REVIEW

Climate change in the oceans: Human impacts and responses

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Although it has far-reaching consequences for humanity, attention to climate change impacts on the ocean lags behind concern for impacts on the atmosphere and land. Understanding these impacts, as well as society's diverse perspectives and multiscale responses to the changing oceans, requires a correspondingly diverse body of scholarship in the physical, biological, and social sciences and humanities. This can ensure that a plurality of values and viewpoints is reflected in the research that informs climate policy and may enable the concerns of maritime societies and economic sectors to be heard in key adaptation and mitigation discussions.

On 1 September 2015, U.S. President Barack Obama, walking on the moraine below the receding Exit Glacier in Alaska, pointed to the distant ice and said, "This is as good of a signpost of what we're dealing with when it comes to climate change as just about anything" (*1*).

We can see retreating glaciers and shrinking lakes or experience heat waves, crop failures, and extended wildfire seasons. By comparison, the ocean appears unchanging to a public that gives greater credence to climate change science when they have seen or directly experienced changes consistent with its predictions (*2*). Unlike the shrinking Exit Glacier, the oceanic components of climate change remain largely hidden beneath the waves. Similarly, the diverse sectors that make up the global ocean economy, such as energy, transport, fisheries, and tourism, have not been the subject of integrated analysis and are thus subsumed within sectoral analyses that fail to highlight their collective value. The "out of sight, out of mind" nature of ocean change is reflected in the ocean's lack of visibility in global climate change policy debates, including the annual Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) (*3*), even though the impacts of climate change on the ocean are well documented (*4*, *5*) and have far-reaching implications for society.

The latest Intergovernmental Panel on Climate Change (IPCC) global assessment identifies the main oceanic elements of observed global environmental change as follows: rising sea surface temperature; thermal expansion of the oceans and melting sea ice, leading to sea-level rise; changes to ocean thermal structure and currents; changes in the periodicity and amplitude of ocean climate cycles such as El Niño; changes in the frequency and severity of hurricanes and typhoons; ocean acidification; and deoxygenation of areas of the sea where thermal stratification is strengthening and nutrients and productivity are rising (oceanic "dead zones") (*4*).

Climate change research in the humanities and social sciences is furthering our understanding of the socially differentiated impacts of climate change, the range of adaptation options being pursued or considered, and the support for and challenges to ongoing technical and political responses to climate change. Much of this insight is missing from most "human dimensions" research in major Earth (and ocean) system science programs; such research is typically limited to attempts to quantify potential vulnerabilities to physical and biochemical changes, economic analyses of the monetary value of threatened ecosystem goods and services, and analyses of the costs and benefits of various options for adaptation and mitigation action (*6*).

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Near and distant impacts

Ocean-related climate change impacts on human society and institutions will necessitate responses at scales from the individual to the global. Oceanic influences on the global climate system mean that populations and economic activities that are far removed from the sea can be influenced by ocean change. For example, predicted changes in the intensity and frequency of El Niño–Southern Oscillation (ENSO) events, driven by ocean warming (*7*), may alter previously experienced patterns of ENSO-driven variability in Peruvian fish catches (*8*), Indonesian rice harvests (*9*), cholera epidemics in Bangladesh (*10*), crop and livestock production in sub-Saharan Africa (*11*), forest fire risks in the western United States (*12*), and the profitability of winter sports tourism in Arizona (*13*)—all with consequences for societies and economies in these areas. More proximally, maritime and coastal societies will also be affected by climate variability and change that are not specifically or exclusively ocean-related—such as glacial melting, summer heat waves, and changes in precipitation frequency, intensity, and timing—as a result of the many teleconnections between global environmental change, the oceans, and human societies (*14*). These often interacting and indirect pathways complicate our understanding of climate change impacts and challenge our ability to plan adaptive responses.

Probably the greatest adaptation challenges are those faced by people who either live close enough to the coast to be directly affected by a combination of sea-level rise and extreme weather events, have a livelihood and way of life closely linked to the health of the marine environment, or are nutritionally dependent on access to marine resources.

Where there is uncertainty regarding climate change impacts, as with projected increases in the severity or frequency of oceanic storms (*15*), improvements in short- and medium-term forecasts, evacuation plans, shelter provision, and knowledge of the social conditions that lead to vulnerability are helping to reduce loss of life: In Bangladesh, Cyclone Gorka killed an estimated 140,000 people in 1991, whereas Cyclone Sidr, in 2007, claimed between 3500 and 10,000 lives (*16*). Extensive social analysis of the aftermath of Hurricane Katrina has shown that a history of systemic inequality led to disproportionate impacts on the city of New Orleans's African American population, which were still evident years later (*17*).

Climate change impacts on the "blue economy"

As terrestrial sources of energy, minerals, and food come under greater strain from growing demand, governments and the private sector have increasingly looked to the oceans for new resource extraction and business opportunities (Fig. 1) (*18*). The framing of much recent research on climate change impacts on the ocean reflects this shift: A key concern is documenting the potential impacts on established and emergent maritime industries and their ability to generate "blue wealth" (*19*). Environmental valuation approaches are used to estimate the market-equivalent value of ecosystem services, such as the contribution of coral reefs to fisheries, tourism, and coastal protection (*20*).

The future of fisheries in a changing climate, for example, is one important issue. Another is the marine renewable energy sector (offshore wind, tidal, and wave power), which could benefit from increased investment and accelerated technological development if there

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is substantial policy support for reducing fossil fuel energy use (*21*). A paradoxical short-term benefit of climate change is that melting Arctic sea ice is making new areas accessible to oil exploration and potentially viable for exploitation (*22*, *23*), thereby contributing to emissions that would accelerate warming and acidification. Without adaptive action, some of the largest economic impacts will be on coastal cities, where sea-level rise is expected to make weathering storms more challenging, irrespective of whether they increase in frequency or severity (*24*).

Not all individuals and societies see their relationship with the sea as primarily an economic one, however, and there is widespread concern among both traditional users of the sea (small-scale fisherfolk and coastal indigenous groups) and environmentalists over the race to extract wealth from the oceans (*25*). An understanding of climate change's effects on other, nonmonetary systems of value is needed if we are to develop a fuller understanding of its potential impact on the human relationship with the sea.

Climate change and fisheries

One of the clearest demonstrations that anthropogenic warming has altered ecosystems is the poleward shift in the ranges of exploited fish species since the mid-20th century (*26*).

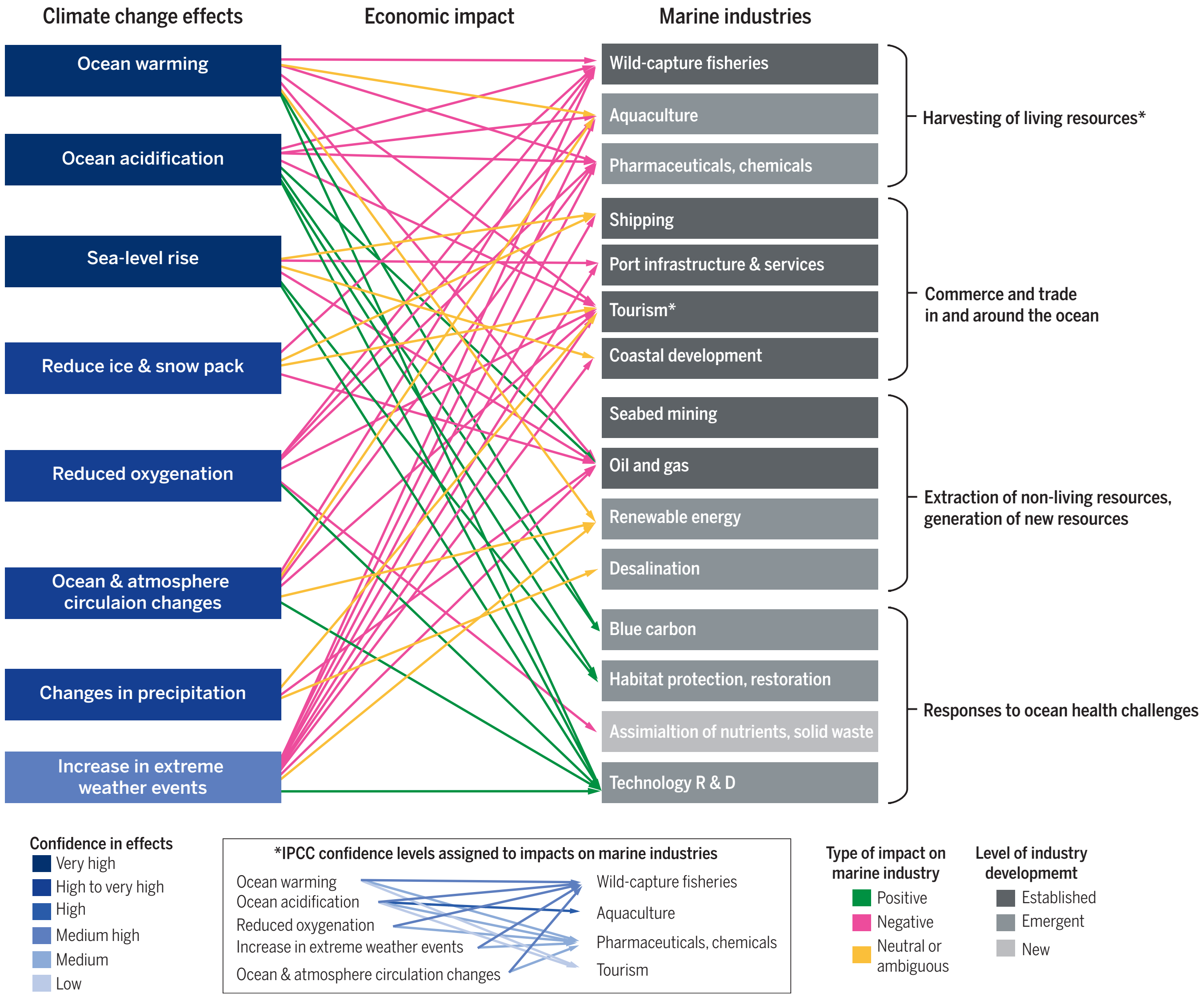

Fig. 1. Established, emerging, and new ocean industries, as identified by the Economist Intelligence Unit (*19*), are listed in the right column; (shades of gray reflect levels of development) and organized by type. Climate change effects are listed in the left column, with shades of blue reflecting the IPCC level of confidence that these changes are taking place and are linked to increased anthropogenic greenhouse gas emissions. The arrows indicate the type of net economic impact (green, positive; pink, negative; yellow, neutral or ambiguous) that these climate change effects are hypothesized to have on the indicated industry. Except where the IPCC has already done so (inset), no level of confidence is ascribed to the hypothesized economic impacts. An IPCC-type systematic review and consensus process would be required to assess all estimates of costs and benefits and add confidence bounds to each potential impact. The IPCC so far has not considered the ocean economy in this way. Globally, negative impacts will be experienced predominantly by industries involved with living-resource harvest, coastal and marine tourism, and ocean commerce and trade. Impacts on nonliving-resource extraction and the generation of new resources are either unstudied, neutral, or negative. Activities involved with responding to ocean health challenges could see high demand and a net positive economic impact. This diagram simplifies what is likely to be a mosaic of regionally differentiated impacts and of multiple interacting pathways of impact. Studies that propose these economic impact pathways and identify their causal mechanisms are given in the supplementary materials (*18*).

Based on relationships between sea surface temperature, ocean circulation, and primary production, two different models have independently predicted slight increases in global ocean fish production capacity by the mid-21st century, with a consistent pattern of decreased production in the tropics and increases at temperate latitudes (*27*, *28*). However, these model-based studies do not consider the range of potentially disruptive factors that could mediate the relationships between climate change, primary production, and fish production. These include the impacts of ocean acidification, which could have severe effects on calcifying organisms in food chains and on commercially harvested shellfish (*29*).

Climate change and ocean acidification impacts on marine ecological dynamics will disproportionately affect people (including indigenous people) living near climate-sensitive environments, such as reef- or ice-dominated coasts, and coastal populations in low-income countries in the tropics, where populations are more nutritionally and economically dependent on marine resources (*30*–*32*).

How is society responding to climate change impacts on oceans and coasts?

Societal responses to climate change range from individual adaptive decisions to attempts by representatives of sovereign states to reach a global consensus on reducing emissions. Although global impact and indicator-based vulnerability studies and global mitigation scenarios are useful starting points for raising awareness of climate change issues and for informing high-level policy, they provide little guidance for action at more local levels. Differences in the way people respond to climate change itself or to policy proposals to address it play out within households and communities and between wealthier and poorer nations. Understanding these social and political dynamics requires different kinds of research than the large-scale, comparative, quantitative, and model-based work that dominates climate science's input to major studies of global environmental change (*6*, *32*).

Efforts to engage citizens in actions to address local and regional effects of climate change in coastal areas have included initiatives such as replanting mangroves, which, if done appropriately (*33*), has benefits for coastal protection, fisheries, and carbon sequestration (*34*). Communications research has shown that nonthreatening images that engage everyday emotions, such as a picture of a community mobilizing to protect their local environment, are more likely to inspire wider citizen action to address climate change impacts than are fear-inducing representations of climate catastrophe (*35*). Citizens engaged in local climate action are in turn more likely to support higher-level policy responses to global change (*36*).

Understanding public perceptions of climate change and the oceans

When asked about climate change, people express a spectrum of views that includes concern, skepticism, belief, denial, and fatalism. Positing a simplistic dichotomy between climate change advocates and deniers is inadequate as a basis for understanding how society is responding, because there is a wide variety of voices in social movements with an interest in climate change (*37*). In the United States, where numerous studies have been conducted, differences in the acceptance of anthropogenic climate change are rooted in conflicting sociopolitical identities rather than in disparities in education or knowledge about climate change (*38*). People's climate change views are thus unlikely to respond to the rationality of more certain and/or more clearly communicated climate science.

Marine- and coastal-focused surveys of public perception are not common and have tended to address climate change in the context of multiple risks. In a large European survey, pollution and the state of fish stocks were the two major environmental issues that came to mind when the oceans were mentioned, with coastal erosion, sea-level rise, and climate change less commonly identified as key concerns (*39*). More than half of the 10,000 people questioned also felt that a change in the frequency of extreme weather was already apparent, although this is among the least certain of climate change effects, according to the IPCC consensus (*4*). Mixed farming-fishing households in coastal East Africa perceived erratic rainfall and rising temperatures to be key risks to their livelihoods, compounded by factors such as wars, unfavorable economic policies, and population increases that have pushed people into living in marginal areas where their livelihoods are more exposed to impacts of climate change (*40*).

Responding to climate change impacts on the ocean: Adaptation

Adaptation responses can be made autonomously by individuals or through planned actions at various scales, from "climate-proofing" coastal urban infrastructure in cities to national and regional agreements. At the local level, for example, coral bleaching often has negative effects on reef fish biomass and therefore on fishers' catches; adaptive responses may include switching to off-reef fisheries or diversifying out of fishing (*38*, *41*).

Climate change adaptation plans formulated by governments and development agencies

Table 1. Some potential contributions of social sciences and humanities to understanding people's responses to ocean climate change.

Themes for social science and humanities research	Potential applications
Understand people's knowledge and perceptions of ocean-related environmental change, including acidification and sea-level rise.	Develop strategies to build support for policies addressing emissions reductions; design effective adaptation measures.
Understand people's moral, political, and emotional responses to climate variability and change.	Influence individual and collective behavior; communicate climate science more effectively; provide targeted material and emotional support to affected communities; articulate moral and ethical positions as well as economic rationales for action.
Identify technological, political, economic, and social trends and forces influencing the climate system.	Identify the best opportunities and processes for transformational change to address climate change drivers.
Understand historical adaptation of societies to variability and change; understand how contemporary adaptation plans and action decisions are made at different scales, from individual to global.	Improve governance, planning, and resource allocation; provide scenarios and visions for future societal adaptation.
Identify social differences and their links to climate vulnerability and resilience.	Target adaptation support; enable marginalized people's voices to be heard in policy; support the agency of those most affected by climate change.
Understand how power is exercised through networks of influence; reveal vested interests; identify people's incentives to undertake or resist climate action.	Challenge power; build coalitions to secure support for climate justice.

tend to focus on material dimensions of life, with adaptive capacity often measured in terms of the asset status of individuals and households. It is less often appreciated that climate change can threaten identity, community cohesion, and sense of place; also, culture shapes how societies respond and adapt to climate-related risks, offering a range of opportunities that may not be apparent to external agents. Many coastal communities that are closely tied to the sea have distinct cultures and ethnicities, with strong attachments to occupation and place. Diversifying and relocating may make sense from an economic rationality or human security perspective, but it may cause irrevocable loss of cultural identity and social well-being (*42*).

Being identified as "vulnerable" may give some leverage to groups in policy negotiations and helps to target financing for adaptation, but there is concern that such labeling also carries risks. Ethnographic analysis of Arctic populations argues that vulnerability analysis can lead to misguided actions based on external perceptions of people's capabilities, and it can shape how people view themselves and undermine their efforts to gain greater autonomy over their own affairs (*43*). Similarly, portraying women in the Global South as being passive victims of climate change undermines their political and social agency (*44*); nevertheless, climate change impacts can reflect, expose, and exacerbate existing gender inequalities, so there are strong arguments for ensuring that adaptation policies are not gender-blind (*45*).

At a more global scale, small-island developing states have exercised moral power in their attempts to secure international, legally binding agreements on emissions and an adaptation fund to assist countries affected by climate change but not responsible for causing it (*46*). Ahead of the December 2009 UNFCCC meeting in Copenhagen, then-President of the Maldives Mohammed Nasheed held an underwater meeting with his ministers to highlight the threat of sea-level rise to his atoll nation. The notion of climate justice provides a moral compass that helps to navigate the complexities of adaptation policy. Small-island states, indigenous coastal people, and the coastal poor in developing countries are among those who have contributed least to anthropogenic climate change, yet they are among the most exposed to its effects. Climate justice is based on a demand that this be recognized. This moral authority is exercised in international climate negotiations and has helped to secure an adaptation fund for which countries preparing national plans of adaptation can apply, though the amount pledged falls short of what was deemed necessary and fair (*47*). The marine fisheries and aquaculture sectors appear in a number of national adaptation plans but may be underrepresented because of the late recognition of the importance of climate change to these sectors (*48*).

One adaptive response that causes particular concern for geopolitical stability is the possibility of people fleeing areas that have become uninhabitable as a result of changes in climate. In the case of coastal zones, sea-level rise in a world in which temperatures have risen by 4°C could displace 187 million people by 2100, unless major investments in coastal defenses are made (*49*).

The potential role of oceans in climate change mitigation

Although the oceans are a major component of global carbon cycles, their ability to contribute to mitigation of climate change though increased carbon sequestration is limited and may decline as the ocean acidifies (*50*). The ocean system can make contributions to mitigation in three ways: (i) conservation and enhancement of "blue carbon" (carbon stored by coastal and marine ecosystems), (ii) improved energy efficiency of ocean-related industries, and (iii) geoengineering. Opportunities to sequester more blue carbon though ecosystem management are largely limited to coastal areas. Although mangroves occupy only 0.5% of the global coastal area, they contribute 10 to 15% (24 Tg of carbon per year) to coastal sediment carbon storage and export 10 to 11% of particulate terrestrial carbon to the ocean (*51*). Along with seagrass meadows and salt marshes, mangroves are being lost or degraded by coastal development, with the resulting release of stored carbon currently negating their contribution to sequestration (*52*). This makes protecting and restoring the ocean's fringing vegetation a high priority. Doing so yields the triple advantages of contributing to mitigation; conferring adaptive benefits to coastal zones through enhanced protection from wave, storm, and tidal erosion; and providing immediate ecological, economic, and social benefits in the form of biodiverse nursery grounds for fish and shellfish that support fisheries and tourism. Conserving and restoring the more hidden but no less important subtidal seagrass beds could confer similar benefits (*53*).

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The main maritime industries are currently oil and gas exploration, shipping, fishing and aquaculture, and coastal tourism (Fig. 1). All could benefit from improved environmental governance resulting in reduced energy consumption and emissions. For the offshore oil and gas industry, the largest gains could be made by switching investments from continued extraction and exploration of fossil fuels to harnessing the potential of the oceans to generate renewable energy from tidal and wave power. This is unlikely in the next half-century (*53*). Environmental governance of shipping lags behind that of other transportation sectors and requires concerted pressure from the International Maritime Organization to address (*54*). Fisheries and aquaculture are both relatively energy-efficient ways of supplying humanity with nutritious animal-source foods, more so than most terrestrial animal production systems (*55*); thus, expansion of carbon- and energy-efficient shellfish aquaculture, increased energy efficiency in capture fisheries (including the reduction of fishing overcapacity), and reduced terrestrial livestock production have potential benefits for fishery management, marine conservation, sectoral economic efficiency, healthy human diets, and terrestrial land and water issues. As people get wealthier, they generally want to eat more meat (*56*) rather than seaweed and oysters, but dietary habits and food cultures do change. There are conflicts between the growth of coastal tourism and increasing emissions due to international travel, but energy efficiency measures in destination hotels and behavior changes among visitors are reducing the resource-consumption footprint of the sector, and ecotourism is raising awareness (*57*).

Ocean-based geoengineering solutions to mitigation challenges remain conceptual or experimental. They include modifying atmospheric albedo by cloud brightening, using a fine mist of seawater droplets sprayed by ships; increasing carbon sequestration through ocean fertilization to enhance primary production; adding materials such as carbonate or silicate, mined from the land, that help remove carbon dioxide from the atmosphere (known as "enhanced weathering"); or artificially inducing upwelling of nutrient-rich deep water to increase primary productivity in surface waters. The effects of all these geoengineering solutions on atmospheric temperature and the carbon cycle are uncertain, and their costs are currently prohibitive. There are also ethical concerns and legal obstacles to such permissible pollution (*53*).

Engaging with policy

Millions of people around the world's coasts are taking actions to influence policy, whether kayaking to protest Arctic oil drilling, marching to demonstrate their support for emissions reduction policies, resisting forced relocation, defending their access to fisheries, choosing their own adaptation pathways, or lobbying for an increase in global adaptation funds. Coastal cities are not waiting for globally binding agreements on emissions reductions before taking their own actions to reduce their energy use and undertaking adaptive actions such as redesigning waterfront areas and coastal defenses (*58*). Documenting and explaining this range of political responses to climate change and reflecting on its implications is a task that the ocean science community has barely begun. Understanding people's interest in climate policy and how they choose to exercise it in terms of their values, means, and ends (*6*) enables an appreciation of the plurality of perspectives that exist outside the ocean science and climate science epistemic communities. Increased attention to people's beliefs and actions, as an integral component of interdisciplinary climate science, could be instrumental in crafting societal responses to the challenges posed by climate change in the oceans (Table 1).

Conclusions

Climate change impacts on the oceans are harder to see than receding glaciers, but they have profound implications for all human societies, not just coastal ones. Increasing societal concern over the fate of the oceans and growing economic interest in generating blue wealth make the oceans pivotal to achieving sustainable development goals. Ocean climate change research, as on land, is dominated by human-natural systems assessments that make good use of economics but limited use of those research disciplines that overlap least with the natural sciences (*59*). Insights from maritime history, ethnographies of coastal cultures, and the political geography of the oceans would strengthen future IPCC assessments of oceanic and coastal change. Including other, nonacademic ways of perceiving and knowing, from indigenous knowledge (*60*) to the moral positions of major world religions (*61*), would allow a wide-ranging dialogue about possible responses to a changing climate in different social, cultural, and political settings. A richer understanding of the human dimensions of ocean climate change would assist in making the oceans more visible in climate change policy.

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SUPPLEMENTARY MATERIALS

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