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Roadmap to success for the International Whaling Commission - Southern Ocean Research Partnership (IWC-SORP) Theme 6 - the Right Sentinel for Climate Change: linking southern right whale foraging ecology to demographics, health and climate

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INTERNATIONAL WHALING COMMISSION

Roadmap to success for the International Whaling Commission - Southern Ocean Research Partnership (IWC-SORP) Theme 6 - the Right Sentinel for Climate Change: linking southern right whale foraging ecology to demographics, health and climate

Report on the southern right whale workshop held at the World Marine Mammal Conference, Barcelona, Spain, in December 2019

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1. INTRODUCTORY ITEMS

1.1 Arrangement for the workshop

The Workshop was held at The Centre de Convencions Internacional de Barcelona (CCIB), Spain, on Saturday 8th December 2019.

Workshop details as follows:

Workshop organizing committee: Emma Carroll, Els Vermeulen and Claire Charlton

Chair Person: Carlos Olavarría was elected Chair

Meeting Rapporteur: Penny Clarke

Workshop Participants: Annex A

Agenda: Adopted as given in Annex B

1.2 Review of the documents and available material

Documents circulated to the workshop participants prior to the meeting included:

- Agenda (Annex B)
- Right Whale Simple Common Model Description – Doug Butterworth (Annex C)
- Long term southern right whale dataset summary table (Annex D)
- Gaps analysis template for completion within each region (Annex E)

In the lead up to the Workshop, participants were requested to provide information for the gaps analysis and the long term southern right whale dataset summary table, in collaboration with other researchers from each region. Participants provided relevant information.

2. SESSION 1: THE RIGHT ADVICE

2.1 Introduction to the IWC-SORP theme and workshop overview

Southern right whale (SRW, *Eubalaena australis*) recovery from commercial whaling has been monitored in wintering grounds in Argentina, Brazil, South Africa, Australia and New Zealand through decades-long photo identification (photo-ID) and genetic monitoring studies. However, in recent years, a decrease in SRW reproduction through increased mortality and the lengthening of calving intervals was observed in some wintering grounds, which has been associated with reduced population growth. Reproduction is dependent on female body condition, which is, in turn linked to foraging success. Therefore, the IWC-SORP SRW theme will combine new knowledge on foraging areas and migratory linkages with existing long-term datasets from wintering grounds to investigate the impact of climate variation on SRW recovery.

The SRW IWC-SORP theme has four objectives:

1. Increase our understanding of SRW foraging habitats and ecology
2. Update our knowledge on SRW population dynamics in a comparative framework
3. Pursue integration of health assessment indicators with long-term monitoring data
4. Investigate the impact of climate variation at foraging grounds on population recovery

The first objective on foraging ecology aims to make use of a range of tools, such as genetics, telemetry, stable isotope analysis and acoustics to identify the location of SRW foraging grounds, investigate habitat use and determine prey species, and assess links between summer foraging and winter nursery/socialising grounds.

The second objective aims to develop a comparative framework with which to estimate population parameters across wintering grounds, using both photo-ID and genetic data.

The third objective aims to integrate health indicators with long-term monitoring data through visual health assessments, photogrammetry, and physiological indicators of health, to provide reliable tools that detect changes in SRW health over time and across wintering grounds.

The final objective is to investigate the impact of climate variation at foraging grounds on population recovery. This will be done by assessing meaningful linkages between foraging, health and reproduction, and assessing the impact of climate change on foraging grounds and prey resources.

The three Workshop objectives were:
(1) Generate discussion with experts on tools that could be used to address the IWC-SORP Theme 6 objectives
(2) Develop a tool to identify research priorities to achieve the IWC-SORP SRW theme objectives
(3) To form working groups under each of the four objectives to increase communication and outreach within the IWC-SORP community and to enhance the network for collaborative research.

The purpose of this report is to present a summary of the workshop and progress towards the workshop objectives to the IWC Science Committee (SC) Southern Hemisphere Sub-Committee in IWC SC68B in May 2020.

Those who were not in attendance of the meeting were acknowledged and in particular, recognition was given to the outstanding contributions of Bannister and Best to the SRW research field.

2.2 Inference from comparing multiple right whale populations: lessons learned (Presenter: Peter Corkeron)

Prior to the paper by Pace et al. (2017), demonstrating that North Atlantic right whales (*E. glacialis*, NARW) were in decline, there had been a general belief in the community of scientists and managers working on the species that it was doing well. This was despite the clear difference in the rates of recovery of NARW and several populations of SRW. NARW seemed to be increasing slower than were SRW. By comparing times series of calf counts between three SRW populations and NARW, we showed that NARW were not recovering at anywhere near the rate at which SRW were (Corkeron et al. 2018). Further, using matrix models of female NARW life history, we also showed that NARW could have increased at least twice the rate that they did through to 2010. The comparison with SRW recovery helped impress the point that NARW recovery has always been inadequate. A clear message of the work was that human-caused mortality had always jeopardized the recovery of NARW. The success of the collaborative project comparing the time series of calf counts was driven by a few factors (1) focus: the project was focused, and had a very clear aim – a scientific paper; (2) success at remote working: the work was web-based, with no meeting needed, which would have caused delay, and incurred costs (3) prioritisation: everyone involved in the project agreed to collaborate and share data quickly; (4) respect: all contributors saw that the conservation aim of the work was important, and everyone respected each other's contributions. Perhaps most importantly, all collaborators trusted each other: their motives, the quality of their science, and everyone's capacity to work together to achieve a shared goal. These are lessons to take forward into IWC-SORP right whale theme.

3. SESSION 2: THE RIGHT TOOLS

3.1 OBJECTIVE 1: FORAGING ECOLOGY

3.1.1 Telemetry (Presenter: Alex Zerbini)

SRW typically migrate between wintering breeding/calving grounds close to land masses and feeding habitats in the open ocean. Their distribution, seasonal occurrence and behaviour during the winter reproductive season is relatively well known in the main calving areas (e.g., eastern coast of South America, South Africa, New Zealand sub-Antarctic and southwest Australia). However, much less is known about their migratory behaviour, feeding destinations and foraging ecology mainly because these whales appear to disperse into middle and low latitude open ocean areas where survey conditions can be challenging and expensive. Telemetry methods have become a powerful tool to assess movements and behaviour of cetaceans in the past two decades, especially in cases where animals move to remote habitats. Whale borne electronic tags are in continuous development; current instruments can carry multiple sensors, are more reliable, and less impactful to individual animals. During his presentation, Zerbini provided a summary of the different telemetry methods available to study foraging ecology of whales, with an emphasis on long-term satellite tracking. Findings from an ongoing study with western South Atlantic SRW were shared as an example of how these technique can be used to investigate movements of whales once they leave the calving grounds, including an assessment of the migratory routes and destinations, as well as preferred foraging habitats (Zerbini et al. 2018).

3.1.2 Stable Isotopes (Presenter: Emma Carroll)

Stable isotopes analysis (SIA) is a tool that has been used extensively in ecology to examine animal diet, habitat use, movement, and physiology (Newsome et al. 2010). In the context of the SORP SRW theme, it offers the ability to use skin samples collected from whales on their wintering grounds to provide information on the foraging grounds visited by whales in the prior 2-3 months. Carroll, presenting also on behalf of Newsome, discussed how the power of such analyses will depend on (1) baseline isotopic variation in the ecosystem or source; (2) isotopic incorporation into the whale's tissue and (3) isotopic discrimination. For (1) there is considerable variation in the Pacific and Atlantic Ocean δ13C and to a lesser extent δ15N that provide the ability to discriminate foraging ground locations on a broad scale (Graham et al. 2010). For (2), it was discussed how isotopic incorporation is dependent on tissue type, which varies from rapid (e.g., breath CO2) to long-term or potentially life-long (e.g., bone collagen).

Baleen was described as the gold standard tissue, because as it grows it becomes a continuous but metabolically inert record (i.e., does not change once synthesised) of the whale's isotopic profile over several migratory cycles. In SRW, this record likely represents up to 8 years of migratory behaviours (Best & Schell 1996). For (3), it was discussed how isotopic discrimination is the difference in isotopic profile between diet and consumer tissue due to physiological processes. The most common SIA uses 'bulk' tissues, which includes two different categories of amino acids (AAs); essential, which cannot be synthesized de novo by the animal, and non-essential, which can be synthesized from macromolecular substrates (e.g., lipids and carbohydrates). As essential AAs are incorporated without alteration, they likely reflect the source or ecosystem the animal was foraging more strongly than non-essential AAs. Compound specific SIA seeks to characterise the isotope profile separately for essential and non-essential AAs, to tease apart the influence of trophic level and source isotopic influences (McMahon & Newsome 2019). This is becoming the gold standard for understanding foraging ecology and migration strategies using stable isotopes (e.g., Polito et al. 2017). Newsome highlighted research opportunities and gaps that could be addressed under the auspices of the IWC-SORP SRW theme, namely identifying and augmenting potential prey datasets to provide datasets against which to compare whale isotope profiles and the identification of SRW baleen collections that could be analysed.

3.1.3 Synthesis and discussion on foraging ecology

The Workshop discussed the value of understanding how habitat use patterns vary between different age and sex classes. In particular, much species-wide work on SRW habitat use to date has focused on the movements of mothers and calves. Thus, gathering information about the habitat use patterns of other demographic classes would be very useful. Analyses of bulk $\delta^{13}C$ or $\delta^{15}N$ skin stable isotope data from New Zealand SRW show that foraging patterns vary between different age and sex classes (Carroll et al. in prep), supporting that it is an important consideration.

Linking telemetry data with demographic information was **encouraged** by the Workshop, for example, by ensuring data are collected on tagged whales that enables them to be matched to long-term photo-ID and/or genetic catalogues. This allows the tagging data to be understood in the context of the site fidelity/residency patterns and demography of individual whales, and strengthens the ability for follow up monitoring of tagged animals. Additionally, collecting skin biopsy samples concurrent to tagging enable the whale's sex to be determined using genetic methods and information on past habitat use gained via matching to genetic catalogues. Furthermore, a SRW epigenetic ageing assay under development (Carroll et al. unpublished data) could be combined with satellite tagging data to allow for better specification of habitat use patterns between different age classes.

The Workshop further discussed that while some telemetry studies with an excellent scientific basis can be successful and provide valuable information, the work is often not feasible to carry out due to logistical or geographical constraints. Recent work in South Georgia (Islas Georgias del Sur) provides an example of the difficulties due to the logistical, operational and environmental complexity of the prevailing field area (Jackson et al. 2018).

With respect to stable isotope analysis, the Workshop discussed that the isotopic turnover rates within skin samples of SRW are currently assumed to be two-three months, based on inferences from a blue whale (*Balaenoptera musculus*) study (Busquets-Vass et al. 2017). Therefore, samples collected on wintering grounds likely reflect the last major foraging area visited by whales prior to migration. The Workshop noted that museums can be a repository for both baleen and skin samples for isotope analysis. Kemper offered assistance to the IWC-SORP community in the identification of such datasets for SRWs in Australia; this was welcomed by the Workshop.

The Workshop further discussed the known prey items of SRWs. The only SRW stomach contents data available is from illegal Soviet catches from the 1950s-1960s. This work showed that the SRW fed on Antarctic krill at high latitudes; on copepods at lower latitudes; and a mixture of both prey in whales caught between 40ºS and 50ºS (Tormosov et al. 1998). However, little is known about present day prey of the SRW. Ongoing relevant work includes the collection of active acoustic data to map prey fields in the vicinity of SRW at South Georgia (Islas Georgias del Sur) (Jackson et al, unpublished data). DNA diet work is also ongoing on opportunistically collected faecal samples from Auckland Islands and South African wintering grounds (see IWC-SORP report 2020, SC68b for more information).

3.2 OBJECTIVE 2: DEMOGRAPHICS

3.2.1 Southern Right Whale Population Models (Presenter: Justin Cooke)

Cooke presented some issues associated with the fitting of SRW population models, illustrated using the data collected from the Argentinian population at Península Valdés by Rowntree's team since 1971. The different components of the population – adult females at various stages of their reproductive cycle, juveniles and adult males – are differentially represented in the data sets, and these different variables also change over time. The differences probably result from a mixture of behavioural factors – which animals enter the study area – but possibly also to some extent from the bias of researchers who focus on the whales of most interest, particularly mother-calf pairs. No component of the population, not even mother-calf pairs, was subject to a 100% sampling rate. The data also showed significant individual heterogeneity in the availability of whales for sampling. A particular issue was whether whales whose calves die young were sampled with or without the calf. In the early years, there were many apparent five-year calving intervals, which were believed to represent cryptic calf loss, but hardly any two-year intervals. In the 2000s, two-year intervals began to be observed in significant numbers, followed by calf death. The "normal" interval, following a successfully weaned calf, remained at three years. A consequence of all these factors is that the data could be explained by a fairly simple biological model, but a fairly complex sampling model was required to relate the observed data to the happenings in the population. Calf survival rates in this population were high in most years, but lower in some years; the fluctuations are likely related to ecological factors that merit further investigation.

3.2.2 Development of a common model to assess SRW population demographics across wintering grounds (Presenter: Prof. Doug Butterworth)

A simple model was presented by Butterworth with the aim to be applicable across a number of SRW populations, in particular so as to provide results that can be compared across these populations (Annex C). For this reason, the model is designed to require only very limited data, specifically a time series of comparable annual calf counts without too many missing values. Right whales are assumed to calve at either three- or five-year intervals, with the associated proportions changing over time. Similarly, the value of the parameter (X) reflecting the product of the proportion of births that are female and the first-year survival rate may change over time. An initial application to calf count data for the South African right whale population suggests that such data do not contain sufficient information for annual variations in both the X parameter and in the annual proportion of calving intervals that are three years to be estimated. Fixing X and estimating annual changes in the proportion of three-year calving intervals only appears to provide the best performing approach.

3.2.3 Synthesis and discussion on demographics

A multi-ocean assessment of demographic parameters is required to investigate the changes to calving intervals in recent years in a comparable framework, with the aim to assess linkages between population parameters and climate variates. The development of the common model has progressed with support of the IWC SC SH sub-committee (IWC 2019, 2020), a version of which was presented on by Butterworth. In contrast, Cooke provided an overview of SRW models used to estimate population parameters to date, particularly for the Península Valdés wintering ground. The Workshop discussed the different approaches to modelling demographics. The simple common model proposed to use count data and assumed constant survival and calving interval probabilities over time and could be compatible with short-term datasets. It was noted that a common model would allow for comparison of data from various wintering grounds (i.e. Annex D), whereas the comprehensive models require long-term datasets, are much more complicated to implement and are specific to individual wintering grounds (i.e., Cooke et al. 2001; Brandão et al. 2018). An approach was encouraged that allowed for a comparable framework with the option to use a simple model or to build on the simple model with more parameters if datasets were available. For example, the Workshop highlighted the importance of being able to detect changes to calving intervals from three to four years, to reflect recent increases in observed in calving intervals reported by Vermeulen et al. (2018) and Charlton et al. (2018 SC67B_for Info), which would require a more complex model than the simple common one described.

The Workshop **agreed** that an important step forward for a multi-ocean assessment of population demographics was to assess biases in each wintering ground dataset, driven by sampling effort, proportion of wintering population included in each survey, and connectivity between wintering grounds (see Section 5.2). Connectivity is being addressed by the comparison of the Argentinian and Brazilian photo-ID catalogue, funded by an IWC grant during IWC SC68A, and the Australasian Right Whale Photo Identification Catalogue, a National Environmental Science Programme funded to combine major SRW photo ID databases in Australia. Furthermore, as populations such as those on the Argentinean and South African SRW wintering grounds may potentially mix and mate on shared feeding grounds (Carroll et al. 2019), this could also provide an avenue for mating on shared migratory corridors. The Workshop discussed how migratory movements between wintering grounds could be factored into the population models, in order to reduce bias in abundance and trend estimates. It was noted that immigration could be included as a parameter in complex models to account for this.

The population status and monitoring of two poorly recovering regions were discussed: Chile-Peru and Southeast Australia. While SRW sightings in Chile are very rare, acoustic data are being collected with the aim of identifying priority areas for future research (Annex E). Further acoustic data exist from a study that focused on blue and fin whales that could be reanalysed for SRW detections (Buchan et al. 2014). In addition, there is difficulty in collecting biopsy and photo-ID data because current Chilean legislation requires any boats in the vicinity of a SRW to depart the area upon sighting the whale. With respect to Southeast Australia, data suggests the population is still small (Stamation et al. 2020) and there has been no increase in calving rates since 1985 (Watson, unpublished data). The workshop **agreed** that dedicated funding for a long-term monitoring project in south eastern Australia was a **high priority**.

The Workshop **agreed** the need for standardising processes and protocols for photo-ID matching and databasing, to identify biases between different datasets to inform population modelling. In regards to this, a photo-ID working group was formed and a circumpolar SRW photo-ID consortium was proposed (see Section 5.2). The Workshop **encouraged** the working group to progress the consortium and explore avenues for standardising matching and database storage for SRW, including between ship-based side on and drone/aerial top-down photographs. The Flukebook Artificial Intelligence project funded by NOAA could be a useful tool along with other regional catalogues including the Australasian Right Whale Photo Identification Catalogue (ARWPIC) and the NARW Consortium and photo-ID database. It was noted that there is already an existing circumpolar genomic collaboration that is using molecular methods to assess connectivity (e.g., Carroll et al. 2020).

3.3 OBJECTIVE 3: HEALTH

3.3.1 Photogrammetry body condition assessments (Presenter: Fredrik Christiansen)

This presentation focussed on the third aim of IWC-SORP SRW related to linking body condition (i.e. health assessment indicators) to population dynamics (i.e. long-term monitoring data). Christiansen first provided an introduction to aerial photogrammetry techniques, focusing in particular on unmanned aerial vehicles (UAVs). Christiansen spoke of the different metrics that can be used and the benefits and limitations of UAV aerial photogrammetry. He then went through a series of case studies based on his current and past research projects focusing on body condition in relation to reproduction in right whales. The first study focused on SRWs in South Australia where body condition of females was linked to the growth rates of their calves. In the second study, he presented an ongoing "global" comparison of right whale body condition, which highlights the poor condition of the North Atlantic right whales, a population that is currently in decline. Last, he presented an ongoing study in Península Valdés, Argentina, where they are trying to link calf body condition to survival. The presentation ended with a discussion about future potential work in linking body condition to vital rates, prey availability and climate.

3.3.2 Assessing energetic cost of entanglement to the fecundity of North Atlantic right whales (Presenter: Michael Moore)

Moore, presenting on behalf of van der Hoop, discussed assessing energetic cost of entanglement to the fecundity of NARW. This species has poor fecundity, and the majority have been entangled once or more (Knowlton et al. 2012). These entangled animals are free-swimming, with a consequent significant loss of body condition in chronic cases. To estimate the energy cost of entanglement, drag forces from entangling gear were measured with a tensiometer (Van der Hoop et al. 2016). Results showed that drag forces varied with gear configuration. If animals do not slow down, entanglement increases power output, leading to entangled whales having thinner blubber at death. The energy cost is comparable to other life history events, and of similar duration (van der Hoop et al. 2017). The team plans to extrapolate costs to other cases, where no gear is in hand, to model the cost of entanglement at the species level in the context of normal life history demands. Better data on the energetic values for foraging, reproduction, migration, basal metabolic rate, and stressors such as entanglement, noise and climate change are needed. With these data, it should be possible to understand the extent to which entanglement contributes to net fecundity, in the context of the dynamics of foraging success. This in turn will predict the extent to which fecundity can be enhanced by meaningful reduction of entanglement. This information could lead US and Canadian management to understand that they need to substantially reduce morbidity as well as reversing their failure to reduce mortality, if the species is to survive.

3.3.3 Physiological indicators of health (Presenter: Joanna Kershaw)

Blubber biopsies, typically taken with a dart deployed either with a cross-bow or a modified air rifle, provide a powerful opportunity to quantify physiological biomarkers in the tissue, as Kershaw discussed in this presentation. Biomarkers are naturally occurring molecules, genes, or characteristics that can provide information on a particular metabolic pathway or process. A recent pilot study at the University of St Andrews (Scotland) aimed to validate the use of commercially available ELISA kits to quantify progesterone and cortisol in SRW blubber biopsies as biomarkers of reproductive and physiological state, respectively (Kershaw et al. 2019). Six blubber samples collected incidental to skin sampling of SRW in the Campbell Islands in 2016, were used to extract, quantify and validate steroid concentrations in the tissue. Quality assessment and quality control (QA-QC) checks showed that a commercially available cortisol ELISA, used in-house for the analysis of samples from other marine mammals, accurately quantified cortisol in these samples. A commercially available progesterone ELISA did not pass the necessary QA-QC checks, likely because the concentrations measured in the samples were too low (Kershaw et al. 2019). Future work will validate the use of a commercially available progesterone ELISA for SRW samples. Other recent work investigating steroid concentrations in NARW have used ELISAs to quantify hormones in blow samples. However, due to the role of steroid hormones in multiple physiological processes, and variability in concentration among individuals, data on single hormones in these samples are difficult to interpret. For this reason, liquid chromatography/mass spectrometry methods have recently been used to simultaneously quantify a full suite of steroid hormones in humpback whale blubber. This full hormone 'profile' approach can provide a huge amount of information on steroidogenesis, and is vital when aiming to map endocrinological pathways, and better interpret steroid concentrations measured in the samples. Another growing field of study uses proteomic and transcriptomic approaches to investigate the use of adipokines as biomarkers of physiological and energetic state. Adipokines are cell signalling proteins that are secreted by adipose tissue and are known to contribute towards the regulation of a huge variety of tissue specific and systemic metabolic processes including, for example, the regulation of appetite and energy balance and immune system function. A handful of studies have started to investigate these proteins in cetaceans and phocid seals. These show huge potential to provide insights into the multifunctional nature of blubber tissue and identify biomarkers of individual health.

3.3.4 Synthesis and discussion on health

The Workshop discussed the difference between quantitative and qualitative health assessments. Quantitative methodology involves measuring body condition through morphometric measurements of whales taken via drone, while qualitative visual health assessments involve trained observers measuring body condition through scoring of visual features such as skin condition and presence of cyamids. The Workshop **strongly supported** the comparative work and ongoing data collection of photogrammetry data and quantitative health assessments, exemplified in a recent global comparative study (Christiansen et al. 2020). Furthermore, a qualitative methodology for visual health assessments in SRW, created by South African and Australian researchers (Hoerbst, Vermeulen, Charlton, Christiansen), based on Pettis et al. (2004) was discussed. It was recognised that there is a need to compare qualitative and quantitative methods to enable comparisons across wintering grounds and datasets, while acknowledging historical datasets may be limited to qualitative analyses.

The Workshop discussed a range of topics pertinent to proteomic studies and the use of blubber biopsy sampling and biomarkers. The potential influence of human induced contamination and water borne pollutants on biomarkers was discussed. For commonly assayed steroid hormones the impact of contaminants is likely to be low in comparison with biological processes such as reproductive maturity and pregnancy.

The Workshop **encouraged** concurrent collection of biopsy sampling with photogrammetry to gather quantifiable data on whale health such as body condition and reproductive state. This was linked to a general consideration discussed by the Workshop, that body condition would vary across the migratory cycle and depending on demographic class, even in healthy whales.

Therefore, being able to detect changes in body condition that are indicative of individual or population level challenges, such as a decrease in prey availability, requires an understanding of 'normal' changes in body condition over the migratory cycle and across age and demographic classes.

While the Workshop discussed efforts to validate single steroid hormones assays from SRW biopsy samples (Kershaw et al. 2019), work was highlighted that showed multi-hormone profiles are more informative for accurately assessing the demographic state of baleen whales (Dalle Luche et al. 2020). It was noted that strandings provided the opportunity to collect material with which to test and develop steroid hormone assays, such as blubber and ear plugs (Trumble et al. 2013). The Workshop recognised that there is a need for standardised necropsy sampling protocols and data sharing platforms, and the group **encouraged** international collaboration. With regards to necropsy, the group agreed it was a **high priority** to secure funding to cover cost of necropsy and pathology testing within regions (see Section 5.3).

3.4 OBJECTIVE 4: UNDERESTANDING CLIMATE

3.4.1 The Southern Ocean under climate change

Presenter: Andrew Meijers

Meijers presented on the international coupled model inter-comparison project (CMIP), which forms the basis for the Intergovernmental Panel on Climate Change (IPCC) projections of future climates for this century and beyond. The present iteration (CMIP5) consists of coupled climate models from more than 20 climate modelling groups around the world, includes atmospheric chemistry and ocean biogeochemistry and simulates both historical hindcasts and multiple future carbon forcing scenarios under a variety of potential climate forcings; totalling almost two PB of output. As we stand on the cusp of the first releases of the next generation of CMIP6 models and over an order of magnitude more data, this presentation reviewed the state of the art in climate modelling of the Southern Ocean. This region is critical for global climate and highly susceptible to climatic change, but is generally poorly represented in model hindcasts in terms of water mass properties, sea-ice extent and ocean circulation. In particular strong sea surface temperature biases are a wide spread problem. In future projections there are some uniform trends across the ensemble, towards strengthening and poleward shifting westerlies, increased precipitation, warming and freshening surface waters and sea ice loss. However, there is a wide variance between models even in these trends, and dramatic differences in future circulation patterns, the trends of which often have completely different signs between models. In order to reduce uncertainty and use model projections as input to higher order models (e.g.

ecosystem models) it is necessary to understand the limitations of the CMIP ensemble and make use of techniques such as emergent constraints to increase confidence in projections.

3.4.2 Synthesis and discussion on climate change

The participants sought clarification from Meijers on which climate models can predict primary and secondary oceanic productivity, and the scale at which such projections are available. When regional projections are modelled by region, and incorporate an average of climate models and defined boundary conditions, they can provide more reliable projections. Downscaling also provides a means to add regional granularity and reduce uncertainty. CMIP5 and CMIP6 models were highlighted as a good choice for understanding climate projections for the Southern Hemisphere, as these models incorporate primary productivity, with the latter likely to perform better.

There was discussion on the movement of Polar (PF) and Subtropical Fronts (STF), key regions for foraging marine predators including SRW, under future climate projections. The PF is projected to move along with couple sea surface temperature isotherms, a key habitat parameter that can have implications on prevailing environmental conditions and in turn, foraging success (Cristofari et al. 2018). Likewise, the STF may shift pole-ward due to an increase in gyre circulation in response to wind stress kernels that are expected to increase with climate change. However, the northern boundary of the STF is poorly oceanographically defined, due to the density compensating driven gradients that have little impact on the currents.

The Workshop also discussed the implications of recent marine heat waves. Such events have not been extensively modelled yet, but could have a larger, albeit temporary, impact on right whale populations compared with the comparatively incremental shifts from climate change. How these long-term (changes in PF and STF) and potentially short term (marine heat waves) climate variations should be incorporated into the common demographic population model was discussed. The Workshop **agreed** that moving forward the application of common models should account for both regional and global climate variables to account for the variation in long-term and short-term climate impacts on different wintering grounds. Again, the discussion highlighted the need to progress Objective 1; understanding foraging habitat and ecology (see Section 5.1).

4. SESSION 3: DEVELOPING THE RIGHT ROAD MAP FOR SUCCESS

4.1 BRINGING THE GOALS AND PRINCIPLES OF IWC-SORP TO THE DISCUSSION

Presenter: Helena Herr

IWC-SORP is an international, non-lethal cetacean research initiative that enhances the delivery of science to the IWC through collaboration, cooperation and coordination. It was established in 2009 with the aim to conduct collaborative non-lethal research in order to maximise conservation of Southern Ocean whales by understanding the status, health, dynamics and environmental linkages of their populations and the threats they face. The SRW theme is one of seven established so far. To date, IWC-SORP has produced 144 peer reviewed papers and 133 IWC Scientific Committee Papers since 2009. All data and methods are shared with the international scientific community, the IWC and in other international forums. There are currently 13 member countries in the Partnership. IWC-SORP warmly welcomes new members.

4.2 IDENTIFICATION OF DATA GAPS AND RESEARCH PRIORITIES

The workshop reviewed a pre-populated spreadsheet summarising information on the research conducted to date for each of the four objectives of the SRW IWC-SORP theme per wintering ground as well as the South Georgia (Islas Georgias del Sur) and Falkland Islands (Islas Malvinas) habitats. This allowed for the identification of data gaps and research prioritisation as follows:

(1) High priority; denoting areas where there is little to no progress or funding, and where there is a significant data gap
(2) Medium priority; those areas where there is progress and funding established, though the data gap remains significant, and
(3) Low priority; representing those areas where a substantial amount of work has already been completed.

The priority categories identified the gaps in research required to fulfil IWC-SORP theme objectives. A low ranking did not suggest that the field of research or project is not of high priority, but that substantial work is already complete to address objectives, or that it is perhaps less relevant for addressing specific IWC-SORP theme objectives. The workshop later agreed that the weight of conservation status of a given population should influence the priority.

It was recognised that several regions that were historically considered to be calving or nursery grounds still show limited or no recovery, including Tristan Da Cunha/Gough Island, Namibia, Mozambique/Madagascar, Southeast Australia and Chile-Peru, remain the least well understood. Chile-Peru was highlighted as being subject to an IWC Conservation Management Plan (CMP) (Galletti Vernazzani et al. 2016). It was **recommended** that research on these regions be made a **high priority** as knowledge gaps exist across all of these areas. However, in most cases, this lack of information also means that demographic trends and their links to climate change cannot be investigated, as neither foraging ground links nor population demography are characterised.

4.2.1 FORAGING ECOLOGY

4.2.1.1 Telemetry

Given that there is considerable ongoing research in Argentina that is funded until 2020, the workshop **agreed** that this region is considered a low priority in comparison to the others. Work in South Africa was agreed as a medium priority given published telemetry work (Mate et al. 2011) and funds likely secured for telemetry work. The workshop **agreed** that the **high priority** areas to identify foraging grounds through satellite tagging are: Brazil, New Zealand, Australia, Uruguay, South Georgia (Islas Georgias del Sur) and the Falkland Islands (Islas Malvinas) given no or limited telemetry data from these regions (e.g. two whales from NZ and one whale from SEA tracked offshore; respectively, (Mackay et al. 2020)) and the need to secure funding.

General principles for guiding telemetry work were discussed, including the agreement to follow best-practice guidelines (Andrews et al. 2019). In this regard, the Workshop **recommended** the deployment of tags that are capable of capturing dive and location data, providing information both on migratory movements and fine-scale habitat use. Furthermore, reiterating earlier discussions, the workshop **agreed** that telemetry data be collected across different demographic groups as much as possible, in addition on both foraging and wintering grounds where feasible.

4.2.1.2 Stable isotopes

The Workshop **agreed** that it was a **high priority** to identify or support the collection of potential prey datasets, to increase the power of isotope data collected from wintering SRWs to resolves foraging ground links and prey species. Stable isotope analysis in areas where studies have already been carried out, or are underway e.g. New Zealand, Australia, South Africa, Argentina, Brazil, Falkland Islands (Islas Malvinas) and South Georgia (Islas Georgias del Sur) are considered a **medium** priority, because funding has already been obtained to progress this work.

4.2.1.3 Satellite imagery

Very high resolution (VHR) satellite imagery (WorldView-3 satellite, 31cm spatial resolution) has been used to successfully detect SRWs off Península Valdés (Cubaynes et al. 2019).

Currently limitations of this method include: cost of commercial imagery; time involved in manual processing; high wind and or cloud cover during image capture; and lack of image contrast between whales and water. Imagery costs can be significantly reduced by using archived images and taking advantage of research institute rates offered under the sustainability goals of Maxar (commercial provider). Manual processing may be reduced by machine learning and deep learning techniques, and algorithms are currently being developed by the British Antarctic Survey. The white callosities of SRWs may help detect whales in otherwise low contrast images. The feasibility of using VHR satellite imagery to detect SRWs has not been tested in offshore environments or in inshore areas around the south-east coast of Australia. It was **agreed** that it is worth exploring this method further to determine its usefulness in detecting high use areas of SRWs on the poorly surveyed south-east coast of Australia and in offshore environments.

4.2.1.4 Acoustics

It was **agreed** that the opportunities for assessing the distribution of SRW in the Southern Ocean using the Southern Ocean hydrophone network and Australian Ocean Data Network - Integrated Marine Observing System should be investigated with **high priority**. The use of automated analysis and coding should be considered, as well as the detectability of SRW in terms of rate and propagation of vocalisations. **High priority** was given to analysing active acoustics data collected in South Georgia (Islas Georgias del Sur) and to applying acoustic technology to increasing our understanding of SRW presence and distribution off the Falkland Islands (Islas Malvinas).

4.2.1.5 Habitat modelling of foraging grounds

Foraging habitat modelling conducted to date has relied on historical whaling data (Torres et al. 2013; González Carman et al. 2019), which is limited in resolution and may not reflect contemporary foraging ecology of SRW. It was therefore **agreed** that a **high priority** is to undertake habitat modelling using all available telemetry data and link this to environmental variables. More generally, the workshop **agreed** it should be a **priority** to compile a review paper to evaluate past and present knowledge of right whale diets and collaborate with experts engaged in potential prey species abundance and distribution to help with understanding SRW habitat selection (See Section 5).

4.2.2 DEMOGRAPHICS

4.2.2.1 Photo-ID and genetic monitoring programmes

The Workshop discussed the importance of monitoring to increasing knowledge in regions with poor recovery and little knowledge of distribution and recovery, and the continuation of long-term datasets that are needed to develop population models that can incorporate health and climate co-variates. A **high priority** was given to the continuation of long-term photo-ID and genetic monitoring studies in Australia, Argentina, New Zealand and South Africa. The Workshop recognised that the southeast and southwest Australian wintering grounds are managed distinctly due to genetic differentiation and differences in recovery, and **recommended** that a dedicated monitoring programme, potentially including systematic aerial surveys, be established for the critically endangered southeast Australian population with **high priority**.

The workshop **prioritised** the need to collate existing photo ID datasets into national or regional repositories. The completion of the Australian Right Whale Photo Identification Catalogue (ARWPIC) is **encouraged**, including sourcing funding required to merge outstanding datasets into ARWPIC, such as historical data from South Australian Museum, Head of Bight and additional data from calving grounds in southwest Australia. The workshop **agreed** that it is a high priority to complete the cross-match of the Brazilian and Argentina datasets, currently partially funded through the IWC. In a related discussion, the Workshop **strongly recommended** the development and funding of a strict protocol to process, print and store archival photo-ID data. This became a sub-committee action (see Section 5.2).

4.2.2.2 Population demographic modelling

Demographic modelling draws on available photo-ID, genetic ID and sightings data. Both Argentina and South Africa have established population models and demographic databases and are considered a medium priority. The group **agreed** that moving in forward the **high priority** is the demographic modelling for Australia and New Zealand, which have long term datasets, after which modelling attempts should be made for Brazil, Chile and South East Australia, where data is more sporadic and opportunistic. **High priority** was given to the development of a common model to assess demographics in a comparative framework for multi-ocean assessment and assessing links to climate variates (see section 5.2)

4.2.3 HEALTH

4.2.3.1 Photogrammetry/Qualitative visual health assessments

The Workshop **recommended** that the photogrammetry and photograph-based visual health assessment methods be standardised across populations and studies. Visual health assessments have also been completed for South Georgia (Islas Georgias del Sur) and are underway for

Australia and South Africa, so these were given a medium priority. While substantial progress has been made in Argentina on assessing health, the Workshop **recommended** this region was a **high priority** for future work under the CMP given the recent die-offs. **High priority** was given to continuation of photogrammetry work in wintering grounds, and its combination with other tools including stable isotopes, genetic sex ID and linkages with long-term monitoring datasets as a way to assess linkages between health, reproduction and climate.

4.2.3.2 Physiological indicators of health

The Workshop discussed the need to reconcile photogrammetry/visual health assessments and hormone/proteomic indicators of health. Therefore, it was **agreed** that where possible, data collection methods should be combined, including photogrammetry, biopsy, visual health data and breath sampling. Furthermore, to ensure that health metrics for different demographic classes are obtained, the group **agreed** it was important to collect combined data from different sexes and reproductive states across populations. It was discussed that where possible archival blubber data should be acquired and analysed, e.g., to validate assays. In addition, the Workshop **recommended** the collection of faecal samples where possible for both health and diet purposes, although it was recognised this may be limited as field work is primarily on wintering grounds.

4.2.3.3 Anthropogenic threats, strandings and necropsy

As the numbers of right whales increase so will mortalities, so it is important to begin planning now. The Workshop discussed the importance of understanding and quantifying anthropogenic treats to SRW populations, including ship strike and entanglement, retrospectively and going forward. The Workshop **recommended** that quantifying threats in all wintering grounds should be set as a priority. The Workshop also **recommended** that the development and funding of stranding, necropsy and pathology testing should be a **high priority** across all regions. Furthermore, the different available necropsy protocols were discussed, including those developed by the North Atlantic right whale consortium, Argentinean researchers involved in the die-off response, and general IWC necropsy protocols. It was **recommended** that collation of these protocols and methods that can be employed alongside capacity building, together with a central database to house necropsy results (see section 5.3). Such methods should also include guidance on best practice on photographing dead right whales.

4.2.4 CLIMATE

The Workshop recognised that there has to be substantial progress on Objectives 1-3 to enable linkages with climate change to be assessed. Regardless, it was a **high priority** that the correlation of demographic parameters with climatic indices be investigated (see section 5.2). To this end, the Workshop (1) **encouraged** collaboration with other research groups studying the impact of climate on other baleen whales or species niches similar to SRW; and (2) placed a **high priority** on collaborating with experts engaged in researching prey abundance and (3) **recommended** that the sub-committee on climate should identify the most important demographic parameters or indices to be used in future work (Section 5.2). It was **agreed** that a time frame of two years be given to reassess what progress can be made towards Objective 4.

5. PROPOSED WORKING GROUPS AND ACTIONS

Working groups were formed for each of the four objectives. This is a summary of proposed working groups and actions to progress new research activities under each objective, that were agreed or recommended by Workshop.

5.1 FORAGING ECOLOGY

- The workshop **agreed** it should be a **priority** to develop a working group that will compile a review paper to evaluate past and present knowledge of right whale diets.
- The workshop acknowledged the importance of historical museum skin and blubber samples for genetic and isotope analysis, and **agreed** funding should be sought to inventory, access and analyse such samples. Kemper kindly offered to identify museums around Australia holding appropriate samples.

5.2 DEMOGRAPHICS

- The IWC SC SH sub-committee working group on 'Multi-ocean assessment of demographics and links to climate variates', co-convened by Vermeulen and Charlton submitted an IWC-SORP proposal in January 2020 to progress the development of a common model to enable the multi-ocean assessment of demographic parameters and links to climate variates. The proposal also included the establishment of a photo-ID consortium and a desktop review of climate variates appropriate for modelling links to demographics. The Workshop **encouraged** the proposal submission and progress of this work.
- The Workshop supported the **establishment** of a **circumpolar SRW photo-ID consortium**, which was created during the WMMC and led by Vermeulen, Rowntree, Hamilton, Charlton. Watson and Kemper. The consortium aims to develop standardised processes and protocols for photo-ID matching, including between side-on and top-down images, and sightings databases as recommended by the Workshop, to enable SRW photo-ID data to be comparable on a circumpolar level. The working agreed that it

would meet annually and Hamilton and Rowntree agreed to move forward with a funding application for the work.

- The Workshop **agreed** that in order to achieve a global comparison of demographics, a **priority** would be to compile a review paper of the wintering ground photo-ID and genetic monitoring datasets, areas, parameters and modelling techniques to identify biases and understand available data.

5.3 HEALTH

- The Workshop **agreed** that a framework should be developed from the available data on body condition and reproductive success across SRW and NARW to understand the relationship between body size, reproductive maturity, and the ability of females to get pregnant and successfully gestate. This framework could then be used with assumptions about energetics to look at correlations between body condition, reproductive output and climate indices.
- The Workshop **recommended** the formation of a **working group** on necropsy protocols that included Kemper, to also include or liaise with Argentine researchers given their experience with necropsy protocols. The necropsy working group should collate existing necropsy and sample archive protocols for NARW and SRW; and collate or develop guidelines for the implementation of necropsies possible at different levels of capacity.

5.4 CLIMATE

- The workshop **recommended** a working group be established to undertake a literature review on long-term top predator and prey monitoring programmes in the Southern Hemisphere. This group could use published information or available datasets to inform hypotheses on how climate change could impact SRW, by (1) assessing potential demographic response variables that were found to be significantly affected by climate variables in other top southern ocean predators; (2) understanding what model prey variables are important to consider and (3) what climate variables are important to both other predators and to prey. The Workshop **agreed** that funding for an IWC-SORP proposal would be beneficial to formulate a literature review. Pendleton agreed to collate information from participants of this discussion to develop a proposal.

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Annex B: Agenda

1. Introductory Items: Welcome and house keeping
2. The right advice
   - 2.1 Introduction to the IWC-SORP theme: building the roadmap to success
   - 2.2 Inference from comparing multiple right whale populations: lessons learned
3. The right tools
   - 3.1 Objective 1: foraging ecology
     - 3.1.1 Telemetry
     - 3.1.2 Stable Isotopes
   - 3.2 Objective 2: Demographics
     - 3.2.1 Right Whale Population Models
     - 3.2.2 Uniting Australian, South African and South American data to estimate population parameters
   - 3.3 Objective 3: Health
     - 3.3.1 Photogrammetry body condition assessments
     - 3.3.2 Assessing energetic cost of entanglement to the fecundity of North Atlantic right whales
     - 3.3.3 Physiological indicators of health
   - 3.4 Objective 4: Understanding Climate
     - 3.4.1 The Southern Ocean under climate change
4. Session 3: Developing the right road map for success
   - 4.1 Bringing the goals and principles of IWC-SORP to the discussion
   - 4.2 Identification of data gaps to meet objectives, and identification of best tools for data gaps
   - 4.3 Formalising workplan: integration of tools, data gaps and models
   - 4.4 Workshop summary and re-cap on workshop objectives/outputs

Annex C: Proposal for a common simple and widely applicable model for right whale population assessments

D.S. Butterworth and A. Ross-Gillespie

Summary

A simple model is presented whose aim is to be applicable across a number of right whale populations, in particular so as to provide results that can be compared across these populations. For this reason, the model is designed to require only very limited data, specifically a time series of comparable annual calf counts without too many missing values. Right whales are assumed to calve at either three- or five-year intervals, with the associated proportions changing over time. Similarly, the value of the parameter (X) reflecting the product of the proportion of births that are female and the first-year survival rate may change over time. An initial application to calf count data for the South African right whale population suggests that such data do not contain sufficient information for annual variations in both the X parameter and in the annual proportion of calving intervals that are three years to be estimated. Fixing X and estimating annual changes in the proportion of three-year calving intervals only appears to provide the best performing approach.

Introduction

The basic idea underlying this document is to develop an as-simple-as-possible model that can be applied to all the various Southern Hemisphere right whale populations to assess demographics and allow for comparison across the populations. The proposed model is outlined in this document, and results are provided for a preliminary application to the South African right whale data to assess feasibility. The full details of the model proposed can be found in the Appendix, but a broad outline of key features is provided here:

- Two key population components are estimated for each year: the total number of adult (past the age at first parturition) females (N_y^t) and the total number of calving females (N_y^c).
- The model assumes that each female will reproduce after either a three-year or a five-year interval.
- The model is fit to annual calf counts (which are assumed not to miss any animals).
- The model estimates:
    - the starting adult female population size for N_{y0-n}^t,
    - the annual proportion of calving females that will enter a three-year calving cycle,
    - a (potentially time-varying) parameter that accounts for juvenile mortality as well as the proportion of calves that are female, and
    - the initial (assumed to be steady) population growth rate.

Results

In order to commence the population's dynamics, the model is started a fair number of n years before the year (y_0) for which the first calf count is available. Several assumptions have been made for this initial analysis, such as:

(a) a constant growth population growth rate (R),

(b) a constant juvenile mortality rate (X_0) and

(c) that a constant proportion (P_0) of calving females will enter a three-year calving cycle during these n years.

This leads to an inter-dependence of three key model parameters R, X_0 and P_0. In the interest of simplicity, and as a first attempt for fitting the model, two approaches have been taken for the results presented in this document.

1. The annual proportion of calving females that will enter a three-year calving cycle (p_y) is assumed to be constant with time. P_0 is fixed at a range of values, R is estimated freely, and X_0 is determined by the values of P_0 and R (see the Appendix for further details).
2. The juvenile mortality (plus proportion of calves that are female) parameter (X_y) is assumed to be constant with time. X_0 is fixed at a range of values, R is estimated freely, and P_0 is determined by the values of X_0 and R.

Results are presented for five runs – runs 1a and b as per approach (1) above for two different values of P_0, and runs 2a-c as per option approach (2) above for three different values of X_0.
Table 1 lists key parameter values and negative log-likelihood components for the five runs. Figure 1 plots the estimated population trajectories, as well as the trajectories for X_y and p_y.

Discussion

Some key discussion points are provided in bullet point form below.

- Approach (2) (a time-invariant proportion of births that are female and juvenile survival rate, X_y) seems in general to be able to provide better fits to the data. Furthermore, approach (1) (constant proportion p_y of three-year calving cycles) appears to require a strong temporal trend in the X_y parameter trajectory in order to fit the data, which may be beyond the range of biological plausibility. For these reasons, it would seem that approach (2) is preferable to approach (1), having greater "flexibility".
- A key feature in the South African right whale data is the noticeable drop in calf counts in very recent years. Approach (2) tries to address that by substantially reducing the p_y proportions in the most recent years considered in the model, i.e. it explains the reduction in calf counts by assuming that a large majority of adult females have entered five- rather than three-year cycles. This supposition can be validated only given future data, as it implies an expected imminent increase in number of calves over the next few years.
- The impact of changing the adult survival rate assumed for these analyses ($S = 0.97$) needs to be explored. This value is somewhat lower than the value of 0.99 that has been estimated in the application of a more complex population model (using more detailed data) for the South African right whale population (Brandão *et al* 2018). The reason for the choice for this analysis was that the model exhibited slightly more stable behavior for this somewhat lower survival rate, given the interdependence of X_0, P_0, R and S for the initial year configuration of the model (see equation A4 of the Appendix).
- Note that the scale of the abundance estimates output by the model is determined by the assumption that the calf counts do not miss any animals (and that there are no mortalities resulting from non-natural causes). If the proportion missed remains about the same over time, abundance estimates would simply need to be scaled upwards by the inverse of that proportion; however, if there was a temporal trend in the proportion missed, the impact on results could be more complex.
- Many more variations of these five runs could be explored (such as estimating both X_y and p_y and fixing R – though preliminary attempts at this suggest that the model has difficulties in distinguishing variations in X_y from those in p_y from the limited data – annual calf counts - available), but this document is primarily intended to outline the proposed model and to provide some preliminary results. Overall the fit of the model to the data (particularly for approach (2)) is not unreasonable, and the estimates of overall population size appear to be fairly consistent across the five variants, suggesting that the

model has some potential to be used as a common widely applicable model for the right whale populations. However, further exploration and development, as well as trial applications to other right whale populations, should first be pursued.

- For applications to other right whale populations, the following information would need to be provided:
  - a few values (considered to be plausible) for the non-juvenile survival rate S;
  - a value for the age at first parturition t_m; and
  - a time series of annual calf counts (desirably complete, though the approach can accommodate missing values for a few of the years).

Reference

Brandão, A., Vermeulen, E., Ross-Gillespie, A., Findlay, K. and Butterworth, D.S. 2018. Updated application of a photo-identification based assessment model to southern right whales in South African waters, focussing on inferences to be drawn from a series of appreciably lower counts of calving females over 2015 to 2017. International Whaling Commission: SC/67b/SH22: 18pp.

Table 1: Summary of results for the five runs presented in this document. The first two runs (1a and b), fix the value of P_0 (the value of p_y prior to y_0, where y_0 is the first year for which data are available), estimate R and allow X_y to vary after y_0 (the value of X_y prior to y_0 (X_0) is determined by P_0 and R, see the Appendix for more details). The next set of three runs (2a-c) fix the value of X_0, estimate R and allow P_y to vary after y_0. Analogous to the first two runs, the value of P_0 is determined by the values of X_0 and R. In the table below, the symbols are defined as follows:

P_0 is the value of p_y prior to y_0 (the first year for which there are data), i.e. the proportion of calving females entering a three-year (rather than five year) cycle prior to y_0,
μ_p is the mean of p_y after y_0,
X_0 is the value of X_y prior to y_0, i.e. the value of the variable taking juvenile survival rate and proportion of calves that are female into account prior to y_0,
μ_X is the mean of X_y after y_0,
σ_X and σ_p are the variance parameters for the fluctuations about the means for X_y and p_y post year y_0 (see the Appendix for more details),
R is the constant growth rate assumed for the initial period prior to y_0,
$\Delta lnL\ (total)$ gives the difference in total negative log-likelihood points between run 1a and the rest,
$\Delta lnL\ (data)$ gives the difference in negative log-likelihood points for the data component between run 1a and the rest, and
$\Delta lnL\ (penalties)$ gives the different in total negative log-likelihood points for the combined penalties between run 1a and the rest.

Run	P_0	μ_p	X_0	μ_X	σ_X	σ_P	R	$\Delta lnL\ (total)$	$\Delta lnL\ (data)$	$\Delta lnL\ (penalties)$
1a	1.00	1.00	0.33	0.28	0.5	0.5	1.054	0.0	0.0	0.00
1b	0.60	0.60	0.38	0.34	0.5	0.5	1.050	15.9	17.4	-1.50
2a	0.57	0.58	0.40	0.40	0.5	0.5	1.052	-66.1	-67.3	1.21

2b	0.66	0.69	0.35	0.35	0.5	0.5	1.046	-73.8	-78.1	4.36
2c	0.71	0.77	0.30	0.30	0.5	0.5	1.038	-53.3	-59.6	6.35

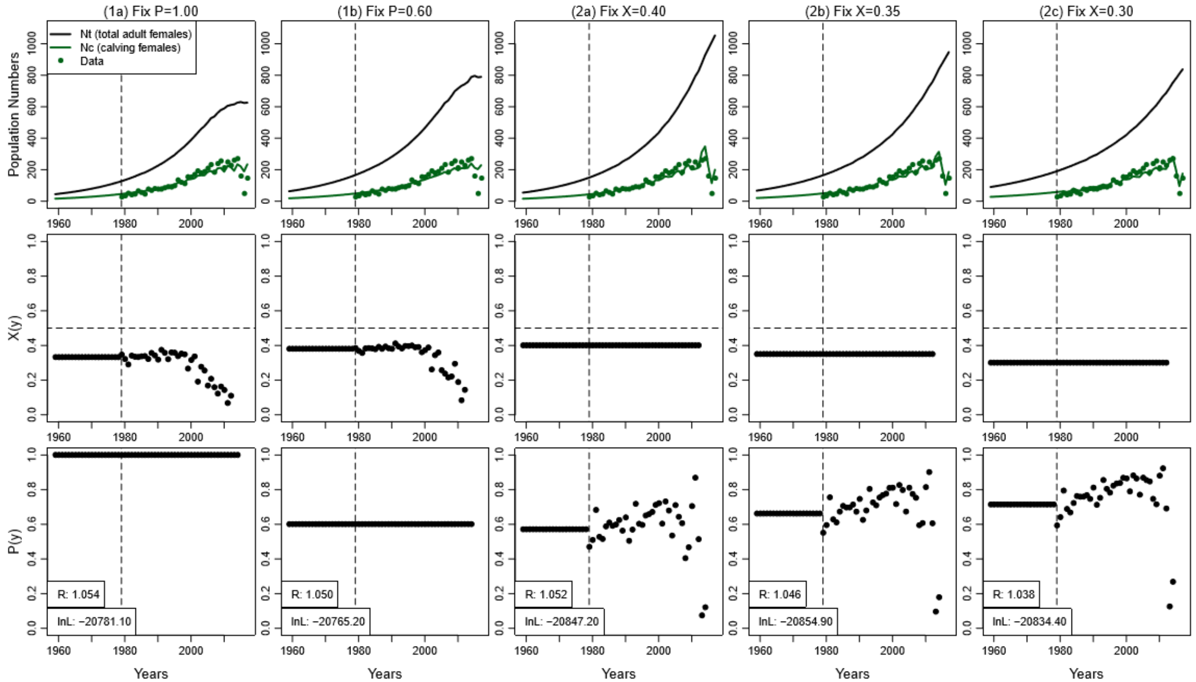

Figure 1: Some graphical output for the five runs presented in this document. The top row shows the population trajectories (in numbers) of the total female population past the age at first parturition (N_y^t), and for the number of females calving each year (N_y^c). The data to which the model is fit (the counts of number of calves per year) are shown by the closed circles. The vertical dashed lines mark the year $y_0 = 1979$, the first year for which data are available. The second row shows the estimates of X_y (combination of juvenile survival rate and proportion of calves that are females) and the bottom row the estimates of p_y (the proportion of calving females each year entering into a three-year calving cycle). The estimated values of the growth rate R and the total negative log-likelihoods are shown in the bottom left corners.

Appendix

Methodology for the proposed right whale common model

The total female population in year y+1 is given by:

$$N_{y+1}^{t} = N_{y}^{t}S \; + \; N_{y-t_m+1}^{c}S^{t_m}X_{y-t_m+1} \qquad \text{(A1)}$$

where

N_y^t	is the total female population past the age at first parturition in year y,
N_y^c	is the number of females calving in year y,
S	is the non-juvenile survival rate,
t_m	is the age at first parturition, and
X_y	is an additional (possibly time-varying) parameter to take juvenile (first year) survival into account. X_y needs to be less than 0.50 to account (at least) for the proportion of calves that are female.

$N_{y-t_m+1}^{c}S^{t_m}X_{y-t_m+1}$ is thus the number of female calves that were born $y - t_m + 1$ years ago and have now reached the age at first parturition.

To calculate the number of calving females in year y, and assumption needs to be made regarding calving interval. For this proposed model, it is assumed that each female will reproduce either after a three-year or a five-year interval. Then:

$$N_y^c = N_{y-3}^c p_{y-3} S^3 + N_{y-5}^c \big(1 - p_{y-5}\big) S^5 + N_{y-tm}^c X_{y-t_m} S^{t_m} \qquad \text{(A2)}$$

where p_y is the proportion calving each year which will take 3 years until they calve again. Therefore, in equation (A2) above:

$N_{y-3}^c p_{y-3} S^3$	is the number of females that calved three years ago which (a) took a three-year calving interval to reproduce again and (b) survived the three years since last calving,
$N_{y-5}^c \big(1 - p_{y-5}\big) S^5$	is the number of females that calved five years ago and which (a) didn't take a three-year calving interval (which by assumption implies they took a five-year interval) and (b) survived the five years since last calving, and
$N_{y-tm}^c X_{y-t_m} S^{t_m}$	is the number of females reaching age at first parturition in year y (i.e. the assumption is made that all females at age of first parturition will produce a calf).

Initial situation (before year y_0)

Start the model some *n* years before the actual first year of interest, y_0, and assume the following for those *n* years.

1. The total number of adult females in year $(y_0 - n)$ is an estimable parameter.
2. Each year a constant proportion ρ of the total population is calving, i.e. $N_y^c = \rho N_y^t$.
3. The proportion of females in three-year calving cycles is constant, i.e. $p_{y+1} = p_y = P_0$.
4. The juvenile mortality and female ratio variable X_y is constant, X_0.
5. The population is growing at a steady rate R so that $N_{y+1}^t = RN_y^t$ and $N_{y+1}^c = RN_y^c$.

With these assumptions, equation (A2) becomes:

$$N_y^c = \frac{N_y^c}{R^3} P_0 S^3 + \frac{N_y^c}{R^5}(1 - P_0)S^5 + \frac{N_y^c}{R^{t_m}} X_0 S^{t_m} \quad \text{(A3)}$$

Therefore X_0 can be calculated as:

$$X_0 = \left(1 - \frac{S^3}{R^3} P_0 - \frac{S^5}{R^5}(1 - P_0)\right) / \left(\frac{S^{t_m}}{R^{t_m}}\right) \quad \text{(A4)}$$

Furthermore, under the assumption that $N_y^c = \rho N_y^t$, equation (A1) can be re-written as:

$$RN_y^t = N_y^t S \; + \; \rho N_y^t S^{t_m} X_0 / (R^{t_m - 1}) \quad \text{(A5)}$$

From this,

$$\rho = R^{t_m - 1}(R - S)/(S^{t_m} X_0) \quad \text{(A6)}$$

Model set-up post y_0

The calculations above provide the values for N_y^t, N_y^c, p_y and X_y for the *n* years prior to y_0. From y_0 onwards, equations (A1) and (A2) are used to calculate the population dynamics. The parameters X_y and p_y are estimated as a mean value with annual residuals that are assumed to be normally distributed with a mean of zero and a standard deviation of σ_X and σ_p – more details can be seen in the table below.

Model parameters

The table below lists key model parameters along with further details.

Parameter		Fixed/Estimable
lnN^t_{y0-n}	Total female population size in start year, n years before the first year for which data are available ($y_0 = 1979$) for SA right whales. Estimated in log space.	Estimable. For the results in this paper n is set at 20 years.
P_0	The constant value of p_y assumed for the initial set-up, n years before 1979.	Fixed on input
S	Non-juvenile survival rate	Fixed (at 0.97[1])
t_m	Age at first parturition	Fixed (at 5 years[2])
$X_y = \dfrac{0.5}{1+e^{-X^*_y}}$	Parameter to take additional juvenile mortality into account as well as the proportion of calves that are female. The estimable parameter is X^*_y, estimated in logit space so that X_y lies between 0 and 0.5, as the female proportion is assumed not to exceed 0.5 .	Estimable
$X^*_y = \mu_X + \epsilon^X_y$	The model estimates a mean for X^*_y and residuals ϵ^X_y, where $\epsilon^X_y \sim N(0, \sigma^2_X)$, with σ_X fixed on input.	Estimable mean and fixed standard deviation
$p_y = \dfrac{1}{1+e^{-p^*_y}}$	The proportion of adult females calving each year that will take three years until they calve again. Similar to X, the estimable parameter is p^*_y, estimated in logit space so that p_y lies between 0 and 1.	Estimable
$p^*_y = \mu_p + \epsilon^p_y$	The model estimates a mean for p^*_y and residuals ϵ^p_y, where $\epsilon^p_y \sim N(0, \sigma^2_p)$, with σ_p fixed on input.	Estimable mean and fixed standard deviation

Data and likelihood

The model is fit to number of calves seen each year assuming a Poisson distribution:

$$-lnL = -N^{c,obs}_y lnN^c_y + N^c_y \tag{A7}$$

where

$N^{c,obs}_y$ is the number of calves (male and female) observed in year y, and

N^c_y is the number of females calving in year *y.*

In addition, a penalty is added to the negative log-likleihood for each of the X_y and p_y parameters so that the estimated residuals correspond roughly to a normal distribution with their mean “forced” to be zero.

$$pen_X = w_X \left(\sum_y \epsilon^X_y \right)^2 + \sum_y \left(\epsilon^X_y\right)^2/(2\sigma^2_X) \tag{A8}$$

and similarly

[1] This value is somewhat lower than the 0.99 estimated in Brandão *et al.* (2018), and was chosen to provide greater stability for these initial explorations.

[2] See Brandão *et al.* (2018).

$$pen_p = w_p\left(\sum_y \epsilon_y^p\right)^2 + \sum_y \left(\epsilon_y^p\right)^2/\left(2\sigma_p^2\right) \tag{A9}$$

Lastly, penalties are added to the negative log-likelihood to force some continuity in X_y and p_y when transitioning from the initial setup (before y_0) to the post-y_0 model dynamics.

$$pen_{X,cont} = \left(X_0 - \frac{1}{10}\sum_{y_0}^{y_0+9} X_y\right)^2 /(2(0.01)^2) \tag{A10}$$

$$pen_{p,cont} = \left(P_0 - \frac{1}{10}\sum_{y_0}^{y_0+9} p_y\right)^2 /(2(0.01)^2) \tag{A11}$$

Annex D: Survey information for long term southern right whale genetic and photo ID datasets for identifying biases for development of common model to compare demographics (note: further information available in Annex E on other regions including Tristan da Cunha, Uruguay, Namibia)

Wintering ground	Systematic/ Opportunistic	Years	Methodology	Timing	Duration	Length: kms²	Relative proportion of Population	calving ground vs mating ground	Other bias
South Africa	Systematic	1969 - 2019	Helicopter	Early October	1 week- 10 days (weather dependent)	Nature's Valley - Muizenberg	~80-100%	Calving ground	Photo ID prioritises CC
Argentina	Systematic	1971-2019	fixed wing	5-10 September	2 days (1 day Golfo Nuevo, 1 day Golfo San José)	320km	~100%	calving ground	Photo ID prioritises CC
Brazil	systematic	1987-1988; 1992-1994; 1997-2019 (except 2014)	fixed wing (up to 1997); helicopter (from 1998 on)	September 1 -28 (main survey); + monthly surveys in some years: July to November)	1 day (usually)	300km usually (some years varied)	~90%	Calving ground (unaccompanied adults also sighted)	Photo ID all individuals but mostly CC sighted
Chile-Peru	Opportunistic	1964-2019	variable	June-February	NA		Unk	Calving and mating grounds	Variable effort. Difficult sampling area.
Australia – SW	Systematic	1975-2019	fixed wing	August 15-Sept 5	5 days	1500km	~100% SW sub-population	Calving and mating grounds	Photo ID prioritises CC. Surveys expanded from Western Australia into South Australia in 1993 to include whole SW population
Australia – Head of Bight	Systematic	1991-2019	Cliff based	August 15-30	Min 14, max 100	30km2	~30% SW sub-population	Calving and mating grounds	Survey effort variable across years. Consistent period for all years Aug 15-30. Surveys extended May-Oct in some years.
Australia – SE	Systematic	2013 & 2014	fixed wing	late August	8 days	Ceduna to Sydney (including Tas)	100% SE sub-population	Calving, mating, migration corridor	N/A
Australia – SE	Opportunistic	1995 - 2019	fixed wing, helicopter, drone, land based	June - October	varied 1 - 2 hours	Variable: Western Victoria, parts of NSW, parts of SA, parts of Tas, parts of QLD	~30% SE sub-population	Calving, mating, migration corridor	Variability temporally and spatially. Opportunistic
New Zealand - Auckland Islands photo-ID	Opportunistic Systematic	1995-1998, 2006-2009 Auckland Islands surveys (UOA) 2010-2013, 2016-2018 Auckland Isl (Otago Uni)	Small boat < 6m. UAV >2016	July/August	11 -21 days	200-700km variable	~20% of area (80% CC detection in survey area)	Calving ground.	Temporal and spatial variability, low elevation.
New Zealand - other photo-ID	Opportunistic	Campbell Island: 1995, 1997 (Project Tohorā), 2014 (NIWA)	Small boat/ variable						

		Mainland: opportunistic since 1976							
New Zealand - Auckland Islands genetics	Opportunistic	Auckland Islands surveys: 1995-1998; 2006-2009; 2020-2021;	Small boat < 6 m	July/August	12-35 days	Port Ross area; not linear survey	Assume Auckland Islands is part of core range for all NZ right whales	Calving ground. All demographic classes present. Mating behaviour observed. Evidence of reproductive autonomy from parentage analyses	Whales also present around mainland and Campbell Island
New Zealand - other genetics	Opportunistic	Campbell Island survey: 2014; Mainland NZ: opportunistic data collection 2001-2018	Small boat/variable	Opportunistic	NA	Opportunistic so variable		Campbell Island: no calves in 2014 Mainland NZ: Calving ground. All demographic classes present. Mating behaviour observed.	Whales also present in the Auckland Islands
Falkland Islands (Islas Malvinas)	Systematic	2017, 2019-2020 (Falklands Conservation)	Small boat 6.5m. Limited aerial shots with drone.	May-August	Several days per month (varied, weather dependent)	North-east Falklands coast, variable	Unknown	Unknown. No calves. Some mating behaviour observed.	Small, localised study area relative to rest of Falklands. Variable effort. Side-on head shots from boat.