OCEAN SCIENCE

Under-Resourced, Under Threat

A coherent global vision is needed to better determine the impacts of climate change on marine systems.

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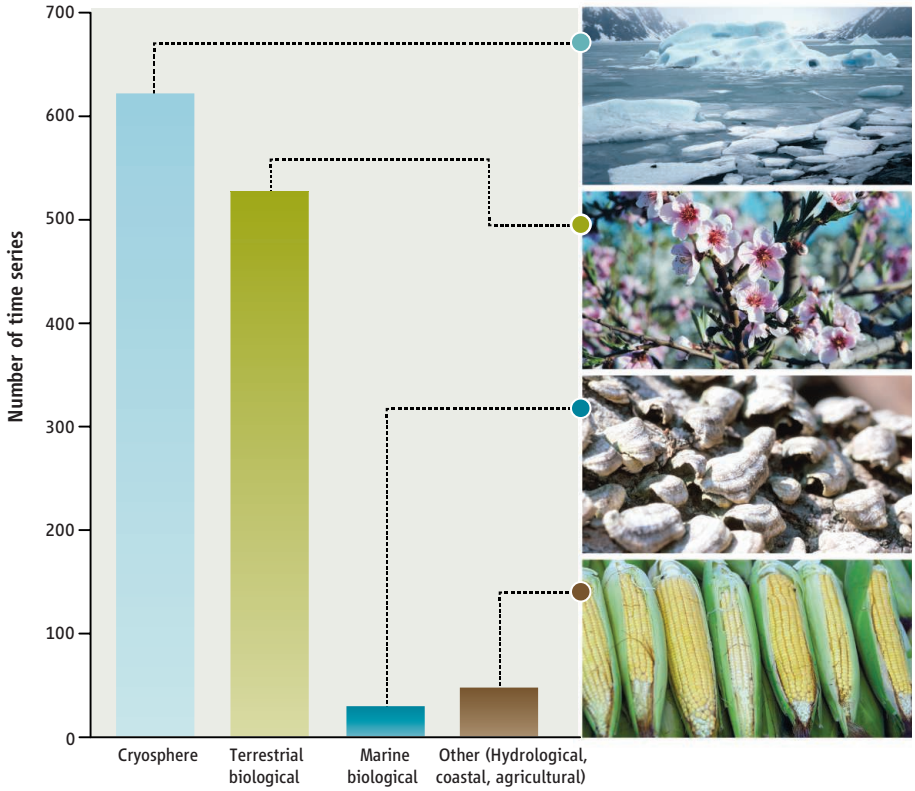
The recent IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (*1*) noted 28,586 significant biological changes in terrestrial systems but only 85 from marine and freshwater systems. Of these few observations from aquatic systems, 99% were consistent with global warming, which suggests that aquatic systems may be extremely vulnerable to climate change. Here, we argue that the dearth of documented changes from marine systems is an artifact of the distribution of global science funding, the difficulty of disentangling multiple stressors from relatively poorly sampled systems, the disconnect between marine and terrestrial ecology, the way marine ecologists report research findings, and limitations in the existing IPCC process.

Marine research is under-resourced compared with that on land. If the number of publications (1996 to 2004, Thomson Scientific ISI) is used as a measure, less than 11% of published papers in each of the fields of ecology, conservation biology, and biodiversity research deal with marine systems (*2–4*). This bias arises in part because investigating the ocean realm is generally difficult, resource-intensive, and expensive.

Observational capacity is also much lower in the oceans than in terrestrial systems. Humans are far removed from much of the ocean expanse, which reduces the likelihood of observing changes there. Research forays into the oceans are transitory and concentrated in coastal waters. Inaccessibility of most marine systems precludes studies by amateur naturalists, who have provided valuable terrestrial data sets on the timing of blossoms or arrival of migratory birds. Satellite observing systems are generally restricted to the sea surface, and even shallow marine ecosystems such as seagrass meadows and coral reefs remain hidden. There are several unique avenues for generating marine time series. Fishery records and fish otoliths (used to estimate fish age and growth, akin to tree rings) provide information over interannual to decadal scales. Reconstructions from sedimentary records and coral cores afford insight over centennial and longer time scales (*5, 6*).



Marine undersampling. The number of time series from different environments included in the recent IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report differ widely. Marine systems are vastly underrepresented compared with terrestrial systems (*1*).

The difficulty of disentangling multiple stressors within poorly sampled systems has also stymied the discovery of marine climate change impacts. No parts of the oceans remain unaffected by multiple human activities, such as eutrophication, fishing, habitat destruction, hypoxia, pollution, and species introductions (*7*). These multiple stressors may have masked more subtle impacts of climate change and may even have misled researchers to interpret climate change impacts as those of local environmental changes.

Furthermore, there is a profound disconnect between marine and terrestrial ecology, evident in the lack of contributions of marine ecology to general ecological theory, journals, and textbooks (*3, 8, 9*). Major differences in concepts (such as the size dependence of predation in marine systems), organization (marine and terrestrial ecologists are usually in different institutes), and funding have resulted in marine research being overshadowed by terrestrial ecology (*8, 9*), and this is evident in biological climate impacts research.

Findings from the Fourth Assessment Report (*1*) reflect the dichotomy between research on marine and terrestrial biological impacts. Chapter 1 of Working Group II's report lists only 30 marine data series (biological and physical) in the synthesis of climate impacts, compared with 622 series from the cryosphere and 527 series from terrestrial biological systems (*1*). Further, only 4 out of 43 authors of this chapter were marine biologists, which results in a greater likelihood that documented changes in marine systems may be overlooked.

IPCC guidelines for inclusion in assessment reports demand that time series must be at least 20 years long and end in 1990 or later. Yet, many marine time series were halted in the late

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1980s, just when ocean warming was accelerating, as a consequence of a funding crisis that shifted marine research toward process-orientated studies (*10*). A possible way to bolster confidence and enhance transparency in the IPCC process would be to specifically detail each marine and terrestrial observation synthesized in the report (in an appendix), as is the norm in large published meta-analyses (*11, 12*). As well as identifying gaps, this will allow the broader scientific community to provide quality control of the data gathering and interpretation that underpin the assessment.

Marine ecologists must also accept responsibility for the paucity of evidence of climate-driven impacts on marine species. Terrestrial studies state observed changes in distribution (as kilometer per degree celsius) and timing (as number of days earlier per degree celsius) explicitly for inclusion in meta-analyses and IPCC reports; these figures are rarely provided in the marine literature. The tendency for marine researchers to report bulk responses for functional groups rather than individual species (*13, 14*) also contributes to underestimates in the number of marine biological changes. Both marine and terrestrial ecologists must develop robust yardsticks against which climate-change impacts can be measured (*15*).

The situation is made more urgent, as emerging evidence suggests that the response of marine organisms to climate change may be faster than on land, despite slower ocean warming. Range shifts of hundreds of kilometers in a few decades have been observed in phytoplankton (*16*), zooplankton (*14*), fish (*17*), and intertidal fauna (*18*). Many organisms can be dispersed widely and rapidly by ocean currents (*19*). High fecundity (for example, many bony fish spawn thousands to millions of eggs per female per year), coupled with free-floating early-life stages, allows far-ranging dispersal in a single reproductive season. Changes in life-cycle events may also be greater for marine organisms, with an advance in seasonal timing by more than 8 days per decade of the appearance of phyto- and zooplankton (*13*, *20*) and breeding in sea turtles (*21*) and seabirds (*22*). Shorter life cycles of oceanic primary producers (days to weeks) compared with land plants (months to years) contribute to this rapid response.

Unfortunately, our greater knowledge of terrestrial climate impacts will not provide the means to understand marine impacts. Ocean and terrestrial (atmospheric) processes commonly operate over fundamentally different time and space scales (*8*). For example, cyclones in the atmosphere are about 1000 km across and last for a week or so, whereas their marine equivalent, ocean eddies, have diameters of about 200 km and exist for months to years. Slow ocean dynamics also means that some changes will be essentially irreversible. For example, declines in ocean pH may impact calcifying organisms, from corals in the tropics to pteropods (winged snails) in polar ecosystems (*23*, *24*), and will take tens of thousands of years to reequilibrate to preindustrial conditions (*23*). Understanding and adapting to climate impacts in the oceans will require some uniquely marine solutions.

Despite these basic differences between marine and terrestrial systems, marine scientists will find many solutions by embracing general principles that transcend the division between these environments. Effects of temperature on organism traits (such as growth and life cycles) may obey similar fundamental rules in the ocean and on land. The metabolic theory of ecology, which formulates predictions on a range of ecological processes based on biophysical principles, is emerging as a unifying principle bridging the marine-terrestrial divide (*9*). Other areas of common interest include fast rates of habitat destruction and critical concepts, such as the likelihood of climatic tipping points beyond which ecosystems may experience abrupt changes. Tackling these research concepts should yield common theory that has predictive capability in both environments.

Marine ecosystems are undoubtedly under-resourced, overlooked, and under threat; our knowledge of impacts of climate change on marine life is a mere drop in the ocean compared with that for terrestrial organisms. To address this disparity, a coherent vision is needed to lobby for greater resources for marine research, to focus marine investigations, and to improve marine coverage in the IPCC process. This vision should address the following points:

- encourage comparative research effort in areas where there is likely to be mutual interaction (and benefit) between marine and terrestrial biologists, such as the effects of temperature on life cycles and metabolism;
- establish multinational observing networks that extend across ocean basins to resolve the rapid and long-range shifts expected in organism ranges;
- address the multiple, interactive modes of impacts of climate change and other global change stressors on marine ecosystems and biodiversity;
- encourage marine biologists to participate more actively in the formulation and testing of general ecological principles, providing the necessary theory to interpret and predict climate impacts in marine ecosystems;
- ensure maximum inclusion of marine impacts in the IPCC process by urging marine researchers to state observed changes explicitly for each species studied;
- call for better representation by marine biologists in the IPCC process;
- recommend that the IPCC list each marine and terrestrial observation they use;
- capitalize on the unique windows into marine ecosystem changes over relatively long time scales afforded by sedimentary records.

Two meetings in Spain this year—the recent symposium on *Effects of Climate Change on the World's Oceans* (19 to 23 May) in Gijon and the upcoming *World Marine Biodiversity Conference* (11 to 15 November) in Valencia—bring together marine biologists concerned with climate change and the conservation of marine biodiversity. These meetings provide ideal opportunities to develop such a global vision.

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