OCS Study
BOEM 2018-030

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DISCLAIMER

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List of Abbreviations and Acronyms

BOEM	Bureau of Ocean Energy Management
NASA	National Aeronautics and Space Administration
DOI	US Department of the Interior
IFAW	International Fund for Animal Welfare
CME	Coronal Mass Ejection
FRD	Fredericksburg
OTT	Ottawa
ESK	Eskdalemuir
EYR	Eyrewell

1 Introduction

Cetacean mass strandings, where numbers of otherwise healthy animals beach for no apparent reason, are one of the great mysteries in marine biology. Some of the largest stranding events, such as the recent pilot whale event in New Zealand in February 2017 (*BBC News*, 2017), can involve hundreds of animals many of which perish as a result of the beaching (e.g., *Groom et al.*, 2012; *Groom et al.*, 2014; *McGovern et al*., 2016). While the strandings are not usually a conservation issue (most frequently affected species are neither threatened, nor endangered), the events have a negative impact on the welfare of the individuals and, without intervention, often lead to death. As such, we are motivated to understand the reasons behind this seemingly inexplicable deadly behavior. Understanding the causes for mass strandings would provide hope for prevention of future events and improve rescue efforts carried out globally by organizations such as the International Fund for Animal Welfare (IFAW).

Cetacean mass strandings have been observed throughout human history and many theories have been proposed to explain the events. Some causes considered are natural, including:

1) Atmospheric weather and oceanic conditions such as winds, storm activity and tides (e.g., *Evans et al.*, 2005; *Clua at al.*, 2014). This is perhaps the most natural cause for mass strandings as cetaceans are exposed directly to local atmospheric and oceanic conditions. Atmospheric and oceanic conditions include influence on the food web and the cetacean response to movements in their food sources.

2) Magnetoreception and corresponding influence of geomagnetic anomalies on animal behavior. It has been suggested that, similar to some other animals such as homing pigeons, marine mammals can sense the magnetic field as an additional navigational cue (e.g., *Kirschvink*, 1990; *Begall et al.*, 2014). While many major questions pertaining to magnetoreception remain open, one of the ways the biological compass could be facilitated involves magnetite that has been found in dolphins' bodies (see *Kremers et al.*, 2014, and references therein). For cetaceans using magnetoreception as a part of their navigation system, geomagnetic anomalies from internal quasi-static sources and external dynamic sources could lead to navigational errors and eventual stranding (e.g., *Klinowska et al.*, 1986; *Kirschvink et al.*, 1986; 1990; *Vanselow et al*., 2009; 2017).

Other potential causes are from anthropogenic sources, such as:

3) Active sonars utilized in military activities (e.g., *Southall et al*., 2013).

4) Seismic surveys and ocean floor mapping using air guns, multi-beam echo-sounders and other acoustic technologies (e.g., *Southall et al*., 2013).

5) Blast trauma from military exercises.

These acoustic disturbances can have both physical and behavioral consequences. Large water pressure changes associated with active sonars may injure or confuse the cetaceans. All of the sound sources above can also lead to behavioral flight response displacing animals from their habitat and leading to a stranding.

In the context of magnetoreception, the internal magnetic field is generated by the dynamo operating in the Earth's core and the field observed on the surface gets modulated by the structures in the Earth's crust. While there is a continuous change seen for example in terms of movement of the magnetic poles, the internal field varies significantly only in time scales of the order of tens of years and longer. External geomagnetic field variations that are driven by the interaction between solar wind plasma and electromagnetic field and the Earth's magnetosphere, are in turn very dynamic (for a review, see e.g., *Pulkkinen*, 2007). During major solar storm events, interplanetary disturbances can generate major changes in the Earth's near-space electric current systems and those changes cause ground geomagnetic field variations at time scales varying from seconds to hours. We refer to these magnetic field variations as "geomagnetic storms." Major geomagnetic storms can cause field perturbations lasting several days.

Ocean bathymetry and coastal conditions such as tides likely play a role in cetacean mass strandings. Some of the hotspots, such as Cape Cod Bay, U.S. and Golden Bay, New Zealand, also have geography of a "trap" or hook shaped land mass (see Fig. 1b, see also *McGovern et al*., 2016). Other common properties of many of the stranding hotspots around the globe are gently sloping beaches, large tidal height fluctuations, and fine sediment. Acoustical "dead zones" where echolocation signals are severely distorted by purely coastal geometric effects have also been identified as a potential contributing factor (*Sundaram et al.*, 2006). Further, most cetacean species that regularly mass strand, are pelagic species that inhabit open ocean waters (*Mazzuca et al.*, 1999). Once outside their normal habitat, animals that are unfamiliar with coastal environments may get confused in complex bathymetric conditions and get caught by the receding tide. Consequently, we hypothesize that the key question that needs to be answered is "what drives these open ocean cetaceans to coastal waters and into these "traps" in the first place?" The movement to the coastal areas or inside treacherous bays does not automatically lead to a stranding. However, animals do expose themselves to the stranding hazard by moving close to the coast. Given that it could take some time for a group of cetaceans to move from the open ocean environment to the coastal areas, depending on factors such as width of the continental shelf, it is possible that there could be a delay between the instigating factor and the resulting strandings. These delays should be taken into account in the search for causes of the strandings.

Cetacean mass strandings are likely caused by a complex combination of multiple biological and environmental factors which may vary between locations and species. Consequently, the search for causes calls for a systematic analysis of a wide range of stranding data sets with a wide range of environmental parameters. The data should also cover long periods of time to allow application of rigorous statistical analyses in the assessments. Such an empirical data analysis challenge was communicated in the cetacean mass stranding context by *Bradshaw et al.* (2006). It is our intent to respond to this challenge. To take a step forward in systematic empirical assessments, in this work, we will shed new light specifically on the possible connection between cetacean mass strandings and externally driven geomagnetic activity. To this end, we carried out the first systematic analysis of extensive cetacean mass stranding data from three key locations around the globe together with an extensive set of space weather and geomagnetic data. Importantly, we also utilized local geomagnetic field recordings that provide the best available characterization of the geomagnetic variations at the stranding locations. We note that we will not study the possible connection between cetacean mass strandings and internal geomagnetic field features. While the internal field features have been proposed to correlate with cetacean mass strandings (e.g., *Kirschvink et al*., 1986; 1990), these features vary at timescales of the order of tens of years and longer and thus cannot trigger individual cetacean mass stranding events. We find it more compelling to study the external field variations that can be very dynamic at shorter time scales.

In Section 2, we describe the different data used in the analyses. Section 3 details the different methods developed and applied in the data analysis. Sections 4 and 5 describe the event-based and statistical analyses of the data, respectively. Section 6 provides the concluding remarks and outlines future work.

2 Data Sets

Cetacean mass stranding data together with space weather and local geomagnetic field data were used in the analyses. Subsections below provide detailed description of these data.

2.1 Cetacean Mass Stranding Data

The traditional and most simple definition of a mass stranding is two or more cetaceans (excluding mother-calf pairs) coming ashore alive at the same time and place (*Geraci and Lounsbury*, 2005). In reality, mass stranding events involve multiple animals that strand in proximity to one another in time and space; it may be over the course of several hours or days, and in one discrete location, or over many kilometers along the beach. For the purposes of this investigation, mass stranding data from three global mass stranding hotspots in New Zealand (1990-2016), the United Kingdom (1991-2015) and the United States (1999-2014) were provided by New Zealand Department of Conservation Marine Mammal Database, UK Cetacean Strandings Investigation Programme and IFAW, respectively. These locations were chosen due to their long-standing, well-documented mass stranding response and data collection activities that provide accurate and homogeneous recordings required in detailed statistical assessments. Although most animals are presumed to have stranded alive in these events, in some cases they are not discovered in a timely manner and some, or all, of the animals are found dead. In order to utilize the most accurate possible timing of a stranding event, only those events in which animals were discovered alive or freshly dead were utilized in the analyses. For simplicity, below we refer to such strandings collectively as “fresh” strandings. Based on the expected rate of decomposition and the likelihood of discovery of the stranded animals (dependent upon proximity to human communities, aerial surveys, etc.), the “fresh” strandings approach provides the best timing of stranding with about 1-day accuracy, which is sufficient for our analyses.

Data were reviewed to ensure that all records represent true mass strandings and are comparable to one another. Each record includes date of stranding, latitude/longitude, species, number of individuals, and detailed comments. A total of 348 fresh mass stranding events involving 5932 individual animals of 17 species were included for analysis. Table 1 presents a summary of the strandings data from the three regions and Fig. 1 shows the geographical distribution of the strandings and the locations of the geophysical observatories used in the analysis.

Table 1: Summary of the cetacean mass stranding data from Cape Cod, U.S., United Kingdom and New Zealand.

Cape Cod, U.S.		United Kingdom		New Zealand	
Years:	1999-2014	Years:	1991-2015	Years:	1990-2016
# Events:	165	# Events:	38	# Events:	237
# Animals:	924	# Animals:	285	# Animals:	5762
# Events Fresh Strand	138	# Events Fresh Strand	24	# Events Fresh Strand	186
Mean # Anim / Event:	5.6	Mean # Anim / Event:	7.5	Mean # Anim / Event:	24.3
Mean # Events / Yr:	10.4	Mean # Events / Yr:	1.6	Mean # Events / Yr:	8.8
Mean # Animals / Yr:	58	Mean # Animals / Yr:	16.8	Mean # Animals / Yr:	213.4
Species:		Species:		Species:	
Delphinus delphis	57.1%	*Globicephala melas*	35.4%	*Globicephala melas*	76.9%
Lagenorhynchus ac.	32.9	*Delphinus delphis*	20.7	*Globicephala sp*	10.7
Globicephala melas	8.3	*Phocoena phocoena*	9.1	*Delphinus delphis*	3.6
Grampus griseus	1.2	*Lagenorhynchus acutus*	8.4	*Mesoplodon grayi*	2.6
S. coeruleoalba	0.2	*Lagenorhynchus albirostris*	7.7	*Tursiops truncatus*	1.5
Tursiops truncatus	0.2	*Unknown*	6.7	*Pseudorca crassidens*	1.0
		Physeter catodon	6.0	Others < 1% each	3.7
		Orcinus orca	3.9		
		Mesoplodon bidens	1.1		
		Stenella coeruleoalba	1.1		

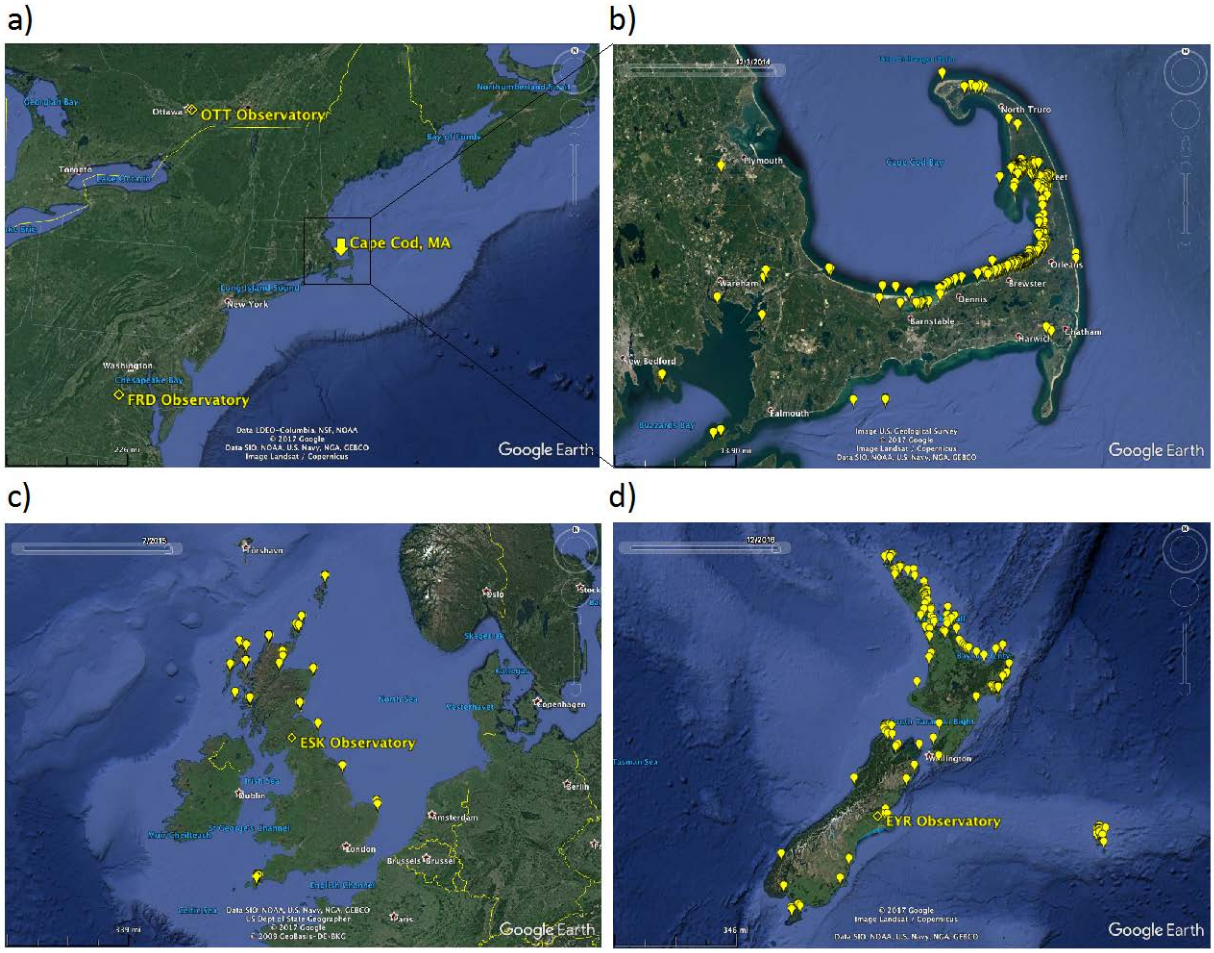

Figure 1: Panel a) Locations of Cape Cod fresh cetacean mass strandings (yellow markers) and the Ottawa (OTT) and Fredericksburg (FRD) geophysical observatories (diamonds). Panel b) Close-up of the Cape Cod stranding locations. Panel c) Locations of United Kingdom fresh strandings and the Eskdalemuir (ESK) geophysical observatory. Panel d) Locations of New Zealand fresh strandings and the Eyrewell (EYR) geophysical observatory.

Figs. 2-4 show the time series of the mass strandings and the sunspot number. The sunspot number is used to give an indication of the phase of the solar cycle and thus reference to the overall level of solar activity. As can be seen from Figs. 2-4 and Table 1, there are clear differences between the stranding data sets. Different species are involved in strandings at different geographical locations and in New Zealand the events have significantly larger number of animals than in Cape Cod or the United Kingdom. Also, the total number of events in the United Kingdom data set is substantially smaller than in the other sets. As a first visual check for a possible connection to space weather and geomagnetic activity, none of the stranding data sets appear to correlate with the sunspot number in Figs. 2-4.

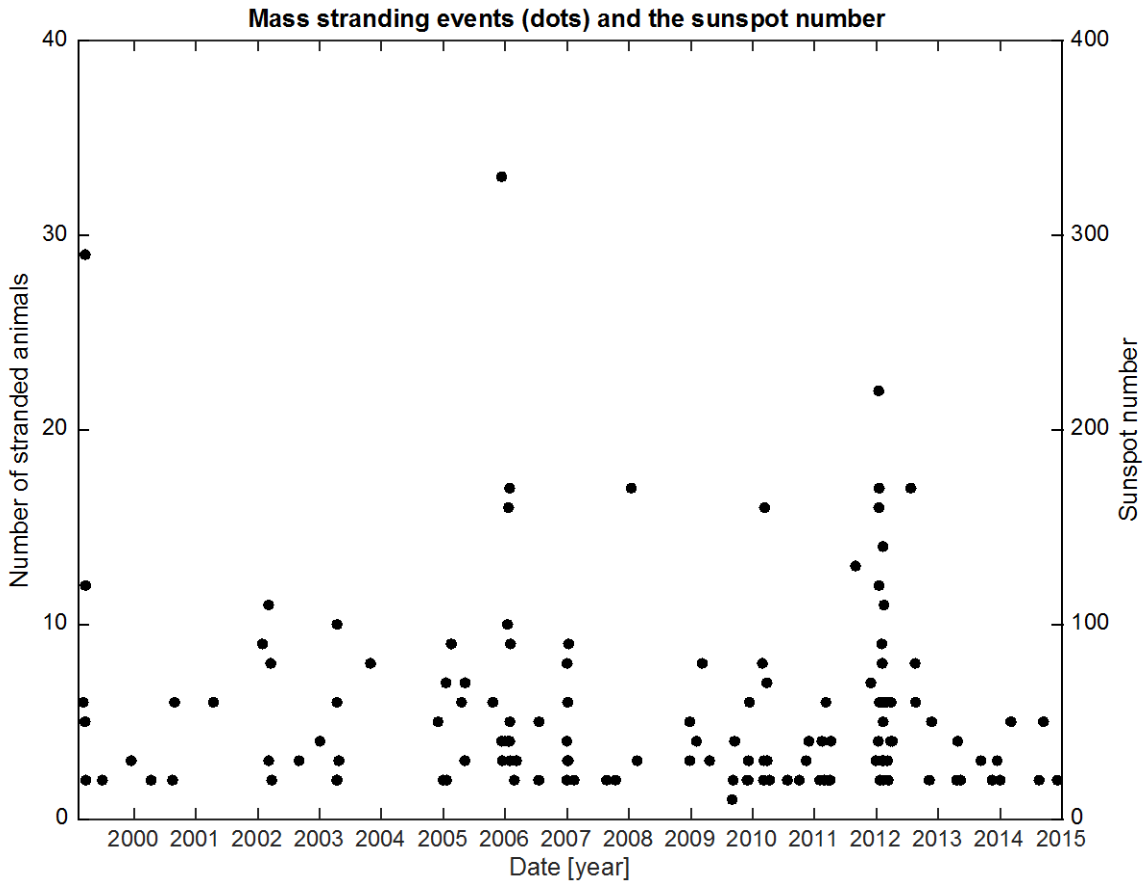

Figure 2: Cape Cod fresh cetacean mass stranding events (black dots) and the sunspot number (gray line).

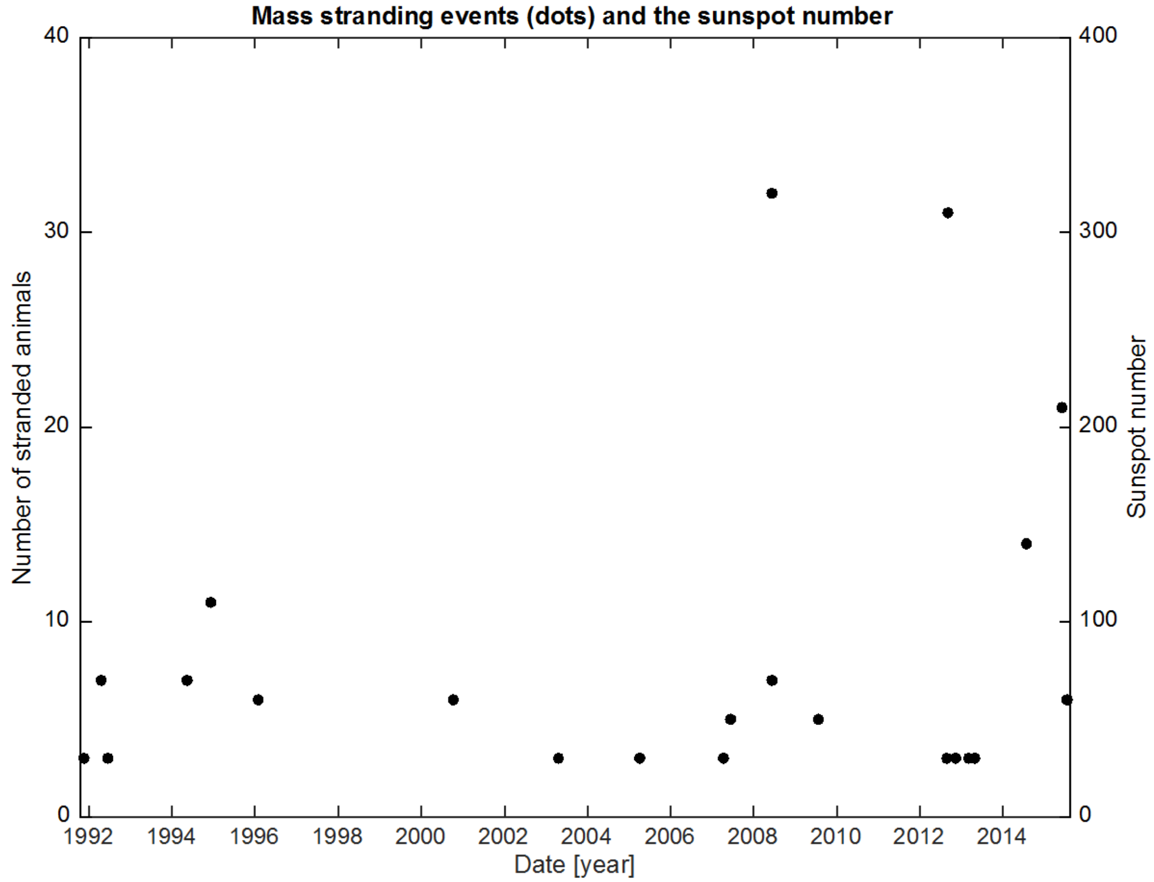

Figure 3: United Kingdom fresh cetacean mass stranding events (black dots) and the sunspot number (gray line).

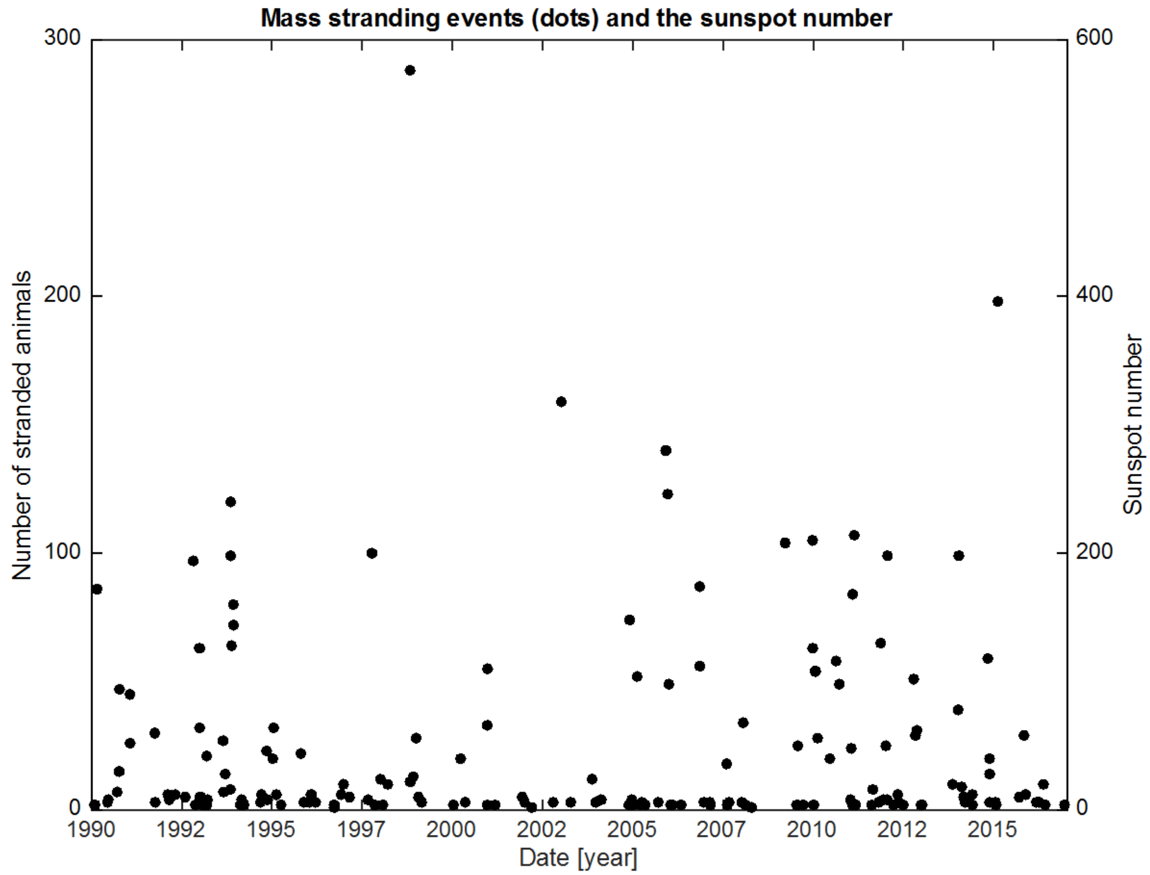

Figure 4: New Zealand fresh cetacean mass stranding events (black dots) and the sunspot number (gray line).

2.2 Space Weather Data

The general space weather conditions are assessed using solar wind plasma, interplanetary magnetic field and energetic proton observations. Plasma and magnetic field observations are from upstream of the Earth. These observations characterize the interplanetary conditions that drive geomagnetic activity (e.g., *Gonzalez et al.,* 1999). Energetic proton observations are from the geostationary orbit and characterize the charged particle storm conditions in the Earth's near-space environment. While we are not expecting energetic protons to have a connection to cetacean mass strandings, they are a useful measure in assessing the level of overall space weather activity around the stranding events.

Global geomagnetic conditions are characterized using the standard *AE*-, *Kp*- and *SYMH*-indices that are derived from global geomagnetic field observations (*Rostoker*, 1972). While geomagnetic indices are not appropriate for characterizing the detailed local geomagnetic conditions, the indices help in providing the global context and are useful when applied jointly with the local observations. In terms of the spatial domains covered by the indices, *AE*-index characterizes the strength of the high-latitude auroral electric current systems, *Kp*-index characterizes mid-latitude activity and *SYMH*-index is a measure of the low-latitude magnetic field perturbations caused by the ring current variations.

Solar wind plasma, interplanetary magnetic field, energetic proton and geomagnetic index data were retrieved from OMNIWeb Plus service provided by NASA Goddard Space Flight Center's Space Physics Data Facility (https://omniweb.gsfc.nasa.gov). The retrieved data covers the period of 1990-2016. Five-minute time resolution OMNIWeb data were used in visual analysis carried out in Section 4 and hourly averaged data were used in the statistical assessments in Section 5.

2.3 Local Geomagnetic Field Recordings

Local geomagnetic conditions are assessed using observatory recordings from sites close to the stranding locations (Fig. 1). The observatory recordings provide the best available means to characterize the geomagnetic conditions at the stranding locations. Cape Cod U.S., United Kingdom, and New Zealand are, under typical space weather conditions, geomagnetically mid-latitude locations. At mid-latitudes, the main external current systems causing the field variations are in the magnetosphere at distances greater than 1000 km from the ground. Consequently, the spatial scales of the geomagnetic field variations associated with the external electric currents are expected to be comparable or larger than the few hundred-kilometer distances between the stranding locations and the referenced geomagnetic observatories. It is thus reasonable to expect that the collected local geomagnetic field observations are a reasonable representation of the external field variations at the stranding locations.

There are two caveats to the above expectation. First, during extreme storms, high-latitude auroral electric currents can expand to mid-latitudes (e.g., *Pulkkinen et al.*, 2012; *Ngwira et al.*, 2013). The high-latitude auroral electric currents are located in the ionosphere at about 100 km above the surface of the Earth. Further, some of the smallest relevant spatial scales in the ionospheric currents can be very short leading to ground magnetic field signatures having scales of the order of 100 km (e.g., *Pulkkinen et al.*, 2015; *Ngwira et al.*, 2015). However, extreme geomagnetic storms are infrequent with only a few occurring over the 11-year solar cycle and thereby the vast majority of the analyzed stranding events took place under typical mid-latitude geomagnetic conditions. Second, electromagnetic induction in the Earth's crust can lead to spatially localized geomagnetic, and in particular, electric field structures. However, the amplitude of the internal magnetic field due to induction is smaller than that due to external excitation and consequently the internal field plays a secondary role in storm-time geomagnetic field variations (*Tanskanen et al.,* 2001). We again note that static crustal magnetic field features have also been indicated to correlate with the stranding events (e.g., *Kirschvink et al*., 1986; 1990). However, as explained in Section 1, we will not study the possible influence of the static internal field features on cetacean stranding behavior. The triggering of the stranding events must occur at shorter time scales.

We collected one-minute time resolution vector magnetic field data from four geophysical observatories: Ottawa (OTT), Canada; Fredericksburg (FRD), Virginia, U.S.; Eskdalemuir (ESK), United Kingdom and Eyrewell (EYR), New Zealand (see Fig. 1). OTT and FRD are used to characterize geomagnetic conditions in Cape Cod, ESK the conditions in United Kingdom and EYR the conditions in New Zealand. OTT/FRD and ESK cover the time periods of the fresh mass strandings records from Cape Cod (1999-2014), United Kingdom (1991-2015), respectively. EYR one-minute data was available only for 1991-2014, which does not fully cover the available fresh mass stranding data from 1990-2016. The geomagnetic field data were collected through INTERMAGNET and World Data Centre for Geomagnetism (Edinburgh). These services are available at http://www.intermagnet.org and http://www.wdc.bgs.ac.uk.

The local geomagnetic conditions are quantified below using the one-minute rate of change of the horizontal magnetic field: *dB/dt* where $B = \sqrt{B_X^2 + B_Y^2}$ and B_X and B_Y are the geographic north-south and east-west components, respectively. The usage of the rate of change solves the challenge with the field baseline determination. If we were to analyze the geomagnetic field B_X and B_Y statistics for the days of the mass stranding events, we would have to remove the main field contribution (baseline) from the measurements to obtain the external field component that we are interested in. As the main field is not constant over the period covered by the cetacean mass stranding data, the removal of the baseline is not straightforward and inappropriate removal could introduce artifacts in the statistics. The differentiation in computing *dB/dt* automatically removes the baseline since the main field does not change in one-minute time scales.

3 Methodology

The data were analyzed using both visual inspection of a subset of Cape Cod mass stranding dates and comprehensive joint statistical analysis of space weather data with mass stranding dates. Visual inspection is discussed in detail in Section 4. The statistical analysis method is described in this section and application of the method to mass stranding data is described in Section 5. To account for the possible dependence of the results on the applied specific statistical technique, complementary analyses were carried out using Kolmogorov-Smirnov statistics. Kolmogorov-Smirnov statistics results are documented in Appendix A.

The primary challenge with the type of analysis carried out in this work pertains to the dual nature of the applied data: mass strandings are points in time (and space) whereas geomagnetic indices and local recordings are continuous in time. Consequently, one cannot carry out direct computation of correlation coefficients, or other standard metrics that are used to measure the strength of statistical association between data. Another challenge is that we do not know how long it could take for the cetaceans to react to geomagnetic activity. How many hours or days from the start of changing geomagnetic activity could it take for animals to get confused and ultimately strand? Also, where does the initial confusion take place? Most of the stranded cetaceans are pelagic species so perhaps initial confusion takes place further out in the ocean and it may take days before the triggering of necessary environmental conditions leads to a stranding event.

To account for these challenges, we adopted the following method for quantifying statistical association between mass strandings and geomagnetic activity:

1) Probability distribution for parameter of interest x is computed for the days of mass stranding events. In other words, we compute probability distributions $p(x|s)$ for parameter x conditioned with mass stranding events s.

2) The data for x is then shifted in time in one day increments and step 1) is repeated for each shift. The sign of the time shift is chosen so that negative time shift means that the time series for x is shifted to the past. In other words, statistical association at negative time shifts indicates delayed response in mass strandings to changing conditions in x.

3) Climatological probability distribution $p(x)$ for x is computed. Climatology includes all data in the date range of mass strandings being analyzed.

4) The “distance” between $p(x|s)$ and $p(x)$ is computed. Many different metrics for measuring the distance could be used but we chose to apply Kullback-Leibler distance, which is used widely in information theory (*Kullback and Leibler*, 1951). The Kullback-Leibler distance is defined as:

$$D_{KL} = \int p(x) \log\left(\frac{p(x)}{p(x|s)}\right) dx \tag{1}$$

In Eq. (1), if the parameter of interest x is statistically independent of mass strandings s, $p(x|s) = p(x)$ and the distance D_{KL} is zero.

The method described above has several advantages. First, it accounts for the fact that mass strandings are a point process and geomagnetic data are continuous. The method can also readily adjust to varying temporal resolutions of the geomagnetic data. The time shifted analysis in step 2 allows gauging possible time delays in statistical association. The method also accounts for full statistical characteristics of the parameters of interest, and not just statistical mean used in some of the earlier studies (e.g., *Klinowska*, 1986; *Vanselow et al.*, 2009). We do, however, note that one needs to pay careful attention in selecting the binning (i.e. Δx in discretized version of Eq. (1)) used to build the probability distributions: too wide bins reduce the sensitivity of the method and too narrow bins may result in poor statistics for certain ranges of parameter values. The selected binning needs to be adjusted based on the data volume available in the analysis. We used experimentation to find the optimal ranges of bins for all geomagnetic parameters studied.

To demonstrate the sensitivity of the selected analysis method, we constructed a synthetic *AE*-index time series. The series representing 1-hour values for years 1999-2014 was constructed by drawing random absolute values from normal distribution with zero mean. The standard deviation of the drawn absolute values was set to 600 nT. We then conditioned the set by linearly superposing, both for the day and the day prior to mass strandings random, absolute values with standard deviation of 60 nT. Such a small additional amplification cannot be identified visually from the data so the setting provides a good test for the sensitivity of the analysis method.

Fig. 5 shows the results of the time shifted analysis of the constructed synthetic *AE*-index data. As can be seen, there is an easily identifiable increase in Kullback-Leibler distance from the climatological distribution at 0- and 1-day time shifts. The elevated distance indicates that there is a statistically significant association between the data sets with 0- and 1-day response times. As can also be seen from Fig. 5, the Kullback-Leibler distance is not exactly zero for time shifts for which we know there is no statistical association between the data. This background level of “noise” in the Kullback-Leibler distance is a reflection of finiteness of the data and level of overall uncertainty in the computed distances which should be taken into account when drawing conclusions from the analysis of real data. Any indication of significant statistical association would have to be seen as Kullback-Leibler distance that is significantly above the background noise level in the analysis.

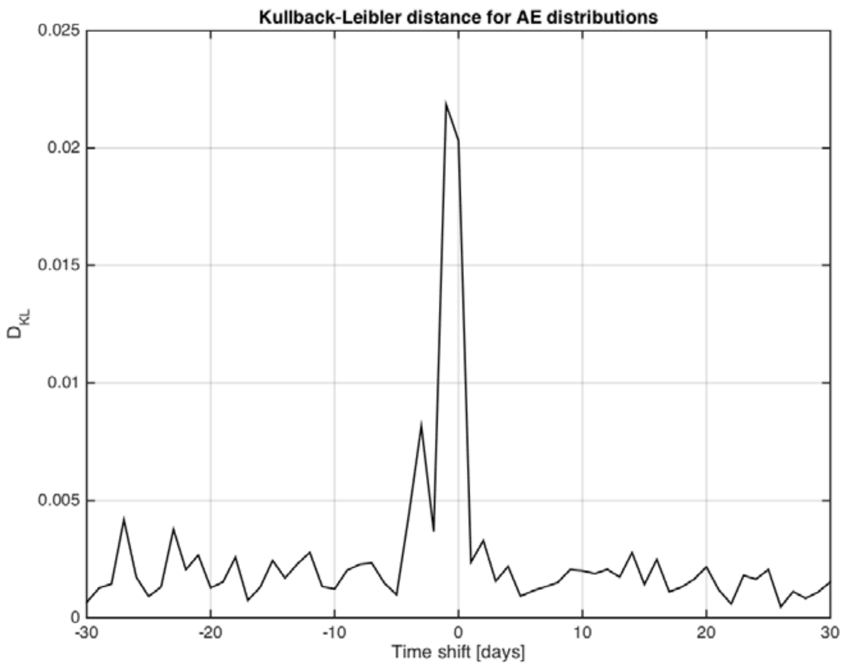

Figure 5: Kullback-Leibler distance for synthetic AE-index data that were conditioned with the stranding events in Cape Cod. See the text for details.

4 Event-Based Analysis

While it is not possible to carry out detailed visual data analysis of all cetacean mass strandings in Figs. 2-4, we carried out detailed event-based visual analysis of the space weather conditions around the four largest stranding events in the Cape Cod stranding data set. These events took place 2002-07-29, 2005-12-10, 1999-03-19, 2012-01-14 with 56, 33, 29 and 22 fresh stranded animals, respectively. We discuss each individual event in separate subsections below.

We use a ten-day window for visual inspection of the space weather conditions around the stranding events. Swim speeds for some dolphin species have been recorded as being about 4 km/h or higher (e.g., *Sakai et al*., 2011; *Fish et al*., 2014) and ten days of travel thus corresponds to a distance of about 1000 km or more. These are long enough distances to move pelagic animals that strand in Cape Cod from offshore habitats to coastal areas. Consequently, a ten-day window is a meaningful time scale to look for changes in environmental conditions that may lead to cetacean confusion, movement to coastal areas and eventual stranding. We note that for completeness even longer 30-day and 730-day windows are used in our statistical analyses.

4.1 2002-07-29 Event

On 2002-07-29, 56 live long-finned pilot whales (*Globicephala melas*) were found stranded in the Cape Cod area. Fig. 6 shows space weather and geomagnetic conditions during the day of the stranding and ten days prior to the event.

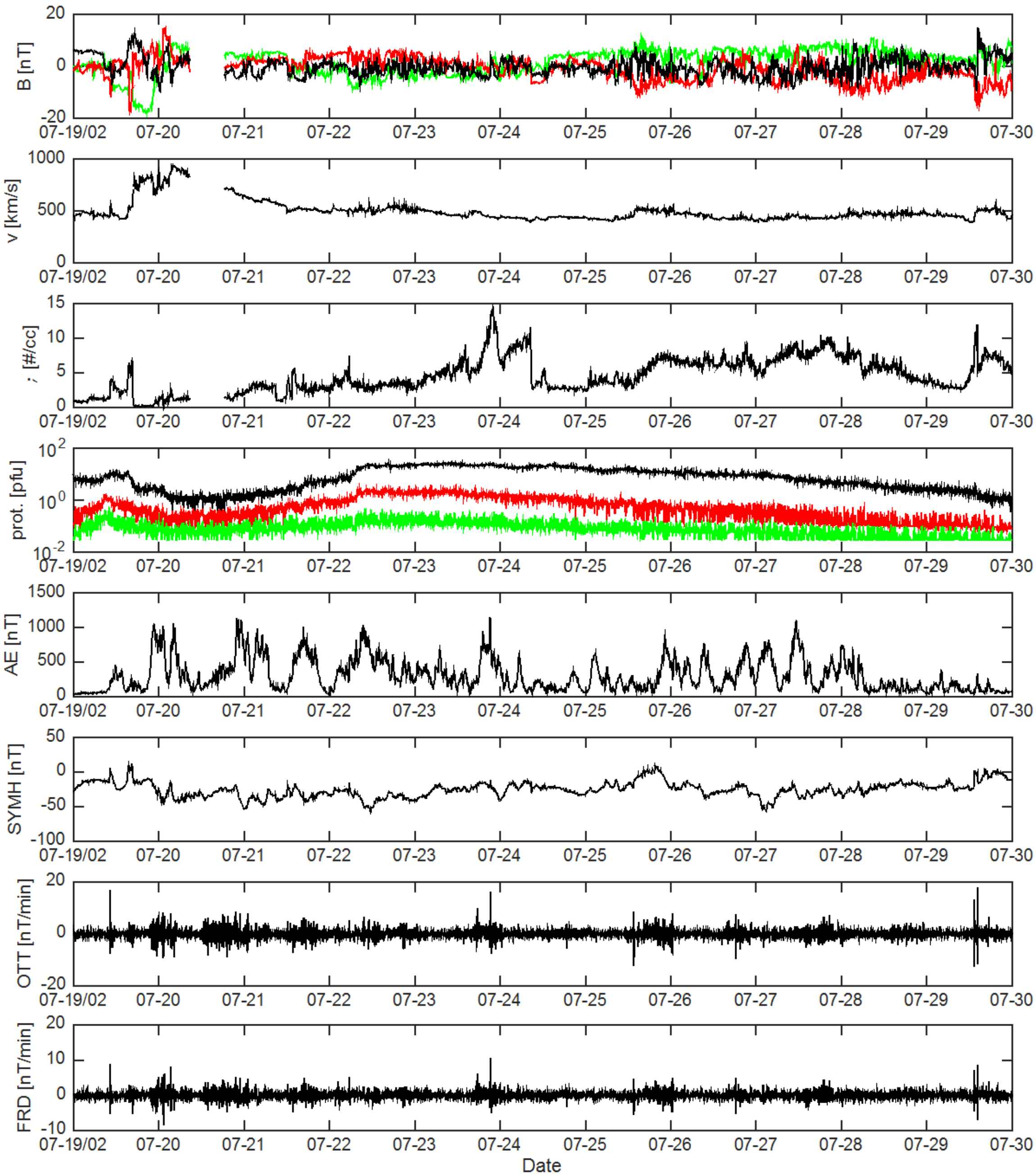

Figure 6: Space weather and geomagnetic conditions around the 2002-07-29 stranding event in Cape Cod. From the top to the bottom: interplanetary magnetic field magnitude, solar wind speed, solar wind density, energetic particles (black line > 10 MeV protons, red line > 30 MeV protons, green line > 60 MeV protons), AE-index, SYMH-index, dB/dt in Ottawa (OTT) and dB/dt in Fredericksburg (FRD).

Fig. 6 shows that there was minor to moderate level of space weather activity around the time of the stranding event. There were interplanetary plasma and magnetic field disturbances throughout the period that drove minor to moderate geomagnetic activity seen in *AE*- and *SYMH*-indices as well as in OTT and FRD observations. There was also an ongoing solar particle event seen in elevation of the energetic proton fluxes.

For a reference, Fig. 7 shows the same observables for major levels of space weather and geomagnetic activity. The shown data is for the "St Patrick's Day storm" of 2015-03-17 (e.g., *Wu et al*., 2016). As can be seen from the solar wind plasma and interplanetary magnetic field data in Fig. 7, coronal mass ejection (CME) that was embedded within the solar wind stream interaction region impacted the Earth on 2015-03-17. The arrival of the CME was also associated with elevated energetic particles observed at the geostationary orbit. The CME drove significant geomagnetic activity and *SYMH*-index decreased below -200 nT. *dB/dt* in OTT and FRD reached maximum amplitudes of about 270 nT/min and 50 nT/min, respectively. The fact that OTT saw much larger amplitude field fluctuations is due to the northern location that was exposed to auroral ionospheric electric currents as was discussed above. FRD observed mid-latitude storm-time field fluctuations. We note that Cape Cod, United Kingdom or New Zealand data sets did not have mass stranding events at or around 2015-03-17.

4.2 2005-12-10 Event

On 2005-12-10, 33 live cetaceans that were a collection of Atlantic white-sided dolphins (*Lagenorhynchus acutus*), short-beaked common dolphins (*Delphinus delphis*) and long-finned pilot whales (*G. melas*) were found stranded in the Cape Cod area. Fig. 8 shows space weather and geomagnetic conditions for the day of the stranding and ten days prior to the event.

Fig. 8 shows that the beginning of the period was covered by a high-speed solar wind stream with observed plasma bulk speed above 700 km/s. The high-speed region was associated with minor *dB/dt* activity in OTT and FRD. The high-speed stream then waned and picked up again toward the end of the period. The second elevation in the solar wind speed caused a stream interaction region with elevated interplanetary magnetic field fluctuations and plasma compression around 2005-12-10. The plasma conditions in the stream interaction region drove minor geomagnetic activity seen both in *SYMH*-index and local geomagnetic field measurements. Energetic particle fluxes were at nominal background levels throughout the period.

4.3 1999-03-19 Event

On 1999-03-19, 29 live Atlantic white-sided dolphins (*L. acutus*) were found stranded in the Cape Cod area. Fig. 9 shows space weather and geomagnetic conditions for the day of the stranding and ten days prior to the event.

Fig. 9 shows that the period was covered with low-speed solar wind. However, there were interplanetary disturbances in terms of solar wind density and magnetic field fluctuations that were embedded in the slow wind. The interplanetary disturbances drove minor geomagnetic storm conditions during the second day of the period. The minor storm conditions were seen in *SYMH*-index and local *dB/dt* levels both in OTT and FRD. The geomagnetic activity returned to background non-storms levels on about 1999-03-13. Energetic particle levels were at nominal background levels throughout the period.

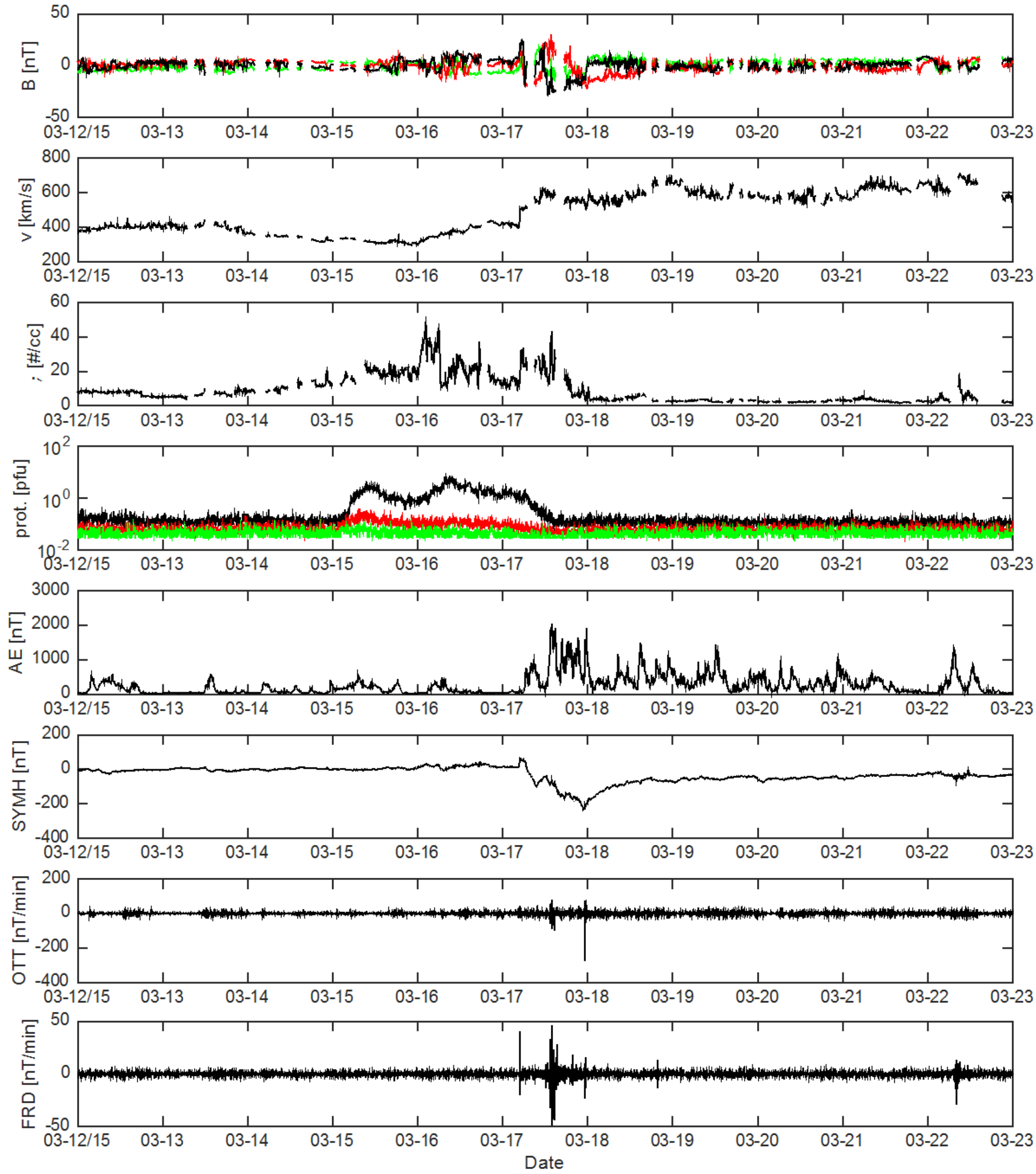

Figure 7: Same as Fig. 6 but for conditions around the "St Patrick's Day storm" of 2015-03-17.

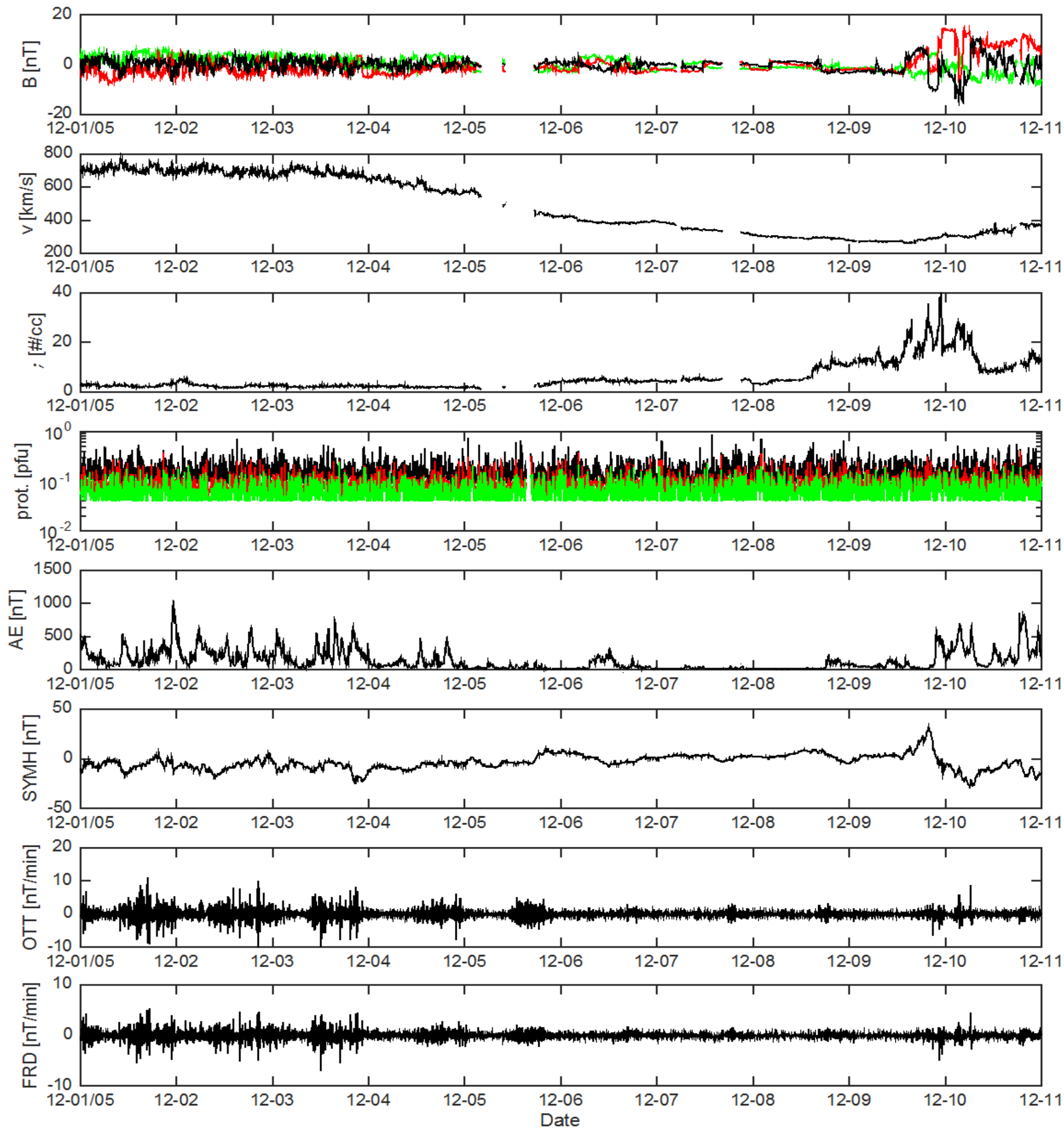

Figure 8: Same as Fig. 6 but for conditions around the 2005-12-10 stranding event.

4.4 2012-01-14 Event

2012-01-14 22 live short-beaked common dolphins (*L. acutus)* were found stranded in the Cape Cod area. Fig. 10 shows space weather and geomagnetic conditions for the day of the stranding and ten days prior to the event.

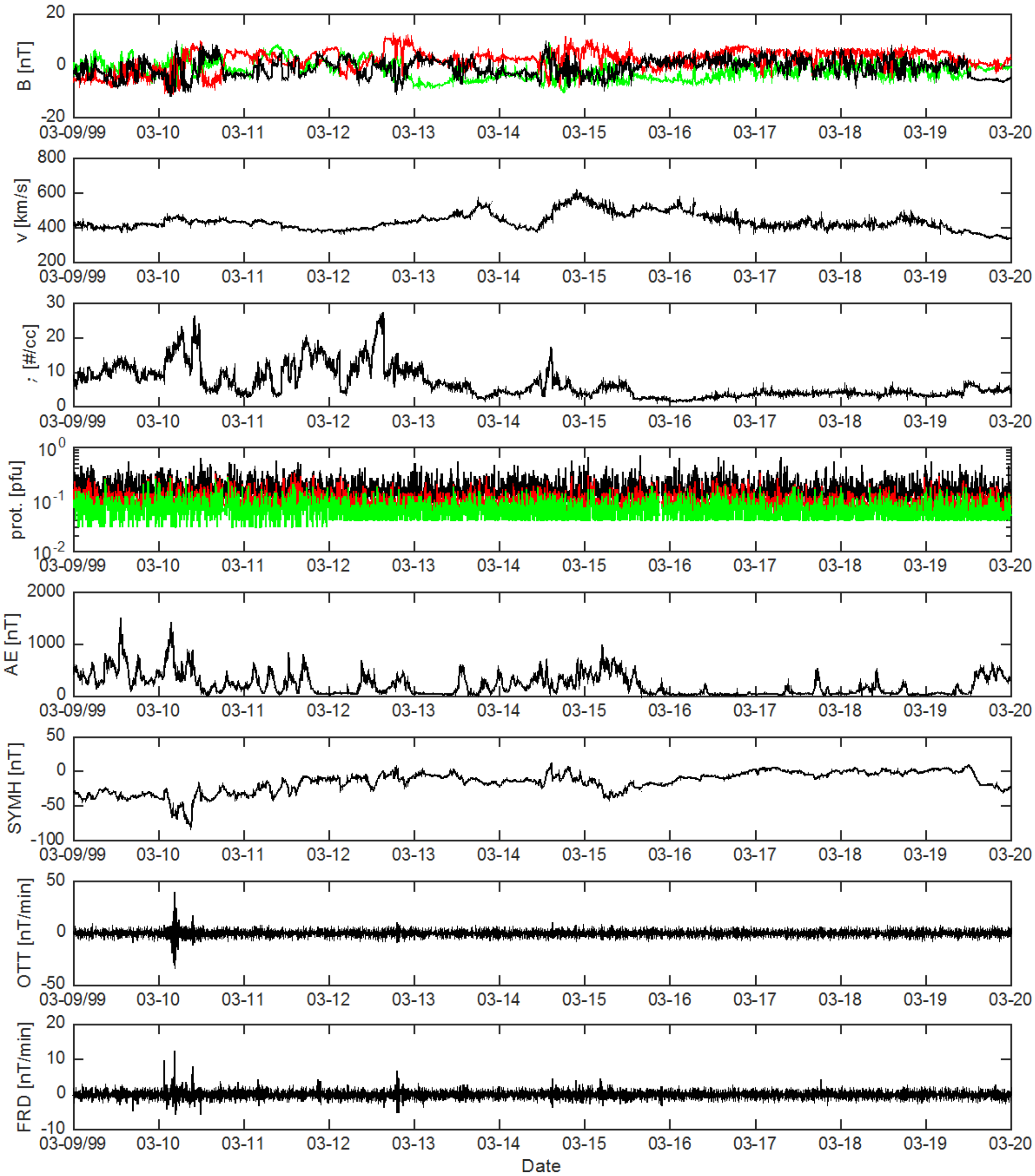

Figure 9: Same as Fig. 6 but for conditions around the 1999-03-19 stranding event.

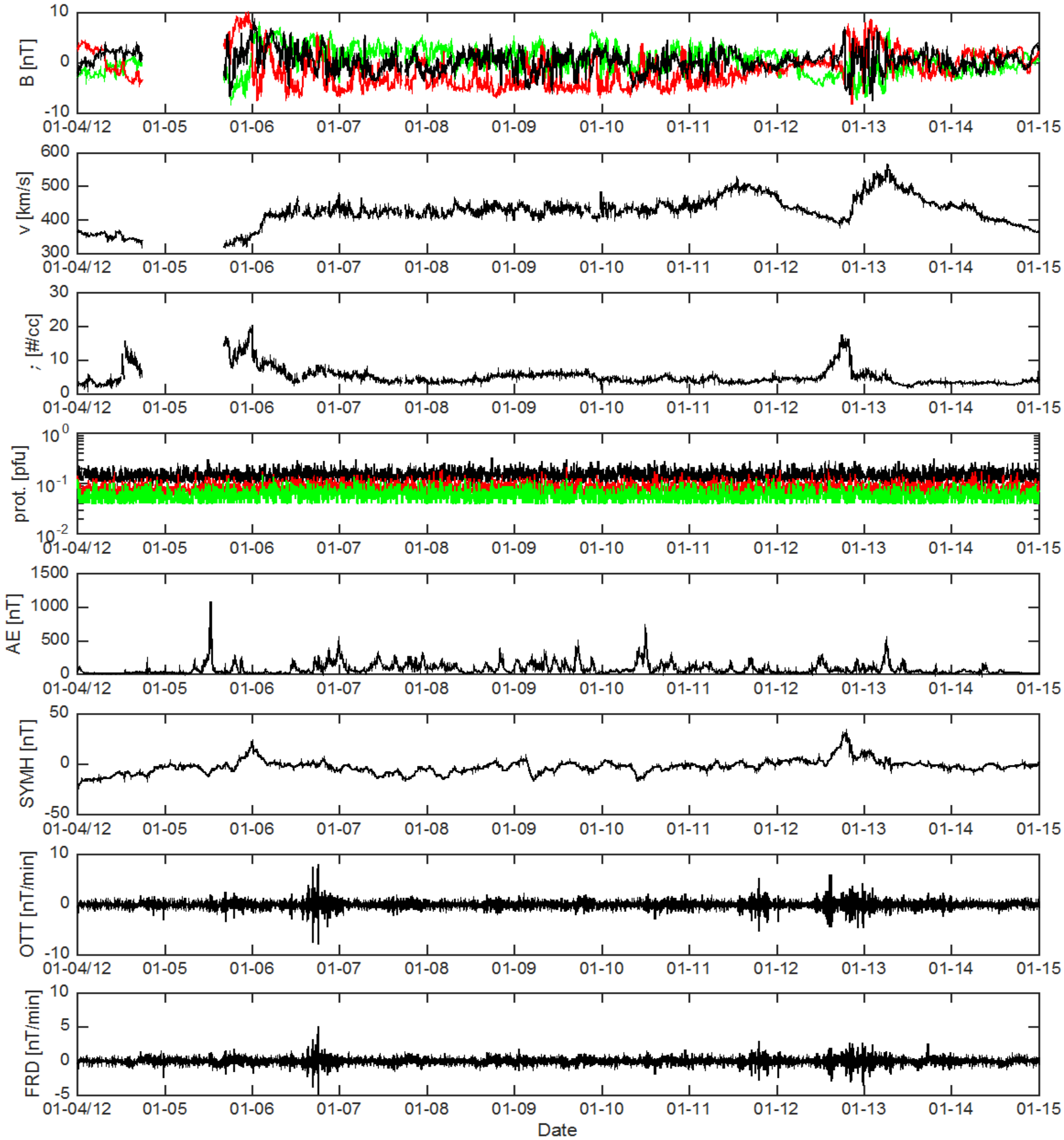

Figure 10: Same as Fig. 6 but for conditions around the 2012-01-14 stranding event.

Fig. 10 shows that there were two solar wind stream interaction regions during the period: one on the second day of the period 2012-01-05 and the second on 2012-01-12. The interaction regions were associated with elevated levels of interplanetary magnetic field fluctuations and plasma densities. While the interaction regions didn't result in any geomagnetic storms that could be measured in terms of the

SYMH-index, they were associated with slightly elevated levels of *dB/dt* in OTT and FRD. Energetic particle levels were at nominal background levels throughout the period.

5 Statistical Analyses

This section describes the rigorous joint statistical analysis of the geomagnetic and cetacean mass stranding data. The method described in Section 3 will be used in the analysis. Supporting Kolmogorov-Smirnov analysis is detailed in Appendix A. To maximize the number of events available for statistical analysis, no distinction is made between different species in the mass stranding data.

Fig. 11 shows the climatological and time shifted Cape Cod mass stranding-conditioned distributions for the *Kp*-index. Note that the raw counts are shown and this results in the much larger count number for the climatological distribution that is built using the entire *Kp*-index data set between 1999 and 2014. Visual inspection of the distributions in Fig. 11 indicates that the *Kp*-index statistics with -5, 0 and 5-day time shifts is very similar to the climatological distribution, which would indicate that conditioning the data with mass strandings does not change the statistics. However, detailed quantification is accomplished by inserting the distributions into Eq. (1) and comparing the conditioned distributions over a wide range of time shifts.

Fig. 12 shows the computed Kullback-Leibler distances between the climatological and mass stranding-conditioned distributions for the *Kp*-, *Dst*-, and *AE*-indices and for time shifts ranging from -30 to 30 days. Negative time shift means that the geomagnetic data is shifted to the past, i.e. statistical association at negative shifts indicates delayed response in mass strandings to changing geomagnetic conditions. Statistical association with positive time shifts would indicate that space weather conditions respond to mass strandings, which is not realistic. Positive time shifts thus provide an additional way to gauge the background noise and confidence levels in the analysis. Per discussion in Section 4, the -30 to 30 range of time shifts was selected based on a reasonable expectation for how long, at most, it would take for the possibly confused cetaceans to move from their generally offshore habitats to the coastal areas and ultimately strand.

When comparing Kullback-Leibler distances in Fig. 12 (except panel d, which is discussed separately in the next paragraph) to those for the synthetic test case in Fig. 5, it can be seen that the analyzed data does not indicate a clear enhancement of the statistical association beyond the background noise levels in the analysis. The small peaks such as those in Fig. 12 panels b and c at time shifts of -8 and -3 days, respectively, are not significant given the overall fluctuations in the Kullback-Leibler distance. We thus conclude that there is no statistically significant evidence for association in 30-day response time scales between the fresh cetacean mass strandings in Cape Cod and global geomagnetic indices.

However, Fig. 12d includes a much larger range of time shifts and does indicate Kullback-Leibler distances that are clearly above the noise level of the analysis. Specifically, four clear peaks separated by one year are seen in Fig. 12d. While it would be tempting to speculate causality, we believe that the detected association is spurious. The reasons why we believe that the association at these time shifts is spurious are two-fold. First, both types of data have seasonal trends. Geomagnetic activity has a well-known seasonal dependence with elevated levels observed around equinoxes due to the Russel-McPherron effect (e.g., *Zhao and Zong*, 2012). The seasonality is seen in both global geomagnetic indices and local geomagnetic field observations. As can be seen from Fig. 13a, Cape Cod fresh mass strandings have a clear seasonality as well. The seasonality is seen as a bimodal distribution with peaks around March and August. As shown in Fig. 13c, seasonality is also seen for the New Zealand mass strandings. Seasonal dependence of both types of data will give rise to a seasonally varying statistical association, even in the absence of causal connection. Second, as seen from Fig. 12d, the peak in statistical association is experienced at -50-day time shift. It is unlikely that changes in geomagnetic conditions would cause mass strandings with an almost two-month delay. Per the discussion in Section 4, we argue that navigational errors due to changing geomagnetic conditions and corresponding animal movement to coastal areas would have to lead to strandings at shorter time scales.

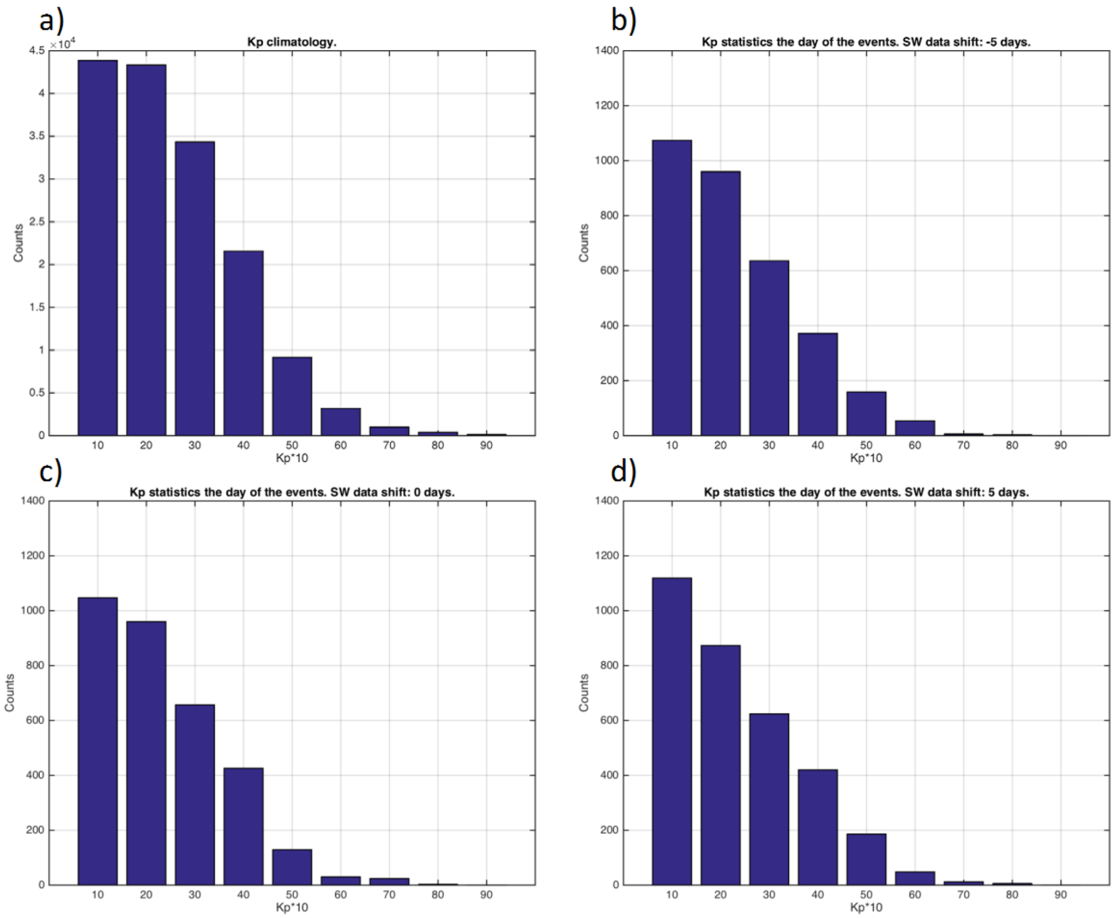

Figure 11: Panel a) K-index climatology between 1999-2014. Panel b) Kp-index statistics for five days before the mass stranding events in Cape Cod. Panel c) Kp-index statistics for the days of the mass stranding events in Cape Cod. Panel d) Kp-index for five days after the mass stranding events in Cape Cod.

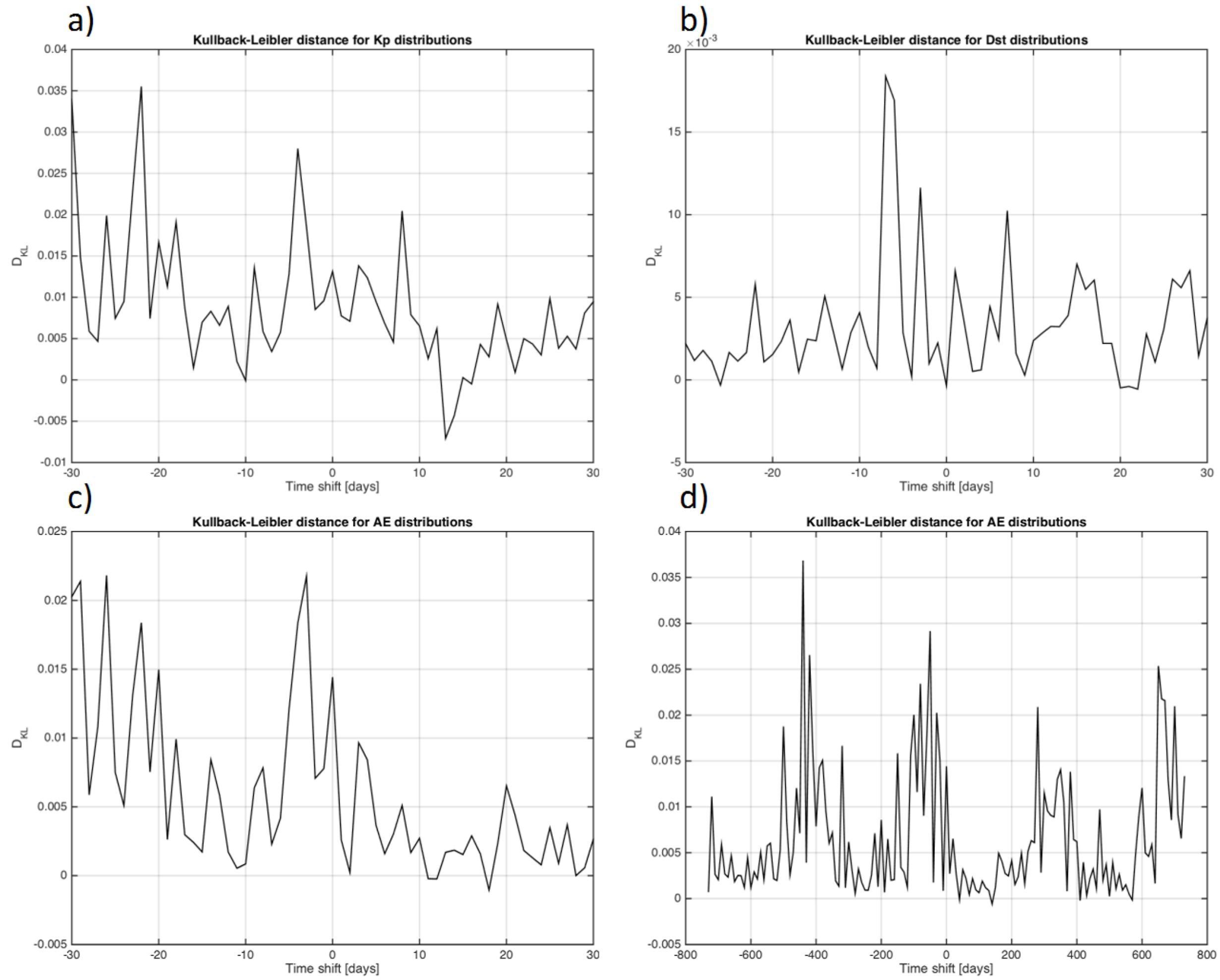

Figure 12: Statistical analysis results for the Cape Cod data set. Panel a) Kullback-Leibler distance for the Kp-index. Panel b) Kullback-Leibler distance for the Dst-index. Panel c) Kullback-Leibler distance for the AE-index. Panel d) Same as panel c) but for time shifts ranging from -730 to 730 days. Compare to synthetic test case in Fig. 5 that shows clear statistical association at time shifts of -1 and 0 days.

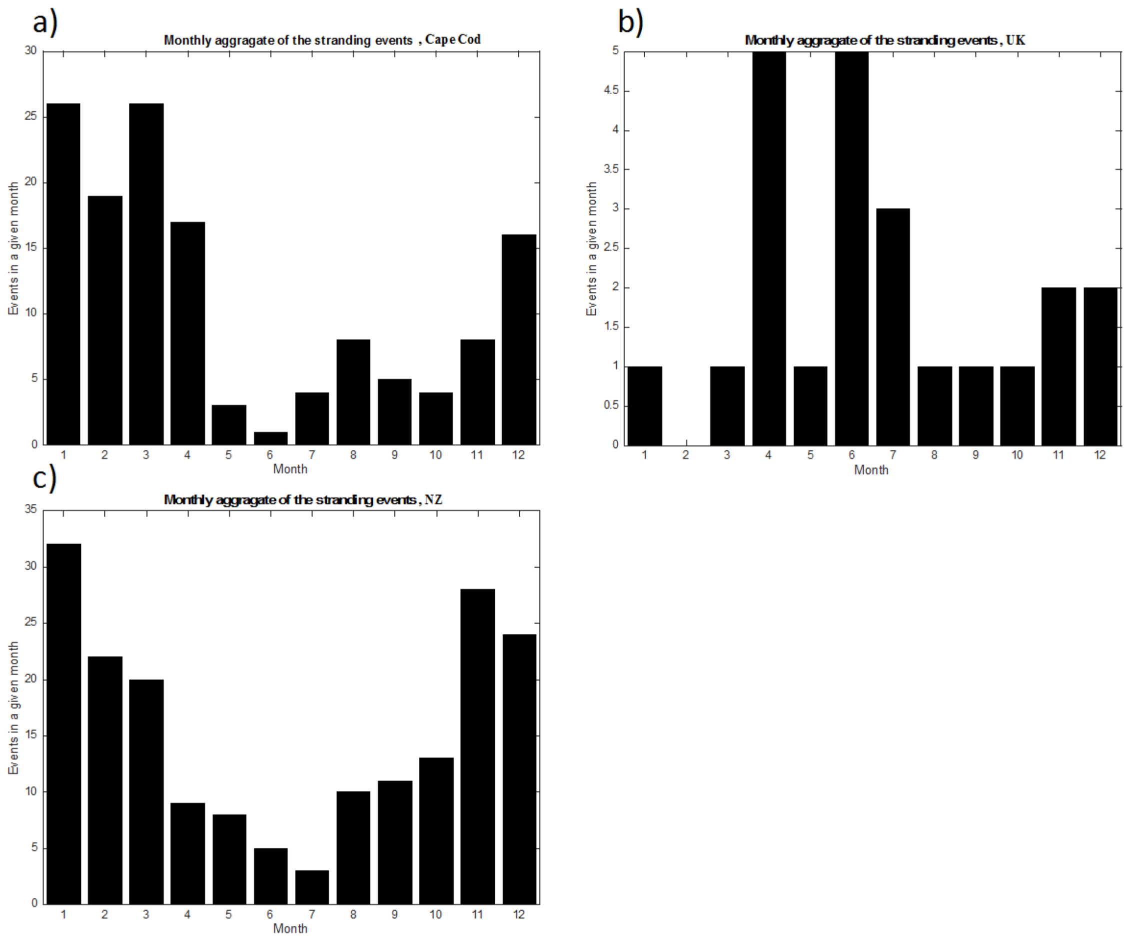

Figure 13: Monthly aggregate of fresh cetacean mass stranding events. Panel a) Cape Cod events between 1999-2014. Panel b) United Kingdom events between 1991-2015. Panel c) New Zealand events between 1990-2016.

Figs. 14 and 15 show the Kullback-Leibler distances for the local *dB/dt* measurements and all three stranding data sets. While no clear statistically significant peaks are seen for -30 to 30 day time shifts, the seasonal dependence is seen in local geomagnetic field observations for the Cape Cod and New Zealand mass stranding data sets for time shifts ranging from -730 to 730 days. As seen from Fig. 15b, there is no clear seasonality in the United Kingdom data. We believe this is due to the very limited number of events in the United Kingdom fresh mass stranding data set that significantly limits the power of the statistical analysis for this location. For the reasons stated above, it is likely that the statistical associations seen for the local geomagnetic field observations in Cape Cod and New Zealand are also spurious and not an indication of causal connection. Further, as is seen from Fig. 15d, the statistical association between New Zealand mass strandings and EYR observations peaks at time shift of about -~200 days. Such a long delay in response is even harder to explain than the 50-day delay observed for the Cape Cod data. Navigational errors due to changing geomagnetic conditions and corresponding animal movement to coastal areas would have to lead to strandings at shorter time scales than 200 days.

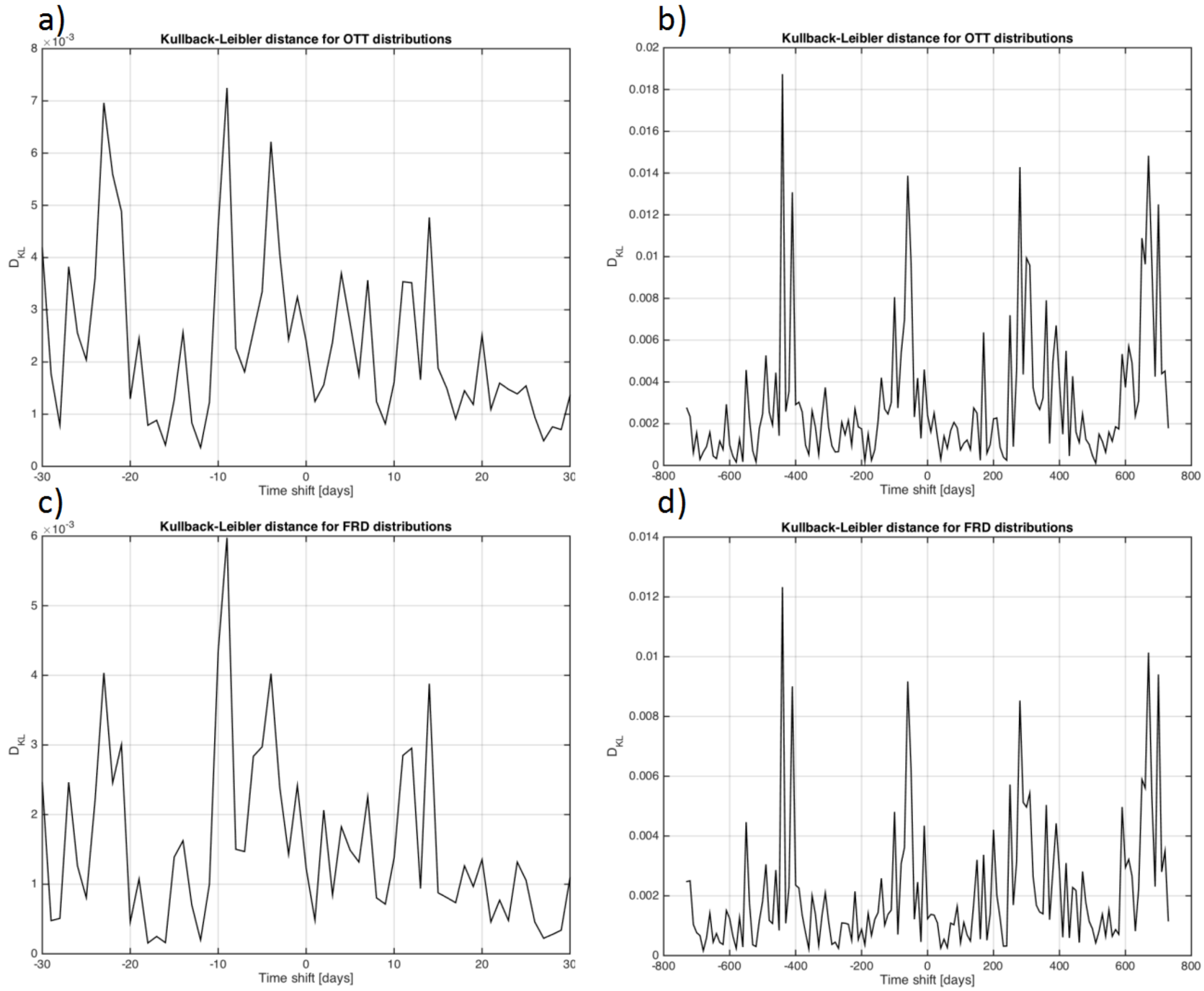

Figure 14 Statistical analysis results for the Cape Cod fresh cetacean mass stranding data set. Panel a) Kullback-Leibler distance for the OTT observations. Panel b) Same as panel c) but for time shifts ranging from -730 to 730 days. Panel c) Kullback-Leibler distance for the FRD observations. Panel d) Same as panel c but for time shifts ranging from -730 to 730 days.

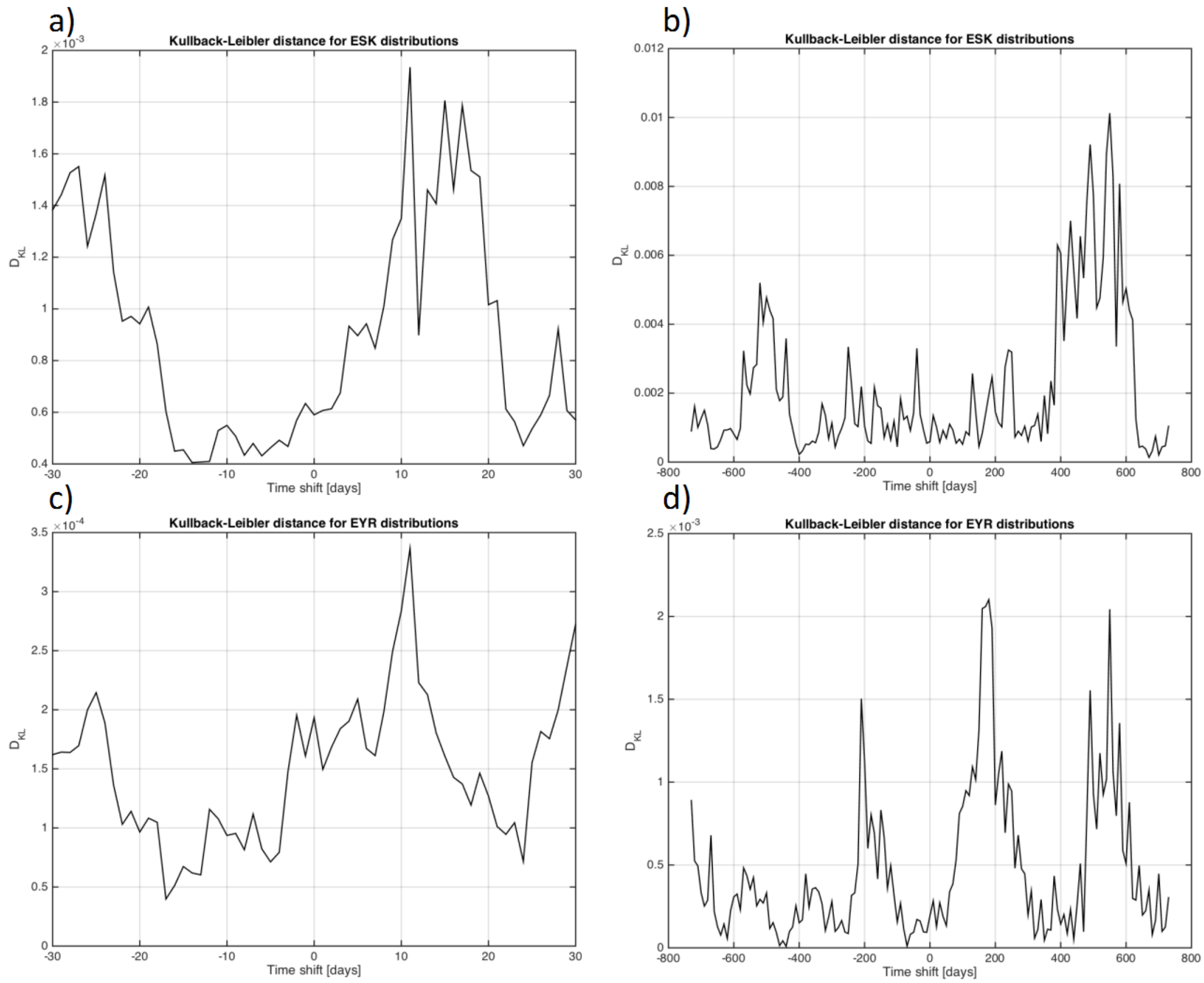

Figure 15: Statistical analysis results for the United Kingdom (panels a and b) and New Zealand (panels c and d) fresh cetacean mass stranding data sets. Panel a) Kullback-Leibler distance for the ESK observations. Panel b) Same as panel a but for time shifts ranging from -730 to 730 days. Panel c) Kullback-Leibler distance for the EYR observations. Panel d) Same as panel c but for time shifts ranging from -730 to 730 days.

6 Conclusions

We investigated the possible connection between cetacean mass stranding events and externally driven geomagnetic variations. We analyzed three major stranding data sets from Cape Cod, U.S., the United Kingdom and New Zealand together with global geomagnetic indices and local geomagnetic field observations. We conducted an event-based visual analysis of the space weather conditions around the four largest stranding events in Cape Cod and undertook rigorous statistical analysis of all fresh mass stranding events in these data sets.

The four largest fresh cetacean mass stranding events in Cape Cod were concurrent with a variety of space weather conditions ranging from ongoing solar energetic particle events and minor geomagnetic storm conditions to negligible overall activity. None of the four events occurred with major geomagnetic activity within the ten-day analysis window. There were no obvious significant signatures in space weather or geomagnetic conditions during the four largest stranding events in Cape Cod that could be detected beyond the background low levels of frequent geomagnetic activity.

We developed and applied a statistical technique to quantify the association between mass strandings and geomagnetic conditions. The method is based on the analysis of distributions for the parameters of interest conditioned with mass stranding events. Additionally, we incorporated this technique with time shifted analysis to gauge possible delays in stranding response to geomagnetic conditions. It is emphasized that this analysis technique can detect changes not only in average conditions but general statistical changes in the characteristics of the parameter of interest.

When the technique was applied with time shifts ranging between -30 and 30 days, we could not detect any clear signature of statistical association between the three cetacean fresh mass stranding data sets and geomagnetic conditions. The relatively small number of fresh mass stranding events in the United Kingdom data set limits the statistical confidence of our analyses for the region. Interestingly, when we investigated time shifts of several years long, seasonally varying statistical associations were found. While it would be tempting to equate these associations with causality, it is unlikely that the connection at these 50+ day timescales is causal. The seasonally varying statistical association is likely caused by the seasonal dependence present in both the mass stranding data and geomagnetic conditions.

To account for the possible dependence of the results on the applied specific statistical technique, we carried out complementary analyses using Kolmogorov-Smirnov statistics. The results of these analyses are described in Appendix A and fully support our findings above. More specifically, the Kolmogorov-Smirnov analysis also indicated a seasonally varying association between fresh cetacean mass stranding events and geomagnetic activity. However, at shorter 30-day time scales no indication of association was found.

While our results are negative, it may still be possible that geomagnetic conditions somehow modulate cetacean mass strandings. However, the effect has to be very subtle and it is quite clear from our analyses that elevated geomagnetic activity alone cannot explain the mass strandings in the three studied locations. Since it is likely that mass strandings are a result of a complex combination of multiple different environmental factors, the next step is to carry out joint analysis of a much larger pool of environmental factors. These factors would include parameters such as sea surface temperatures, chlorophyll concentrations, tides and space weather conditions. We are in the process of expanding our initial space weather and geomagnetic-focused assessment to include a more comprehensive set of environmental factors.

Finally, our team strongly advocates open data and software practices. Both the data and analytical software developed and applied in this paper are available publicly and we hope to encourage further community-wide investigations of cetacean mass strandings. The data and software can be obtained by contacting the primary author of the paper. We also emphasize the need for homogenous cetacean mass stranding data sets. Collection of long homogeneous mass stranding data sets with common data standards is critical for systematic statistical examination of causes for the phenomenon. We recommend establishment of a single international data base that would allow collection, publication and analysis of global cetacean mass strandings.

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A Appendix: Kolmogorov-Smirnov test for geomagnetic conditions associated with cetacean mass stranding events

A.1 Method

For an additional statistical verification if the studied set of cetacean stranding events were associated with changes in geomagnetic conditions, we have applied the two-sample Kolmogorov-Smirnov test. The Kolmogorov-Smirnov test is used to determine if probability distributions of any two data sets, including those obtained from a single set of measurements, differ from each other at a given level of statistical significance.

The time series $\boldsymbol{x} = \{x_1, \ldots, x_N\}$ of daily averages of a studied geomagnetic parameter was divided into two subsets: the set of data points on the days associated with stranding events, and the remaining data used as a reference data set. For this purpose, the set $\boldsymbol{s}$ of shifted time geomagnetic data near the stranding dates were formed from the condition $\boldsymbol{s} = \{t : t - \tau \in T\}$, where T is the list of calendar dates on which animal strandings were recorded, and τ is the time shift. Based on $\boldsymbol{s}$, the set of data points associated with strandings was formed as $\boldsymbol{x_S} = \{x_{t \in s}\}$, while the reference data set was defined as the complement: $\boldsymbol{x_R} = \{x_{t \notin s}\} \equiv \boldsymbol{x} \setminus \boldsymbol{x_S}$. Note that if the time shift $\tau = 0$, the set $\boldsymbol{x_S}$ contains the geomagnetic parameter values on the dates of the stranding events; for a non-zero time shift, it contains the values before or after the standings depending on the sign of τ. The sign choice for the time shifts is the same as for Kullback-Leibler analyses in Section 5.

For the stranding and reference data sets $\boldsymbol{x_S}$ and $\boldsymbol{x_R}$, cumulative distribution functions (denoted correspondingly as F_S and F_R) were calculated. The Kolmogorov-Smirnov measure D_{KS} is defined as the maximum absolute difference between the two cumulative distributions (*Press et al*., 1996):

$$D_{\mathrm{KS}} = max_{-\infty<x<\infty} \mid F_S(x) - F_R(x) \mid \qquad \text{(A.1)}$$

The significance level $p(D_{\mathrm{KS}})$ of an observed value of D_{KS} at which the null hypothesis (that the distributions F_S and F_R are the same) is rejected, is approximated by the formula (*Stephens*, 1970):

$$p = (1 - Q_{KS}\,([\sqrt{N_e} + 0.12 + 0.11/\sqrt{N_e}\,]\,D_{\mathrm{KS}}\,)) \times 100\%, \qquad \text{(A.2)}$$

where $Q_{KS}(\lambda)$ is a monotonic function with the limiting values $Q_{KS}(0) = 1$ and $Q_{KS}(\infty) = 0$ given by

$$Q_{KS}(\lambda) = 2\,\sum_{j=1}^{\infty}(-1)^{j-1}\,e^{-2j^2\lambda^2}, \qquad \text{(A.3)}$$

and $N_e = N_S N_R/(N_S + N_R)$ is the effective number of data points, and N_S and N_R are the sizes of the $\boldsymbol{x_S}$ and $\boldsymbol{x_R}$ data sets, correspondingly.

For practical purposes, the infinite sum in (A.3) is truncated to attain a required numerical accuracy ε measured by the ratio of the last to the last but one term. The first term of the sum yields a simplified expression $Q_{KS} \approx 2e^{-2N_e D_{KS}^2}$, which is commonly used when the compared samples are large, with the caveat that the accuracy depends on N_e. Since the effective number of points varied significantly across our tests, we used a more robust adaptive approach in which a fixed numerical accuracy ($\varepsilon = 0.001$) was attained by adjusting the necessary number of summation terms which varied from test to test.

A.2 Results

To analyze causal relationships between the cetacean mass stranding events and geomagnetic conditions, the Kolmogorov-Smirnov methodology described above was applied to the daily averaged values of *Kp*, *Dst*, and *AE* geomagnetic indices, as well as daily averages of absolute values of one-minute time differences of the horizontal components of ground geomagnetic perturbations recorded at OTT, FRD, EYR and ESK geophysical observatories. The aggregation of the geomagnetic data over the one-day time scale reflecting the resolution of the stranding data was necessary to avoid oversampling which can lead to erroneous results (*Lazic and Stanley, 2009; Chicheportiche and Bouchaud, 2012*) due to the presence of heavy distribution tails and intraday autocorrelations in the geomagnetic data (see e.g. *Pulkkinen et al., 2006; Wanliss and Uritsky, 2010* and references therein).

Figure A.1 shows the application of the Kolmogorov-Smirnov analysis to the synthetic *AE*-index data used to demonstrate the performance of the Kullback-Leibler technique in the main section of the paper (Fig. 5). The short-term correlations present in the studied data set are evident from the peak of the D_{KS} at 0-1 day time shifts. The second plot represents a similar dependence for the Kolmogorov-Smirnov *p*-value (Eq. (2)), which approaches 100 percent for the range of the time shifts corresponding to the D_{KS} peak. This combination of signatures indicates that the synthetic *AE*-index correlates with the stranding data at a high level of significance.

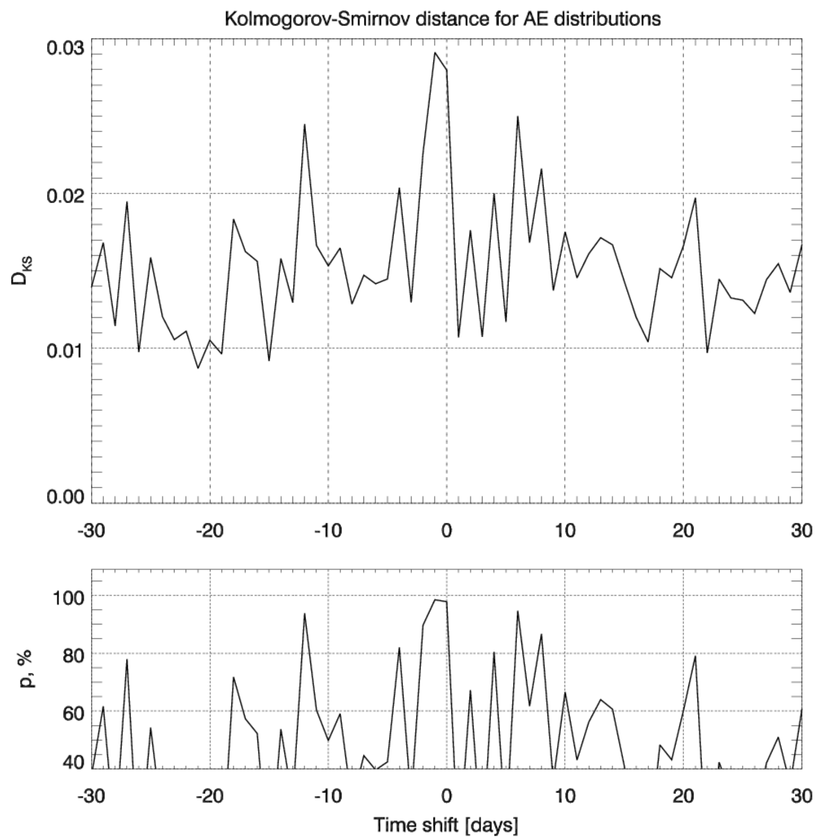


Figure A.1: Kolmogorov-Smirnov distance (top) and significance level (bottom) of synthetic AE-index data conditioned with the stranding events in Cape Cod. See the text for details.

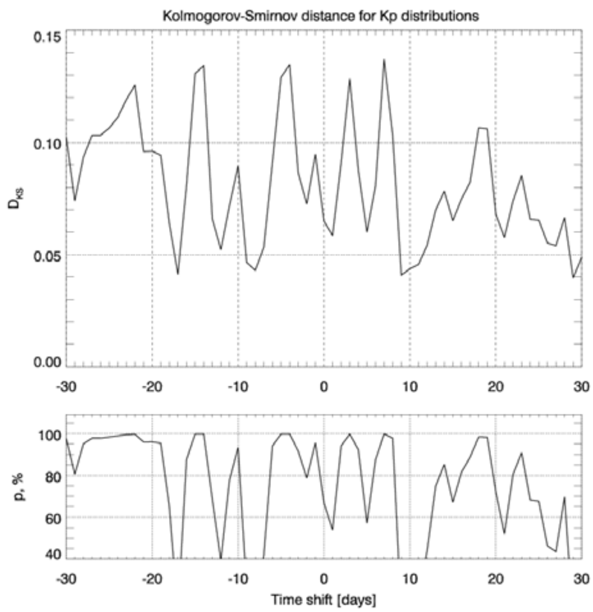
Figures A.2, A.3 and A.4 show the Kolmogorov-Smirnov versions of Figs. 12, 14 and 15, correspondingly, which report the results of the Kullback-Leibler analysis in the main part of the paper.

Figure A.2 shows the absence of clear statistical dependence between the Cape Cod stranding events and the three studied geomagnetic indices. Figure A.3 shows similar findings for the local observations at OTT and FRD. Both measures of the Kolmogorov-Smirnov analysis, D_{KS} and p-value demonstrate significant variability for the time shifts ranging from -30 to 30 days, without revealing any systematic dependence on τ which would indicate a causal link between the stranding events and the geomagnetic conditions. In particular, no noticeable peaks of D_{KS} and p were observed at $\tau = 0$ for any of the studied parameters. Also, no reproducible local or global maxima are seen within a reasonable range of negative τ shifts. With the time shifts extended to -730 to 730 days, the same seasonal dependence between Cape Cod fresh mass strandings and local geomagnetic field observations at OTT and FRD to that in Section 5 was discovered. Further, the peak statistical association takes place with about with -50 day time shift. The Kolmogorov-Smirnov analysis of the Cape Cod data thus fully supports the results obtained in Section 5.

Similar statistical results – the absence of consistent D_{KS} and p-value peaks at $\tau = 0$ or small negative time shifts – were obtained for the stranding events in the United Kingdom and New Zealand (Figure A.4). It should be noted that in some cases, the Kolmogorov-Smirnov confidence level can approach 100 percent signaling that the stranding-conditioned and reference data sets have distinct probability distributions. However, given the strong fluctuations in the confidence level as a function of the time shift, this is rather an indication of the "noise" in the analysis (discussed in Section 5) than sign of actual difference in the statistical distributions. The Kolmogorov-Smirnov results indicating association between the two kinds of data most likely results from a combination of sparse stranding event reports with seasonal trends and does not provide evidence for a cause-and-effect link between the geomagnetic disturbances and fresh mass strandings. In conclusion, the conducted Kolmogorov-Smirnov analysis suggests that the changes in the geomagnetic environment have no clear causal connection with the stranding events.

a)

b)



c)

d)

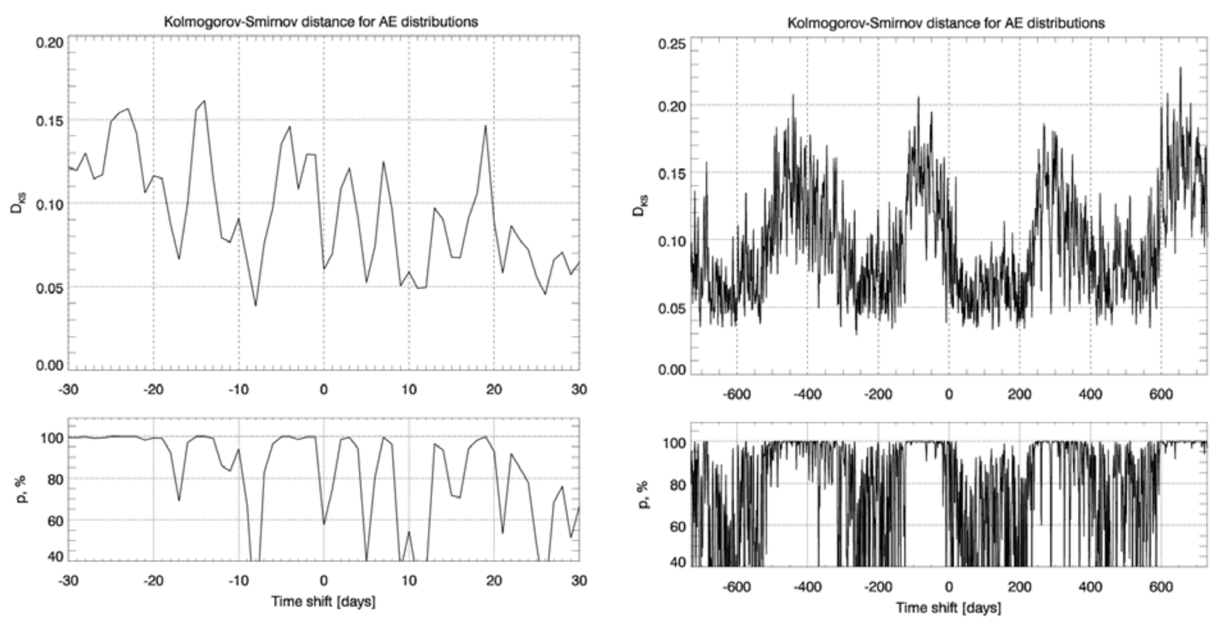


Figure A.2: Statistical analysis results for the Cape Cod data set. Panel a) Kolmogorov-Smirnov distance and significance level for the Kp-index. Panel b) Kolmogorov-Smirnov distance and significance level for the Dst-index. Panel c) Kolmogorov-Smirnov distance and significance level for the AE-index. Panel d) Same as panel c) but for time shifts ranging from -730 to 730 days.

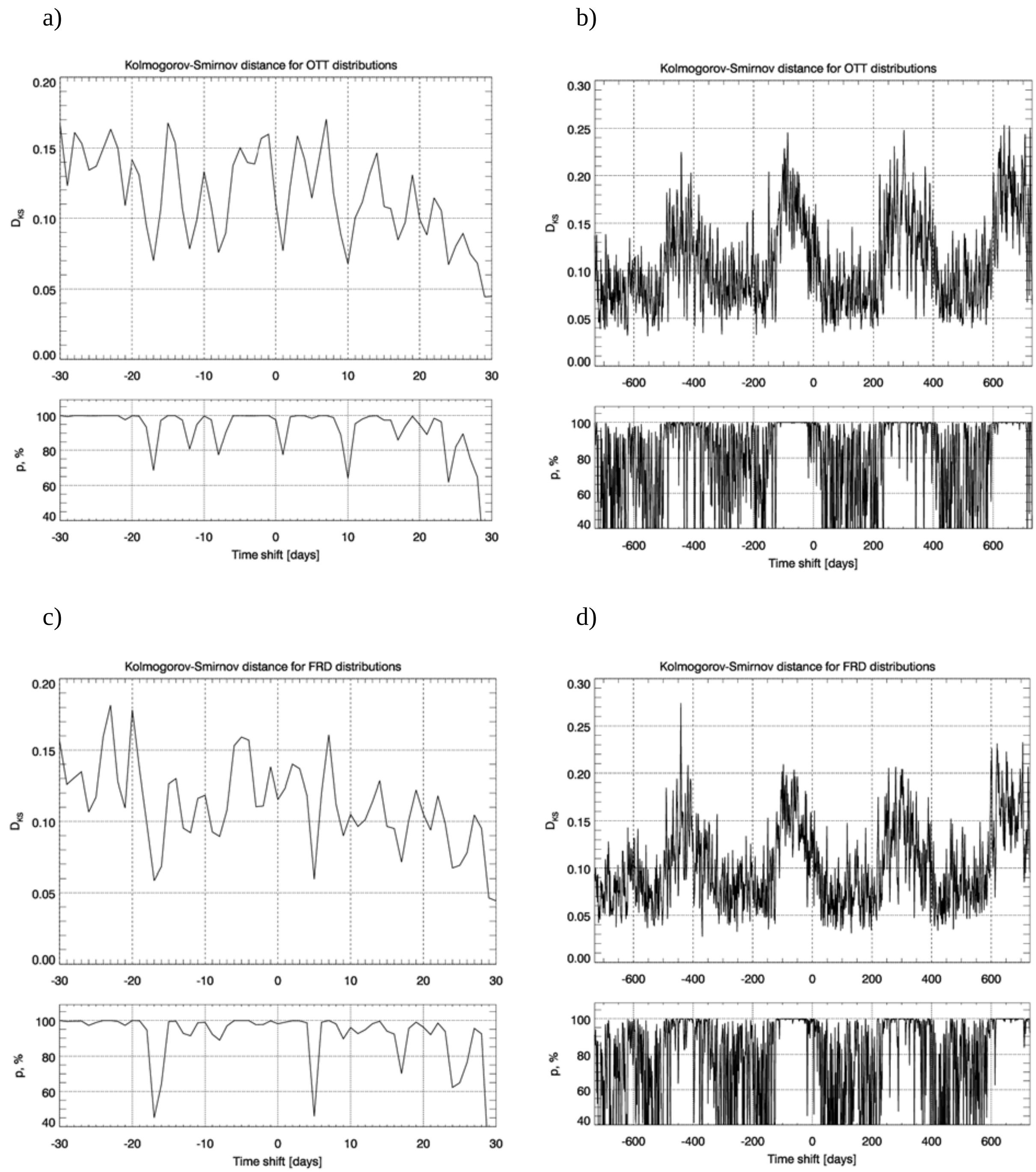


Figure A.3: Statistical analysis results for the Cape Cod fresh cetacean mass stranding data set. Panel a) Kolmogorov-Smirnov distance and significance level for the OTT observations. Panel b) Same as panel c) but for time shifts ranging from -730 to 730 days. Panel c) Kolmogorov-Smirnov distance and significance level for the FRD observations. Panel d) Same as panel c but for time shifts ranging from -730 to 730 days.

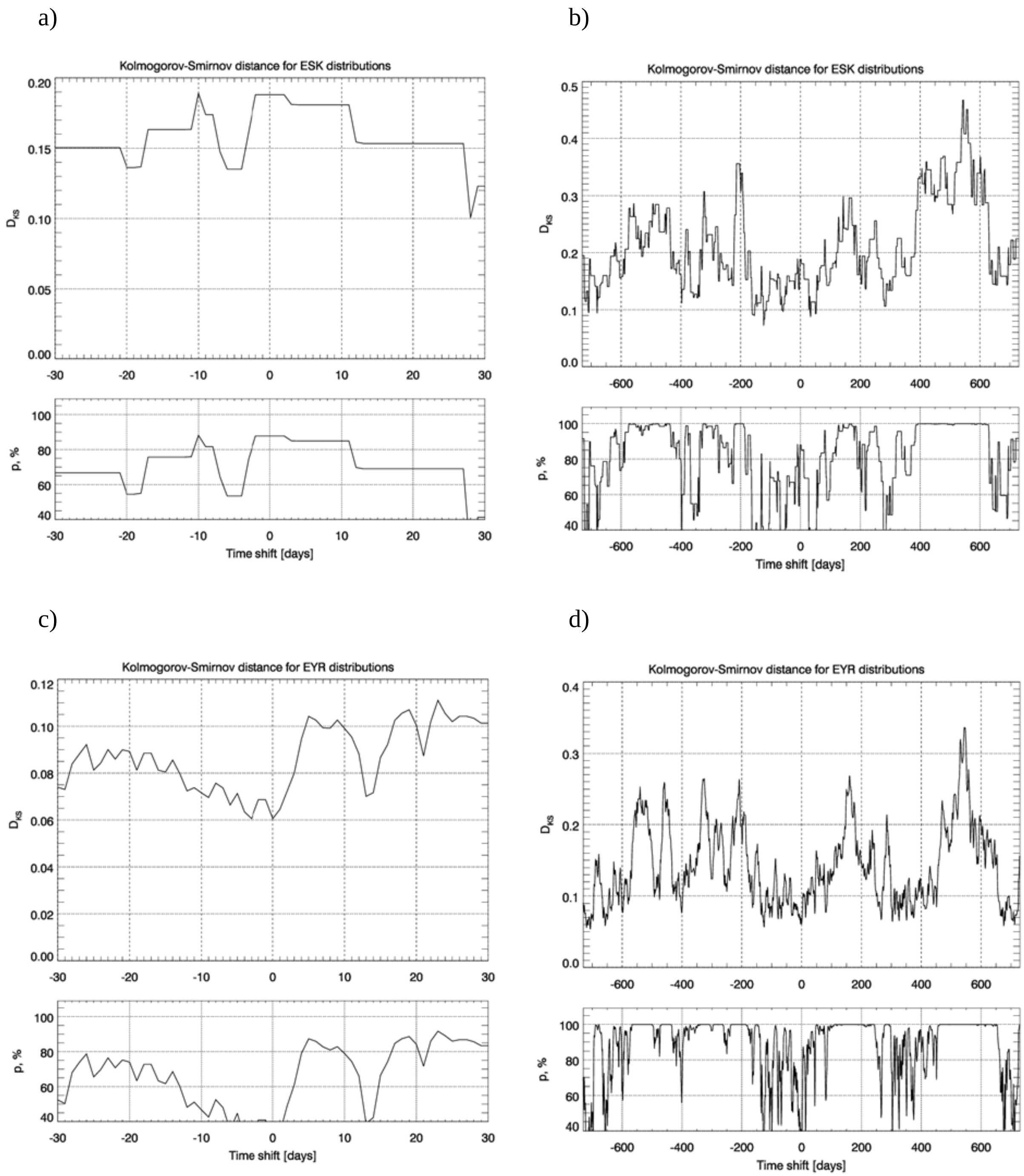


Figure A.4: Statistical analysis results for the United Kingdom (panels a and b) and New Zealand (panels c and d) Cod fresh cetacean mass stranding data sets. Panel a) Kolmogorov-Smirnov distance and significance level for the ESK observations. Panel b) Same as panel a but for time shifts ranging from -730 to 730 days. Panel c) Kolmogorov-Smirnov distance and significance level for the EYR observations. Panel d) Same as panel c but for time shifts ranging from -730 to 730 days

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

The Bureau of Ocean Energy Management

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.

The BOEM Environmental Studies Program

The mission of the Environmental Studies Program (ESP) is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments.