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Are solar activity and sperm whale *Physeter macrocephalus* strandings around the North Sea related?

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Abstract

In the final decades of the last century, an increasing number of strandings of male sperm whales (*Physeter macrocephalus*) around the North Sea led to an increase in public interest. Anthropogenic influences (such as contaminants or intensive sound disturbances) are supposed to be the main causes, but natural environmental effects may also explain the disorientation of the animals. We compared the documented sperm whale strandings in the period from 1712 to 2003 with solar activity, especially with sun spot number periodicity and found that 90% of 97 sperm whale stranding events around the North Sea took place when the smoothed sun spot period length was below the mean value of 11 years, while only 10% happened during periods of longer sun spot cycles. The relation becomes even more pronounced (94% to 6%, n = 70) if a smaller time window from November to March is used (which seems to be the main southward migration period of male sperm whales). Adequate chi-square tests of the data give a significance of 1% error probability that sperm whale strandings can depend on solar activity. As an alternative explanation, we suggest that variations of the earth's magnetic field, due to variable energy fluxes from the sun to the earth, may cause a temporary disorientation of migrating animals.

Keywords: Sperm whale strandings; North Sea; Solar cycles; Sun spots; Geomagnetic storms

1. Introduction

Sperm whale beachings are spectacular happenings of great human interest and so for centuries have been comparably well documented. The high number of reported strandings around the North Sea seems to indicate, especially for male sperm whales, that the frequency of such events increased towards the end of the last century. Anthropogenic encroachments such as contaminants or intensive sound disturbances which disturb the natural behaviour of cetaceans have been considered to be a cause (e.g. Simmonds, 1997; Goold et al., 2002), while other authors, for instance Smeenk (1997), have discussed the fact that the increasing number of sperm whales after the massive

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reduction of hunting in the last century may have resulted in a rising number of strandings. The most recent and detailed overview of possible causes of beaching is given by Goold et al. (2002).

In contrast to the still open question of why sperm whales strand, it is well known that they undertake long and well-directed journeys through the oceans. They seem to have a kind of 'global positioning system' that allows them to find the right and best way through their habitat. On their migration some animals, birds for example, get their bearings from the earth's magnetic field (Phillips, 1996; Kirschvink, 1997; Lohmann and Johnsen, 2000; Walker et al., 2002; Fischer et al., 2003) and it is conceivable that some whales, such as sperm whales, do the same. The magnetic field is available anytime and almost everywhere on the earth's surface, and the animals may take advantage of the global characteristics of the earth's magnetic field as well as of existing local anomalies related to the geological structure of the ocean floor (Klinowska, 1988; Walker et al., 1992).

It is known that solar radiation with its changing flux of ionised particles can temporarily interfere with the earth's magnetic field particularly in geomagnetic storms (Silbergleit, 1999; Burch, 2001). If sperm whales do use the earth's magnetic field for navigation purposes, it seems possible that such interference can lead to their disorientation (Phillips, 1996; Walker et al., 2002).

The energy flux of the sun is not constant and shows periodic variations (Hoyt and Schatten, 1997). One of the best-known cyclicities of the sun's energy flux is related to the number of sun spots. The cycle length of sun spot activity is around 11 years (Burroughs, 1992; Hoyt and Schatten, 1997; Berner and Hiete, 2000). This averaged period is based on observations over three centuries; the single periods vary from 8 to 17 years (Hoyt and Schatten, 1997). The energy radiated by the sun is approximately inversely proportional to the period length of sun spot activity. Short cycles imply intervals of high energy radiation and longer solar cycles have periods of lower energy flux. An illustration of this possible relation is given by Berner and Hiete (2000, e.g. their Fig. 2.8). A phase of low radiation from 1780 to 1910 correlates well with a period in which very few sperm whale strandings were documented (Smeenk, 1997). This observation leads to the question of whether sperm whale beachings around the North Sea can be correlated with sun spot activity and its effects on the earth's magnetic field. In this study we analyse to what extent strandings are related to solar activity and attempt to find alternative explanations for strandings.

2. Material and methods

The frequency of strandings of sperm whales (*Physeter macrocephalus*) around the North Sea was taken from Smeenk (1997, 1999, 2004 unpubl. data) and one report on a sperm whale beaching in 1848 on the island of Borkum (Germany) was added.

In general, we distinguish between "strandings" and "stranding events" around the North Sea. While the first term takes into account the number of beached individuals, the latter does not. Since sightings happen mostly during phases with many strandings, both values are highly correlated. So an additional consideration of the limited number of sperm whale sightings (e.g. Smeenk, 1997, 1999, 2004 unpubl. data) leads to no substantial improvement of the database.

Since the coasts of the North Sea have always been relatively densely populated, there is a good prospect that local people will have detected a high number of stranding events of these huge animals (Evans, 1997). The countries around the North Sea have a long tradition of records in written documentation of events of public interest, and we think that this very large dataset is good enough to be taken into account, although Smeenk (1997, 1999) rightly stresses that the past is decidedly underreported as compared to the present.

The cycles in sun spot activity are derived from the number of sun spots. These have been listed since 1712 (after the Maunder Minimum with nearly no sun spot activity) as shown in Fig. 1. At least over these three centuries the number of sun spots varies periodically with a mean cycle length of around 11 years. This solar cycle is called the 'Schwabe cycle' (Hoyt and Schatten, 1997) but for reasons of simplicity we shall call it the 'solar cycle'. The data used in this study are taken from the Internet page ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/maxmin, also described by NASA (2000) and for the last cycles from Thejll's Internet page

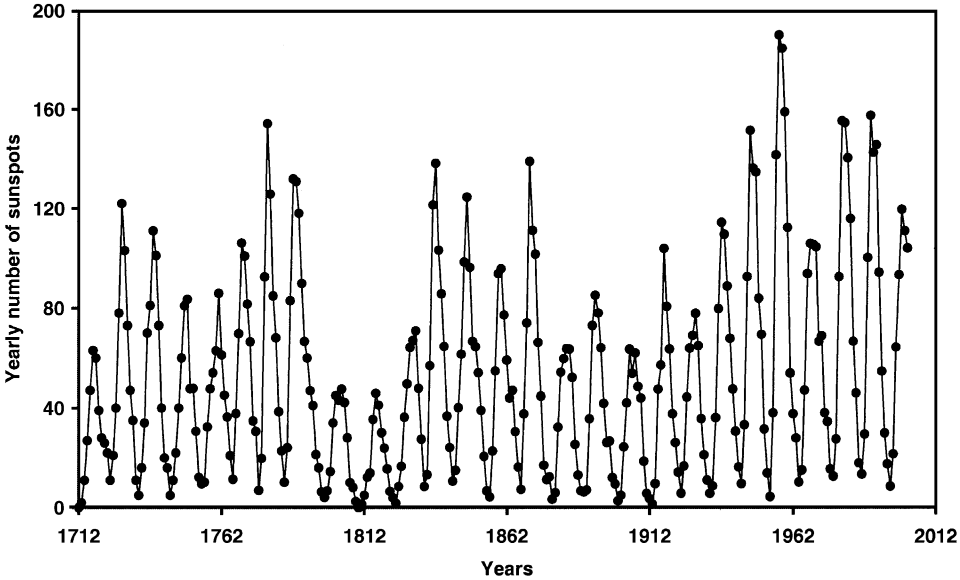

Fig. 1. Solar activity as yearly observed number of sun spots (circles, created by the Wolf or Zurich sun spot numbers R_Z) since 1712 (after Hoyt and Schatten, 1997).

(http://web.dmi.dk/fsweb/solarterrestrial/sunclimate/SCL.txt), which refers to Friis-Christensen and Lassen (1991), Lassen and Friis-Christensen (1995) and Thejll and Lassen (2000). Here the cycle length is determined from one sun spot minimum to the next.

To avoid noise effects the length of each single solar cycle (L) was calculated as the 1-2-1 weighted average of three subsequent individual periods, using the following equation:

$$\mathrm{L121_n} := \left(\mathrm{L_{n-1}} + 2 \times \mathrm{L_n} + \mathrm{L_{n+1}}\right) \times 4^{-1}$$

A further motivation to use a smoothed cycle length is that the 11-year ‘Schwabe cycle’ is part of the 22-year ‘Hale cycle’ (Burroughs, 1992; Hoyt and Schatten, 1997; Schatten, 2003). This cycle is related to the so-called ‘solar dynamo’ theory which expresses a reversal of the solar magnetic field roughly every 11 years and so a direct coupling of two successive ‘Schwabe cycles’ to one ‘Hale cycle’.

To incorporate the recent strandings into the dataset it is necessary to include and to smooth the period of the still ongoing 27th sun spot cycle, which will continue until 2006 (Sello, 2003). For the smoothed 27th cycle, a duration of at most 10.25 years has been calculated assuming that the predicted 28th cycle will last from 2006 to 2016 (Schatten, 2003; Sello, 2003) with a cycle length shorter than 10.8 years. Please note that Sello and Schatten start their cycle series at 1755, so their ongoing 23rd cycle is identical to our 27th cycle starting with the first cycle in 1712. For the analysis it is only important that the smoothed 27th cycle stays below 11 years.

To compare the sperm whale beachings of the past 291 years around the North Sea with sun spot activity, 27 smoothed 11-year cycles, covering the period from 1712 to 2003, were considered. The sperm whale strandings are classified by the original solar cycle lengths from one minimum to the next and evaluated against the solar activity given by the smoothed solar cycle lengths. The analyses were performed using two different time windows. One takes into account all stranding events throughout the year and the other one only those during the main north-south migration period of male sperm whales, which in the North Atlantic lasts from November to March (N-M).

To have an idea of a ‘reference interval’ for sperm whale strandings with very low solar sun spot activity we can use the Maunder Minimum from 1645 to 1715 with only a few sun spots (Hoyt and Schatten, 1997) and a totally unexploited sperm whale population. In this time window of 70 years, only 10 single sperm whale beachings are known (Smeenk, 1997). Assuming that this low number is not completely unrealistic in relation to our long-term analysis this would mean only one beaching every 7 years or 0.143 strandings per year.

The actual data interpretation was done by percentage calculations of different datasets and by using the Chi-square test for 2 × 2 tables in accordance with Sachs (1992) to facilitate the interpretation.

3. Results

3.1. When do sperm whales strand?

Fig. 2 presents the temporal distribution of the number of sperm whale strandings and sightings added for each solar cycle as well as the smoothed length (L121) of the solar cycle length considered. The time axis is given in terms of cycle number 1 to 27 covering the period from 1712 to 2003. The smoothed period length is plotted inversely to demonstrate more clearly that with shorter periods of sun spot activity, the solar energy flux becomes more intensive.

The time interval from cycle 9 to 19 in Figs. 2 and 3 coincides with the period 1785 to 1913 with nearly no sperm whale strandings. This seems to be consistent with the solar cycle length, which is longer than 11 years for this time window.

Fig. 2 also shows the stranding data since 1913 for the shores of Scotland, England, Wales and Ireland reported by Goold et al. (2002). The curve runs parallel to that from the North Sea strandings, which means that it adds no further information to our analyses but shows the good quality of the North Sea data collected by Smeenk (1997, 1999) in connection with solar cycles.

Fig. 3 shows nearly the same pattern as Fig. 2 but only for sperm whale stranding events. All curves in Figs. 2 and 3 show similar characteristics. The curve for the stranding frequency can be divided fairly clearly into phases in which the solar cycle period is shorter or longer than the mean cycle length of 11 years. It turns out that 87 of the 97 (90%) stranding events around the North Sea happened within the

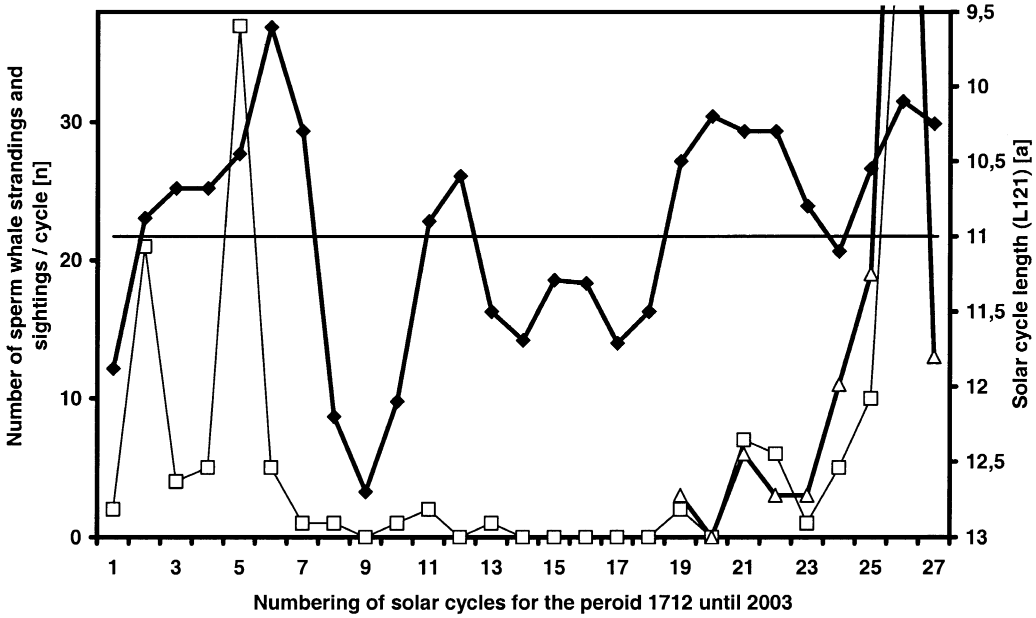

Fig. 2. Sperm whale strandings and sightings between 1712 and 2003. The thin curve with open squares shows all strandings and sightings around the North Sea (see the left axis, the value for cycle 26 is 50 and for cycle 27 is 56). The curve with open triangles gives the stranding raw data from the shores of Scotland, England, Wales and Ireland by Goold et al. (2002) (see the left axis, the value for cycle 26 is 74). The smoothed solar cycle length values (filled diamonds) refer to the axis on the right side. They vary around the solar cycle mean value of 11 years (horizontal line). The cycles in the time axis are given by the sun spot periods.

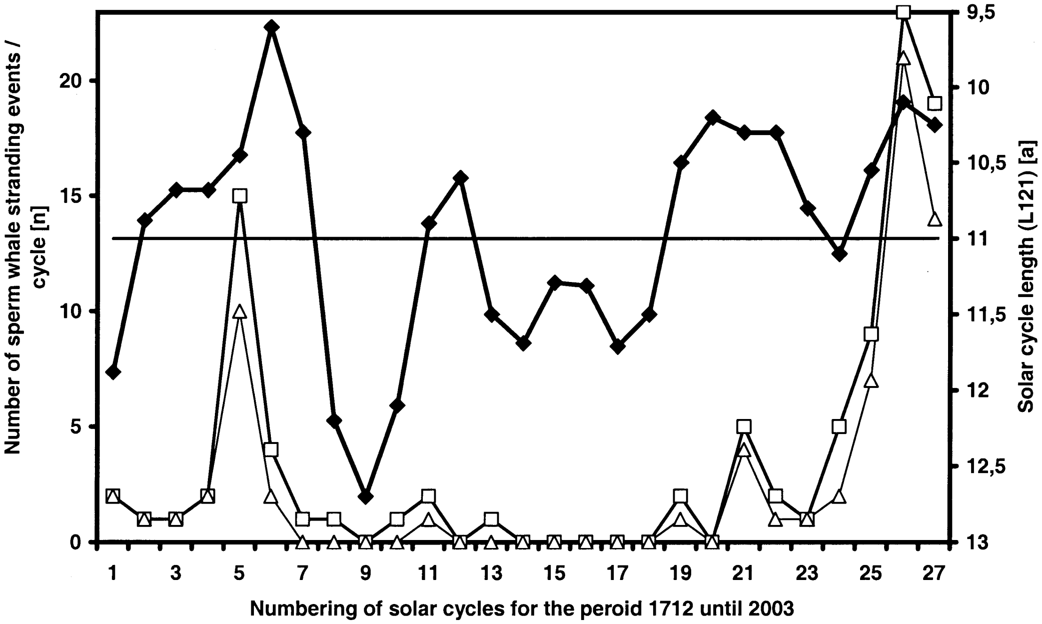

Fig. 3. Sperm whale stranding events between 1712 and 2003. The two thin curves with open squares for all strandings and with open triangles for those events from November to March refer to the left axis. Further descriptions see legend of Fig. 2.

shorter cycles, and only 10 events (10%) during longer cycles. For strandings and sightings in Fig. 2 the values reach 95% to 5%. Applying a shorter time window from November until March, which seems to be the main migration period southwards of the male sperm whales in the North Atlantic, results in 66 of the 70 stranding events (94%) in Fig. 3 happening within the shorter cycles. Only 4 beaching events (6%) were recorded during cycles with a duration of more than 11 years.

In order to check whether these relations may have been caused by the data smoothing, we have also compared the stranding numbers with the actual, rather than smoothed, cycle lengths. This shows that 72 of the 97 stranding events (74%) happened at cycle lengths shorter than 11 years, and 25 events (26%) happened within longer solar cycles. Taking the 70 stranding events in the time window from N-M, 56 (80%) of these events occurred within the shorter cycles, and 14 (20%) within longer cycles. Although in this analysis the relation between strandings and sun spot activity is not so pronounced, it still clearly reflects our findings.

A comparison of sun spot activity in terms of cycle length and sperm whale strandings is given in Fig. 4. The graph shows an apparent relation between the length of solar cycles and the number of events. Most strandings can be found at a period length of approximately 10.4 years, whereas the number of events is lower during shorter and longer cycles.

3.2. When do sperm whales not strand?

If we consider cycles with no strandings (Fig. 4) a clear difference emerges between short and long cycles. There are only two out of 16 cycles shorter than 11 years in which no strandings were documented. This is 12.5%, much lower than the 55% calculated for the longer cycles. Here six out of 11 cycles are ‘zero event cycles’. Conversely, this approach results in a value of 87.5% (14 out of 16 cycles) for stranding events which happen within cycles of less than 11 years. Of the cycles longer than 11 years, only 45% have sperm whales strandings (5 out of 11 cycles). Repeating the analysis of the dataset for the time window N-M results in very similar values.

Treated purely statistically ‘zero event cycles’ should be rather rare. Spreading all 97 stranding

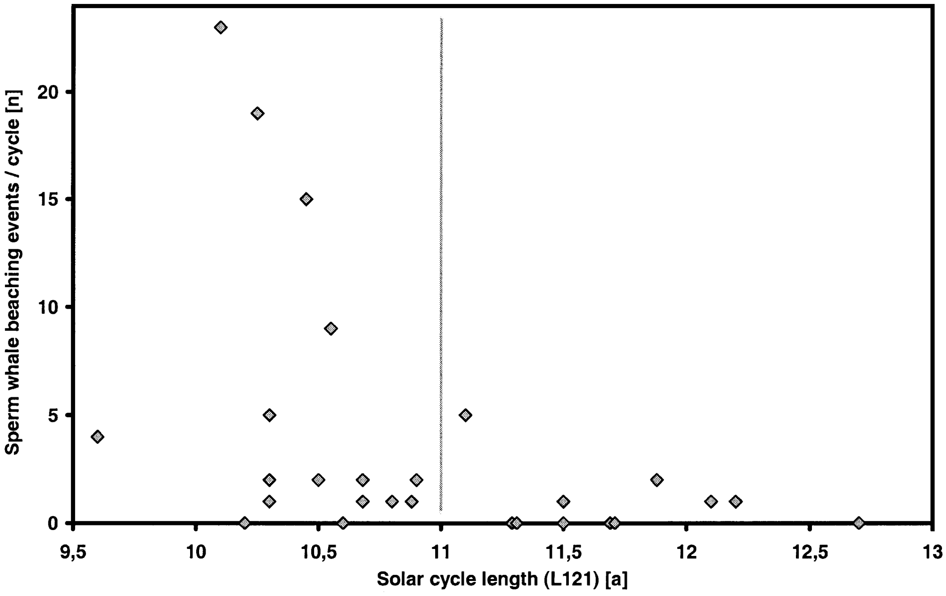

Fig. 4. Coherence between the smoothed solar cycle length (L121) and the number of sperm whale stranding events. The vertical line represents the mean cycle length of 11 years. When two identical numbers of events occurred at the same cycle length, the period duration has been slightly varied by 0.02 years to make all data points visible.

events evenly over the 27 solar cycles of the past 291 years results in approximately 3.6 strandings per cycle (for the time with sun spot activity). Related to the actual cycle length this number shifts to approximately 3.1 (3.6 * 9.5/11; 11 = mean cycle duration) for a 9.5-year cycle, and to 4.3 (3.6 * 13/11) for a 13-year cycle. This means that there should be significantly more zero events (fewer strandings) during shorter cycles. As shown before this is not the case. In fact more whales managed to keep clear from the North Sea coast when the cycle length was above the mean of 11 years.

3.3. Verifying the stranding hypothesis by the Chi-square test

A further approach to show a possible relation between strandings and solar cycle length is to use the Chi-square test for 2 × 2 tables. In the 2 × 2 table we distinguish between cycles shorter than 11 years and those longer or equal to 11 years. For these two groups we also distinguish between cycles with a number of strandings > or ≤ a given threshold value “n”. In this analysis it is not substantial if there are only two strandings or a much higher number of beachings within a cycle if the “n” is set to one. So the very high stranding values of the last two cycles (26 and 27) do not carry more weight than other ones.

It is very difficult to say how many sperm whale strandings happen within 11 years without solar influence. The possible reference interval during the Maunder Minimum with nearly no sun spots gives a value of 1.6 strandings for the mean solar cycle (0.143 * 11; see Material and methods). Otherwise the mean value of strandings for 11 years can be calculated over the 27 cycles in the 291 years including the Maunder Minimum of 70 years to 3.26 strandings ((107/361) *

Table 1
Chi-square test for the 2 × 2 table to proof the coherence between strandings and solar cycle length

Strandings over the whole year	Number of cycles with strandings n > 3	Number of cycles with strandings n ≤ 3	Sum
L121 < 11 years	10	6	16
L121 ≥ 11 years	1	10	11
Sum	11	16	27

Chi-square = 7.70, error probability = 0.0055. Same table values are given for n = 2.

Table 2
Chi-square test for the 2 × 2 table to proof the coherence between strandings and solar cycle length

Strandings over the whole year	Number of cycles with strandings $n > 1$	Number of cycles with strandings $n \leq 1$	Sum
L121 < 11 years	12	4	16
L121 ≥ 11 years	2	9	11
Sum	14	13	27

Chi-square = 8.43, error probability = 0.0038.

11) if there is no coherence expected. However, we tested the association of increasing number of strandings n with shorter period solar cycles for $n > 3$ in Table 1 and $n > 1$ in Table 2.

Using the Chi-square test method as given by Sachs (1992, Eq. 4.41a, here N (=27) is replaced by N-1 for small N) we prove with a 1% error probability the assumption that the strandings can depend on the length of the solar cycle. The relation between the length of a sun spot cycle and the number of whale strandings in Tables 1 and 2 is good but becomes still more pronounced if only the strandings from the main migration period southwards (N-M) of male sperm whales are used. The hypothesis is verified only for strandings in the N-M time interval by the Chi-square test. The criterion for sun-influenced strandings is selected as $n > 2$ and $n > 0$ considering the number of strandings within 5 months per year must be fewer than for 12 months ($3.26 * 5/12 = 1.36$).

The analyses of the data from Tables 1–4 support the hypothesis that sperm whale strandings above a defined stranding level can probably be associated with solar cycle length. This means that the frequency of sperm whale strandings is significantly higher for cycles shorter than 11 years than for longer ones. The values of Tables 1–4 were also verified by Fisher's exact test and the results likewise hold for the 1% error probability level.

Table 3
Chi-square test for the 2 × 2 table to proof the coherence between strandings and solar cycle length

N-M strandings	Number of cycles with strandings $n > 2$	Number of cycles with strandings $n \leq 2$	Sum
L121 < 11 years	10	6	16
L121 ≥ 11 years	0	11	11
Sum	10	17	27

Chi-square = 10.92, error probability < 0.0016.

Table 4
Chi-square test for the 2 × 2 table to proof the coherence between stranding events/strandings and solar cycle length

N-M strandings / stranding events	Number of cycles with strandings $n > 0$	Number of cycles with strandings $n = 0$	Sum
L121 < 11 years	13	3	16
L121 ≥ 11 years	2	9	11
Sum	15	12	27

Chi-square value of 10.5, error probability < 0.0016. The table data are the same for strandings and stranding events.

4. Explanations and discussion

Our results indicate a possible relation between the length of solar cycles and strandings of sperm whales around the North Sea for the last three centuries. The findings in this study, while statistically convincing, are not proven beyond doubt, because the dataset consists of only 27 solar cycles and a limited number of sperm whale beachings over the 291 years of observations.

Although this study does not focus on the discussion of whether sperm whales have a 'magnetic sense' of orientation, we would like to consider some aspects of this question. The results of various studies (Kirschvink, 1997; Walker et al., 2002) give evidence that at least some whale species use features of the earth's magnetic field to find their way through the oceans (Walker et al., 1992) or are misled by geomagnetic anomalies (Klinowska, 1988). As Walker et al. (2002) also explained only very small intracellular particles are needed to achieve the required magnetic sensitivity. Magnetically sensitive cells have been found in the visual system of birds (Lohmann and Johnsen, 2000; Wiltschko et al., 2002) and small amounts of magnetite were detected in the heads of common Pacific dolphins (*Delphinus delphis*) (Zoeger et al., 1981). This may explain why up to now no specific region of magnetic sensitivity has been detected in whales.

Temporary disturbances of the geomagnetic field due to sun spot activity are well known. The sun's influence on the magnetic field of the earth is most intense in the high polar latitudes. In geomagnetic storms, the strength of the earth's magnetic field can locally vary over a range of some hundreds of nano Tesla (nT) (Silbergleit, 1999; Burch, 2001). Such variations, with typically rapid changes at the beginning and a slow decay over one to three days, are of the same order as spatial variations of the geomagnetic field (Semm and Beason, 1990; Walker et al., 1992, 2002; Fischer et al., 2003). Moreover, the intensity of some hundreds of nT is far above the magnetic threshold sensitivity of 10 to 50 nT that has been shown experimentally in homing pigeons, and is also known in sharks and whales (Walker et al., 2002). Therefore it cannot be ruled out that rapid and very intense changes of the local geomagnetic field, albeit induced by astronomic processes, are misinterpreted by the animals as relevant routing information. This type of interference in the detection of magnetic fields has already been proved for pigeons (Phillips, 1996; Walker et al., 2002). The presence of geomagnetic storms not only leads to navigation problems of homing pigeons but also to difficulties in technical exploitation of the Earth's magnetic field.

As already mentioned, over the last 291 years sun spot activity has followed a distinct cyclic pattern. This pattern is described by solar cycles ranging in periods from 9.5 to 13 years during the shorter cycles in which the geomagnetic storm intensity, and therefore the temporary disturbance of the geomagnetic field, increases. On the basis of different data sets several authors (Hoyt and Schatten, 1997; Fligge et al., 1999; Solanki and Fligge, 1999) identify in more detail an increase of solar energy flux starting at longer cycle lengths towards periods somewhat below the mean of 11 years. A proxy of solar activity given by the global wavelet power calculated from the Zurich sun spot numbers R_z by Fligge et al. (1999) shows its maximum at a mean period of 10.7 years. Around this maximum the intensity remains at a relatively high level. For shorter cycles, tantamount to even higher numbers of sun spots, the solar energy flux decreases again.

As cycle periods from 13 to 9.5 years show a clear coupling between solar energy flux and geomagnetic storm activity and temporary geomagnetic anomalies, respectively, it can be assumed that the possible decrease of energy flux at very short solar cycles could also result in a less intensive disturbance of the geomagnetic field. This may explain the low number of reported strandings for the shortest cycle of the dataset (Fig. 4).

The presented coherencies of the solar energy flux and the number of sperm whale beachings seem to show clearly that biological phenomena can be related to astronomical processes. However, persistent regularities can be of abiotic nature, as outlined above, but also of biotic origin. Regularities that are inherent in the animals for instance allow some birds species to switch to a different navigation system (Kirschvink, 1997) if the one in use is found to be degraded.

Returning to sperm whales, we cannot be sure which, if any, of these mechanisms are relevant to them. However, for male sperm whales on their way from the Norwegian Sea it seems to be valid that once they are misled by a disturbed 'magnetic sense' or some another interference, the North Sea basin functions as a kind of natural 'sperm whale trap' (Smeenk, 1997; Jauniaux et al., 1998). In this shallow shelf sea with a contourless seabed, often with soft bottom sediments, their deep water sonar and other adaptations to their normal habitat may not function properly.

In conclusion, our results support the hypothesis that extreme solar events can lead to beaching of sperm whales, the mechanism of which is still unknown.

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