are reported in the appendix of each planning report (IWC, 1991; 1992). From the 1993/94 cruise, there were some additional changes in relation to coverage: the guideline for minimum coverage in the northern stratum was reduced from 100% total coverage to 50%; and survey transects were sub-divided by mode into equal-length segments restricted in length to less than 100 n.miles. For the 1995/96 cruise, the guideline for minimum coverage on primary effort in the northern stratum was reduced from 50% to 46.5%. From the 1996/97 cruise, the lower limit of coverage in southern stratum was reduced (from total coverage) to 80%. The guideline for minimum coverage in the northern stratum was reduced to 45%. The current cruise track construction methods and guidelines for coverage are unchanged (IWC, 2000)[4].

Conditions acceptable for primary search effort

Primary search effort is only conducted in acceptable weather conditions. These conditions were formalised for the 1984/85 cruise as being able to see a minke whale blow (or other sighting cue) at a distance of at least 1.5 n.miles, with wind speed <25 knots and Beaufort Sea state <6. Prior to the 1984/85 cruise, the same criteria were used in practice. These were unchanged until the 1996/97 cruise when they were redefined as being able to see a minke whale blow (or other sighting cue) at a distance of at least 1.5 n.miles, with wind speed <25 knots (in the vicinity of the ice-edge) and <20 knots (remote from the ice-edge), and Beaufort Sea state <6.

These conditions are used as guidelines; in some circumstances, less severe conditions may still be inappropriate for search effort. The assessment of acceptable conditions is subjective and depends on many other factors other than wind speed. The redefinition of acceptable wind speeds in 1996/97 did not result in any significant changes to assessments of acceptable survey conditions.

Survey mode

Since the 1985/86 cruise, the survey has been conducted in two primary modes: (1) Closing mode; and (2) Passing with Independent Observer mode. In both cases, survey speed averages about 11.5 knots.

Closing mode (NSC) survey protocol

Closing mode has been used since the first cruise. Although essentially the same, the procedure (see below) has been refined slightly over the years; most importantly with respect to standardisation of trackline procedures (from the 1983/84 cruise), establishing a 3 n.mile bound on either side of the trackline before closing (from the 1985/86 cruise) and then further refinement of return to trackline protocol following installation of the GPS (from the 1991/92 cruise).

Two topmen observe from the barrel at all times with no observer in the IOP. There are open communications between the barrel and the upper bridge. When a sighting is made, the topman (or upper bridge observer) gives an estimate of the distance and angle to the sighting and (apart from the cases outlined below) the ship turns immediately, regardless of the angle, to the sighting; vessel speed is increased to 15 knots to hasten the closure and then decreased when the group is neared, usually 0.2-0.4 n.miles from the initial sighting position. The species, group size, estimated lengths, number of calves present and behaviour are determined and recorded. After as many data as possible have been collected, other activities might take place, such as natural marking or biopsy experiments. All subsequent sightings are regarded as secondary until normal search effort is resumed.

Exceptions to this procedure of closing now include: if the initial sighting distance is more than 3 n.miles (perpendicular distance) from the vessel's trackline *and* the sighting is thought to be of minke whales; if the group can be positively identified as long-diving species (such as sperm whales or beaked whales) and it is considered (before or during closure) that the animals have dived. In such cases, either closing does not occur or is abandoned.

Passing mode with independent observer (IO)

Passing mode was introduced in 1985/86, to avoid possible bias in estimating sighting rate (number of sightings per unit distance) in closing mode arising from stoppages to go off effort when confirming, with associated secondary sightings having to be ignored in the abundance analyses. Passing mode with independent observer was introduced on an experimental basis in 1985/86 and routinely covered half of the planned trackline from 1986/87. Two topmen observe from the barrel at all times and a third topman is stationed in the independent observer platform (IOP). The topmen report information to the upper bridge observers, but no information is exchanged between the barrel and IOP. The observers on the upper bridge communicate with the topmen (using their independent telephone systems) only when clarification of information is required, thus avoiding disruption of the barrel and IOP's normal search procedure. The barrel and the IOP are not informed of any sightings made by the upper bridge. Separate sightings records are completed for all standard barrel and IOP sightings.

Immediately after a sighting is made from the barrel or IOP, the topman informs the bridge of his estimate of the distance and angle to the sighting (and also, if possible, the species, number of animals and their swimming direction), but does not change his normal searching pattern in order to track the sighting. The topman gives no further information to the upper bridge unless the whale group happens to surface again within the normal searching pattern of the topman. The observers on the upper bridge track sightings made from that platform, and attempt to locate and track sightings made by the barrel or IOP, to confirm the species and number before the sighting passes abeam of the vessel.

If the upper bridge makes a sighting prior to the same whale group being observed by the topmen in either the barrel or IOP, then a separate record is completed; otherwise any additional information from the resighting from the upper bridge information is added to the sighting record(s) completed for the barrel and/or IOP. Thus if the observers on the upper bridge are the first to sight a whale group, and it is subsequently seen from both the standard barrel and IOP, three sighting records will be completed for the same school, with independent estimates of angle and distance for initial sightings from each of the platforms.

ASSESSMENT OF DUPLICATE STATUS

The researchers on the upper bridge determine which of the sightings made from the barrel, IOP and upper bridge are duplicates. There is usually discussion among the researchers and the captain (and other upper bridge observers, if necessary). In almost all cases there is consensus of opinion regarding the assessments. In the rare cases of disagreement, a lower 'level' of duplicate status is selected. Duplicate status is assessed in the following

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[4] Usage Notes are available from the IWC Secretariat.

categories defined below. Although the assessments are largely subjective (there are no fixed rules), they are conservative and take into consideration *inter alia* comparability of estimated angles and distances, temporal and spatial relationship of sightings and type of cues, species, group size, swimming direction, behaviour and the compactness of the group.

DEFINITE

These are often simultaneous (or almost simultaneous) sightings from the different platforms, and/or with estimated angles within approximately 5° and estimated distances within approximately ±20%, and where the species (and group size) are the same. If the sighting times are somewhat separated, then for this category, the sighting has usually been tracked by the upper bridge. If not tracked then the location of the sighting is exactly as anticipated taking into account vessel movement and the whale(s) swimming direction.

POSSIBLE

Here, the difference between the estimated angles and/or distances is just outside the threshold for definite status but the sightings are reasonably close spatially. There may also have been difficulty tracking the sighting(s). If not resighted from the upper bridge and tracking was not possible, the sightings may also have been temporally and spatially within the threshold for definite status but the platforms indicated that the species were different.

REMOTELY POSSIBLE

Here, there is an ‘outside chance’ the sightings are possible duplicates. Such cases may be the result of a combination of the following: (1) not seen by the upper bridge; (2) difficulty tracking the sightings and considerable difference between the estimated angles and/or distances; and (3) the platforms indicated a difference in species.

NON-DUPLICATE

This is when the sighting is from one platform only, or if there is a candidate, the spatial/temporal or other distinction between them is obvious.

UNKNOWN

This is used when uncertainty exists, for example when entering a high-density area.

The practice of a researcher (or the captain) plotting the ship’s track and position of any sightings (using the estimated angles and distances) on plotting sheets (as first employed during the parallel ship experiments; see later section for explanation) has been routinely applied during survey in IO Mode. Upper bridge personnel have the option of using the plotting sheets as an aid in determining the duplicate status of sightings. In practice, few sightings are plotted in this manner, and the plotting sheets are usually only used to help resolve potentially confusing situations. The plotting procedure is particularly useful as an aid for tracking sightings with a large initial sighting distance in the vicinity of the trackline (with a concomitant long time interval before the sighting comes abeam) and particularly when such groups exhibit long dive times.

DATA RECORD

The observers and topmen always give the angle, distance, cue, and (if available) their initial estimate of the species, school size and swimming direction, etc. The observer’s initial data for angle, distance, cue and swimming direction are those recorded on the respective sightings data forms. With regard to species, school size and the remainder of the data, the researchers on the upper bridge (even in the case when the observers on the upper bridge never see the group) evaluate what is the most reliable and detailed information and use that to complete the sightings data form. If more information is required, or if there is conflicting information from two or more platforms about one school, the researchers may communicate with the topmen via their independent telephone systems to request more specific information from them (usually after the sighting is estimated to have past abeam).

The following practice has been adopted as standard when completing the data forms:

(a) for sightings assessed as a Definite Duplicate, the data forms are completed with the SAME species and SAME numbers;
(b) for sightings assessed as Possible, Remotely possible, Unknown and Non-duplicate, the species and numbers on the data forms may be the SAME or may be DIFFERENT.

This practice of entering the SAME species and the SAME group size information on the respective data forms for Definite Duplicate sightings has not always been followed exactly, and this explains how there were some (although extremely few) sightings assessed as Definite Duplicates, where the species recorded for the various platforms were different. Another possible explanation is that errors were made in the data records, or the groups had been composed of mixed species and the observers in the different platforms observed separate species.

Normal passing mode (NSP)

This mode is identical to the IO mode except that there is no Independent Observer in place.

Research hours

Research hours used on the cruises are shown in Table 3. Hours on effort were reduced from the 1995/96 cruise onwards to comply with a revised agreement on Japanese labour rules (IWC, 1996).

Table 3

Maximum research hours per day.

First circumpolar series	
1978/79 – 1983/84	04:00-20:00 (16 hours)
Second circumpolar series	
1984/85 (Experiment cruise)	04:00-20:00 (16 hours)
1985/86 - 1990/91	06:00-20:00 (14 hours). Reduced to 13 hours when IO mode conducted.
Third circumpolar series	
1991/92 – 1995/96	06:00-20:00 (14 hours). Reduced to 13 hours when IO mode conducted.
1996/97 – 2000/01	06:00-19:00 (13 hours). Included for each a 30-minute meal when IO mode conducted.

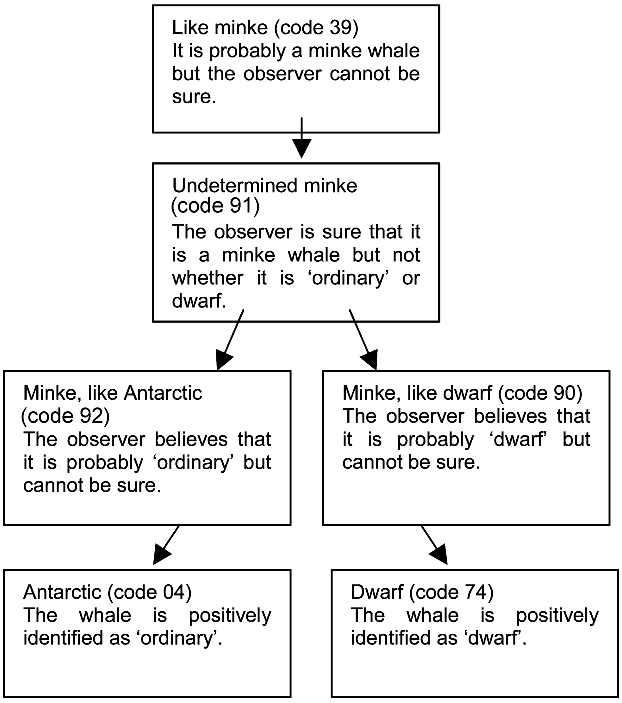
Number of primary and secondary observers on effort

The total number of observers has not changed during the history of the cruises (apart from the additional observer used in IO mode, which became routine from the 1985/86 cruise). The number of observers on the front (upper) bridge has not changed, however, there has been a change in the status of one observer (the status of the helmsman was changed from secondary to primary in 1985/86). Details are given in Table 4.

Table 4

Numbers of observers.

First circumpolar series	
Top barrel	Two primary observers (06:00-18:00) One primary observer between 04:00-06:00 and 18:00-20:00
Front bridge	One primary observer (Captain)
Front bridge	Five secondary observers (three researchers, helmsman and one engineer)
Second circumpolar series	
Top barrel	Two primary observers (06:00-20:00)
IO platform	One primary observer (only IO mode)
Front bridge	Two primary observers (Captain and helmsman)
Front bridge	Four secondary observers (three researchers and one engineer)
Third circumpolar series	
Top barrel	Two primary observers (06:00-20:00 between 1991/92 and 1995/96) (06:00-19:00 between 1996/97 and 2000/01)
IO platform	One primary observer (only IO mode)
Front (upper) bridge	Two primary observers (Captain and helmsman)
Front (upper) bridge	Four secondary observers (three researchers and one engineer)



Like minke (code 39)
It is probably a minke whale but the observer cannot be sure.

Undetermined minke (code 91)
The observer is sure that it is a minke whale but not whether it is 'ordinary' or dwarf.

Minke, like Antarctic (code 92)
The observer believes that it is probably 'ordinary' but cannot be sure.

Minke, like dwarf (code 90)
The observer believes that it is probably 'dwarf' but cannot be sure.

Antarctic (code 04)
The whale is positively identified as 'ordinary'.

Dwarf (code 74)
The whale is positively identified as 'dwarf'.

Fig. 3. Current classify the species identification diagram for Antarctic minke and dwarf form minke whales (International Whaling Commission, 2000 in Appendix 2).

Standardisation of species identification across years with particular reference to minke whales

The current *general* guidelines for identification on the IWC/SOWER cruises are as follows:

> Record the common or scientific name (such as 'minke' or 'fin') for *positively identified* species; a positively identified species is one for which the diagnostic features have been observed. Where this is not the case but the observer has seen enough to be reasonably sure of the species identity then record the qualification 'like' (e.g. use 'like minke' if a clear view of the body was not obtained but the observer believed the sighting was *probably* a minke whale).

For minke whales, in particular, the current identification guidelines are shown in Fig. 3 and further explained in the following sections. The final category decision is made by the cruise leader/senior scientist (or designated researcher).

Like minke (code 39)

The cue observed is usually the whale blow. In most cases there is no observation of the body or the view obtained is poor and insufficient to observe the diagnostic features of the species. Characteristics of the blow (small, 'baleen whale type' blow) indicate it is a probably a minke whale.

Undetermined minke (code 91)

The sighting is positively identified as a minke whale by observation of the diagnostic features of the body shape (shape of dorsal fin and head). The colouration pattern of the body is not clearly visible and it cannot be determined whether it is 'Antarctic' or 'dwarf'.

The distance at which a sighting can be positively identified as undetermined minke depends on many factors such as the sighting conditions, swimming direction and behaviour of the animals. Under normal conditions positive identification is possible up to about 1.5 n.miles. Under very favourable circumstances, determinations are possible up to about 3.5 n.miles.

Minke, like Antarctic (code 92) or like dwarf (code 90)

The sighting is positively identified as a minke whale based on the diagnostic features of the body shape. The colouration pattern of the body is not viewed in sufficient detail for the observer to be able to positively discriminate between the two forms, however, based on the details of the colouration pattern the observer believes that it is probably 'Antarctic' or is probably 'dwarf'.

Antarctic minke (code 04) and dwarf minke (code 74)

The sighting is positively identified as a minke whale based on the diagnostic features of the body shape. The colouration pattern of the body is viewed in sufficient detail for the observer to be able to positively discriminate between the two forms. The whale is positively identified as 'Antarctic' or 'dwarf'.

For all codes, the distance at which such determinations can be made is variable and depends on many factors such as the sighting conditions, water clarity, swimming direction and behaviour of the animals.

Comparability across years

There has been an increase in the number of species codes for minke whales during the course of the cruises, particularly in recent years. However, although there have been changes to the codes, there is consistency shown in the guidelines for identification of 'like minke' across years. For the first six cruises, a 'Status' cell was used to record both whether the species was identified and whether the school size was confirmed. This cell was separated into two in 1984/85, and it is probable that the clear definition of 'identified' was first drafted for the 1985/86 cruise. However, there were minke whale sightings classed as unidentified in the first six cruises, and these were subsequently recorded as 'like minke' (code 39) in the Database Estimation Software System (DESS) program.

The identification guidelines for 'like minke' have been essentially the same since the 1985/86 IWC/IDCR cruise. The guidelines for identification of 'like minkes' are shown in the excerpt below (the 'Identified' category, a simple Y/N cell, was introduced to the sightings data record for the 1985/86 cruise):

> Record as (Y) if the species (as indicated below) is 'positively' identified; otherwise record as (N) (i.e. both for 'probable' and 'unidentified' categories). 'Positive identification' of species is based on the multiple cues and usually requires the clear observation of the whale's body. Occasionally repeated observations of the shape of the blow, surfacing and other behavioural patterns may also be sufficient: this judgement should be made only by a researcher. Positively identified whale species are recorded as such on the sighting form (e.g. 'Antarctic minke' or 'undetermined minke'). 'Probable identification' of species is based on multiple cues but these are insufficient to be absolutely confident in identification. This usually occurs when blows are seen, the surfacing pattern is correct but the whales' body (characteristic of species) cannot be seen. Probable identifications are qualified with the term 'like' (e.g. 'like minke'). 'Unidentified' whales should be clearly indicated. The sighting may be qualified by size (unidentified small, medium, or large whale), order (unidentified baleen or toothed whale) or suborder (unidentified ziphiid). If a species is suspected but no additional information is available to provide possible or probable identification, the species should be listed with a query, in brackets, after listing it as unidentified (e.g. 'unidentified small whale [minke?]).

A similar situation existed for the identification of southern bottlenose whales before the 1984/85 cruise (Kasamatsu and Joyce, 1995). At that time there was neither an identification standard nor a great deal of experience in identification of this species. During this research period, whales described as 'Unidentified Ziphiidae' represented 'Unknown akabo' and 'Like akabo'. Researchers at the post-cruise meeting after the 1983/84 cruise resolved that many of the unidentified Ziphiidae were probably in fact southern bottlenose whales (Nishiwaki, pers. comm.) and following discussions there the identification of southern bottlenose whales became standardised, and more strict than unidentified Ziphiidae (Anonymous, 1986)[5].

The introduction of the passing mode procedure also had an influence on the relative numbers of the various categories of minke whale sightings. Positive identification in passing mode can be more difficult because of the differences in likely closest distance to a sighting. Most of the sightings identified to be 'like minke' and unidentified Ziphiidae in passing mode are sightings for which the closest distance exceeds 0.6 n.miles and for which there are few sighting cues. Thus, although passing mode was introduced to avoid possible bias in estimating sighting rate (see above), it also results in increasing the proportion of unidentified sightings and the precision of group size estimates.

Change of the species code

Whale species codes have increased over the years, from 22 codes used on the 1978/79 cruise to the current total of 82 codes. The number of codes increased due to additional species being encountered and clarification of levels of identification. The changes to species codes for minke whales are shown in Fig. 4. Code 39 (like minke) was entered in DESS during the course of data validation before the introduction of this code in the field. Further information can be found in the DESS user manual (Strindberg and Burt, 2000). Code 39 has been used since 1984/85. Branch and Ensor (2001) noted that code 39 (like minke/?minke) was used from 1978/79 to 1992/93, but that the description was somewhat misleading.

Confirmation of school size

Accurate determination of the school size of all sightings is not possible. It is the responsibility of the researchers to evaluate if the school size has been accurately determined. Schools where the number of animals, or an accurate estimated range of the number of animals, is determined are classified as *confirmed* schools. The data from the confirmed schools are used in the analysis to determine a mean school size. It is therefore critical that confirmed schools are representative in size of the schools that are in the survey area. Normally, schools believed to be confirmed are approached to within 0.3 n.mile, but sometimes it is possible to confirm school size at greater distances.

Ice-edge determination and definition of the Southern Boundary of the Research Area

For several years, the ice-edge was mapped by either the Soviet vessel or the southern survey vessel. Only in the later cruises did the present standard procedure develop. The southern boundary of the research area for the cruises has been established as either the 'ice-edge' or the 100 fathom isobath, if this has extended beyond the 'ice-edge'. The position of the 100 fathom isobath was established from the navigation charts. The position of the 'ice-edge' for each cruise was established using information from a number of sources: visual and radar observations of ice from the IDCR/SOWER research vessels; satellite imagery; and observations relayed from other ships and/or land bases. These sources of information have been used to construct an estimate of the 'ice-edge'. This 'ice-edge' has then been used in the construction of the cruise tracks. After the completion of the southern stratum of each sector, the senior scientist has used all the data to record the maximum (most northerly), minimum (most southerly), and best estimates of the 'ice-edge'.

Estimation of the position of the ice-edge from the IDCR/SOWER vessels

Fundamental to determination of the position of the 'ice-edge' from the IDCR/SOWER vessels is a definition of what constitutes the 'ice-edge'. From these vessels, the position of the 'ice-edge' has been established using visual observations (especially from the Top Barrel) and radar observations. Information from other sources (such as satellite imagery of ice concentration boundaries and bathymetric information from navigation charts) has also been used for confirmation. No single definition of what constitutes an 'ice-edge' can be used for all 'ice-edge' situations due to the variability in the ice concentration, ice type (e.g. sea ice, glacial ice), floe size and ice development (thickness). However, a common theme running through the estimations of all 'ice-edge' boundaries is the navigational safety of the ships. The ships are not ice-strengthened and although they frequently navigate through ice, difficult ice situations are avoided. The principles involved in defining the position of the 'ice-edge' and the range of difficulty involved in making that estimate is demonstrated in the following examples.

When the ice/ice-free boundary is well defined and the pack ice is of high concentration (7/10-10/10) and there are no large ice-free areas inside the pack ice, then estimation of the ice-edge is a simple matter. An 'ice-edge' such as this is usually obvious, both visually and on radar. The ice-edge waypoint is established 2.5 n.mile from the 'ice-edge.'

When the ice is of substantially lower concentration (3/10-4/10), or is highly variable in concentration, and/or the ice is arranged in belts separated by substantial ice-free areas (for example ice-free areas of physical dimension greater than 1 n.mile), estimation of the position of the 'ice-edge' is problematic. In this situation the position of the 'ice-edge' is determined largely by the limits of safe navigation of the ship. Attempts may be made to navigate through or around

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[5] Cruise reports are available from the IWC Secretariat.

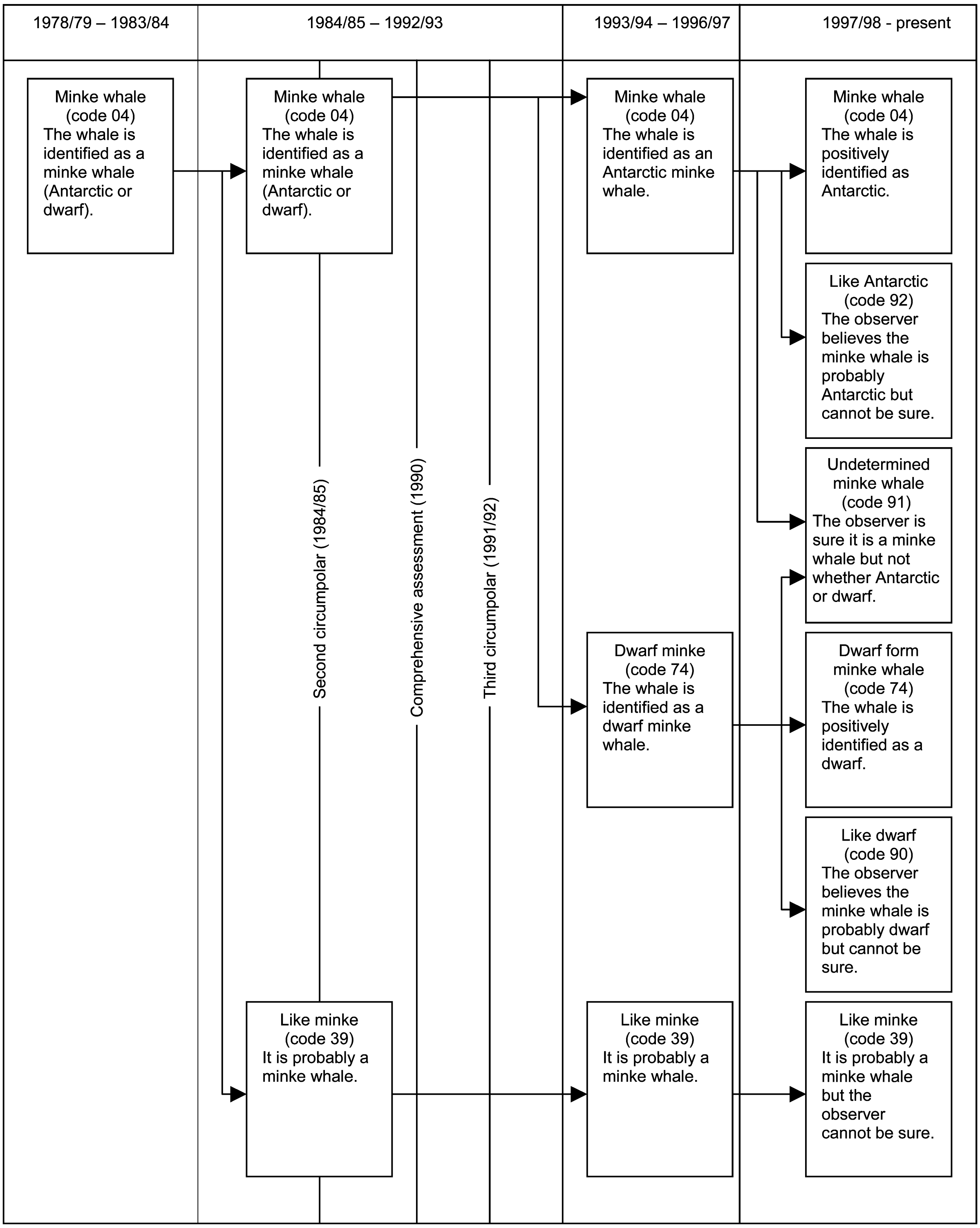

Fig. 4. Overview of the species code in IWC/IDCR and SOWER survey for Antarctic minke and dwarf form minke whale from 1978/79 to 2000/01.

the belts of sea ice to confirm the ‘ice-edge’ dependent on what areal extent of ice-free water is visible south of the outer limits of the ice (and depending on the relationship to other information such as bathymetry and perhaps satellite imagery). If navigation through the ice proves difficult, the ‘ice-edge’ is defined as the limit of safe navigation of the ship. The ice-edge waypoint on the cruise track is established 2.5 n.mile from this ‘ice-edge’.

If there are no ice-free areas to the south and when the ice is composed of small melted floes and of very low concentration (1/10-2/10), estimating the ice-edge is also problematic. However, generally such scattered small ice is relatively consistent in concentration over a wide geographic area and this makes estimation of the ‘ice-edge’ easier than in the above case.

Estimation of the ice-edge is usually based on how the ice concentration and development relates to navigation of the vessels at normal searching speed (11.5 knots). The ‘ice-edge’ is usually defined as when the ice forms a continuous visual barrier (or radar image) on the horizon or when normal searching speed cannot be maintained for the majority of time without help from the topmen to navigate through the ice. The ice-edge waypoint on the cruise track is established 2.5 n.mile from this ‘ice-edge’

Expansive ice-free areas or pack ice of much lower concentration may be visible inside the pack ice extending beyond the horizon south of the 'ice-edge'. In such cases, the areal extent of ice-free areas extending beyond the horizon cannot be substantiated and whether the ice represents the true 'ice-edge' or is separated from the main ice-edge cannot be established. The position of the ice-edge and details of the ice-edge observations from the research vessels are indicated on the detailed cruise track charts produced during the cruise.

Estimation of the position of the ice-edge from satellite information

Cruise vessels have received satellite information from the US Navy NOAA Joint Ice Center (JIC) and latterly the National Ice Center (NIC). Summaries of these analyses were sent to the ships by morse code from at least the 1980/81 cruise. Also during the early cruises, an estimation of the ice-edge for the entire Antarctic, based on both satellite and aerial observations, was available twice monthly (via weather chart radio fax) from the Soviet station *Molodezhnaya*, located in Enderby Land. More detailed information was received by facsimile after the Inmarsat system was installed on the ships for the 1991/92 cruise (and by e-mail on recent cruises). The type of satellite information received, and its usefulness has generally remained the same across the years, with a variety of satellite methods: passive, microwave radiometers, visible and infrared sensors, synthetic aperture radar, or sometimes only estimated boundaries. The JIC/NIC ice information has been vital for estimating the position of the ice-edge and has been more important in the absence (since the 1985/86 cruise) of the Soviet vessels and their dedicated ice-edge role in mapping and survey.

Ice information from other ships and/or land stations

Useful ice information has been received, from time to time, from other ships and Antarctic land bases.

Consistency of estimates of the ice-edge/southern boundary over years

The methods used for estimating the position of the ice-edge have not changed significantly during the history of the cruises. The only major change is that the estimates for later cruises lack the precision of the earlier cruises when the position was determined by the ice-edge survey and mapping vessels. On the later cruises there has been a trend towards fewer ice-edge waypoints due to changes in the cruise track construction methods. However, since the information for estimating the ice-edge has come from a number of sources and uses a variety of methods it is fair to say there has been consistency over time. The Antarctic pack ice is a highly variable, dynamic system, the distribution and characteristics of which are determined by, and strongly reflect, the underlying oceanographic processes (and on a shorter temporal scale, the meteorological conditions; particularly wind force). 'Ice-edge' characteristics are not necessarily restricted to the northernmost sea ice/open water boundary. The positions of the estimated ice-edges established during these cruises, are based mainly on the safe navigation of the research vessels.

Discovery marking

From the 1978/79 to 1983/84 cruises, the primary method of abundance estimation was the mark-recapture method. The procedure was basically to conduct a sightings survey until an appropriate whale group was observed and then the group would be pursued for marking. Minke whales at least 8.0m in length were the primary target but sperm and humpback whales were also marked in some of the cruises. Minke whales were marked using the small 0.410 Discovery mark, while sperm and humpback whales were marked with the more standard 12-gauge Discovery mark. Details of these activities and results are given in the cruise reports and the first 10-year review paper (Joyce *et al.*, 1988). Discovery marking was discontinued after the 1983/84 cruise after an analysis by Cooke (1986) showed that it was unlikely an adequate number of marks could be deployed and recovered to provide an accurate population estimation.

Experiments

Over the years, experiments have been conducted during the cruises to answer specific questions related to abundance estimation. Experiments related to Discovery marking took place only during the first circumpolar cruises and are reviewed in Joyce *et al.* (1988). The first major experiments relating to sighting surveys came from the 1980 Workshop on the Design of Sightings Surveys (IWC, 1982). Subsequently, other experiments arose from Annual Meetings of the IWC Scientific Committee, the Tokyo planning meetings, and especially the occasional specialist meetings held in conjunction with the Tokyo planning meetings. Experimentation reached a peak during the 1984/85 cruise when over half the cruise was dedicated to conducting sighting experiments. A special workshop on minke whale sightings was held in 1985 to evaluate the results of these experiments (IWC, 1986). Tables 5 and 6 list the experiments conducted on the cruises since 1978/79.

Routine experiments for recent cruises

Estimated distance and angle experiment

This experiment was designed to examine the precision and accuracy of distance and angle estimates to a sighting. A buoy with a radar-reflecting transponder is used as the sighting target and distance and angle estimates are made by the observers while the ship is underway at normal searching speeds. Buoys of the same design have been used for the entire history of this experiment. The mast of the buoy is 3.5-3.6m high. The design of buoy is shown in the 1984/85 cruise report. At pre-determined distances and angles from the buoy, visual observations by the observers are taken simultaneously with radar readings.

Six trials per observer, per sighting platform are scheduled. Primary observers are tested from platforms where they normally conduct sightings effort, using the same procedures and equipment as during normal searching. It is stressed to the observers that all angle readings must be made using angle boards with pointers, both during the experiments and during sightings effort. The experiment is conducted during weather and sea conditions that are not unrepresentative of the conditions encountered during the survey. However, due to radar imaging problems, the experiment has usually been conducted in better-than-average conditions. Additionally there is a safety aspect, since the deployment and retrieval of the buoy requires relatively calm conditions.

For both theoretical and practical reasons, it is preferable for the experiment to be scheduled in the middle of the survey period. Since sea conditions near the ice-edge are usually less changeable, it is recommended that the experiment be attempted near the middle of the cruise about the time that the vessels swap strata. The cruise leader/senior scientist randomly selects distances from six of the following seven ranges (in n.miles): 0.00-0.25; 0.26-0.50; 0.51-1.00;

Table 5

Summary of the cruises from 1978/79 to 2000/01 (positioning system and non-sightings related experiments). Abbreviations: CP = circumpolar survey, Cel = Celestial, NS = Naval navigation Satellite System, GPS = Global Positioning System, V = Vessel observation, J = Joint Ice Centre Information, N = Naval Ice Centre Information, Eff = Recovery efficiency, Tf = Trial-firing for dart modification and target position, Ver = Mark verdict experiment using VTR, Pid = Photoidentification or natural marking, Biop = Biopsy, Md = Marine debris observation, Poll= Air and sea pollutants, Ac = Acoustic survey, CTD and XBT = Oceanography.

								Experiments									
			Positioning system			Ice info					Marking			Environment			
CP	Cruise	Area	Cel	NS	GPS	V	J/N	Pid	Biop	Ac	Eff	Tf	Ver	Md	Poll	CTD	XBT
CP I	1978/79	IV	Y	-	-	Y	-	-	-	-	Y	-	-	-	-	-	-
	1979/80	III	Y	-	-	Y	-	-	-	-	Y	Y	-	-	-	-	-
	1980/81	V	Y	-	-	Y	Y	-	-	-	-	-	-	-	-	-	-
	1981/82	II	Y	Y	-	Y	Y	-	-	-	-	-	-	-	-	-	-
	1982/83	I	Y	Y	-	Y	Y	-	-	-	-	-	Y	-	-	-	-
	1983/84	VI	-	Y	-	Y	Y	-	-	-	-	Y	Y	-	-	-	-
CP II	1984/85	IV	-	Y	-	Y	Y	Y	-	-	-	-	-	-	-	-	-
	1985/86	V	-	Y	-	Y	Y	-	-	-	-	-	-	-	-	-	-
	1986/87	II	-	Y	-	Y	Y	Y	-	-	-	-	-	-	-	-	-
	1987/88	III	-	Y	-	Y	Y	Y	-	-	-	-	-	Y	-	-	-
	1988/89	IV	-	Y	-	Y	Y	Y	Y	-	-	-	-	Y	-	-	-
	1989/90	I	-	Y	-	Y	Y	Y	Y	-	-	-	-	Y	-	-	-
	1990/91	VI	-	Y	-	Y	Y	Y	Y	-	-	-	-	Y	-	-	-
CP III	1991/92	V	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	-	-	-
	1992/93	III W	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	-	-	-
	1993/94	I	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	Y	Y	-
	1994/95	III E, IV W	-	-	Y	Y	Y	Y	Y	Y	-	-	-	Y	Y	Y	-
	1995/96	VI W	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	Y	Y	Y
	1996/97	II E	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	-	Y	Y
	1997/98	II W	-	-	Y	Y	Y	Y	Y	Y	-	-	-	Y	-	-	-
	1998/99	IV	-	-	Y	Y	Y	Y	Y	Y	-	-	-	Y	-	-	-
	1999/00	I E, II W	-	-	Y	Y	Y	Y	Y	Y	-	-	-	Y	-	-	-
	2000/01	VI E, I W	-	-	Y	Y	Y	Y	Y	-	-	-	-	Y	-	-	-

1.01-1.50; 1.51-2.00; 2.01-2.50; 2.51-3.00. Similarly the angles are randomly selected from six of the following seven trials (in degrees): 00-10 two trials; 11-20 two trials; 21-40 two trials; 41-60 one trial.

Potential sources of bias that would not occur in normal searching have been identified and avoided; the following procedures are followed:

(1) observers should not know the distances and angles being examined;
(2) observers should not discuss the previous test with other observers;
(3) observers should be below deck between trials;
(4) observers should not look for the buoy until told to;
(5) observers should not be told the results of the test until after the survey;
(6) distances and angles should be over a range and not consistently a single value for all observers during a single trial.

Priority is given to the barrel and IOP trials. Trials with researchers as observers have the lowest priority. The results of the experiment are recorded on the Estimated Angle and Distance Data Record. Two examples of the protocol followed while conducting the experiment on recent cruises are presented in Appendix 3.

ESTIMATED ANGLE AND DISTANCE TRAINING EXERCISE

A training exercise is conducted on a priority basis near the beginning of the cruise to familiarise the observers with distances, angles, and the use of reticle binoculars and angle boards. The exercise uses the estimated distance and angle experiment procedures, except that several observers can make estimates at one time, and the observers are informed of the radar values in each trial. The exercise is conducted with the ship underway or stationary. The number of trials conducted is at the discretion of the Cruise leader/Senior scientist. During the cruises, there are often informal 'competitions' in which observers are asked to estimate the distance to icebergs and small pieces of ice (but not usually the angle). Estimates of the distance to the latter takes place particularly in calm weather when small pieces of ice can be more easily detected by radar. Observers are only informed of the radar measurement after they have made their estimates. Most frequently these 'competitions' were among the Front/Upper Bridge personnel but sometimes observers on all platforms were involved.

OBSERVERS CODES AND EXPERIENCE

A list of codes for observers as used on the data forms and their relevant experience has been submitted to the IWC, for each cruise since the 1993/94 cruise. An example is shown in Appendix 4.

CHANGES OVER TIME

The Estimated Angle and Distance Experiment has been conducted on each ship, on each cruise, since 1981/82 and the protocol for conducting the experiment has been essentially unchanged since the 1987/88 cruise (apart from minor logistical details). Prior to the 1987/88 cruise, the following modifications to the experimental protocol were made: (1) angle boards and reticle binoculars were used by the observers from the 1984/85 cruise; (2) the Captain and helmsman were included in the experiment from the 1984/85 cruise; (3) to improve the resemblance of the buoy to a whale

Table 6

Summary of experiments related to estimating abundance from sighting data.

Experiment	Primary aim	Seasons	References
Variable speed	Estimation of $g(0)$	1980/81; 1982/83 -84/85	Butterworth *et al.* (1982); Hiby (1986)
Density gradient	Relationship of density to distance from ice-edge	1980/81-81/82	Butterworth *et al.* (1982); Butterworth *et al.* (1984)
Parallel ship	Reaction of whales to vessel, $g(0)$	1980/81 - 84/85	Butterworth *et al.* (1982); Butterworth *et al.* (1984); Hiby (1986); Kishino (1986); Cooke (1987); IWC (1987)
Hazard rate	Collect data for use in hazard rate model	1983/84	Joyce (1984); Hiby and Thompson (1985)
Topmen behaviour	Bias in search effort	1980/81, 1985/86	Ward *et al.* (1986)
Secondary sightings	Comparison of passing and closing modes	1984/85 - 85/86	Anon. (1985)
Length estimation	Check accuracy of visual estimates	1984/85	Gordon (1985)
Dive time	Cue-counting, $g(0)$	1980/81 - 81/82, 1984/85, 1989/90 - 92/93	Hiby and Ward (1986); Ward and Hiby (1987)
Blow rate	Cue-counting; $g(0)$	1980/81- 81/82, 1984/85 - 86/87	Hiby and Ward (1986); Ward (1988); Ward and Hiby (1987)
Blow duration	$g(0)$; cue-counting;	1980/81, 1982/83	Butterworth *et al.* (1982)
Radio tracking	Various incl. dive time	1986/87	Joyce (1987)
Whale reaction to the survey vessel		1986/87	
Swimming speed		1982/83	Butterworth *et al.* (1983)
Cue counting	Abundance estimation technique	1984/85 - 86/87, 1988/89	Hiby and Ward (1986); Ward and Hiby (1987)
NNSS (naval navigation satellite system) closure	Accuracy of determining position of sightings	1981/82 and 1984/85	Butterworth *et al.* (1984); Joyce (1986)
Estimated distance and angle	Abundance estimation	1981/82 to present	e.g. Butterworth *et al.* (1984)
Photographic angle measurement	Abundance estimation	1983/84 - 84/85	Thompson and Hiby (1985); Ward *et al.* (1986)

sighting, from 1984/85 a flag on the mast of the buoy was replaced with an inverted white cone (c.f. a blow); (4) an Estimated Angle and Distance Training Exercise has been conducted on each ship since the 1985/86 cruise; (5) since the 1985/86 cruise, researchers have also been included in the experiment (with the exception, for logistical reasons, of the senior scientists and Japanese researchers); (6) the number of distance and angle estimates made by each observer from each platform was initially 10, this was reduced to eight from the 1986/87 cruise; (7) the number of distance and angle estimates was further reduced (to six) from the 1987/88 cruise; (8) from the 1987/88 cruise, the experiment was conducted from the ship while it was underway at normal searching speed (prior to this, the ship was stationary while each estimate was made).

Resighting

The resighting experiment is conducted during IO mode. The resighting data provide an additional source of information for the estimation of $g(0)$ and for the assessment of duplicate status. This experiment has been conducted since the 1992/93 cruise. These data have not been recorded for all IO mode sightings which have been resighted during tracking, for a variety of reasons. However, resighting data exist for a large number of sightings (322 sightings for the period 1997/98 to 2000/2001).

Biopsy

This experiment started on the 1988/89 cruise. Blue, right and humpback whales are targeted (low priority for killer and sperm whales). The following equipment was available: Japanese airguns (from 1989/90); the Paxarm system (from 1995/96); the *Larsen* gun (from 1998/99); and crossbows (1988/89 in feasibility; from 1993/94 in use). There are limits to the amount of time available for biopsying on each cruise.

Photo-identification

This experiment started on the 1987/88 cruise. Blue, right and humpback whales are targeted. Equipment includes 35mm SLR data back cameras equipped with 70-300mm lenses and motor drives, and black and white 400 ASA film (*Kodak* T-Max or *Ilford* HP5) pushed (i.e. exposed at) to 800 ASA.

SIGHTING SURVEY RECORDS

The following records for sightings survey are completed during each cruise by ship officers or researchers. Each record has undergone minor changes over the three circumpolar series of cruises. Details can be found in the Usage Notes prepared for each survey.

Weather

The Weather Record is maintained by the ship's officers and is completed every hour while in the research zone. Environmental conditions and data have been collected using consistent methodology throughout the surveys. The type of information recorded has been consistent with some minor additions such as the inclusion of swell conditions from the 1995/96 cruise.

Effort

The Effort Record is completed every day of the research programme. The Chief and Second Officers are responsible for the completion of the daily records. Research activities are identified by effort codes that are classified into four categories: On-effort; Off-effort; Experiments; and Navigation. These codes indicate the initiation or termination of full-effort sighting survey.

Sighting record

This Sighting Record is completed by the researchers. A single record is used for each cetacean sighting, regardless of search effort mode or composition of the sighting. Thus one form is completed for each distinct aggregation of cetaceans seen, e.g. a pod of whales with dolphins around them is a single sighting. If a group of animals separates when approached, all sub-groups are to be considered part of the original sighting.

Ice-edge

The Ice-edge Record is used to record information on the position of the pack ice/open water boundary and is completed by either vessel that encounters pack ice during the survey. Data for this form can come from a variety of sources: visual; satellite; other ship observations; charts (for land boundaries); and interpolations based on these sources. The senior scientist integrates the sources for the most robust estimate of the ice-edge.

Glare

Glare has been recorded on a separate data record since the 1999/2000 cruise (previously glare was recorded, in a slightly different format, on the weather data record). A recording is made at the beginning of each on-effort period and then at any time during the research if changes in the glare are considered to be significantly affecting the sighting conditions.

Charts

Exact copies (tracings) of all charts developed during the cruises are made by the ships' officers. These very detailed charts show the tracklines, waypoints, the positions of all sightings (all species) the positions of all effort mode changes (such as closing and returning to trackline), and details of the ice-edge etc. Copies of the charts (for all vessels and all cruises from the start of the programme) are sent, with the cruise data, to the IWC Secretariat.

RESULTS

The cruises have been conducted successfully for over 23 years (including the 1984/85 experiment cruise) with all six IWC management Areas investigated twice, and five of the Areas sampled thrice (Table 7). Each cruise has utilised a standard methodology, which has contained minor modifications in the procedures dictated by the results from the previous cruises.

Searching effort and ship-days

A total searching distance covered in primary search mode was 70,340 n.miles with 6,027 primary Antarctic minke whale sightings during 2,448 ship-days in the Antarctic.

International researchers

A total of 69 international researchers from 14 nations selected by the IWC have been involved in this programme. The cruise leaders have usually participated for many years. There was an additional researcher (total of four on each

Table 7

Summary of the cruises from 1978/79 to 2000/01 (effort, sightings and abundance). [a]From cruise reports. [b]From 1978/79 to 1997/98: Branch and Butterworth (2001), from 1998/99 to 2000/01: Ensor *et al.* (1999, 2000 and 2001). [c]Branch and Butterworth (2001). Numbers in parentheses are those agreed at the 1990 IWC Scientific Committee meeting.

			Searching distance (n.mile)[a]			Antarctic minke whale					
CP	Cruise	Area	Closing	IO	Total	Primary schools seen[b]	D (whales/ 100n.m^2)	P[c] (ind)	CV[c]	(P)	(CV)
CP I	1978/79	IV	7,764.1	-	7,764.1	498.3	26.6	113,569	0.218	-	-
	1979/80	III	6,966.3	-	6,966.3	419	25.0	123,714	0.242	-	-
	1980/81	V	5,299.9	-	5,299.9	545	33.7	161,695	0.264	-	-
	1981/82	II	6,581.8	-	6,581.8	447	11.5	45,580	0.262	-	-
	1982/83	I	4,823.3	-	4,823.3	576	17.2	63,932	0.254	(73,302	0.254)
	1983/84	VI	4,190.6	-	4,190.6	190	13.8	99,786	0.277	(106,901	0.277)
	1984/85	IV	-	-	-	-	-	-	-	-	-
	1985/86	V	3,485.3	4,227.9	7,713.2	1,056	31.1	299,793	0.231	(294,610	0.138)
	1986/87	II	3,329.6	3,650.7	6,980.3	781	26.5	131,177	0.256	(122,156	0.190)
CP II	1987/88	III	2,069.5	3,329.6	5,399.1	300.4	28.8	138,022	0.543	(88,735	0.273)
	1988/89	IV	2,067.2	2,378.5	4,445.7	422.7	10.1	58,170	0.375	(74,692	0.257)
	1989/90	I	2,430.2	2,980.9	5,411.1	487.5	14.9	63,972	0.258	-	-
	1990/91	VI	1,453.4	2,159.5	3,612.9	146.6	10.2	56,807	0.399	-	-
CP III	1991/92	V	1,702.8	2,029.0	3,731.8	535.9	22.2	98,682	0.200	-	-
	1992/93	III W	2,540.9	2,748.6	5,289.5	325.6	5.7	25,363	0.183	-	-
	1993/94	I	2,362.1	2,477.4	4,839.5	224.3	5.6	37,479	0.220	-	-
	1994/95	III E, IV W	2,052.3	2,248.0	4,300.3	216.1	7.4	31,620	0.210	-	-
	1995/96	VI W	1,647.4	1,733.8	3,381.2	174	8.5	37,839	0.223	-	-
	1996/97	II E	1,568.6	1,769.4	3,338.0	131.2	6.3	28,158	0.241	-	-
	1997/98	II W	1,377.2	1,688.1	3,065.3	114	5.0	15,434	0.325	-	-
	1998/99	IV	1,734.8	2,098.4	3,833.2	390	-	-	-	-	-
	1999/00	I E, II W	1,022.8	790.9	1,813.7	108	-	-	-	-	-
	2000/01	VI E, I W	1,629.6	1,556.5	3,186.1	614	-	-	-	-	-

ship) on the 1998/99 and 1999/2000 cruises. The additional researcher was an acoustics expert and did not take part in sighting activities.

Crewmembers

A total of 1,093 crewmembers (217 Soviet and 876 Japanese) have been engaged in this programme. The survey experience of Japanese crewmembers on each cruise is shown in Table 8. Younger, less experienced primary observers have mainly participated from the 1992/93 cruise. Since the 1998/99 cruise, an additional two topmen who have been inexperienced observers have been present on both the SM1 and SM2 (increasing the crew complement to 19). These additional observers have been on board to meet a need for crew training. While the numbers of observers in the platforms were unchanged, experienced observers were always present; inexperienced observers were either in the top barrel (under the tutelage of an experienced observer), or on the front/upper bridge. The inexperienced observers (beginner; the first year for the survey) have not been assigned to the IOP.

Table 8

The number of primary observers in each rank of experience for Japanese vessels between 1978/79 and 1999/2000 cruise. Survey experience included Antarctic commercial whaling and JARPA (Japanese Whale Research Program under special permit in the Antarctic). Data from Kyodo Senpaku, Kaisha, Ltd.

Cruise	Experience		
	1-5 years	6-9 years	10+ years
1978/79	0	1	11
1979/80	0	0	12
1980/81	0	0	12
1981/82	0	2	10
1982/83	0	0	12
1983/84	0	0	18
1984/85	1	0	18
1985/86	0	0	18
1986/87	0	0	18
1987/88	0	0	12
1988/89	0	0	12
1989/90	0	0	12
1990/91	0	0	12
1991/92	1	0	11
1992/93	4	1	7
1993/94	5	0	7
1994/95	5	0	7
1995/96	6	1	5
1996/97	6	0	6
1997/98	5	0	7
1998/99	8	2	5
1999/00	4	5	5

Discovery marking

Discovery marking was conducted during the 1978/79 to 1983/84 cruises, with 2,716 minke whales, 25 sperm whales and 7 humpback whales successfully marked. Details of this experiment were reported by Joyce *et al.*, (1988).

Surveyed Area (A)

Fig. 5 shows the comparison, by strata, of the research area surveyed (A, n.miles^2) in each cruise by Area from 1978/79 to 1997/98. In Areas I, II and III, the area of the northern stratum is larger in the 3rd circumpolar cruise. Although comparable data are still being calculated for Area IV, and for the 2000/01 cruise in Area VI), it appears the same tendency is to be expected.

Searching distance (L)

Fig. 6 shows for each cruise the comparison of the distance searched on primary effort (L, n.miles) by survey mode (Closing mode: black; IO mode: white) from 1978/79 to 2000/01. In Areas I, II, III and VI, the northern stratum component of L is higher in the 3rd circumpolar cruise with the expansion of the research area in the northern stratum. The northern part of L was decreased in Area IV in the 3rd circumpolar cruise.

Number of primary sightings of minke whales (n_s)

Fig. 7 shows the comparison of the number of the primary sightings of minke (code 04+91) whales (n_s) in each cruise by survey mode (Closing mode: black; IO mode: white) from 1978/79 to 2000/01. In Areas III and VI, n_s for the northern stratum component is higher in CPIII (with the expansion of survey effort in the northern stratum). However, n_s for the northern part is lower in Areas I, II and IV in CPIII (despite of the expansion of survey effort).

Encounter rate of the primary school of minke whales (n/L)

Fig. 8 shows the comparison of the number of primary sightings of minke whales (n/L; schools/100 n.miles) with CV in each cruise by survey mode (Closing mode: black; IO mode: white) from 1978/79 to 1997/98 (from Branch and Butterworth, 2001b).

Effective search half width of minke whales (ESW)

Effective search half widths of the primary minke whale schools (as analysed by Branch and Butterworth, 2001b) are shown, with the coefficient variation (CV), in Fig. 9.

Estimated mean school size of minke whales (E(s))

The estimated mean school size of minke whales (E(s)) of the primary minke whale schools (from Branch and Butterworth, 2001b) are shown, with the coefficient variation (CV), in Fig. 10.

Number of primary sightings of 'like minke'

The identification category 'Like minke' was first used during the 1985/86 cruise in Area V. Fig. 11 shows the comparison of the number of the primary sighting of the 'like minke' in each cruise by survey mode (Closing mode: black; IO mode: white) from 1978/79 to 2000/01. The number of sightings identified as 'like minke' has increased in Areas IV, V and VI through the circumpolar series. More 'like minke' sightings tended to be recorded during IO mode.

Sighting compositions of each Area

Fig. 12 shows the species compositions of the primary sightings (schools) in each circumpolar set by Area, except for the 1984/85 experiment cruise (from DESS − Strindberg and Burt, 2000; and cruise reports − Ensor *et al.*, 1999; 2000; 2001).

For CPIII, two cruises are combined in Area I (1993/94 + 1999/2000), Area II (1996/97 + 1997/98), Area III (1992/93 + 1994/95), Area VI (1995/96 + 2000/01). Although Area V has already been surveyed in the third set, the coverage of the far north of the northern strata was inadequate.

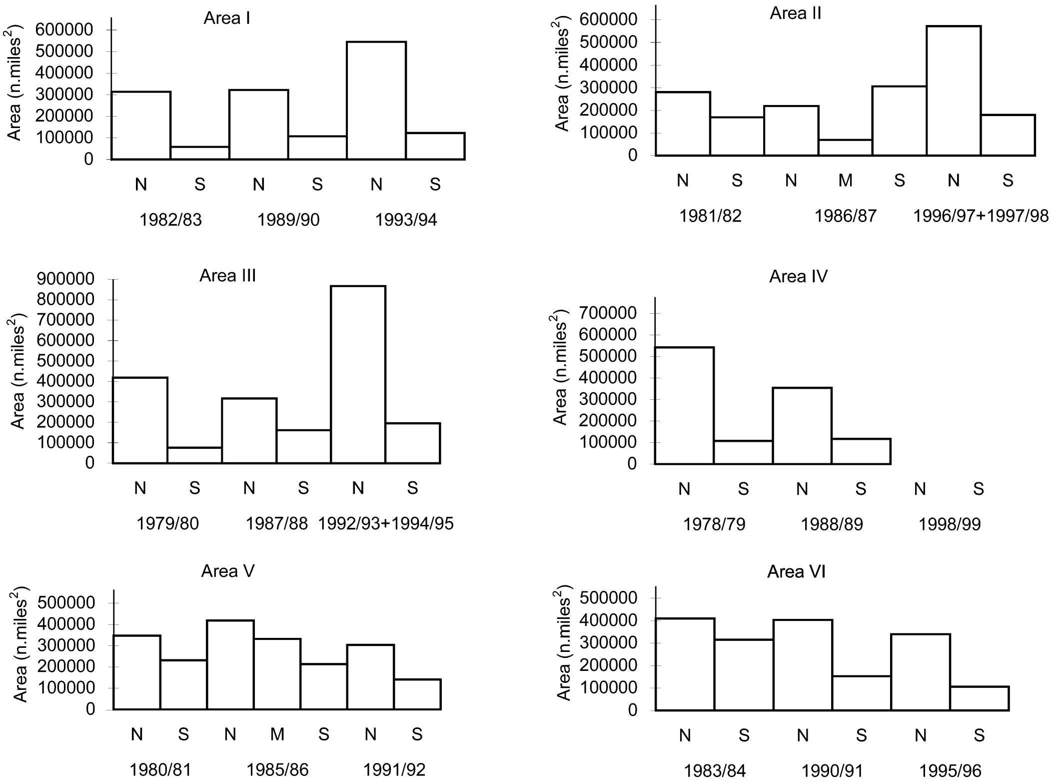

Fig. 5. Comparison of the research area surveyed (*A*, n.miles^2) in each cruise by Area from 1978/79 to 1997/98. In Areas I, II and III, the northern part of the area surveyed are increased in 3rd circumpolar cruise. Although Areas IV and VI (2000/01) are still calculating, it seemed that they expected same tendency. N: northern strata, M; middle strata, S; southern strata. Each stratum was established in different latitude by each circumpolar cruise.

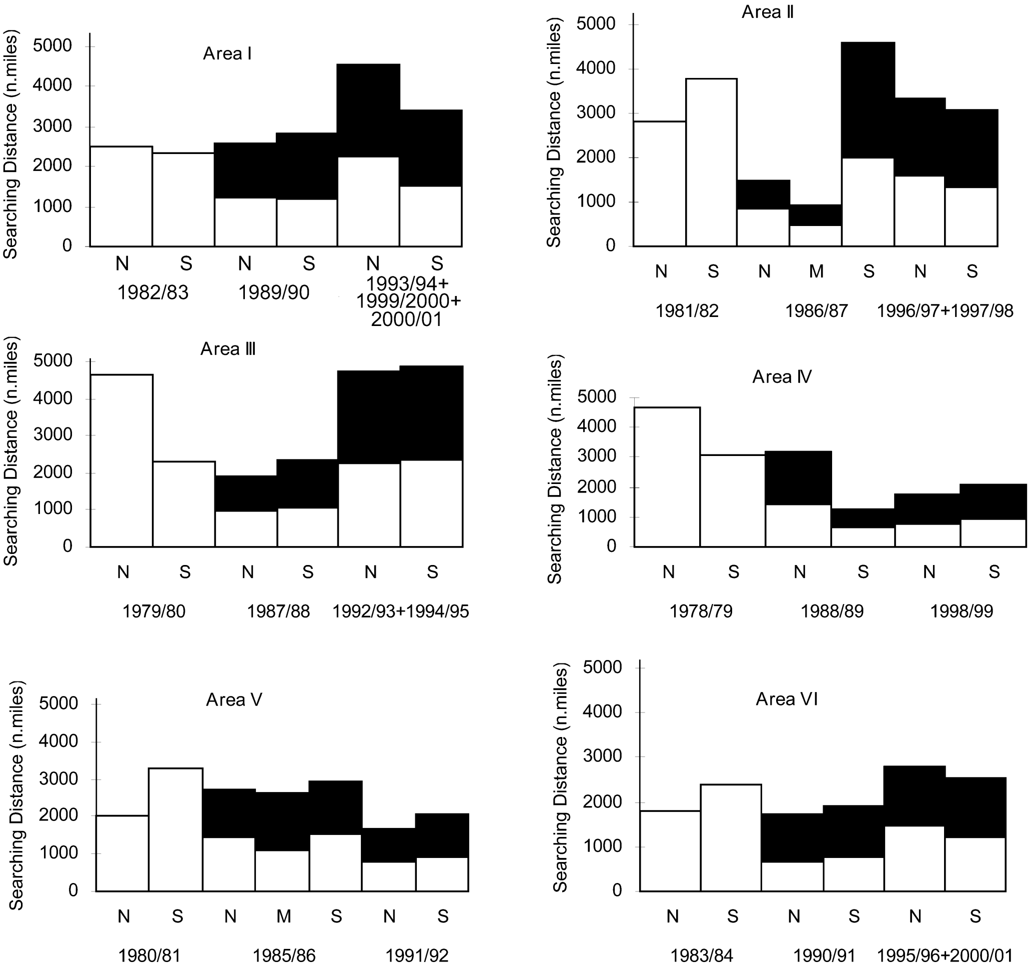

Fig. 6. Comparison of the Searching distance (*L*, n.miles) in each cruise by survey mode (Closing mode; white and IO mode; black) from 1978/79 to 2000/01. In Areas I, II, III and VI, the northern part of the L are increased in 3rd circumpolar cruise with the expanding of research area in northern stratum. N: northern strata, M; middle strata, S; southern strata. Each stratum was established in different latitude by each circumpolar cruise.

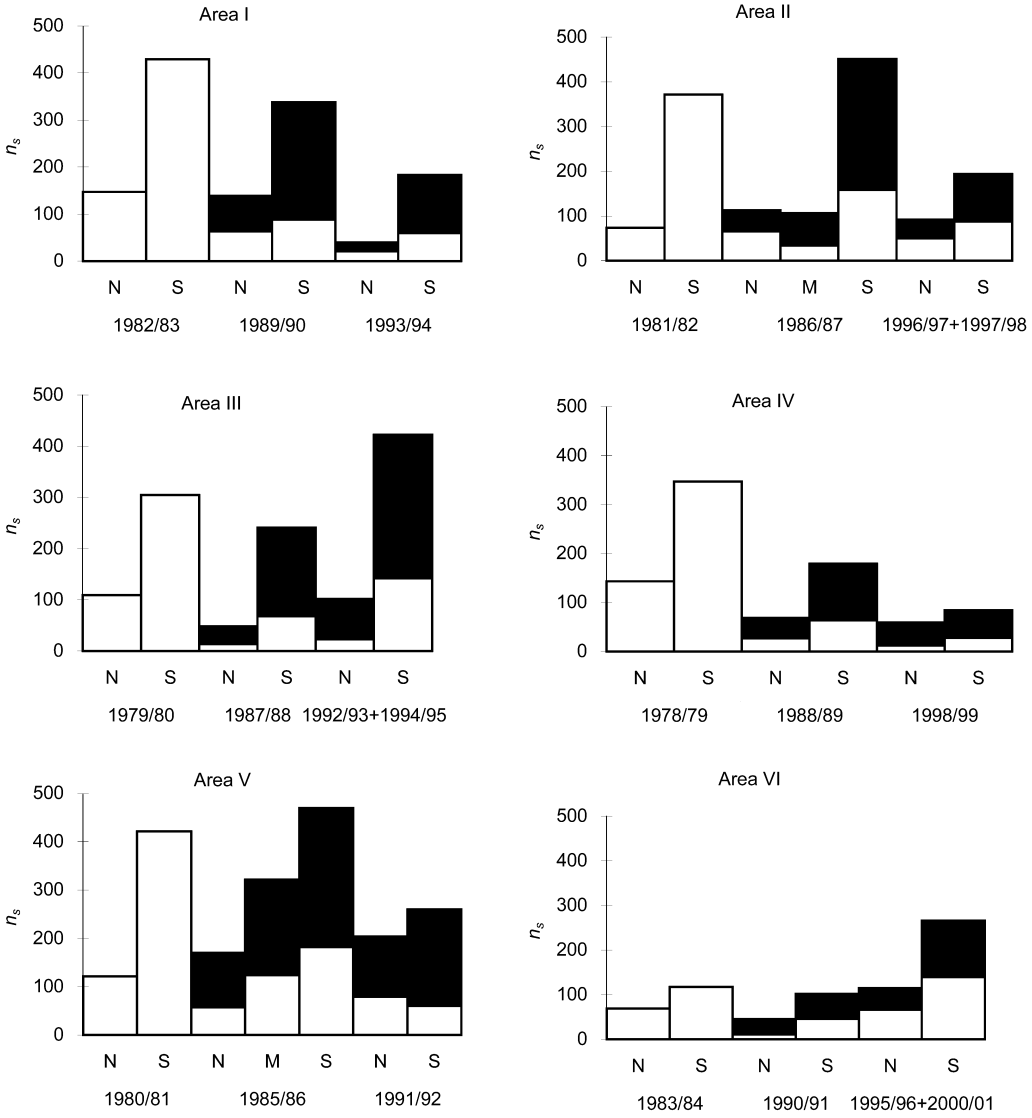

Fig. 7. Comparison of the number of the primary sighting of minke whale schools sighted (n_S) in each cruise by survey mode (Closing mode; white and IO mode; black) from 1978/79 to 2000/01. N: northern strata, M; middle strata, S; southern strata. Each stratum was established in different latitude by each circumpolar cruise (see Fig. 2a-2f).

The proportion of minke whale schools is consistent in Areas II, III and V, but it decreases (with a corresponding increase in humpback and fin whales) in Areas I and IV, over the three circumpolar cruise series. The reverse is true for Area VI. The proportion of humpback whales has increased in Areas I and IV, whilst that of fin whales has increased in Areas I, II, IV and VI.

Ziphiid (code 11) and unidentified whales tended to decrease in proportion from the second circumpolar set after whale identification standards were established. Unidentified whales include code 09 (unidentified whale); 64 (unidentified large baleen whales); 73 (unidentified large whale); 63 (unidentified small whale); and 76 (unidentified small cetacean).

DISCUSSION

Overview of data collection

It is concluded that the programme has conducted sightings surveys in a consistent way whilst developing standard procedures that are the best possible compromise between statistical needs and logistic feasibility. The experience gained over the cruises has also improved the precision of whale identification standards in the Antarctic and Southern Ocean.

Noting changes over time

Change of survey priority

After much discussion (IWC, 1986), the programme was modified from a Discovery marking cruise (for data analysis and evaluation, see Buckland and Duff, 1989) to a rigidly structured sightings cruise after CPI. With this as a turning point, rigid sighting survey procedures (especially strata design and cruise track design) and strict whale identification standards were established for the line transect abundance estimation.

Change of coverage of the northern stratum

For CPIII, the survey design was further modified to ensure complete coverage south of 60°S. The latitudinal coverage (from the ice-edge to 60°S) has taken precedence over the longitudinal coverage (this is especially the case in Areas I, II and III, compared with CPI and CPII). The width of the southern stratum has also been expanded compared to the previous cruises (Fig. 2a-f). An outcome of this change is that the distribution of effort within the overall research area

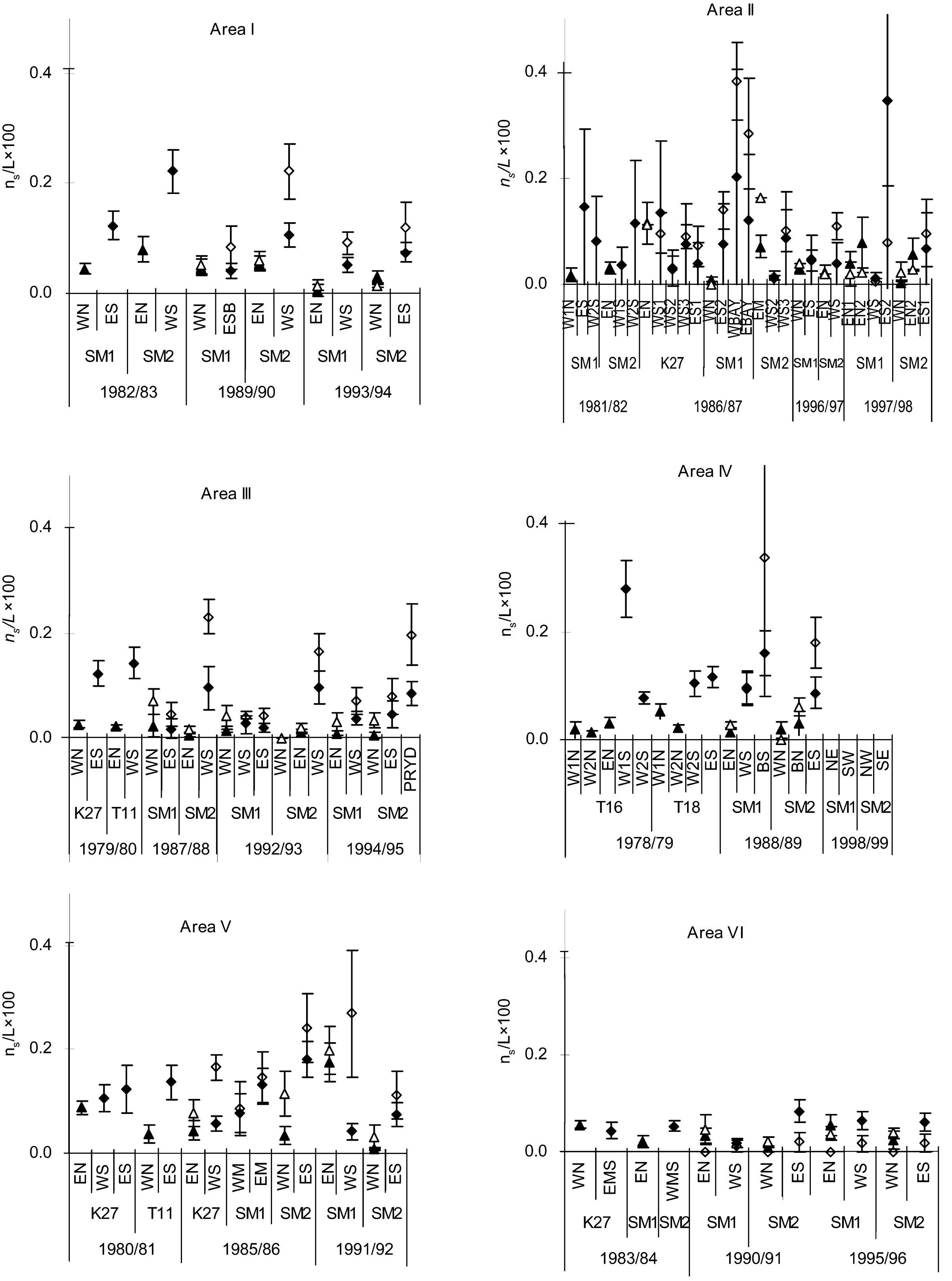

Fig. 8. Comparison of the number of the primary sighting of minke whale (*n*/*L*; schools / 100 n.miles) with the ±1 STD error in each cruise by survey mode (Closing mode; black and IO mode; white) from 1978/79 to 1997/98 (data from Branch and Butterworth, 2001b). N: northern, M; middle, S; southern. Each stratum was established in different latitude by each circumpolar cruise (see Fig. 2a-2f).

has not been consistent, not only in the south (where minke density is expected to be the higher) but also in the north (Fig. 2a-f and 3). As a result, the distance searched on primary effort in the northern stratum has increased by over 30-50% in Areas I, II, III and VI (Fig. 6). These effects possibly led to a decrease in the encounter rate in the northern stratum in CPIII (Fig. 8).

Change of whale identification standard

Systematic sighting procedures were developed and strict rules for identification of Antarctic minke, like minke, Southern bottlenose and Ziphiid whales were established from the 1985/86 cruise, along with increasing expertise of observers and researchers in identification of the species previously grouped as ‘akabo’. As a result of this progress,

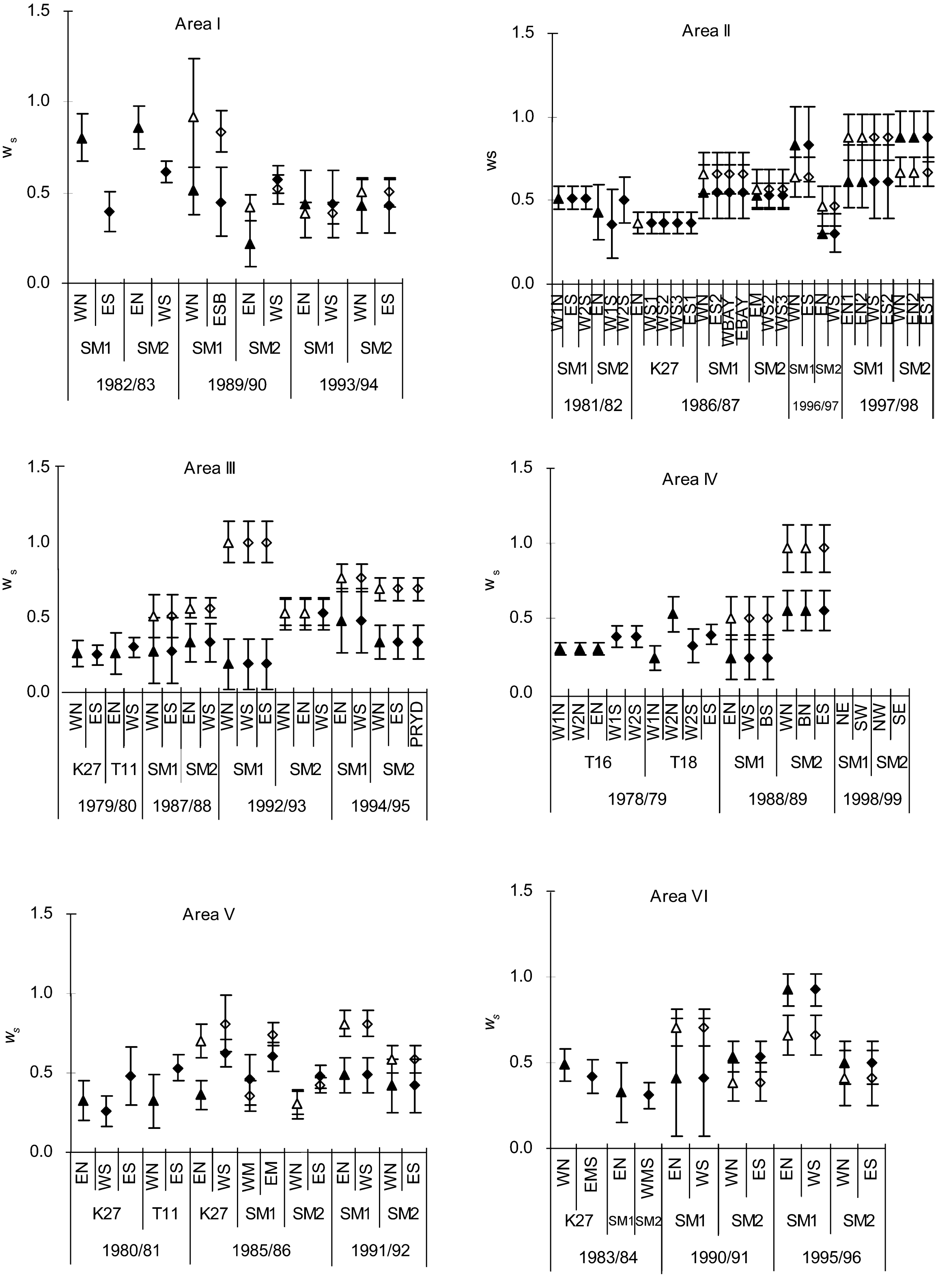

Fig. 9.The effective search half width (ESW) of the primary minke whale schools with the ±1 STD error (data from Branch and Butterworth, 2001b). The ESW were pooled by each vessel in 3rd circumpolar series. Northern stratum; triangle, southern stratum; circle. Closing mode; closed, IO mode; empty

the number of schools of 'unidentified whale (code 09)' and 'unid. Ziphiid' have decreased while 'like minke' and 'southern bottlenose' whales have increased in Areas II, III and IV (Figs 11 and 12). In relation to the standardisation of identification and research procedures, there is no single clear reason to account for the change in proportion, across years, of minke identifications and 'like minke' identifications. Plausible explanations may include the following.

(1) Changes in the distribution of survey coverage (northwards) may have increased the likelihood of encountering smaller group sizes of minke whales, particularly solitary animals (an increase in solitary animals would lead to a decrease in the success rate of closures and identification in closing mode and increased difficulty tracking and identification in IO mode). There may also have been changes to the clustering pattern of minke whales (towards a more

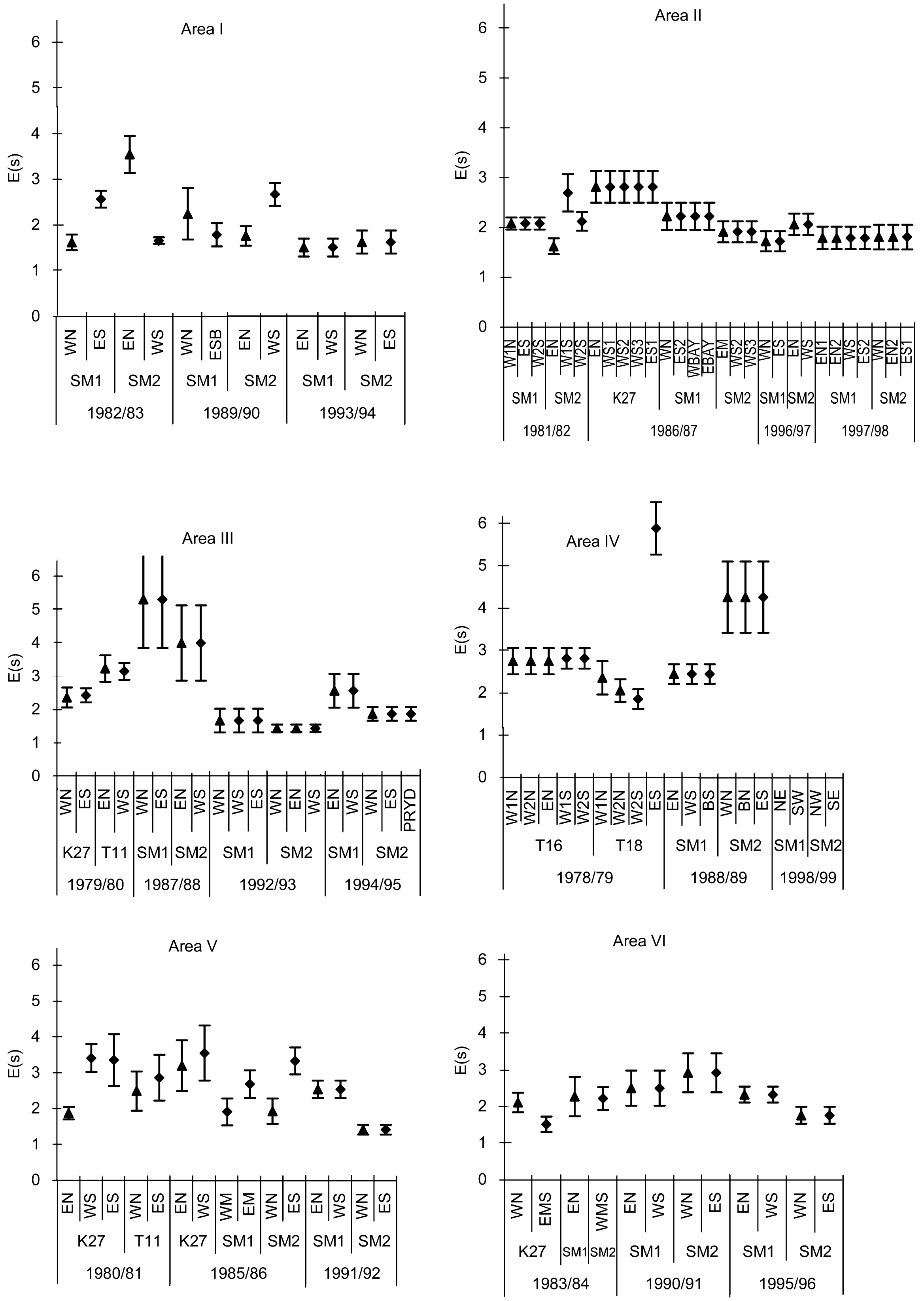

Fig. 10. The estimated mean school size of minke whales (*E(s)*) of the primary minke whale schools with the ±1 STD error (data from Branch and Butterworth, 2001b). The *E(s)* were also pooled by each vessel in 3rd circumpolar series. Northern stratum; triangle, southern stratum; circle.

dispersed distribution) or a change in age structure (smaller animals are generally more difficult to identify) or change in school size or distribution of prey species (*Euphausia*).

(2) Areas of higher sighting rate of minke whales may have been encountered in some years and not in other years. In both survey modes (and particularly in IO mode), when the sighting rate is high there is greater likelihood

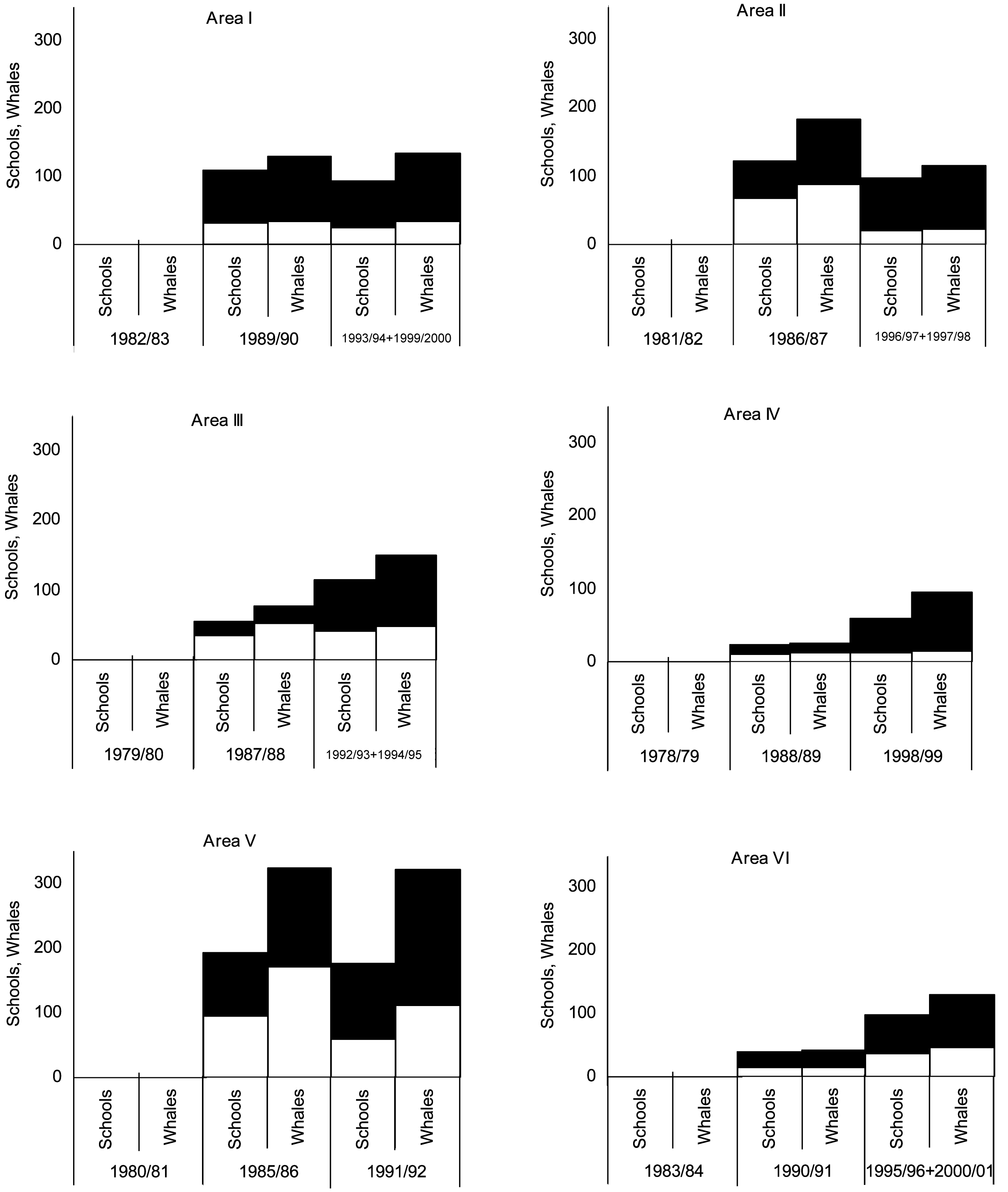

Fig. 11. Comparison of the number 'like minke' (primary schools and whales) by each Area during 1978/79 to 2000/01 cruises (Closing mode; lower, IO mode; upper). More 'like minke' sightings tended to be recorded during IO mode.

that the increased time spent assessing duplicate status means that not all groups will be tracked and identified.

(3) The introduction of younger, less experienced observers into the programme.
(4) Researchers may have had different levels of strictness, across years, in assigning identifications.

Change of research schedule

The two- to three-week delay in the schedule for the cruises since the 1994/95 cruise may have had some subtle effects on the results of the sighting survey. Prior to, and after the changes to the schedule there was a significant difference in effective half width between the ships. Consistently on all recent cruises, the SM1 has had a significantly greater effective half width, than SM2, (Borchers, 1993; Burt and Borchers, 1996; Burt and Borchers, 1999), except for the 1992/93 cruise (when SM2 went to the Southern Stratum first (Borchers and Cameron, 1995) and excluding the 1997/98 cruise results when strata were pooled (Burt and Stahl, 2000).

It is possible to speculate that there may be a difference in minke whale sightability between the strata from early-season to late-season. The methods and equipment

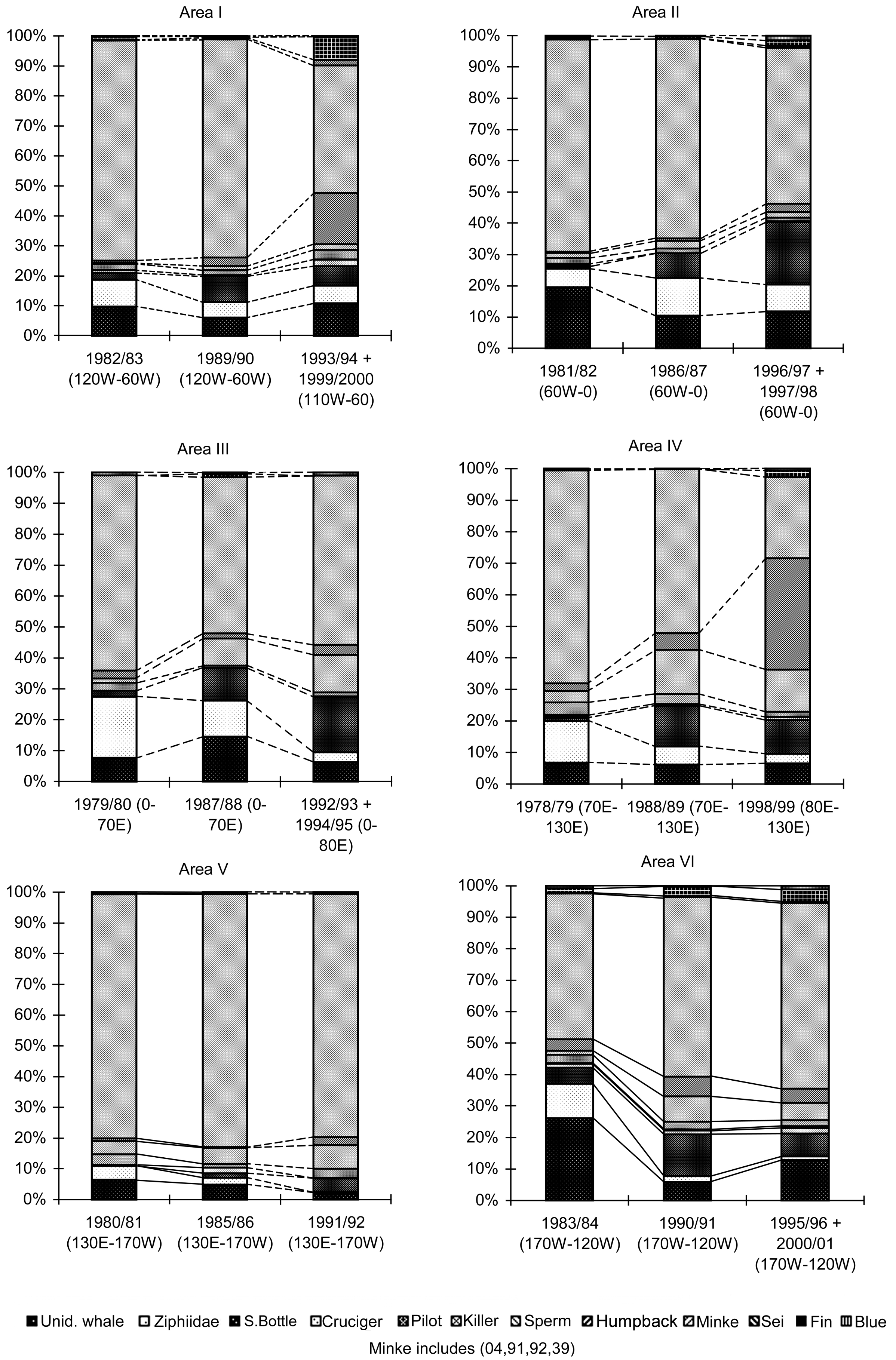

Fig. 12. Compositions of the primary school sightings in each circumpolar set by Area, during 1978/79 to 2000/01. Blue, fin, sei, minke, humpback, sperm, killer, pilot, cruciger, southern bottlenose, Ziphiidae and unidentified whales are analysed. Minke whale includes codes ‘04; Minke’, ‘91; Undetermined minke’, ‘92; like Antarctic form’ and ‘90; like Dwarf form’ and ‘39; like minke’.

used for distance estimation are the same between the ships; the sighting ability of the crews should not differ significantly as the crews are rostered 'randomly' to the ships for each cruise. The standards used for acceptable sighting conditions should also be the same on each ship. Factors affecting sightability may be the result of differences in weather conditions (in sightability conditions) or differences in group size, behaviour, body size (and related cue size). For example, a proportion of the 'larger?, behaviourally more obvious?' animals (for which closing/tracking are completed more easily, thereby aiding identification) may change their clustering pattern and/or behaviour during the season, or move further south into the pack ice and be inaccessible for survey. This may also have implications for the identification of species, particularly the change in proportion of minke and 'like minke' identifications.

Change of research hours

The reduction in research hours from 16 hours per day for the earlier cruises, to the current 12 hours per day may have had an impact on the sighting efficiency of observers. Although the observers have always had scheduled 'rest' periods, they have always had additional ship maintenance and management tasks to complete. The reduction in working hours would have reduced the fatigue of the observers and it is possible there has been a related increase in their sighting efficiency, while total distance searched during a cruise had decreased. In this regard, Branch and Butterworth (2001a) indicate that the shape of the detection function for minke whales (and humpback and sperm whales) has changed over the three circumpolar series, with broadening of the shoulder (see Branch and Butterworth, 2001a; fig. 2) implying sightings of these whales are now made at greater distances.

Distance estimation across years

The Estimated Angle and Distance Experiment protocol has been described here in detail. Since it has been conducted in a consistent manner using the same equipment for many cruises, and because several observers have taken part on several different cruises, it may be possible to test if there has been any trend in distance estimation over time. This may also help explain the change in the shape of the detection function for minke whales as indicated in Branch and Butterworth, (2000a; b).

ACKNOWLEDGEMENTS

We acknowledge the very generous support of the Government of Japan and the Soviet Union for providing the ships and crews for this research programme. Thanks are due to all researchers, Captains, officers, crewmembers for their hard work under difficult conditions and also to the port organisers for their help and support. Peter Best, Gerald Joyce and Seiji Ohsumi provided a wealth of advice and previous documents of cruises. Hirihisa Shigemune provided the data of crew and their experience in this programme. Doug Butterworth and Trevor Branch consented to use their figures and results of analysis data. We also thank the IWC Secretariat for use of DESS and to Atsushi Wada for his data work in this report. Photographs of the research vessels are provided by Kyodo Senpaku Kaishū Ltd. and Hiroto Murase. We thank the two reviewers, Gerald Joyce and Doug Butterworth who made valuable suggestions to this manuscript, as did the Editor. Very sadly, one of our co-authors, Fujio Kasamatsu passed away suddenly on 22 July 2001. We lost a great friend and colleague. We are indebted to Fujio for his special contribution to the knowledge of Antarctic cetaceans; he was graced with an unerring enthusiasm for work at sea, matched by a sustained interest in the analysis of these data. May he rest in peace.

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Date received: January 2002.
Date accepted: July 2003.

Appendix 1

SPECIFICATIONS OF THE JAPANESE RESEARCH VESSEL IN IWC/IDCR AND SOWER CRUISES

Note: a list of all crew members and researchers for each cruise can be found at
http://www.iwcoffice.org/publications/additions.htm

	Shonan-Maru	*Shonan-Maru No.2*	*Kyo-Maru No.27*	*Toshi-Maru No.11*	*Toshi-Maru No.18*	*Toshi-Maru No.16*
Call sign	JFBW	JFCF	JBOT	JNOL	JPMQ	JPLG
Register length (m)	64.80	64.80	63.50	63.20	63.20	63.20
Molded breadth (m)	10.20	10.20	9.90	9.90	9.90	9.90
Gross register tonnage	709	710	729.55	740.37	758.33	758.33
Barrel height (m)	20	20	17	17	17	17
IOP height (m)	14	14	-	-	-	-
Upper bridge height (m)	11.8	11.8	10	10	10	10
Bow height (m)	6.5	6.5	6.5	6.2	6.2	6.2
Maximum continuous output	5,280	5,280	3,600	3,500	3,500	3500
Main sailing technique	GPS	GPS	Celestial	Celestial	Celestial	Celestial
NNSS from 1981, GPS from 1991						

Appendix 2

PHOTOGRAPHS OF RESEARCH VESSELS IN IWC/IDCR AND SOWER CRUISE BETWEEN 1978/79 AND 2000/01 (SEE TABLE 1)

Photographs opposite

Toshi Maru No. 11

Toshi Maru No. 16

Toshi Maru No. 18

Kyo Maru No. 27

Vdumchivy 34

Vderzhanny 36

Shonan Maru

Shonan Maru No. 2

Appendix 3

EXAMPLES OF THE PROTOCOL USED FOR THE ESTIMATED DISTANCE AND ANGLE EXPERIMENT

Example 1, 1998-99 IWC-SOWER Antarctic cruise *Shonan Maru*

The Estimated Angle and Distance Experiment was conducted on the *Shonan Maru* on 30 January 1998.
Selected target distances and angles were:

Distance (nmile)	Angle
2.87	P 004°
2.38	S 015°
1.73	P 034°
1.44	S 028°
0.78	P 011°
0.41	S 007°

Persons taking part in the experiment were divided into five teams (A-E). The members of the teams and their allocation to the platforms are shown in Table 1.

Table 1

IWC/SOWER Antarctic Cruise 1998-99. Estimated Angle and Distance experiment from the *Shonan Maru*.

	Top barrel	IOP	Upper bridge
A	Nitta	Kurisu	Kurogi and captain
B	Abe and Sakimukai	Nitta	Kurisu
C	Wakazuki	Abe	Sakimukai & Kleivane
D	Kurogi	Wakazuki	Abe and Doherty
E	Kurisu	Kurogi	Wakazuki

The observers undertook the Experiment only from platforms where they normally conducted sighting effort. For example, Nitta (the Boatswain) did not normally conduct sighting effort from the Upper Bridge therefore did not undertake the Experiment from that platform. Similarly, Sakimukai (a young sailor with no previous Antarctic sighting survey experience) did not conduct sighting effort from the IOP and therefore did not undertake the Experiment from the IOP. (This was the first IDCR/SOWER cruise with participation of a young sailor with no previous Antarctic sighting survey experience and it had been agreed at the Planning Meeting that the observer rotation schedules would be arranged to ensure that the least experienced crewman would not be assigned to the IOP).

The teams were selected for the angle and distance estimates in a random order. The order of selection of teams and the target angles and distances for each trial are shown in Table 2.

Note, as shown in Table 2, that the tested angle and distance usually differ from the target angle and distance.

Example 2, 2000-2001 IWC/SOWER Circumpolar Cruise, *Shonan Maru*

The Estimated Angle and Distance Experiment was conducted on the *Shonan Maru* on 25 January 2001
Selected target distances and angles were:

Persons taking part in the experiment were divided into six teams (A-F). The members of the teams and their allocation to the platforms are shown in Table 3.

Table 2

IWC/SOWER Antarctic cruise 1998-99. Estimated Angle and Distance experiment from the *Shonan Maru*.

Trial no.	Team	Target dist./angle	Time	Compass	Radar angle	Radar distance
1	A	2.87 P 004°	132514	089	P003	2.70
2	C	2.38 S 015°	132827	068	S018	2.16
3	E	1.73 P 034°	133144	118	P035	1.60
4	B	1.44 S 028°	133445	057	P028	1.16
5	D	0.78 P 011°	133801	093	P014	0.62
6	A	0.41 S 007°	134002	068	S007	0.28
7	E	2.87 P 004°	135448	078	P004	2.72
8	B	2.38 S 015°	135803	059	S015	2.13
9	C	1.73 P 034°	140032	110	P036	1.73
10	A	1.44 S 028°	140257	047	S027	1.34
11	E	0.78 P 011°	140543	085	P013	0.87
12	B	0.41 S 007°	140749	061	S005	0.48
13	D	2.87 P 004°	142207	096	P006	2.71
14	A	2.38 S 015°	142451	074	S015	2.25
15	B	1.73 P 034°	142723	125	P035	1.77
16	D	1.44 S 028°	143011	065	S025	1.28
17	C	0.78 P 011°	143200	099	P011	0.74
18	E	0.41 S 007°	143445	080	S006	0.43
19	B	2.87 P 004°	144939	095	P006	2.81
20	D	2.38 S 015°	145204	073	S014	2.34
21	A	1.73 P 034°	145510	118	P035	1.82
22	C	1.44 S 028°	145734	048	S033	1.41
23	B	0.78 P 011°	150136	096	P012	0.67
24	D	0.41 S 007°	150343	068	S011	0.26
25	C	2.87 P 004°	151820	088	P003	2.76
26	E	2.38 S 015°	152055	070	S015	2.32
27	D	1.73 P 034°	152413	118	P035	1.70
28	E	1.44 S 028°	152626	049	S031	1.30
29	A	0.78 P 011°	152939	092	P009	0.71
30	C	0.41 S 007°	153134	069	S012	0.33

Distance (nmile)	Angle
2.67	P 009°
2.25	P 001°
1.63	S 027°
0.71	S 018°
0.32	P 014°
0.24	S 058°

Table 3

Estimated Angle and Distance experiment from the *Shonan Maru* IWC-SOWER circumpolar cruise 2000-2001

	Barrel	IOP	Front bridge
A	Suzuki	Nakato	Captain Sakai
B	Nishi	Suzuki	Nakato
C	Nakamura	Nishi	Van Waerebeek & Fukitome
D	Kawaragi	Nakamura	Takada
E	Fukitome and Takada	Kawaragi	Nakamura
F	Nakato	-	Kawaragi

Table 4

IWC/SOWER circumpolar cruise 2000-2001. Estimated Angle and Distance experiment from the *Shonan Maru*.

Trial no.	Team	Target dist./angle	Time	Compass	Radar angle	Radar distance	Ship GPS position	Ship GPS position
BUOY	XXX	XXX		XXX	XXX	0.00	6811.42S	12846.05W
1	A	2.67 P 009°	08:25	293	S010	2.65	6812.70S	12840.43W
2	E	2.25 P 001°	08:30	309	P002	2.04	6812.36S	12842.05W
3	C	1.63 S 027°	08:37	278	S025	1.56	6812.01S	12843.11W
4	F	0.71 S 018°	08:43	300	S018	0.71	6811.66S	12845.19W
5	D	0.32 P 014°	08:50	336	P014	0.32	6811.36S	12845.93W
6	B	0.24 S 058°	08:58	299	S061	0.24	6811.29S	12846.48W
BUOY	XXX	XXX	09:01	XXX	XXX	0.00	6811.05S	12846.66W

For all trials, (on both ships), the GPS position of the ship was recorded simultaneously with each trial of observers' estimates. Also on both ships, the GPS position of the buoy was recorded at the end of each set of six trials when the ship passed within a few meters of the buoy (thus the set and drift of the buoy could be determined). The aim of this was to provide verification of the GPS distances calculated from the results of the GPS Experiment.

Note that observers undertook the Experiment only from platforms where they normally conducted sighting effort. For example, Suzuki (the Boatswain) did not normally conduct sighting effort from the Upper Bridge therefore did not undertake the Experiment from that platform. Similarly, Takada and Fukutome (observers with no previous Antarctic sighting survey experience) did not conduct sighting effort from the IOP and therefore did not undertake the Experiment from the IOP.

The teams were selected for the angle and distance estimates in a random order. The sample of order of selection of teams and the target angles and distances for each trial are shown in Table 4.

Appendix 4

EXAMPLE OF LIST OF OBSERVER CODES AND DETAILS OF PREVIOUS IDCR/SOWER EXPERIENCE, IWC-SOWER CIRCUMPOLAR CRUISE 2000-2001

For the purposes of data validation the codes used to identify observers on the data records are listed below.

Table 1

Example lists of observer codes and details of previous IDCR/SOWER experience.

		Experience (years)	
Code	Name	IDCR/SOWER	JARPA/JARPN
Shonan Maru			
1	Suzuki	4	8/5
2	Nishi	2	6/4
3	Nakamura	3	3/4
4	Kawaragi	2	2/2
5	Nakato	1	1/1
6	Takada	1	0/0
7	Fukutome	1	0/0
8	Captain Sakai	5	5/3
C	Crew (and when no researchers present)		
E	Ensor		
M	Murase		
K	Van Waerebeek		
Shonan Maru No.2			
1	Nitta	7	7/7
2	Hirai	3	6/6
3	Maeda	3	3/3
4	Sawabe	1	3/2
5	Sakimukai	2	2/1
6	Nagai	1	2/2
7	Yamaguchi	1	0/0
C	Captain Miura	4	5/3
S	Crew (and when no researchers present)		
M	Matsuoka		
P	Pitman		
F	Marques		

Rediscovery of a humpback whale (*Megaptera novaeangliae*) feeding ground in the Straits of Magellan, Chile

JORGE GIBBONS[*], JUAN J. CAPELLA[+] AND CARLOS VALLADARES[#]

Contact e-mail: yubarta@emcali.net.co

ABSTRACT

New information is presented on the summer distribution of southeastern Pacific humpback whales along the Southern Chilean fjords. Sightings of 128 humpback whales observed between December and June from 1997-2001 were analysed. Sightings occurred between 48°50′S to 54°18′S and were concentrated in the waters surrounding Isla Carlos III in the Straits of Magellen (53°37′S, 72°21′W) and in the Canal Wide (49°36′S–5°S). To date, 23 individual whales have been identified from photographs of the ventral surface of the flukes. Throughout the austral summer, seven individuals were resighted near Isla Carlos III over periods between 2-5 months. Two individuals were observed in 1999 and 2000, and two individuals were previously recorded in 1997 in Canal Wide, about 365km north of Isla Carlos III. Historical records show the occurrence of whales in the area from the 16th to the 20th Century. From historic records, scattered whaling data, the small amount of scientific literature available, and the results of this study, it is suggested that the southwestern part of the Straits of Magellan, especially the waters surrounding Isla Carlos III, is the first known feeding ground for humpback whales along the Pacific coast of South America.

KEYWORDS: HUMPBACK WHALE; SOUTH AMERICA; PACIFIC OCEAN; SIGHTINGS SURVEY; PHOTO-IDENTIFICATION; FEEDING GROUNDS

INTRODUCTION

Humpback whales (*Megaptera novaeangliae*) are widely distributed throughout the oceans of the Southern Hemisphere. The question of stock identity has recently been reviewed by the IWC Scientific Committee (e.g. IWC, 1998b; 2001). Seven distinct Southern Hemisphere breeding stocks have been identified, including Group G – the West South America stock (see Fig. 1, IWC, 1998a, p.27). The general distribution and migratory destinations of humpback whales in the West South America stock (Group G) are known from studies based on whaling data (Townsend, 1935; Clarke, 1962; Aguayo, 1974; Ramírez, 1988), occasional sightings (Oporto, 1986; Guerra *et al.*, 1987; Aguayo *et al.*, 1998; Gibbons *et al.*, 1998; Capella *et al.*, 1999) and from the identification of individual animals (Stone *et al.*, 1990; Flórez, 1991; Flórez *et al.*, 1998; Scheidat *et al.*, 2000; Félix and Haase, 2001).

The known summer feeding grounds of the southeastern Pacific humpback whale stock extend along the western coast of the Antarctic Peninsula (Omura, 1953; Mackintosh, 1965; Olavarría *et al.*, 2000), south to the Antarctic Convergence. The cold inshore waters of the southern Chilean fjords, including the Straits of Magellan, have not been considered part of the summer range of humpback whales in the Eastern South Pacific.

In recent years, however, there has been an apparent increase in the frequency of sightings of humpback whales off the coast of Chile (Aguayo, *et al.*, 1998; Capella *et al.*, 1999), especially during summer and autumn in the Patagonian fjords between 49°S to 53°S (Gibbons *et al.*, 1998). This paper considers sightings and photo-identification data that have been collected since 1997 in the Southern Chilean fjords, as well as a compilation of historic records and opportunistic observations. These data are used to examine local distribution, seasonality and the possible existence of feeding grounds in the Straits of Magellan.

METHODS

Study area (Fig. 1)

The study was carried out along inner waters in the Southern Chilean fjords, from south of the Golfo de Penas (47°40′S) and the Beagle channel (55°S). The region exhibits a varied physiography, with more than 37,000km of coastline, great environmental heterogeneity and extreme oceanographic conditions.

Due to its large geographical extent, the area has been divided into the three regions described below.

Region (1). Patagonian fjords, from the south of Golfo de Penas (47°22°S, 74°50W) to the western area of the Straits of Magellan (52°40′S).

The area under study included the main channels that connect this area with the Pacific Ocean (Canal Messier, Canal Wide and Canal Concepción), interior channels and fjords that are adjacent to the Southern Ice fields (a 300km × 40km wide field of ice). This area is characterised by cold waters with low salinity due to the high rainfall, fresh water influx from rivers and glacial melting.

Region (2). The Straits of Magellan.

This is a 570km long V-shaped channel that connects the Pacific and the Atlantic Oceans and separates the southern part of the continent from Tierra del Fuego. Linked with the Straits are the sounds, Seno Almirantazgo, Seno Otway and Seno Skyring; due to their characteristics these last two sounds are considered true inner seas (Magazzú *et al.*, 1996). This region has rich habitat diversity as a result of the different influences of the water masses coming from the Pacific and the Atlantic Oceans, the east-west gradient in precipitation, the freshwater contribution of rivers and glaciers, and major differences in coastal morphology, tides and water depths (Panella *et al.*, 1991).

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[*] *Instituto de la Patagonia, Universidad de Magallanes, Punta Arenas, Chile, Casilla 113-D.*

[+] *Fundación Yubarta, Apartado Aéreo 33141, Cali, Colombia.*

[#] *España 666, Punta Arenas.*

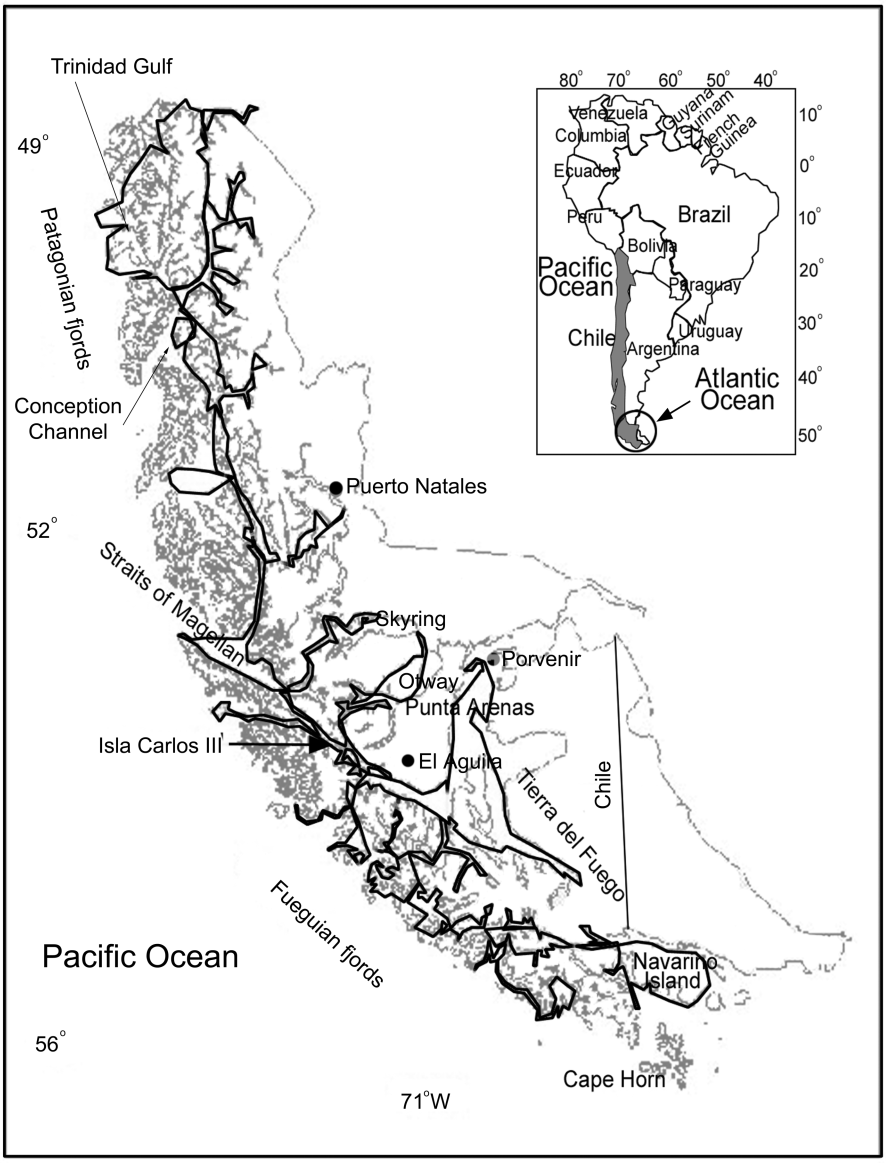

Fig. 1. Humpback whale survey track in the Patagonian and Fuegian fjords and the Straits of Magellan.

Region (3). Fuegian fjords located to the south of the Straits of Magellan.

These are similar to the Patagonian fjords in extent, environmental heterogeneity and varied physical geography, although glacial influence from the Darwin mountains is less important than from the Southern Ice fields. They are influenced in the east by Atlantic waters.

Survey methods and effort

Region 1

A total of 16 trips were made in different boats (14-16m in length, similar in height and speed) for a total of 126 days of work: 52 days in 1997, 47 in 1998, 25 in 2000 and 2 in 2001 (Table 1). The surveys followed a predetermined track of approximately 1,172km (Fig. 1), with minor variations in five excursions. Iceberg Fjord, Peel Fjord, Golfo de Trinidad and Seno Ladrones were occasionally visited in addition to the predetermined track.

Region 2

Both systematic and non-systematic sampling occurred. In the Primera Angostura of the Straits of Magellan, 227 crossings were made on commercial ferries between Punta Delgada (52°29′S, 69°30′W) and Bahía Azul (52°029′, 69°31′W) for a total of 22 days between May 2000 and June 2001, on a twice-monthly basis (Fig. 1).

Table 1

Survey effort and sightings by month in the whole study area (three sectors) for the period 1997-2001.

	Region 1		Region 2		Region 3	
Month	Days	Groups	Days	Groups	Days	Groups
Jan.	0	0	7	11	4	0
Feb.	28	7	15	20	5	1
Mar.	30	15	11	32	0	-
Apr.	9	3	13	17	21	1
May	11	3	11	12	0	-
Jun.	14	3	7	0	0	-
Jul.	0	-	7	0	0	-
Aug.	8	0	4	0	7	0
Sept.	0	-	10	0	0	-
Oct.	20	0	6	0	8	0
Nov.	0	-	10	0	7	0
Dec.	6	1	7	1	11	0
Total	126	32	108	93	63	2

In the central area (Paso Ancho) of the Straits of Magellan, 48 trips were made between Punta Arenas (53°07′S, 70°55′W) and Bahía Chilota, Tierra del Fuego (53°18′S, 70°26′W) onboard commercial ferries (Fig. 1), for a total of 24 days between June 2000 and June 2001, on a twice-monthly basis.

Between Seno Otway and the southern portion of the Straits of Magellan (Fig. 1), surveys were conducted along a 259km predetermined (entire or partial) track. A total of 57 days over 21 months from 1999 to 2001 were dedicated to surveys (Table 1). Two main vessels were used: a 10m rigid inflatable boat with an inboard diesel engine and a *Zodiac* MK5 equipped with a 40Hp outboard engine. Shore based surveys around Isla Carlos III and vessel surveys along the Straits of Magellan from Punta Arenas to the western mouth of the Straits were occasionally conducted.

Seno Skyring was surveyed opportunistically on 3 and 21 February 2000 and 30 March 2001, as was Seno Almirantazgo on 1 September 2000 and 8 February 2001.

Region 3

A total of seven trips was made in December 1999, April, August, October and November 2000 and February 2001, for a total of 63 days (Table 1). These trips were made using different boats (14-16m in length, similar in height and speed), along a predetermined 497km track between Paso Shag (Bárbara Channel) and the east of Isla Navarino (Fig. 1). Other surveyed sections, where the effort was more irregular, have not been considered in this analysis.

Data collection

For each sighting of a whale or a group of whales, the following information was recorded: date, time, GPS position, group size and feeding behaviour. Whenever possible, pictures of flukes or dorsal fins were taken. Humpback whales were usually individually identified by their unique patterns of ventral fluke pigmentation (Katona and Whitehead, 1981). Whales were photographed with a 35mm camera using a 70-210mm zoom lens, black and white or colour print film (ISO 100 and 200) and colour slide film (ISO 100 and 400). Photo-identification effort was low for Region 1 section and minimal for Region 3. Search effort does not include fieldwork carried out in rain or seastate > 4 Beaufort.

For the literature survey to determine the historic presence of whales in the study area, shipping reports, historic chronicles written since the European discovery of the Straits of Magellan in the 16th century, other non-referenced sources of information on whales, as well as available scientific literature were reviewed. Opportunistic records of humpback whales in recent years, obtained from photographs or detailed observations provided by qualified observers that included date and location, were also collected.

Data management and analysis

Sightings data were analysed by month in order to examine the temporal and geographic distribution of humpback whales.

Relative abundance (defined as the number of whales surveyed per hour during systematic sampling) was estimated by region and month. Analysis units of a constant length of 86.5km were established in the Fuegian and Patagonian fjords and in Seno Otway – Straits of Magellan. Relative abundance was compared among all the units with whale records in order to identify concentration areas of humpback whales.

High-quality fluke photographs (60% or more of the fluke surface and a vertical angle sufficient to distinguish the shape of the trailing edge of the fluke) were used to identify individual animals and create a catalogue. Poor-quality photographs were not considered in the dataset. Photographs were used to assess annual returns and within-season ‘residency’. The term ‘residency’ means here the interval from the first to the last sighting of an individual whale in a season. Photo-identification data collected along the Patagonian fjords (two whales) north to 51°S between 1997 and 1998 (Gibbons *et al.*, 1998) were also included for regional comparison between Regions and verification of local movements.

RESULTS

Distribution, abundance and seasonality of whales

An overall summary of effort and whales observed in the three regions is given in Table 1. A total of 128 groups were observed. These groups were distributed from Canal Messier (48°50′S) in the north to the Fuegian fjords (54°18′S) in the south. Whales were not evenly distributed, with a number of concentrations being observed. The highest relative abundance in the period December to May, was observed in the units that included the Straits of Magellan between Canal Jerónimo and Isla Charles, with 1 animal/hour, increasing to 1.51 animals/hour in the specific area of Isla Carlos III but decreasing to 0.21 animals/hour in Canal Wide in the Patagonian fjords region (Fig. 2). Humpback whales were not seen in Seno del Almirantazgo, Seno Skyring or in the western Primera Angostura and the central areas (Punta Arenas – Porvenir) of the Straits of Magellan. They were only occasionally seen in the northernmost part of Fuegian fjords (2 sightings) with just one sighting on a systematic track in good conditions (Figs 1 and 2).

Humpback whales were observed from late spring to late autumn. The first sighting was made on 1 December (1998) and the last on 8 June (1997). No whales were directly observed between July and November although there is evidence from other observers of the presence of humpback whales in the months of August, October and November (see below). The greatest frequency of sightings (98%) occurred between January and May (Fig. 3).

Group size

Humpback whales formed small groups, with a maximum of five, a mean of 1.9 (SD = 0.73) and a mode of two. Group size distribution is given in Fig. 4.

Resighting, local movements and residency of individuals

Twenty-seven individual whales have been identified from fluke photographs. A total of six different animals have been resighted between years, indicating that at least some individuals return to the area. The observed ‘residence’ time of individuals throughout the summer season ranged from 1 to 5 months, with three different whales being seen more than once in a year. The individual with the longest ‘residence’ was identified in January, February and May 1999. Short-range movements were recorded in different years for two individuals photographed in Canal Wide (50°03’S, 74°33’W) in February and June 1997 respectively, and again in the proximity of Isla Carlos III in February and April 1999, respectively. These sites are separated by approximately 365km.

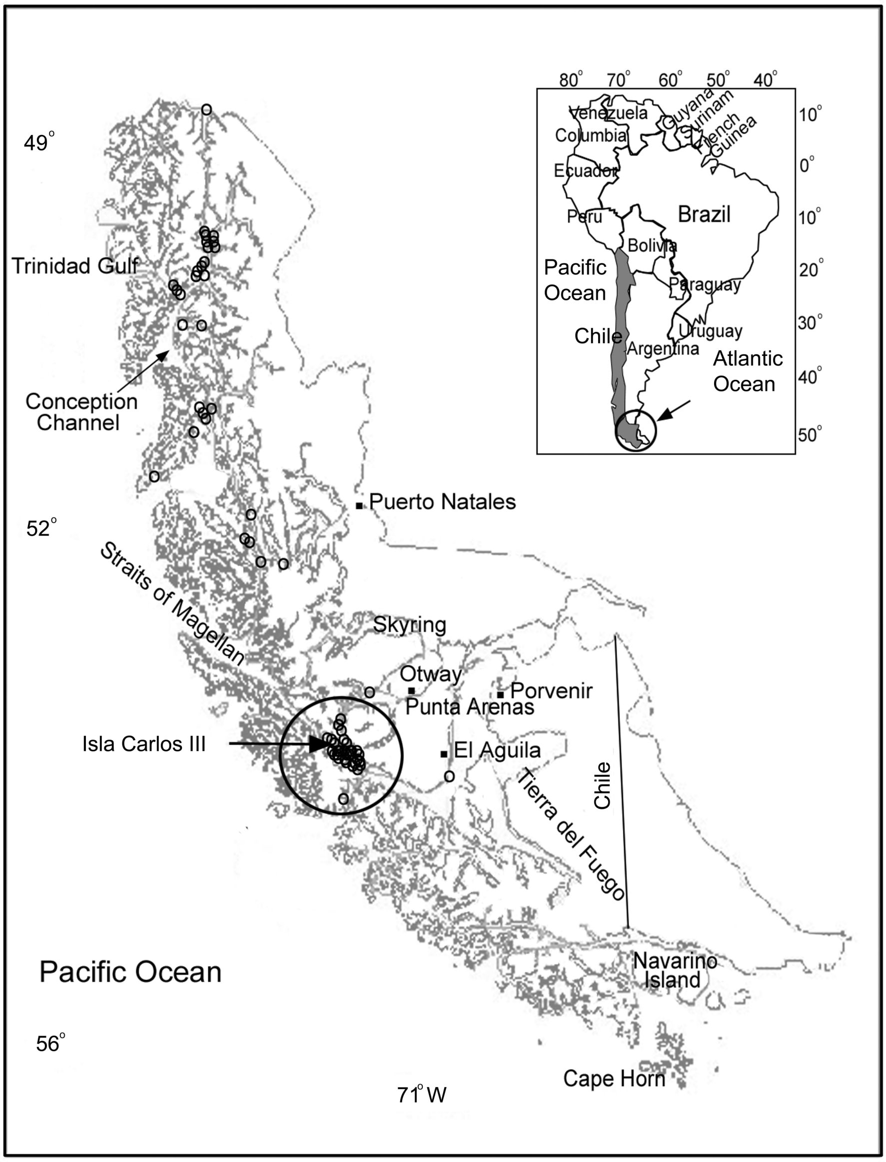

Fig. 2. Humpback whales sighting distribution on the Patagonian and Fuegian Fjords and the Straits of Magellan.

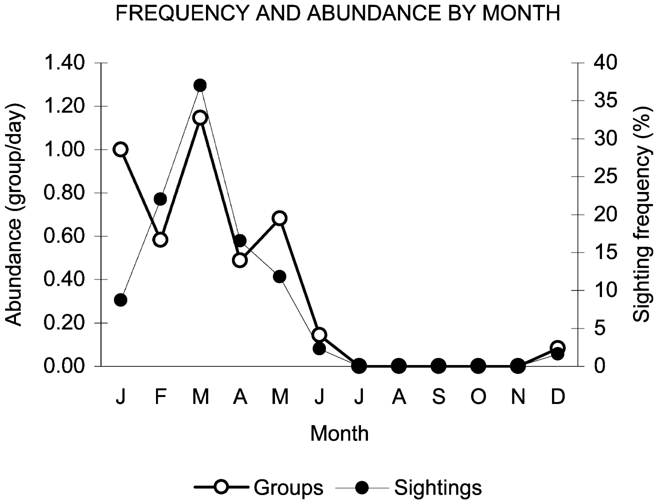

Fig. 3. Seasonal changes in abundance of humpback whales throughout the study period (1997-2001) in the Southern Chilean fjords region.

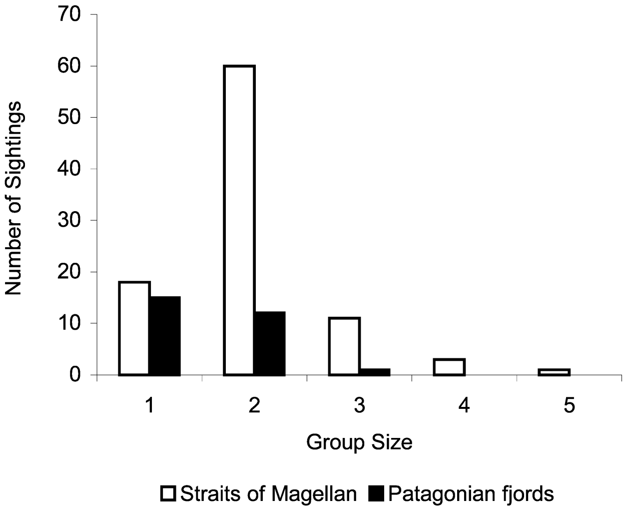

Fig. 4. Frequency histogram of group size in the Patagonian fjords and the Straits of Magellan during the study period.

Foraging activities

Common humpback whale feeding behaviour was observed throughout the summer and autumn, including surface feeding (both vertical and horizontal lunge feeding; Jurasz and Jurasz, 1979) and 'flick' feeding. However, other typical feeding behaviour described for the species in the Northern Hemisphere, bubble net and bubble cloud feeding (Jurasz and Jurasz, 1979; Hain *et al.*, 1982), was not recorded. Defecation was not observed during the study.

Other behaviour, presumed to be subsurface feeding, was also observed. This included observations of regular diving in the same location for 7-15 minutes whilst simultaneous surface feeding by South American fur seals (*Arctocephalus australis*) and sea birds (skuas, *Catharacta chilensis*; South American stern, *Sterna hirundinacea*; black-browed albatross, *Diomedea melanophris*; and Southern fulmar, *Fulmarus glacialoides*) occurred. These events were observed for several hours on 12 different days in 1999 and 2000. The prey species recorded, based on surface observations during these events, were Galatheid crab (*Munida subrugosa*) and schooling fish such as herring (*Sprattus fueguensis*).

Historic and present time records

There is evidence of the presence of whales in the Straits of Magellan, mainly near Isla Carlos III, for six consecutive centuries. Up to the middle of the 19th century, these reports referred in a general way to 'whales'. Pedro Sarmiento de Gamboa, a 16th century explorer, charted numerous sightings around Isla Carlos III (53°37′S, 72°21′W) and the western branch of the Straits of Magellan during the summer (February) in 1583 (Sarmiento de Gamboa, 1954). Less than one hundred years later, John Narborough observed whales in the same area in November 1670 (Mantellero, 2000) and L.A. Bougainville one century later, on 27 December 1767 (Bougainville, 1946)[1]. In the 19th century, Phillip Parker King (Adventure and Beagle Expedition) sighted large numbers of whales near Caleta Bradley, 20km south of Isla Carlos III in April 1828 (King and Fitz Roy, 1839). The first explicit mention of humpback whales was made by C. Skogman in 1841. He stated that the frigate *Eugenia* encountered 'many humpbacks and finbacks' around Isla Carlos III (south of the English Narrows) in February, 1841 (Skogman, 1942)[2]. B. Phillipi mentioned humpback whales in the Straits of Magellan in 1843 (Martinic, 2001). A shore whaling station was established to the southeast of Punta Arenas (see Fig. 2) in Bahía El Aguila (70°58′S, 53°48′W), on the northern coast of the Straits of Magellan in 1905. Hunting operations from this shore station were concentrated on the coastal waters of the southern tip of western South America (Martinic, 1977), although the species hunted were not clearly documented. The first confirmed report of humpback whales in the Patagonian fjords during the 20th century concerns whales taken in 1914 and 1915 by Chilean whalers (Martinic, 1977).

Since the 1970s, several confirmed records of humpback whales have been collected. In 1972 and 1973, photographs of the same individual were taken in the Patagonian channels and the Straits of Magellan (Orlando Dollenz, pers. comm.); two whales were sighted in the Canal Wide in the Patagonian fjords in January, 1984 (Oporto, 1986); a picture of two humpback whales from Mussel Bay, Isla Carlos III in April, 1984 (Alfonso Martinez, pers. comm.); two sightings from the Canal Abra Channel, 40km north of Isla Carlos III in March, 1997 (Francisco Garrido, pers. comm.); two individuals near Isla Carlos III in January, 1998 (Rodrigo Hucke, pers. comm.); one individual in Mussel Bay, Isla Carlos III in October, 1999 (Porter, pers. comm.); pictures of one individual from Primera Angostura, in the eastern portion of the Straits of Magellan in August 1999 and near Punta Arenas in June, 2000 respectively (Carlos Leal, pers. comm.); pictures of one individual from the Fuegian fjords in March, 2000 (Alejo Contreras, pers. comm.); and a videotape of two individuals from Seno Unión (52°10′S) in the Patagonian fjords in November 2000 (Gonzalez, pers. comm.). Gibbons *et al.* (1998) detailed 32 sightings obtained in surveys along the Patagonian fjords (48°S-52°40′S); these are included in this paper.

DISCUSSION

Distribution and seasonality

The information shows that Isla Carlos III, in the southwestern section of the Straits of Magellan, appears to be a suitable feeding habitat for humpback whales. However, the sample size and effort is still too small to determine the limits of this feeding ground or to eliminate the possibility of others in the southern Chilean fjords.

The occasional sightings of humpback whales in the Straits of Magellan (Leal, pers. comm.) and the Patagonian channels during winter suggest that not all animals undertake the migration to low latitudes each year, (c.f. Brown *et al.*, 1995). Some whales may remain in this feeding ground through the austral winter.

Residence

The sightings of the same animal over a 5-month period in the study area, is similar to the upper range reported for some summer areas from the Northern Hemisphere (e.g. Baker *et al.*, 1985; Clapham and Mayo, 1987; Katona and Beard, 1990; Clapham *et al.*, 1993). The annual return reported here (two whales) provides some evidence for the existence of foraging area philopatry. Studies conducted elsewhere have suggested that this is the case for humpbacks on other high-latitude feeding grounds in the North Atlantic and North Pacific (Baker *et al.*, 1985; Katona and Beard, 1990; Clapham *et al.*, 1993; IWC, 2002). It is probable that the data presented here under-represent the true rates of residence and annual returns given the low level of observations and effort.

Despite the inevitable uncertainty surrounding the species identity of early historical records, the probable residence of humpback whales in the area is reinforced by historical information that constitutes a complementary line of evidence. The existence of reports of 'whales' from each century after the 16th century, confirmed in conjunction with the presence of humpback whales from early 20th century, has led us to suggest that humpback whales have traditionally occupied this region as a summer habitat. A possible recolonisation by whales to their historic feeding area might reflect a recovery of the Group G stock from relatively recent commercial exploitation. However, there are no reliable estimates of the population size in their summer grounds and the extent to which humpback whales return to a specific location has not been fully documented.

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[1] Bougainville De, L.A. Viaje alrededor del mundo por la fragata del rey la 'Boudeuse' y la fusta la Estrella en 1767, 1768 y 1769. Segunda Edición. Espasa – Calpe Argentina, S.A. Buenos Aires 1946. Colección Austral.

[2] Skogman, C. Viaje de la fragata Eugenia. 1851-1853. Brasil, Uruguay, Argentina, Chile, Peru. Ediciones Argentinas Solar, Buenos Aires.

CONCLUSION

Although the data collected during the three years remains limited, it does show that feeding behaviour is observed. Together with the inference information about residence, it suggests that the area of Isla Carlos III is a feeding ground, the first identified for humpback whales in South America. It is located about 2,000km closer to the tropical areas than the principal feeding area near the Western Antarctic Peninsula (Stone *et al.*, 1990).

The relationship between the humpback whales of the Straits of Magellan with animals from Colombia and the Western Antarctic Peninsula is being investigated through analysis of genetic and photo-id evidence.

ACKNOWLEDGMENTS

We thank the Universidad de Magallanes and Instituto de Fomento Pesquero (IFOP) for helping to fund this research. We are grateful to Conrado Alvarez, Ricardo Matus, Olivia Blank, Stefan Bräger, Alejandro Kush, Jaime Gibbons, Alfonso Martínez, Jaime Cárcamo and Carlos Seguel for their field assistance and to Antonio Larrea, Isabel C. Avila and Alexander Tobón for helping in photographic laboratory work. We also thank Alejo Contreras, Patricio Contreras, Orlando Dollenz, Rodrigo Hucke, Carlos Leal, Francisco Garrido, Jorge Ramírez, Mariano Riveros and Tim Scoones for providing us with records and numerous photographs: Alfredo Prieto and Mateo Martinic helped us generously in assembling historical data.

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Date received: November 2001.
Date accepted: July 2003.