Surfacing time, availability bias, and abundance of humpback whales in West Greenland

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Abstract

Visual aerial surveys of large whales are negatively biased unless correction factors are developed for correcting for the availability of whales at the surface. One method for developing a correction factor for this bias is by instrumenting whales with recorders that measure the amount of time the whales spent at the surface. A total of 31 satellite-linked time-depth-recorders of three different types were deployed on humpback whales (*Megaptera novaeangliae*) in West Greenland in May and July 2009-2010. Over the period whales were tracked, the SLTDRs recorded the fraction of a 6-hour period that the whales spent at or above 2 m depth. This depth is considered to be the maximum depth humpback whales are reliably detected on visual aerial surveys in West Greenland. Eighteen transmitters provided both data on the surface time and the drift of pressure transducer. The average surface time for these whales over the entire tracking period and during the two 6-hr periods with daylight was 28.3% (cv=0.06). Six whales that met data filtering criteria had reduced drift of the depth transmitter and their average surface time was 33.5% (cv=0.10). Previous analyses of visual aerial survey data have shown that the amount of time whales are available to be seen by observers is not an instantaneous process. Therefore the surface time needs to be corrected for a positive bias of about 10% when developing a correction factor for availability bias which increases the availability to 36.8% (cv=0.10). The most recent survey of humpback whales in West Greenland was conducted in 2007 and corrections with this availability factor provides fully corrected abundance estimates of 4,090 (cv=0.50) for mark-recapture distance sampling analysis and 2,704 (cv=0.34) for a strip census abundance estimate. These estimates are about 25% larger than previous estimates from the same survey.

Introduction

Accurate and reliable abundance estimates are essential for management of exploited populations of baleen whales. In general abundance estimates have been based on visual encounters from aerial or ship-based survey platforms or through mark-recapture studies with photo or genetic identification of the whales. Aerial and ship-based surveys essentially count the portion of the population available at the surface and through various measures account for the proportion that were not available at the surface to be detected by the observers. This so called availability bias (Marsh and Sinclair 1989) can be substantial and has a large impact on the abundance estimates if bias correction is not applied to the at-surface-estimate or if the correction is inaccurate.

One method for estimating the availability of cetaceans to be detected by visual surveys of the sea surface is through instrumentation of whales with dive-data collection telemetry systems. These are generally archival instruments that are attached to and released from whales after few days and retrieved at sea before download of data on dive patterns. Archival recorders will usually log high resolution data over short time periods but it is often desirable to collect data over longer time spans and over in less accessible offshore areas. Other instruments utilize concatenated dive information to be transmitted through satellite connections preferably the Argos Data Collection System. The amount of data that can be collected by the Argos method is limited to the brief messages transmitted during the short surfacing events of the whales. Therefore no full resolution dive cycles can be relayed by this method, and instead only pre-defined summary information can be transmitted. The limited, filtered and pre-analyzed data relayed through this system does not allow for a post-deployment instrument calibration and it is therefore critical that the instruments perform reliably and show no signs of drift. One way of monitoring the performance of the transmitters is through examination of the instrument's ability to detect the surface, as when the instrument is above the water surface and exposed to air. This is of course of particular importance for quantifying the at-surface-time used for correcting for availability bias. Any drift of what the instrument assume to be the surface could change the bias correction and lead to erroneous estimates of abundance.

Visual aerial surveys have proven to be the most cost efficient method for abundance estimation of humpback whales (*Megaptera novaeangliae*) in West Greenland (Heide-Jørgensen 2008, 2012) but it relies heavily on proper estimation of the fraction of the whales that are available to be detected at the surface by the observers. In this study we examine a data set of surfacing time obtaining by satellite telemetry and assess the importance of transducer drift for estimating the surfacing time. The acceptable average surface time is then used for correcting an aerial survey of humpback whales conducted in West Greenland in 2007.

Material and methods

Three types of satellite-linked time-depth-recorders were used in this study; all manufactured by Wildlife Computers (Redmond, Seattle) and modified for use on whales by Mikkel Villum Jensen (www.mikkelvillum.com).

A cylindrical tag (Mk10A) was designed to be implanted in the blubber and muscle of the whales. It consisted of a 151 mm long (22 mm in diameter) stainless steel tubing where a 38 mm (in diameter) stop plate prevented the tag from being implanted deeper that 113 mm. The forward part of the steel tube had a 6 mm screw used for mounting of a 205mm long and 8 mm wide cylindrical stainless steel anchoring spear (tulip anchor) equipped with a sharp triangular pointed tip and foldable barbs (40-50 mm) along the spear to impede expulsion from the blubber-muscle layer. The rear end of the steel tube had the antenna (160 mm length) extending and the salt water switch that ensured that transmissions were only conducted when the rear part of the tag was out of the water. The pressure transducer was positioned just below the stop plate, the weight of the transmitter with the anchoring spear was 250 gr and the tag had one AA cell in the front part of the steel tube.

The external positioned tag (SPLASH-200) used a spear similar to the one described above to anchor the tag in the blubber and muscle, however the transmitter was mounted on a steel plate attached to the rear end of the spear and was externally placed on the whale. The total length of the (8 mm diam.) anchoring spear was 235 mm of which 210 mm with barbs were implanted into the blubber and muscle layer, and 25 mm remained outside the skin with the attachment to the steel plate. The steel plate with the transmitter (85x50x25 mm) could swivel freely around the spear and thereby keeping the tag in a position with the least drag. Salt-water switch and pressure transducer was mounted on top of the transmitter next to the antenna and the tag, that weighed 300 gr, had 2 AA cells as power supply.

A third tag was a small Mk10A with two M3 batteries (35x53 mm, 100 grams). It was mounted on a rubber plate attached to a short (100 mm x 6mm) stainless steel spear with a cutting tip and one set of small (30 mm) barbs. The cylindrical Mk10A tags was deployed either with the Air Rocket Transmitter System (Heide-Jørgensen et al. 2001) or an 8 m fiberglass pole (Heide-Jørgensen et al. 2006). The external SPLASH and the small Mk10A were deployed with the fiberglass pole, requiring much closer distance to the whales. The small Mk10A was delivered by a small airgun (Dan Inject).

Positions of the whales were determined from transmitter uplinks received by Argos satellites and a daily average position was calculated for all whales. The tags also provided data on the time-at-depth of the whales recorded during four 6-hr periods starting at 00:00 GMT or 22:00 local time. The depth readings were collected from the pressure transducer every 1s at a resolution of 0.5 m and the readings were binned in 12 time-at-depth bins of which only the first two, 0 m and 0-2 m, were used for this study. The data were sequentially (previous 24 hr transmitted while new 24 hr data were collected) relayed through the Argos Data Collection and Location System and decoded using Argos Message Decoder (DAP Ver. 3.0, build 058, Wildlife Computers). Time-at-depth data for two depth bins 0 m and 0-2 m were extracted for May-July. Drift of the pressure transducer (obtained from status messages included in every 50 transmission) was assessed for the study period.

Data from the first day of deployment were omitted and time-at-depth observations with surfacing times recorded as 0 or 100% were considered erroneous and the data stream was discarded.

The speed of the change in drift of the pressure and time-at-depth data was examined by linear regression ($y=\beta*\text{Daynr} + k$) of the recordings against day number (from 1 January) where β is a measure of the rate of change.

It was assumed that the whales were available for detection when $\leq$2 m of the surface and the time spent at or above this depth was used to estimate the availability correction factor from the satellite-linked time-depth-recorders.
Abundance (corrected for availability bias) was then estimated as

$$\hat{N}_c = \frac{\hat{N}}{\hat{a}}$$

with estimated cv

$$cv\left(\hat{N}_c\right) = \sqrt{cv\left(\hat{N}\right)^2 + cv\left(\hat{a}\right)^2}\,.$$

Results

Thirty-one tags were deployed on humpback whales: 12 tags in 2009 and 19 tags in 2010 in West Greenland (Table 1, Fig. 1). Twenty-two humpback whales were instrumented with the large model of the implantable Mk10A's, eight whales were tagged with Splash tags, and one whale was tagged with the small Mk10A tag during May-July 2009-2010 (Fig. 2). Eight of the Mk10As failed in providing data on time spent at the surface. Additional five tags did not provide data on drift of the pressure transducer although they did provide records of the time spent at the surface. Data from the remaining 18 tags were examined for the range and speed of the drift of the pressure transducer and for temporal changes in surfacing time. All whales were located in the shelf area of West Greenland which is the same area covered by aerial and ship-based surveys for estimating the abundance in West Greenland.

Most transmitters had a positive transducer drift (i.e. increasing the depth assumed to be 0 m) but a few also had negative drift that moved the surface above 0 m. The average drift of the 18 tags was about 40 cm per day and most transducers did not correctly identify the surface when they provided the first data on surface times (Fig. 3).

The surface times showed changes over time and this was most consistent for the Mk10 tags used in 2009 using tag ware generation 1.24d (Fig. 4). If the zero depth readings were gradually biased to be reading deeper than the actual surface, the time at surface would show a similar decrease which would not be detected or corrected. Probably the tags with tag ware 1.24d did not correctly adjust the depth transducer for the surface readings from the conductivity switch and due to this suspicion data from Mk10 with tag ware 1.24d are excluded from developing estimates of surface time. The later generations of tag ware could not be associated with a simultaneous drift of the pressure transducer which indicates that any drift in the pressure transducer may not affect the overall perception of the surface time when data from many instruments are examined. It was nevertheless decided to restrict the data to instruments and periods when the transducer drift indicated values in the range from 0 to ±1 m, or the resolution of the depth readings. This further reduced the number of useful data series to six whales with a total of 89 days of data. Even though there was no statistical difference between the four six hour periods that the surface time data were collected data were only included from 10:00-16:00 and 16:00-22:00, the relevant periods for correcting visual aerial surveys.

The average surface time for the six animals that provided data with a minimum drift of the pressure transducer was 33.5 % (cv=0.10) of the time spent at or above 2 m depth. If data from all twenty-three whales with surfacing data during daylight hours were examined the average surfacing time declined to 28.3 (cv=0.06) which is not significantly different from the restricted dataset.

Detection of whales at the surface from a passing plane cannot be considered an instantaneous process because the whales are in view for a small but certain amount time. To account for this Heide-Jørgensen et al. (2012) applied a correction of 10% to the surface time which increases the availability correction factor from 33.5% to 36.8% (cv=0.10).

At-surface abundance estimates of humpback whales in West Greenland are available from a survey in 2007 (Heide-Jørgensen et al. 2012); two of them are corrected for perception bias (strip census and mark-recapture-distance-sampling) and one conventional distance sampling estimate is not. When applying the availability correction factor developed above to these estimate the strip census and conventional distance sampling estimates are in good agreement whereas the mark-recapture-distance-sampling estimate is slightly, but not significantly, larger (Table 2).

Discussion

Richard et al. (1994) and Heide-Jørgensen (2004) made experiments with models of narwhals (*Monodon monoceros*) to estimate the depth to which these whales reliably can be detected and they found that a detection depth of 2 m could be used for visual surveys of narwhals. No similar studies have been conducted for humpback whales, but it can be argued that while the white flippers of North Atlantic humpback whales are easy to detect below the surface, humpback whales occur in more turbid and muddy water than narwhals. Therefore we decided to use 2 m as the detection depth for humpback whales. None of the sightings in the 2007 survey had recordings of whales below the surface.

Perhaps of greater concern is the calibration of the depth transducer, something that is mandatory in oceanography but rarely seen in marine mammal studies. This study stresses the importance of assessing the drift of the pressure transducer in studies where fine scale resolution of the surface layer is involved. Ideally the pressure transducer should calibrate its reading of the surface from the conductivity switch when it breaks the surface. The software version in the tags deployed in

2009 (tag ware 1.24d) did not correctly use the conductivity switch information for correcting the surface readings and the pressure transducers drifted rapidly out of the range critical for assessing the surface time. The drift was unidirectional towards increasing depths (except for 1 tag with only three data points) which led to a negatively biased surface that could not be recovered. The problem was apparently solved with tag ware 1.24k but the drift message from the tags still reported some level of fluctuating drift, and even though no clear direction in the surface time could be detected, only whales were included for periods where the drift was within the depth resolution of the tags.

In a previous study of surface time of humpback whales in West Greenland in 2000 (Heide-Jørgensen et al. 2012) Telonics SDR-T16 satellite-linked time-depth-recorders were used but there was at that time no consideration of drift of the pressure transducer. Due to the resolution of the depth readings the surface was defined as 0-4 m rather than the more optimal definition of 0-2 m used in this study. Even though the values obtained in the previous study are not significantly different from this study, the later instrumentation technique and the more rigorous examination of the drift of the pressure transducer render the current estimates more reliable. The availability correction factor developed here is slightly lower than the estimate of 0.46 developed in 2000 and it results in fully corrected abundance of humpback whales that are about 25% larger than the previous estimate for 2007 (Heide-Jørgensen et al. 2012).

The simplest availability correction factors $\hat{a}$ is the estimated proportion of time an animal is available for detection, which is an estimator of the probability that an animal is available at any randomly chosen instant. This is therefore an appropriate correction factor when the survey is instantaneous e.g. photographical surveys (Heide-Jørgensen 2004). However, even for aerial survey where the survey platform is moving at high speed, there is still a period where the animals are within view of the observers. Borchers et al. (in press) developed hidden Markov models to account for the detection process in situations where the diving whales are available for detection for a certain period (time-in-view) and the animals are either submerged or at the surface in a certain sequence. Detailed data on the diving sequence of humpback whales in West Greenland are missing for this population and even though the bias correction may differ for a stochastic series of diving events the deterministic availability bias correction factor is still applicable to the surveys off West Greenland.

Acknowledgements

We express our sincere thanks to Mikkel Villum Jensen, Hans Christian Schmidt and the hunters from Qeqertarsuaq that did most of the tagging of the whales. This study was funded by NOPP the National Ocean Partnership Program (NSF and ONR) and the Greenland Institute of Natural Resources

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Table 1. Overview of humpback whales tagged with satellite linked time-depth-recorders in West Greenland 2009-2010 with data on drift of pressure transducer and surface time (ST) during day light hours (22-22 hrs), during 24 hrs and during days with limited drift (0-1 m) of the pressure transducer.

PTT ID	**Tag type/ tag ware**	**Date**	**Position °N °W**	**Place-ment**	**Sex**	**Length (m)**	**Deploy-ment method**	**n**	**ST change/ day (%)**	**Drift change per day (β, m)**	**Range drift (m)**	**ST (22-22 hrs) (%)**	**ST (24 hrs) (%)**	**Day number with drift within 0-1 m**	**ST with drift within 0-1 m (%)**
13280	Mk10/ 1.24d	27 May 2009	68°38.433 53°07.414	RBH	♂	13	Pole	67	-1,9	0	3-3	28,78	31,61		
20160	Mk10/ 1.24d	31 May 2009	68°44.984 52°51.940	LBL	♀	13	Pole	Unreliable data							
20164	Mk10/ 1.24d	03 June 2009	68°45.778 52°37.507	LMH	♂	14	ARTS	130	-0,3	na	na	19,67	21,57		
20165	Mk10/ 1.24d	01 June 2009	68°38.281 53°12.942	RFH	na	14	Pole	Unreliable data							
20166	Mk10/ 1.24d	01 June 2009	68°44.788 52°54.172	RMH	♂	14	ARTS	107	-0,6	0,1	2-2.5	18,66	18,02		
20168	Mk10/ 1.24d	03 June 2009	68°44.995 52°37.857	LMH	♀	11	Pole	3	1	na	na	26,30	24,20		
20682	Mk10/ 1.24d	07 June 2009	68°43.057 52°18.683	RMH	♂		ARTS	104	-0,2	0,1	2-2.5	19,88	28,07		
20683	Mk10/ 1.24d	06 June 2009	68°43.586 52°51.730	LMH	♂	8	ARTS	Unreliable data							
20684	Mk10/ 1.24d	03 June 2009	68°46.144 52°29.688	RMM	♂		ARTS	47	-1,4	na	na	18,55	19,92		
20690	Mk10/ 1.24d	07 June 2009	68°43.454 52°35.735	RMH	na	11	ARTS	Unreliable data							
20692	Mk10/ 1.24d	07 June 2009	68°43.044 52°21.630	RMH	na	13	ARTS	Unreliable data							
20693	Mk10/ 1.24d	11 June 2009	68°43.255 52°07.776	LMH	na	11	ARTS	Unreliable data							
7931	Mk10/ 1.24k	1 July 2010	65°25.656 52°43.784	LMH	na	na	Pole	18	2,9	na	na	22,53	21,67		
13280	Mk10/ 1.24k	2 June 2010	68°43´019 52°16°714	RMH	♂	na	Pole	102	-0,1	0,3	1-4	22,96	22,22		
20157	Mk10/ 1.24k	2 July 2010	65°25.177 52°47.461	RMH	na	na	Pole	102	-0,5	0	1-1.5	26,85	28,61		
20158	Mk10/ 1.24k	7 July 2010	68°44.003 52°46.667	RMH	na	na	Pole	80	0,3	0,1	0.5-2.5	34,24	31,91	189-204	32,92

20160	Mk10/ 1.24k	20 June 2010	69°14.256 53°24.395	LMH	♀	na	Pole	120	0,3	0,1	0-3	51,58	52,46	171-178	45,40
20167	Mk10/ 1.24k	1 July 2010	65°26.054 52°43.787	RMM	na	na	Pole	Unreliable data							
26712	Mk10/ 1.24k	7 July 2010	68°43.259 52°19.194	LMH	na	na	Pole	44	0,1	0	0-1	31,65	28,76	188-218	31,60
27260	Mk10/ 1.24k	19 June 2010	69°11.660 53°47.129	LMH	♂	na	Pole	106	0,4	0	1.5-2	45,33	40,18		
50681	Mk10/ 1.24k	18 June 2010	69°27.263 54°13.699.	LMH	♂	na	Pole	39	0,4	na	na	25,18	26,93		
50684	Mk10/ 1.24k	2 July 2010	65°32.137 52°59.260	LMH	na	na	Pole	Unreliable data							
20692	Splash/ 1.001	2 June 2010	68°40.165 52°08.802	RMM	♀	na	Pole	61	-0,1	0	-2- -2	18,23	16,79		
20693	Splash/ 1.001	3 June 2010	68°33.060 53°11.815	RMH	♀	na	Pole	148	0,6	0	3-3	25,86	22,24		
20696 *)	Splash/ 1.001	2 June 2010	68°39.825 52°09.659	RMM	♂	na	Pole	32	0	-0,2	2-1	28,14	26,72	157-162	29,85
21791	Splash/ 1.001	9 June 2010	69°15.933 53°25.628	LMH	♂	na	Pole	137	0,2	0	2-2	22,40	23,58		
21792	Splash/ 1.001	4 June 2010	68°43°501 52°21°657	RMM	♂	na	Pole	66	-0,6	0	-2- -6	31,32	27,21		
21794	Splash/ 1.001	7 June 2010	69°14.141 53°48.691	RMH	♂	na	Pole	76	-0,7	0	0	41,12	40,43	160-177	38,68
21800	Splash/ 1.001	18 June 2010	69°26.979 54°15.524	LMH	♂	na	Pole	94	0,2	0,5	-2 0	21,87	22,09	178-193	22,25
21802	Splash/ 1.001	11 June 2010	69°10.170 51°28.388	LMH	♂	na	Pole	41	-0,6	-0,3	-3- -7	37,68	36,52		
46135	Mini Mk10/ 1.24k	20 June 2010	69°14.177 53°24.431	LMH	♂	na	Pole	38	-0,4	0,1	5-5.5	40,89	39,79		
											Average	28,68	28,33		33,45
											cv	0,06	0,06		0,10

*) Later tagged with #27260 on 19 June 2010

Table 2. Aerial survey data on humpback whale abundance in West Greenland in 2007 (Heide-Jørgensen et al. 2012). The data were not corrected for whales that were submerged during the passage of the airplane (availability bias). Availability bias estimated to 36.8% (cv=10).

Method	Estimate	Estimate corrected for availability bias	95% conf limits
Conventional distance sampling without correction for perception bias	1020 (0.35)	2772 (0.36)	1388-5534
Mark-recapture distance sampling corrected for perception bias	1505 (0.49)	4090 (0.50)	1620-10324
Strip census estimation corrected for perception bias	995 (0.33)	2704 (0.34)	1402-5215

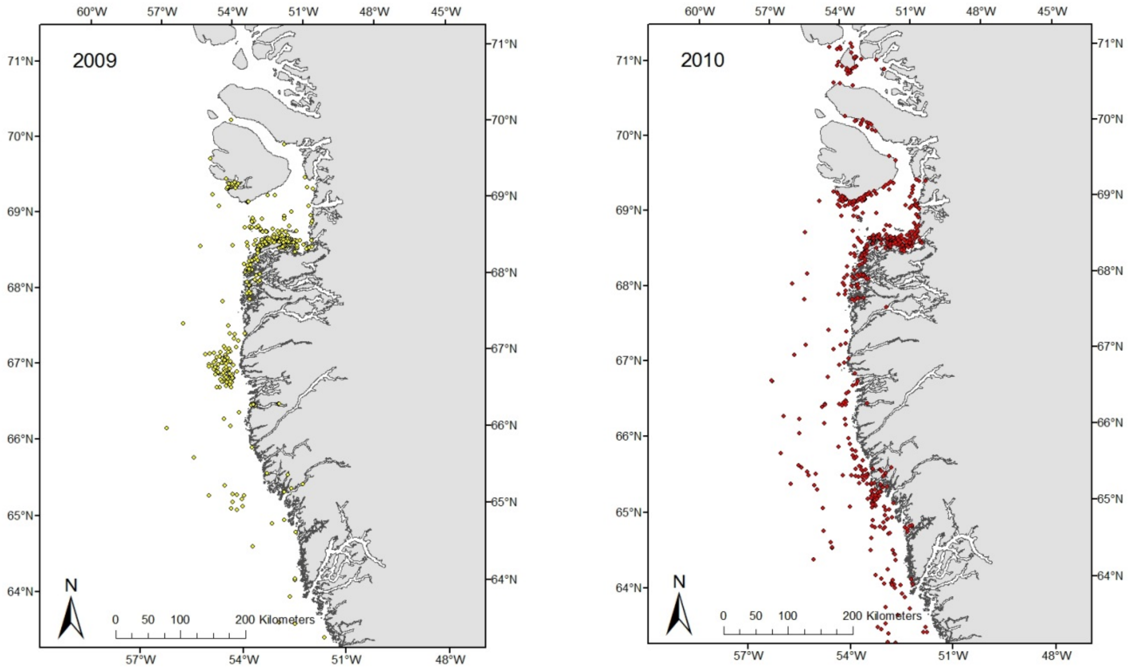

Fig. 1. Daily positions of the whales instrumented with SLTDRs in West Greenland in 2009 (left) and 2010 (right).

Fig. 2. Humpback whales instrumented with a Mk10A transmitter (left), Splash transmitter (middle) and a mini Mk10 (right).

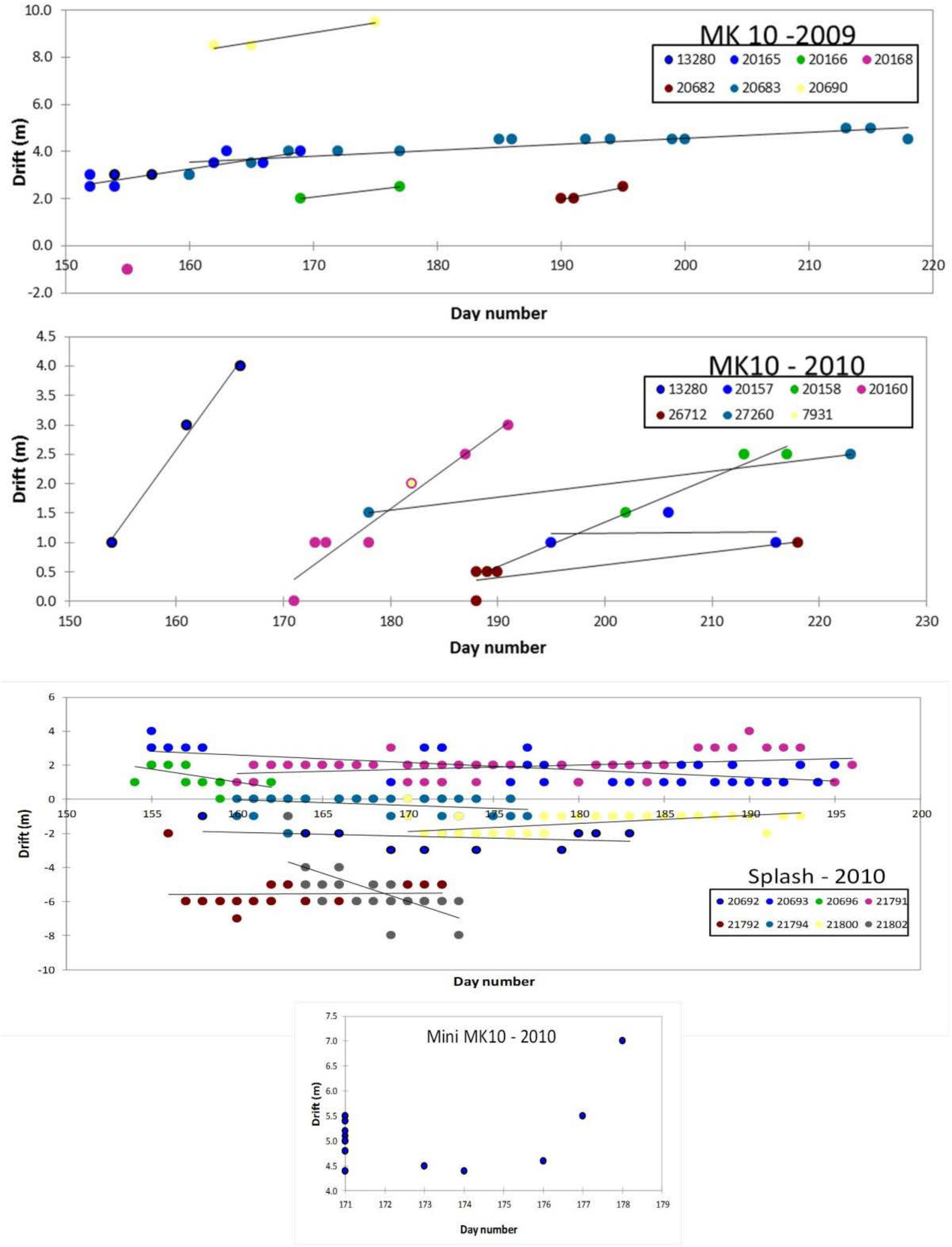

Fig. 3. Drift of pressure transducer for Mk10 and Splash transmitters used on humpback whales in West Greenland in 2009 and 2010.

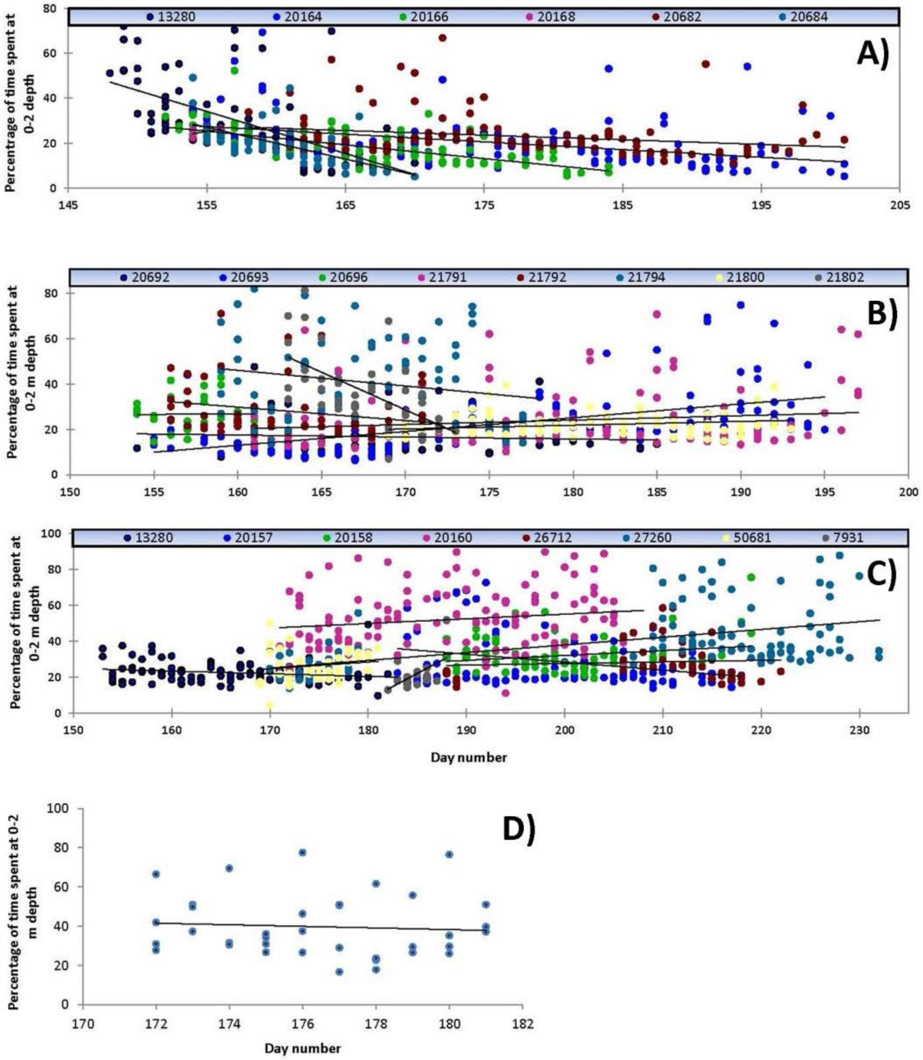

Fig. 4. Trends in surfacing times for humpback whales instrumented with A) Mk10 transmitters in 2009, B) Splash transmitter 2010, C) Mk10 transmitters 2010, D) Mini Mk10 transmitter in 2010.