Aquatic Mammals 1986, **11.3,** 109–119

Cetacean live stranding dates relate to geomagnetic disturbances

M. Klinowska

Anatomy Department, University of Cambridge, Downing Street, Cambridge CB2 3DY, UK

KEY WORDS: Cetacean, geomagnetic disturbance, orientation, strandings, biological rhythms, time

Abstract

Further analysis of the UK cetacean strandings records has revealed more information about the way the animals use the geomagnetic field as part of a travel strategy. Animals make the key mistakes, which result in live strandings, at some distance from shore. The distances implied by the analyses fit well with the distance of major choice points in the geomagnetic topography of the usual migration routes. Live strandings are associated with geomagnetic disturbances. The pattern of magnetic disturbance, not the absolute level of disturbance is the key factor for live strandings at all latitudes investigated. If disturbances occur in that part of the day available for monitoring geomagnetic time information (the second to fourth parts of the Greenwich day), live strandings result. This indicates that the animals are using geomagnetic time information to re-set a 'biological travel clock'. It also implies that the receptor system involved is likely to be multidomain.

Introduction

Earlier studies (Klinowska, 1983; 1985a) have shown that cetacean live strandings can provide information about travel strategies. It was found that the positions of live strandings can be explained as mistakes made while using geomagnetic topography for orientation. The original work was based on the United Kingdom (UK) strandings records, and has now been confirmed for the USA east coast (Cornwell-Huston, 1985; Kirschvink, Westphal and Dizon, 1984), for Canada (Fraser, 1984) and for New Zealand (Dawson, Whitehouse & Williscroft, 1984). More importantly, known cetacean tracks (Evans, 1974) also seem to follow geomagnetic topography in the manner indicated by the strandings data (Evans—personal communication).

Animals using goemagnetic information for travel may be expected to make relatively more mistakes when the geomagnetic field is disturbed. Our first attempt (Easton, 1980) to explore this question was not successful because heterogenous strandings data were used as well as an inappropriate measure of geomagnetic disturbance. However, since homogeneous samples of stranding events had revealed the relationship between live stranding sites and geomagnetic topography, it seemed worthwhile to have another look at the question of possible relationships between live strandings and geomagnetic disturbances, using these samples. (Further information on the first study is summarized in Klinowska, 1985c.)

Data and methods

Geomagnetic disturbances

The earth's magnetic field has two sources (Chernosky *et al.* 1966). The main source is generated within the earth, from electric currents flowing in a molten metallic core. Movements in this core produce slow surface changes, including alterations in the position of the geomagnetic poles. The second, relatively weak, source is generated by the flow of ions in the jet streams of the upper atmosphere. The atmospheric field, however, is the main source of geomagnetic variation at the surface of the earth. The heating of the atmosphere in the daytime and the cooling at night cause the atmospheric ion streams to move north and south in a daily rhythm which changes local field by 30–60 nano Tesla (nT) over a day. There are also tidal variations related to the movements of the sun and moon. These regular variations provide daily and seasonal time information in much the same way as the familiar light/dark cycle (Pittendrigh, 1981). Solar activity creates bursts of ionized particles which can affect the earth's field, creating relatively more disturbance in the auroral zones than towards (but not at) the equator (Lincoln, 1967). During the greatest magnetic storms, as major events of this type are known, changes can be of the order of thousands of nT, although small disturbances of tens to the low hundreds of nT are an almost constant feature of the earth's magnetic environment. These irregular events can be regarded as magnetic 'weather', disrupting the regular field variations in a similar fashion to the disruption of light/dark cycles by meteorological events. Unlike meteorological events, however, geomagnetic weather is a little more predictable. In general, disturbances are greater during the evening and early part of the night, while the early morning is a much quieter time. This is because of the interactions between solar corpuscular radiation and night-side ring currents in the polar zones of the upper atmosphere. Seasonal variations in magnetic disturbances also occur for these reasons.

The dynamic aspects of the earth's magnetic field are known through the network of magnetic observatories. The most usual observations are the declination, horizontal intensity and vertical intensity of the field. These are published as hourly values, but are difficult to interpret, particularly when comparing observatories, and several types of indices are used to describe dynamic magnetic phenomena, the main intent being to separate the undisturbed or quiet-day normal variations from the rest and to compensate for geographical effects. The K index, which is commonly used for general purposes (e.g. Keeton, Larkin & Windsor, 1974; Martin & Lindauer, 1977), is intended to be a measure of solar corpuscular radiation based upon the intensity of geomagnetic activity caused by the electric currents produced in the ionosphere by such radiation. The K index is a measure of the activity during each 3-hour interval of the Greenwich day (which begins at midnight). The index has a quasi-logarithmic scale from 0 (least disturbance) to 9 and is based on the sum of maximum deviations from the undisturbed or quiet-day variations. The conversion of K indices into nT depends on the magnetic latitude of the observatory. K9 represents disturbances of 300 nT and above at low latitudes (except at the equator) and 2,500 nT or more in the auroral zones. Intermediate K values are adjusted accordingly. Several summary K indices are also published, giving geomagnetic activity for larger areas and longer time periods. There are three geomagnetic observatories in the UK, Lerwick in the Shetland Islands, Eskdalemuir near Edinburgh and a southern station which started at Abinger, south of London and moved to Hartland on the west coast in 1956/57. At Lerwick K9 represents disturbances of 1,000 nT and above and at Abinger/Hartland 500 nT.

Normal quiet-day geomagnetic fluctuations are published as the Sq series of indices. We may think of the Sq index as providing information analogous to the regular pattern of light levels (solar and lunar contributions) which would be observed at a point on the earth's surface if there was no meteorological disturbance. The K indices represent maximum deviations from this base but do also show diel and longer term patterns on average, for the reasons mentioned above.

The K indices themselves for Lerwick, Eskdalemuir and Abinger/Hartland are almost identical, because of the inherent latitude compensation. For the present purpose the three hourly K indices for 1929 to 1980 were obtained through the British Geological Survey, since these are the longest set.

Strandings

Of the 137 live strandings of cetaceans recorded in the original report files at the British Museum (Natural History), 89 occurred within the period for which K indices are available. As was shown previously (Klinowska, 1985a, b; Easton, Klinowska & Sheldrick, 1982), there are a number of biases in the UK stranding records, mainly attributable to uneven observer effort. The most important source of longitudinal biases is reduced effort (for obvious reasons) during and possibly just after the wars. The most important sources of regional biases are the distribution of Coastguard establishments (the main primary reporting network) and the more restricted legal reporting requirements in Scotland. These biases, however, affect the recording of passive strandings (at least in the regional dimension); live or active strandings are distributed in accordance with geomagnetic topographical features and have no relation to observer distribution (Klinowska, 1985a). Therefore, if the entire sample for this period of over 900 passive strandings (cases where animals were clearly described as having been dead for some time when first washed up) was taken as a control group, in effect this would compare events mainly recorded on the south and east coasts with live stranding events known to be distributed in a quite different way all around the country. Since the magnetic disturbances are greater at higher latitudes, there must be some *a priori* expectation that any relationship between strandings and magnetic disturbances will have a latitudinal component. Thus a control group heavily biased towards the south will not in fact be an effective control for two reasons. If passive strandings and active strandings are both related to geomagnetic disturbances the reporting biases will obscure any latitudinal relationships. On the other hand, if only live strandings are related to geomagnetic disturbances, the bias in reporting passive strandings will exaggerate the latitude effect. A calculation of regression on latitude *versus* dispersion of K-indices in a continuous fashion would not solve the problem as the long UK south coast contains about half the passive strandings within one degree of latitude, whereas in the far north records are sparse. There are also breaks in distribution between the mainland and the Orkney and Shetland islands to consider.

I therefore decided that the most effective way to generate an adequate control group for the live strandings would be to work on a regional basis, drawing from the pool of passive strandings within a region a number of events equal to the number of live strandings in that region, thus avoiding the grosser latitude biases in passive stranding records. The coast was divided into twelve sections for this purpose (Figure 1). Except for using the Scottish border as one division (in the west the border was projected latitudinally to the end of the land) because of the different Scottish reporting conditions, the other regional divisions were arbitrary and served only to divide the records in a convenient manner. (The origin of these divisions is simply the way the coast fitted on to available sheets of drawing paper, with the Scottish border as origin. Section 9 is smaller because it was the 'remainder'. The system was started in the early stages of the previous investigations and was retained here for convenience. A system based strictly on latitude is impractical because the Scottish border alignment would impose divisions which are too small.)

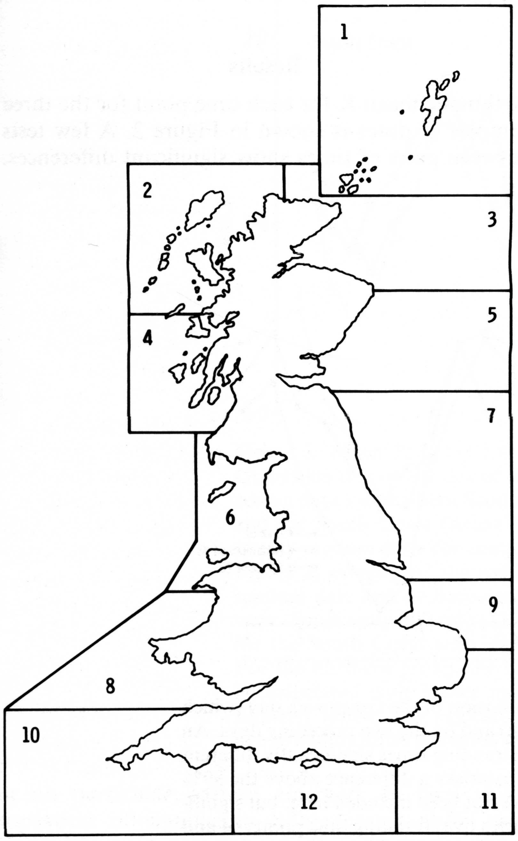

Figure 1. Coastal divisions used in this analysis.

Since it is known that there are longitudinal reporting biases in the passive strandings records, which may also affect the live strandings reporting (there are so few live strandings in the long record that a meaningful test of this is impossible), it seemed preferable to preserve the time sequence in the passive strandings record as far as possible. There are, on average, about ten times more records of passive strandings, so taking on average every tenth record from the sequential list of passive strandings has the desired effect. In specific regions, however, the proportion required varies from every 7th to every 12th record.

This regional method, however, does not control for the possibility that both passive and active strandings may be related to geomagnetic disturbances. To cover this, a group of random dates within the period were generated using random number tables. Since the key analyses were to be on a regional basis, the number of random dates taken was similar to the number of cases in the three extreme northern and southern regions. The exact times of live strandings are often unknown or difficult to specify within hours, so K indices for each three hour period of a stranding or control date were taken. K indices for the two days before these dates were also included, to provide further information on the behaviour of the geomagnetic field at these times. Some geomagnetic records were not complete, resulting in final samples of 87 live and 88 passive stranding dates and 20 random dates.

Analysis

The problem for analysis of such data is how to compare a process which is essentially continuous (K index) with strandings data, which is essentially discrete (175 stranding dates out of just under 18,700 dates). Easton (1980) considered three possible solutions. The first was to treat the strandings as a continuous process in time, by defining a 0–1 variable, S, such that $S(t) = 0$ or 1 according to whether a stranding occurred on day t. The disadvantages of this approach are that the K indices have a somewhat non-Gaussian distribution, raising problems for parametric statistical analysis and the strandings data are not very suitable for non-parametric tests as their ranks are extensively tied. These considerations also effectively rule out any macro time-series analysis. The second was to extract a point process from the magnetic data and then attempt to relate the two point processes. The problems here are that it is difficult to predict *a priori* which features of the K index to take (large rises or falls, absolute change, relative change). Also, with such a disparity between the numbers of days with and without strandings, any such analysis is almost bound to be comparing stranding events in the low tens with K index events in the hundreds. The third method (which was considered the most useful) was to look at the K index distribution at around the time of each stranding to see to what extent this variation is typical of the K index as a whole. This is the method which has been adapted here.

Arthmetic mean K for each time point for the three samples of dates was calculated and T tests between pairs of times performed. Similar calculations were performed for three groups of regional data, North Scotland (areas 1, 2 and 3 in Figure 1), the middle (areas 6, 7, 8 and 9) and the South Coast (areas 10, 11 and 12). Area 4 contained no records of live strandings, allowing area 5, where records are additionally biased by the activities of coastal marine laboratories, to be left out also. Analysis of smaller sections is not practical because of inadequate numbers of cases.

In order to explore the data further, stepwise discriminant analyses (Klecka, 1975) (Method RAO) were performed. Discriminant analysis does, in theory, demand normally distributed data, but in practice the method is robust and this requirement need not be strictly followed (Klecka, 1975).

The patterns of geomagnetic disturbance around the strandings dates were investigated by fitting trigonometric polynominal functions to the K indices for each date (Batschlet, 1981). As a specific test for the key aspect of geomagnetic disturbance patterns, the behaviour of the field in day divisions 2, 3 and 4 for the stranding or control days and for the two days before, was examined. On average, these should be the quietest times in the 24 hours. Each date was examined to see whether this was the case or not for North Scotland, the South Coast and the random sample of dates. Contingency tables were drawn up on the basis of the number of days where the day divisions in question did not contain the quietest period for that day (i.e. all three of the days, two of them, one or none). The pattern for the random dates was taken as the expected distribution and the live and passive stranding date patterns compared with this, using chi square. The process was repeated for divisions 2 and 3, and for 3 and 4 separately. Similarly, divisions 6, 7 and 8 were tested to check whether they contained the highest activity for that day.

Results

Arthmetic mean K for each time point for the three samples of dates is shown in Figure 2. A few tests between pairs of times show significant differences,

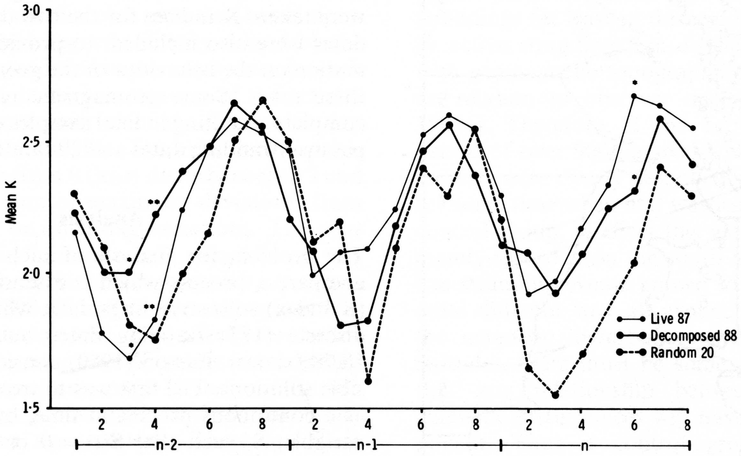

Figure 2. Mean K index for each three hour division of the Greenwich day (which begins at midnight) on the day of stranding (n) and on the two preceding days. An asterisk indicates a pair of live/decomposed stranding times significantly different above the 95% level (T test-two tailed); two asterisks a difference above the 99% level. The T test results for random dates have not been included here, but significant differences at the 95% level were found with live stranding time points 04 and 01 and with decomposed stranding time points 24 and 25. (Time points are named to day by the first digit, with day n as 0 and to day division by the second digit.)

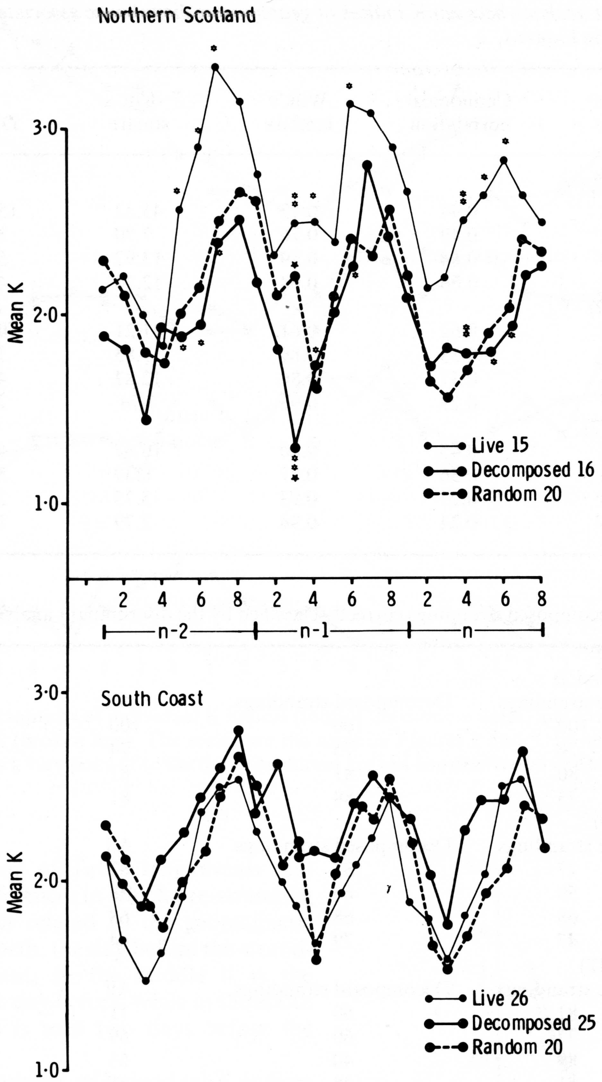

Figure 3. Mean K index for each three hour period of the Greenwich day on the day of stranding (n) and on the two preceding days for northern Scotland (Areas 1, 2 and 3 in Figure 1) and the South Coast (Areas 10, 11 and 12 in Figure 1) with twenty random dates for comparison. Other symbols are as for Figure 2, except that the solid stars indicate the only pair of random date and decomposed stranding date mean Ks which were significantly different (13, at the 95% level). No time pairs for the South Coast were significantly different on T testing. For the northern group, the live stranding dates do appear to be associated with higher mean K. Intermediate areas were similarly tested. The association between higher mean K and live stranding dates increased with increasing latitude.

but no particular pattern emerged. In fact, this proportion of significant differences is about as expected for such a sample of pairs of points drawn from the same population. However, on dividing the samples by latitude (Figure 3), a connection between live stranding dates and higher geomagnetic disturbances appeared in the most northerly group. Since the random sample of dates

Table 1(a) Stepwise discriminant analyses between K indices of geomagnetic disturbance associated with cetacean stranding dates. Areas used are shown in Figure 1.

Days	Percent correct	Eigen value	Cannonical correlation	Wilk's lambda	Chi square	DF	Significance
Northern Scotland (Areas 1, 2 and 3)							
All	100	7.23	0.94	0.12	45.32	15	0.0001
N	74	0.32	0.49	0.76	7.70	3	0.0526
N–1	81	0.69	0.64	0.59	13.92	5	0.0101
N–2	81	0.57	0.60	0.64	12.24	4	0.0156
Middle areas (Areas 6, 7, 8 and 9)							
All	82	0.63	0.62	0.61	41.21	10	0.0000
N	58	0.12	0.33	0.89	9.85	3	0.0199
N–1	68	0.16	0.37	0.86	12.87	4	0.0119
N–2	64	0.09	0.29	0.92	7.74	2	0.0209
South Coast (Areas 10, 11 and 12)							
All	71	0.26	0.45	0.80	10.67	5	0.0584
N	69	0.14	0.36	0.87	6.39	3	0.943
N–1	65	0.08	0.27	0.93	3.75	2	0.1536
N–2	55	0.06	0.24	0.94	2.79	1	0.0948

Table 1(b) Percent of live and decomposed strandings correctly classified by the discriminant analysis.

Northern Scotland (Areas 1, 2 and 3)				
Days	Live strandings	Decomposed strandings	All	Significance
All	100	100	100	0.0001
N	74	75	74	0.0526
N–1	80	81	81	0.0101
N–2	73	88	81	0.0156
Middle area (Areas 6, 7, 8 and 9)				
Days	Live strandings	Decomposed strandings	All	Significance
All	77	87	82	0.0000
N	50	66	58	0.0199
N–1	68	68	68	0.0199
N–2	47	79	64	0.0209
South Coast (Areas 10, 11 and 12)				
Days	Live strandings	Decomposed strandings	All	Significance
All	81	60	71	0.0584
N	77	60	69	0.9430
N–1	89	40	65	0.1536
N–2	81	28	55	0.0948

showed no particular differences in mean K from the passive stranding dates, either in general or in regions, it was concluded that the passive strandings are, as expected, not related to geomagnetic events and indeed form an adequate control.

When all the K index time points were included, the entire northern sample could be correctly classified as live or passive strandings by the discriminant analysis. Even the southern sample, which appears from Figure 2 to have little relationship with geomagnetic disturbance, could be classified with 71% success on this basis (Table 1a). In order to explore the time relationships further, the calculations were repeated for each day alone. The magnetic events on the stranding day are most important in the north, but least important in the south. From Table 1(b) it can be seen that, while in the north the discriminant analysis is reasonably successful in defining both live and passive strandings, in the south it is the live strandings which are most easily distinguished. This must mean that there is a particular pattern of geomagnetic disturbance in the south around live stranding dates while there is no consistent pattern around decomposed stranding dates. Hence, the apparent lack of relationship in the south between live strandings and geomagnetic disturbances when only mean K is considered, as in Figure 3.

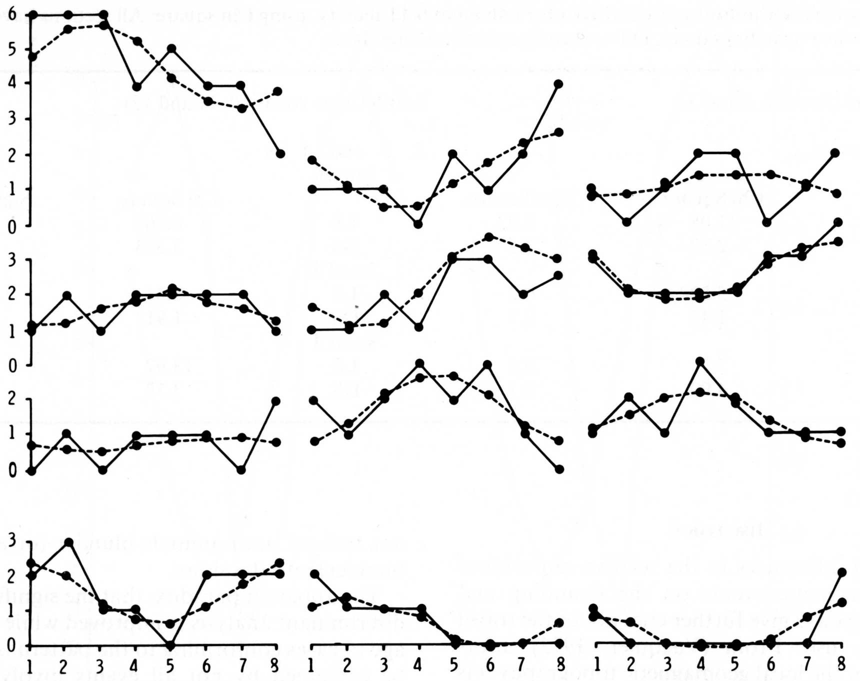

Figure 4. Examples of individual K indices (four of the random dates) and fitted first harmonic sine curves (broken line). The scales are the same as Figures 2 and 3. In most cases the sine curve gives a very poor fit to the data and curves are not consecutive on consecutive days.

Further examination of Table 1(b) reveals that there are regional differences in which pre-stranding days seem to be best related to the geomagnetic phenomena. In the north, the day before the stranding is most important, in the middle it is the stranding day and the day before, while in the south the best relationship is seen two days before the stranding date.

Figure 4 shows examples of individual K indices and their fitted sine curves. It is obvious that the fitted first harmonic curves are a very poor description of the daily K indices and that often there is no continuity from one day to the next. However, when the average K indices for all the dates used in this study are taken, such a sine curve gives an almost perfect description of the data (Figure 5).

Table 2 shows the results of the chi square analysis for the 2, 3 and 4 day divisions. None of the 6, 7 and 8 analyses revealed any pattern, although one live (South Coast, all times) and one decomposed (North Scotland, all times) group did reach significance. For north Scotland, the live stranding date divisions were associated with significantly more disturbance in divisions 2, 3 and 4 but not in divisions 2 and 3 or 3 and 4 alone, while on the South Coast the opposite is true. Here, divisions 3 and 4 are of the most importance, with divisions 2 and 3 as well as the whole period of little interest. No decomposed stranding date patterns differed significantly from the random sample of dates.

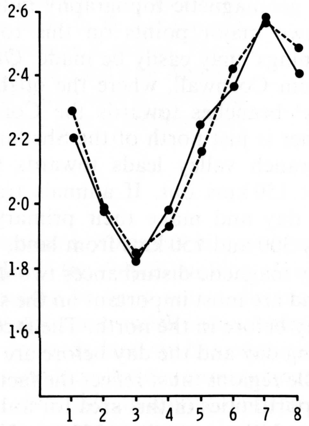

Figure 5. Mean K indices for all dates used in this analysis, with fitted sine curve (broken line). On average, such a first harmonic sine curve gives a very good description of the data. Scales as for Figures 2 and 3.

Table 2 Testing the early morning day divisions for minimum field activity, using Chi square. All sections have 3 degrees of freedom. LS = live strandings dates, DS = decomposed strandings dates.

North Scotland (Areas 1, 2 and 3)	Chi Square	Significance	South Coast Areas 10, 11 and 12)	Chi Square	Significance
2, 3 and 4 as lowest			2, 3 and 4 as lowest		
LS	11.08	0.02	LS	6.567	0.1
DS	2.57	0.5	DS	3.333	0.7
2 and 3			2 and 3		
LS	5.228	0.2	LS	8.51	0.05
DS	1.42	0.7	DS	1.91	0.7
3 and 4			3 and 4		
LS	3.0	0.5	LS	13.97	0.01
DS	4.09	0.3	DS	3.77	0.5

Discussion

The regional differences in the relative importance of the geomagnetic events on the stranding and pre-stranding days give further cues about the travel strategies in use. From (Vacquier, 1972) information about the local geomagnetic topography it is possible to make reasonable guesses about where animals may be making the mistakes which may lead to live strandings. The usual travel route for offshore species moving from north to south or *vice versa* is from the Bay of Biscay around western Ireland and on to the north north east (Evans, 1980). The geomagnetic topography indicates that there are two major points on this route where 'wrong turnings' may easily be made. One is some 300 kms from Cornwall, where the offshore 'magnetic valley' branches towards the Cornish coast and the other is just north of the Shetland islands, where a branch valley leads towards the North Sea—about 150 kms out. If animals travel about 150 kms a day and make their primary mistakes respectively 300 and 150 kms from land, this would explain why magnetic disturbances two days before meeting land are most important on the south coast and one day before in the north. The fact that both the stranding day and the day before are important in the middle regions must reflect the fact that there are few opportunities in this area for animals to be further from UK coasts than 150 km. Hence most of their mistakes must be made within a day's journey from land. The implied average rate of travel, around 6 kph, is within the known range (Leatherwood & Evans, 1979). The delay in arrival on shore can be explained by the distance between the place where the primary mistake was made and the nearest land in the direction of travel. Further, since the travel speed is relatively great, this is further support for the idea that the mistake is not noticed until animals blunder (or are about to blunder) into the shore.

The apparent paradox, that the significance of the discriminant analysis is improved while the percentage of cases conforming to the pattern is lower, may be explained by not all events involving animals trying to use the offshore route. Some animals or groups make their mistakes at points nearer shore. An attempt was made to follow this further, by comparing the species of cases conforming or not conforming to the pattern, but no clear results were obtained. However, since the numbers of cases for each species were low, it might be worthwhile testing this again for areas with more numerous records.

This relationship between live stranding dates and geomagnetic disturbance could simply be through disruption of information about the geomagnetic topography base map, but since geomagnetic topography is a local distortion of the total geomagnetic field through the magnetic characteristics of the local geology, its basic shape should be relatively immune to total field fluctuations. Also, the results of the discriminant analysis, particularly in the south, indicate live strandings are not simply related to the size of the geomagnetic disturbances, but to some aspect of the pattern of disturbances. The behaviour of the geomagnetic field can provide an answer to these questions. This will firstly be illustrated by analogy. Consider a number of stationary buoys marking a tidal estuary. The depth of the water under the buoys will change regularly with the tide, but the buoys will retain their relative positions. The buoys represent the local geological formations responsible for the geomagnetic topography, while the water in the estuary respresents the normal quiet-day pattern of geomagnetic fluctuations (Chernosky *et al.*, 1966). The effect of a geomagnetic storm on this system can be rep-

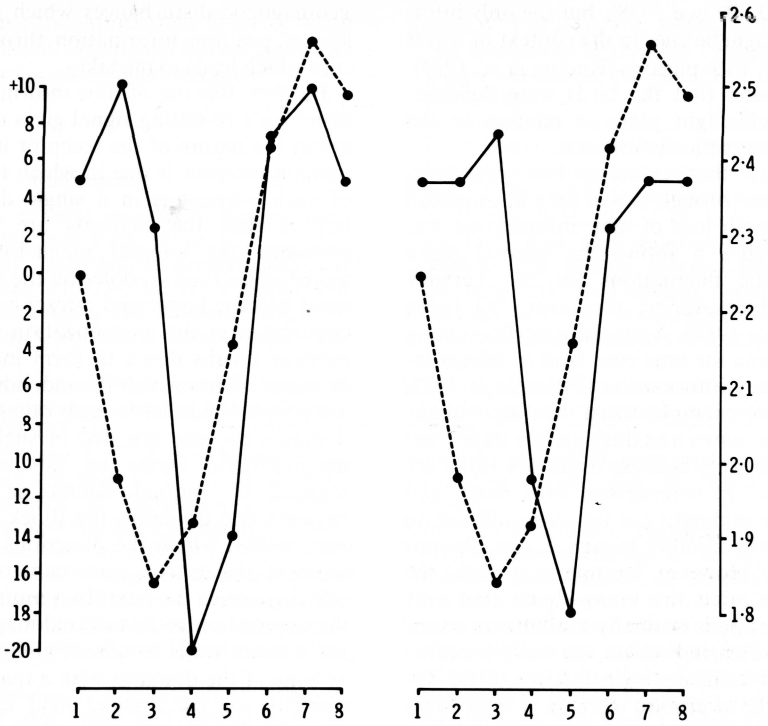

Figure 6. Normal mean daily geomagnetic fluctuations (Sq index) in nT (left scale) for Lerwick (left) and Abinger (right) redrawn from Chernosky *et al.* (1966) with fitted sine curve for mean K indices (broken line) for all dates (as in Figure 5) (right scale). The points which could be used for obtaining time information are 2, 3, 4, 5 and 6 for Lerwick and 3, 4, 5 and 6 for Abinger because these are times with maximum change in the field. However, the later times are likely to be lost through geomagnetic disturbances on average as shown by the increasing K indices. Therefore the only useable times are between 2 and 4 for Lerwick and 3 and 4 for Abinger. As shown in Table 2, these are the points where magnetic disturbance is associated with live strandings dates, indicating that loss of these time cues is an important factor in chain of events leading to live strandings.

resented by considering the effect of the opening or closing of sluices higher up the river, resulting in temporary changes in depth of water in the estuary. Again, the basic position of the buoys will not change, but depending on when the sluices are manipulated, a false impression of the state of the tide may be given because the water in the estuary will be higher or lower than it should be at a particular state of the tide. If a ship is moving along the channel marked by the buoys, an estimate of current position is required in order that decisions to avoid obstacles or change channel may be made. The simplest way to estimate position is by dead reckoning, where if speed and journey time are known, distance travelled may be estimated. If the only available time measuring device is on the ship, but has to be reset using a particular tide state as an external standard, mistakes in position calculation are possible. If the ship is moving along a straight channel leading to open sea, a distance miscalculation may not cause much inconvenience, but if it is moving towards land or has obstacles to avoid, mistakes could have serious consequences.

How far does this analogy cover the problem of the cetacean trying to move along a geomagnetic topography map in the face of geomagnetic disturbances? The geomagnetic field shows regular daily fluctuations (Chernosky *et al.*, 1966) which are used by many organisms from bees (Martin & Lindauer, 1977) to hamsters (Brown & Scow, 1978) and humans, (Wever 1968) as *zeitgebers* or time cues for resetting their biological clocks. Biological clocks are also important components of animal orientation, and particularly of navigation systems

(Pittendrigh 1981, Brown 1978), but the only information on geomagnetic cues in the context of travel comes from work with pigeons (Keeton *et al.* 1974), where it was found that the birds were deflected from their normal flight paths in relation to the intensity of the magnetic disturbance.

The possibility that cetacean live strandings represent mistakes through loss of time information rather than through loss of map information was investigated. Figure 6 shows the normal mean daily geomagnetic fluctuations for the Lerwick and Abinger observatories, the mean SQ index (Chernosky *et al.*, 1966). Animals using fluctuating natural phenomena for time cues tend to take transition times as key information (Pittendrigh 1981, Brown, 1978). For example, when the ratio of light to dark is the cue, dawn and dusk are the important times. This is probably because transition times are easy to monitor—in comparison with dawn and dusk, midday or midnight are far more difficult to perceive. Here, the midday trough is one obvious transition time. However, comparison with the average K index fitted sine curve shows that only half of this transition is normally available as a time cue (Figure 6). This is because the early morning decrease in field coincides with low magnetic disturbance while the afternoon increase is most likely to be masked by increasing geomagnetic activity. But this is only true on average, as Figure 4 demonstrates the pattern on individual days is much more complex and the fitted sine curves provide an inadequate description of the patterns. The chi square test for disturbance during time periods when the field should on average be quietest demonstrates very clearly the importance of the early morning decrease in field when Table 2 and Figure 6 are compared. In the north, the Sq index pattern is such that the morning decrease in field coincides with the 2, 3 and 4 day divisions and this is where disruption of this pattern is associated with live strandings. Neither of the divisions 2 and 3 or 3 and 4 alone is important, only the whole period. In the south, the slightly different Sq index pattern means that only divisions 3 and 4 coincide with the average quiet field and here it is not the whole 2, 3, 4 period which is important, but exactly the 3–4 period, although the 2–3 period may play some role. The failure to show any equivalent pattern for the 6, 7, 8 divisions supports the argument that disruption in the average pattern of geomagnetic disturbance is only important at specific times.

This relationship between the times at which magnetic disturbance is associated with strandings and the features of the normal daily geomagnetic fluctuations which could most easily be used as resetting signals for biological clocks (Pittendrigh 1981) leads to the conclusion that it is disruption of perception of geomagnetic topography through geomagnetic disturbances which is important, but loss of position information through loss of time cues which leads to mistakes.

Further, this use of time information and dependence on a re-setting signal gives more information about the nature of the receptor involved. A single domain receptor is one in which the magnetization of each element is in a single direction and this implies that the elements are small. In larger elements, the internal magnetostatic forces are increased as the two poles on the surface of the element become larger and attract each other. In such circumstances the magnetization within each large element breaks down to form individual areas or domains within which the individual electron spins are coupled parallel to each other but the different domains become oriented in such a way that the magnetostatic forces on adjacent domains are reduced by mutual interaction. The boundary between two domains, the Block wall, is a narrow zone within which the directions of the magnetization of the eletron spins cant over from that of one domain to the next. In a multidomain element, the application of an external magnetic field causes the domain walls to unroll, giving a growth in the volume of the domains with a magnetization in the direction of the applied field at the expense of domains that are at right angles to the applied field. If the applied field is weak, the domain walls roll back to their previous position when the field is removed, however as stronger fields are applied, the domain walls can jump past the energy barriers within the element and on removal of such a field, not all domain walls are capable of rolling back through energy barriers to their previous location. However, if left long enough, thermal agitations will eventually allow the wall to unroll (Tarling, 1983).

Clearly, a single domain receptor is incapable of information storage and would not require any resetting, but a multidomain receptor, through changes in the domain walls, can store information. The changes are not permanent and do require resetting. From the evidence above, the cetacean receptor is most likely to be multidomain as it seems to store information for about 24 hours and to be reset by a decrease in field.

Thus it appears that cetaceans have access to an integrated travel system based on two aspects of total geomagnetic field. The basic map is supplied by the geomagnetic topography, while the means for monitoring progress is supplied by geomagnetic time cues.

Acknowledgements

I wish to thank H.M. Coastguard and the Receivers of Wreck who provide the primary stranding reporting network and the British Museum (Natural

History) for access to unpublished records. Miss K. Dyson of the British Geological Survey was most helpful in locating the geomagnetic records.

References

Batschlet E. (1981). Circular statistics in biology. Academic Press. London, New York. 371 pp.

Brown F. A. (1978). Interrelations between biological rhythms and clocks. 215–234. In: H. V. Samis and S. Capobianco (ed.) Aging and Biological Rhythms. Plenum Publishing Corporation, London and New York.

Brown F. A. & Scow K. M. (1978). Magnetic induction of a circadian cycle in hamsters. *Journal of Interdisciplinary Cycle Research.* **9(2),** 137–145.

Chernosky E. J., Fougere P. F. & Hutchinson R. O. (1966). The geomagnetic field. 11–1 – 11–61. In: S. C. Valley (ed.) Handbook of Geophysics and Space Environments. McGraw-Hill Book Company Inc. New York, San Francisco, Toronto, Sydney.

Cornwell-Huston C. (1985). Magnetic anomalous conditions affecting cetacean live mass strandings. The case of Cape Cod Bay, Massachusetts. M.S. Thesis. Department of Geography, Boston University, Boston, Mass.

Dawson S. M., Whitehouse S. & Williscroft M. (1984). A mass stranding of pilot whales in Tryphena Harbour, Great Barrier Reef. Investigations on Cetacea. (In press.)

Easton D. F. (1980). A report on strandings of the common porpoise on British coasts and their relationship to geomagnetic variation. Diploma in Statistics Thesis. Statistical Laboratory, Cambridge.

Easton D. F., Klinowska M. & Sheldrick M. C. (1982). A preliminary analysis of the British stranding records of the harbour porpoise (*Phocoena phocoena*). *Rep. Int. Whal. Commn.* **32,** 120–121.

Evans P. G. H. (1980). Cetaceans in British waters. *Mammal Review* **10,** 1–52.

Evans W. E. (1974). Radiotelemetric studies of two species of small Odontocete cetaceans. 385–394. In: W. E. Schevill (ed.) The whale problem: a status report. Harvard University Press. Cambridge, Mass.

Fraser A. M. (1984). An analysis for Eastern Canada of the hypothesis that cetacean live strandings are due to mistakes made by the animals trying to use geomagnetic topography for orientation. MST Part II Project Report. Department of Applied Biology, Cambridge.

Keeton W. T., Larkin T. S. & Windsor D. M. (1974). Normal fluctuations in the earth's magnetic field influence pigeon orientation. *Journal of Comparative Physiology* **95,** 95–103.

Kirschvink J. L., Westphal J. A. & Dizon A. E. (1984) Poster presented at the Annual Meeting of the American Geophysical Union, San Francisco.

Klecka W. R. (1975). Discriminant analysis. 434-467. In: N. H. Nie, C. H. Hull, J. G. Jenkins, K. Steinbrenner and D. H. Bent. (eds) Statistical Package for the Social Sciences. 2nd. Edition. McGraw-Hill Book Company Inc. New York, San Francisco, Toronto, Sydney.

Klinowska M. (1983). Is the cetacean map geomagnetic? Evidence from strandings. (Abstract) *Aquatic Mammals* **10(1),** 15.

Klinowska M. (1985a). Cetacean live stranding sites relate to geomagnetic topography. *Aquatic Mammals* **11(1),** 27–32.

Klinowska M. (1985b). Interpretation of the UN cetacean stranding records. *Rep. Int. Whal. Commn.* 35. (In press.)

Klinowska M. (1985c). The cetacean magnetic sense—evidence from strandings. In: M. M. Bryden and R. J. Harrison (eds) Research on Dolphins. Oxford University Press. (In press.)

Leatherwood S. & Evans W. E. (1979). Some recent uses and potentials of radiotelemetry in field studies of cetaceans. 1–32. In: H. E. Winn and B. L. Olla (eds) Behaviour of Marine Mammals. Volume 3. Cetaceans. Plenum Press. New York, London. 438 pp.

Lincoln J. V. (1967). Geomagnetic indices. 67–100. In: S. Matsushita and W. H. Campbell (eds). Physics of Geomagnetic Phenomena. Volume 1. Academic Press. New York and London.

Martin H. & Lindauer M. (1977). Der Einfluss der Erdmagnetfelds und die Schwereorientierung der Honigbiene. *Journal of Comparative Physiology* **122,** 145–187.

Pittendrigh C. S. (1981). Circadian organisation and the photoperiodic phenomenon. 1–35. In: B. K. Follett and D. E. Follett (ed.) Biological clocks in seasonal reproductive cycles. Proceedings of the 32nd Symposium of the Colston Research Society. Scientechnica. Bristol.

Tarling D. H. (1983). Paleomagnetism. Chapman and Hall. London, New York. 379 pp.

Vacquier V. (1972). Geomagnetism in marine geology. Elsevier Publishing Company. Amsterdam, London, New York. 185 pp.

Wever R. (1968). Einfluss Schwacher electro-magnetischer Felder auf die circadiane Periodik des Menschen. *Naturwissenschaften* **55,** 29–32.