Impacts of climate change on marine ecosystem production in fisheries-dependent societies

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Contributions

M.B. designed the study and wrote the text. J.I.A., J.Harle and J.Holt designed and conducted the physical-biological model runs. J.L.B and S.J. designed the size-based approach and model. J.L.B. conducted model runs and summarized outputs. G.M. contributed to the size-based fisheries outputs and prepared the figures. E.H.A. and J.S. computed the dependency estimates. All authors contributed to the text.

Competing financial interests

The authors declare no competing financial interests.

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Growing human populations and changing dietary preferences are increasing global

demands for fish[1], adding pressure to concerns over fisheries sustainability[2]. Here we develop and link models of physical, biological and human responses to climate change in 67 marine national Exclusive Economic Zones (EEZ), which yield ca 60% of global fish catches, to project climate change yield impacts in countries with different dependency on marine fisheries[3]. Predicted changes in fish production indicate increased productivity at high latitudes and decreased productivity at low/mid latitudes, with considerable regional variation. Overall, increases and decreases by 2050 are estimated to change by < 10% (mean +3.4%) from present yields. Among the nations showing a high dependency on fisheries[3], climate change is predicted to increase productive potential in West Africa and decrease it in South and Southeast Asia. Despite projected population increases and per capita fish consumption rates[1], ongoing technological development in the aquaculture industry suggest that projected global fish demands in 2050 could be met, challenging existing predictions of inevitable shortfalls in fish supply by the mid-21st century[4]. This conclusion, however, is contingent on successful implementation of strategies for sustainable harvesting and effective distribution of wild fish products from nations and regions with a surplus to those with a deficit. Changes in management effectiveness[2] and trade practices[5] will remain the major influence on realized gains or losses in global fish production.

Marine fisheries provide 80Mt of protein and micronutrient-rich food for human consumption per year and contribute US$230 billion to the global economy, offering livelihood support to 8% of the world's population[5]. With demand for fish products predicted to increase, efforts to support food and livelihood security need to be informed by predictions of changes in fish production and their societal and economic consequences. Biological predictions based on Ocean-Atmosphere General Circulation Models (GCMs), have demonstrated that climate change will modify the physical and chemical properties of the oceans, affecting the productivity, distribution, seasonality and efficiency of food webs, from primary producers[6] to fish[7,8]. However, using GCMs to predict fish production has several uncertainties, in addition to their structural and natural variability uncertainties[9]. First, the resolution of (GCMs) is too coarse (typically 1-2°) to capture the processes that dominate the dynamics of the world's coastal and shelf regions, such as coastal upwelling and tidal mixing[10], and display significantly different responses to climate than the open ocean. Directly addressing the effects of these processes is an important challenge because coastal and shelf regions contribute a quarter of the global primary production and the large majority of the global fish production[11]. Second, predicting the impacts of climate change on ecosystem and fish production remains a major challenge, as it depends on the transfer of energy through complex and often compensatory food chain processes[12]. Current approaches have either strong habitat or energy transfer assumptions[8,13], or focus on predicting impacts on individual species[14].

Here we directly address these challenges by developing and applying a highly resolved coupled physical-biological shelf-seas model to 67 marine national EEZs. The model was forced using a single GCM (IPSL-CM4) under the IPCC SRES A1B scenario, providing 10-year mean outputs for present day and ca 2050. These were used to drive a dynamic size-based food web model to estimate the ecological consequences of climate change on fish production capacity. Finally, we evaluate the societal relevance of these results by looking at the dependency of individual countries on their fisheries sectors in terms of food and livelihood security, and at the expected global demand for fish products for a growing human population.

Our results show that in all the shelf regions considered the mixed layer depth temperature (MLDT, the depth to which the density difference from the surface $<0.03 kg.m^{-3}$) is expected to increase referenced to present day. By 2050 predicted warming of the mixed layer of shelf seas will range from a moderate 0.2°C in the Irish EEZ to 2.9°C off Korea and East China (Figure 1a, 2a).

Our models predict average increases in net primary production (NPP) of shelf seas of about 14%, slightly larger but consistent with existing estimates of global primary production change based on coarse-scale GCMs[6]. Ecosystems in higher (lower) latitudes will generally experience production increases (decreases) (Figure 1b, 2a). An important consideration to understand these results is that shelf regions are only seasonally stratified, a distinction generally omitted from global GCMs[10], which often predict decreased primary production in the open ocean as a result of increased permanent stratification. The balance of NPP across phytoplankton size classes is also predicted to change by 2050, with flagellates (size class 2-20µm) expected to increase by a global average of 10.2% versus 3.3% for diatoms (size class >20µm), reflecting a shift to more recycled production. This differential trend is consistent with contemporary observations[15] and modelled predictions[16]. Smaller phytoplankton is expected to support longer food chains with lower overall transfer efficiency[16].

Global fisheries production potential was estimated to increase by a moderate 3.4% on average, with differential regional responses[17] (Figure 2a). In general, results indicate that fisheries production is governed by available primary production[18]. The largest average increases in fish catch potential are predicted in the Nordic Sea (29.3%), Gulf of Guinea (23.9%) and the Kuroshio Current region (21.3%). The largest average decreases are expected in the Canary Current (-14.6%) and in the North Western American shelf region (-13.2%). At EEZ level, Peruvian potential catch is predicted to decrease significantly while increasing in Iceland and Norway.

To indirectly validate our fish production algorithms we forced our models with Ocean and Atmospheric reanalysis data sets used to provide boundary conditions to the physical-ecosystem model. Fish production estimates were compared with EEZ catch data, assuming a community fishing mortality rate of 0.8 yr^{-1} [17]. Model predictions fall within the range of observations, despite some differences in some upwelling regions and/or small geographical areas[17]. Additional validation of our results can be found in related studies that examine fish production dynamics and potential fish yields in greater detail[4,17].

Bio-climate envelope approaches have recently predicted a 30-70% increase in fish catch potential in high latitudes, and a 40% drop in the tropics, with a global 1% overall increase by 2050[7,8]. Our predictions are consistent with this despite being based on models that simulate differently the ecological processes leading to fish production, reflecting that primary production and temperature changes underpin both approaches. However, downscaling to regional or national scales highlights uncertainties and contradictions between models. We predict significant decreases in production in the California Current region[17], consistent with species based projections[8], but contrary to a size-based projection based on a low resolution model framework[19]. We predict increases in potential fish production in the Gulf of Guinea, while a different OA-GCM model combination and a species-based bioclimate model predicted 8-26% decline in fish landings by 2050[20]. It is not surprising that different modelling frameworks result in different quantitative projections. Our higher resolution shelf models are likely to be better at capturing the dynamics of, for example, coastal upwelling systems, but in general the use of single models to project complex physical-chemical processes has limitations which would be better addressed through ensemble modelling approaches[21].

How significant are the expected biological impacts to the economies of the countries exploiting them? Among the nations covered, those most nutritionally and economically dependent on fisheries are in West Africa (from Senegal to Nigeria), the Bay of Bengal (Bangladesh and Burma) and in SE Asia (Indonesia, Cambodia), with fisheries also playing a significant role in the economies and food systems of Peru and Ecuador, Iceland, NW and SW Africa, India, Thailand, Vietnam and Japan (Figure 3). While other nations such as Norway, Chile and China have globally significant marine fisheries interests, these countries also have large diverse economies to which fisheries contribute little in overall terms. Combining dependency with projected impact of climate change on fish catches (Figure 4) suggests that these impacts will be of greatest concern to the nations of South and South East Asia, South West Africa (from Nigeria south to Namibia), Peru, and some tropical small-island developing states[22]. These countries rely relatively heavily on their fisheries sector in terms of wealth, food and employment creation, while climate change is projected to negatively impact their potential fish catches. Marine fishery dependent nations that may benefit from climate change effects on fisheries are mostly along the West African coast (from Benin north to Mauritania), and Iceland.

Our results indicate greater instances of predicted negative impacts in parts of the tropics. Least Developed Countries (LDC) in tropical regions have already been identified as particularly vulnerable to climate change[23], because of their greater economic and nutritional dependence on fish and fewer available resources to invest in climate adaptation[3]. Thus, there is an expectation that climate change would have more significant consequences (positive or negative) for marine-based food, income and revenue provision, for fishery-dependent developing nations. Human population growth is likely to be faster in LDCs, where fish provide a larger contribution to non-grain protein needs. South Asia stands out (Figure 4) as the region which is not only projected to face decreasing catches, but also has a high fisheries dependency and a sizable, rapidly growing population whose consumption of fish is likely to increase with its rapid economic development[1,23]. The importance of quantifying regional impacts of climate change to develop adaptation programmes and achieve global food security targets in the future cannot be emphasized enough[4,24].

While climate change will alter the current geographical distribution of shelf sea ecosystems productivity, in most of the regions and EEZs considered the overall potential impact on fish production is projected to be low to moderate (±10%), highlighting the importance of other factors such as management strategies over direct climate effects[2]. This partially reflects the relatively short projection period considered in climate change terms. Longer projections would have more significant but also more uncertain impacts, including changes to coral reefs and other habitat-forming species, and to ocean acidification. Combined, climate change and exploitation impacts are likely to be of greatest concern in maritime countries of South and Southeast Asia, where fishing pressure is already very high and poorly regulated. However, these countries have some of the world's fastest-growing aquaculture industries. With decreasing dependence of aquaculture on wild-caught fishmeal, aquaculture expansion could make a significant contribution to food security as the region adapts to climate change. West African nations may see increased production in their EEZs by 2050 and, if their coastal people are to benefit, a key task would be to ensure that fisheries governance improves and that distant-water fishing nations do not jeopardize local opportunities to benefit from increased productivity and value of their fisheries.

Our predictions of EEZ-based fish production changes have been used, in combination with country-level scenarios of human population growth, trade models of fishmeal and fish oil, and aquaculture development scenarios, to explore the conditions under which capture and culture fisheries would allow current per capita fish consumption rates in the near future[4]. Results suggest that sustaining fish consumption rates is feasible even in a changing climate. This is, however, contingent on a number of conditions, including the assumption of a sustainability transition in fisheries management across all regions and ecosystem components, reductions in the use of wild fish in the animal feed industry, and a fishmeal trade that stabilizes price and distribution despite regional fluctuations in availability[4].

These assumptions are optimistic but not utopian. There are demonstrated successes in managing both industrial and artisanal fisheries in developed and developing countries[2]. Farming of shellfish, herbivorous and omnivorous species is rising. Rapid technological innovation, for example in the development of microalgal foods, is reducing aquaculture's dependence on wild stocks[25].

In summary, by developing and linking models of physical, biological and human responses to climate change, we can predict impacts on fish yields and dependent societies. Our adoption of highly-resolved shelf-sea physical-biological models rather than GCMs gives greater confidence in predicting consequences at national scales, although there are significant trade-offs. As demand for fish continues to grow, we suggest that linked social-ecological assessments such as this are essential tools to guide the development of adaptation measures. Conclusions from this analysis provide a relatively positive message about adaptation through 2050. Despite projected increases in human population and per capita fish consumption rates, projected global fish demands could be met, contingent on successful implementation of strategies for sustainable harvesting, ongoing technological development in the aquaculture industry and effective distribution of wild fish products from nations with a surplus to those with a deficit.

Methods

Physical- Biological models

We simulated coastal and shelf-sea processes, primary, and secondary production, by means of a three-dimensional, high-resolution (0.1°x0.1°), hydrodynamic model (POLCOMS[26]), coupled with a generic, functional type ecosystem model (ERSEM)[27]. The coupled model was run under three particular experiments: a) a present-day control experiment, b) a near-future climate experiment (*ca* 2050) using data taken from IPCC SRES A1B emissions scenario (business-as-usual, using the IPSL-SM4 OA-GCM), and c) re-analysis simulation using data from a global ocean assimilation and re-analysis simulation[17]. Differences in ten-year means were considered as indicative of climate change, while recognizing that climate variability may contribute to these differences. The outputs of these models were used to drive a size-structured ecosystem model[28] that explicitly accounts for food web interactions, linking primary production to fish production through predation, to project climate-driven changes in potential fish production. This modelling framework was applied to 11 coastal and shelf sea regions, covering 30 Large Marine Ecosystems and including 67 marine national Exclusive Economic Zones (EEZ). With this modelling structure, we obtained fine-scale temperature, primary production and size-based estimates of biological production change by 2050, referenced to present day, for an area currently yielding 77% of the global landings recorded from EEZs (see Supplementary material 1, www.seaaroundus.org,). The use of size-based models recognizes that in marine environments predation is strongly driven by body size rather than taxonomic identity, and that direct climate change impacts are likely to be on ecological and physiological relationships that are size and temperature dependent, but overlooks processes linked to species identity. For each EEZ and scenario, the model was first run to equilibrium using time-averaged input before applying the model to time-varying environmental conditions for the duration of a 10-year time slice, under each of the scenarios. The results used in this paper are time-averaged across a 10 year time slice during which the size spectrum model has been dynamical forced using daily time-varying inputs of temperature (near sea floor and mixed layer depth), detritus and the intercept of the plankton. The intercept of the size spectrum is determined by the temporal changes in phytoplankton and microzooplankton biomass density, with the consequences that higher primary production leads to size spectra with higher intercepts. Phytoplankton and microzooplankton functional groups (outputs of the POLCOMS-ERSEM model) are assumed to occupy size ranges. Assuming invariant biomass in body mass log bins and a -1 numerical density slope across a size range of 10^{-14} to 10^{-4} g size margin, we estimated the intercept. Recent work has shown that size spectrum dynamics can be influenced by the variation in intercepts, slopes and the size range of phytoplankton, and our results may therefore be sensitive to these simplifying assumptions.

Fisheries Dependency

Vulnerability to climate change depends on three key elements: *Exposure* to the physical effects of climate change, economic and social *Dependency* on the changing variable(s) and *Adaptive Capacity* to the changes. To investigate the potential societal impact of climate-induced changes in fish production potential, we developed an index of fisheries *dependency* of 58 nations defined as "the importance of fish and fisheries to the national economy and food security"[3]. A country's dependence score was determined from global fisheries statistics[29] by using three indicators measuring the contribution that fisheries makes to the national diet, to employment and to gross domestic product. The national-scale indicators were standardized on a scale of 0 to 1 and averaged to generate an overall dependency score. The dependency analysis builds on data obtained from UN FAO statistics (dietary contributions) and the Sea Around Us project (economic contributions, www.searoundus.org), while contributions in terms of employment were obtained from FAO[29] and published literature[30].

Modelling assumptions

We conduct a single, but dynamically consistent, future climate projection based around the sensitivity of the system to this imposed change, but without an assessment of its likelihood. The forcing scenario (A1B) was chosen as it sits near the middle of the envelope of projected CO2 emissions. The IPSL CM4 model sits close to the centre of spread of CMIP3 models in terms of global temperature, and for the 2050 forecast horizon model uncertainty would be expected to dominate over scenario uncertainty. We recognize that a different combination of OA-GCM and regional model would have resulted in some quantitative differences in the results, and where there are competing processes in the models these may lead to qualitative differences.

- ## Figure legends

Figure 1. Results of the modelling runs for the shelf seas of 20 LMEs, showing changes in temperature (in °C) of the mixed layer (a) and Total primary production (in %, b), in 2050, referenced to the Present Day Control (PDC) scenario. Each map reflects 10 years of model outputs (modified from Merino et al. 2012, Glob. Environ. Chang. 22, 795-806, with permission from Elsevier).

Figure 2. Percentage changes in temperature of the mixed layer (MLDT) and biomass of different size classes of phytoplankton (a), and potential total and per size class fish catch (b), by Exclusive Economic Zone. Changes for 2050 are referenced to the Present-Day Control (PDC) scenario. Change in catch potential assumes that community fishing mortality is 0.8 in all model runs.

Figure 3. Overall national Dependency on fish and fisheries in the regions considered

Figure 4. Kobe plot of potential catch change (in %, a measure of exposure to climate change) and national dependency to fisheries (combining food, economic and employment provision) per national EEZ. Circles correspond to the regional centroid, scaled by the expected population in the regions by 2050.

Acknowledgements

This work was funded by the UK Natural Environment Research Council's Quantifying and Understanding the Earth System programme as part of the 'QUEST-Fish' project (http://www.quest-fish.org.uk/). This is a contribution to the ICES-PICES Strategic Initiative on Climate Change impacts on Marine Ecosystems (SICCME).

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