



Forecasting the consequences of climate-driven shifts in human behavior on cetaceans

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ABSTRACT

While climate change is expected to affect cetaceans primarily via loss of habitat and changes in prey availability, additional consequences may result from climate-driven shifts in human behaviors and economic activities. For example, increases in shipping, oil and gas exploration and fishing due to the loss of Arctic sea ice are highly likely to exacerbate acoustic disturbance, ship strikes, bycatch and prey depletion for Arctic cetaceans. In the tropics, climate change may result in increased hunting pressure on near-shore dolphins and whales off Asia, Latin America, Africa, and elsewhere as the availability of other marine resources diminishes. This study explores the range of potential consequences to cetaceans worldwide from predicted climate-driven shifts in human behavior, and evaluates the risks to particular species given their geographic ranges and habitat preferences. While concern about impacts of climate change on cetaceans has largely focused on polar species, the analysis presented here suggests tropical coastal and riverine cetaceans such as the Irawaddy dolphin, Indo-Pacific humpback dolphin, and finless porpoise are particularly vulnerable to those aspects of climate change that are mediated by changes in human behavior. Policy recommendations include the following: (1) information about cetacean populations should be incorporated into national, regional and international climate adaptation decisions wherever possible (for example, via GEF-sponsored adaptation initiatives); and (2) human-mediated impacts of climate change should be included in cetacean conservation and management plans, such as the management procedures of the International Whaling Commission (IWC), where possible. Because human responses to climate change are likely to evolve rapidly over the coming years and decades, it is important that local, regional and international cetacean conservation and management plans include regular reviews to allow them to adapt to new information.

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1. Introduction

Climate change is expected to affect cetaceans primarily via loss of habitat (given the distinct thermal ranges of most species), changes in prey availability, quality and distribution, and potentially increased competition from range expansions of other species [1–4]. However, changes in human behavior or activities resulting from increasing temperatures, flooding, storm surges, aridity, decreasing ice cover and other environmental shifts may also impact cetacean populations. For example, reduced ice cover in the Arctic is projected to lead to increased shipping, oil and gas exploration, and fishing [5], which will result in additional noise

and chemical pollution in marine ecosystems, among other effects. Würsig et al. [6] classify these impacts as “tertiary effects” based on a framework that defines primary effects of climate change as impacts at the individual level, and secondary effects as impacts at the population level mediated by changes in prey or habitat. Though the importance of these human-mediated or tertiary effects on wild marine populations has not been quantified, it is likely that for particular populations and regions they could equal or even outweigh the primary and secondary effects of climate change on cetaceans [2,6].

Furthermore, while designing management initiatives to mitigate the direct effects of climate change on cetaceans is difficult given the current state of knowledge, devising precautionary policies to address tertiary effects (as well as attempting to reduce non-climate related stressors) may be a more practical approach. Currently, numerous governments including the UK, Finland, Germany, the US and Canada, are developing climate adaptation plans and the United Nations Development Pro-

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gramme's (UNDP's) Global Environmental Facility (GEF) is coordinating a response plan among nations at a larger scale. It is important and timely, therefore, to ensure that effects on cetacean populations are considered in policy decisions regarding adaptation to climate change.

This study explores the range of potential human-mediated or tertiary effects of climate change on cetaceans, along with the physical and biological changes underlying them. In addition, factors that may make particular cetacean taxa especially sensitive to human-mediated climate impacts are discussed. Finally, the international and country-specific regulatory frameworks that may be useful in managing human-mediated impacts to cetaceans are reviewed. This review is specifically focused on threats deriving from climate-induced changes in human behavior, rather than the more general topic of direct impacts of climate on cetaceans, which have been covered in depth in other studies [e.g., 1,2,3,7].

2. A summary of human-mediated impacts of climate change on cetaceans

Despite broad uncertainties in how the earth's climate will change in the future and human responses to those changes, emerging trends can be used to build predictions about the human-mediated impacts of climate change. Numerous physical and biological changes have already been observed and attributed to climate change, including diminishing sea ice, changes in terrestrial and marine surface temperature, sea level rise, changes in ocean circulation, rainfall, and storm severity. According to the most recent Intergovernmental Panel on Climate Change (IPCC) report, eleven of the last twelve years (1995–2006) rank in the twelve warmest years since instrumental record keeping began (1850) [8]. Human societies and economies have begun to adapt to all of these changes, with many implications for cetacean populations.

The effects of climate change on human societies are unlikely to be uniform around the world, as particular areas will experience more severe impacts on physical and biological systems, and some societies have less economic or cultural capacity to adapt. Therefore, human-mediated impacts of climate on cetaceans are also likely to be concentrated in certain regions and, as such may have disproportionate effects on certain species or communities. The 2007 IPCC report [8] lists four regions that are “likely to be especially affected by climate change”:

- the Arctic (due to high rates of warming and impacts on natural systems and human communities).
- Africa (because of low adaptive capacity in the face of projected climate change impacts).
- Small islands (due to high exposure to climate change impacts).
- Asian and African megadeltas (because of large population concentrations and high exposure to sea level rise, storm surges and flooding).

Below, the major physical and biological changes in marine and coastal environments expected to result from climate change are reviewed, and the ways in which these changes may impact human behavior with cascading effects on cetacean populations are explored. Results are summarized in Table 1.

2.1. Decline in sea-ice extent

Since 1978, annual average Arctic sea extent has diminished by 2.7% per decade (with a decrease in summer ice of 7.4% per

decade) [8]. Under some IPCC scenarios, Arctic late-summer sea ice is projected to disappear altogether by the last half of this century [9]. The annual temperature in the Arctic has increased at nearly twice the rate of the rest of the globe over the past several decades [10].

While reductions in sea ice are likely to have numerous direct effects on Arctic cetacean populations, indirect effects from increasing human activities in newly ice-free areas may also have large impacts. It is highly likely that sea ice reduction will result in increased shipping as the navigational season is extended and seasonal passage through the Northwest Passage (NWP) and the Northern Sea route becomes more consistent [10,11]. Increasing ice movement may make particular channels of the NWP more difficult to navigate initially [12]. Ships using a westerly route from the Pacific to Atlantic Oceans will be forced to use the Bering Strait, resulting in a high concentration of traffic in this region. Oil and gas exploration and extraction are also increasing in the Arctic, and development of unconventional mineral resources such as large offshore deposits of heavy oil, coalbed methane and methane hydrate deposits may occur as existing reserves are depleted. Likewise, future fishing pressure is likely to increase in the Arctic as fisheries productivity grows and the fishing season lengthens in ice-free areas [10,12].

Impacts to Arctic areas from reduced sea ice are likely to differ by region. In the North Atlantic sector (East Greenland, Iceland, Scandinavia, Northwest Russia and adjacent seas including the Barents and Kara Seas), oil, gas and mineral extraction and fisheries are likely to increase. Development of oil resources in this region is likely to include additional marine terminals and Arctic tanker traffic [13]. Shipping increases could have a large effect in the Siberian region as navigational opportunities through the Northern Sea route improve. In the western Arctic Seas (Chukchi and Beaufort Seas, Mackenzie Delta), increases in oil and gas exploration are ongoing and may be stimulated by the completion of the Mackenzie Valley gas pipeline. The central and eastern Canadian Arctic and West Greenland are likely to experience increases in shipping through the Northwest Passage, and possibly increases in fisheries as new species such as haddock, herring and tuna shift their ranges northward [10].

Increasing human activities in the Arctic may have both acute and chronic effects on cetacean populations. Increased ship traffic is likely to result in a higher incidence of mortality or serious injury due to ship strikes. In addition, low-frequency (< 1000 Hz) shipping noise can mask sounds that baleen whales use for communication, potentially affecting critical behaviors such as mating, foraging and migrating, and can cause other behavioral disruptions. Shipping is thought to be the primary source of overall anthropogenic noise in the oceans [14]. While concern over auditory masking or behavioral disruption has focused on baleen whales, due to the fact that their use of sound overlaps with the main frequency band of shipping noise, broadband cavitation noise from fast-moving vessels may also transmit higher frequencies with potential effects on toothed whales [15] such as beluga (*Delphinapterus leucas*) or narwhal (*Monodon monoceros*).

Like shipping, fisheries and oil and gas development also present both acute and chronic risks to cetacean populations. An increase in fishing activity presents direct risks of mortality or serious injury from bycatch [16], and indirect threats from prey depletion [17–19]. A catastrophic oil spill could be extremely harmful to bowhead (*Balaena mysticetus*), beluga, and narwhal populations, particularly if a spill were to occur during overwintering or migration when animals are more constrained by pack ice. While cetaceans are less vulnerable to oiling than many other marine species such as otters and seabirds, oil may harm eyes and baleen and surface vapors may be dangerous if inhaled,

Table 1

Summary of major climatological, oceanographic or ecological impacts of climate change, changes in human behavior expected to occur as a result of these impacts, and potential effects on cetacean species.

Change in physical or biological environment	Potential change in human behavior	Impact on cetaceans	Species that may be affected
Diminishing sea ice	Increased shipping	Acoustic disturbance	Large whales inhabiting Arctic and subarctic waters
	Increased fishing pressure As ice-dependent pinnipeds decline, Arctic communities may shift hunting effort to cetaceans	Depletion of prey base; bycatch Direct hunt	Polar and subpolar cetaceans Arctic cetaceans subject to harvest
Decline of coral reef health	Increase in military presence Displacement of tourism to whale and dolphin-watching	Acoustic disturbance Harrassment, acoustic disturbance	Arctic cetaceans Coastal tropical cetaceans in regions where coral reef tourism is prominent
Warming of high latitude waters	Increase in aquaculture	Coastal eutrophication; cetacean interactions with aquaculture operations may lead to harrassment/culling	Coastal high latitude species, particularly small toothed cetaceans
Drought and decreasing precipitation	Increase in fisheries as target species move north	Increase in bycatch	Polar and subpolar cetaceans
	Decline in food security may result in greater reliance on marine ecosystems for food	Prey depletion; direct catch of cetaceans for food	Tropical coastal cetaceans in EEZs of drought-prone nations
	Increase in human migration to coastal areas Increase in desalination	Increase in urban and agricultural runoff, potential increases in tourism Localized disturbance	Tropical coastal cetaceans in EEZs of drought-prone nations Coastal cetaceans of drought-prone nations, particularly those that use shallow lagoon or bay habitat
	Increase in intensive agriculture	Increase in anoxic zones and potentially HABs	All coastal cetaceans in drought prone nations, particularly those near river mouths
Warming of high latitude terrestrial ecosystems	Increase in human densities and terrestrial activities (e.g. agriculture)	Increase in urban and agricultural runoff, potential increases in tourism	Subpolar and polar coastal cetaceans
Increase in storm severity	Construction of breakwaters, jetties, etc may increase coastal noise propagation	Acoustic disturbance	Coastal cetaceans
Sea level rise	Coastal construction projects (dykes, etc) to manage flooding	Habitat fragmentation	Coastal cetaceans (particularly estuarine and riverine)
	Land acquisition and creation of marsh and wetlands	Habitat loss; introduction of foreign contaminants and disease	Coastal cetaceans (particularly estuarine and riverine)
	Construction of wind, wave and tidal generators	Acoustic disturbance; potential for habitat disruption or displacement; collisions	Cetaceans in areas with high potential for renewable energy
New focus on renewable energy sources	Increase in hydroelectric power sources	Destruction of freshwater habitat for cetaceans and prey	Riverine and estuarine cetaceans; species that depend on freshwater fish prey

and oil spills may have long-term impacts on prey populations including fishes and benthic invertebrates [13]. Spills in the Arctic Seas are more difficult to contain and respond to because of the difficulties of operating in sea ice. Populations of cetaceans may also be at risk from cumulative effects of chronic oil pollution from small tanker spills, pipeline leaks and other accidents. Further, petroleum hydrocarbons persist longer at low temperatures, increasing the susceptibility of Arctic wildlife to long-term cumulative impacts from these substances [13].

In addition, the exploration of the sea floor for oil and gas resources involves seismic testing. The loud, broadband sounds produced by seismic airguns have been shown to cause avoidance and other behavioral responses in gray (*Eschrichtius robustus*), bowhead, and beluga whales (in addition to other species) [20–22]. Seismic impulses can travel for long distances, and in some cases have been detected over 3000 km from the source [23]. Of particular concern for migratory species such as bowhead whales is the possibility of multiple seismic operations at the same time that could effectively create a wall of sound through which whales would be unwilling to pass or which might displace them from important habitat such as feeding grounds. Seismic airguns may also affect cetacean prey including fish and squid [24,25].

Other changes in human behavior from loss of sea ice include a potential increase in military activity as ice-free zones are claimed

by various nations, and increased hunting effort targeting cetaceans for food resources as ice-dependent seals and walrus become less available. While the harvest of Arctic cetaceans has generally been closely managed [e.g., 26], unsustainable harvest has been cited as a primary cause of decline in Cook Inlet beluga whales [27] and West Greenland beluga whales [28]. Nielsen [29] presents evidence that changing ice conditions are increasing the take of narwhals in Siorapaluk, Greenland. Effort has not increased and the hunters attribute the significantly increased take since 2002 to changed sea ice conditions that allow access by boat to Smith Sound as early as June or July. Nielsen [29] suggests that this indicates that climate change will have a considerable impact on narwhal hunting in northern Greenland.

However, it is important to recognize that marine mammal harvests may also become more unpredictable as spring pack ice and wind conditions change. Hovelsrud et al. [30] conclude that many of the consequences of climate change are likely to be negative for marine mammal hunters as well as marine mammals. They postulate that hunting will be affected by changing ice conditions; shifting species abundance and distribution; introduction of new species; increased ocean temperature; and changes in marine mammal health and reproduction. This could cause a shift in hunting pressure to other species and/or increased pressure on other stocks. Hovelsrud et al. [30] comment that sea ice conditions may become more hazardous to the point at which

traditional knowledge would have been 'supplemented with modern technology' and they note that already many hunters carry small boats on their sledges to avoid becoming stranded.

The potential for increases in takes by subsistence hunters has been recognized by certain management organizations, like the International Whaling Commission (IWC) [26]. For example, simulation testing of the Strike Limit Algorithms (SLAs) used to set quotas under the Aboriginal Whaling Management Procedure (AWMP) of the IWC is based on a range of plausible parameter space designed to evaluate (among other factors) the performance of the SLAs to a doubling and even tripling of need over a 100 year time frame. To the extent possible, these trials integrate the uncertainty inherent in anticipating the possible consequences of climate change [31]. In order to ensure that the current state of nature does not fall outside the realm of plausibility envisioned during testing and adoption of the SLAs, Implementation Reviews are scheduled every five years. Further, substantial events (e.g., a spike in need, evidence of mass mortality, etc.) can trigger an Implementation Review during the interim between scheduled reviews. This provides an example of a management strategy which is both precautionary and proactive. In general, all management organizations should formally anticipate the consequences of future climate-driven shifts in human behavior on cetaceans, and regularly review newly available information to ensure that they do not lag behind that potentially rapid evolution of tertiary and other threats.

2.2. Increase in ocean temperatures and ocean acidification

Coral reef systems are highly vulnerable to warming ocean waters and ocean acidification, resulting in projected increases in bleaching events and large-scale mortality. The widespread loss of entire reef ecosystems, particularly in densely populated coastal areas where corals face additional stressors such as run-off, may cause the marine tourism sector to switch or place increased effort on whale and dolphin-watching rather than snorkeling or diving excursions. A growing body of work on the population-level effects of whale and dolphin-watching suggests that these activities can produce significant levels of disturbance [e.g., 32] and require careful management and enforcement. Such displacement is likely to impact all coastal cetaceans in tropical areas where coral reef-based tourism is high [33], and may be a particular problem for species like spinner dolphins (*Stenella longirostris*) in Hawaii, which rest during the day in coastal lagoons that are easily accessible to tour operators.

The redistribution of important fisheries such as tuna or herring to higher latitudes or further offshore may increase interactions with fisheries and habitat disturbance for cetacean populations in mid- and high latitude areas [18]. A recent study predicts that climate change may lead to a 30–70% increase in catch potential in high latitude regions, particularly in offshore regions, and a decline of up to 40% in tropical regions [12]. Catch potential is expected to decrease in enclosed seas such as the Mediterranean Sea and in tropical coastal waters. High latitude areas for which increases are predicted include the North Atlantic, North Pacific, Arctic and northern edge of the Southern Ocean. Expansion of gillnet fisheries for species such as Atlantic cod (*Gadus morhua*) and hake (*Merluccius* spp) pose a particular risk to cetaceans, as gillnet fisheries accounted for the vast majority (84%) of bycatches in a study of US fisheries [34]. As fisheries contract in other regions of the world such as the Mediterranean, cetaceans and fisherman may increasingly compete for fish leading to a greater incidence of harassment [7]. Species such as the Mediterranean common dolphin (*Delphinus delphis*) may thus be affected both by a climate-induced decline in prey including

European anchovy (*Engraulis encrasicolus*), European pilchard (*Sardina pilchardus*), round sardinella (*Sardinella aurita*) and sprat (*Sprattus sprattus*) and by the negative effects of competition (or perceived competition) with fisheries over these species. In addition, as northern water temperatures become more suitable for temperate fish and shellfish species, the aquaculture sector is likely to expand. Deleterious effects of aquaculture operations on small toothed cetaceans can include nearshore eutrophication, loss of coastal habitat, entanglement, and shooting or other harassment [35].

2.3. Increases in terrestrial surface temperature

Over the past 100 years, the Earth's global surface temperature has risen by an estimated 0.74 [0.56–0.92] °C [8]. Continued warming for the next two decades at a rate of roughly 0.2 °C per decade is predicted under a range of emission scenarios, but future warming rates depend greatly on the particular emission scenario. Regardless of the rate, warming is projected to be greatest at high northern latitudes. Warmer surface temperatures will likely result in an increase in human density and agricultural practices at higher latitudes. Resulting urban and agricultural runoff, and potential increases in hunting and tourism, may affect mid- to high latitude coastal cetaceans such as harbour porpoises (*Phocoena phocoena*).

In Arctic communities, warmer terrestrial surface temperatures may lead to more hunting difficulty inland or a decline in terrestrial food resources such as caribou and reindeer (*Rangifer tarandus*) [36] or birds, which may result in additional pressure on marine food resources including harvests of marine mammals. For example, hunters in Barrow, Alaska, typically conduct spring goose hunting inland after the spring bowhead whale hunt. Inland travel depends on a sufficient amount of snow, which has been melting earlier in recent years in Barrow [37]. Likewise, fall snow cover necessary for inland caribou hunting has been developing later than in the past. As these terrestrial resources become less reliably available, it is possible that hunters will increasingly utilize marine food sources. However, as noted above, marine mammal hunting may also become more unpredictable with changing spring ice conditions [30].

2.4. Decrease in precipitation in many terrestrial ecosystems

Since 1900, precipitation has declined significantly in the Sahel, Mediterranean, southern Africa and parts of southern Asia. This trend is very likely to continue for most subtropical land regions as well as other semi-arid areas including the western US, southern Africa and north-eastern Brazil. Water availability is projected to decrease overall by 10–30% in some mid-latitude dry regions and in the dry tropics [8].

Conflicts over food and water resources in areas with increasing aridity and drought may result in greater reliance on marine ecosystems for food, as well as diminished concern/resources for conservation. In some African nations, agricultural yields could diminish by up to 50% due to decreases in precipitation, and food production could be severely compromised [8]. Compounding this problem is continued population growth that is projected to increase global demand for food threefold over the next 50 years [38]. Crop productivity and livestock production may also decrease in parts of Latin America. As increasing aridity affects agricultural practices at lower latitudes, the need for food security may lead to other ecosystem effects including water diversion.

Drought and aridity may cause additional human migration to coastlines in some parts of the world, leading to increases in

coastal development and pollution with a resulting increase in anoxic ocean zones and potentially harmful algal blooms (HABs) in coastal zones. Harmful marine biotoxins have been implicated in the mass mortalities of a number of marine mammal species including humpback whales (*Megaptera novaeangliae*), bottlenose dolphins (*Tursiops truncatus*), Florida manatees (*Trichechus manatus latirostris*) and California sea lions (*Zalophus californianus*) [39–41]. Approximately 37% of the global population in 1994 lived within 100 km of a coastline [42] and this number is likely much higher today. Conflicts over water resources exacerbated by drought may also lead to reduced habitat for freshwater cetaceans, and may disrupt life cycles of anadromous prey species such as salmon. For example in the western US and Canada, warming is projected to result in decreased snowpack, increase in winter flooding and reduction in summer river flows, leading to conflict over allocation of water resources [8]. Habitat destruction in the form of water diversion for agriculture as well as dams has been implicated in the decline in chinook salmon (*Oncorhynchus tshawytscha*) populations in the Pacific Northwest and the failure of Southern Resident killer whales (*Orcinus orca*) to recover [43].

2.5. Increase in sea level rise and storm frequency/severity

Global sea level has risen at a rate of 3.1 mm/yr on average since 1993, and will continue to rise by 0.18–0.59 m by the end of the century [8], although these estimates may be conservative. Sea level rise in low-lying coastal areas will result in inundation, increasing flooding by storm surges, and intrusion of sea water [44]. For example, Nicholls et al. [45] estimate that given a 0.5 m rise in sea level, the number of people experiencing flooding by storm surges in a typical year would increase six-fold. Additionally, the intensity of tropical cyclones is likely to increase [8], resulting in further coastal erosion and damage to coastal infrastructure. The effects of sea-level rise may be exacerbated by drainage and excessive groundwater withdrawal in coastal urban areas. Coastal communities will adapt to these threats through flood management and protection, including the construction of both “hard” protective structures (e.g. seawalls, dikes, levees, floodwalls, revetments, bulkheads, breakwaters, flood-gates and tidal barriers) and “soft” protection (e.g. wetland restoration and creation, beach replenishment, dune restoration and creation) [46]. Small island regions, deltaic areas and coastal wetlands are the most vulnerable to increased flooding [47]. From a regional point of view, the threat of flooding is highest for South and Southeast Asia, Africa, southern Mediterranean coasts, the Caribbean, and most islands in the Indian and Pacific Oceans [45].

Coastal construction to protect against flooding and storm surge may affect cetaceans in several ways. In the short-term, construction may involve localized but intensive noise-producing activities including dredging and pile-driving. Pile-driving creates broad-band noise that can carry for up to 40 km [48]. These loud noises can cause cetaceans to flee the area over short and long periods of time, as has been documented for harbour porpoises [49] and Indo-Pacific humpback dolphins (*Sousa chinensis*) [50]. In the long-term, coastal construction projects can result in habitat loss and/or degradation. Dredging and dumping can result in resuspension of contaminants including heavy metals and persistent organic pollutants contained in seafloor sediments, and land reclamation can permanently remove shallow-water habitat [51]. Coastal construction projects to manage flooding may fragment populations of freshwater dolphins, further disrupting habitat that may already be directly threatened by sea level rise and/or diminished freshwater flows [52]. Off the western coast of Taiwan, extensive seawall construction has been

listed as a possible threat to the endangered Eastern Taiwan Strait population of Indo-Pacific humpback dolphins [53].

Richard et al. [46] note that despite evidence that “soft” protection may be more effective and less ecologically destructive in many areas, hard protection such as seawalls and jetties are often politically preferred perhaps due to their greater visibility and tangibility. As noted above, while soft protections may have impacts on cetacean populations through potential loss of habitat (wetlands construction) or the introduction of foreign pathogens or contaminants (when filling materials are derived from dredge spoils), these impacts can potentially be mitigated by considering fine-scale cetacean habitat in the planning stages, and obtaining fill materials from uncontaminated sources.

2.6. Increase in offshore renewable energy sources

As governments strive to decrease fossil fuel consumption while meeting global energy needs, the construction of offshore renewable energy platforms is expected to increase. These platforms include offshore wind turbines, tidal and wave-powered generators [54]. Offshore wind farms are the most prevalent of these and are currently concentrated off the coast of Europe (including Denmark, Germany, the Netherlands and the UK) [55]. Two of the world’s largest wind farms are off the coast of Denmark in shallow water <20 m, but future construction is planned for a variety of depths up to 100 m [56]. Studies suggest that the pile-driving during construction of wind turbines is potentially the greatest threat to cetaceans from such activities but it is difficult to judge the potential consequences of an emerging industry deploying rapidly evolving new technologies [54,57]. As noted above, pile-driving is known to create acoustic disturbances for at least some species. Carstensen et al. [49] found that construction affected long-term habitat use by harbour porpoise in the Atlantic. Further studies show that operational turbine noise can be detected by harbour porpoises, but it is unclear what effect this may have on behavior [58]. The cetacean species most likely to live in habitats suitable for wind farms include temperate and subarctic coastal cetaceans including (but not limited to) harbour porpoises, white-beaked dolphins (*Lagenorhynchus albirostris*), common and Indo-Pacific bottlenose dolphins (*Tursiops truncatus* and *T. aduncus*), minke whales (*Balaenoptera acutorostrata*) and the northern right whale (*Eubalaena glacialis*).

The impacts of tidal and wave-powered energy on cetaceans are much more poorly known but will involve construction, potentially including pile-driving [54]. Tidal generators may pose a risk of collision with blades, and cables carrying power to the mainland may produce strong electromagnetic currents that could affect navigation or fish populations. Tidal and wave platforms have the greatest potential in temperate latitudes with strong winds and swiftly flowing water, which also tend to be highly productive areas that attract cetaceans. For example, sites identified as suitable for tidal power include the Bay of Fundy [59] as well as the western sounds of Scotland [60], both of which are well-known as areas of high cetacean density. Means of mitigating potential negative impacts of marine renewables projects on cetaceans include spatial planning to avoid critical habitat and use of acoustic deterrent devices.

3. Assessing the vulnerability of cetacean taxa

To better understand the vulnerability of particular species to climate-driven changes in human behavior, potential impacts from each category were assessed for all cetacean species, based on their geographic distribution and habitat preferences. For each species, temperature niches and depth preferences were obtained

from Kaschner et al. [61] and geographic distribution from the IUCN Redlist (iucnredlist.org). These habitat preferences were evaluated using the categories of cetacean species likely to be affected from Table 1 (column 4). Given uncertainties about the scale of impacts from each threat, no attempt was made to determine the likelihood or severity of each impact. Instead, for each species we assessed whether a reasonable potential exists for the threat to affect one or more distinct populations. Impact scores were then calculated as the total number of potential threats for each species. The number of species that may be affected by each threat was also tabulated.

Results, summarized in Table 2, show that species predicted to be affected by the greatest number of climate-driven changes in human behavior are those that occur primarily in coastal, estuarine and riverine habitat, and particularly those living in tropical coastal regions. The top 10% of species with the highest impact scores include the gray whale, South Asian river dolphin (*Plantanista gangetica*), franciscana (*Pontoporia blainvillei*), baiji (*Lipotes vexillifer*), boto (*Inia geoffrensis*), beluga whale, finless porpoise (*Neophocaena phocaenoides*), Indo-Pacific humpback dolphin, Atlantic humpback dolphin (*Sousa teuszi*), Indo-Pacific bottlenose dolphin, Heaviside's dolphin (*Cephalorhynchus heavisidii*), and Irrawaddy dolphin (*Orcaella brevirostris*). Of these species, six are listed by the IUCN as vulnerable or endangered, and one (the baiji) is provisionally considered extinct. Interestingly, the gray whale was found to have the highest impact score overall. Gray whales are predominantly coastal and their migrations span a wide range of latitudes from subtropical to polar environments, putting them at risk for a large number of anthropogenic activities, including climate-adaptive actions. Additional species with high impact scores included widespread coastal species including the humpback whale and harbour porpoise. Species that are less likely to be widely affected by a large number of threats include oceanic and deepwater species found in temperate and tropical regions, such as pilot whales and some beaked whales.

The climate-driven changes in human activities predicted to impact the greatest number of species were redistribution of fisheries and adaptations related to protecting against storm surge and sea level rise. Though most of the changes in human behavior explored here are concentrated around coastal areas, the redistribution of fisheries will affect offshore high-latitude marine environments more broadly, and therefore has the potential to impact large numbers of oceanic species through bycatch and prey depletion. Adaptations for storm and sea level rise protection also may affect large numbers of species due to the global extent of these problems.

4. Discussion: vulnerable taxa and policy priorities

4.1. Vulnerability of particular cetacean taxa

While concern about impacts of climate change on cetaceans has largely focused on polar species, the evidence presented here suggests that tropical coastal cetaceans may also be particularly vulnerable to those aspects of climate change that are mediated by changes in human behavior. Overall, some of the largest impacts to human societies and economies are predicted to occur in densely populated, low-lying coastal areas such as megadeltas in Africa and Asia. Recent studies indicate that Africa is one of the most vulnerable continents to climate variability due to low adaptive ability and multiple climate stressors [8]. Growing populations along coastlines will place additional demands on marine ecosystems including cetaceans, and conservation concern for cetaceans and other marine megafauna may decline in the face

of very real human emergencies. Coastal species, and in particular those that depend on riverine or estuarine habitat, may be affected by food insecurities, growing coastal populations, and coastal construction to prevent flooding and storm damage. This category includes many species that are already threatened or endangered, such as the South Asian river dolphin, Irrawaddy dolphin, and finless porpoise. Small resident island-associated populations, such as bottlenose dolphins (including both *T. truncatus* and *T. aduncus*) and Indo-Pacific humpback dolphins in the Indian and Pacific Oceans, may also be vulnerable to construction of coastal infrastructure as human communities attempt to adapt to rising sea levels and changes in precipitation and surface temperature.

Human-mediated impacts of climate change are also likely to disproportionately affect Arctic cetaceans. As sea ice declines and high-latitude temperatures become more habitable for humans and commercial fisheries, human activities will inevitably encroach on an increasing amount of cetacean habitat in the Arctic [5,62]. Shipping and oil and gas development, in particular, are likely to have wide-spread impacts on the acoustic environment of the Arctic and may cause avoidance and/or disruption of critical behaviors by bowhead and gray whales, as well as possible impacts on beluga and narwhal populations. Laidre et al. [63] found that narwhal and bowhead whales were among the most vulnerable of Arctic marine mammal species to climate change based on nine biological indicators of vulnerability. The development of such vulnerability indicators for cetaceans was also considered at a recent workshop on the eastern Pacific [64]. Future work to evaluate relative vulnerability of populations should take into account these vulnerabilities where possible—for example, an indicator for susceptibility to disturbance from noise could be added. More consideration should also be given to the population level in these matters as the status of populations of the same species can vary greatly.

The redistribution of fisheries is likely to have widespread impacts on marine mammal populations. In the North Atlantic, the North Pacific and Arctic Oceans, intensified fishing pressure is expected to result in increases in cetacean bycatch and prey depletion, particularly in offshore areas where productivity is expected to increase the most. Bycatch has been recognized as “the greatest immediate and well-documented threat to cetacean populations globally” [65], but it is unclear whether projected redistributions of fisheries are likely to result in overall increases in global bycatch levels. While many EU and many high-latitude nations have regulations in place to reduce bycatch, as fisheries move offshore they may become increasingly difficult to monitor. Species most vulnerable to increased levels of bycatch include high-latitude populations with threatened status, and those that already experience high bycatch mortality, such as North Atlantic and North Pacific right whales, harbor porpoises, short-beaked common dolphins, and western gray whales.

Particular attention should be given to cetacean populations in areas that are likely to experience significant cumulative effects of climate change and other anthropogenic activities. One way to identify such areas would be to determine overlap between marine and coastal regions experiencing high anthropogenic impact and areas expected to be most impacted by climate change. Data collected through the National Center for Ecological Analysis and Synthesis (NCEAS) could potentially be utilized for such a comparison. Halpern et al. [66] synthesized data from a broad variety of threats (including climate change as well as other threats) and produced a global map of cumulative impacts on the marine environment. They found that particularly impacted areas include the North Sea, South and East China Sea, Bering Sea, and portions of the coasts of Europe, North America, the Caribbean, China and Southeast Asia. Climate change (using Sea Surface

Table 2
Cetacean species predicted to be affected by major shifts in human behavior caused by climate change.

[illegible]

Table 2 (continued)

Common Name	Temperature niche	IUCN Status	Diminishing sea ice				Coral decline	High latitude marine warming		Drought				High latitude terrest warming	Increase in storm severity	Sea level rise		Marine renewable energy		SUM
			In-creased shipping	In-creased fishing pressure	Shifting hunting effort	Increase in military presence		Increase in aquacul- ture	Increase in high- lat fisheries	Greater reliance on marine ecosys- tems	In- creased migra- tion to coasts	Increase in desalina- tion	Increase in intensive agricul- ture			Con- struction of seawalls, etc	Flood manage- ment projects	Land acquisi- tion etc	Construction of offshore wind, tidal and wave utility	Increase in hydro- electric power
Indo-Pacific humpback dolphin	Subtropical-full tropical	NT					x			x	x	x	x		x	x	x			8
Atlantic humpback dolphin	Subtropical-full tropical	VU								x	x	x	x		x	x	x		x	8
Tucuxi	Full tropical only	DD					x			x	x	x	x		x	x	x			8
White-beaked dolphin	Polar-cold temperate	LC		x					x					x					x	4
Atlantic white-sided dolphin	Subpolar-cold temperate	LC	x	x					x											3
Dusky dolphin	Cold temperate- warm temperate	DD																		0
Pacific white-sided dolphin	Cold temperate- subtropical	LC							x											1
Hourglass dolphin	Polar-warm temperate	LC		x																1
Peale's dolphin	Subpolar-warm temperate	DD						x						x	x	x	x	x		6
Risso's dolphin	Cold temperate-full tropical	LC							x											1
Common bottlenose dolphin	Cold temperate-full tropical	LC					x		x	x	x	x	x		x				x	8
Indo-Pacific bottlenose dolphin	Full tropical only	DD					x			x	x	x	x		x	x	x			8
Atlantic spotted dolphin	Subtropical-full tropical	DD																		0
Pantropical spotted dolphin	Full tropical only	LC																		0
Spinner dolphin	Full tropical only	DD					x													1
Clymene dolphin	Full tropical only	DD																		0
Striped dolphin	Cold temperate- tropical	LC							x											1
Common dolphin	Cold temperate-full tropical	LC							x											1
Long-beaked common dolphin	Subtropical only	DD																		0
Fraser's dolphin	Subtropical-full tropical	LC																		0
Northern right whale dolphin	Subpolar- subtropical	LC							x											1
Southern right whale dolphin	Polar-subtropical	DD		x																1
Commerson's dolphin	Subpolar-cold	DD						x							x	x	x	x		5

Chilean dolphin	Subpolar-warm temperate	NT						x							x	x	x	x	x			6
Heaviside's dolphin	Cold temperate-warm temperate	DD						x		x	x	x	x			x	x	x	x			9
Hector's dolphin	Cold temperate-warm temperate	EN						x								x	x	x	x			5
Melon-headed whale	Full tropical only	LC																				0
Pygmy killer whale	Full tropical only	DD																				0
False killer whale	Warm temperate-full tropical	DD																				0
Killer whale	Polar-tropical	DD																		x		2
Long-finned pilot whale	Polar-warm temperate	DD		x																		2
Short-finned pilot whale	Subtropical-tropical	DD																				0
Irrawaddy dolphin	Full on tropical	VU				x				x	x	x	x			x	x	x				8
Shepherd's beaked whale	Subpolar-w. temperate	DD																				0
Baird's beaked whale	Polar-subtropical	DD																		x		1
Arnoux's beaked whale	Polar-subtropical	DD																		x		1
Sowerby's beaked whale	Subpolar-w. temperate	DD																		x		1
Blainville's beaked whale	W temperate-tropical	DD																				0
Gervais' beaked whale	Subtropical-tropical	DD																				0
Strap-toothed whale	Polar-subtropical	DD																		x		1
Hector's beaked whale	C. temperate-subtropical	DD																				0
Gray's beaked whale	Subpolar-subtropical	DD																		x		1
Stejneger's beaked whale	Subpolar-w. temperate	DD																		x		1
Andrews' beaked whale	C. temperate-subtropical	DD																				0
True's beaked whale	W temperate-subtropical	DD																				0
Ginkgo-toothed beaked whale	Subtropical-full tropical	DD																				0
Hubbs' beaked whale	C. temperate-subtropical	DD																				0
Pygmy beaked whale	Subtropical-tropical	DD																				0
Cuvier's beaked whale	C. temperate-full tropical	LC																				0
Northern bottlenose whale	Polar-w.temperate	DD																		x		1
Southern bottlenose whale	Polar-subtropical	DD																		x		1
Perrin's beaked whale	W.temperate-subtropical	DD																				0
Spade-toothed beaked whale	C.temperate-subtropical	DD																				0
Indo-pacific beaked whale	Subtropical-full tropical	DD																				0
SUM			12	15	4	4	8	12	36	13	13	12	13	10	19	17	17	18	6			

Temperature niches and depth preferences for each species are detailed in Kaschner et al. [61].

Temperature as a proxy) was found to be a particular threat in the North Sea, Bering Sea, Mediterranean, mid-Atlantic and the coast of China among other areas. While a cetacean-specific analysis is needed to improve the relevance and spatial resolution of conclusions, the study by Halpern et al. [66] suggests that conservation and adaptation efforts to mitigate the effects of climate change on cetaceans might initially focus on the North Sea, Bering Sea, the South China Sea and the western coast of Japan. Several of these areas, particularly the South China Sea and the coast of Japan, also correspond to regions of high cetacean diversity [Kaschner et al. unpublished data, 67] and thus may warrant special attention.

4.2. Policy priorities and mechanisms

Ultimately, improving the robustness of management strategies in the face of both direct and human-mediated threats from climate change will require two approaches: (1) integrating knowledge about cetacean populations into climate adaptation decisions and (2) including projections about how climate change may influence human behaviors into cetacean-specific management plans.

Policy-makers and resource managers are increasingly considering how human communities should adapt to climate change threats to coasts and oceans, but few of these discussions or plans have included explicit consideration of cetaceans and other marine megafauna. One approach to improving this situation would be to ensure that marine mammal specialists are represented as part of marine expert panels in assessing potential effects of adaptation activities on ocean life. For example, the North Pacific Fisheries Management Council in the US is considering a proposal that would limit commercial fisheries in the US Arctic until enough data are available to determine how fishing might affect Arctic ecosystems [68,69]. The calculation of catch limits for this region should include consideration of cetacean populations, their conservation status, and any other human activities that may have cumulative impacts upon populations such as acoustic disturbance.

Another approach is to ensure that management plans for cetacean populations incorporate expected changes in human

behavior due to climate change. For example, protection areas for cetaceans could be developed that are off-limits to shipping, oil and gas development, and fisheries. Hunting quotas could be adjusted for populations that are expected to sustain direct, indirect or human-mediated losses from climate change such as range contraction following coastal construction. As a first step toward the goal of incorporating the potential effects of climate change into management plans, a recent IWC Workshop recommended that the scenarios used during the simulation trials be re-evaluated in light of additional climate change impacts [70]. The results presented here suggest that any such re-evaluations of the trials should include consideration of human-mediated as well as direct effects of climate change.

To achieve these goals of integrating cetacean concerns and climate adaptation plans, policy and management actions will be needed at national, regional and international levels. Some examples of policy mechanisms at each of these levels are provided in Table 3. At the level of individual nations, natural resource agencies should ensure that cetaceans are included in climate adaptation discussions, such as the ongoing National Academies study, “America’s Climate Choices” in the US Both direct and human-mediated potential impacts of climate change should be explicitly included in cetacean stock assessments and management reports. Regional efforts could occur under the auspices of bodies such as ACCOBAMS, ASCOBANS, and the Arctic Council (until a stronger regional framework for this area exists).

At the international level, there are several routes for integrating cetaceans into climate adaptation discussions. First, the UNDP–GEF administers adaptation funding under the UN Framework Convention on Climate Change (UNFCCC), and recently approved initial allocations for adaptation projects under a \$50 million Strategic Priority on Adaptation initiative. GEF has also developed the Adaptation Policy Framework to develop and implement adaptation strategies. Bangladesh and island states in the Caribbean and the Pacific are assessing adaptation options with assistance provided under UNFCCC. The IWC should make a request to the UNDP–GEF that cetacean populations (in addition to other marine environmental concerns) be considered in the formulation of GEF-sponsored adaptation plans. Second, marine conservation should be integrated into development aid programs

Table 3
National, regional and international institutions with jurisdiction over policy and management for marine economic activities and industries.

Potential change in human behavior	National	Regional	International
Increased shipping	NOAA (US)	ACCOBAMS, ASCOBANS, NAMMCO	International Maritime Organization
Increased fishing pressure	NOAA (US)	ACCOBAMS, ASCOBANS, NAMMCO	FAO, UNCLOS
Increased hunting of cetaceans	NOAA (US), First Nation governments (Canada)	NAMMCO, Arctic Council	
Increase in military presence in Arctic	Department of the Navy (US)	NATO	UN General Council
Displacement of tourism to whale and dolphin-watching	NOAA (US)		IWC
Increase in aquaculture	NOAA (US)		FAO
Increase in fisheries as target species move north	NOAA (US)		FAO
Increase in human migration to coastal areas	State governments		
Increased water conflict	State governments		
Increase in desalination			UNDP, World Bank
Increase in fertilizer use	EPA, Dept of Agriculture (US)		UNDP, World Bank
Increase in human densities and terrestrial activities (e.g. agriculture)	EPA, Dept of Agriculture (US)		FAO
Construction of seawalls, jetties, etc may increase coastal noise propagation	Army Corps of Engineers		UNDP
Erosion prevention measures such as beach renewal	Army Corps of Engineers		UNDP, World Bank
Coastal construction projects to manage flooding	Army Corps of Engineers		UNDP, World Bank
Construction of offshore wind farms	NOAA/MMS/FERC		
Construction of tidal and wave-powered energy sources	NOAA/MMS/FERC		
Increase in hydroelectric power sources			UNDP, World Bank

through bilateral aid, the World Bank and other organizations. Bilateral aid programs have already committed \$110 million to more than 50 adaptation projects in 29 countries. Ensuring that cetaceans are considered as such projects are planned will be an important step toward mitigating the human-mediated impacts of climate change on populations of whales and dolphins worldwide.

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