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Our changing oceans: conclusions of the first International Symposium on the *Effects of climate change on the world's oceans*

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Introduction

If we want to characterize the unique qualities of our planet with only two words, these would be "water" and "life". The current composition of our atmosphere is a result of the interaction of both. Covering more than two-thirds of the earth's surface, the oceans are a central part of the climate system and control the timing and regional distribution of the earth's response to climate change, primarily through the absorption of carbon dioxide and heat. Similarly, the global water cycle is driven mainly by evaporation from the oceans. Climate shapes the environment, natural resources, economies, and social systems worldwide, and understanding the role of the oceans as a regulator of the earth's climate system is a challenge for environmental sciences, such as climatology and oceanography.

In addition, the oceans sustain a great wealth of biological diversity and, through fisheries, supply humankind with essential proteins and fatty acids. The oceans also play a key role in the carbon cycle of our planet, and they have absorbed approximately one-third of the total anthropogenic CO_2 emissions of the past century. A healthy marine environment is an important factor for economic development, social well-being, and human quality of life.

However, in our time, the oceans are changing rapidly. Surface waters are warming, sea level rise is accelerating, and the oceans are becoming increasingly acidic, jeopardizing marine biodiversity and even entire ecosystems (e.g. coral reefs). Human activities are causing changes in the oceans that have been without precedent in the past several million years. Humanity is thus interfering with pivotal mechanisms of the Earth System.

Climate change is recognized as the most important threat to life on the earth. Even if we stabilize CO_2 concentrations, the 2007 Intergovernmental Panel on Climate Change (IPCC) assessment projects that warming will continue for decades and sea levels will continue to rise for centuries and even millennia. Some direct effects of climate change on the marine environment are already visible, but others wait to be revealed by enhanced observations, analysis, and modelling. We have only a rudimentary understanding of the sensitivity and adaptability of natural and managed ecosystems to climate change. An assessment of the consequences of climate change on the world's oceans has high scientific and social relevance. Moreover, assessments are urgently needed, because although we are beginning to document the local effects and consequences of climate change on the functioning of marine ecosystems, there is no comprehensive vision at the global scale, and only limited ability to forecast the effects of climate change at short- and medium-term scales.

Scientific congresses and symposia constitute an effective and practical manner for the scientific community to communicate progress in their research field, discuss practical applications of new technological developments, interchange experiences, identify synergies, and find new research directions and hypotheses. It was with this conceptual approach that the International Symposium on *Effects of climate change on the world's oceans* was convened. It focused on the major issues of climate change that affect all aspects of the oceans, and it was the first worldwide symposium to focus on this great concern. As such, it represented an important opportunity to develop further the truly international nature of research related to the effects of climate change on the world's oceans.

The symposium covered a wide range of topics: oceanic circulation, sea level rise, coastal ecosystems and erosion, cycling of carbon and other elements, acidification, oligotrophy, changes in species distributions and migratory routes, climate-change scenarios, and the possibilities for mitigating and protecting the marine environment and living marine resources. It also assessed model predictions, discussed the role of the IPCC in assessing climate change in the ocean, reviewed possible scenarios and methods for adaptation, identified the most immediate challenges and hotspots for special consideration in the short term, and finally stated the uncertainties in current measurements and observation programmes as well as the need for new instrumentation.

Documenting climatic change in our oceans

Many new and exciting results were reported during the symposium. Here, we highlight just a few examples that have especially wide ranging implications for the oceans and humanity. The symposium heard that the annual growth rate of atmospheric CO_2 had been 2.2 ppm year^{-1} in 2007 and averaged >2.0 ppm for the period 2000–2007, whereas the average annual mean growth rate for the previous 20 years had been ~1.5 ppm year^{-1}. This acceleration, together with a decreasing efficiency of ocean and terrestrial sinks, means that the atmospheric CO_2 concentration is currently following the upper bound of the scenarios in the Fourth Assessment Report of IPCC (IPCC AR4) and that future climate changes could be greater than previously anticipated.

Anthropogenic warming and sea level rise are likely to continue for centuries and even millennia, even if greenhouse gas (GHG) concentrations were stabilized at or above the levels at the beginning of the 21st century. IPCC AR4 estimates a sea level rise of 0.2–0.6 m during this century using currently available models and without any additional allowance for the poorly understood dynamic response of the ice sheets. However, there is a great uncertainty in the potential future contribution of the Greenland and Antarctic ice sheets, and recent results indicate that Greenland's contribution to global sea level rise has more than doubled in one decade, from 0.23 mm year^{-1} in 1996 to 0.57 mm year^{-1} in 2005. This contribution is increasing (complete melting of the Greenland ice sheet would raise the global sea level by ca. 7 m) and makes Greenland, along with the West Antarctic ice sheet, a "hotspot" to be monitored over coming decades. The potential effects of sea level rise, coastal erosion, extreme storm events, and the effects on our coastal society and natural ecosystems were discussed. Another cause for concern is the intensity and duration of hurricanes because the surface of the ocean is warming and accumulating more energy earlier in the year and covering a larger area.

Warming and acidification are having substantial, yet poorly characterized, effects on marine ecosystems and biota. Current coral reef ecosystems might not be viable at CO_2 levels of >450–500 ppm. This poses a risk not only to the corals, but also to their entire ecosystem, which includes several thousands of species, approximately half of which are at risk of disappearing. High-latitude surface waters are likely to become undersaturated with respect to calcium carbonate during the 21st century, and some coastal upwelling areas in the California Current are already exposed to undersaturated waters at shallow depths. As a result, some calcifying species, such as pteropods, corals, and echinoderms among others, may be unable to form shells and other body structures. The depletion of O_2 in upwelling areas must also be carefully monitored in coming years, because areas of hypoxia appear to be expanding. The size of the oligotrophic oceanic gyres is expanding in the North Pacific and Atlantic Oceans. On a global scale and in regional seas, the strengthening of water-column stratification and the resultant reduced nutrient flux and decline in primary production should also be explored. Finally, there is evidence that the distribution of zooplankton, fish, and other taxa has shifted hundreds of kilometres polewards in some locations, especially in the North Atlantic, the Arctic Ocean, and the Southwest Pacific Ocean.

The observed declines in fish populations over recent decades may be more a consequence of cumulative and interactive effects of fishing, pollution, and coastal development than of climate change. In particular, habitat destruction, bycatch, and the selective catching of larger female fish (which may make a disproportionately large contribution to recruitment) have been considered to date to have a greater influence on fish population dynamics than the effects of climate change. Nevertheless, climate-change effects can already be detected in the migratory routes of tuna and in northern displacement of small pelagic fish in the north hemisphere (and east–west displacements in the southern hemisphere). In the future, it is likely that climate-change effects will combine with and further exacerbate already critical pressures on ecosystems. Increased water temperatures are also likely to result in the migration of some species to higher latitudes with, as yet, unknown effects on ecosystem structure.

In addition to the current work in assessing climate-change effects, new challenges for the next 5–10 years include studying the non-linear effects on biological processes leading to shifts in ecosystem structure and function (which are not currently well understood), the decadal variability underlying the signal of climate change, the rate of contribution to sea level rise from the Greenland and West Antarctic ice caps, ocean acidification, the expansion of oligotrophic gyres (how the productivity in the oceans will change in the future), the modification to the intensity of coastal upwelling (which affects both productivity and acidification in coastal upwelling regions), species sensitivity to climate change, and the interaction of climate change with other human effects and activities. These changes are likely to affect ecosystem services and biodiversity increasingly during this century and beyond it.

Observing our changing oceans

The symposium participants also identified key needs for the effective study of climate change in the marine environment.

Estimates of physical changes in the ocean are based on *in situ* and satellite observations and modelling studies, but even for the most well-observed physical variables, the records are often short, spatially and temporally incomplete, have insufficient metadata, and are sometimes plagued by instrumental biases. Our capability and capacity for observing ocean carbon and other physical variables has improved greatly in the past decade. The ocean–climate community has benefited from the development of automated *in situ* observing systems, satellites, and importantly, through the formulation of a single ocean-observing plan. A major challenge is to complete implementation of and maintain the agreed observing systems.

However, long time-series of geochemical and especially biological and ecosystem parameters are still rare to non-existent, and there is a lack of proved, long-term, autonomous *in situ* observing systems for these variables. Although ocean colour satellites have high value, they only measure near-surface values. Also, there is no agreed plan for monitoring corresponding *in situ* parameters globally nor for how to make best use of *in situ* and remote instruments.

It was also recognized that our observational capacity is much lower in the oceans than in terrestrial systems. Many ocean observations are made as part of transitory oceanographic research programmes, often concentrated in coastal waters. Inaccessibility of most marine systems prevents many nations from investing the economic resources needed to establish permanent programmes to monitor both the coastal seas and the open ocean. Satellite observing systems are generally restricted to the sea surface; even shallow marine ecosystems, such as seagrass meadows and coral reefs, remain hidden from view by satellites. New and powerful instruments, such as gliders, are now available to observe the physical properties of oceans, but we remain lacking in our technological capacity to monitor biological communities with the appropriate spatial and temporal resolution. The southern hemisphere, especially the South Pacific and Indian Oceans, is a vast region that is poorly covered (or not covered at all) by monitoring programmes. Consequently, there is likely a bias in our perception and in the predictions of our models. International collaboration should be pursued to establish permanent research and observational programmes in these areas.

The importance of maintaining existing time-series was emphasized. These will provide essential data to understand interdecadal variability in climate, as well as the effects of global warming *per se*. Exploring the effects of climate change does not rely only on observations; greater understanding, based on carefully designed experiments, is needed (this is especially true for acidification, which might have many unforeseen consequences on marine ecosystems far beyond its effect on coral reefs). The importance of good communication, not only to obtain data in real time, but also to interchange data and to be aware of data from other disciplines, was also emphasized (data from different sources are often complementary, and the collective value of datasets is greater than its dispersed value). Finally, more complex and finer-resolution models are essential to respond to policy-makers' and society's needs accurately and in timely manner.

Conclusions and priorities

(i) The global warming trend and increasing emissions of CO_2 and other GHG are already affecting environmental conditions and biota in the oceans on a global scale.

(ii) We neither fully appreciate nor do we understand how significant these effects will be in the near and more distant future; furthermore, we do not understand the mechanism and processes that link the responses of individuals of a given species with shifts in the functioning of marine ecosystems.

(iii) Marine scientists need urgently to address climate-change issues. In particular, the IPCC assessment would benefit from increased participation of marine scientists concerned with climate variability and change and their effect on ecosystem structure, biodiversity, and fisheries', species', and society's adaptation to these changes.

(iv) It is essential to complete the design and implementation of a comprehensive *in situ* and satellite ocean observing system, including expanding the system beyond its current physical and carbon variables. Particularly important are maintaining existing time-series of ocean observations, establishing more in some regions, doing more experimental research, and developing more complex and higher-resolution models. It is also essential to sustain the global-scale observing systems over decades and to compile the data into quality controlled and easily accessible databases.

(v) We also need to measure terrestrial inputs into the ocean (e.g. terrestrial run-off and its nutrient/pollution load), the atmosphere, and the cryosphere. For example, to evaluate the risks of sea level rise and possible changes in thermohaline circulation, there is an urgent need to measure accurately the response of the Greenland and Antarctica ice sheets. In addition, because of its importance for future atmospheric concentrations, it is important that we continue to verify the rate of incorporation of CO_2 in the ocean and the effect of ocean acidification on marine ecosystems.

(vi) Almost all ocean observations are supported by short-term research funding, with the resultant effect of changing institutional priorities. Sustained funding is critical for sustained observations. A significant step would be mandating and funding national institutions tasked with the responsibility to collect the critical environmental observations. This urgently requires a significant and sustained commitment of funding by nations from around the world.

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