The perfect storm: can sperm whale (*Physeter macrocephalus*) strandings in the North Sea be linked to storm activity?

J.H. Nielen

Master Thesis

Utrecht University
Faculty of Geosciences
Department of Earth Sciences
Master Marine Sciences

1th supervisor: dr. M.F. Leopold
2nd supervisor: dr. ir. C.J.M. Philippart

05-01-2018

Universiteit Utrecht

WAGENINGEN UNIVERSITY & RESEARCH

Contents

Abstract

In early 2016, 30 male sperm whales (*Physeter macrocephalus*) stranded along North Sea coasts. Sperm whale mass strandings in the North Sea area have occurred several times over the past century and are relatively well documented. Most strandings occur when sperm whales migrate south from the Norwegian Sea, and enter the shallow North Sea by accident. There are multiple theories regarding the cause of why sperm whales sometimes take the wrong turn into the North Sea 'trap'. One hypothesis focuses on a positive association between higher temperatures and increased probability of sperm whale strandings. Another hypothesis focuses on a link between solar storms and disturbances in Earth's magnetic field, and sperm whale strandings. In this study, a third hypothesis is investigated: a possible link between the occurrence of (severe) storms and sperm whale strandings. It is important to gain additional insight in what drives North Sea sperm whale strandings, since climate change will affect sea surface temperature and will also lead to increased storm frequency and activity. This might lead to a further increase of the frequency of sperm whale stranding events in the future. The storm activity results indicate that wind speed, measured off southwest Norway, is not directly related to the early 2016 sperm whale stranding event. Historical records of storm activity on Iceland and in the North Sea area also show no good correlation with the historical North Sea stranding record, indicating that there is no direct link between (severe) storm activity and sperm whale strandings. Other parameters that have been investigated on short time scales, such as chlorophyll levels, SST and sea surface currents, are also excluded as major drivers behind the early 2016 event. For now, the hypothesis regarding the solar storms and the corresponding disturbances in Earth's geomagnetic field seems to be the most likely.

1. Introduction

Between the 8th of January and the 24th of February 2016 multiple sperm whales (*Physeter macrocephalus*) stranded at different locations along the North Sea coastlines. A total of 30 male sperm whales stranded individually or in groups of up to eight animals along the coasts of Denmark, Germany, The Netherlands, The United Kingdom and France (Unger et al., 2016). These so-called 'mass stranding events', involving multiple animals within a short period of time (Klinowska, 1985; Vanselow et al., 2009), have occurred several times over the past centuries in the North Sea region (Smeenk, 1997; Vanselow & Ricklefs, 2005; Pierce et al., 2007).

Whale strandings usually draw attention and receive a lot of public interest (Pierce et al., 2007). This was also the case in the early 2016 stranding event. Over the past centuries, this interest, combined with a relatively densely populated North Sea coast (Lamp, 1991; Evans, 1997) led to a multitude of documentations of strandings, which resulted in a 440 year-record of North Sea sperm whale strandings (Smeenk, 1997; Pierce et al., 2007). A visualization of this record, with data added since 2007, can be seen in Figure 1. From Figure 1 and from the historical record (see Appendix I), some conclusions can be drawn. First, mass stranding events have also occurred in the past. Second, almost all strandings occur in winter months, and third; there is an increase in sperm whale strandings since the late 20th century (conform Smeenk, 1997). The latter may be explained by the fact that sperm whale numbers increased after whaling stopped (Evans, 1997; Smeenk, 1997). However, Goold et al. (2002) stated that the increase in strandings has been too rapid to be caused by increased population size alone.

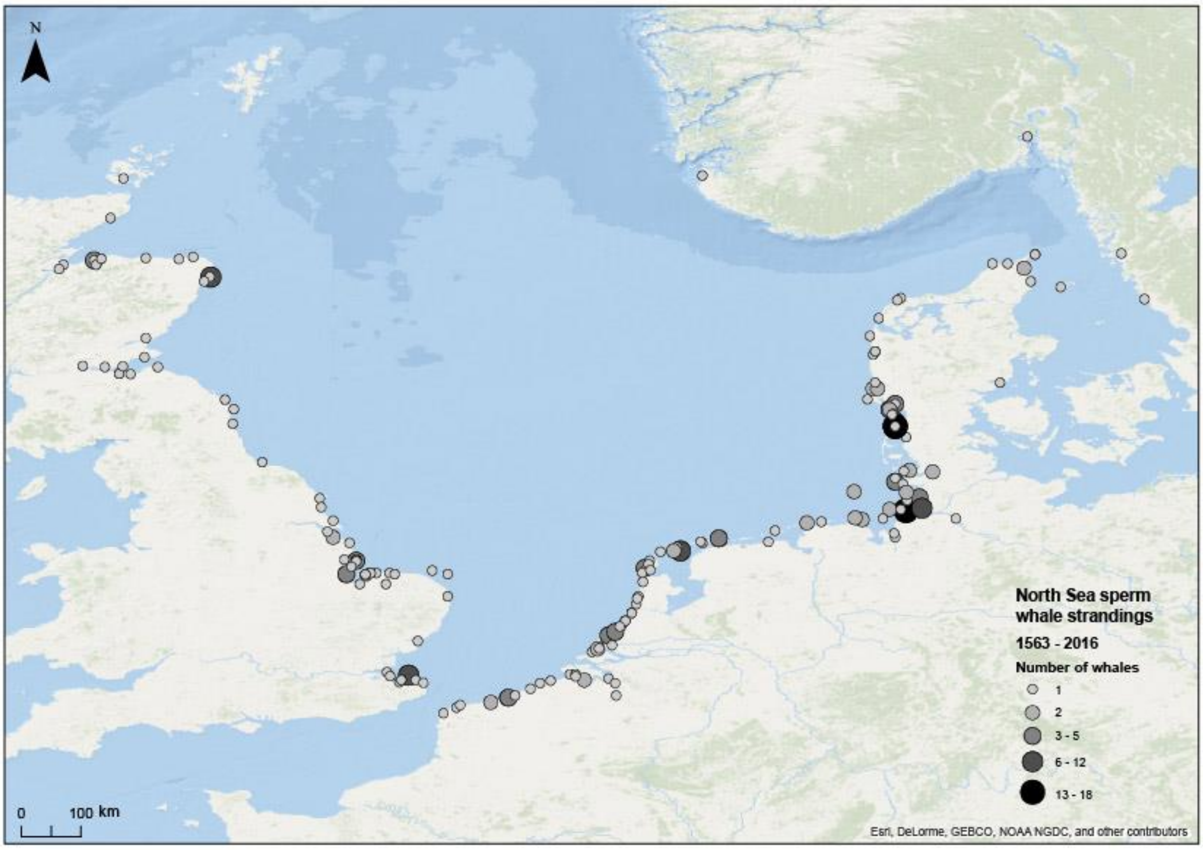

Figure 1. North Sea sperm whale strandings between 1563 and 2016. The size of the dots represents the number of the strandings.

Sperm whales show strong sexual dimorphism and sexual segregation (Smeenk, 1997; Pierce et al., 2007). Female and juvenile sperm whales remain at lower latitudes all year round. Male sperm whales that do not take part in reproduction migrate annually between these lower latitudes and the (sub-)Arctic. The male sperm whales are drawn towards the higher latitudes due to high concentrations and widespread abundance of the squid *Gonatus fabricii* (see Figure 2), one of the whales' main food sources in e.g. the Norwegian Sea (Clarke, 1996; Santos et al., 1999; Bjørke, 2001; Gardiner et al., 2010). The whales might be attracted to spawning females of *Gonatus fabricii*, which are easily caught due to their lack of active locomotion (Arkhipkin & Bjørke, 1999; Simon et al., 2003; Roper et al., 2010). The distribution of sperm whales north of the North Sea is dependent on the location and timing of spawning of *Gonatus fabricii,* which peaks during the winter months (Bjørke, 1995; Roper et al., 2010). Whale surveys conducted between 1995 and 2001 have given some insight in the distribution of sperm whales in this area during summer months (Øien, 2009). In Figure 3 sightings locations of sperm whales during the 1995 survey (left) and the surveys between 1996 and 2001 (right) are shown. According to Øien (2009), both distribution patterns are relatively similar to the distribution conducted by an earlier survey in 1989. In 1995, some sperm whales were observed in the southern Norwegian Sea, but in the surveys conducted between 1996-2001 fewer sperm whales were spotted in this region. Summer surveys conducted in 2009, 2010 and 2011 show that, in summer, the sperm whales are located mostly in the northern Norwegian Sea (Nøttestadt et al., 2015), thus the southern sightings seem to be an exception. After the main *Gonatus fabricii* winter spawning events in the Norwegian Sea are over, most of the male sperm whales return to the lower latitudes.

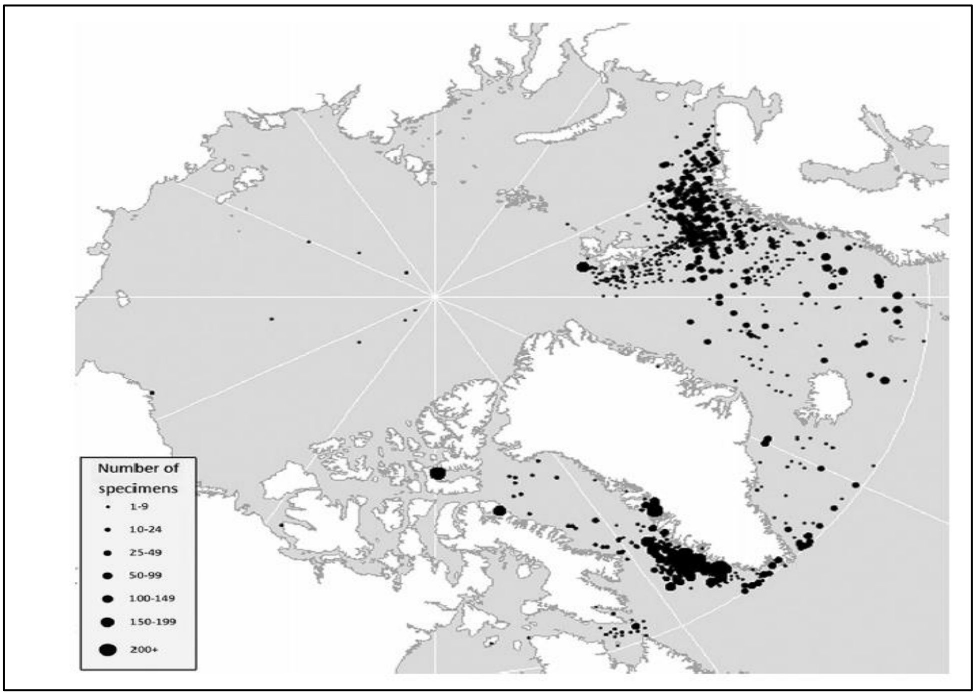

Figure 2. Circumpolar distribution of *Gonatus fabricii*. After Gardiner et al. (2010).

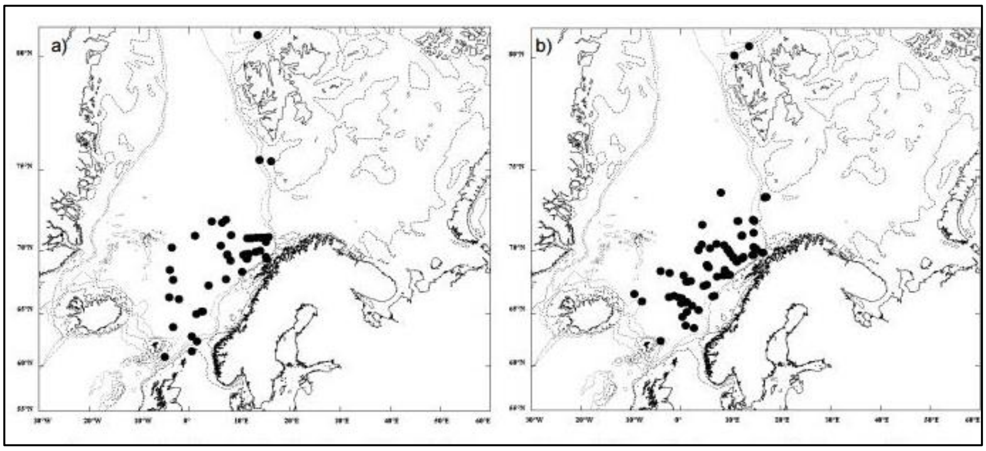

Figure 3. Sperm whale distribution in the Norwegian Sea and adjacent waters in summer, during a 1995 survey (a) and a 1996-2001 survey (b). After Øien (2009).

An important route in the southward migration from the Norwegian Sea is through the Shetland-Faroe Channel (see Figure 4), which leads the whales around the British Isles and southwards towards the Azores (Evans, 1997). However, whales sometimes enter the North Sea by accident, which can result in disorientation, distress and eventually stranding (Smeenk, 1997). According to Smeenk (1997) and Jauniaux et al. (1998) the North Sea is a 'sperm whale trap': the sperm whales' ability to navigate probably decreases in shallow waters (Klinowska, 1985) and although it is unknown if sperm whales feed often during their migration to lower latitudes, we do know that their main source of prey is absent in the shallow North Sea. Also, cetacean sightings records from the English Channel do not include sperm whale sightings (Reid et al., 2003). This endorses the statement that the North Sea is not a usual migration route for sperm whales, or at least, that very few sperm whales that enter the North Sea in the north, eventually manage to 'escape' through the English Channel in the south. The stomach contents of sperm whales that stranded in the North Sea often contain masses of *Gonatus fabricii* beaks (Pierce et al., 2007). This not only confirms that *Gonatus fabricii* is the whales' main source of prey before migration starts, it also confirms that the animals were travelling south when entering the North Sea, since *Gonatus fabricii* is a sub-Artic species (see Figure 2). Also, dissected sperm whales from the 2016 stranding event were found to be healthy and thus did not become stranded due to illness or intoxication (Unger et al., 2016; Vanselow et al., 2017). Finally, the lack of substantial 'fresh' prey in the stomachs of stranded sperm whales confirms that these whales hardly feed in the southern North Sea.

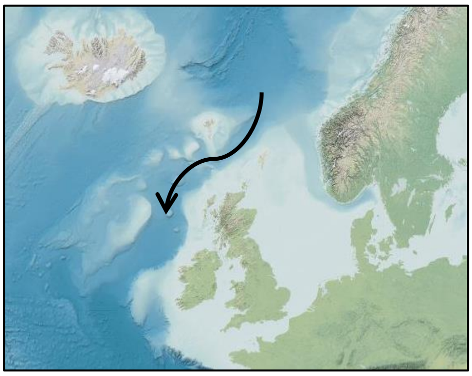

Figure 4. The correct sperm whale migration route. Modified from NOAA's bathymetric data viewer.

Finding explanations on why sperm whales enter the North Sea and strand along North Sea coasts has proven to be a challenge. We do not exactly know what mechanisms sperm whales use to navigate between the Norwegian Sea and lower latitudes. It is thought that the whales' navigation is related to the earth's magnetic field (Klinowska, 1985; Kirschvink, 1997; Vanselow and Ricklefs, 2005; Vanselow et al., 2017), as we know from some other migrating animals, such as certain bird species (Vanselow and Ricklefs, 2005). However, this has not yet been proven for (sperm) whales. Another option is that the whales might have receptors that have a high sensitivity to water temperature, or perhaps are sensitive to changes in sea (surface) currents. It could be hypothesized that the sperm whales use temperature sensitivity to follow the Gulf Stream when they migrate north, and swim against the Gulf Stream when they return south again. Another possibility is that the whales become disoriented when large storms occur in the sub-Arctic area.

Earlier research by Pierce et al. (2007) has shown a correlation between higher sea water temperatures in general and the probability of sperm whale strandings in the North Sea. The authors state that higher temperatures might influence the distribution of *Gonatus fabricii*, which in its turn affects the distribution of the sperm whales at higher latitudes. However, there is no information on Gonatus distribution in relation to (anomalies in) water temperature and it remains unclear how, in warmer years, these squid would choose to move south, i.e., closer to the North Sea. Another hypothesis was proposed and tested by Vanselow and Ricklefs (2005): during years with a shorter length in the sun spot activity cycle than the mean cycle length of 11 years, 90% of the sperm whale stranding events took place. Of course, both temperature and sun spot cycle length might be correlated and also, both hypotheses cannot explain all sperm whale strandings. Another paper by Vanselow et al. (2017) has been published very recently. In this paper, the authors state that solar storms might lead to short-term disruptions in the Earth's magnetic field on a scale large enough for sperm whales to take the wrong turn into in the North Sea. They show that such disruptions occurred just before the 2016 stranding event, suggesting that the timing of these disruptions was right to have steered these sperm whales into the North Sea.

As mentioned above, there is also the possibility that weather events such as large storms lead to disorientation in sperm whales. This hypothesis has not been tested yet. Since stranding events do not occur after every storm, the storm should be large enough to affect the sperm whales navigation in some way and be timely, that is, coincide with sperm whale migration. If (sub-)Arctic storms can indeed be linked to sperm whales strandings in the North Sea, this would have implications for future stranding events as well. Due to climate change, weather patterns are changing, storm activity increases and storms become more severe. Also, water temperature including that of the North Sea will further increase due to climate change. The North Sea stranding event of early 2016 shows that sperm whale strandings are a current issue that receives global attention, and that if climate change plays a role in the strandings, the frequency of these events will most likely further increase in the future. Thus, it is important to gain additional insight on why all of the sperm whales swam into the North Sea early 2016 and eventually died.

Besides the two existing hypotheses concerning sperm whale strandings, the temperature and solar activity hypotheses, storm activity will be added as a third hypothesis. Until now, this third hypothesis has not been tested yet and in this study, storm activity will be researched as an alternative hypothesis in order to explain sperm whale strandings in the North Sea. The storm activity hypothesis will be compared with the existing temperature and solar activity hypotheses in order to discuss which hypothesis is, with the current data available, the best explanation for sperm whale strandings in the North Sea. First, the research focuses on the early 2016 event by looking into different parameters to further investigate the hypothesis proposed by Pierce et al. (2007), and also to see whether a storm might have influenced the early 2016 stranding event. These parameters are chlorophyll, temperature, sea surface temperature, sea surface currents and wind speed. The parameters are presented on a short timescale, just to see whether large anomalies pop up that may be related to the early 2016 stranding event. Next, historical storm data from Iceland and the North Sea area will be used to match with the extended historical sperm whale stranding record. The hypotheses of Vanselow et al. (2005 and 2017) will also be further discussed and will be compared with the storm activity results. This research will test whether (sub-)Arctic storm activity is related to sperm whale strandings in the North Sea and will also give new insights in the discussion regarding the different hypotheses proposed by Pierce et al. (2007) and Vanselow et al. (2005 and 2017).

2. Methods

2.1 Extension of the North Sea sperm whale stranding record

An updated overview of all known sperm whale strandings along North Sea coasts with dates and coordinates is given in Appendix I. Note that sperm whales that washed ashore along Scottish coasts in a state of advanced decomposition have not been taken into account, because the location of their death cannot not be determined and might not have been in the North Sea. The record from Smeenk (1997) is used as the basis for all sperm whale strandings along the North Sea coasts since 1563. Pierce et al. (2007) expanded this record further. All strandings since 2007 have been documented by different countries themselves. For Dutch strandings, the website 'walvisstrandingen.nl' provides an overview of sperm whale strandings. For strandings along the Scottish coasts, the Scottish Marine Animal Stranding Scheme Database provides data. For England, annual reports by the UK Cetacean Strandings Investigation Program were consulted. For an overview of stranding events for specifically Germany the following website was used: http://www.ndr.de/nachrichten/schleswig-holstein/Chronologie-Das-grosse-Pottwalsterben,pottwal276.html and was confirmed by Ursula Siebert. For Danish sperm whale strandings, the following document was used: http://hvaler.dk/onewebmedia/13%20kaskelothvaler%20p%C3%A5%20R%C3%B8m%C3%B8%201997.pdf and was confirmed by Carl Kinze. For Belgium and France, Internet was searched for news items. For Norway, no reported strandings were found after 2007. To create the map in Figure 1, ArcGIS: ArcMap version 10.3.1. was used. The coordinates in the records provided by Smeenk (1997) and Pierce et al. (2007) are transferred to decimal degree coordinates in order to fit with the uploaded map in

ArcMap. The uploaded map is a world ocean map created by Esri, DeLorme, GEBCO, NOAA NGDG and other contributors. The coordinate system used is GCS_WGS_1984.

2.2 Satellite and database study

In Figure 6 the chlorophyll-α content (as a proxy for surface productivity) is visualized with the NOAA View Data Exploration Tool. The data are provided by satellite observations that measure different wavelengths of light absorbed by the surface. A Moderate Resolution Imaging Spectroradiometer (MODIS) on board of the satellites is able to measure the reflected wavelengths of light. These reflected wavelengths are used to calculate the amount of green pigment associated with the presence of chlorophyll-α in the surface waters (Hu et al., 2012). The chlorophyll content cannot be measured through cloud coverage, as indicated by the grey patches in Figure 6.

The sea surface temperature (SST) in Figure 7 is also visualized with the NOAA View Data Exploration Tool. The data within this tool are composed of daily Optimum Interpolation Sea Surface Temperature (OISST) data provided by the NOAA. The OISST analysis is based on combining data from different observation platforms (including ships, buoys and satellites). The two satellite sensors that detect sea surface temperature are the Advanced Very High Resolution Radiometer (AVHRR) and the Advanced Microwave Scanning Radiometer on the Earth Observing System (AMSR-E). The first one has the longest SST record; the second can measure through clouds and in most weather conditions (Reynolds et al., 2007).

For the zonal sea surface current velocities shown in Figure 8, data provided by the Ocean Surface Current Analysis Real-time (OSCAR) project are used (third degree resolution). The current velocities at a depth of 15 meter are estimated based on both satellite data and measurements from in situ instruments. The dataset has been made accessible by the Physical Oceanography Distributed Active Archive Centre (PO.DAAC) and is visualized by using their Live Access Server (LAS) V8.6.1. (ESR, 2009).

The last parameter that was researched in the timeframe before the early 2016 stranding event is wind speed (and corresponding wave height). In Figure 9 wind speed is plotted together with wave height in the days preceding the early 2016 stranding event. The highest daily wind speed and wave height have been used for the graph. The observations were provided on request by the Norwegian Meteorological Institute (see Appendix II). Wind speed and wave height are measured at oil rig stations in the North Sea southwest of Norway. Figure 5 shows the locations of the two stations (represented by the red arrows) that are used for the graph in Figure 9. Most of the data used comes from the Ekofisk station (56.423, 3.2235). Wind speed observations on 7-12, 14-12, 15-12 and 16-12 are from the Sleipner A station (58.3711, 1.9091). Wave height observations from 9-12, 10-12, and 9-1 are also from the Sleipner A station, since the Ekofisk station has no measurements of those days.

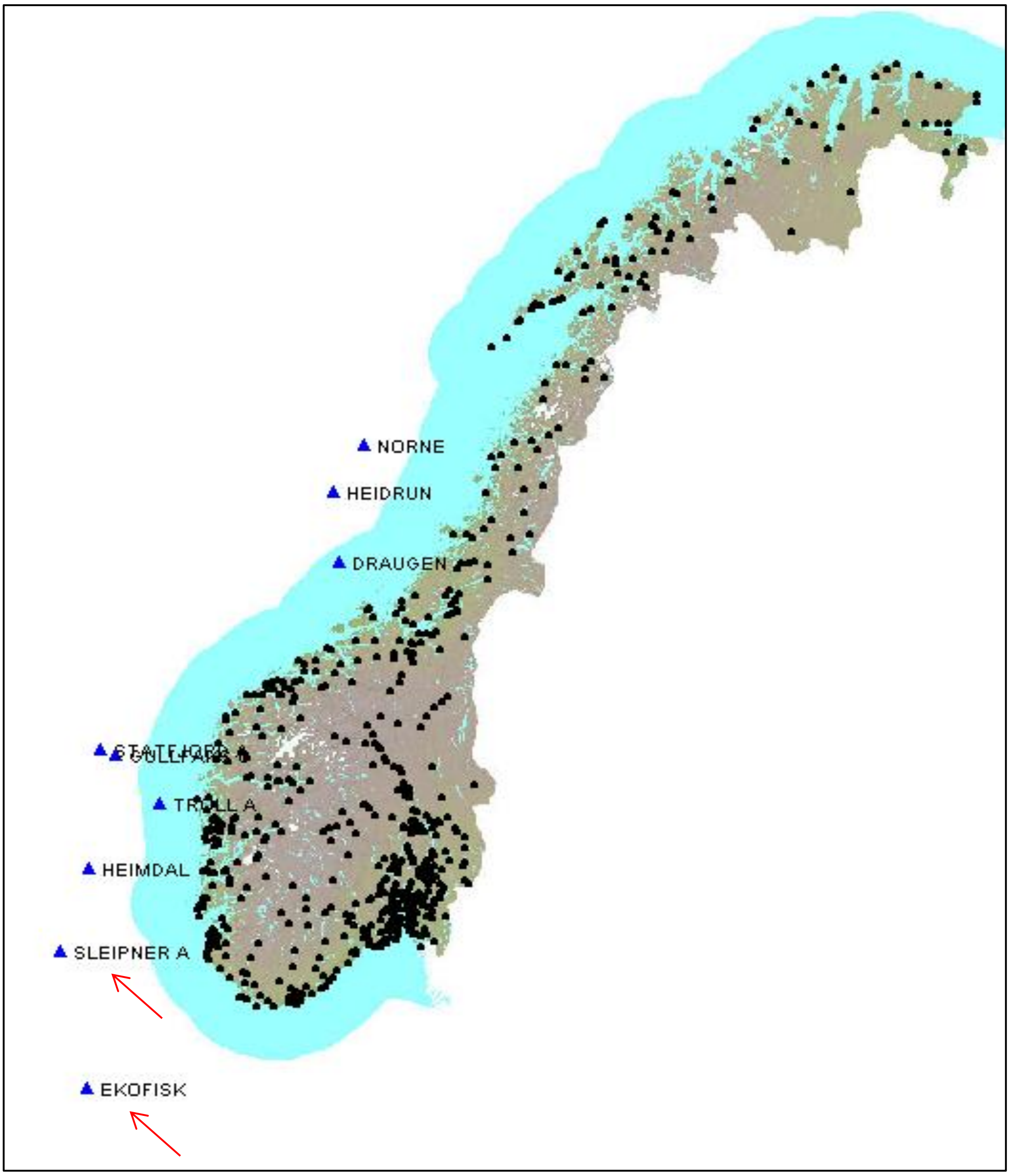

Figure 5. Locations of the Ekofisk and Sleipner A stations in the North Sea, off the coast of southwest Norway. Source: the Norwegian Meteorological Institute.

2.3 Storm activity

There are multiple ways to classify storms. The most common measure to express wind speed or wind effect in is the Beaufort number (see Table 1). A Beaufort number of 10 indicates a storm, with wind speeds starting from 24.7 m/s, Beaufort numbers of 11 and 12 indicate heavier storms. Another way to measure storms is the Storm Severity Index. This index uses the maximum wind speed, the maximum area affected and the length of a storm to measure its intensity: 'Storm Severity Index (SSI) = V^3 x A_{max} x D. Here, V is the maximum surface wind speed A_{max} is the greatest area affected by damaging winds and D is the overall duration of occurrence of damaging winds (or, alternatively, the duration in some place or area of interest)' (Lamp, 1991). The units used are knots x $10^5 km^3$ x hours (Dunlop, 2008).

Beaufort number	Description	Wind Speed (km/h)	Wind Speed (m/s)	Wave height (m)
0	Calm	<1	<0.3	0
1	Light air	1-5	0.3-1.6	0.1
2	Light breeze	6-11	1.7-3.2	0.2
3	Gentle breeze	12-19	3.3-5.5	0.6
4	Moderate breeze	20-28	5.6-8.0	1
5	Fresh breeze	29-38	8.1-10.7	2
6	Strong breeze	39-49	10.8-13.8	3
7	High wind, moderate/near gale	50-61	13.9-17.1	4
8	Gale, fresh gale	62-74	17.2-20.7	5.5
9	Strong gale	75-88	20.8-24.6	7
10	Storm, whole gale	89-102	24.7-28.5	9
11	Violent storm	103-117	28.6-32.7	11.5
12	Hurricane	>118	>32.8	>14

Table 1. The Beaufort scale with corresponding descriptions and corresponding wind speeds and wave heights, referred to as 'well-developed wind-waves of the open sea' (Met Office, 2016).

In this research, the main focus lies on the relation between storms and sperm whale strandings, as a possible alternative for the water temperature and solar activity hypotheses. Since sperm whales end up in the North Sea by accident, we assume that relevant storms occur north of the North Sea and are severe enough to affect migrating sperm whales, a large ocean wanderer. Storm data are used from different sources: wind speed data were provided on request by the Norwegian Meteorological Institute. Secondly, data from Iceland are used since both Norway and Iceland border the area from which sperm whales presumably originate. Storm data from Iceland between 1949-2016 were provided on request by the Icelandic Meteorological Office (see Appendix III) and are visualized in Figure 10. The Storm Index that is used for Figure 10 was calculated in the following manner: all Icelandic stations where wind speed exceeded 20 m/s during the day were counted, divided with the total number of stations on Iceland and then multiplied with 1000. Thus, this index gives an indication of the extent of a storm, comparable with 'the greatest area affected' in the Storm Severity Index. The data contains days with an index of 45 or higher. The Icelandic observations were measured on land and not in the Norwegian Sea between Iceland and Norway, which is the focus area. There are four options that need to be taken into account when comparing storm activity to sperm whale strandings:

- a year with a storm, but without a stranding (1, 0)
- a year with a storm and with a stranding (1, 1)
- a year with no storm, but with a stranding (0, 1)
- a year with no storm and no stranding (0, 0).

For options (0, 0) and (0, 1), the data have been added in-between the storm data. This led to a continuous record from 1949-2016. Only storms that occurred between September-March have been included, due to this research's focus on sperm whale migration. If multiple storms occurred within this period in one year, selection was based first on wind direction. A wind direction between W and N is preferred. Secondly, if multiple storms remained, the strongest storm was selected. Strandings that occurred between September-March were added. However, one stranding in April has been added as well, since it occurred two weeks after a storm in March. A maximum of two months is set for a stranding following a storm (based on estimates since no time frame is available between the occurrence of a storm and a stranding).

Lastly, historical North Sea storm data are used that were documented by Lamp (1991). Note: this data focuses mainly on the North Sea area and thus many storms that occurred between Norway and Iceland that did not affect the North Sea are excluded. Lamp composed a storm record dating back to the 16th century. The North Sea has always been one of the busiest shipping traffic areas and is surrounded by densely populated countries (Lamp, 1991). For areas with less shipping traffic, such as the Norwegian Sea, strong storms at sea may have gone unnoticed or were not documented. The long North Sea storm record provided by Lamp (see Appendix IV) is combined with all historically known North Sea sperm whale strandings (see Appendix I) in Figure 11. Only storms that occurred between September-March have been taken into account. Strandings have also been taken into account for the period September-March. However, two strandings that occurred in April are added as well, since they occurred within two months of two February storms. The four options are taken into account here as well, for a continuous record from 1563 to 1989.

2.4 Fisher's exact test of independence

In order to statistically check whether storm and strandings are related, Fisher's exact test of independence was used (McDonald, 2014). Here, the p-value represents the probability *p* that under assumption of the null hypothesis H_0, the observed results are a coincidence. H_0 is in this case the assumption that there is no difference in data frequencies between sperm whale strandings that occurred during a storm and sperm whale strandings that did not occur during a storm. The following formula was used to calculate p:

$$p = \frac{(a+b)!\,(c+d)!\,(a+c)!\,(b+d)!}{a!\,b!\,c!\,d!\,N!}$$

Here, the individual frequencies are expressed in a, b, c and d of the data tables in Table 2 and Table 3, and N is expressed as the total frequency (all data points within the table). A p-value <0.05 is considered significant. A high p-value would indicate that there is a coincidence in the data, and that the null hypothesis should be accepted. A low p-value would indicate that the coincidence within the data table is low, and thus that the null hypothesis can be rejected.

3. Results

3.1 Satellite and database study

Sperm whale stranding events such as the early 2016 event do not occur annually, even though male sperm whales migrate between lower latitudes and the Norwegian Sea on an annual basis. There may thus have been specific conditions that differed significantly from 'normal' years prior to the early 2016 stranding event or other stranding events. By looking into satellite and observation data, it is possible to see whether some conditions showed large or remarkable anomalies compared to other years. Also, we may be possibly excluding parameters that behaved normally to be the major cause of the event. Since the early 2016 stranding event is the most recent North Sea mass stranding, the satellite and database study focuses on the short timeframe around this event. Although a longer time series would provide a better and more reliable overview, the data surrounding the early 2016 event will provide some information about the presence of large anomalies. Afterwards, storm activity on longer time scales will be taken into account to look for a link with (severe) storm activity in relation to historical strandings.

Chlorophyll

In Norwegian waters, sperm whales have a diet that consists by approximation 95% of *Gonatus fabricii* (Santos et al., 1999; Bjørke, 1995; Gardiner & Dick, 2010). Thus, the winter abundance and distribution of *Gonatus fabricii* is likely to be an important factor in the distribution of sperm whales in this region. Since the whales seem to be dependent on *G. fabricii* as their main food source, it seems likely that when the cephalopods migrate to lower latitudes, the whales might follow. A reason to migrate to lower latitudes would be food availability, which all starts with the presence of phytoplankton. An important assumption in looking for changes in phytoplankton abundance, is the assumption that G. fabricii responds to indirect changes in the presence of their food during spawning periods. If we assume that they do and might move southwards in response to a southward phytoplankton shift, it is useful to look for large differences or anomalies in phytoplankton presence in and around the Norwegian Sea and North Sea in 2015. If there was a large decrease in phytoplankton in the Norwegian Sea, or a large increase in the northern North Sea, this might be a factor that contributed to the stranding event of early 2016. Determining the exact timing of the chlorophyll event is difficult, because we do not know how fast the reaction between changes in phytoplankton and the migration of *Gonatus fabricii* is (if it even exists at all), and how fast sperm whales might react to this in their turn. Since chlorophyll is poorly measured in winter months due to low productivity and cloud coverage, mid-September is chosen for the images. Chlorophyll data of September 2015, September 2014 and 2016 have been examined. Figure 6 shows that in September 2014, the chlorophyll content of the surface waters was relatively low in the North Sea and up along the coast of Norway (~0.5 mg/m^3) and that it was higher east of Iceland (compared to 2015, ~2 mg/m^3 in 2014). In September 2015 the chlorophyll content in the North Sea was slightly higher near the coasts (note that values very close to the shores can exceed 30 mg/m^3), and was also higher south of Norway and north of Iceland. In September 2016 the chlorophyll content had increased even more near the North Sea coasts, west of central Norway and east of Iceland (~23mg/m^3). North of Iceland, the chlorophyll content had decreased. In the middle of the North Sea, the average chlorophyll content remained the same throughout the three years (~0,5 mg/m^3).

If zoomed in to a smaller region, to the Norwegian Deep south of Norway, data from early October can be taken into account as well. In Figure 6 A & B chlorophyll content from early October 2014 and 2015 is shown (data from October 2016 were not available). In October 2015, the chlorophyll content in the coastal Norwegian North Sea and especially the Norwegian Deep was high compared to October 2014 (~20, 18 and 24 mg/m^3 compared to values around 15 and 1.5 mg/m^3 in 2014).

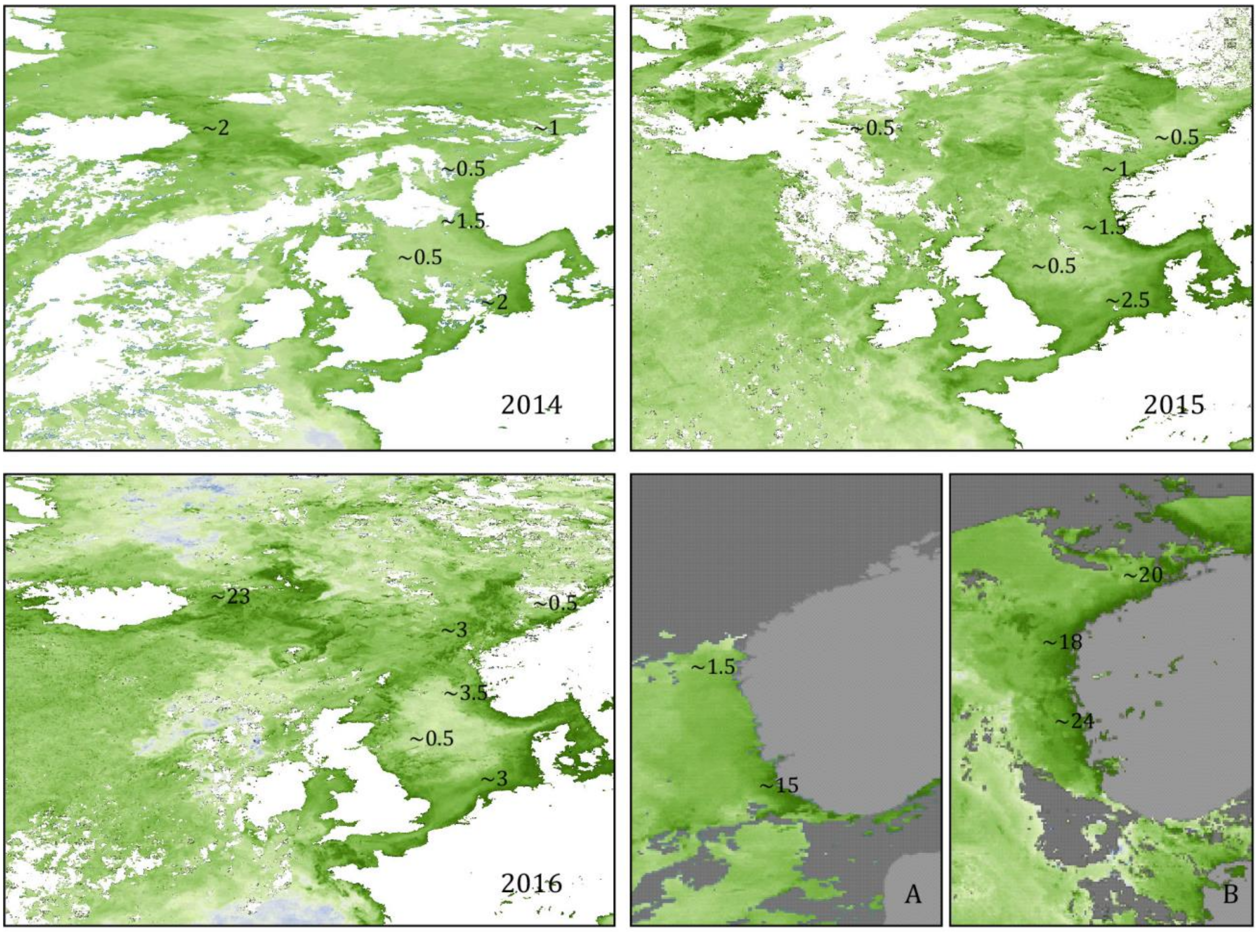

Figure 6. Satellite images of sea surface chlorophyll-α content mid-September. Numbers are approximate averages for the area and expressed in mg/m^3. The upper left figure represents 2014, the upper right 2015 and the lower left 2016. Lower right represents October 2014 (A) and 2015 (B) with focus on the Norwegian Deep. Dark green colors indicate chlorophyll levels of 30 mg/m^3 or higher. Light blue colors indicate chlorophyll levels lower than 0.173 mg/m^3. Images are created with the NOAA View Data Exploration Tool.

Sea surface temperature

Pierce et al. (2007) stated that the probability of sperm whale strandings in the North Sea is higher in years with positive temperature anomalies, possibly due to a shift in prey distribution as mentioned above. Another hypothesis related to temperature could be that sperm whales are possibly sensitive to sea surface temperature (SST), and that their navigation during migration is based on this sensitivity. It is possible that the whales use this temperature sensitivity to distinguish warmer or colder water currents, such as for example the Gulf Stream, and use this to navigate. In Figure 7 the sea surface temperature of November and January is visualized in the year prior to the early 2016 stranding event, the year of the event itself and the year following the event. An important assumption in visualizing sea surface temperature is that sperm whales are indeed affected by water temperatures at the surface. Since we have little knowledge on the average depths sperm whales swim in when they migrate over long distances, it is possible that sea surface temperature is not that relevant to them at all. However, if this parameter would show striking anomalies prior to the early 2016 stranding event, it is interesting to gain additional insight in this parameter related to sperm whale strandings.

When comparing the images in Figure 7, the sea surface temperature (SST) in the North Sea area seems relatively high in November 2014 and relatively low in November 2016. In November 2014, temperatures are on average 0.5 to 1 °C higher in the North Sea than in November 2015 and 2016. In January 2016, the month in which the early 2016 stranding event began, SST in the North Sea area seems to be slightly higher than the same month in the previous and following year. In the North Sea, sea surface temperature is 1-3 °C higher than in the other years. This fits within the theory of Pierce et al. (2007), where the probability of strandings increases at positive temperature anomalies of 1 to 1.5 °C. East of Iceland, SST is also higher by 1-2 °C. Near the Shetland-Faroe channel, temperature is not higher in January 2016. In the Norwegian Sea, east of Norway and west of Iceland, the SST is also relatively higher in January 2016. However, in November 2015 (prior to the stranding event) there is no significant difference in SST.

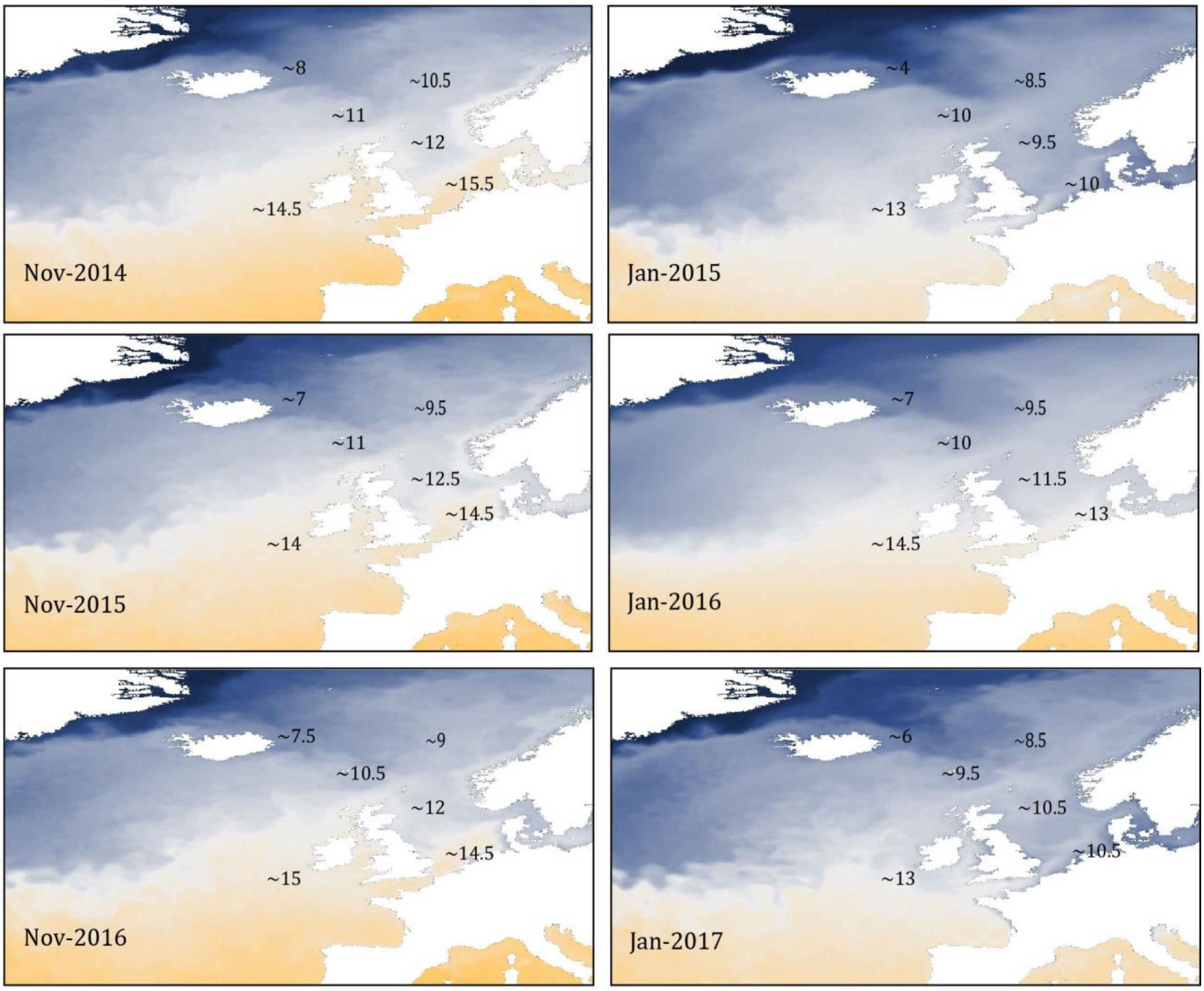

Figure 7. Satellite images of sea surface temperature (SST) in November (left) and January (right) 2014-2016. The numbers are approximate averages for the area and are in °C The darkest blue color indicates a temperature of -2°C, the dark yellow color indicates a temperature of 21°C and higher. Images are created with the NOAA View Data Exploration Tool.

Sea surface currents

Another parameter that might have an influence on sperm whale movements, are sea surface currents. In winter, up to the first 100 meter of water depth is influenced by atmospheric parameters such as wind stress (Talley et al. 2011). Wind stress influences wave forcing and the velocity and direction of water movement in the upper layer. The direction and velocity of sea surface water movements might affect sperm whales in such a way that they might deviate from their intended course and end up in the North Sea. Also, it can be hypothesized that sperm whales might be able to use differences in current velocity to navigate during migration. In Figure 8 zonal sea surface current velocities at a depth of 15 meter are shown in December and January prior to the early 2016 stranding event, and in December and January of the stranding event itself. Compared to December 2014, sea surface current velocity in the North Sea and near the Norwegian Deep is higher in December 2015, while the velocities in the Norwegian Sea are somewhat lower. Compared to January 2015, velocities are lower in the Norwegian Deep in January 2016, but higher east of Southern England and along the Dutch and German coasts.

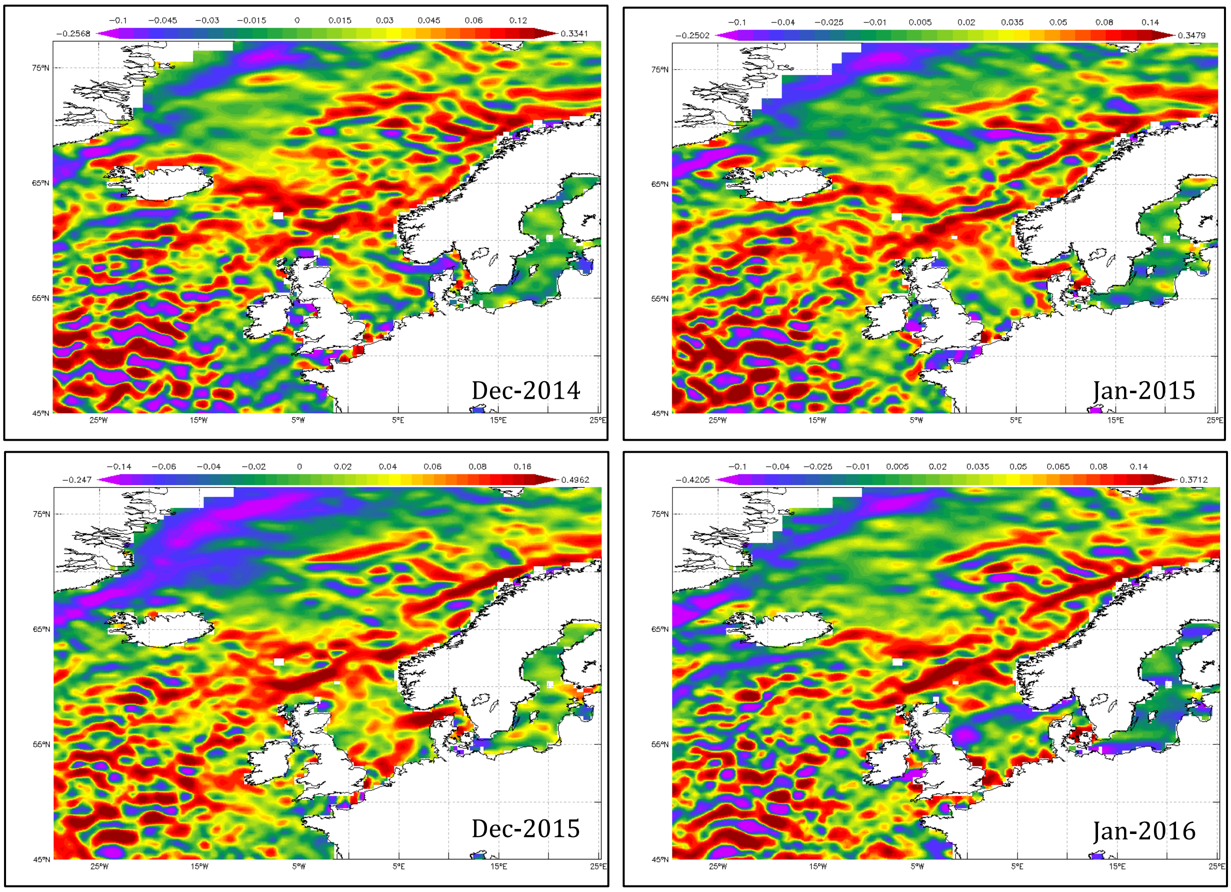

Figure 8. Zonal sea surface current velocities in m/s at a depth of 15 meter. Red colors indicate relatively high current velocities; purple colors indicate relatively low current velocities. Dataset accessed from ESR (2009).

Wind speed

Wind speed is of course closely related to storm activity and is a main focus of this research. The North Sea and especially the Norwegian Sea experience multiple storms every year. Since sperm whale stranding events do not occur that often, we may assume that if storms affect sperm whale migration and possibly lead to stranding, only the more severe storms will affect the whales. To investigate whether a (severe) storm might have influenced the early 2016 stranding event, we look into the wind speeds and corresponding wave heights prior to (and during) the early 2016 event. In Figure 9 these wind speeds are plotted with wave height between December 1 2015 and January 31 2016. The figure shows there is a lot of variation of wind speeds and wave heights within this timeframe. Also, the figure shows that wind speed and wave height can differ significantly from day to day up to almost a doubled value on the next day. Finally, the highest wave heights do not necessarily correspond with the highest wind speed. The highest wind speed occurred on January 26th and measured 22.2 m/s (see also Appendix II), with a corresponding wave height of 4.7 meter. This wind speed is assigned to a Beaufort number of 9 (see Table 1), and thus is not classified as a storm. Storms start at a Beaufort number of 10, and a severe storm would assign to a Beaufort number of 11 or even 12.

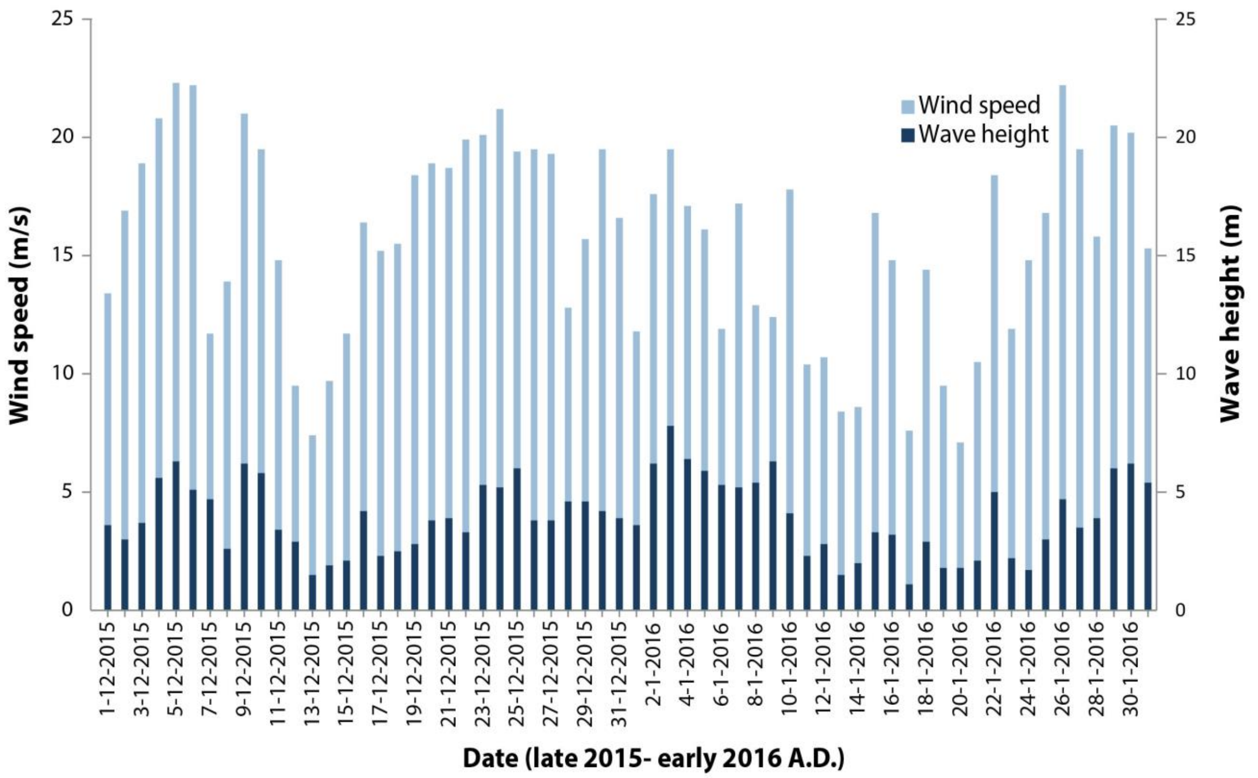

Figure 9. Wind speed in m/s (left y-axis, light blue) plotted with wave height in m (right y-axis, dark blue), measured off South-west Norway between December 1th 2015 and January 31 2016 (x-axis).

3.2 Storm activity

In Figure 10 the Icelandic storm record from 1949-2016 is plotted with the sperm whale strandings during the same period. There is one year with no storm but with a stranding (0, 1), there are 11 years with no storm and no strandings (0, 0), there are 24 years with a storm and no stranding (1, 0) and there are 36 years with a storm that also have strandings (1, 1). In the three years were 20+ sperm whales stranded along the North Sea coasts, storms (although not severe) occurred as well. In Figure 12 the relationship between Icelandic storms and strandings in the North Sea area is visualized.

In Figure 11 the long-term North Sea record is plotted with the historical sperm whale stranding record. In this longer record (1563-1989), there are many more years without a storm and without a stranding (0, 0): 301. There are 14 years with a storm and a strandings, 66 years with a storm but no strandings and 45 years with no storm but with strandings. The years with high stranding numbers are not concurrent with (severe) storms. And the other way around, the years with severe storms are not supported by (higher numbers of) strandings. In Figure 13 the relationship between historical storms and strandings in the North Sea area is visualized.

3.3 Data correlation

In Figure 12 numbers of stranded sperm whales are plotted against Icelandic storm data. Here, it is better visible that there are many years with a storm, but without a stranding. Although there is an upward trend shown in the trend line, the R^2 value of 0.0224 of this plot is very low. This indicates that there is no significant trend in the data, and thus that there is no good correlation between Icelandic storm (intensity) and increased sperm whale strandings.

In Figure 13 numbers of stranded sperm whales are plotted against historical North Sea storm data. Although there are many overlying data points that lie at the junction of the x- and y-axis, this is visible as only one data point in the graph. Also, there are many data point on the y-axis, indicating a storm but no associated stranding. The trend line gives insight in the extent of these data points: the line is almost straight and the corresponding R^2 value of 8^{-7} is extremely low. This also indicates that there is no correlation between North Sea storm intensity and increased sperm whale strandings.

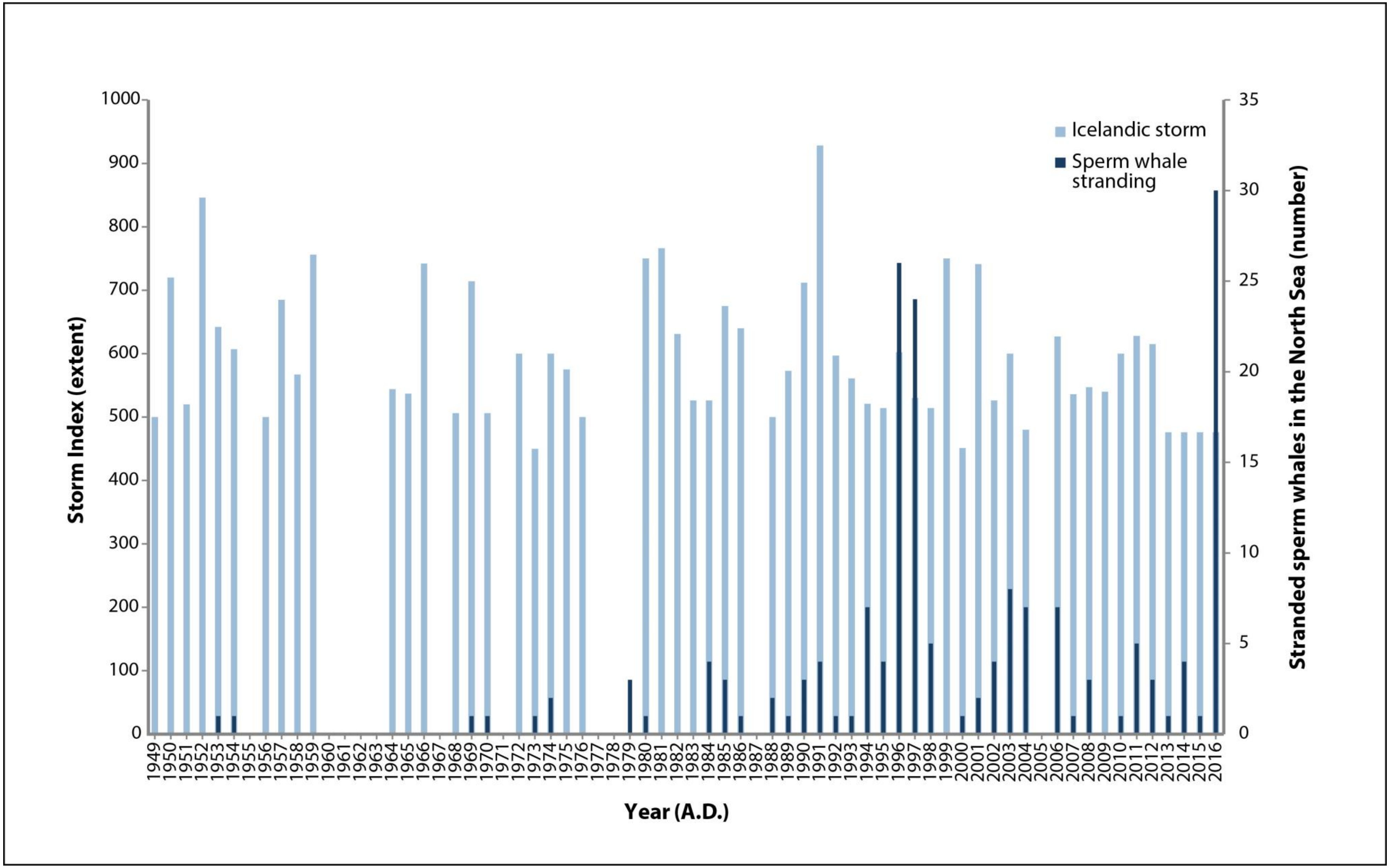

Figure 10. Icelandic storm data (light blue) plotted with whale strandings (dark blue). The storm data are expressed as Storm Index, which is an indication of the extent of a storm, (left y-axis) and are plotted with North Sea stranded sperm whale numbers (right y-axis) between 1949-2016 (x-axis).

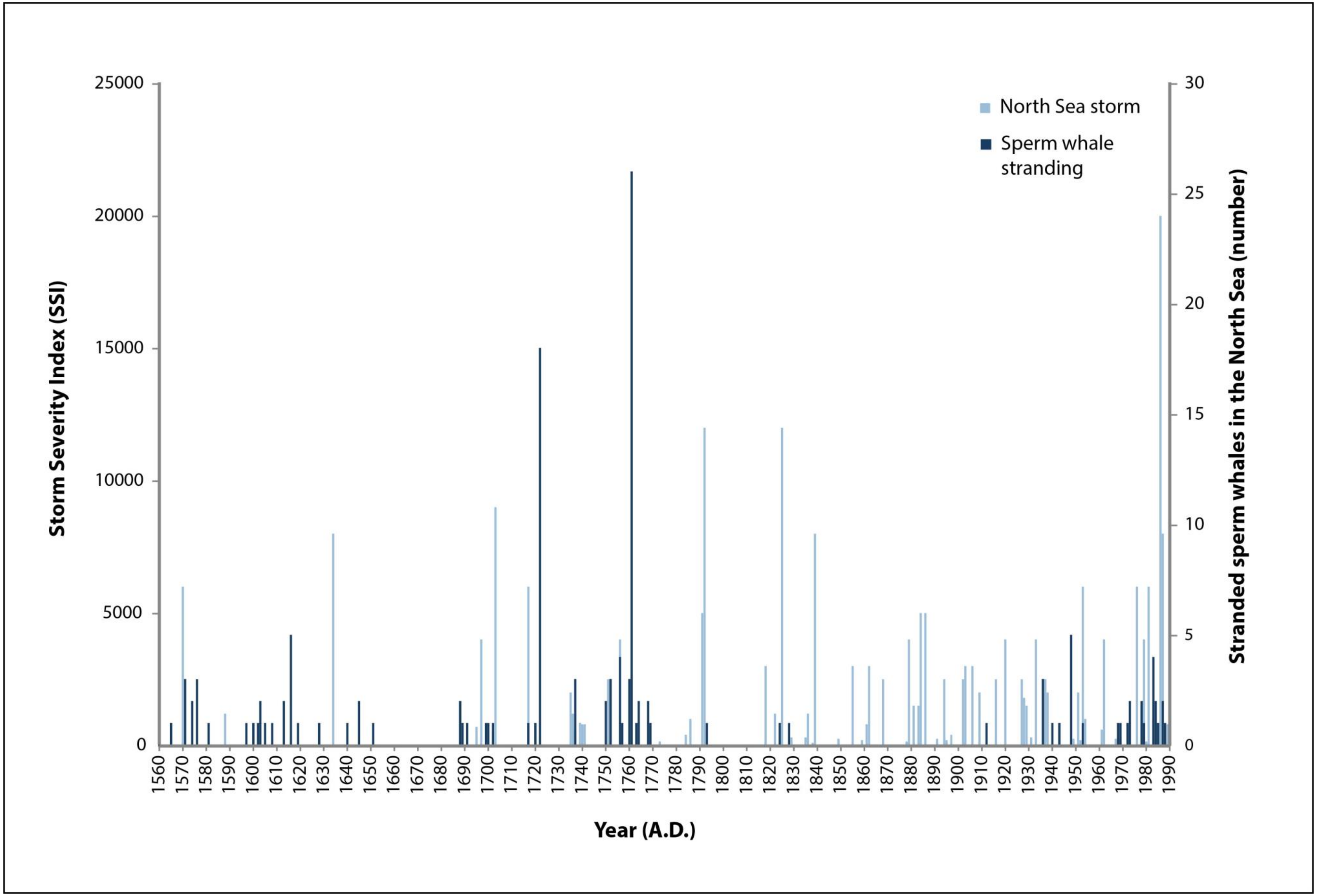

Figure 11. Historical North Sea storm data (light blue) plotted with whale strandings (dark blue). The storm data are expressed as Storm Severity Index, measured in knots x $10^5 km^3$ x hours (left y-axis) and are plotted with North Sea stranded sperm whale numbers (right y-axis) between 1563-1989 (x-axis).

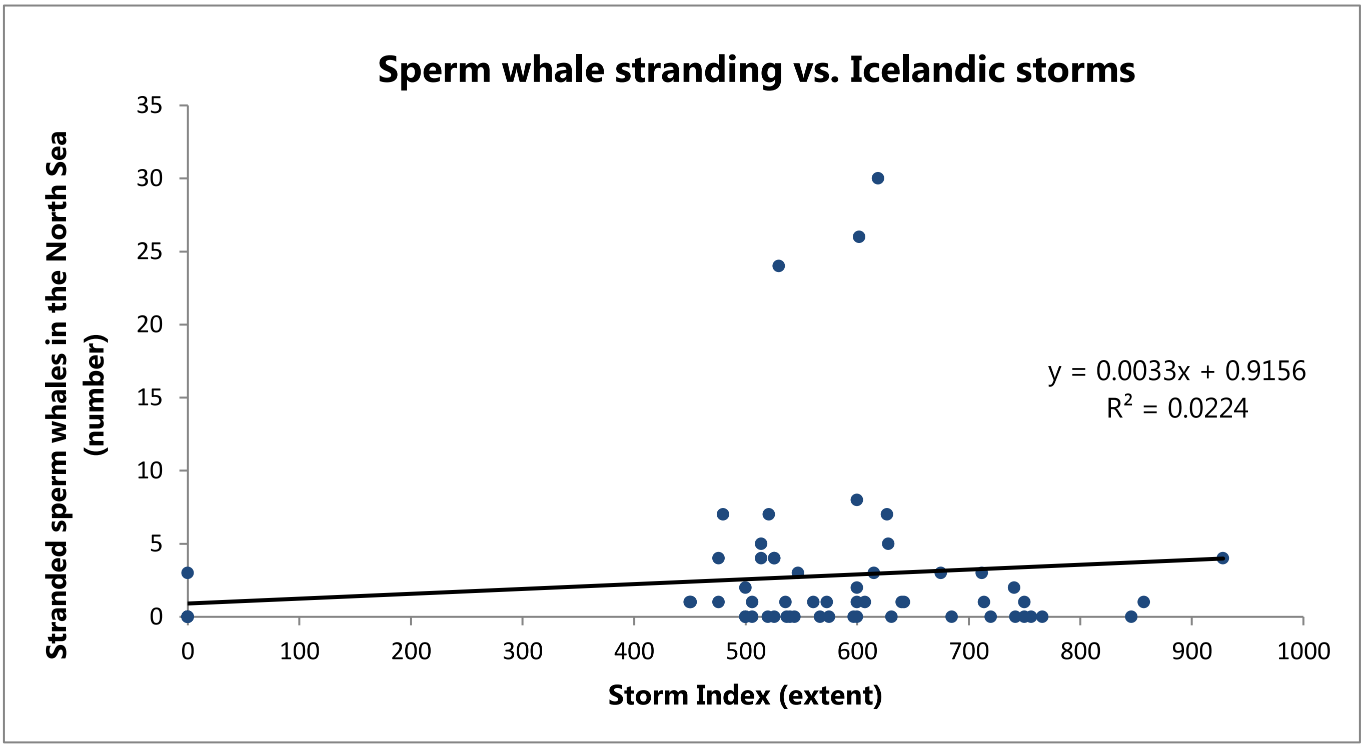

Figure 12. Sperm whale strandings (y-axis), plotted versus Icelandic Storm Index (x-axis). The formula y and R^2 values are shown in the graph.

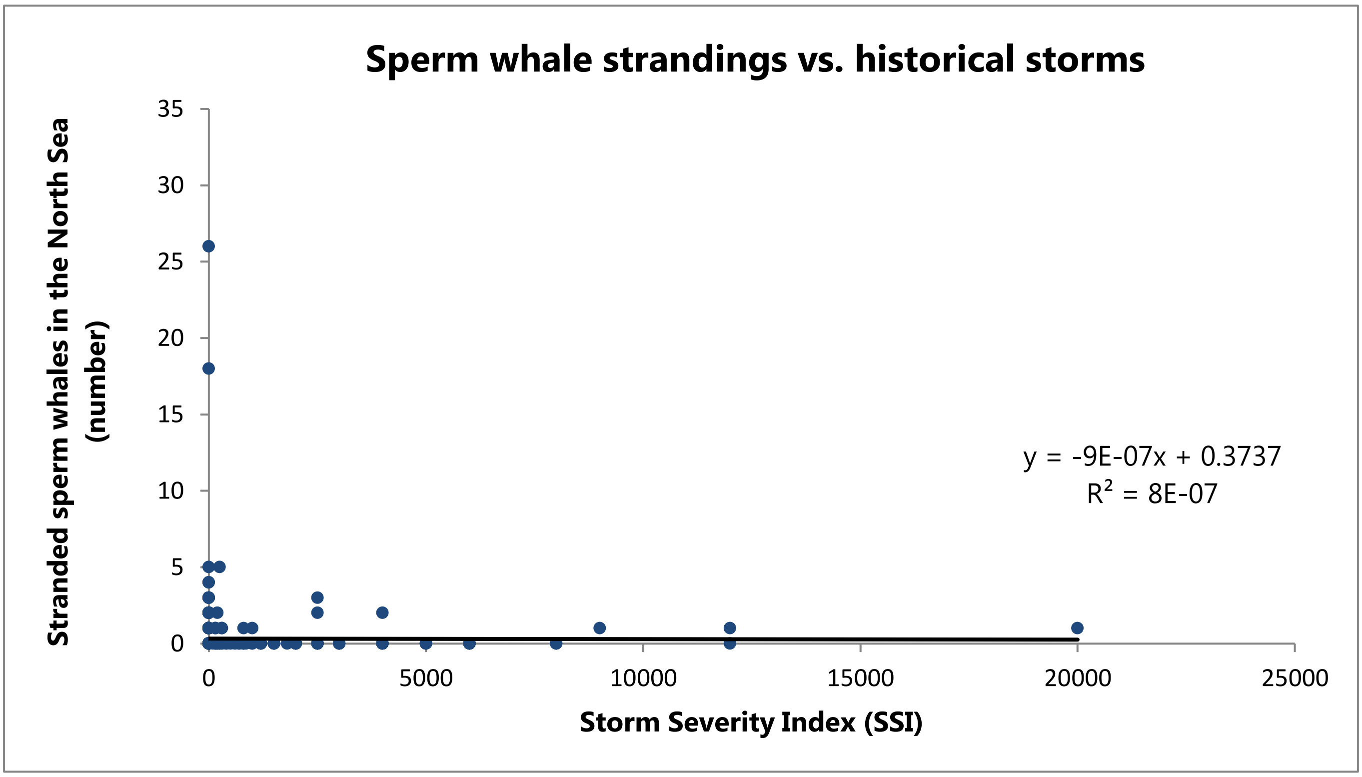

Figure 13. Sperm whale strandings (y-axis), plotted versus historical Storm Severity Index (x-axis). The formula y and R^2 values are shown in the graph.

3.4 Fisher's exact test of independence

Iceland	Stranding	No stranding	Total
Storm	36	24	60
No storm	1	11	12
Total	37	35	72

Table 2. Iceland storm and strandings data table for Fisher's exact test of independence.

For the Icelandic storm data, the p-value is $p = 0.00100$, indicating that the probability is 99.1% that there is a difference between strandings during a storm and strandings that did not occur during a storm. Since p is smaller than 0.05, this probability is considered significant. This means that the null hypothesis H_0 can be rejected; there is a significant indication that there is a difference between the variables storm and no storm in relation to sperm whale strandings.

North Sea	Stranding	No stranding	Total
Storm	14	66	80
No storm	45	301	346
Total	59	367	426

Table 3. North Sea storm and strandings table for Fisher's exact test of independence.

For the North Sea storm data, the p-value is $p = 0.07878$, indicating that the probability is 92.2% that there is a difference between strandings during a storm and strandings that did not occur during a storm. Since p is larger than 0.05, this probability is not considered to be significant. This means that the null hypothesis H_0 cannot be rejected; there is no statistically significant indication that there is a difference between the variables storm and no storm in relation to sperm whale strandings.

4. Discussion

Both the recent data and the historical data on wind speed and storm activity show that there is no direct link between (severe) storm activity and sperm whale strandings in the North Sea. Although there is no direct relationship between storms and strandings, the findings lead to several points of discussion.

The chlorophyll measurements show that there was an increase in primary productivity along the North Sea coasts before the early 2016 event. It seems unlikely that a change in chlorophyll that occurred during October is involved in a stranding event starting in January, but if we assume this might be connected, some points can be made. Considering their natural habitat, it is unlikely that *Gonatus fabricii* will follow their prey to such a shallow environment. It is however possible that the increase in primary productivity near the Norwegian Deep in autumn 2015 might have shifted the occurrence of *G. fabricii* southward. The waters of the Norwegian Deep are deep enough for this species to live here. If the sperm whales would follow their prey, they might come in closer proximity to the North Sea and its so-called 'trap'. However, there is no evidence of *G. fabricii* occurring in the Norwegian Deep in large numbers (Gardiner et al., 2010; Roper at al., 2010). Either their presence is irregular and fishermen do not catch the species in the Norwegian Deep, or they just do not occur there. The latter seems most likely. The differences in sea surface temperature (SST) in adjacent years seem very small. Although in January during the stranding event, temperature in the North Sea is on average 1-3°C higher than the previous and following year, the whole area is a bit warmer than usual. The Shetland-Faroe channel is the exception and has a more or less constant STT of approximately 10 °C within the three years, indicating that there was no anomaly present there in early 2016 as well. Thus if sperm whales would indeed use temperature sensitivity to navigate, there is no reason why they would enter the North Sea instead of following for example the Gulf Stream. Also, there is no large temperature anomaly that would prevent the whales from following the Shetland-Faroe channel. Thus, it does not seem likely that sperm whale use temperature sensitivity to navigate. Based on visuals alone, sea surface currents are also not likely to be the main cause of the early 2016 stranding event. Although the sea surface currents in the Southern North Sea and Norwegian Deep differ from the previous year, the currents in the Northern North Sea and Norwegian Sea are quite similar in both years. Thus, sperm whales might only be affected if they are already in the Norwegian Deep or in the northern North Sea. Since differences so small can occur on a daily scale, it does not seem likely that sperm whales use changes in se surface currents to navigate e.g. southward against the Gulf Stream. Concluding, sea surface currents might have a small influence on sperm whales that are already close to entering the North Sea, but currents probably did not cause the whales to stray from their usual migration route. This is only true if sea surface currents or their deeper counter currents affect sperm whales at all, which is unknown at the moment. For all satellite measurements, an uncertainty in the data is caused by the 'compression' of hourly or daily measurements into weekly averages. It is thus possible that anomalies in the data are missed or appear as a weaker signal than they originally were. Due to their very short timeframes and lack of substantive quantification, especially for the sea surface currents, the different parameters tested with satellite data do not prove a solid point concerning sperm whale strandings. However, it is possible that some of the parameters can indirectly contribute to sperm whale stranding events in the North Sea.

The wind speed measurements off the coast of southwest Norway also exclude storm activity as the cause for the early 2016 stranding event. The highest wind speeds correspond with a Beaufort number of 9 and although these winds will cause disturbances at sea, Beaufort 9 wind speeds are not classified as a storm, let alone a severe one. Since strandings do not occur globally after every storm, we can assume that sperm whales are not bothered by some wind and that wind speeds should be high in order to have an (indirect) affect on the whales. However, it is unknown how high this boundary wind speed is, if it exists at all. Ideally, there would be a weather station in the middle of the Norwegian Sea, between Iceland and Norway. However, we may assume that if a severe storm occurs there, its extent is most likely measurable on the stations off Southern Norway as well. Both storm records with longer timescales, those from Iceland and the North Sea area, confirm that there is no direct relation between storm activity and sperm whale strandings, further confirmed by the R^2 values. The p-values of Fisher's exact test of independence show different results. For the Icelandic storm data, it results in a significant difference between strandings that occurred during a storm and did not occur during a storm. The low p-value might be a result of the timeframe of the Icelandic storm record, which is much shorter than the North Sea record. Also, in the Icelandic storm record almost all years had at least one storm, which highly increases the probability that a sperm whale stranding occurred as well. It is possible that the way in which the Storm Index is calculated for Icelandic storms, has led to the inclusion of storms in the record that were not considered strong enough in the North Sea storm record, which leads to the Icelandic record having notable storms almost every year. In order to see whether these factors indeed influenced the low p-value, future research should compare this record with Norwegian records. If severe storms occurred, they should have been measurable for both countries and this might give better insights in the value of the Icelandic storms.

There are quite some uncertainties in this research. To determine whether storms indeed might have an influence on sperm whale strandings in the North Sea, one must first determine the area of interest. The storm must occur somewhere where it influences migrating sperm whales, so it must occur over a large area, or we must specifically know where the sperm whales are. The latter is uncertain. As mentioned before, there have been some surveys in the Norwegian Sea where sperm whales were counted (Øien, 2009; Nøttestadt et al., 2015). However, these surveys were all executed in summer months, while this research focuses on sperm whales in winter months. Since there are no surveys conducted in winter, the estimates made by summer surveys are all that is currently available on sperm whale distribution in the sub-Arctic. Since most sperm whales migrate southward during mid-winter, summer distributions are likely to be a small indication of the distribution in winter at best. Thus, there is no current estimation on winter sperm whale distribution in the area between Norway and Iceland. As a result, the area used in this study is large and might not be entirely correct. If this area, and the time window for migration could be narrowed down, possible influences on sperm whales during migration can also be narrowed down. Another difficulty is that there are no storm observations in the middle of the Norwegian Sea, let alone a record that goes back to the 16th century. It is possible that if we would have a weather station in that area, the results regarding storm activity might be different and might be more in line with the Icelandic results. Another difficulty in choosing the relevant data is that we do not exactly know how fast sperm whales swim when they migrate, or their exact routes. This means that if a sperm whale becomes stranded, it is difficult to count back the distance and thus time to a roughly determined area in the sub-Arctic. This makes it challenging to choose a timeframe to focus on. Is a storm relevant if it occurs a few days before the stranding, or is it relevant if it occurs up to two weeks before the stranding? Jaquet et al. (1999) provide us with an estimate that sperm whales move with an average of 4 km/h. However, this was measured in the South Pacific and with groups of mostly females, which do not migrate over large distances and might swim at a different speed. The uncertainties in swimming speed and the lack of detailed knowledge on the routes sperm whales use, make it difficult to set a time frame. Finally, another uncertainty with the data is that the strength of the storms measured cannot be validated for the historical records. It is based on amongst others eyewitness stories and paintings and thus their strength is often an estimate. Also, due to lack of historical measurements in the Norwegian Sea, many severe oceanic storms might have gone unnoticed. The same goes for sperm whale strandings. Although researchers generally believe that the North Sea stranding record is detailed and reliable due to the North Sea's densely populated coasts (e.g. Lamp, 1991; Evans, 1997), there are more remote areas along the North Sea coasts where a stranding might have gone unnoticed.

The hypothesis proposed by Pierce et al. (2007), with a larger probability of sperm whale strandings with higher temperatures is not convincing for the early 2016 sperm whale stranding event, although sea surface temperature in the North Sea did show small differences compared to other years. However, as mentioned before, the entire area was warmer, and thus it does not make sense why sperm whales would end up in the North Sea because of higher temperatures. Also, the correlation between strandings and temperature proposed by Pierce et al. (2007) does not provide solid explanations for the mechanism behind these temperature changes. The authors state it might be related to a southward shift in their prey, but as discussed above, this does not seem very likely. It is possible that the temperature changes are related to the Vanselow and Ricklefs (2005) hypothesis on solar cycle length, with shorter cycles leading to higher solar activity and thus higher temperatures. Pierce agrees (pers. comm.): ''the relationship with temperature is interesting, but does not prove anything about the underlying mechanism." Extending both the temperature correlation and the sun spot correlation with data up to recent might give a slightly different outcome, but as Pierce stated: "we could of course revisit both hypotheses with the slightly longer data series now available, but whatever the outcome I think that it will be hard to go beyond proposing plausible hypotheses. I suspect we will never know for sure what happened over the last 500 years.'' Thus, this sea water temperature does not seem likely to be one of the major drivers behind North Sea sperm whales strandings. In the Vanselow and Ricklefs (2005) study, the authors already mention the probability that disturbances in the geomagnetic field as a result of sun spot activity might be responsible for sperm whale strandings. In 2009, Vanselow et al. proposed some evidence for this theory. Recently, Vanselow et al. (2017) published another paper on this topic. Here, they explain how solar storms can affect the geomagnetic field and alter it significantly for hours and up to days. Prior to the early 2016 stranding event, two solar storms occurred: one on December 20-21, and one on December 31-January 1th. The authors state that under normal conditions the North Sea basin is closed-off for the sperm whales because of a 'magnetic mountain chain' that sperm whales can recognize. Due to a solar storm, the chain can be opened up for up to a few days. A sperm whale can travel about 100 km per day (Jaquet et al. 1999; Vanselow et al., 2017) and is capable of crossing this mountain chain within a day. Within the timeframe of a solar storm and its effects, any whale that is in the proximity of the magnetic mountains is in danger of crossing it and taking the wrong turn into the North Sea. Some birds are known to calibrate their geomagnetic direction once a day and are capable of switching to another navigational system when they sense a mistake (Cochan et al., 2004). However, even if a sperm whale has these abilities as well, once a day means the whale may have travelled 100 kilometers and may have already strayed too far from the correct route. Moreover, at high latitudes, the impact of solar storms on the geomagnetic field is much higher than at lower latitudes. Young male sperm whales migrating from lower latitudes that have little experience with geomagnetic disturbances may thus become disoriented relatively easy (Vanselow et al., 2017). This theory is supported by the fact that all stranded sperm whales in the early 2016 event (and in earlier strandings mostly as well) were adolescent males. Further evidence for this theory comes from another study on stranded cetaceans that shows a relation with geomagnetic disturbances and strandings around the world (Ferrari, 2017). Although other (global) research did not find geomagnetic disturbances to be a major cause of cetacean strandings (NASA/Goddard Space Flight Center, 2017), the researchers state that it might be possible that these disturbances are 'part of a cocktail of contributing factors'. With the current data available, the theory proposed by Vanselow et al. (2017) seems the most likely to be true. For future stranding events, we are able to check whether a solar storm occurred and to further confirm this hypothesis. For the historical strandings record, this will be more difficult and we might never know for certain what exactly happened.

Although this study shows that storms cannot be directly related to historical North Sea sperm whale strandings, it is possible that storms can indirectly contribute to sperm whale strandings and this might occur in the future as well. If sperm whales are in closer proximity to the 'magnetic mountain chain' they are more vulnerable to being affected by short-term changes due to solar flares and have a higher chance of entering the North Sea and possibly stranding. If severe storms coincide with a solar storm and whales are near the disrupted magnetic mountain chain, the currents caused by the weather, or the physical distress due to the storm might give them a push in the wrong direction or lead to further disorientation of the whales. The same applies for changes in productivity. Should *Gonatus fabricii* indeed move towards the Norwegian Deep in particular years, the whales might follow their prey and also end up in closer proximity to the magnetic mountain chain, or even circumvent it altogether. Thus, although at the moment solar storms seem to be the most convincing cause of sperm whale stranding events, it is possible that other parameters can contribute to increasing the probability of a stranding as minor contributors. However, this remains uncertain until further research on this subject is performed.

Due to climate change, storm severity is expected to increase and areas of higher productivity might shift. This might contribute to more whales 'taking the wrong turn' or failing to find the right migration route again after a navigational error, and thus might lead to more sperm whale strandings in the North Sea. Future research will have to point out whether climate change is indeed a factor that might seriously affect future sperm whale strandings.

5. Conclusion

This study shows that there is no direct link between North Sea sperm whale strandings and (severe) storm activity. Wind speed measured off southwest Norway showed that no major storm occurred in the area prior to the early 2016 stranding event, where 30 sperm whales became stranded along North Sea coasts. The historical records also do not show a good correlation with the historical stranding record. This is another indication that sperm whale strandings in the North Sea are not directly caused by storms. In order to exclude other parameters, this study looked into several other potential causes, searching for large anomalies. Based on limited datasets and visuals, chlorophyll levels, sea surface temperature, sea surface currents, wind speed and corresponding wave height all seem to have had little impact, no large anomalies were present in the data sets. Sea surface temperature during the early 2016 stranding was slightly higher than the other two years (1-3 °C), but the whole area was a bit warmer, (except for the Shetland-Faroe channel), and thus theory that this sperm whale stranding event can be linked to a positive temperature anomaly as the major cause seems unlikely. The theory that sperm whales become disoriented through disturbances in Earth's magnetic field due to solar storms seems more likely to be true. Multiple cetacean beachings around the world can be linked to geomagnetic disturbances. Although some researchers do not agree, they do say that it is possible that geomagnetic disturbances can contribute to stranding events as 'part of a cocktail of contributing factors' (NASA/Goddard Space Flight Center, 2017). Future North Sea stranding events will show if this theory is strengthened by further evidence, at least for the North Sea area. Although storms cannot be linked to sperm whale strandings directly, they might have an indirect effect in further disorienting already confused sperm whales, e.g. shortly before the actual stranding.

For further research on this subject, some recommendations can be given. Firstly, more accurate data on sperm whales' whereabouts and movements in the Norwegian Sea in winter would be very helpful in narrowing down the research area. More insight can be gained on the distribution and movements of sperm whales by placing tags on migrating whales. Even a few days' worth of information would provide us with new insights. Secondly, further research on the winter distribution of *Gonatus fabricii* and whether changing temperatures or changing primary productivity areas affect the species would be useful as well. Also, investigating the different parameters on much longer time series and in much greater details might provide us with some new insights. Thirdly, with modern techniques such as data buoys, it should be possible to measure storm activity in the middle of the Norwegian Sea and create a record at a scale closer to where the sperm whales are known to occur. Finally, if sperm whales indeed navigate by using the Earth's magnetic field, evidence may be found in their brains. Magnetically sensitive cells have been found in birds (Kirschvink, 1997) and in the heads of common dolphins *Dephinus delphis* small amounts of magnetite were detected (Zoeger et al., 1981). According to Walker (2002) very small particles are necessary to acquire magnetic sensitivity, which might explain why it has not been found in the massive heads of sperm whales yet. Although a sperm whale's brain is difficult to access due to its skull, if these substances can be found it might prove that sperm whales rely on Earth's magnetic field and further confirm the theory proposed by Vanselow et al. (2017).

Acknowledgements

This master thesis represents my final work as a Marine Sciences master student. Fortunately, I was able to work on a subject that I am truly passionate about. I would like to thank my supervisor, Mardik Leopold, for enabling me to work on this subject, for the guidance during the project and for the useful discussions that led to this thesis. I thank Ursula Siebert and Carl Kinze for confirming the record of German and Danish sperm whale strandings post-2007. Also, I thank the Norwegian Meteorological Institute and the Icelandic Meteorological Office for providing wind and storm data and answering any questions I had regarding the data. I would also like to thank Graham Pierce for kindly responding to my questions. Finally, I would like to thank Huub Zwart for offering a helping hand (while being in China) when ArcMap refused to give me the result I wanted, and Wilrieke Boterblom for introducing me to the wonderful world of Adobe Illustrator.

References

Arkhipin, A.I. & Bjørke, H., 1999. Ontogenetic changes in morphometric and reproductive indices of the squid *Gonatus fabricii* (Oegopsida, Gonatidae) in the Norwegian Sea. Polar Biology, 22, 357-365

Bjørke, H., 1995. Norwegian investigations on *Gonatus fabricii* (Lichtenstein). International Council for the Exploration of the Sea, CM 1995, K:12

Bjørke, H., 2001. Predators of the squid *Gonatus fabricii* (Lichtenstein) in the Norwegian Sea. Fisheries Research, 52, 113-120

Clarke, M.R., 1996. Cephalopods as prey. III. Cetaceans. Philosophical Transactions of the Royal Society of London, Series B, 351, 1053-1065

Cochran, W.W., Mouritsen, H. & Wikelski, H., 2004. Migrating songbirds recalibrate their magnetic compass daily from twilight cues. Science 304, 405–408

Dunlop, S., 2008. A Dictionary of Weather. Oxford University Press, 2008

ESR. 2009. OSCAR third degree resolution ocean surface currents. Ver. 1. PO.DAAC, CA, USA. Dataset accessed at http://dx.doi.org/10.5067/OSCAR-03D01.

Evans, P.G.H., 1997. Ecology of sperm whales (*Physeter macrocephalus*) in the Eastern North Atlantic, with special reference to sightings & strandings records from the British Isles. Bull. Inst. R. Sci. nat. Belg., Bio. 67 (Suppl.), 37-46

Ferrari, T.E., 2017. Cetacean beachings correlate with geomagnetic disturbances in Earth's magnetosphere: an example of how astronomical changes impact the future of life. International Journal of Astrobiology, 16, 163–175

Gardiner, K. & Dick, T.A., 2010. Arctic cephalopod distributions and their associated predators. Polar Research, 29, 209-227

Goold, J.C., Whitehead, H., Reid & R.J., 2002. North Atlantic sperm whale, *Physeter macrocephalus*, strandings on the coastlines of the British Isles and Eastern Canada. Canadian Field-Naturalist, 116(3), 371-388

Hu, C., Lee, Z. & Franz, B., 2012. Chlorophyll *a* algorithms for oligotrophic oceans: A novel approach based on three-band reflectance difference. Journal of Geophysical Research, 117, 1-25

Jaquet, N. & Whitehead, H., 1999. Movements, distribution and feeding success of sperm whales in the Pacific Ocean, over scales of days and tens of kilometers. Aquatic Mammals, 25, 1–13

Jauniaux, T. Brosens, L., Jacquinet, E., Lambrigts, D., Addink, M., Smeenk, C. & Coignoul, F., 1998. Postmortem investigations on winter stranded sperm whales from the coasts of Belgium and the Netherlands. Journal of Wildlife Diseases, 34, 99-109

Kirschvink, J.L., 1997. Homing in on vertebrates. Nature, 390, 339-340

Klinowska, M., 1985. Cetacean live stranding sites relate to geomagnetic topography. Aquatic Mammals, 1, 27-32

Lamp, H.H., 1991. Historic storms of the North Sea, British Isles and Northwest Europe. Cambridge University Press 1991

McDonald, J.H. 2014. Handbook of Biological Statistics (3rd ed.). Sparky House Publishing, Baltimore, Maryland

Met Office, 2016. Retrieved January 4, 2018 from: https://www.metoffice.gov.uk/guide/weather/marine/beaufort-scale

NASA/Goddard Space Flight Center, 2017. Marine mammal beachings not likely due to space weather. ScienceDaily. Retrieved January 4, 2018 from www.sciencedaily.com/releases/2017/12/171208113545.htm

Nøttestad, L., Krafft, B.A., Anthonypillai, V., Bernasconi, M., Langård, L., Mørk, H.L. & Fernö, A., 2015. Recent changes in distribution and relative abundance of cetaceans in the Norwegian Sea and their relationship with potential prey. Frontiers in Ecology and Evolution, 2, 1-11

Øien, N., 2009. Distribution and abundance of large whales in Norwegian and adjacent waters based on ship surveys 1995-2001. NAMMCO Sci. Publ., 7, 31-47

Pierce, G.J., Santos, M.B., Smeenk, C., Saveliev, A. & Zuur, A.F., 2007. Historical trends in the incidence of strandings of sperm whales (*Physeter macrocephalus*) on North Sea coasts: An association with positive temperature anomalies. Fisheries Research, 87, 219-228

Reid, J.B., Evans, P.G.H. & Northridge, S.P., 2003. Atlas of Cetacean Distribution in North-West European Waters. Joint Nature Conservation Committee, Peterborough

Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S. & Schlax, M.G., 2007. Daily high-resolution-blended analyses for sea surface temperature. Journal of Climate, 20, 5473–5496

Roper, C. F. E., Jorgensen, E. M., Katugin, O. N. & Jereb, P. (2010). Cephalopods of the World. An Annotated and Illustrated Catalogue of Cephalopod Species Known to Date, Vol. 2: Myopsid and Oegopsid Squids. FAO Species Catalogue for Fishery Purposes, 4, 1-605

Santos, M.B., Pierce, G.J., Boyle, P.R., Reid, R.J., Ross, H.M., Patterson, I.A.P., Kinze, C.C., Tougaard, S., Lick, R., Piatkowski, U. & Hernández-García, V., 1999. Stomach contents of sperm whales *Physeter macrocephalus* stranded in the North Sea 1990-1996. Marine Ecology Progress Series, 183, 281-294

Simon, M.J., Kristensen, T.K., Tendal, O.S., Kinze, C.C. & Tougaard, S., 2003. *Gonatus fabricii* (Mollusca, Teuthida) as an important food source for sperm whales (*Physeter macrocephalus*) in the Northeast Atlantic. Sarsia, 88, 244–246.

Smeenk, C., 1997. Strandings of sperm whales *Physeter macrocephalus* in the North Sea: history and patterns. Bull. Inst. R. Sci. nat. Belg., Bio. 67(Suppl.), 15-28

Talley, L.D., Pickard, G.L., Emery, W.J. & Swift, J.H., 2011. Descriptive Physical Oceanography: an introduction. Academic Press, Elsevier (2011)

Unger, B., Bravo Rebolledo, E.L., Deaville, R., Gröne, A., Ijsseldijk, L.L., Leopold, M.F., Siebert, U., Spitz, J., Wohlsein, P. & Herr, H., 2016. Large amounts of marine debris found in sperm whales stranded along the North Sea coast in early 2016. Marine Pollution Bulletin, 112, 134-141

Vanselow, K.H. & Ricklefs, K., 2005. Are solar activity and sperm whale *Physeter macrocephalus* strandings around the North Sea related? Journal of Sea Research, 53, 319-327

Vanselow, K.H., Ricklefs, K & Colijn, F., 2009. Solar driven geomagnetic anomalies and sperm whale (*Physeter macrocephalus*) strandings around the North Sea: an analysis of long term data sets. The Open Marine Biology Journal, 3, 89-94

Vanselow, K.H., Jacobsen, S., Hall, C. & Garthe, S., 2017. Solar storms may trigger sperm whale strandings: explanation approaches for multiple strandings in the North Sea in 2016. International Journal of Astrobiology, 1-9

Walker, M.M., Kirschvink, J.L., Ahmed, G. & Dizon, A.E., 1992. Evidence that fin whales respond to the geomagnetic field during migration. Journal of Experimental Biology 171, 67–78

Whitehead, H., 2003. Sperm whales: social evolution in the ocean. Chicago, University of Chicago press, 248-250

Zoeger, J., Dunn, J.R. & Fuller, M., 1981. Magnetic material in the head of the common Pacific dolphin. Science 213, 892–894.

Appendix I – List of North Sea sperm whale strandings

The list above the first solid line indicates work done by Smeenk (1997). The list between the first and second solid line indicates work done by Pierce et al. (2007) and the list below the second solid line is compiled from own research.

Strandings that occurred between April-August were excluded from the storm activity results except for a few April strandings that occurred after a late February or March storm.

UK = United Kingdom, NL = The Netherlands, DEN = Denmark, BE = Belgium,
FR = France, SWE = Sweden, N = Norway

Year	Month	Number	Country	Coordinates
1563	December	1	Grimsby, UK	53.583333, -0.083333
1566	March	1	Zandvoort, NL	52.366667, 4.516667
1572	November	3	Skallingen, DEN	55.5, 8.5
1575	?	1	Isle of Thanet, UK	51.366667, 1.25
1575	?	1	Tønder, DEN	55, 8.666667
1577	July	3	Schelde, NL/BE	51.383333, 4.166667
1577	July	3	Schelde, NL/BE	51.316667, 4.266667
1577	July	3	Schelde, NL/BE	51.45, 3.583333
1577	November	3	Ter Heijde, NL	52.033333, 4.166667
1582	?	1	Great Yarmouth, UK	52.616667, 1.733333
1598	February	1	Berckhey, NL	52.1666667, 4.35
1601	December	1	Wijk aan Zee, NL	52.5, 4.583333
1603	December	1	Schelde, BE	51.133333, 4.283333
1604	November	2	Pellworm, DEN	54.5, 8.716667
1606	January	1	Brouwershaven, NL	51.783333, 3.916667
1609	March	1	Rammekens, NL	51.45, 3.666667
1614	January	1	Calais, FR	50.95, 1.866667
1614	December	1	Noordwijk, NL	52.25, 4.416667
1617	January	1	Berckhey, NL	52.166667, 4.35
1617	January	2	Goeree, NL	51.833333, 4
1617	February	1	Noordwijk, NL	52.25, 4.416667
1617	February	1	Harwich, UK	51.95, 1.283333
1620	February	1	Zwartewaal, NL	51.883333, 4.216667
1626	June	1	Hunstanton, UK	52.95, 0.5
1629	January	1	Noordwijk, NL	52.25, 4.416667
1641	October	1	Callantsoog, NL	52.833333, 4.683333
1646	?	1	Wells, UK	52.966667, 0.85
1646	December	1	Holme, UK	52.966667, 0.533333
c. 1652	?	1	Yarmouth, UK	52.95, 1.733333

1689	February	1	Limekilns, UK	56.05, -3.45
1689	?	1	Norfolk, UK	53, 1.5
1690	?	1	The Nore, UK	51.483333, 0.816667
1692/1693	March	1	Lincolnshire, UK	53.166667, 0.166667
1700	?	1	Læsø, DEN	57.25, 11
1701	?	1	Cramond, UK	55.95, -3.233333
1703	February	1	Monifieth, UK	56.483333, -2.833333
1718	November	1	Överö, SWE	57.75, 11.916667
1721	January	1	Wischhafen, GER	53.783333, 9.416667
1723	December	18	Neuwerk, GER	53.9, 8.666667
1738	January	1	St. Peter, GER	54.3, 8.616667
1738	January	2	Husum, GER	54.483333, 9.0666667
1751	March	2	Oldeoog, GER	53.766667, 8
1753	February	3	Findhorn, UK	57.65, -3.616667
1757	January	1	Hvidbjerg, DEN	56.783333, 8.25
1757	February	3	Fanø, DEN	55.416667, 8.416667
1758	?	1	Earlsferry, UK	56.2, -2.85
1761	?	1	Bovbjerg, DEN	56.516667, 8.116667
1761	March	1	Wissant, FR	50.866667, 1.666667
1761	December	1	Eierland, NL	53.15, 4.783333
1762	?	1	Borkum/Memmert, GER	53.6, 6.683333
1762	January	7 to 8	Frisian Islands, NL	53.3, 5.25
1762	January	1	Bredene, BE	51.233333, 2.983333
1762	January	1	Blankenberge, BE	51.316667, 3.133333
1762	February	2	Scharhörn/Neuwerk, GER	53.916667, 8.416667
1762	February	1	Zandvoort, NL	52.366667, 4.516667
1762	February	12	Norfolk/Essex/Kent, UK	52.5, 1.316667
1763	June	1	Texel, NL	53, 4.716667
1764	February	1	Egmond, NL	52.616667, 4.616667
1765	January	2	Bunken Strand, DEN	57.533333, 10.45
1765	May	1	Skallingen, DEN	55.5, 8.5
1767	April	1	Thisted, DEN	57.083333, 8.583333
1769	?	1	Kent, UK	51.333333, 1
1769	December	1	Cramond, UK	55.95, -3.233333
1770	December	1	Hjarnø, DEN	55.816667, 10.083333
1781	May	1	Zandvoort, NL	52.366667, 4.516667
1794	?	1	Whitstable, UK	51.366667, 1.033333
1822	August	1	Lynemouth, UK	55.2, -1.516667
1825	April	1	Holderness, UK	53.75, 0
1829	February	1	Whitstable, UK	51.366667, 1.033333
1913	December	1	Fort George, UK	57.583333, -4.083333
1917	May	1	Latheron, UK	58.283333, -3.366667
1937	January	1	Bridlington, UK	54.083333, -0.2
1937	February	2	Terneuzen, NL	51.366667, 3.8

1937	July	2	Dunkerque, FR	51.033333, 2.383333
1941	March	1	Hirtshals, DEN	57.6, 9.966667
1944	February	1	Skagen, DEN	57.733333, 10.616667
1949	December	2	Fanø, DEN	55.416667, 8.416667
1949	December	1	Mandø, DEN	55.283333, 8.55
1949	December	1	Knudedyb, DEN	55.283333, 8.55
1949	December	1	Darum, DEN	55.35, 8.466667
1953	July	1	Texel, NL	53.1, 4.766667
1954	December	1	De Panne, BE	51.1, 2.583333
1969	April	1	Westerhever, GER	54.383333, 8.5
1970	January	1	Spijkerplaat, NL	51.416667, 3.666667
1973	October	1	Boulmer, UK	55.416667, -1.5
1974	January	1	Saltfleet, UK	53.416667, 0.25
1974	September	1	Skagen, DEN	57.733333, 10.616667
1979	February	1	Tversted, DEN	57.6, 10.2
1979	August	1	Cullen Bay, UK	57.683333, -2.833333
1979	December	1	Egmond, NL	52.583333, 4.6
1980	February	1	Trischen, GER	54.083333, 8.683333
1984	January	2	Henne Strand, DEN	55.733333, 8.233333
1984	September	1	Brunbjerg, DEN	56.233333, 8.166667
1984	November	1	Tegeler Plate, GER	53.783333, 8.316667
1985	January	1	Crovie, UK	57.666667, -2.333333
1985	March	1	Skegness, UK	53.166667, 0.35
1986	November	1	Holkham, UK	52.8, 0.8
1988	November	1	Sæby, DEN	57.333333, 10.55
1988	December	1	Träslövsläge, SWE	57.066667, 12.266667
1989	February	1	Koksijde, BE	51.1, 2.65
1990	February	1	Findhorn, UK	57.65, -3.616667
1990	April	1	Terschelling, NL	53.35, 5.2
1990	November	1	Nymindegab, DEN	55.816667, 8.2
1991	November	1	Brancaster, UK	52.966667, 0.65
1991	December	3	Fano, DEN	55.416667, 8.416667
1992	May	1	Husby Klit, DEN	56.283333, 8.2
1993	December	1	Heacham, UK	52.916667, 0.5
1994	November	1	Atwick, UK	53.95, -0.183333
1994	November	1	Baltrum, GER	53.733333, 7.383333
1994	November	1	Terschelling/Ameland, NL	53.416667, 5.583333
1994	November	3	Koksijde, BE	51.1, 2.65
1994	November	1	Nieuwpoort, BE	51.133333, 2.75
1995	January	3	Scheveningen, NL	52.083333, 4.266667
1995	March	1	Nairn, UK	57.583333, -3.583333
1996	January	1	Skagen, DEN	57.733333, 10.616667
1996	January	6	Cruden Bay, UK	57.4, -1.85
1996	January	1	Norderney, GER	53.7166667, 7.166667

1996	March	16	Rømø, DEN	55.166667, 8.5
1996	July	1	Klitmøller, DEN	57.05, 8.533333
1996	July	1	Husby, DEN	56.283333, 8.2
1997	March	1	Airth, UK	56.066667, -3.783333
1997	November	1	Wassenaar, NL	52.166667, 4.333333
1997	November	4	Ameland, NL	53.483333, 5.833333
1997	December	13	Rømø, DEN	55.166667, 8.5
1997	December	1	Skegness, UK	53.166667, 0.35
1997	December	2	Humber Estuary, UK	53.5, 0
1997	December	1	Bremerhaven, GER	53.5, 8.5
1997	December	1	Sahlenburg, GER	53.916667, 8.583333
1998	January	3	Eiderstedt, D	54.333333, 8.5
1998	August	1	Rosehearty, UK	57.7, -2.116667
1998	August	1	Bettyhill, UK	58.5325, -4.21215
2000	June	1	Rømø, DEN	55.166667, 8.5
2001	April	1	Kolnes, N	58.916667, 5.583333
2001	October	1	Trondra, UK	60.1265, -1.27827
2002	January	3	Meldorfer Bucht, GER	54.1, 8.866667
2002	June	1	Hopetoun, UK	55.9981, -3.45582
2003	January	1	Ouse Estuary, UK	52.8, 0.4
2003	February	1	Oslofjorden, N	59.5, 10.5
2003	March	1	Canty Bay, UK	56.05, -2.65
2003	April	1	Stiffkey, UK	52.95, 0.933333
2003	April	1	Cruden Bay, UK	57.4, -1.866667
2003	November	2	Norderney, GER	53.716667, 7.166667
2003	March	1	Dunkerque, FR	51.000232, 2.046892
2004	January	1	Thornham, UK	52.966667, 0.566667
2004	February	1	Koksijde, BE	
2004	March	1	Stutton Bridge, UK	52.966667, 0.566667
2004	June	1	Noordpolderzijl, NL	53.433333, 6.583333
2004	June	1	Vlieland, NL	53.283333, 4.95
2004	November	2	Richel, NL	53.3, 5.15
2006	February	5	Skegness, UK	52.95, 0.2
2006	March	1	Hackley Bay, UK	57.333333, -1.95
2006	October	1	Burghead, UK	57.6723, -3.50552
2007	February?	1	Skegness, UK	53.149398, 0.351264
2008	January	1	Burntisland Harbour, UK	56.063, -3.182
2008	August	1	Alturlie Point, UK	57.5166, -4.1436
2008	December	1	Cava, UK	58.875, -3.16891
2010	January	1	Collith Hole, UK	55.562523, -1.632775
2011	March	1	Pegwell Bay, UK	51.324144, 1.367812
2011	May	1	Redcar, UK	54.622231, -1.073166
2011	November	1	Stellendam, NL	51.837053, 4.019522
2011	November	1	Pellworm, GER	54.490185, 8.630486

2011	December	1	Hunstanton, UK	52.937501, 0.482812
2012	February	1	Knokke-Heist, BE	51.354785, 3.291428
2012	March	1	Skegness, UK	53.140611, 0.351119
2012	December	1	Razende Bol, NL	52.972566, 4.673171
2013	July	1	Terschelling, NL	53.437189, 5.558375
2014	January	1	Edinburgh, UK	55.9464, -3.06316
2014	February	2	Henne, DEN	55.732762, 8.168746
2014	February	1	Isle of Sheppey, UK	51.421295, 0.864528
2015	February	1	Fanø, DEN	55.341877, 8.450144
2016	January	2	Wangerooge, GER	53.794314, 7.898224
2016	January	2	Helgoland, GER	54.183941, 7.878969
2016	January	1	Bremerhaven, GER	53.559757, 8.486411
2016	January	1	Trischen, GER	54.055219, 8.678397
2016	January	5	Texel, NL	53.038414, 4.712708
2016	January	1	Texel, NL	53.007442, 4.793175
2016	January	1	Hunstanton, UK	52.936120, 0.481938
2016	January	1	Wainfleet, UK	53.060120, 0.277373
2016	January	3	Skegness, UK	53.149372, 0.351307
2016	January	8	Kaiser-Wilhelm-Koogs, GER	53.939158, 8.902487
2016	February	2	Büsum, GER	54.173207, 8.671104
2016	February	1	Hemmes de Marck, FR	50.989008, 1.923564
2016	February	1	Hunstanton, UK	52.941898, 0.485644
2016	February	1	Blåvandshuk, DEN	55.568171, 8.079359

Appendix II – Norwegian wind speed and wave height data

Wind direction is expressed in degrees. 0°/360° = wind direction N, 180° = S. Dates that are underlined are observations from the Sleipner A station. All other observations are from the Ekofisk station.

Date	Wave height (m)	Wind speed (m/s)	Wind direction (d)
1-12-2015	3.6	13.4	279
2-12-2015	3	16.9	224
3-12-2015	3.7	18.9	184
4-12-2015	5.6	20.8	213
5-12-2015	6.3	22.3	218
6-12-2015	5.1	22.2	234
7-12-2015	4.7	11.7	148
8-12-2015	2.6	13.9	179
9-12-2015	6.2	21.0	210
10-12-2015	5.8	19.5	224
11-12-2015	3.4	14.8	234
12-12-2015	2.9	9.5	288
13-12-2015	1.5	7.4	319
14-12-2015	1.9	9.7	79
15-12-2015	2.1	11.7	123
16-12-2015	4.2	16.4	134
17-12-2015	2.3	15.2	227
18-12-2015	2.5	15.5	215
19-12-2015	2.8	18.4	197
20-12-2015	3.8	18.9	193
21-12-2015	3.9	18.7	264
22-12-2015	3.3	19.9	200
23-12-2015	5.3	20.1	249
24-12-2015	5.2	21.2	243
25-12-2015	6	19.4	248
26-12-2015	3.8	19.5	198
27-12-2015	3,8	19,3	204
28-12-2015	4.6	12.8	133
29-12-2015	4.6	15.7	146
30-12-2015	4.2	19.5	161
31-12-2015	3.9	16.6	202
1-1-2016	3.6	11.8	237
2-1-2016	6.2	17.6	106
3-1-2016	7.8	19.5	103
4-1-2016	6.4	17.1	110
5-1-2016	5.9	16.1	105
6-1-2016	5.3	11.9	104
7-1-2016	5.2	17.2	110

8-1-2016	5.4	12.9	92
9-1-2016	6.3	12.4	146
10-1-2016	4.1	17.8	194
11-1-2016	2.3	10.4	89
12-1-2016	2.8	10.7	65
13-1-2016	1.5	8.4	289
14-1-2016	2	8.6	61
15-1-2016	3.3	16.8	355
16-1-2016	3.2	14.8	335
17-1-2016	1.1	7.6	208
18-1-2016	2.9	14.4	203
19-1-2016	1.8	9.5	314
20-1-2016	1.8	7.1	323
21-1-2016	2.1	10.5	172
22-1-2016	5	18.4	156
23-1-2016	2.2	11.9	250
24-1-2016	1.7	14.8	247
25-1-2016	3	16.8	196
26-1-2016	4.7	22.2	195
27-1-2016	3.5	19.5	207
28-1-2016	3.9	15.8	267
29-1-2016	6	20.5	250
30-1-2016	6.2	20.2	249
31-1-2016	5.4	15.3	271

Appendix III – Icelandic storm data

Wind direction is expressed in number: 1 = N, 3 = NE, ... 15 = NW.
Values were provided in 'storm index'. This is assumed to be Storm Severity Index (SSI), unit: knots x $10^5 km^3$ x hours

Year	Month	Day	Direction	SSI	Stranding
1949	1	9	9	500	0
1950	12	10	1	720	0
1951	12	7	3	520	0
1952	1	5	11	846	0
1953	11	16	11	642	1
1954	2	16	9	607	1
1955	x	x	x	0	0
1956	11	24	13	500	0
1957	1	14	13	685	0
1958	1	16	11	567	0
1959	2	15	11	756	0
1960	x	x	x	0	0
1961	x	x	x	0	0
1962	x	x	x	0	0
1963	x	x	x	0	0
1964	10	21	11	544	0
1965	2	9	13	537	0
1966	1	30	3	742	0
1967	x	x	x	0	0
1968	3	17	1	506	0
1969	3	5	13	714	1
1970	2	6	11	506	1
1971	x	x	x	0	0
1972	12	22	11	600	0
1973	2	17	11	450	1
1974	12	31	13	600	2
1975	12	14	13	575	0
1976	3	21	11	500	0
1977	x	x	x	0	0
1978	x	x	x	0	0
1979	x	x	x	0	3
1980	12	28	13	750	1
1981	2	17	11	766	0
1982	11	16	15	631	0
1983	1	5	3	526	0
1984	12	28	9	526	4
1985	11	15	7	675	3

1986	12	15	5	640	1
1987	x	x	x	0	0
1988	12	12	13	500	2
1989	2	12	13	573	1
1990	1	9	11	712	3
1991	2	3	9	928	4
1992	2	24	13	597	1
1993	1	29	9	561	1
1994	1	29	5	521	7
1995	1	16	15	514	4
1996	2	21	13	602	26
1997	1	24	11	530	24
1998	1	20	7	514	5
1999	1	16	1	750	0
2000	2	28	1	451	1
2001	11	10	13	741	2
2002	2	2	1	526	4
2003	9	21	1	600	8
2004	10	18	1	480	7
2005	x	x	x	0	0
2006	11	5	11	627	7
2007	12	30	7	536	1
2008	1	27	9	547	3
2009	10	9	5	540	0
2010	12	17	1	600	1
2011	1	7	1	628	5
2012	11	2	1	615	3
2013	12	24	1	476	1
2014	12	10	9	476	4
2015	12	5	1	476	1
2016	2	16	11	476	30

Appendix IV – Historical North Sea storm data

All storms with corresponding stranding data have been documented below. Storms that occurred between April-August are excluded from the storm activity results. All other years without storms that did have strandings are present in Appendix I. All remaining years had no storm and no stranding. SSI = Storm Severity Index, unit: knots x 10^5km^3 x hours

Year	Month	Day	SSI	Direction	Remarks
1570	November	11 to 12	6000	SW to NW	Questionable
1588	August	14 to 18	600		Questionable
1588	September	21	1200		Questionable
1634	October	22	8000	WNW	Questionable
1695	September	22	700		Approximate
1697	October	1 to 2	4000	NW	Questionable
1702	October	22	500		Questionable
1703	December	7 to 8	9000	SW to W	
1717	December	24 to 25	6000	SW to NW	Approximate
1735	January	1	2000	S to SW	
1736	February	27	1200	N	
1737	August	14	600	E and NW	
1739	January	25	850		Between 800-900
1740	September	18 to 19	500	S and SW	
1740	November	12	800	Mainly N-NE	Questionable
1741	September	19	800		Questionable
1751	March	9 to 10	400	NW	Strong winds indicated
1751	September	11	2500		
1756	October	7	4000		
1773	December	6	150		
1784	January	2 to 3	400	SE	Approximate
1786	September	14 to 15	1000	WSW to NW	Approximate
1791	March	1	150	NW-N	
1791	March	21 to 22	5000	NW-NNE	Approximate
1792	December	5	1200		
1792	December	10 to 12	12000	W-NW	10000-20000 taken as 12000
1792	December	21 to 22	1000	W-NW	
1795	May	6 to 9	3000	N	Approximate
1818	January	12 to 16	3000	SW-NW	Approximate
1822	March	11	1200		
1825	February	4	12000	NNW to NNE	
1829	August	3 to 4	150	N-E	Approximate
1829	November	25	300	E	
1835	November	18-19	300		
1836	November	23	300		

1836	November	27 to 29	1200		
1838	September	7	100		Approximate
1839	January	6 to 7	8000	SW-WNW	Approximate
1849	January	10	150	E	Questionable
1849	December	28	250		Approximate
1855	January	1	3000	NW	
1859	October	27 to 29	200		
1861	February	21	800		
1862	December	26 to 27	3000	WSW-NW	
1868	January	24	2500	S to WSW	
1869	June	15 to 16	150		Approximate
1878	March	27	150		
1879	December	28	4000		
1881	October	14 to 15	1500	All directions	
1883	March	6	1500		
1884	January	25-27	5000	SW-W	
1886	October	14 to 16	7000	SW-W later NW-W	
1886	December	8 to 9	5000	SW-NW	
1891	March	9 to 10	250	NE	Approximate
1894	February	11 to 12	2500	SW-NW	
1895	March	24	200		
1897	November	28 to 29	400	NW-N	
1902	December	25 to 26	2500		
1903	February	26 to 27	3000		
1906	March	12 to 13	3000	N	
1909	December	3	2000		
1916	December	16	2500	WSW-WNW	
1920	January	26 to 27	4000	S-SSE	
1927	January	28	2500		
1927	October	28-29	800		
1928	January	6	1600		Approximate
1928	November	16 to 17	500		
1928	November	23 to 25	1800		
1929	December	5 to 7	1500	SSW-W	
1931	November	10 to 11	300		
1933	April	9	4000	N	Approximate
1936	October	17 to 19	1200	W-NW	
1936	October	26 to 27	2000	mainly W-NW	
1937	January	17 to 19	2500	SE to S	
1937	December	5	250	S	
1938	January	15	300		
1938	February	10 to 13	500		
1938	June	1 to 2	150		

1938	November	23 to 24	2500		
1938	December	15 to 17	2000	SE	
1949	February	9 to 10	250		
1949	October	23 to 25	250		
1949	October	26	200		
1951	December	30	2000		
1952	December	17	200		
1953	January	31 to 1	6000	N	
1954	December	23	1000	W-NW	
1961	September	16 to 17	600		Approximate
1962	February	16 to 17	4000	Mainly NW	
1967	February	23	250		
1967	September	4	250		
1968	January	14 to 15	150		
1969	February	7	300		
1972	November	12 to 13	700		
1973	April	2	700		
1973	November	19	150		
1976	January	2 to 3	6000	SW-W to NW-N	
1978	January	11 to 12	1500		
1979	February	13 to 14	300	E	
1979	August	13 to 14	200		
1979	December	4 to 5	4000	SW-W	
1980	March	27	150		
1981	November	23 to 25	6000		
1983	January	18	1000	W-NW	
1983	February	1	1500	W-N	Approximate
1986	December	15	20000	All directions	Approximate
1987	October	16	8000		
1988	February	9 to 10	200		
1988	March	3 to 4	200	N	
1989	February	13	800	W-NW	