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Review

Potential Effects of Anthropogenic Radiofrequency Radiation on Cetaceans

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Simple Summary: The number of mass stranding events is dramatically increasing in recent decades affecting cetacean diversity and conservation. They consist in the accumulation of cetacean carcasses or live animals along the coast following certain temporal and spatial patterns. Although some cases can be explained based on a combination of physical or biological natural factors, direct human intervention is contributing to many of them. However, there are still many cases with unknown causes that demand to increase the efforts to describe possible new threats to cetacean species. In this context, we evaluate the potential effect of anthropogenic radiofrequency radiation (i.e., from meteorological and military radars) that has had a great expansion in the last years and is known to alter the magnetic receptor organs in several groups of animals. The aim of this work, was to conduct a bibliographic review reporting mass stranding events together with a search of radars in the vicinity areas. The results obtained suggest that anthropogenic radiofrequency radiation may be considered as a novel factor to understand some stranding events with unknown causes and proposes some plausible mechanisms of action.

Abstract: Cetaceans are cast to shore for a large number of reasons, although sometimes it is not clear why. This paper reviews the types and causes of cetacean strandings, focusing on mass strandings that lack a direct scientific explanation. Failure of cetacean orientation due to radiofrequency radiation and alterations in the Earth's magnetic field produced during solar storms stand out among the proposed causes. This paper proposes the possibility that anthropogenic radiofrequency radiation from military and meteorological radars may also cause these strandings in areas where powerful radars exist. A search of accessible databases of military and meteorological radars in the world was carried out. Research articles on mass live strandings of cetaceans were reviewed to find temporal or spatial patterns in the stranding concentrations along the coast. The data showed certain patterns of spatial and temporal evidence in the stranding concentrations along the coast after radar setup and provided a detailed description of how radars may interfere with cetacean echolocation from a physiological standpoint. Plausible mechanisms, such as interference with echolocation systems or pulse communication systems, are proposed. This work is theoretical, but it leads to a hypothesis that could be empirically tested. Further in-depth studies should be carried out to confirm or reject the proposed hypothesis.

Keywords: anthropogenic radiofrequency radiation; communication; odontocetes; orientation systems; radars

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1. Introduction

Cetacean (Cetacea) strandings, which have been occurring since ancient times, involve animals coming close to shores or stranding themselves on land [1]. However, the causes of some strandings, especially those involving numerous living specimens, and the reason for their increase in recent times have not yet been explained [2–4].

1.1. Stranding Types and Causes

Hundreds of strandings happen worldwide every year. Depending on the cetacean stranding event, a variety of types can be identified, which may be used to find out the cause [2]. The first differential criterion is the number of individuals involved, varying from a single animal to hundreds of animals (mass strandings) in some cases [5]. Additionally, we can take into account the condition of the animals when they are beached on the coast (alive and uninjured, injured, or dead). Another differential criterion is the classification of the stranded species into either mysticetes or odontocetes groups.

Strandings of solitary animals are more common than mass strandings [6]. Mass strandings are rare in the suborder Mysticeti, but certain Odontoceti are frequently involved in multiple live strandings of several to hundreds of individuals. Their degree of sociality may play an important role in these events [2,7–10].

Strandings of cetaceans are likely the result of a sequence of events rather than a simple cause-and-effect [6]. A range of anthropogenic and natural events can cause single and mass strandings [3,4]. There may also be interactions between physical (weather, tides, currents, coastline) and biological conditions (predators, feeding, disturbance of echolocation, disease) [6]. To systematize the causes of strandings, we will divide the general causes proposed thus far into strandings with direct or no direct human intervention [11].

1.1.1. Strandings with Direct Human Intervention

These strandings can be caused by fisheries activities, such as bycatch [2,3,11–16] and entanglement [17–19]. Larger species are often victims of ship strikes, whereas smaller cetacean species may become entangled in fishing gear [3,9].

Other causes include hunting, chemical spills, explosions, naval maneuvers, sonar operations [3,4,20–25], gas bubble lesions and sound disturbance [26,27], acoustic trauma from dynamite [22,28,29], seismic surveys conducted mainly in the oil and gas industries [22,30], increased pollution [27], and toxicity of pollutants in the environment [31].

1.1.2. Strandings with No Direct Human Intervention

These strandings can be caused by sick, injured, or disorientated animals being driven ashore due to different factors, such as diseases [3,4,6,32], morbillivirus infections, particularly in striped dolphins (*Stenella coeruleoalba*) and pilot whales (*Globicephala melas*) [32–36], auditory trauma [31], parasitism [3,31,32], harmful algal toxin blooms [3,9,29,32,37], predatory attacks [32], and rock and sand ingestion [32].

Other causes include the coastal configuration, oceanographic events, topographical factors or turbulent weather [31,38], geomagnetic topography and navigational errors [4,32], wind anomalies and climate change [1,3,12,39,40], and shifts in prey distribution and availability [1].

1.2. Spatial Distribution and Numerical Trends of Strandings

The high-fidelity location of the stranding record implies that the ecological structure of living cetacean communities is recorded in the death assemblage [9]. The spatial distribution patterns and the trends of cetacean incidents may be the result of natural distribution, population changes, and the composition of cetacean populations, along with human population density, the reporting effort of a greater number of observers in populated areas, and accessibility of the coast [9,38,41].

1.3. Mass Live Strandings without a Known Cause

Single dead strandings are scattered around the coast, as opposed to live strandings, which are highly correlated with their natural distribution. This is not merely a result of high cetacean numbers in stranding hotspots [42]. Single strandings can often be explained upon post-mortem or necropsy examinations (without these it is often difficult to ascertain the cause of death). Species that live in small groups or are solitary, mainly mysticetes, are rarely found in mass live strandings [2]. Species involved in mass strandings are organized in large social groups and mostly belong to odontocetes [7,8,38,42,43]. Mass strandings accounted for 20% of the stranding episodes in Tasmania from February 1978 to May 1983 [38] and were the leading type of strandings in three of the four small cetacean species in the USA from 2000 to 2006: *Lagenorhynchus acutus* (69%), *Globicephala melas* (71%), and *Delphinus delphis* (61%) [32].

1.4. Proposed Explanations for Mass Live Strandings

As explained previously, various human or natural factors can explain single strandings, whereas mass strandings are the result of a complex combination of causes, likely associated with behavioral factors [2,6,8]. Some suggested theories of mass strandings include entrapment due to unusually falling tides; sick, injured, or senile leaders who are followed by the group; following ancient migratory routes; response to over-population; phases of the moon; auditory trauma; presence of pollutants in the environment; parasitism; meteorological or oceanographic events; coastal topography conditions; or confused echolocation and disorientation caused by geomagnetic factors [2,8,31,36,44]. According to Brabyn [42], some of these theories can be rejected because they do not sufficiently explain the highly concentrated nature of live strandings.

1.5. Aims and Objectives

In this paper, we investigated the possible causes of mass live strandings, which are still unknown and are of great importance for the conservation of marine mammals [8]. This review examines a new hypothesis proposing that anthropogenic radiofrequency radiation (RFR) emitted from radars may interfere with cetacean orientation and communication, intervening in some way in their mass live strandings. In this context, we propose that anthropogenic RFR may be responsible for some mass live strandings for which no plausible explanations have been found so far.

Anthropogenic electromagnetic fields represent a poorly understood, potentially important emission that is increasing in marine environments, possibly disrupting or masking vital environmental cues for electromagnetic-sensitive species [45]. Some authors have warned that anthropogenic electromagnetic fields constitute the fastest-growing form of environmental pollution [46,47] and may be a threat to wildlife orientation [48]. Extended reviews of the effects of man-made electromagnetic fields on animals (including mammals) have recently been published [49,50].

2. Methods

A bibliographic review of the literature on mass live strandings of cetaceans was conducted. For the search, Google Scholar and Web of Knowledge applications were used, employing the keywords: “cetacean strandings” and “mass strandings”. Research articles on one or more cetacean species were considered.

In parallel, a search of accessible databases of military and meteorological radars throughout the world was carried out in the following sources: https://www.radars.org.uk/ (military radars, accessed on 1 December 2023) and https://wrd.mgm.gov.tr/Home/Wrd (meteorological radars, accessed on 1 December 2023). The installation sequence of military and meteorological radars throughout the world and the strandings over the years were considered for possible links with mass live strandings without a known cause to find temporal or spatial patterns in stranding concentrations along the coast or for spatial recurrent concentrations in certain locations.

Finally, to determine whether anthropogenic RFR from military and meteorological radars caused some of these strandings from a quantitative point of view, we performed a linear regression analysis between the cumulative number of radars and strandings with or without a known cause in the United Kingdom (UK), where the data were more systematically recorded, combining the military radar dataset covering the period 1913–2015 (https://www.radars.org.uk/, accessed on 1 December 2023) and the stranding data extracted from Coombs et al. [51].

3. Results

The bibliographic review revealed numerous studies showing an increase in the number of cetacean strandings over the last few decades [11,51–55], but it is not yet clear whether this increase is associated exclusively with the increased detection capacity due to human presence and greater surveillance of the coasts. For North America and the UK, there has been a dramatic increase in the number of stranding reports since 1970, particularly since 1990, most likely due to an increase in fishing activities and efforts by the public to report strandings [12,56]. The high increase in porpoise strandings, mostly observed since 2000 along the Dutch, Belgian, and northern French coasts, was consistent with local visual surveys [57].

There has been a continuous increase in strandings in the 20th century along the UK and Irish coasts, especially since the 1970s/1980s [51,52] and between 2002 and 2014 [54]. There has been an increase in reported strandings of the sperm whale (*Physeter macrocephalus*) in Northwest Europe [28]. There has been a general trend of increasing stranding events without a known cause in the Philippines since 2004 [11]. On the Galician coast (Spain), there is a clear increase in the analysis of live or recently dead specimens, and the increased monitoring of the coasts does not fully explain this trend [58]. In Western Australia, the recorded mortality of stranded humpback whales (*Megaptera novaeangliae*) is increasing, irrespective of the number of observers [53]. Reports of cetacean strandings in Chile have increased steadily over time, especially over the past 20 years, and the authors urge an immediate response to understand the unknown causes of this phenomenon [55].

Since World War II, numerous air and naval military radars have been installed along coasts worldwide [59]; more recently, many meteorological radars have been added (Figure 1). In recent decades, strandings have become more prominent in the literature [11,28,51–55,58].

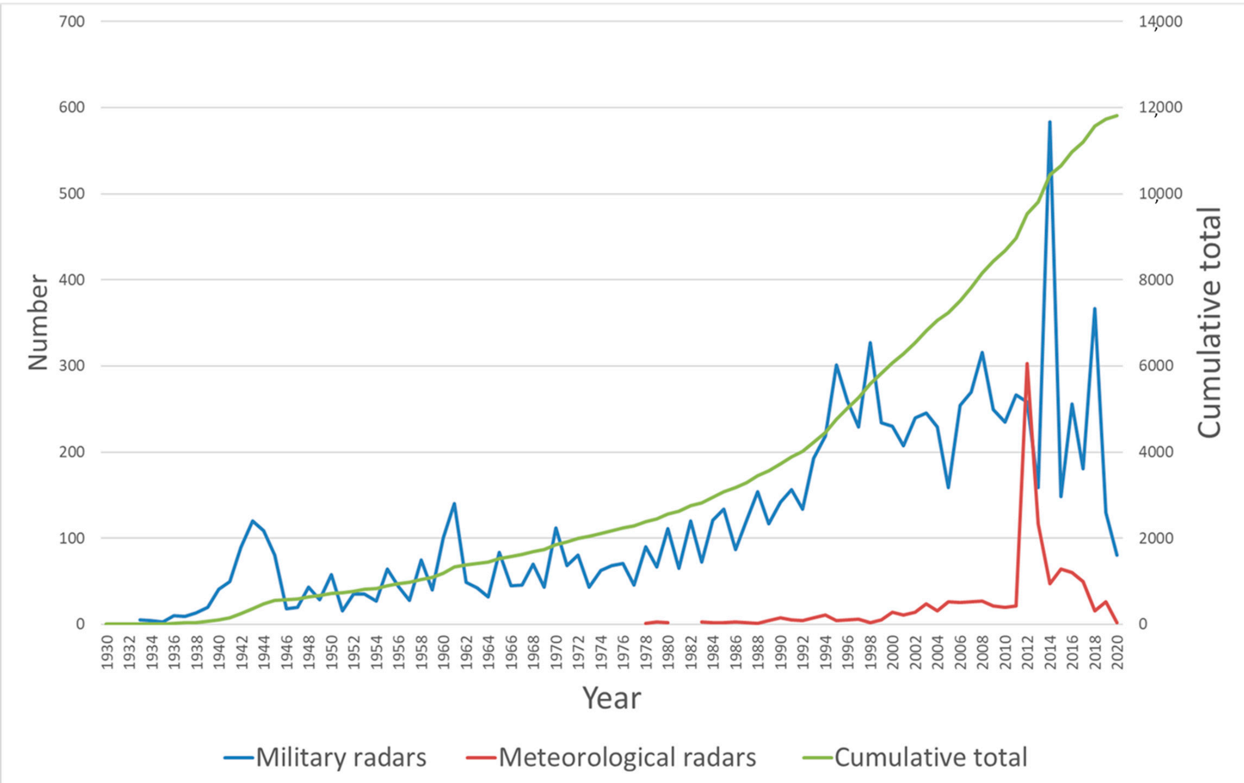

Figure 1. Trends of the installations of military and meteorological radars in the world, as well as the cumulative trend for radars from both sources. Source: https://www.radars.org.uk/ (military radars, accessed on 1 December 2023) and https://wrd.mgm.gov.tr/Home/Wrd (meteorological radars, accessed on 1 December 2023).

Linear regression analysis of the cumulative number of military radars (https://www.radars.org.uk/) and stranding records (with animals involved in mass strandings counted individually) in the UK [51] shows a positive relationship (R^2 = 0.67, p < 0.01; Figure 2). Based on the coefficients obtained from the model, the fitted regression is $\log_{10}(y) = 0.0013\ (x) + 1.373$.

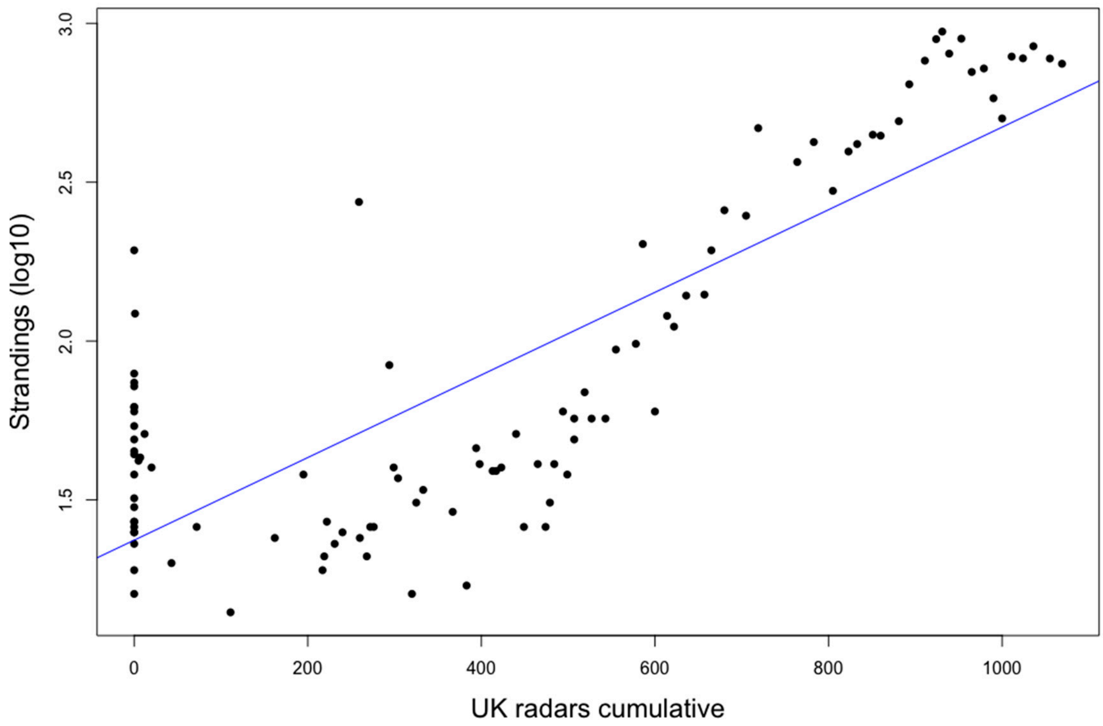

Figure 2. Linear regression relationship between the cumulative number of military radars in the UK from 1913 to 2015 and stranding records (individual animals, log 10) from Coombs et al. [51] (dataset from https://doi.org/10.5519/qd.k5cfxhlg, accessed on 1 December 2023). Although only military radars from the UK were considered, stranding records include those from the UK and Ireland.

We identified a total of 31 studies in the literature reporting concentrations of strandings in time and space with unknown causes (Table 1). These studies were carefully assessed to identify radars in their vicinities (~50 km) using public databases and visual inspections of the areas in Google Earth (Table 1). Radars were found in 65% (20 out of 31) of the cases where strandings occurred. The fact that many of the radars are set up in protected areas makes this task complicated and we cannot guarantee that other radars are not present in the surroundings. After discarding studies with missing radar running dates, scattered data, anecdotical events, or those conducted prior to the radar setup, we ended up with eight studies (seven with spatial visualizations and three with temporal comments; see considerations in Table 1), which we reviewed in depth.

Regarding the spatial concentrations of strandings, we found seven articles showing clear patterns of increased stranding concentrations along the coast following radar installation (Figure 3). Most strandings in these areas were from unknown causes and included dozens to hundreds of records.

Table 1. Studies reporting stranding events with unknown causes, indicating the species, area, time frame, and information on the closest military and meteorological radar(s) and their running dates. The methodological considerations of the studies and their inclusion in the spatial (S) and temporal (T) sections are also included.

Reference	Study Species	Time Period	Study Area	Closest Radar(s) Found	Date	Considerations	S	T
Leeney et al., 2008 [12]	Cetaceans	1911–2006	UK (Cornwall and the Isles of Scilly)	Cornwall meteorological radar (Predannack)	1986		Yes	Yes
Pikesley et al., 2012 [60]	Cetaceans	1991–2008	UK (Cornwall and the Isles of Scilly)	Cornwall meteorological radar (Predannack)	1986	Data after radar setup	Yes	
Podesta et al., 2006 [61]	Cuvier's beaked whales	1803–2003	Mediterranean Sea	Marconi radar	1962		Yes	Yes
Bogomolni et al., 2010 [32]	Marine mammals	2000–2006	USA (Massachusetts)	Cape Cod Air Force Station	1980	Data after radar setup	Yes	
Maldini et al., 2005 [62]	Odontocetes	1950–2002	USA (Hawaii, Oahu)	Pearl Harbour base	1941	More prospection in that island		
Lloyd and Ross, 2015 [41]	Cetaceans	1970–2013	Australia (NSW)	Woolloomooloo base	1941	Data after radar setup; scattered stranding hotspots		
D'amico et al., 2009 [24]	Beaked whales	1874–2015	Global	Yokosuka naval base	1951	Strandings linked to naval sonars		
Brownell et al., 2009 [63]	Pygmy killer whales	1968–2006	Taiwan	Tainan and Kaohsiung military bases	-	Without radar running date		
Masski and De Stéphanis 2018 [64]	Cetaceans	1980–2009	Morocco	1: Tarifa radar 2: Casablanca marine base	1: 2009 2: -	Data before radar setup		
Groom and Coughran 2012 [5]	Cetaceans	1981–2010	Australia (WA)	Perth meteorological radar	2009	Data before radar setup		
Mcgovern et al., 2016 [54]	Cetaceans	2002–2014	Ireland	-	-	Radar not found		
Walker et al., 2005 [31]	Cetaceans	1977–2001	USA (Florida)	Key West meteorological radar and naval air station (south Florida)	2012	Data before radar setup		
Gonçalves et al., 1996 [65]	Cetaceans	1992–1996	Portugal (Azores)	-	-	Radar not found		
Pimper et al., 2008 [66]	Sperm whales	1977–1981	Argentina (Tierra del Fuego)	-	-	Radar not found		
Mazzariol et al., 2011 [67]	Sperm whales	2009	Italy (Adriatic)	Remote radar squadron and Jacotenente Air Force detachment	1963	Only one stranding event after radar setup		
Bearzi et al., 2011 [1]	Sperm whales	1955–2009	Italy (Adriatic)	Potenza Picena radar	1970–1998	Strandings scattered in time		
Song 2016 [19]	Cetaceans	1997–2004	Korea	-	-	Radar not found		
Augé et al., 2018 [10]	Cetaceans	1980–2015	UK (Falkland Islands)	Mont Pleasant Air Base	1986	Scattered stranding hotspots; reliable only from 2007		
Aragones et al., 2010 [29]	Marine mammals	1998–2009	Philippines	-	-	Radar not found; scattered stranding hotspots		
Borsa 2006 [68]	Marine mammals	1877–2005	New Caledonia	-	-	Radar not found		
Caracappa et al., 2018 [69]	Striped dolphins	2013–2016	Sicily	Sigonella Naval Air Station	1959	Data after radar setup; some morbillivirus effects	Yes	
Coughran et al., 2013 [53]	Humpback whales	1989–2012	Australia (WA)	-	-	Radar not found		
López et al., 2002 [58]	Marine mammals	1990–1999	Spain (Northwest)	Iroite military radar	1980	Data after radar setup	Yes	

Table 1. *Cont.*

Reference	Study Species	Time Period	Study Area	Closest Radar(s) Found	Date	Considerations	S	T
McManus et al., 1984 [38]	Cetacean strandings	1978–1983	Tasmania	Hobart Military and Naval Base	-	Without radar running date		
Meynecke & Meager 2016 [18]	Humpback whales	1989–2014	Australia (Queensland)	1: Ipswich Base 2: Marburg meteorological radar 3: Brisbane meteorological radar	1: 1938 2: 1993 3: 2005	Difficult to correlate strandings and localities	Yes	
Rojo-Nieto et al., 2011 [70]	Cetaceans and sea turtles	1991–2008	Spain and Morocco	Tarifa radar	2009	Data before radar setup		
Alvarado-Rybak et al., 2020 [55]	Cetaceans	1968–2020	Chile	Bío Bío radars	2016	Only one stranding event after radar setup		Yes
Brabyn 1991 [42]	Cetaceans	1840–1989	New Zealand	-	-	Radar not found		
Brabyn & McLean 1992 [71]	Cetaceans	1840–1993	New Zealand	-	-	Radar not found		
Sundaram, 2006 [36]	Whale strandings	1850–2005	USA (Massachusetts) and New Zealand	-	-	Radar not found		
IJsseldijk et al., 2018 [72]	White-beaked dolphins	1991–2017	North Sea	-	-	Radar not found		

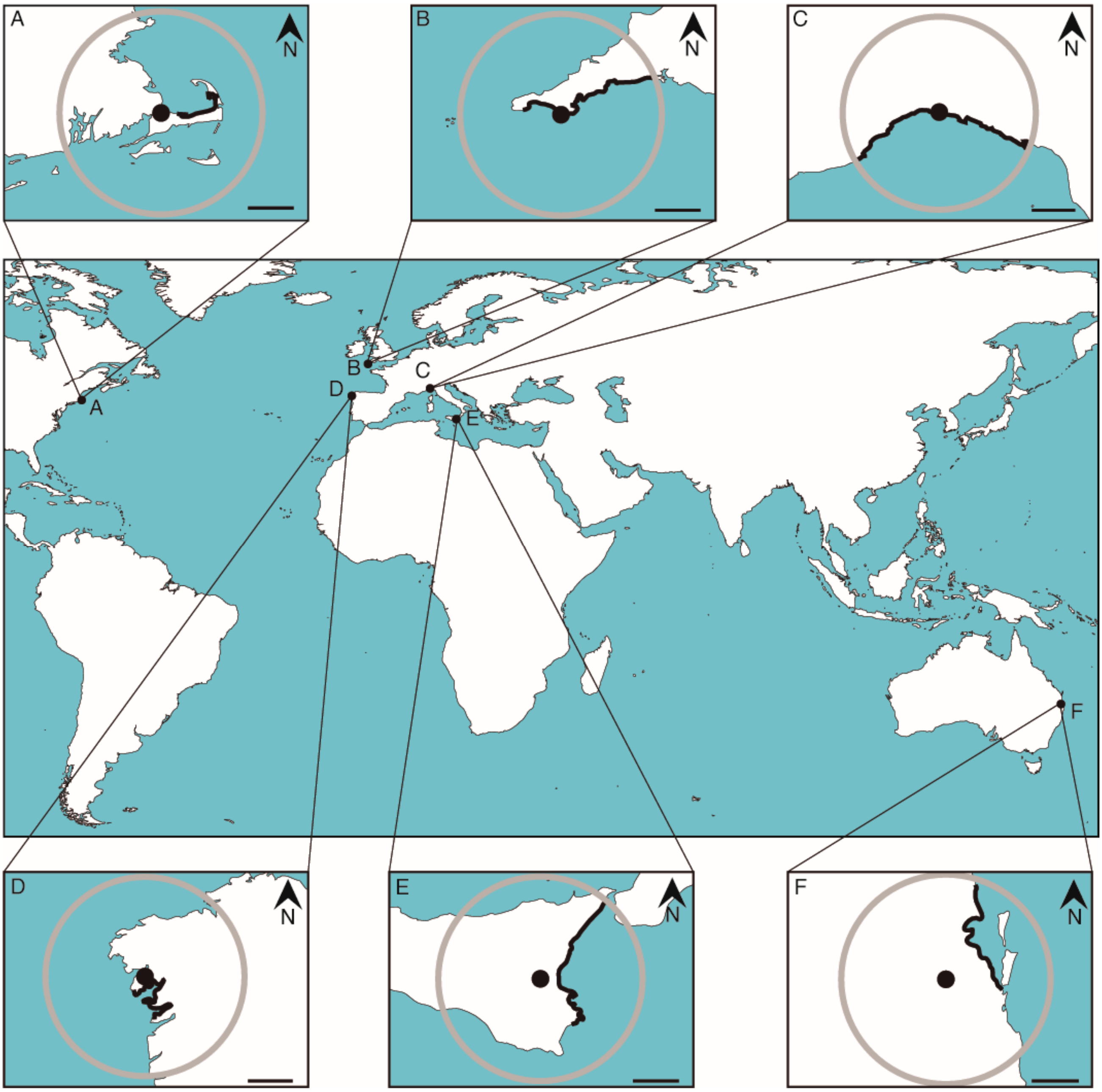

Figure 3. Unexplained accumulation of strandings observed in bibliographic reviews of different areas around the globe following radar installation (black dots). Grey circles in the small panels represent a buffer of ~100 km covering the area most affected by radar radiofrequency radiation, and the thicker black coastline indicates areas with a high number of stranding records described in the literature ((**A**) [32]; (**B**) [12,60]; (**C**) [61]; (**D**) [58]; (**E**) [69]; and (**F**) [18]). The military and weather radar stations and their running dates are as follows: (**A**), Cape Cod Air Force Station (Massachusetts, 1980); (**B**), Predannack (UK, 1986); (**C**), Marconi (Italy, 1962); (**D**), Iroite (Spain, 1980); (**E**), Sigonella Naval Air Station (Sicily, 1959); and (**F**), Ipswich (Australia, 1938). The scale bar represents 50 km.

In addition, we found some supplementary temporal evidence. In November 1962, a radar was installed in Genoa (Italy), dedicated to Marconi (Figure 3C). The first recorded mass stranding event in Genoa occurred in January and February of 1963 [61]. The Cornwall weather radar in Predannack (UK) was built in 1986, which is when strandings in the area started to increase [12]. In 2017, several strandings were reported in the Bio Bio region of Chile [55]; two weather radars were installed in the area in 2016.

4. Discussion

This manuscript proposes a possible hypothesis to explain the massive cetacean stranding problem, which has not been evaluated until now, and the results show certain patterns of spatial and temporal evidence for stranding concentrations following radar setup (Figures 2 and 3). Although the obtained regression is not demonstrative of causality, the results of the analysis carried out are indicative; thus, the existence of a relationship between the implementation of radars and the occurrence of massive strandings is plausible.

Although it could be argued that radar waves do not affect cetaceans because they live underwater, it is well known that RFR can penetrate water up to a certain depth. For instance, other electromagnetic radiation with shorter wavelengths, such as visible light, penetrate dozens of meters into the water in the photic zone. On the other hand, many species of cetaceans, such as pilot whales or dolphins, spend a lot of time on the surface, with part of their body out of the water due to how they move, and their need to breathe.

4.1. Magnetoreception in Cetaceans and Its Involvement in Mass Live Strandings

There is accumulating evidence indicating that the magnetic sense plays an important role in cetacean orientation and migration. Whales follow features of the geomagnetic field for long-distance navigation to guide migration and live strandings are associated with anomalies in this geomagnetic field [2,44,73–77]. Thus, one plausible explanation for live strandings is the disorientation of migrating cetaceans, triggered by solar storms that cause disturbances in the geomagnetic field due to variable energy fluxes coming to the Earth from the sun [76,78,79].

Sunspots are strongly correlated with solar storms, and RFR from solar storms is closely associated with strandings in grey whales [4] (Figure 4). The relationship between historical stranding data for the grey whale (*Eschrichtius robustus*) and two aspects of Earth's magnetosphere that are altered by solar storms, namely radiofrequency noise and displacements in the Earth's magnetic field, have shown that an RFR broadband causes the strandings [4]. These results suggest that the increase in strandings under high solar activity is best explained by an effect on the sensor, not on the magnetic field itself [4], and this is consistent with the radical pair hypothesis of magnetoreception, which is predicted to be disrupted by the radio frequency [80].

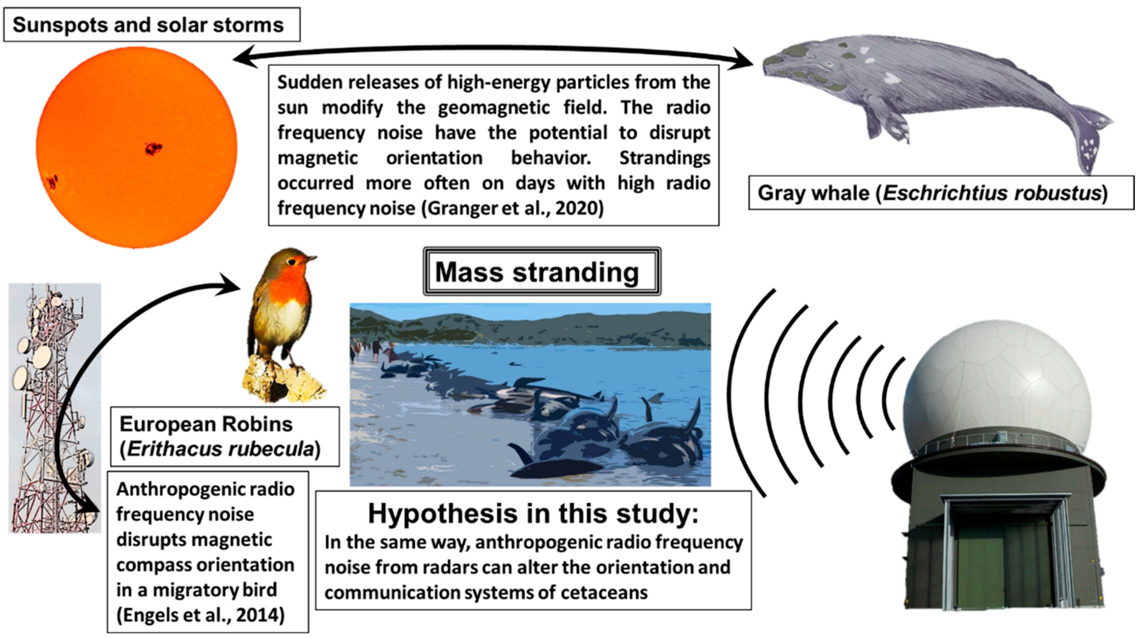

Figure 4. The hypothesis proposed in this study taking into account the studies of Granger et al., 2020 [4] and Engels et al., 2014 [81].

4.2. Anthropogenic RFR May Have the Same Effects

Research conducted on migratory birds showed that RFR interferes directly with the primary processes of magnetoreception and disables the avian compass as long as they are present [80,82]. Other researchers have confirmed that migratory birds are unable to use their magnetic compasses in the presence of urban electromagnetic noise, and anthropogenic radiofrequency electromagnetic fields disrupt the function of their sensory systems [81]. Radiofrequency electromagnetic noise also disorients mice and arthropods [83,84], and this effect is not restricted to a narrow frequency band [81]. Low intensities of RF fields alter the response of the mouse magnetic compass [85]. A study by Bartos et al. [86] provided evidence that weak broadband radiofrequency noise can impact the clock of the German cockroach (*Blatella germanica*); the low-frequency modulation of man-made RFR may be responsible.

Since RFR interferes specifically with radical-pair magnetoreception mechanisms [87,88], similar mechanisms may explain orientation alterations in cetaceans. With the currently available knowledge on the interference of RFR with the magnetoreception process [48], it is plausible that radars installed by humans (operating in the order of a few GHz) could disorient cetaceans and intervene in mass live strandings (Figure 4). A study of the effects of airport radars on birds provided evidence that birds can detect the radars' presence, and slight differences in power density and pulse properties can potentially alter avian behavior [89].

4.3. Plausible Action Mechanisms

The radar typically consists of a repetitive string of short-duration pulses, while the carrier is a radiofrequency signal. There are several ways by which the radiofrequency pulses from the radars can cause strandings. On the other hand, it is well known that sonars are harmful to cetaceans [20,25]. Together with sonar, radars may be carried by ships, and radars on navy vessels may be especially powerful. In a recent review of cetacean strandings, 27 mass stranding events occurred near ships and naval bases without evidence of sonar use [24]. Therefore, these effects are independent but possibly complementary to those caused by sonars, which are already well-recognized by the scientific community [20,24,61,90,91].

4.3.1. The Thermoelastic Expansion Mechanism

Human auditory perception of pulsed RFR has been reported since the 1940s and could be a result of the thermoelastic expansion mechanism [92–96]. All subjects heard a buzzing sound at a pulse repetition rate (PRR) greater than 100 pulses/s, whereas individual pulses were heard at a PRR below 100 pulses/s [95]. Cetaceans may be highly sensitive to the thermoelastic effects of the radar pulses, even more so than humans, since they perceive pulses much closer in time even when the distance between pulses is milliseconds [97]. It would take RFR of lower frequencies to cause this effect in large animals, such as whales, than it would in humans, and maybe the different cetaceans require different resonance frequencies for auditory effects to occur, due to their size.

4.3.2. Delphinid Vocalizations

Delphinid vocalizations have two functional classes: echolocation clicks, used for navigation and orientation in the ocean, and burst-pulsed sounds and frequency-modulated whistles, used for communication purposes (social signals) [97]. Cetaceans may use high-frequency (50–200 kHz) pulses for detecting prey whereas pulses of lower frequencies (down to 20 Hz) are prefered for communication and navigation [36]. Thus, radar pulses could interfere with both echolocation and communication tasks.

4.3.3. Interference with Echolocation Systems

Odontocetes use echolocation both for the detection of prey and for navigation. For instance, dolphins possess a well-developed auditory system, conceivably the most developed one among animals; they can hear in a large frequency range and have a great ability to perceive extremely short signals of tens of microseconds [36,97]. Specific characteristics of the cochlea and the auditory nervous system suggest a greater need for details and rapid processing of acoustic information in the aquatic environment, which transports sound more rapidly than air does [97].

4.3.4. Interference with the Pulse Communication Systems of Odontocetes

All odontocetes produce specific burst-pulsed sounds with high repetition rate (> 300 pulses per second) or low inter-pulse intervals (<3 ms; [97]). Radar may simulate these communication pulses and confuse them. In this case, mass strandings would occur particularly in the more social species that usually form pods, such as pilot whales and dolphins.

The posterior throat of the melon appears effective as a partial waveguide, whereas the larger forward lobe of the melon operates as a lens in the acoustic emission process [97] and may be highly sensitive to the thermoelastic effect of radar pulses. Odontocetes are most frequently involved in mass live strandings [82], and this could also explain the stubbornness of returning again and again to the coast, a frequently seen scene when rescue teams try to return the animals to the open sea.

4.3.5. Other Possible Mechanisms

Further, there are other well-known mechanisms of action of low-frequency pulsed RFR. Some of the disruptive effects of RFR may be associated with interference with voltage-gated calcium channels in cells [98–103] and interference with brain waves [104–106]. However, some studies in foraging bats, another well-known echolocating mammal, have shown that the electromagnetic radiation associated with radar installations can elicit an aversive behavioral response that deters these animals from going near wind turbines [96]; this may be an argument against radar/RFR being a cause of mass strandings of cetaceans.

5. Conclusions

There are many mass strandings events with unknown causes that demand to increase the efforts to describe new threats to cetacean species. In this review we have found radars in close proximity (~50 km) in more than half of the studies analyzed, showing patterns of spatial and temporal accumulation across different coasts of the globe. The information provided in this manuscript may be useful to other researchers studying strandings, correlates of strandings, and radar/radio frequency interference, in order to make progress in cetacean conservation.

We also underline the importance of conducting exhaustive local studies to verify the proposed hypothesis. As there may be radars distributed with some frequency along each coast, we suggest confirming these patterns to determine the direct impact of radars in specific areas (e.g., assessing the number of stranding events in the area before and after radar setup). Since different types of radars (such as weather and military radars) emit different frequencies and pulse rates of radiation with different depths of penetration in water, they may have different stranding effectiveness. One measurement for directly experimentally analyzing the impact on behavior may consist of turning the radar off when a flock approaches or mass stranding occurs, as is done with wind turbines when a flock of birds is approaching, and checking if this action changes their behavior, e.g., they move towards the sea once again.

Along with other natural sources of radiofrequency radiation, the anthropogenic radar pulses must be included as a source of sound in the ocean soundscape that has not been considered yet [107]. The precise potential effects of an increase in electromagnetic radiation on wildlife (such as interference with echolocation systems or pulse communication systems studied in this work), which are not yet well recognized by the global conservation community, have been identified as an important emerging issue for global conservation and biological diversity [108].

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