



## Introduction

# The evolving and increasing need for climate change research on the oceans

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The 3rd International Symposium on the Effects of Climate Change on the World's Oceans was held in Santos, Brazil, in March 2015, convened by the International Council for the Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), and the Intergovernmental Oceanographic Commission of UNESCO (IOC), and organized locally by the Oceanographic Institute, University of Sao Paulo (IO-USP). The symposium was designed to do two things. First, to get updates on new scientific developments that would address recognized uncertainties that remained from Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report and to contribute to building bridges between research in the natural and social sciences in respect to the human dimensions of climate change, with a focus on coastal communities, management objectives, governance and adaptation measures. The choice of the venue in Santos, Brazil, was aimed to stimulate and widen this thematic discussion in Latin America and southern Atlantic regions, where there still are important knowledge gaps and scientific, politic and societal challenges to be overcome. The meeting was attended by 280 participants from 38 countries, contributing 336 oral and poster presentations. This paper summarizes the main outcomes of the symposium and introduces a number of papers submitted to this special issue.

**Keywords:** climate change, Global Oceans, marine ecosystems, international symposium.

In 2007, the IPCC produced its 4th Assessment Report (IPCC, 2007). A mammoth task demonstrating that climate change was occurring, caused largely by human activities, and that it posed significant risks for—and often was already affecting—a broad range of human and natural systems. Ocean scientists, particularly biologists, noted that the report included 25 586 examples of significant biological changes in terrestrial ecosystems but for only 85 examples from marine or freshwater systems (Richardson and Poloczanska, 2008). The authors argue that this imbalance was an artefact 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, and the way marine ecologists report research findings. It is in this context that the International Council for the Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), and the Intergovernmental Oceanographic Commission of UNESCO (IOC)

organized the first International Symposium on the *Effects of Climate Change on the World's Oceans* in Gijon, Spain (Valdés *et al.*, 2009), to capture some of the latest evidence on the degree that the oceans were changing, in terms of warming, sea level rise, acidification, biodiversity loss and ecosystem function. The symposium concluded that humanity was interfering with pivotal mechanisms of the Earth System. The preparation and ground work for Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) took note of this emerging evidence and, in a sign of departure from AR4, included dedicated chapters on ocean systems (Chapters 6 and 30).

The 2nd ICES/PICES/IOC International Symposium in this series was hosted in Yeosu, Korea in 2012, in the midst of intense IPCC AR5 drafting. Much of the work presented in Yeosu was included in the IPCC AR5 WGII report (IPCC, 2014). Gattuso *et al.* (2015) summarized the IPCC AR5 conclusions with respect to the ocean in four

dramatic messages: Oceans strongly influence the climate system and provide important services to humans; impacts on key marine and coastal organisms, ecosystems, and services are already detectable, across all latitudes, and will face high risks well before 2100; immediate and substantial reduction of CO<sub>2</sub> emissions is required to prevent irreversible impacts on ocean ecosystems and their services; not limiting emissions to drastic levels will result in a substantially different ocean. As atmospheric CO<sub>2</sub> increases, protection, adaptation, and repair options for the ocean become fewer and less effective.

The rationale for the 3rd International Symposium on *Effects of Climate Change on the World's Oceans* was to continue reinforcing the message that oceans are crucial to understand climate change, that the impacts of climate change on the oceans are to be taken seriously, and that both are needed in the ongoing re-evaluation of the relationship we as humans have with nature and the ecosystem services it provides. Oceans are central to the climate system, recycling half of the oxygen we breathe and absorbing half of the carbon dioxide we emit through the burning of fossil fuels. They accumulate over 95% of the Earth's water and mobile carbon, providing food and livelihood opportunities. Discussing the effects of climate change on the world's oceans is thus critical to understanding what is changing, how is it changing and in what way these changes will influence dependent communities. While there is recognition that direct and indirect effects of climate change are already visible, most impacts can only be projected based on existing observations, experimentation and modelling efforts. The choice of venue in Santos, Brazil, was aimed to stimulate and widen this thematic discussion in Latin America and southern Atlantic regions, where there are still important knowledge gaps and significant scientific, politic, and societal challenges to overcome (Turra *et al.*, 2013).

The Symposium, like the others in the series, was jointly convened by the ICES, PICES, and IOC. It was organized locally by the Oceanographic Institute, University of Sao Paulo, and was designed to do two things. First, to get updates on new scientific developments that would address recognized uncertainties that remained from Intergovernmental Panel on Climate Change Fifth Assessment Report (e.g. Gattuso *et al.*, 2015; Weatherdon *et al.*, 2015; WCRP, 2015), and in particular:

- The extent of warming in deep water masses (<700 m).
- The likelihood of climate-induced changes to major upwelling systems.
- The ways in which climate-induced changes in the physiology and biogeography of an individual species may alter ecosystem structure, species interactions, and foodwebs.
- The sensitivity of ecosystems impacted by multiple drivers (e.g. ocean warming, acidification, and hypoxia), multiple stressors, and synergistic impacts.
- The capacity for phenotypic and evolutionary adaptation over generations in response to long-term climate change.
- The emerging climate-impacts to coastal sectors, such as tourism and aquaculture, and the consequences of change in terms human well-being and regional economic development, and finally.
- Our ability to forecast impacts and changes at national and ecosystem scales and to scale these to fisheries food production and security, including potential adaptation responses.

Our second objective was to contribute to the building of bridges between research in the natural and social sciences in respect to the

human dimensions of climate change, with a focus on coastal communities, management objectives, governance, and adaptation options. A Keynote address from Prof. Chris Field, Co-chair of IPCC 5AR WGII set the scope for the symposium, mapping the potential impacts of climate change to socio-economic processes (adaptation, mitigation, and governance) through assessments of risks and uncertainty. This was followed by 12 sessions covering different but interconnected themes, from physical processes and their interaction with ecosystem dynamics, to resource provision and ocean governance (see Supplementary material). The latest developments in predicting changes in biodiversity, phenology, fisheries, and ecosystems, as well as in the physical systems that sustains these, were presented with a view to inform discussions on the risks and opportunities that climate change will bring to coastal communities and to society at large.

The outcomes of the symposium have been used widely, and in particular were presented at the July 2015 international conference *Our Common Future Under Climate Change* (<http://www.commonfuture-paris2015.org/>):

- Ocean warming is evident from the recent observational record, and is projected to continue in coming decades, although the degree of warming is not geographically consistent. What we need to measure, with what frequency and for what purpose requires careful consideration.
- Climate change is affecting a very large number of physical, chemical, biological, and ecological properties. The magnitude of the changes varies between variables. Much discussion was devoted to non-linearity of processes and the potential for tipping points.
- While modelling the future ocean has developed significantly in recent years, increasing the spatial and temporal resolution of these models remains crucial, especially to understand climate change impacts in coastal regions, shelf seas, and upwelling systems, and to consider the role of climate variability in intensifying or reducing underlying trends.
- Most studies indicate an ongoing geographical displacement of organisms towards polar regions, although the displacement rate and settlement success varies between regions and species. For some species, displacement is not an option.
- Phenological changes are increasingly observed, with concerns that these can lead to a degree of mismatch between predators and their prey. Some species are capable of adjusting life history strategies to cope with change, while others have a more rigid and thus vulnerable life history.
- Ocean acidification is one of the most active and successful areas of global change research. As the discipline matures, we not only recognize impacts but also their vast geographical variability, as well as the significant roles of acclimation and evolutionary adaptation in response to change.
- Research on the impacts of climate change on dependent coastal communities highlights the narrative of winners and losers, and the difficulty to find solutions that benefit or reduce impacts for all in equal ways or reduce.
- In particular, climate change is an additional stressor, reinforcing other impacts such as overfishing, pollution, and habitat loss, and causing cascades of impacts across assets and communities. Understanding vulnerability footprints at the right scale is a prerequisite for the development of successful adaptations.

- In the end, climate change impact management is about managing risk, a process to advance toward sustainable pathways in the midst of incomplete information. Developing a new narrative based on risk management is essential if we want the oceans to be part of the climate solution.

The meeting was attended by 280 participants from 38 countries, contributing 336 oral and poster presentations in Theme Sessions and Workshops. All symposium presentations (with author's permission) are available for viewing ([http://www.pices.int/meetings/international\\_symposia/2015/2015-Climate-Change/scope.aspx](http://www.pices.int/meetings/international_symposia/2015/2015-Climate-Change/scope.aspx)) as well as the book of abstracts (see Supplementary material). As climate change research has become mainstream in the scientific literature most of the papers presented have been or are in the process of appearing in the many journals concerned with this topic. This issue of the *ICES Journal of Marine Science* includes nine papers from the symposium.

[Kristiansen et al. \(2016\)](#) explores the links between *Calanus* spp. and water masses in the Norwegian Sea, and in particular the relationship between copepod dynamics and the inflow of warm and saline water from the southwest and cold and less saline water from the northwest of the study region. These two water masses meet and form the Iceland Faroe Front (IFF), where *Calanus finmarchicus* plays a key ecological role. Their goal was to explore how changes in circulation patterns under climate change could affect Norwegian Sea ecosystems. The paper describes that the main reproductive period of *C. finmarchicus* historically started consistently earlier south of the IFF, resulting in different life cycles and stage compositions in the two water masses. However, record high values of temperature and salinity were recorded in 2003 north of the IFF, which resulted in some peculiar changes: North populations of *C. finmarchicus* reproduced earlier, increasing from one to two new generations per year, and giving the species a competitive advantage over *C. hyperboreus*. They conclude that this is an example of the potential strong effects of climate change on the ecosystem and pelagic fish in this subpolar Atlantic region.

The impacts of climate change on complex predator–prey relationships are investigated by [Spencer et al. \(2016\)](#). Their work focuses on recent adaptations of arrowtooth flounder (*Atheresthes stomias*) to climate variability and what they may tell us for the long-term dynamics of the species under climate change. Arrowtooth flounder prey on juvenile walleye pollock, but their spatial overlap—a requirement for successful predation—is determined by the size and location of the so called “cold pool”, a region of cold bottom waters in summer which arrowtooth flounder avoids. Projections of sea surface temperature (SST) and “cold pool” area were obtained from nine global climate models and used within an age-structure population model to project walleye pollock abundance. The projections show a wide range of variability but an overall trend of increasing SST and decreasing cold pool area, which in turn drove a decreasing trend in projected walleye pollock biomass. A sensitivity analysis indicated that the decline in projected walleye pollock biomass would be exacerbated if arrowtooth flounder expanded their distribution in the eastern Bering Sea in warm years.

The impacts of geographical changes caused by climate change were one of the most discussed topics in the symposium, as shifts are one of the most common fingerprints of climate change in the marine environment. [Alabia et al. \(2016\)](#) examines the potential changes in the habitat distributions in the North Pacific of the neon flying squid (*Ommastrephes bartramii*) under three climate

scenarios (IPCC RCP4.5, RCP6.0, and RCP8.5), based on the statistical dependence of squid habitat on SST. They note that future squid habitat predictions in the western and central North Pacific will suffer from a net reduction in suitable habitat coupled with a northward habitat retreat, proportional to the levels of warming. These trends could translate into shorter squid fishing periods and offshore shifts of the squid fishing grounds, providing useful input to fishery management options and adaptations under climate change.

Following on the same narrative of geographical shifts, [Cormon et al. \(2016\)](#) investigated the impacts of species migrations on the dynamics of marine ecosystems. They did so by estimating the consequences of the expansion of European hake (*Merluccius merluccius*) to the North Sea over the last 15 years, in response to warmer temperatures. They used a multispecies assessment model that focused on hake, as a new predator, and North Sea saithe (*Pollachius virens*) and Norway pout (*Trisopterus esmarkii*) as competitors. Modelling revealed a clear negative impact of hake on saithe biomass, emerging from an increase in predation pressure on Norway pout. This provides a good example of the indirect impacts that can be expected from climate change on the functioning of marine ecosystems.

[Van Putten et al. \(2016\)](#) followed the narrative of geographical shifts, but this time focused on the potentially dramatic changes in the distribution of subsequent economic, social, and cultural opportunities. The authors argue that a reluctance to attribute marine range shifts to climate change may undermine the effectiveness of climate change communications and pose a potential barrier to successful adaptation. They explore three cognitive processes that underpin the formation of marine resource users' beliefs using examples of range shifts experienced in a marine hotspots in southeast Australia. These processes are engrained mental representations of environmental phenomena, scientific complexity in the attribution pathway, and dissonance from the positive or negative nature of the impact. They conclude that all three play a part in explaining the complex pattern of attribution of marine climate change range shifts, and should be considered when planning for engagement with stakeholders and managers around adaptation to climate change.

[Szuwalski and Hollowed \(2016\)](#) focused their work on how to incorporate climate change impacts into fisheries management processes. They start by recognizing that management targets for fishing mortality and spawning biomass are often calculated by assuming stationary population processes, but that climate change will violate this assumption. They note that there are very few accepted frameworks that incorporate the changing influence of the environment on exploited populations into management strategies, and call for such frameworks to be developed. They emphasize that Management Strategy Evaluations could be useful to understand the potential benefits and costs of changing management targets under changing environmental conditions.

In one of the few examples presented on climate change impacts on developing regions, [Fernandes et al. \(2016\)](#) project changes to the long-term productive capacity of Bangladesh marine fisheries under climate and fisheries management scenarios. They did so by down-scaling a global climate model, using associated river flow and nutrient loading estimates and projecting high-resolution changes in physical and biochemical ocean properties. Their interest was on future catch potential for Hilsa shad (*Tenualosa ilisha*) and Bombay duck (*Harpadon nehereus*). They concluded that under sustainable management practices Hilsa shad catches may show a minor decline in potential catch by 2030 but a significant decline

by 2060. For Bombay duck, potential catches under sustainable scenarios will produce a decline of <20% compared with current catches. The results demonstrate that management interventions can mitigate or indeed exacerbate the effects of climate change on ecosystem productivity.

One of the most recognized issues in the climate change scientific literature is the treatment of uncertainty in predictions. The special issue includes two contributions on this topic. [Cheung et al. \(2016\)](#) discuss the lack of formal and systematic treatment of uncertainty in living marine resource projections. They synthesize the different sources of uncertainty by drawing from climate model inter-comparison efforts, and suggest an ensemble of available models and projections as a starting point to quantify uncertainties. They use two examples, global and regional projections of SST and catch projections of sablefish (*Anoplopoma fimbria*) in the 21st century, to illustrate their approach to explore uncertainties. [Payne et al. \(2016\)](#) on the other hand discuss how adaptation strategies need to formally identify, quantify, and communicate uncertainty to both evaluate the risk associated with a projection and to build confidence in its robustness. They break uncertainties down into structural (model) uncertainty, initialization and internal variability uncertainty, parametric uncertainty and scenario uncertainty, and review the state of the art in respect to the marine science literature. They conclude that marine science should strive to reach the point where scenario is the dominant source of uncertainty in projections.

Overall, the work presented at the symposium demonstrated the increased maturity of climate change research, particularly in relation to biological and ecological systems. Earlier work based on simple parameterizations, short-term experiments, and low-resolution modelling is increasingly being replaced with high-resolution ensemble modelling, complex experimental set ups, and increased recognition of acclimation and adaptation processes. Despite some significant advances, linking natural and social science in tackling marine socio-ecological systems remains challenging, particularly in relation to bridging differences of scale, process connectivity and linearity, and attribution. We foresee that a 4th international symposium on the effects of Climate Change in the World's Oceans will be needed to provide significant progress in this area, harness contributions to the IPCC AR6, as well as other global initiatives such as the United Nations Regular Process for Global Reporting and Assessment of the State of the Marine Environment.

### Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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