BY PHILIP W. BOYD, CLIFF S. LAW, AND SCOTT C. DONEY

# A Climate Change Atlas for the Ocean

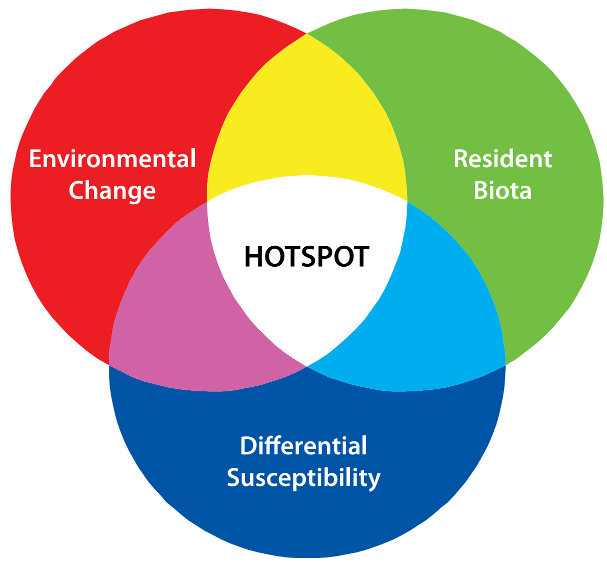


Figure 1. A Venn diagram illustrating the concept of the Climate Change Atlas. The intersection of information on the distribution of resident biota, their susceptibility to change, and predictions of how their environment will be altered informs scientists, resource managers, and policymakers about where nodes of change (i.e., hotspots) are most likely, and indicates whether different components of the resident biota may be particularly vulnerable to the effects of climate change.

## INTERACTIVE TOOLS FOR OCEAN POLICY FORMULATION

At both regional and national levels, there is an urgent need to develop a clear picture of how climate change will alter multiple environmental properties in the ocean. Specifically, what will such cumulative alterations mean for local biological productivity, ecosystem services, climate feedbacks, and related effects ranging from biodiversity to economics? Currently, a wide range of confounding issues, such as the plethora and complexity of information in the public domain, hinders accommodating climate change into future planning and development of ocean resource management strategies. This impediment is especially true at the regional level, for example, within national Exclusive Economic Zones (EEZs), where critical management decisions are made but for which substantial uncertainty clouds climate change projections and ecosystem impact assessments. Evaluating the susceptibility of a nation's marine resources to climate change requires knowledge of the geographic and seasonal variations in environmental properties over an EEZ and the range, spatial patterns, and uncertainty of projected climate change in those properties (Boyd et al., 2007). Furthermore, information is needed on the climate sensitivity of the biological species or strains that comprise particular marine resources (Boyd et al., 2007; Nye et al., 2009) and/or contribute to food-web interactions, and also on potential implications for human resource exploitation patterns and intensity.

However, increasingly interactive and flexible tools (Tollefson, 2009) and scenario-building exercises (Boyd et al., 2007; Biggs et al., 2010; Machlis and McNutt, 2010) are being developed by scientists, and used by both researchers and policy analysts to better understand complex environmental problems, such as managing major oil spills and the effects of climate change. For example, scenario-building exercises can help identify the breadth of issues, range of stakeholders, and contingencies among cascading impacts and possible solutions. Encouraged by the merits of these approaches, we advocate assembling ocean climate change atlases to bring together and compare disparate strands of information (Figure 1). We then illustrate how such an atlas can be constructed using the example of a regional atlas recently published for the New Zealand EEZ (Boyd and Law, 2011). To meet the challenges of incorporating climate change information into broader resource management decisions, such an atlas may be used in conjunction with other interactive tools. These tools include complex decision-making software (Hansen and Ombler, 2009) that can be used to provide a decision-making framework that links environmental and other issues, such as socio-economics, by weighting each of them using agreed criteria (see later).

## A CLIMATE CHANGE ATLAS

An interactive climate change atlas would facilitate the process of science informing resource management strategies and policy. The atlas would be built on customized suites of relevant environmental and resource data sets, providing an accessible format for conveying how climate change will manifest itself at a regional level across multiple dimensions. Spatial patterns of change for a range of marine environmental properties that impact biota—from pH to nutrient supply—could be readily communicated. Such an illustrative approach has been applied at the global level (Dow and Downin, 2007) and detailed for both the terrestrial biosphere (Matthews et al., 2004) and more recently for the ocean (Boyd and Law, 2011). The maps that form this regional atlas, in this case based on the output of climate-modeling predictions (Boyd et al., 2007), can in turn be overlaid with other graphics produced from disparate sources of data, such as distributions of ocean biota—what species reside in each body of water?—as well as economic information, such as where they are harvested, and their economic value and ecological services (Figure 2). Augmenting GIS-based tools, the atlas also includes graphical information, from manipulation studies on the vulnerability of a particular species or group to changing climate (Figure 2b). Via an interactive graphical summary, this information then conveys complex issues, such as how the resident biota will respond to such changes and the resulting regional implications for water bodies of ecological and economic significance.

Figure 2 illustrates the utility of this regional climate change atlas approach for the New Zealand EEZ using the coccolithophores, phytoplankton with carbonate shells that form massive blooms in certain regions, and whose productivity may be influenced by a range of factors—temperature, nutrients, irradiance, pH, and $CO_2$ (Zondervan, 2007)—that are linked to climate change. In this simple example, we compare projected spatial trends in ocean properties with the present-day location of coccolithophore blooms, and then cross-reference these spatial trends with data from experiments in which coccolithophores were subjected to a matrix of treatments comprising both elevated temperature and $CO_2$ (Figure 2b). The experiment indicates that warming or increased $CO_2$ alone are unlikely to affect coccolithophores, whereas together ("greenhouse") they have a detrimental effect due to reduced cellular calcification. The comparison of their environmental sensitivity with the predictive maps of $CO_2$, surface temperature, and present-day coccolithophore distribution then provides an indication of where their distribution may be altered dramatically in the future (Figure 2). The intersection of these factors identifies a potential climate change "hotspot" where coccolithophore blooms coincide with projected elevated temperature and $CO_2$ to the east of New Zealand.

Furthermore, by replacing the coccolithophore distribution map and experimental data with those of another algal group or species from a different trophic level, we can initiate a stepwise analysis of the differential susceptibility of the biota that comprise the resources of the water bodies within a national EEZ. Subsequently, we could combine the results from perturbation experiments with other environmental data to produce maps of, for example, altered diversity or ocean productivity.

## BROADER APPLICATION OF THE ATLAS

We foresee a range of applications, such as the development of atlases for different oceanic regions, and also the transition from static publications (Boyd and Law, 2011) to application that can be readily amended and used in conjunction with other tools in resource management. The New Zealand EEZ atlas is used here as an example to illustrate the utility and flexibility of this format, and to encourage its immediate application to regions where there is already dramatic evidence of the

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influence of climate change, for example, the Southern Ocean along the West Antarctic Peninsula (Schofield et al., 2010). Our ultimate goal is an interactive electronic version where users can control multiple layers of information for adjustable time slices and spatial domains. A linked suite of such regional climate change atlases is particularly relevant for proposed coastal and marine spatial planning initiatives (Lubchenco and Sutley, 2010), as the information can be displayed geographically and readily broken down to include only the salient aspects of a particular issue, such

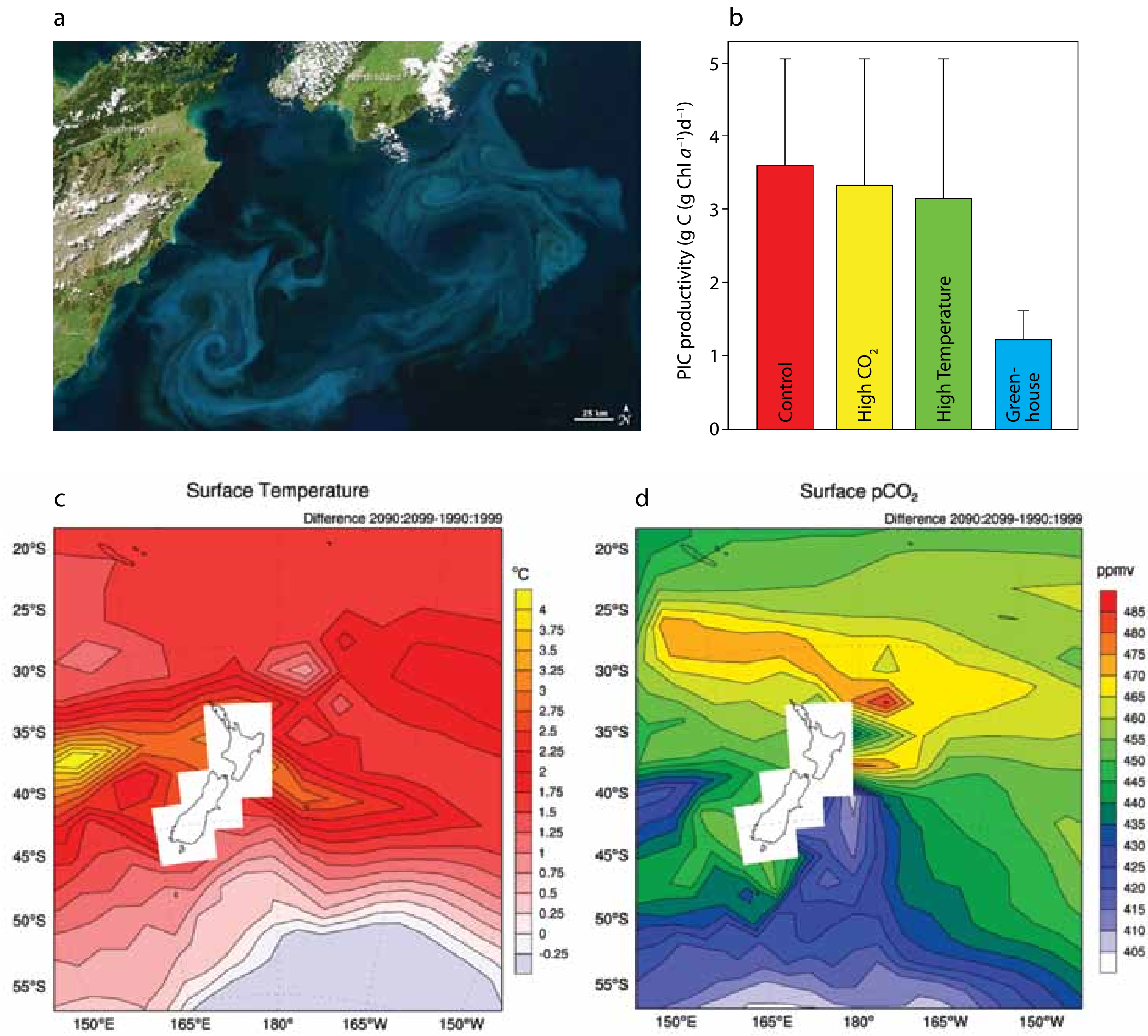


Figure 2. An illustrative example from a recently published atlas for the New Zealand EEZ (Boyd and Law, 2011) that combines: (a) the present-day location of coccolithophore blooms, denoted by "milky" turquoise waters east of the upper South Island of New Zealand, (b) the response of the coccolithophores' calcification rate (i.e., particulate inorganic carbon [PIC] productivity) to increased temperature, $CO_2$ concentrations, and both perturbations (i.e., greenhouse treatment), (c) climate change model predictions for surface ocean temperature in the coming decades around New Zealand (i.e., mean of year 2090 to 2099 minus that for 1990 to 1999), (d) predictions for $pCO_2$. *(a) Image courtesy of NASA/Orbimage. (b) From Feng et al. (2009). (c) and (d) are replotted from Boyd et al. (2007)*

as the likely response of a commercially important or ecological keystone species to altered ocean conditions. As such, this interactive Web-based atlas will provide new opportunities to evaluate the relative merits of combining different information strands. In addition, climate change hotspots, as identified in the coccolithophore example (Figure 2), can be targeted for more detailed analysis of resource management, for example, ecosystem services, fish catch statistics, and socioeconomic impacts (Cooley et al., 2009).

## LINKING THE ATLAS TO RESOURCE MANAGEMENT

A wide range of both environmental and human factors must be incorporated into future resource management decisions. For example, balancing the economic and environmental issues that result from both bottom-up (climate change) and top-down (resource exploitation) environmental effects, and their interplay, requires exploration of all issues. To develop agreed criteria for weighting individual strands of information, the atlas must be used in conjunction with other tools.

In particular, complex decision-making software would complement the insights offered by the atlas approach, and supplement or replace previous approaches such as working groups or expert testimony. Such software can help to clarify the interplay of complex metrics involved in the development of policy (Hansen and Ombler, 2009), for example, assessment of different regional adaptation strategies to climate change. Most policy solutions have both costs and benefits that are unequally distributed among stakeholder groups, who, in turn, may place different values and weights on resulting environmental, social, and economic impacts. Decision-making software can help to systematically assess and inform the potential trade-offs among different groups and goals. Taken together, these tools both encourage the construction of multifaceted data sets and enhance their utility to scientists, stakeholders, and decision makers.

More widespread use of adaptive and flexible user-friendly tools would highlight impacts at regional scales relevant to resource managers and foster a broader acceptance that the forthcoming issues, while complex and highly interlinked, are addressable. Such tools would also increase the ability of policymakers to explore a wide range of trends, issues, and options within less-complicated frameworks. Together, such analysis would both expose areas of uncertainty and ambiguity and help foster an in-depth understanding of the key issues and impasses that might take considerably longer through conventional approaches used by policymakers.

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