PERSPECTIVE

The silent services of the world ocean

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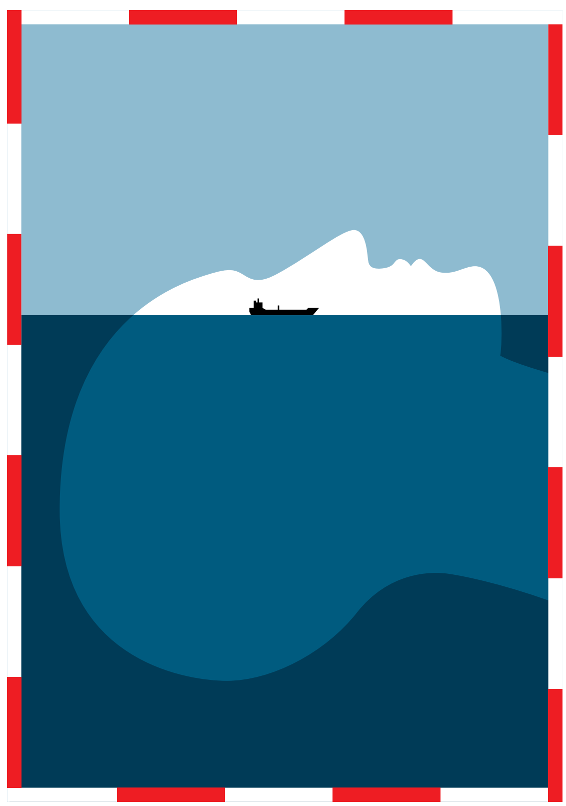
The most recent comprehensive assessment carried out by the Intergovernmental Panel on Climate Change has concluded that "Human influence on the climate system is clear," a headline statement that was approved by all governments in consensus. This influence will have long-lasting consequences for ecosystems, and the resulting impacts will continue to be felt millennia from now. Although the terrestrial impacts of climate change are readily apparent now and have received widespread public attention, the effects of climate change on the oceans have been relatively invisible. However, the world ocean provides a number of crucial services that are of global significance, all of which come with an increasing price caused by human activities. This needs to be taken into account when considering adaptation to and mitigation of anthropogenic climate change.

Earth's oceans are an integral component of the climate system, and as they change and are changed by climate (*1*), so are the services that they provide to people. The ocean service most directly related to human welfare is food production, which is increasingly needed in addition to that from land (*2*). However, there are other, less obvious services that are provided by the ocean, which are associated with some of its key physical properties. The ocean takes up more than 90% of the excess energy in the climate system that results from the altered energy balance at the top of the atmosphere (*3*). The ocean continues to take up energy year after year, and the warming is now detectable on a worldwide scale down to depths of more than 2000 m (*4*). This is unequivocal evidence of recent global warming. Ocean heat uptake continuously and significantly slows atmospheric warming. This physical ocean service is thus an important element in the natural mitigation of climate change, but that heat uptake is only temporary and will be weakening in the future: Excess heat is mixed downward from the sea surface, so the ocean water column will become more stable and capable of less heat uptake as atmospheric warming progresses. Vertical mixing and circulation processes, particularly in the deep-water formation areas of the North Atlantic and the Southern Ocean, may slow down as a consequence of increased water column stability and thus make surface-to-depth transport of heat less efficient in the future. Some indication of a decline has been measured in the North Atlantic (*5*), but continued observation programs there, and in other critical locations in the ocean, are essential to learn more about ocean tipping elements in the Earth system (*6*, *7*).

There is a high price to be paid for this ocean system service, which has the potential to alter a number of parts of a complex and fragile system. Ocean warming will affect large-scale ocean circulation, the distribution of heat and salt in the ocean, the extent of areas of tropical cyclone genesis, and the land-ocean temperature difference, which is the key driver of monsoon systems and determines the statistics of important modes of climate variability (*8*). A warming ocean also affects both the intensity and frequency of extreme events. Recent studies indicate that different rates of heating in the equatorial Pacific Ocean profoundly affect the El Niño–Southern Oscillation by making the positive phase more extreme and thereby causing heavier rainfall in the eastern equatorial Pacific (*9*). El Niño has robust teleconnections to equatorial South America (wetter and warmer in the west and drier in the east), the western equatorial Pacific (drier and warmer), and a southern section of North America (wetter and cooler). Similar increases in extremes are projected for the Indian Ocean Dipole (*10*), with serious implications for the monsoon system, which is crucial for agriculture and food production in many countries in this region. Warming of the surface ocean also enlarges the area over which tropical cyclones pick up energy and thus increases the probability of conditions favorable for the development of these extreme events. Although it remains difficult to provide robust projections of changes in the location, frequency, and intensity of tropical cycles (*1*), a poleward shift of the zone of maximum intensity has already been observed (*11*). This shift will require new efforts of adaptation in regions that were previously less affected by these tropical storms. The altered regional variability and extremity of these storms both exacerbate the impacts on some of the most vulnerable countries. This has to be added to the price tag of the global ocean service of heat uptake, caused by the modification of Earth's energy balance due to the burning of fossil fuels and deforestation.

The second key ocean service is the storage and global distribution of excess water from rapidly melting land glaciers (*12*) and the ice sheets of Greenland and Antarctica (*13*), a result of the role of the ocean as the most important reservoir of the global water cycle (*14*). The price of this service is, of course, sea-level rise, which threatens low-lying islands and coastal communities around the world (*15*). Currently, almost 50% of global mean sea-level rise stems from the storage of this excess water. A somewhat smaller fraction is caused by ocean heat uptake, which accounts for about 40% of current sea-level rise. There is growing evidence that the price for this service may rise to much higher levels, possibly even beyond control. Recent model results suggest that critical thresholds for the stability of the West Antarctic Ice Sheet may have been crossed already (*16*). This would mean that sea level could rise by more than 4 m more than the rise projected by calculations based on ocean thermal expansion, glacier melting, and mass loss from polar ice sheets



Climate change as seen by Claude Kuhn, a renowned graphics artist from Bern. Sea-level rise is a consequence of climate change, caused by human activities, that will have pervasive and irreversible impacts.

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alone (*17*). Although such a scenario would take many centuries to unfold, the challenge associated with adaptation to the loss of coastal land around the world would be beyond imagination. The ocean plays a crucial role in accelerating this process. Although the surface of the Antarctic ice sheet is still quite well shielded from the immediate consequences of atmospheric warming, the fringes of the Antarctic ice sheet are in contact with the ocean water. Global ocean heat uptake now also has warmed the waters circulating around Antarctica (*18*), thus causing very effective and continuous melting of the floating ice shelves from below, the loss of which contributes to a destabilization of vulnerable ice streams through the loss of the buttressing effect that ice shelves provide. Effective management of this risk, by geoengineering for example, seems futile because the extra energy that the ocean has accumulated through our past CO_2 emissions is "safely" stored and will continue to heat the fringes of Antarctica for centuries to come, even though the atmosphere may slowly cool again if global CO_2 emissions are stopped (*19*).

The third key service is the world ocean's uptake of CO_2 emitted by humans. This uptake causes ocean acidification; i.e., an increase in the acidity of seawater. The best estimate for the recent uptake of anthropogenic CO_2 is 2.9 ± 0.5 Gt of carbon in 2013, or nearly 30% of the total global emissions that year (*20*). About 28% of the cumulative anthropogenic CO_2 emissions from 1750 to 2011 is stored in the world ocean (*1*), an amount roughly equivalent to the carbon uptake by the land biosphere since the beginning of the Industrial Revolution. Although the ocean has been a very dependable reservoir of carbon uptake, this service also comes at a price. That price is ocean acidification, a process whose price tag is still largely a blank because we do not know the consequences of large-scale ocean acidification for marine ecosystems, even though they already are recognized as a serious committed risk, particularly in scenarios of high greenhouse gas emissions (*21*). Possible impacts of ocean acidification on marine organisms are changes in growth, body size, feeding, and reproductive success. Impacts such as these have the potential to disrupt the world's largest food webs and ultimately to diminish the fish catch potential in many regions of the world ocean (*22*). For example, one direct impact of warming on ocean food production is that tropical species are increasingly favored, a shift that already has been observed (*23*) and which poses a specific adaptation challenge to those coastal societies, particularly in the tropics, which already have to cope with high levels of vulnerability.

Of all the projections of future climate change, those of ocean acidification on a global scale have the smallest uncertainties (*1*). For a given emission scenario, those small uncertainties enable possibly the only case of robust predictability of an Earth system tipping element: the crossing of the critical threshold of calcium carbonate undersaturation. Model simulations show that this threshold will be first crossed in the Arctic (*24*), even as early as this decade. Progressively larger areas of the ocean will be affected by undersaturation as CO_2 emissions continue. Undersaturation is considered a significant stressor for calcifying organisms and thus will have a serious impact on marine ecosystems worldwide.

Given the prominent role of the ocean in the Earth system as a vital service provider, one wonders why so little attention is still paid to its physical state and the health of its ecosystems in the policy arena. Should we not step up efforts to better measure, understand, and project ocean processes? Many impacts on land due to climate change have been documented, and some irreversible changes have already been identified, such as committed global glacier melting, for instance. Our ignorance of the state of the ocean does not mean that impacts are not happening there; impacts occur whether they are visible to us or not. Perhaps the vastness of the world ocean makes us think that it is safe from our influence and that there still is time to act and avoid the most dangerous and pervasive impacts and consequences of our activities on ocean system services.

We must recognize that Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which calls for the prevention of "dangerous anthropogenic interference with the climate system," encompasses much more than the currently agreed-upon maximum warming target of 2°C by the countries that are party to the UNFCCC. The ocean is not explicitly mentioned in Article 2, although there are ample reasons to argue that it should be. Of equal importance to climate warming are the problems of ocean acidification, which is not at all addressed by the warming target; sea-level rise, also not well represented by a target of atmospheric warming; and marine food production, which involves many more drivers than just atmospheric temperature and will suffer impacts due to human activities that are still poorly identified and understood. For each of these issues, we could formulate an additional target.

A combination of such targets must guide our progress toward a sustainable climate future. The challenges of a more holistic approach to Earth system change mitigation will require much more effort by all parties (*25*), in order to keep the door to limiting climate change at a level where most regions and communities will be able to adapt, from closing before our very eyes (*26*). Thorough research, well-designed scientific programs, and international initiatives will provide us with a much better understanding of the ocean and its key influence on all other components of the Earth system. That scientific understanding will be a prerequisite for a responsible stewardship of the world ocean and therefore continued ocean system services and functioning marine ecosystems.

REFERENCES AND NOTES

1. Intergovernmental Panel on Climate Change, Summary for Policymakers, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1–30.
2. R. A. Watson *et al.*, *Nat. Commun.* **6**, 7365 (2015).
3. M. Rhein *et al.*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge University Press, Cambridge, 2013), pp. 255–316.
4. D. Roemmich *et al.*, *Nat. Clim. Change* **5**, 240–245 (2015).
5. M. A. Srokosz, H. L. Bryden, *Science* **348**, 1255575 (2015).
6. T. F. Stocker, A. Schmittner, *Nature* **388**, 862–865 (1997).
7. T. M. Lenton *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1786–1793 (2008).
8. J. H. Christensen *et al.*, Climate phenomena and their relevance for future regional climate change, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1217–1308.
9. W. Cai *et al.*, *Nat. Clim. Change* **5**, 849–859 (2015).
10. B. Ng, W. Cai, K. Walsh, A. Santoso, *Sci. Rep.* **5**, 11697 (2015).
11. J. P. Kossin, K. A. Emanuel, G. A. Vecchi, *Nature* **509**, 349–352 (2014).
12. M. Zemp *et al.*, *J. Glaciol.* **61**, 745–762 (2015).
13. E. Hanna *et al.*, *Nature* **498**, 51–59 (2013).
14. T. F. Stocker, The ocean as a component of the climate system, in *Ocean Circulation and Climate, 2nd Edition. A 21st Century Perspective*, G. Siedler *et al.*, Eds. (Academic Press, Oxford, ed. 2, 2013), pp. 3–30.
15. A. B. A. Slangen *et al.*, *Clim. Change* **124**, 317–332 (2014).
16. I. Joughin, B. E. Smith, B. Medley, *Science* **344**, 735–738 (2014).
17. J. A. Church *et al.*, Sea level change, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2013), pp. 1137–1216.
18. S. Schmidtko, K. J. Heywood, A. F. Thompson, S. Aoki, *Science* **346**, 1227–1231 (2014).
19. G.-K. Plattner *et al.*, *J. Clim.* **21**, 2721–2751 (2008).
20. C. Le Quéré *et al.*, *Earth System Sci. Data* **7**, 47–85 (2015).
21. J.-P. Gattuso *et al.*, *Science* **349**, aac4722 (2015).
22. H.-O. Pörtner *et al.*, Ocean systems, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C. B. Field *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2014), pp. 411–484.
23. W. W. L. Cheung, R. Watson, D. Pauly, *Nature* **497**, 365–368 (2013).
24. M. Steinacher, F. Joos, T. L. Frölicher, G.-K. Plattner, S. C. Doney, *Biogeoscience* **6**, 515–533 (2009).
25. M. Steinacher, F. Joos, T. F. Stocker, *Nature* **499**, 197–201 (2013).
26. T. F. Stocker, *Science* **339**, 280–282 (2013).

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