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Solar Driven Geomagnetic Anomalies and Sperm Whale (*Physeter macrocephalus*) Strandings Around the North Sea: An Analysis of Long Term Datasets

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Abstract: To stimulate the discussion about possible reasons for whale strandings, we suggest solar driven geomagnetic variations as one further explanation for this phenomenon. Following this hypothesis that whales may strand due to geomagnetic disturbances we compared annual means of stranding event numbers of sperm whales (*Physeter macrocephalus*) along the North Sea coasts with yearly averaged numbers of geomagnetic anomaly intensities (aa-indices). Based on a Generalised Additive Model technique, our new approach suggests that over the last 400 years 20% of the stranding events can be correlated with aa-index variabilities. Furthermore, the increased stranding numbers of the last decades could be explained by the exceptional intensive disturbances of the earth's magnetic field in the same period.

Keywords: Strandings, sperm whales, sun spot cycle, solar activity, geomagnetic anomalies, temperature anomalies, North Sea.

INTRODUCTION

Cetacean and especially sperm whale (*Physeter macrocephalus*) strandings are at anytime spectacular events of great human interest. Around the North Sea they have been comparably well documented for centuries. The high number of reported sperm whale strandings at the end of the last century seems to indicate that the frequency of these events increased. Anthropogenic encroachments such as contaminants or intensive sound disturbances which derange the natural behaviour of the cetacean, have been considered to be a cause (e.g. [1, 2]), while other authors like Smeenk [3] have discussed the fact that an increasing number following the ban of sperm whale hunting in the last century may have resulted in a rising number of strandings. A detailed overview about a large number of possible beaching causes is given e.g. by [1-4]. In order to stimulate the discussion about backgrounds of strandings, we focus on a different possible reason for this phenomenon without diminishing the other legitimate reasons.

Life on earth is influenced significantly by climate. Climate is driven strongly by the energy provided by the sun [5, 6]. Furthermore, the energy flux from the sun undergoes changing activities and periodicities. Best known are the 27-day rotation period of the sun, the 11-year Schwabe sun spot cycle, the 22-year Hale magnetic cycle and the 80-90-year Gleisberg cycle [7]. Over the last decades new findings were published, showing further relations between solar activity, earth climate and possible effects on whale strandings. To introduce the background leading to the assumptions of this paper a listing of some correlations between solar activity and climate on earth in terms of possible reasons for whale strandings due to solar activity is given as follows.

Labitzke & van Loon [8-10] found a strong coupling between atmospheric parameters (e.g. prevalence of easterly or westerly winds in late northern winter) and the 11-year solar cycle. They showed that changes in UV radiation of up to 10% between solar maximum and minimum within the 11-year solar cycle can influence stratospheric variations in the total ozone concentration as well as in the wind and temperature conditions which can have effects down to the Earths surface climate. Shindell *et al*. [11] demonstrated this likewise by modelling solar cycle variability (especially the 11-year oscillation), and ozone concentration variations which triggered climatic effects. They concluded that solar cycle variability affects earth surface winds and air pressures and may play a significant role in regional surface temperatures. Friis-Christensen & Lassen [12] found a close relationship between solar cycle length and earth's surface temperature in the northern hemisphere over the last 130 years. Reid [13, 14] described a correlation between the 11-year running mean of the sun spot numbers and sea-surface temperature anomalies in all three major ocean basins. Numerical experiments by Weng [15] using a nonlinear approach demonstrate that the 11-year solar activity could be the cause for regional sea surface temperature (SST) variations. Based on modelling results and diatom proxies Jiang *et al*. [16] suggest a link between solar forcing and natural climate variability. For the last 2000 years their data evaluation for the northern North Atlantic realm shows correlations between the SSTs and irradiance at statistical significant levels. White & Cayan [17] found periodicities in the global ocean temperature variability with durations comparable to the Hale and Schwabe cycles of the sun. Many of these presented relationships were discussed in a

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review by Tsiropoula [7]. He concluded that the variabilities in sun activities are reflected in the earth climate even though some physical mechanisms are still insufficient known.

In addition to the fact that the sun affects the physical world, physical environmental changes (e.g. day and night, seasonal effects, changes in temperature etc.) in numerous ways can influence biological behaviour and processes on earth. So, *a priori*, it can not be excluded that, although some aspects of whale strandings are currently not understood and many explanations have been proposed [1, 3, 18, 19], fluctuations in solar activity to a certain extent either directly (e.g. disturbance of the magnetic sense) or indirectly can lead to strandings of cetaceans and especially of sperm whales.

For sperm whales in the North Sea Pierce *et al.* [4] found a relation of 8.8% between strandings and positive temperature anomalies. They analysed the same long-term datasets as in this paper using the Generalised Additive Mixed Model. Pierce and co-workers [4] hypothesised that higher temperature anomalies in the waters off southern Norway may result in a shift in prey items of sperm whales into the North Sea and therefore sperm whales may follow those prey items into areas where they are more likely to strand. Especially the preferred prey of sperm whales the boreoatlantic armhook squid (*Gonatus fabricii*) needs further research about its distribution in the deep water off southern Norway at different environmental conditions. They also stated, that mechanisms linking sperm whale strandings and climate are possible but speculative.

Evans *et al.* [19] demonstrated correlative associations of cetacean strandings at beaches of Tasmania and southeast Australia from 1920 to 2002 to the weather cycle phenomenon of the zonal westerly winds. They hypothesised that the colder waters produced by these winds resulted in more nutrient rich areas, likely with higher food contents, closer to the shore, which in turn could result in a shift in cetacean distribution into areas where a higher probability of whale strandings every 10 to 13 years occurs [19]. There are indications that these weather phenomena may also be driven by solar activity [20] with a concomitant influence on the atmosphere, resulting in corresponding winds.

In an earlier paper Vanselow & Ricklefs [21] related the frequency of sperm whale strandings to solar cycle lenghts. Based on a relatively simple statistical approach they showed that over the last three centuries the time series curve for sperm whale strandings around the North Sea [3, 22, personal comm. by Smeenk] and for the smoothed solar cycle length run widely parallel.

According to Georgieva *et al.* [23] many aspects of solar activity can be detected best by deviations of the geomagnetic field. So in our new analysis, we no longer focus only on the relatively abstract parameter 'smoothed solar cycle length' with its typical periods of roughly 11 years (as applied by [21]). Instead, we investigated the degree of correlation between annual stranding frequency and aa-index. The aa-index is a simple planetary geomagnetic activity index [24], derived from measurements from two approximately antipodal observatories. The easily retraceable time series of measured data goes back to 1868 and for modelled data to 1619, respectively [24].

DATA AND METHODS

For the period of the last three centuries all years with observed or predicted minimum sun spot activity (data mainly taken from the internet page ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/maxmin.new; see also [21]) relating to the roughly 11 year sun spot cycle are listed in Table **1**.

Table **1** also includes the actual length of the solar cycles. To reduce 'noise' in the dataset (a solar cycle is determined by observed sun spots, varying over a wide range from roughly 8 to 17 years) and to take into account that two successive, unequally intensive and at reverse solar polarity 11 years 'Schwabe cycles' are part of one superior 22-years 'Hale cycle' [6], we used smoothed cycle length values. Each solar cycle length (L) was calculated as the 1-2-1-weighted average of three subsequent individual periods [21]. The following equation was used (for further explanation see [21]):

$$L121_n = (L_{n-1} + 2 \times L_n + L_{n+1}) \times 4^{-1} \quad (1)$$

Hereby, the smoothed dataset covers the period of the last 27 solar cycles (291 years). The corresponding numbers of sperm whale strandings around the North Sea in the time span of 1712 to 2003 [3, 22, personal comm. by Smeenk] are allocated to these 27 intervals. Solar cycle data from before 1712 are not included, because in the Maunder Minimum (1645 to 1715) with only very few sun spots [6] nearly no solar cycles are determinable.

We defined strandings happening in one short period (e.g. a few days) and around one specific location as one 'stranding event". The limited number of sperm whale sightings around the North Sea reported by Smeenk and others were not included, because these sightings happened mostly during cycles with many strandings, hence, their consideration would not improve the quality of the performed analyses. To calculate the correlation between number of stranding events per year and the annual geomagnetic deviation given by the aa-index we used the wavelet transformation simulated annual indices from 1619-2003 given by Nagovitsyn ([24], data available at: http://www.gao.spb.ru/database/ esai/). Sperm whale stranding data again are taken from Smeenk [3, 22, personal comm. by Smeenk].

Compared to our earlier work [21], where results were based on the comparison of 27 parameter pairs of solar cycle lengths and adequate sums of stranding events covering a period of 291 years, now 385 parameter pairs of annual stranding numbers and geomagnetic anomaly indices are analysed. Moreover, the higher temporal resolution of these 385 parameter pairs allows more insight into processes on shorter time scales.

Generalized Additive Models (GAM) [27, 28] were used to investigate possible relations between stranding events and solar cycle lengths and aa-indices, respectively. All analytical runs were performed with the package 'mgcv' [28, 29] in R 2.4.1 (www.r-project.org) using the quasi-poisson distribution for the analysis related to solar cycles and the poisson distribution for the analysis related to aa-indices. In the analysis we used the variance explained by the adjusted coefficient of determination r^2. For the sake of completeness,

stranding numbers in the second half of the last century in more detail (Table **1**). Applying the GAM analysis on 385 parameter pairs of mean annual aa-indices and temporarily corresponding sperm whale stranding data (1619-2003) results in the smoothed curve presented in Fig. (**2**). It suggests a high probability of whale strandings in years of high geomagnetic deviation. The 95% confidence bands run close and largely parallel to the curve and also the calculated statistical values d.f. = 1.91, the result of the χ^2-test χ^2 = 73.74, $p < 0.0001$ with a adjusted $r^2 = 0.204$ (the proportion of the null deviance explained by the model is 17.5%) document the significant correlation between the two parameters.

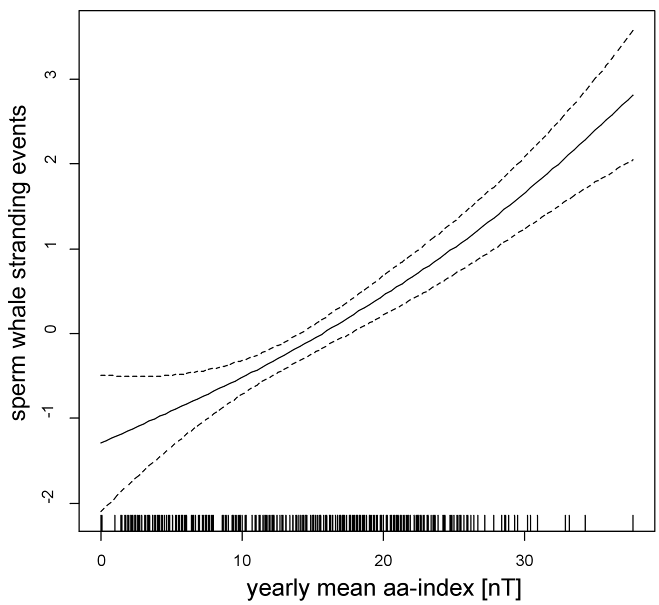

Fig. (2). GAM correlation curve of simulated yearly mean geomagnetic anomalies versus yearly sperm whale stranding events. The dataset covers the period from 1619 to 2003. The aa-index values are given directly as geomagnetic deviations in nT. The dotted lines represent the 95% confidence bands. The ticks on top of the x-axis mark the used aa-index values.

Phase shifts of ±1, 2 and 3 years for the correlation between strandings and yearly aa-index data show an adjusted $r^2 < 0.09$ for all six correlations (data not shown).

DISCUSSION

All performed statistical analyses show that during phases of higher solar activity, either characterised by shorter sun spot cycle lengths or higher yearly mean aa-index values, more sperm whale strandings have been observed along the North Sea coasts. Using the GAM analysis up to an annual resolution and evaluating the whole curve shape in contrast to the interval analysis used by Vanselow & Ricklefs [21], 20% of all sperm whale stranding events around the North Sea can be assigned to the magnitude of the annual mean aa-indices and 22% on the basis of smoothed solar cycle length data.

Especially in the case of the aa-index it is an interesting aspect that whales may use features of the geomagnetic field for orientation [30, 31]. Klinowska [18] and Walker *et al.* [32] reported that magnetic contour lines in the oceans often follow continental margins and whales may take advantage of these ‘invisible lines’ for navigating along their migration routes. The magnitude of these natural geomagnetic field anomalies frequently is of the same order as the disturbances temporarily induced by solar activity [21]. Assuming again that whales actually have a magnetic sense, which is used for orientation along the geomagnetic field lines (possibly by ‘seeing’ the magnetic field as recently hypothesised for migrating birds by Heyers *et al*. [33]), temporal deformations of the natural earth's magnetic field anomalies might cause problems for their navigation ability, because the animals are not able to distinguish between both phenomena. So, up to 20% of the sperm whale strandings around the North Sea could be related to these geomagnetic disturbances quantified by the aa-index values.

This new approach might give a new impulse in the discussion of possible explanations for the significant increase of sperm whale strandings during the past decades (Table **1**). In this context it is essential to state that during the last 60 to 70 years the sun’s activity has been unusually high compared to the last 1000 years [34] or even 8000 years [35]. Correspondingly, high aa-index values have been observed over this period [36]. According to the relation presented in Fig. (**2**) or the simple comparison of Fig. (**3**) the probability of whale strandings should significantly increase in years with high geomagnetic deviances and high aa-indices, respectively.

Fig. (3). Comparison of 10 year averaged aa-index values and 10 year averaged whale stranding events for the period from 1901 to 2000.

The plausibility of this finding gets even more distinct by the fact that other explanations for the high number of sperm whale strandings during the past decades like increasing noise exposure in the oceans due to human activities [37] or a recovery of the sperm whale population after the end of the commercial whaling in the 1980ies [1] were already challenged by Whitehead [38]. Whitehead stated that the sperm whale population size in 1999 was roughly half as big as in 1945, when intensive commercial hunting started. Compared to a pre-whaling value from 1712 the population size in 1999 was even 72 % smaller [38]. This means that around the millennium compared to the past centuries fewer sperm whales were exposed to the risk to end on a North Sea beach. On the other hand it can not be neglected, that there are suggestions that some species of whales, particularly those of the beaked whale family (*Ziphiidae*), may be particularly sensitive to military sonar activities [39, 40].

However, other associations of cetacean strandings to high levels of noise describe coincidental strandings occurring contemporaneously (but not necessarily nearby) to anthropogenic derived noise.

As outlined, solar driven effects might be directly responsible for some sperm whale strandings around the North Sea by disturbing the whales' magnetic sense. However, Georgieva *et al*. [23] showed a close parallelism in the temporal evolution of geomagnetic activity (aa-index) and global temperature anomalies (time series from 1856 to 2000). The close correlation of both parameters poses that temperature, or temperature related effects respectively (e.g. [4]) and/or magnetic anomalies exert influence on a part of whale strandings.

Boberg & Lundstedt [41] suggested a relationship between the electric field strength of the solar wind and the North Atlantic Oscillation (NAO) index. On the other hand, typical meteorological situations influencing sea surface temperature anomalies or even biological processes, like growth rates and distribution patterns of plankton or fish, often can be related to changes of the NAO [42-44]. Zuur & Pierce [45] found a correlation between catches of squid, a potential prey for sperm whales, in the northern North Sea and the NAO for the time window August to November (data from 1970 to 1999). On a more general basis Learmonth *et al*. [46] discussed the effect between climatic implemented SST changes, shifts in prey distribution and the spreading of marine mammal species. They reported e.g. that the distribution of some feeding whales can be predicted by means of the surface temperature values and other bathymetric variables due to their effects on prey availability or that some whale species shift their geographic ranges to tracks preferred or required temperature conditions. According to Evans *et al*. [19], changes in food availability due to cyclic climatic variation can also explain trends in whale strandings. So all this suggests that cetacean strandings are likely to be the result of a complex of many factors, some of which may be more predominant in particular situations, and that it is likely that not one environmental feature is likely to explain all cetacean strandings.

CONCLUSION

Although the statistical correlation between sperm whale strandings and solar cycle length is pronounced, we agree that it might not be easy to accept the biological relevance of such an abstract parameter like ‘smoothed solar cycle length’. However, by the examination of the geomagnetic anomaly (aa-index) a parameter is introduced, which has a relatively high temporal resolution and which physical characteristics can doubtlessly influence animal life (proved e.g. for birds). The relatively close correlation can be considered as a hint for the importance of geomagnetic deviations for whale strandings or also as circumstantial evidence for the general existence of a magnetic sense in whales.

In spite of the fact that our statistical analysis shows a significant correlation of 20% of all data between a pure physical parameter (geomagnetic field variation) and sperm whale stranding event numbers in the North Sea, we nevertheless concur with many other stranding theories, e.g. with the more biologically substantiated hypothesis that shifts in the distribution and abundance of whales’ prey can lead to changes in the whales movement patterns (e.g. [1, 3, 4, 19]). Changes in prey distribution are often due to climatic variation, which can frequently result from astronomical and solar fluctuations. Consequently, it can be difficult to filter out the driving force(s) for whale strandings. However, the next decades may give us the opportunity with the increasing effects of global warming to test whether higher temperature (influenced by man and/or sun) or sun driven geomagnetic anomalies have a consistent effect on the number of strandings. In this context it is noteworthy that the next solar cycles are predicted to be relatively long [47]. This is tantamount to low solar activity compared to the past decades - a phase which was characterised by intensive solar activity and by high numbers of sperm whale strandings around the North Sea.

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