ICES Journal of Marine Science Advance Access published July 6, 2013

ICES Journal of Marine Science

ICES Journal of Marine Science; doi:10.1093/icesjms/fst081

Projected impacts of climate change on marine fish and fisheries

Anne B. Hollowed[1]*, Manuel Barange[2], Richard J. Beamish[3], Keith Brander[4], Kevern Cochrane[5], Kenneth Drinkwater[6], Michael G. G. Foreman[7], Jonathan A. Hare[8], Jason Holt[9], Shin-ichi Ito[10], Suam Kim[11], Jacquelynne R. King[3], Harald Loeng[6], Brian R. MacKenzie[12], Franz J. Mueter[13], Thomas A. Okey[14], Myron A. Peck[15], Vladimir I. Radchenko[16], Jake C. Rice[17], Michael J. Schirripa[18], Akihiko Yatsu[19], and Yasuhiro Yamanaka[20]

[1]*Alaska Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, WA 98115, USA*
[2]*Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH, UK*
[3]*Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Rd., Nanaimo, BC, Canada V9T 6N7*
[4]*Center for Macroecology, Evolution and Climate, DTU Aqua-National Institute of Aquatic Resources, Technical University of Denmark, Charlottenlund Castle, Jaegersborg Allé 1, 2920 Charlottenlund, Denmark*
[5]*Department of Ichthyology and Fisheries Science, PO Box 94, Grahamstown 6150, South Africa*
[6]*Institute of Marine Research, PO Box 1870, Nordnes, 5817 Bergen, Norway*
[7]*Fisheries and Oceans Canada, Institute of Ocean Sciences, 9860 W. Saanich Rd, PO Box 6000, Sidney, BC, Canada V8L 4B2*
[8]*NOAA Fisheries, Northeast Fisheries Science Center, Narragansett Laboratory, Narragansett, RI, USA*
[9]*National Oceanography Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK*
[10]*Tohoku National Fisheries Research Institute, FRA, 3-27-5 Shinhama-cho, Shiogama, Miyagi 985-001, Japan*
[11]*Department of Marine Biology, Pukyong National University, 599-1 Daeyeon-3dong, Nam-gu, Busan R 608-737, Korea*
[12]*Center for Macroecology, Evolution and Climate and Center for Ocean Life, DTU Aqua-National Institute of Aquatic Resources, Technical University of Denmark, KavalergûËrden 6, DK 2920 Charlottenlund, Denmark*
[13]*School of Fisheries and Ocean Sciences, Juneau Center, University of Alaska, Fairbanks, 17101 Pt. Lena Loop Rd, Juneau, AK 99801, USA*
[14]*School of Environmental Studies, University of Victoria, PO Box 3060 STN CSC, Victoria BC V8W 3R4, Canada*
[15]*Institute for Hydrobiology and Fisheries Science, Olbersweg 24, 22767 Hamburg, Germany*
[16]*Pacific Research Institute of Fisheries and Oceanography (TINRO-Center), 4 Shevchenko Alley, Vladivostok, Primorsky Kray 690950, Russia*
[17]*Science Sector, Department of Fisheries and Oceans, 200 Kent Street Station 12S015, Ottawa, ON, Canada K1A0E6*
[18]*Southeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 75 Virginia Beach Dr., Miami, FL 33149, USA*
[19]*Seikai National Fisheries Research Institute, Fisheries Research Agency, 1551–8 Taira-machi, Nagasaki 851–2213, Japan*
[20]*Graduate School of Environmental Science, Division of Environmental Resources, Hokkaido University, Hokkaido, Japan*

**Corresponding author: tel: +1 206-526-4223; fax: +1 206-526-6723; e-mail: anne.hollowed@noaa.gov*

Hollowed, A. B., Barange, M., Beamish, R., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M., Hare, J., Holt, J., Ito, S-I., Kim, S., King, J., Loeng, H., MacKenzie, B., Mueter, F., Okey, T., Peck, M. A., Radchenko, V., Rice, J., Schirripa, M., Yatsu, A., and Yamanaka, Y. Projected impacts of climate change on marine fish and fisheries. – ICES Journal of Marine Science, doi:10.1093/icesjms/fst081.

Received 7 December 2012; accepted 3 May 2013.

This paper reviews current literature on the projected effects of climate change on marine fish and shellfish, their fisheries, and fishery-dependent communities throughout the northern hemisphere. The review addresses the following issues: (i) expected impacts on ecosystem productivity and habitat quantity and quality; (ii) impacts of changes in production and habitat on marine fish and shellfish species including effects on the community species composition, spatial distributions, interactions, and vital rates of fish and shellfish; (iii) impacts on fisheries and their associated communities; (iv) implications for food security and associated changes; and (v) uncertainty and modelling skill assessment. Climate change will impact fish and shellfish, their fisheries, and fishery-dependent communities through a complex suite of linked processes. Integrated interdisciplinary research teams are forming in many regions to project these complex responses. National and international marine research organizations serve a key role in the coordination and integration of research to accelerate the production of projections of the effects of climate change on marine ecosystems and to move towards a future where relative impacts by region could be compared on a hemispheric or global level. Eight research foci were identified that will improve the projections of climate impacts on fish, fisheries, and fishery-dependent communities.

Keywords: climate change, fish, fisheries, fisheries-dependent communities, uncertainty, vulnerability assessment.

Introduction

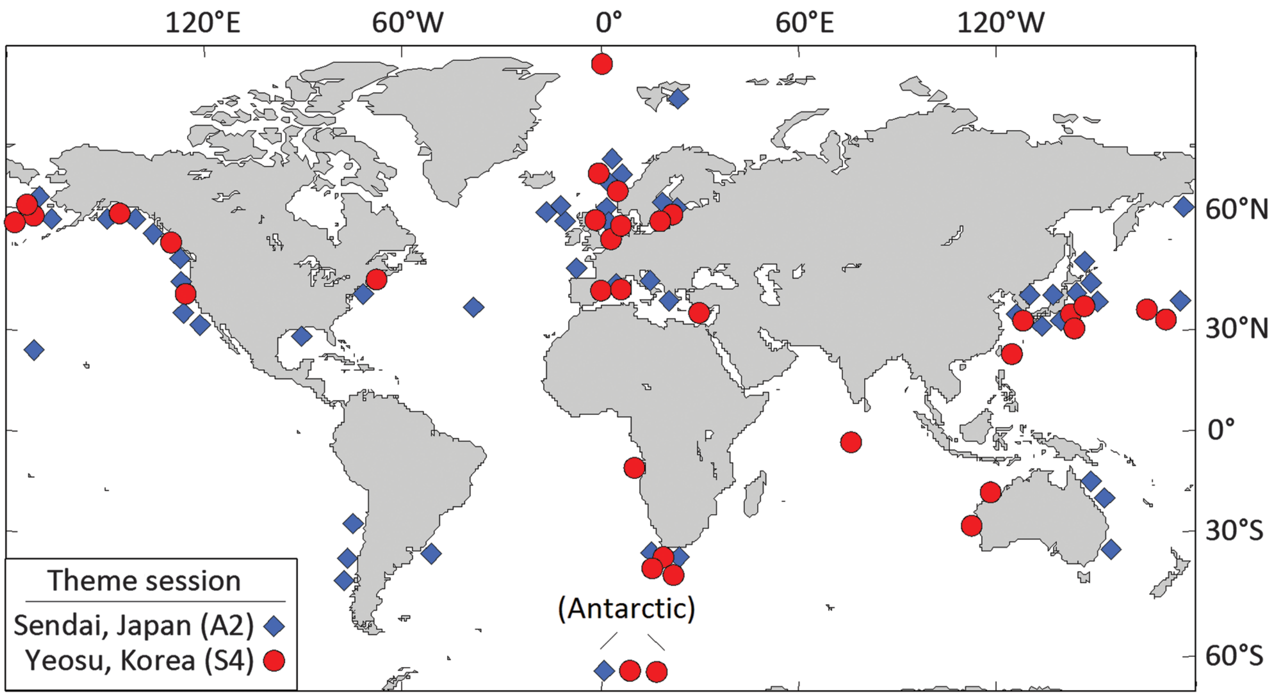
The marine science community now regularly uses climate change projections released by the Intergovernmental Panel on Climate Change (IPCC; IPCC, 2007) to make qualitative and quantitative projections of marine ecosystem responses to environmental changes associated with the accumulation of greenhouse gases in the atmosphere (e.g. climate change and ocean acidification). These projections indicate that climate change will affect fish, fisheries, and fisheries-based economies around the globe as well as broader components of marine ecosystems (ACIA, 2005; Allison *et al.*, 2009; Cochrane *et al.*, 2009; Drinkwater *et al.*, 2010; Blanchard *et al.*, 2012; Doney *et al.*, 2012; Merino *et al.*, 2012). The potential implications of climate change for marine ecosystems, and goods and services derived from marine ecosystems, have prompted the formation of integrated interdisciplinary research partnerships to quantify these impacts in many regions throughout the world (Figure 1; Barange *et al.*, 2011; Wiese *et al.*, 2012). Several international organizations [e.g. the International Council for Exploration of the Sea (ICES), the North Pacific Marine Science Organization (PICES), the Intergovernmental Oceanographic Commission (IOC), the World Meteorological Organization (WMO), and the Food and Agriculture Organization of the United Nations (FAO)] and international research programmes (e.g. Ecosystems Studies of Sub-Arctic Seas, ESSAS) have sponsored symposia focused on climate change effects on marine ecosystems to encourage international research partnerships and to widely disseminate new research findings (Valdés *et al.*, 2009; Hollowed *et al.*, 2011; Drinkwater *et al.*, 2012; Salinger *et al.*, in press).

In this paper, we synthesize existing information to elucidate the expected effects of climate change on fish and fisheries to guide future research. Other international (e.g. the IPCC) and national climate assessment teams have provided a comprehensive evaluation of climate change impacts on marine and terrestrial ecosystems on regional (e.g., Arctic Climate Impact Assessment; ACIA, 2005; Arctic Monitoring Assessment Program; AMAP, 2011; and National Climate Assessment; Howard *et al.*, 2013) and global scales (IPCC, 2007). Our synthesis focuses on the implications on a limited set of components of marine ecosystems and the goods and services they provide. We consider the following themes: (i) expected impacts on ecosystem productivity and habitat quantity and quality; (ii) impacts of changes in production and habitat on marine fish and shellfish species including effects on the community species composition, spatial distributions, interactions, and vital rates of fish and shellfish; (iii) impacts on fisheries and their associated communities; (iv) implications for food security and associated changes; and (v) uncertainty and modelling skill assessment. Using this synthesis of information, key research activities are identified that may serve to guide future investigations.

Impacts on ecosystem productivity and habitat

In a world with high atmospheric CO_2 levels, global physical models project increased sea temperatures in many regions, changes in locations and magnitudes of wind patterns and ocean currents, loss of sea ice in Polar Regions, and a rise in the sea level (IPCC, 2007). The accumulation of CO_2 in the atmosphere and associated climate changes is expected to cause ocean acidification and expansion of oligotrophic gyres (Doney *et al.*, 2012). These physical and chemical changes are expected to result in shifts in the timing, species composition, and magnitude of seasonal phytoplankton production (Figure 2; Cochrane *et al.*, 2009; Wang and Overland, 2009; Polovina *et al.*, 2011; Doney *et al.*, 2012). Changes in phytoplankton species composition may include shifts to smaller sizes that could lengthen food chains and increase assimilation losses to higher trophic levels (Morán *et al.*, 2010; Bode *et al.*, 2011).These physical, and resulting biological, changes will occur at different spatial and temporal scales throughout the world's oceans (Burrows *et al.*, 2011; Gnanadesikan *et al.*, 2011; King *et al.*, 2011). Changes in temperature, nutrient supply, mixing, light availability, pH, oxygen, and salinity are expected to affect the ecological functions and, consequently, the sustainable harvests available from the ocean's biological communities (Cochrane *et al.*, 2009; Brander, 2010; Denman *et al.*, 2011; Doney *et al.*, 2012). Exposure of marine organisms to ocean acidification and oxygen depletion will vary regionally, and other anthropogenic impacts (e. g., eutrophication) may also contribute. The vulnerability of species to these changes varies considerably (Whitney *et al.*, 2007; Feely *et al.*, 2008; Vaquer-Sunyer and Duarte, 2008; Levin *et al.*, 2009; Ries *et al.*, 2009; Rabalais *et al.*, 2010).

Regional differences in primary production are also anticipated. In mid-latitudes the mixed layer depth (MLD) is projected to shoal, which could decrease nutrient supply and ultimately primary production. For example, an intercomparison study of 11 models projected that the ocean's MLD will change (decrease or shoal) in most regions of the North Pacific during the 21st century as the result of increased stratification resulting from warming and/or freshening of the ocean surface and changes in the winds (Jang *et al.*, 2011). A study using four Earth System Models (ESMs) found a similar pattern in the North Atlantic (Steinacher *et al.*, 2010). Capotondi *et al.* (2012) also provide a global treatment of stratification changes. Primary production in mid-latitudes is expected to be reduced by this MLD shoaling through decreased nutrient supply (Hashioka and Yamanaka, 2007; Barange and Perry, 2009). However, production may increase in higher latitudes especially in seasonally ice-covered areas through increased light levels and a longer period of production and changes in the ice-edge bloom (Perrette *et al.*, 2011). Increased stratification caused by sea surface freshening and/or warming is also a main driver of ocean deoxygenation through decreased ventilation (Whitney *et al.*, 2007). Rykaczewski and Dunne (2010) hypothesized that decreased ventilation in upwelling zones may increase production due to increased residence times (the period where producers are retained in the high production zone) and nutrient remineralization; however, we note that these benefits could be offset by reduced nutrient supply. There remain important questions regarding how physical and biological processes are incorporated



Species/group	A2	S4	Species/group	A2	S4	Species/group	A2	S4
American lobster		1	European eel	1		Rabbitfish		1
Arrowtooth flounder	1	1	European hake	1		Red mullet	1	
Atlantic cod	3	2	European lobster		1	Sablefish		1
Atlantic herring	2	1	European sardine		1	Saffron cod	1	
Atlantic mackerel	1		European sprat	1		Pacific sardine	1	1
Bigeye tuna	1		Haddock		1	Seaweeds	1	
Black rockfish	1		Japanese anchovy	5		Sciaenid fishes	1	
Blue marlin	1	1	Japanese sardine	4	1	Snake pipefish	1	
Blue whiting	1		Japanese squid	2		Sockeye salmon	1	
Bluefin tuna	1		Moon jellyfish		1	Spear squid		1
Chilian hake	1		Pacific cod	2		Spiny lobster		1
Chilian sardine	1		Pacific hake	1		Striped marlin		1
Chinook salmon	1		Pacific halibut	1		Swordfish	2	
Chum salmon	1		Pacific herring	3		Skipjack tuna		1
Daubed shanny	1		Pacific oyster	1		Walleye pollock		1
Echinoderms		1	Pacific saury	1		Yellowfin tuna	2	1
Euphausids	1		Pink salmon	1		Yellowtail	2	
European anchovy		2	Plaice	1		Interspecific	14	16

Figure 1. Overview of species and geographic location of investigations presented at the 2010 ICES/PICES/FAO symposium in Sendai, Japan (session A2) and the 2012 ICES/PICES/IOC symposium in Yeosu, Korea (session S4) (also see special volume Hollowed *et al.*, 2011).

into projection models (e.g. temperature response; Taucher and Oschlies, 2011) and how these models represent coastal and shelf sea areas (e.g. Holt *et al.*, 2012).

The responses of secondary production to climate change are not clear, partially because the data available for zooplankton are more limited and the mechanisms linking secondary production to ocean conditions are complex. In the North Atlantic, the total abundance of zooplankton changed with sea surface temperature (SST) change (Richardson and Schoeman, 2004). However, this overall pattern masks important trends in the zooplankton community where the abundance of both herbivorous and carnivorous copepods increased with phytoplankton abundance but the abundance of neither group was directly correlated with SST. Several authors have recognized that the phenology of zooplankton may also be affected by a changing climate in both the Atlantic and Pacific (Chiba *et al.*, 2004; Edwards and Richardson, 2004; Mackas *et al.*, 2007). Although climate change results in an earlier onset of production cycles, the actual timing and changes in the magnitude of production

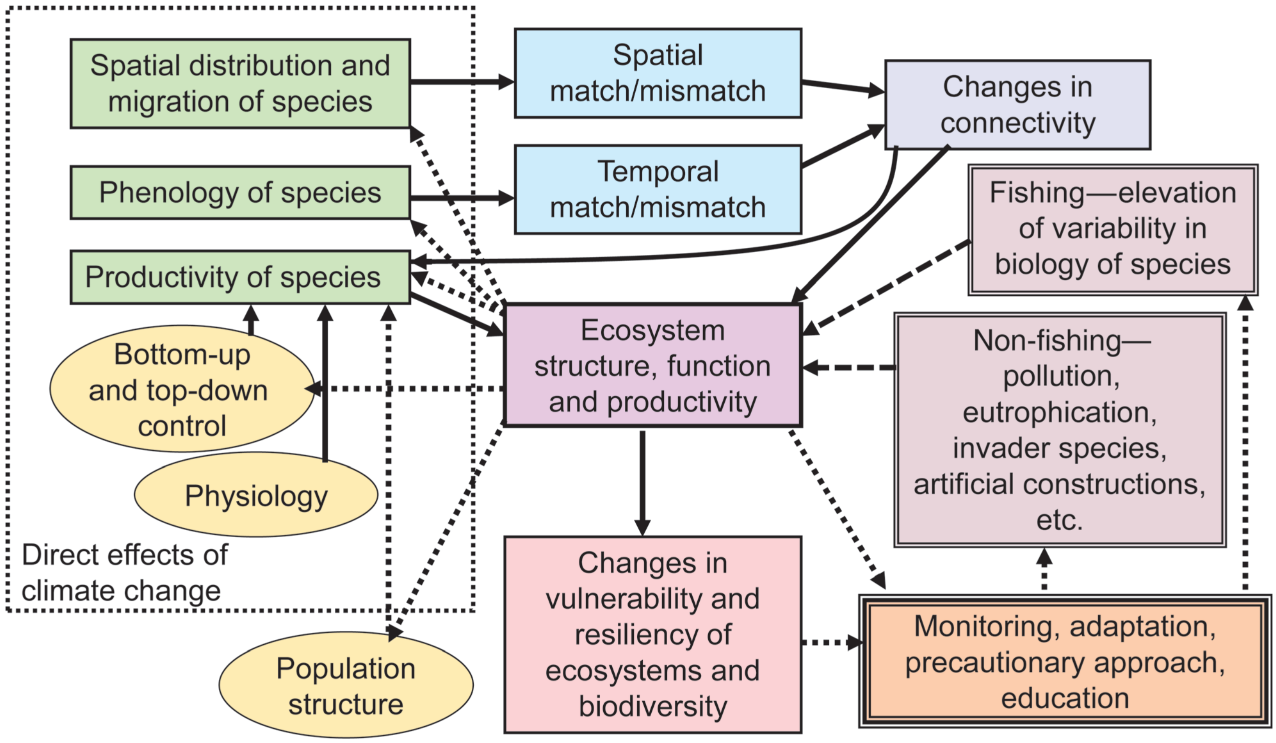


Figure 2. Conceptual pathways of direct and indirect effects of climate change and other anthropogenic factors on marine ecosystems, with their implications to adaptation and management. Solid arrows, consequences of climate change; dotted arrows, feedback routes.

varied in direction and was influenced by different mechanisms among regions (Richardson, 2008). Our limited understanding of the trophodynamic linkages between phytoplankton and zooplankton adds considerable uncertainty to projections of the responses of these groups to global change (Ito *et al.*, 2010).

Impacts on marine fish and shellfish

Climate-driven changes in the environment may affect the physiology, phenology, and behaviour of marine fish and shellfish at any life-history stage, and any of these effects may drive population-level changes in distribution and abundance (Loeng and Drinkwater, 2007; Drinkwater *et al.*, 2010; Jørgensen *et al.*, 2012). Fish and shellfish will be exposed to a complex mix of changing abiotic (e.g. temperature, salinity, MLD, oxygen, acidification) and biotic (shifting distribution, species composition, and abundance of predators and prey) conditions making it difficult to predict the responses.

Many climate-related changes have already been observed (Table 1; Perry *et al.*, 2005; Mueter and Litzow, 2008; Barange and Perry, 2009; Nye *et al.*, 2009). Kingsolver (2009) identified three types of potential responses of species to climate change: distribution changes in space and time, productivity changes, and adaptation. The extent of population-level changes may be mediated by the capacity for individual species/populations to adapt to changes in important abiotic and biotic factors through changes in the phenology of important life-history events (e.g. migration, spawning), or through changes in organismal physiology (e.g. thermal reaction norms of key traits such as growth; Pörtner, 2010) and/or through acclimation (Donelson *et al.*, 2011). Mismatches may occur when shifts in the environment lack consistent patterns or out-pace the species ability to adapt or acclimate to change (Burrows *et al.*, 2011; Duarte *et al.*, 2012).

Changes in life cycle dynamics will occur in concert with climate-induced expansion, contraction, and/or shifts in the quality and quantity of suitable habitat, and different life stages may be affected differently by changes in habitat characteristics (Petitgas *et al.*, 2013). Moreover, in some regions, changes in temperature will be accompanied by changes in other abiotic factors. For example, expected regional changes in precipitation could lead to decreases or increases in local salinities which will have major impacts on distributions and productivities of fish species in coastal and estuarine areas. Thus, perhaps future thermal conditions may be suitable for new immigrant species, but shifts in salinities could make these waters uninhabitable, illustrating the challenges of projecting future trends in species richness of fish communities.

Table 1 summarizes recent literature on observed and expected shifts in spatial distributions of marine fish and shellfish. Although there are many accounts of temperate species moving to higher latitudes, presumably in response to warming (Table 1; e.g. Beare *et al.*, 2004; Perry *et al.*, 2005), there is less evidence of contraction of ranges of boreal species (Genner *et al.*, 2004; Rijnsdorp *et al.*, 2010). The distributional changes may be the result of either active migration of living marine resources to higher latitudes or from differential productivity of local populations in lower and higher latitudes (Petitgas *et al.*, 2012), and usually the causal factors are poorly documented. The sensitivity of fish and shellfish stocks to climate change may differ depending on whether the stock is at the leading, trailing or center of the species range (Beaugrand and Kirby, 2010). In some cases, latitudinal shifts will exacerbate mismatches due to concurrent changes in the light cycle and the duration of the growing season (Kristiansen *et al.*, 2011; Shoji *et al.*, 2011).

Table 1. Recent studies of climate impacts on spatial distribution of marine fish and shellfish.

Reference	Publication year	Region	LME	Type	# Species
Cheung *et al.*	2009	Global	NA	Retrospective and Projection	
Hollowed *et al.*	In press b	Arctic/Subarctic	Barents Sea, Bering Sea, Arctic	Vulnerability	17
Huse and Ellingsen	2008	Arctic/Subarctic	Barents Sea	Retrospective and Projection	1
Ciannelli and Bailey	2005	Subarctic	E. Bering Sea	Retrospective	1
Mueter and Litzow	2008	Subarctic	E. Bering Sea	Retrospective	46
Spencer	2008	Subarctic	E. Bering Sea	Retrospective	5
Sundby and Nakken	2008	Subarctic	Norwegian Sea	Retrospective	1
Drinkwater	2005	Subarctic	North Atlantic	Projection	1
Drinkwater	2006	Subarctic	Northern North Atlantic	Retrospective	24
Dulvy *et al.*	2008	Subarctic	North Sea	Retrospective	29
Engelhard *et al.*	2011	Subarctic	North Sea	1913–2007	2
Petitgas *et al.*	2012	Subarctic	North Sea	Retrospective	1
Perry *et al.*	2005	Subarctic	North Sea	1977–2001	36
Welch *et al.*	2001	Subarctic	North Pacific Ocean	Retrospective and Projection	1
Tseng *et al.*	2011	Subarctic	Oyashio Current	Retrospective and Projection	1
Fogarty *et al.*	2008	Temperate	NE US Continental Shelf	Retrospective and Projection	1
Hare *et al.*	2012a	Temperate	NE US Continental Shelf	Projection	1
Nye *et al.*	2009	Temperate	NE US Continental Shelf	Retrospective	36
Hare *et al.*	2010	Temperate	NE US Continental Shelf	Retrospective and projection	1
Last *et al.*	2011	Temperate	Australian Shelf	Retrospective	45
Ito *et al.*	2010	Subarctic / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Projection	1
Okunishi *et al.*	2012	Subarctic / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Projection	1
Yatsu *et al.*	2013	Subtropical / Subtropical	Kuroshio/Oyashio current, Kuroshio Extension	Vulnerability	4
Hare *et al.*	2012b	Subtropical	SE US Continental Shelf	Projection	1
Agostini *et al.*	2008	Subtropical	California Current	Retrospective	1
King *et al.*	2011	Subtropical	California Current	Vulnerability	8
Hsieh *et al.*	2009	Subtropical	California Current	Retrospective	34
Stewart *et al.*	2012	Subtropical	California Current	Retrospective	1
Muhling *et al.*	2011	Tropical	Gulf of Mexico	Retrospective and Projection	1
Su *et al.*	2011	Tropical	Pacific Ocean	Retrospective and Projection	1
Lehodey *et al.*	2012	Tropical	Pacific Ocean	Retrospective and Projection	1

The aforementioned impact of climate change on MLD and ocean chemistry has been shown to exacerbate vertical habitat compression for some highly migratory species of billfish and tunas in the tropical Northeast Atlantic Ocean. Initial work demonstrated how the near-surface density of many high-oxygen demand species of pelagic fish was much higher in the eastern than in the western tropical Atlantic (Prince *et al.*, 2010). Eastern boundary current conditions off the west coast of Africa create an oxygen minimum zone that is much closer to the surface than in the western tropical Atlantic. The habitat compression has led to higher vulnerabilities to surface fishing gear and artificially high indications of abundance. Stramma *et al.* (2011) reported that a decrease in the upper ocean layer dissolved oxygen occurred in the tropical Northeast Atlantic. This change equated to an annual habitat loss of ~15% over the period 1960–2010. Climate change is expected to further expand the Atlantic oxygen minimum zone due to increased ocean temperatures and decreased oxygen levels, potentially threatening the sustainability of the pelagic fisheries and their associated ecosystems.

Climate change may also influence recruitment success, which will impact population productivity (e.g. Hare *et al.*, 2010; Mueter *et al.*, 2011). The resilience to shifts in production may vary by region. In many regions, fish and shellfish have evolved within systems impacted by intermittent (1–2 years) or longer term events that occur on decadal or multidecadal timescales (Baumgartner *et al.*, 1992; Hare and Mantua, 2000;

Greene and Pershing, 2007; Di Lorenzo *et al.*, 2008; Hatun *et al.*, 2009; Overland *et al.*, 2010; Alheit *et al.*, 2012). These events will probably continue to occur in the future. It is unclear whether species and communities that have experienced such variability in the past will be better adapted to future climate change. In some well-documented cases, climate variability is thought to provide opportunities for dominance switching and ecosystem reorganization (Skud, 1982; Southward *et al.*, 1988; Anderson and Piatt, 1999; Rice, 2001; Stenseth *et al.*, 2002; Chavez *et al.*, 2003). Climate change may interrupt or accelerate these cycles of dominance switching with unknown implications for both dominant and subordinate species within each phase of a cycle.

The responses of individual marine species to climate change will vary by species and region resulting in a broad spectrum of potential shifts in geographic ranges, vertical distributions, phenologies, recruitment, growth, and survival. Thus, alterations in both the structure (i.e. assembly and connectivity) and function (i.e. productivity) of biological communities are expected (Figure 2). Community responses are the most uncertain types of ecosystem responses to climate change because they involve more players (all the species in the community and the habitats that are used), their interactions, and direct as well as indirect effects of climate drivers (Stock *et al.*, 2011), as well as the spatial and temporal complexity of responses (Burrows *et al.*, 2011; Gnanadesikan *et al.*, 2011). However, there is some evidence that community assemblages tend to move in concert based on retrospective studies of species spatial patterns and species richness (Hofstede *et al.*, 2010; Lucey and Nye, 2010).

Impacts on fishers, fisheries, and fishery-dependent communities

Fisheries and fishery-dependent communities have been subjected to fluctuations in fish stocks, extreme weather events, and natural changes in climate and sea-level throughout history. Coastal livelihoods have depended on the capacity to cope with such changes through the alteration of fishing practices or switching to alternative livelihoods (Allison *et al.*, 2009; Perry *et al.*, 2011). The capacity for human communities to respond to changes in the species composition, abundance, and availability of marine resources vary regionally (Daw *et al.*, 2009). Climate change effects on fish and fisheries will occur within the context of existing and future human activities and pressures, as well as the combined effects of multiple stressors and natural agents of change acting directly and through feedback pathways (Figure 2; Ruckelshaus *et al.*, 2013). In coastal ecosystems, pollution, eutrophication, species invasions, shoreline development, and fishing generally play more important roles as drivers of change than on the high seas.

It will be difficult to tease out the additional effect of climate change from other anthropogenic activities (such as fishing; Rogers *et al.*, 2011). In some cases, where time-series are long enough or can be re-constructed, the relative importance of different forcings can be quantified (e.g. Eero *et al.*, 2011). Hare *et al.* (2010) examined the combined effects of fishing and climate in a modelling context and found that fishing likely remains the dominant pressure, especially at the historically high fishing levels. Other researchers found that it was difficult to separate the influence of anthropogenic climate change from decadal environmental variability and fishing even with a century of data (Engelhard *et al.*, 2011; Hofstede and Rijnsdorp, 2011), whereas others note that fisheries can amplify or moderate climate signals (Ottersen *et al.*, 2006). Some promising alternative approaches to address these issues include: comparative studies, experiments, and opportunistic studies of major natural or anthropogenic events (Megrey *et al.*, 2009; Murawski *et al.*, 2010). Ainsworth *et al.* (2011) used five Ecopath with Ecosim models to simulate changes in primary production, species range shifts, zooplankton community size structure in response to ocean acidification, and/or ocean deoxygenation. Fishing pressure was also included as an additional perturbation to the modelled foodweb. Their study revealed that responses to the cumulative effects of climate change and fishing may result in different patterns than would have been predicted based on individual climate effects, indicating possible interactions.

The degree to which fisheries are managed sustainably varies globally (Worm and Branch, 2012). In many regions, efforts are underway to prevent overfishing, rebuild overfished stocks, and implement an ecosystem approach to management (Murawski, 2007). In the future, the detrimental effects of climate change on fish stocks may, to some extent, be buffered in stocks that have a large and productive spawning-stock biomass, a less truncated age structure, and sustainable exploitation rates (Costello *et al.*, 2012). For example, cod have remained abundant with wide size/age structure in some areas (i.e. Øresund) where exploitation has been low, although temperatures have increased and while abundance has declined and age structure has narrowed in neighbouring areas (North Sea, Baltic Sea; Lindegren *et al.*, 2010).

Natural scientists and economists are partnering to develop the projections of how fishers may respond to changes in fish distribution and abundance (Haynie and Pfeiffer, 2012). It is unclear how complex management systems involving measures such as catch shares, bycatch limits, mixed species catch or effort limits, and spatial or temporal closures will perform as the species composition, distribution, and abundance of fish species change (Criddle, 2012). An equally challenging issue is predicting how different nations will utilize the broad range of ecosystem services that marine ecosystems provide (Halpern *et al.*, 2012). Multispecies management strategy evaluations can be used to evaluate the expected performance of management frameworks with respect to balancing these complex issues (Plagányi *et al.*, 2011). However, selecting the functional form of responses necessary to predict how fishers will respond to changes in marine resources will continue to be challenging.

The fish stocks, fisheries, and marine ecosystems that coastal communities depend on can be described as components of coupled marine social-ecological systems (Perry *et al.*, 2011). This is a particularly useful representation when considering the policy goals of preserving the health of the marine ecosystem while maintaining the supply of desirable goods and services that support human livelihoods. The representation requires specifying the scale of the system, its properties (e.g. resilience, biodiversity, productivity, social capital), how it is, or can be, governed, and what structures and information are required for such governance. Management and governance approaches may need to be adapted to the available scientific and management capacity (including financial and social resources). While strengthening capacity may put extra demands on management agencies and stakeholders, it also brings with it greater sustainable benefits through reduced uncertainty (Cochrane *et al.*, 2009, 2011). Anthropogenic climate change is an increasingly influential driver of change in such social-ecological systems, added to an already complex set of natural and anthropogenic drivers. The impacts of climate drivers are manifested on time-scales that are generally longer than most other anthropogenic drivers to which these social-ecological systems routinely respond.

There is growing recognition of the need for much stronger integration of social and ecological sciences in developing adaptation options for industries and coastal communities (Allison *et al.*, 2009; Daw *et al.*, 2009; Miller *et al.*, 2010; Gutierrez *et al.*, 2011). In this context, there may be much to learn from the dynamics of small-scale fisheries in coastal communities. Institutions such as the FAO and Worldfish are active in working on climate change adaptation in such systems. Adaptation and mitigation depend on actions and behavioural choices by the communities who are exploiting the marine resources (whether for fisheries, tourism, or other goods and services), as well as a supportive wider governance environment to address threats and constraints to adaptation and mitigation that are outside the control of local communities. Resource users and communities, within the context of an integrated ecosystem approach, must have the capacity and the will to adapt and mitigate. Viable adaptation and mitigation actions require the identification of vulnerabilities at levels from the household to macroeconomic ability to diversify livelihoods for income and the availability of environmentally sustainable livelihoods and development options. For example, "co-benefits" of both adaptation and mitigation can arise from biodiversity conservation, and protection and restoration of mangroves, and other coastal vegetation (Ruckelshaus *et al.*, 2013). Coastal resources governance can be encouraged to develop community-based disaster risk management and to integrate climate change issues into the local and national socio-economic development planning. These actions may help to prepare communities for climate change impacts on livelihoods that depend on marine resources.

Implications for future security of the food supply

The expansion of the world's human population and current levels of hunger in many parts of the world have raised concerns over the security of the food supply in the future (OECD, 2008; Godfray *et al.*, 2010, 2011). Fish currently provide essential nutrition to 4 billion people and at least 50% of the animal protein consumed by 400 million people (Laurenti, 2007; FAO, 2012), currently contributing ~17 kg of fish per capita and year. Most of the expected increase in the human population to 2050 occurs in regions where fish provide most of the non-grain dietary protein (UN-DESA, 2009; UN-WHO, 2002). The extent to which marine fisheries will be able to provide fish for the world's population in the future will depend on climate-driven changes to the productivity of the world's oceans and the performance of fisheries management systems (Bell *et al.*, 2009; Worm *et al.*, 2009; Costello *et al.*, 2012). Several scientists have used outputs from IPCC global climate models to explore quantitatively or qualitatively the potential consequences of climate change on fish and fisheries production and the implications in terms of food security targets (e.g. Merino *et al.*, 2012). These studies concluded that even with improved management, there is only a modest scope for increases in sustainable global yields for capture fisheries (Rice and Garcia, 2011; Brander, 2012). However, innovation in both large-scale and small-scale aquaculture may support a continued increase in production from marine and freshwater systems (FAO, 2008a, b; OECD, 2008; Garcia and Rosenberg, 2009; Rice and Garcia, 2011; Merino *et al.*, 2012). At present, global aquaculture production is very unevenly distributed with Asia accounting for 89% of world production (FAO, 2012). In addition, the effects of climate change on prospects for fisheries and aquaculture show strong regional differences (Merino *et al.*, 2012). Substantial political and financial investment in aquaculture will be required in suitable climatic and environmental regions if it is to provide greater contributions to food security and meet the growing demand for fish and seafood products. Growing international trade in fish products and fishing fleet capacities is accentuating regional differences in potential fish consumption (OECD-FAO, 2009; Kim, 2010). Hence, in addition to direct impacts of climate change on fish populations and communities, and thus food production, there can be indirect impacts through changes to the availability of alternative sources of protein, to the conditions suitable for intensive culture of fish and shellfish, and even to the complex interactions of climate on the global trade in food.

Uncertainty and skill assessment

Almost all attempts to forecast the impacts of climate change on fish and fisheries involve models of one form or another, and all these models will include uncertainties in both model structure and parameter values. A range of model types is used in fisheries research, from simple empirical relationships through population dynamics models to detailed system models (Hollowed *et al.*, in press a). Consideration of the diverse and complex interactions that occur between the underlying drivers of climate change and their ultimate impacts on fish and fisheries tends to require the use of relatively complex models in an effort to achieve scientific realism. However there are trade-offs since increasing model complexity to achieve greater realism can reveal additional uncertainty associated with incomplete knowledge of both the functional form and parameterization of the model (FAO, 2008a, b; FAO, 2009).

There are many such uncertainties in assessing impacts of climate change on marine ecosystems. For example, physical–biological pathways are elucidated for only a few species or functional groups. Our empirical knowledge may also not apply beyond previously observed ranges of environmental factors, or outside of historical rates and amplitudes of environmental change. Adaptation of a species to new environmental conditions is one of the most difficult issues to evaluate, especially when attempting to project connectivity among ecosystem components (Planque *et al.*, 2011). Furthermore, projecting climate change effects on fish and fisheries is challenging due to the cumulative effects of climate change, other anthropogenic activities, and feedback mechanisms (Fulton, 2011).

When physical–biological pathways are known, analysts must consider what long-range forecast and a modelling method should be used to project future states of nature. Long-term quantitative forecasts of climate change effects are generally based on outputs from one or more global circulation models (GCMs) providing boundary conditions for species or ecosystem predictive models. Inferences about biological responses to climate change based on GCM outputs commonly deal with uncertainty in the emission scenario forcing the GCMs (Hawkins and Sutton, 2009), structural uncertainty in the GCMs, internal variability, and the generally coarse resolution of the GCM, as well as uncertainty in modelling the biological responses. The relative importance of different sources of uncertainty associated with GCM predictions depend on the temporal and spatial scales of interest. Although these have not been quantified in coupled atmosphere-ocean GCMs, climate model predictions on both global and regional spatial scales have been shown to be dominated by internal variability in the climate over short time-scales (5–15 years), by model uncertainty on intermediate scales (15–40 years), and by scenario uncertainty on longer time-scales (Hawkins and Sutton, 2009). Although sensitive to emissions scenarios, there is broad agreement among climate models for some parameters such as temperature, even at short time-scales and on regional spatial scales (Deser *et al.*, 2012). Similarly, GCMs provide credible projections for regional ocean temperatures (Wang *et al.*, 2012). In contrast, derived quantities computed from the GCM output (e.g. MLD) can vary widely among models if they are based on parameters that are poorly estimated by GCMs (Jang *et al.*, 2011). Moreover, there is generally a mismatch in spatial scales between the output of the GCMs, which tend to have skill at an ocean-basin scale, and the need for resolution of finer scale ocean processes on the coastal shelves needed to project impacts on fish and fisheries (Stock *et al.*, 2011; MacKenzie *et al.*, 2012; Meier *et al.*, 2012). Although there is a clear need to capture regional-scale processes, there is no guarantee that high-resolution regional models will provide improved predictions of regional climate changes compared with GCMs (Racherla *et al.*, 2012). Therefore, it is important that scientists investigating fish responses to climate change correctly understand the robustness and uncertainty of GCM-derived variables when they use these variables to predict biological responses.

In addition to uncertainty in GCM outputs, many sources of uncertainty exist in models of biological responses (Planque *et al.*, 2011) and these should be accounted for when making projections (Hare *et al.*, 2012b). Various approaches have been used to quantify the uncertainty associated with the projections of the potential impacts of changing ocean conditions on marine fish and shellfish (e.g. Loukos *et al.*, 2003; Cheung *et al.*, 2009, 2010; Lindegren *et al.*, 2010; Fulton, 2011; Blanchard *et al.*, 2012). These include bioclimate envelope models to determine expected shifts in species distributions as a result of changes in the availability of preferred temperatures (Cheung *et al.*, 2009, 2011; Jones *et al.*, 2012), fish population models and end-to-end ecosystem models coupled to regionally downscaled climate-physical oceanographic models (e.g., MacKenzie *et al.*, 2012; Meier *et al.*, 2012). Methods used to address uncertainty include, but are not limited to, the following:

(i) Hierarchical models: these models, using a fully Bayesian or a empirical Bayes approach, provide a powerful tool for quantifying uncertainty in the estimated responses of fish populations to climate variability across multiple stocks, regions, or other "replicate" units (e.g. Mueter *et al.*, 2002; Helser *et al.*, 2012). Because of the computational demands, such models are only beginning to be applied to coupled biophysical models (e.g. Fiechter *et al.*, 2009).

(ii) Multiclimate model scenarios: the most basic approach to characterizing, if not quantifying, uncertainty about potential future responses to climate change consists of presenting results and implications from the analysis of different models and comparing and contrasting the resulting patterns across models (A'mar *et al.*, 2009; Hare *et al.*, 2010).

(iii) Ensemble modelling: this approach is commonly used to characterize uncertainty in climate projections across multiple models (Hollowed *et al.*, 2009; Wang and Overland, 2009) and has recently also been used in coupled models to examine uncertainty in both climate trajectories and in the biological responses (Ito *et al.*, this volume; Mueter *et al.*, 2011). This approach is used when analysts find that some of the different oceanographic models may perform better than others to reproduce the physical or biological oceanographic variables (e. g., temperature, plankton production) that influence the fish population dynamics (MacKenzie *et al.*, 2012). Biological models in these ensemble approaches may be driven by dynamically (e.g. Ito *et al.*, this volume) or statistically downscaled climate scenarios (Meier *et al.*, 2012; MacKenzie *et al.*, 2012). An outstanding issue in ensemble modelling is the criteria to decide which models should be included in the ensemble and/or how they should be weighted. Overland and Wang (2007) reduced a set of 22 GCMs to 10 based on how well they simulated the variability of 20th century North Pacific SSTs. Depending on which particular variables are of interest, other selection criteria could of course be devised. Additionally, good model performance evaluated based on historical or present climate does not necessarily imply certainty in predictions of future climate. However, Reichler and Kim (2008) note that the retrospective assessment of the skill of simulations relative to observations is an important way to evaluate confidence in projections.

(iv) Monte-Carlo approaches: whether or not the impacts of multiple models are investigated, a simulation (Monte Carlo) approach can generally be used to quantify uncertainty when making projections. Simulations can account for known uncertainty in future climate (random draws of climate trajectories based on different emission scenarios), in population dynamics (random draws of important population parameters from multiple univariate or, better, a single multivariate distribution), and in environment–biology relationships (random draws of parameter values for estimated or assumed functional relationships from a suitable probability distribution or from historical values; Mueter *et al.*, 2011; Planque *et al.*, 2011). A simulation approach is also utilized in the context of Management Strategy Evaluations, which allows the robustness of management strategies to be tested in the face of system uncertainty, but at the expense of considerable time and processing power (Ianelli *et al.*, 2011). The reliability of such simulations depends on specifying both the functional forms and the sampling distribution of the parameters correctly, which in some data-limited situations can be more difficult than merely estimating the central moment of the distribution correctly and using other means to incorporate uncertainties in the final result (Rochet and Rice, 2009).

(v) Parameter sensitivity: estimating the sensitivity of model outputs to changes in values of parameters is the primary means for identifying particularly influential parameters (Maunder *et al.*, 2006; Haltuch *et al.*, 2009; Peck and Hufnagl, 2012). If models are particularly sensitive to a given parameter, uncertainty about the true parameter value is an important source of overall uncertainty. Sensitivity analyses are typically used to prioritize field and laboratory studies (e.g. Peck and Hufnagl, 2012), but they can also be used to quantify uncertainty in projections by repeatedly running models across different values of the important parameters to bracket possible responses. However, this requires some knowledge of the likely distribution of parameter values and it can be challenging with complex models that have multiple, important parameters that require a large number of model runs. Gibson and Spitz (2011) and Fiechter (2012) provide examples of exploring the effects of parameter uncertainty in a nutrient–phytoplankton–zooplankton–detritus (NPZD) model on estimates of phytoplankton biomass in the eastern Bering Sea and Gulf of Alaska, respectively.

Each modelling approach has strengths and weaknesses and, as for the physical realm, multimodel projections may provide additional insights into the range of impacts to fish and fisheries that could occur under future climate change (Plagányi *et al.*, 2011; Stock *et al.*, 2011; Link *et al.*, 2012; Hollowed *et al.*, in press a). A parallel alternative is the development of models that combine principles and algorithms from several modelling frameworks, such as the inclusion of size-based ecological constraints embedded in bioclimate envelope models (Fernandes *et al.*, in press). This approach helps assess the relative strengths of each model and makes predictions more realistic and robust to assumptions.

Uncertainty in fish population simulations may be more fully characterized by using a suite of models representing different components of the climate–ocean–ecosystem complex. Compounding the uncertainty of projected fish responses is the availability of multiple representations of the fish population dynamics (e.g. single-species model, predator–prey interactions model, foodweb models, etc.) which can be coupled to the outputs from the available physical oceanographic models. Consequently, the availability of different climate-physical oceanographic and ecological models for a given system presents an opportunity to investigate a wide range of climate-oceanographic and biological model assumptions and parameterisations (e.g. via sensitivity analysis), particularly by combining the different climate-oceanographic and population models (MacKenzie *et al.*, 2012; Meier *et al.*, 2012). This approach can identify both the range and similarity of possible biological responses to different model frameworks and identify critical gaps in knowledge and new hypotheses for investigation.

Recommendations

Our synthesis elucidated several research foci that will be needed to improve the projections of climate impacts on fish and fisheries. The scale and ecological importance of climate change research for the marine community will require coordination at the local, national, and international level. In many nations, research programmes are emerging that will address the data gaps and research identified below. International marine research organizations are facilitating coordination and integration of national research at the hemispheric or global level. A key element of the success of these local, national, and international research collaborations will be the formation of interdisciplinary research teams that include earth system modellers, ecologists, fisheries scientists, and fisheries managers who will work together to develop new and improved projection capabilities for the future. We identify the following key research needs.

Increased physiological measurements

Physiological measurements of key life stages of all target marine fish species are needed. Studies should examine the effects of multiple factors on growth and bioenergetics (rates of energy losses and gains). There is an urgent need to explore interactive effects (temperature × pH × O_2) on the survival and growth performance in a variety of fish and invertebrates and to gain more data on the growth physiology of all life stages. This will not only help in the short term for linking physiological responses to statistically downscaled drivers but also in the long-term to build physiologically-based models (Pörtner and Peck, 2010; Jørgensen *et al.*, 2012) that can make use of dynamically downscaled forcing variables. Longer term experiments are also needed (Denman *et al.*, 2011) to gauge the adaptive capacity of individuals and populations and test how the sensitivity to climate-driven factors may change from one generation to the next. Operational techniques to incorporate physiology directly into stock projection type models should be explored.

Integrated ecological monitoring to identify mechanisms underlying fish and shellfish responses to environmental drivers and fishing

Systematic ocean sampling of interacting physical, chemical, and biological components must be continued to improve our understanding of the key climate-driven processes underlying observed trends. The marine environment is chronically undersampled, and we have limited historical time-series to gauge the past and recent magnitude of natural variability (abundance, distribution) of marine fish and shellfish resources relative to more recent responses to multiple, anthropogenic stressors (climate, eutrophication, pollution, etc.). Efforts to establish a global network of observations (e.g. distribution, growth) are particularly useful for tracking climate change impacts on spatial distributions and abundance. In addition, continued efforts to understand critical biomass thresholds will be needed. Knowledge of the responses of key prey fields (zooplankton and forage fish) to changes in ocean conditions will be needed to adequately project shifts in the distribution and abundance of exploited fish and shellfish stocks. Efforts to identify cost-effective ways of augmenting existing fish and shellfish surveys to collect information on these prey fields is needed to fill existing gaps in knowledge for these species (e.g. Handegard *et al.*, 2012; Ressler *et al.*, 2012). Maintenance and enhancement of fish and shellfish consumption is also needed to adequately project responses to shifting prey density and species composition. Trophodynamic monitoring (e.g. combination of stomach contents and isotope ratio) is also required to detect match–mismatch changes with climate change in future.

Short-term forecasts (1–10 years) based on observed ocean conditions

Short-term projections of biological responses using observed ocean conditions are a powerful way to assess the predictive skill of functional relationships. For physical models, these short-term projections will allow analysts to test the models ability to capture the correct physics. For harvested fish and shellfish stocks, this may be part of routine stock assessments. Over time, results from these skill assessments will provide the estimates of process error for long-term projections.

Process studies to test functional relationships

Survival and growth efficiency of early life stages of marine fish and invertebrates mostly ensures a formation of year-class productivity. Despite a century of research, many key functional relationships remain uncertain and they do not appear to be static. Studies of bioenergetic responses to climate change and their effect on larval and juvenile development (especially with respect to ocean acidification), growth and reproduction are needed. Process studies of species interactions including predator-prey responses to climate change are also needed. Studies to identify the factors influencing the distribution of juveniles would provide valuable information for modelers.

Comparative studies to test hypotheses

Continued emphasis should be placed on identifying (and/or comparing) the drivers of recruitment variability between and within species. Comparative analyses among stocks can reveal broad, climate-related patterns in productivity (e.g. Dutil and Brander, 2003; Shuntov and Temnykh, 2011) that would otherwise be elusive. Furthermore, continued process-oriented investigations are necessary to reveal how various abiotic (temperature, salinity, pH) and biotic (trophodynamic) factors interact with fishing pressure to make populations most susceptible to climate-driven changes. In terms of understanding recruitment, "non-stationarity" is an important point to consider in understanding historical and current recruitment drivers (Haltuch *et al.*, 2009). Such information should help identify how various factors contribute to changes in the productivity and distribution of marine fish observed in the last two to three decades (e.g. Rose, 2005; Rijnsdorp *et al.*, 2010) and to make more robust projections of future changes.

Improvement of ESMs and/or regional coupled biophysical models

The horizontal resolution of some GCMs is too coarse to capture shelf-region ocean processes. The spatial scales are not adequate to resolve many of the important mesoscale structures such as eddies, fronts, tides, and wind-driven upwelling that are important for biological processes. This will require downscaling from GCMs to more spatially resolved regional models. Although such regional models are being developed, it is important that there be coupling (one-way or two-way) between the regional and global models to capture the correct physics.

Coupled biophysical projection models should be extended to include the responses of fish and shellfish, fishers, and managers to climate-driven change (Stock *et al.*, 2011). New classes of models that explore the synergy between climate change effects and human activities are needed to provide meaningful and realistic projections and to allow adaptation and mitigation measures and their trade-offs, and to emerge from evolving management systems (Barange *et al.*, 2010).

Vulnerability assessments for fish, fisheries, and fishery-dependent communities

Allison *et al.* (2009) provided an important preliminary estimate of the vulnerability of countries to climate change impacts on fisheries. The authors concluded that for countries depending on fisheries but without sufficient capacity to adapt, climate-related changes in fisheries are likely to result in either greater economic hardships or to those countries missing opportunities for maintaining or improving the benefits obtained from their fisheries. Further research is required to increase the resolution of the results from the Allison *et al.* (2009) study and to explore the opportunities and constraints to adaptation in the most vulnerable countries in greater detail to allow for targeted efforts to build adaptive capacity where it is most needed and will yield the greatest benefits.

Coping strategies

As presented in this paper and in references included here, there is considerable general information available on what adaptive strategies are likely to be effective in response to climate-induced changes in fisheries and aquaculture. However, to date, there are very few examples of successful, or not so successful, implementation of adaptation strategies or plans in practice. There is an urgent need to select cases, of diverse social and ecological characteristics, where climate change is already having an impact on fisheries and aquaculture social-ecological systems and to develop, implement, and monitor adaptation plans in accordance with current best practices and understanding. This will allow the existing theories to be tested and improved where required from the lessons learned. Issues of food security and marine conservation may require new approaches to satisfy the growing demand for marine resources.

ICES–PICES strategic initiative

To coordinate and encourage research to address the some of the research needs outlined in the previous section, the governing bodies of both PICES and ICES approved the formation of the first joint ICES–PICES Strategic Initiative on Climate Change effects on Marine Ecosystems (SICCME). The key deliverables for ICES and PICES are the development of sufficient knowledge and understanding to successfully predict the future implications of climate change on marine ecosystems and the ability to use this information to develop strategies for managing living marine resources under a changing climate. The SICCME is designed to facilitate and accelerate the acquisition of new knowledge and to ensure that new knowledge is communicated and published on a schedule that would allow it to be useful to, and considered by, international scientific organizations responsible for providing advice on climate change such as the IPCC and the United Nations.

Members of the SICCME will focus their work on four critical issues:

(i) identifying techniques for predicting climate change impacts in systems impacted by decadal variability,
(ii) defining the vulnerability of commercial species to climate change and identifying which species would be most likely to experience shifts in spatial distributions,
(iii) engaging the global earth system modelling community in modelling climate change effects on marine ecosystems and identifying opportunities for collaborations, and
(iv) building response scenarios for how the human community will respond to climate changes as an extension (added dimension) of RCP scenarios described by van Vuuren *et al.* (2011).

The eight key research issues identified in this paper map into the four SICCME critical issues as follows:

(i) SICCME Critical Issue a: research recommendations 2, 3, and 5
(ii) SICCME Critical Issue b: recommendations 1, 2, 3, 4, and 7
(iii) SICCME Critical Issue c: recommendation 6
(iv) SICCME Critical Issue d: recommendations 7 and 8

This suggests that the leading marine science organizations in the northern hemisphere are well poised to facilitate advancements in our ability to understand and project the effects of climate change on marine ecosystems in the future. Their track record, to date, suggests that partnerships between science organizations will lead to more rapid global dissemination of research findings and analytical approaches through workshops, symposiums, and publications.

Acknowledgements

We thank ICES, PICES, and IOC for their support and encouragement to participate in symposiums focused on climate change effects on marine ecosystems that were held in Sendai, Japan, in 2010 and Yeosu, Korea, in 2012. We thank Pat Livingston and Mike Sigler for helpful comments and suggestions that improved this manuscript. We also thank Nathan Ryan who helped to compile the literature presented in Table 1.

References

ACIA, 2005. Arctic Climate Impact Assessment, Cambridge University Press, New York, N.Y. 1042 pp.

Agostini, V. N., Hendriz, A. N., Hollowed, A. B., Wilson, C. D., Pierce, S. D., and Francis, R. C. 2008. Climate-ocean variability and Pacific hake: a geostatistical modeling approach. Journal of Marine Systems, 71: 237–248.

Ainsworth, C. H., Samhouri, J. F., Busch, D. S., Cheung, W. W. L., Dunne, J., and Okey, T. A. 2011. Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. ICES Journal of Marine Science, 68: 1217–1229.

Alheit, J., Pohlmann, T., Casini, M., Greve, W., Hinrichs, R., Mathis, M., O'Driscoll, K., *et al.* 2012. Climate variability drives anchovies and sardines into the North and Baltic Seas. Progress in Oceanography, 96: 128–139.

Allison, E. H., Perry, A. L., Badjeck, M-C., Adger, W. N., Brown, K., Conway, D., Halls, A. S., *et al.* 2009. Vulnerability of national economies to potential impacts of climate change on fisheries. Fish and Fisheries, 10: 173–196.

AMAP. (Ed.) 2011. Snow Water Ice Permafrost in the Arctic, Executive Summary. Arctic Monitoring and Assessment Program, Secretariat, Oslo, Norway.

A'mar, Z. T., Punt, A. E., and Dorn, M. W. 2009. The evaluation of two management strategies for the Gulf of Alaska walleye pollock fishery under climate change. ICES Journal of Marine Science, 66: 1614–1632.

Anderson, P. J., and Piatt, J. F. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. Marine Ecology Progress Series, 189: 117–123.

Barange, M., and Perry, R. I. 2009. Physical and ecological impacts of climate change relevant to marine and inland capture fisheries and aquaculture. *In* Climate Change Implications for Fisheries and Aquaculture. Overview of Current Scientific Knowledge, pp. 7–106. Ed. by K. Cochrane, C. De young, D. Soto, and T. Bahri. FAO Fisheries and Aquaculture Technical Paper, 530. FAO, Rome.

Barange, M., Cheung, W. W. L., Merino, G., and Perry, R. I. 2010. Modelling the potential impacts of climate change and human activities on the sustainability of marine resources. Current Opinion in Environmental Sustainability 2(5-6): 326–333.

Barange, M., *et al.* 2011. Predicting the impacts and socio-economic consequences of climate change on global marine ecosystems and fisheries: the QUEST fish framework Pages 31–59. *In* World Fisheries: a Social-Ecological Analysis. Ed. by R. E. Ommer, R. I. Perry, K. Cochrane, and P. Cury. Wiley-Blackwell, Oxford, NY.

Baumgartner, T. R., Soutar, A., and Ferreira-Bartrina, V. 1992. Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara basin. CALCOFI Reports, 33: 24–40.

Beare, D. J., Burns, F., Greig, A., Jones, E. G., Peach, K., Kienzle, M., McKenzie, E., *et al.* 2004. Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. Marine Ecology Progress Series, 284: 269–278.

Beaugrand, G., and Kirby, R. R. 2010. Climate, plankton and cod. Global Change Biology, 16: 1268–1280.

Bell, J. D., Kronen, M., Vunisea, A., Nash, W. J., Keeble, G., Demmke, A., Pontifex, S., *et al.* 2009. Planning the use of fish for food security in the Pacific. Marine Policy, 33: 64–76.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J., *et al.* 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society B, 367: 2979–2989.

Bode, A., Hare, J. A., Li, W. K. W., Morán, X. A. G., and Valdés, L. 2011. Chlorophyll and primary production in the North Atlantic. *In* ICES Status Report on Climate Change in the North Atlantic, pp. 77–102. Ed. by P. C. Reid, and L. Valdés. ICES Cooperative Research Report, 310. 262 pp.

Brander, K. 2010. Impacts of climate change on fisheries. Journal of Marine Systems, 79: 389–402.

Brander, K. 2012. Climate and current anthropogenic impacts on fisheries. Climatic Change. doi:10.1007/s10584-012-0541-2.

Burrows, M. T., Schoeman, D. S., Buckley, L. B., Moore, P., Poloczanska, E. S., Brander, K. M., Brown, C., *et al.* 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science, 334: 652–655.

Capotondi, A., Alexander, M. A., Bond, N. A., Curchitser, E. N., and Scott, J. D. 2012. Enhanced upper ocean stratification with climate change in the CMIP3 models. Journal of Geophysical Research: Oceans, 117.

Ciannelli, L., and Bailey, K. M. 2005. Landscape dynamics and resulting species interactions: the cod-capelin system in the southeastern Bering Sea. Marine Ecology Progress Series, 291: 227–236.

Chavez, F. P., Ryan, J., Lluch-Cota, S. E., and Niquen, C. M. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science, 299: 217–221.

Cheung, W. W. L., Dunne, J., Sarmiento, J. L., and Pauly, D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES Journal of Marine Science, 68: 1008–1018.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., and Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 10: 235–251.

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R., Zeller, D., and Pauly, D. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Global Change Biology, 16: 24–35.

Chiba, S., Ono, T., Tadokoro, K., *et al.* 2004. Increased stratification and decreased lower trophic level productivity in the Oyashio region of the North Pacific: a 30-year retrospective study. Journal of Oceanography, 60: 149–62.

Cochrane, K., De Young, C., Soto, D., and Bahri, T. 2009. Climate change implications for fisheries and aquaculture. FAO Fisheries and aquaculture technical paper, 530: 212.

Cochrane, K. L., Andrew, N. L., and Parma, A. M. 2011. Primary fisheries management: a minimum requirement for provision of sustainable human benefits in small-scale fisheries. Fish and Fisheries, 12: 275–288.

Costello, C., Ovando, D., Hilborn, R., Gaines, S. D., Deschenes, O., and Lester, S. E. 2012. Status and solutions for world's unassessed fisheries. Science, 338: 517–520.

Criddle, K. R. 2012. Adaptation and maladaptation: factors that influence the resilience of four Alaskan fisheries governed by durable entitlements. ICES Journal of Marine Science, 69: 1168–1179.

Daw, T., Adger, W. N., Brown, K., and Badjeck, M-C. 2009. Climate change and capture fisheries: potential impacts, adaptation and mitigation. *In* Climate Change Implications for Fisheries and Aquaculture. Overview of Current Scientific Knowledge, pp. 107–150. Ed. by K. Cochrane, C. De young, D. Soto, and T. Bahri. FAO Fisheries and Aquaculture Technical Paper, 530. FAO, Rome. 530 pp.

Denman, K., Christian, J. R., Steiner, N., Pörtner, H. O., and Nojiri, Y. 2011. Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research. ICES Journal of Marine Science, 68: 1019–1029.

Deser, C., Phillips, A., Bourdette, V., and Teng, H. 2012. Uncertainty in climate change projections: the role of internal variability. Climate Dynamics, 38: 527–546.

Di Lorenzo, E., Schneider, N., Cobb, K. M., Franks, P. J. S., Chhak, K., Miller, A. J., McWilliams, J. C., *et al.* 2008. North Pacific gyre oscillation links ocean climate and ecosystem change. Geophysical Research Letters, 35: L08607.

Donelson, J. M., Munday, P. L., McCormick, M. I., and Nilsson, G. E. 2011. Acclimation to predicted ocean warming through developmental plasticity in a tropical reef fish. Global Change Biology, 17: 1712–1719.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., *et al.* 2012. Climate change impacts on marine ecosystems. Annual Reviews in Marine Science, 4: 1–27.

Drinkwater, K. F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES Journal of Marine Science, 62: 1327–1337.

Drinkwater, K. F. 2006. The regime shift of the 1920s and 1930s in the North Atlantic. Progress in Oceanography, 68: 134–151.

Drinkwater, K. F., Beaugrand, G., Kaeriyama, M., Kim, S., Ottersen, G., Perry, R. I., Pörtner, H. J., *et al.* 2010. On the processes linking climate to ecosystem change. Journal of Marine Systems, 79: 374–388.

Drinkwater, K. F., Hunt, G. L., Astthorsson, O. S., and Head, E. J. H. 2012. Comparative studies of climate effects on polar and subpolar ocean ecosystems, progress in observation and prediction: an introduction. ICES Journal of Marine Science, 69: 1120–1122.

Duarte, C. M., Agustí, S., Wassmann, P., Arrieta, J. M., Alcaraz, M., Coello, A., Marbá, N., *et al.* 2012. Tipping elements in the Arctic Marine Ecosystem. AMBIO, 41: 44–55.

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmüller, V., Dye, S. R., and Skjoldal, H. R. 2008. Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. Journal of Applied Ecology, 45: 4.

Dutil, J-D., and Brander, K. 2003. Comparing productivity of North Atlantic cod (*Gadus morhua*) stocks and limits to growth production. Fisheries Oceanography, 12: 502–512.

Edwards, M., and Richardson, A. J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature, 430: 881–884.

Eero, M., MacKenzie, B. R., Köster, F. W., and Gislason, H. 2011. Multi-decadal responses of a cod (*Gadus morhua*) population to human-induced trophic changes, exploitation and climate variability. Ecological Applications, 21: 214–226.

Engelhard, G. H., Pinnegar, J. K., Kell, L. T., and Rijnsdorp, A. D. 2011. Nine decades of North Sea sole and plaice distribution. ICES Journal of Marine Science, 68: 1090–1104.

FAO. 2008a. Climate change for fisheries and aquaculture. Technical Background document from the Expert Consultation on Climate Change for Fisheries and Aquaculture, (FAO), Rome, 7–9 April 2008.

FAO. 2008b. Report of the FAO Expert Workshop on Climate Change Implications for Fisheries and Aquaculture. FAO Fisheries Report, 870, FAO, Rome, 7–9 April 2008. 32 pp.

FAO. 2009. FAO Technical Guidelines for Responsible Fisheries Supplement 4, Addition 2, Fisheries Management 2. The ecosystem approach to management, 2.2 The Human Dimensions of the ecosystem approach to management. FAO, Rome. 88 pp.

FAO. 2012. The State of World Fisheries and Aquaculture 2012. Rome. 209 pp.

Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., and Hales, B. 2008. Evidence for upwelling of corrosive 'acidified' water onto the continental shelf. Science, 320: 1490–1492.

Fernandes, J. F., Cheung, W. L., Jennings, S., Butenschön, M., de Mora, L., Frölicher, T. L., Barange, M., *et al.* in press. Modelling the effects of climate change on the distribution and production of marine fishes for an ecosystem approach to fisheries management: accounting for trophic interactions in a dynamic bioclimate envelope model. Global Change Biology, doi: 10.1111/gcb.12231.

Fiechter, J. 2012. Assessing marine ecosystem model properties from ensemble calculations. Ecological Modelling, 242: 164–179.

Fiechter, J., Moore, A. M., Edwards, C. A., Bruland, K. W., Di Lorenzo, E., Lewis, C. V. W., Powell, T. M., *et al.* 2009. Modeling iron limitation of primary production in the coastal Gulf of Alaska. Deep Sea Research II, 56: 2503–2519.

Fogarty, M., Incze, L., Hayhoe, K., Mountain, D., and Manning, J. 2008. Potential climate impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. Mitgation Adaptation Strategies for Global Change, 13: 453–466.

Fulton, E. A. 2011. Interesting times: winners, losers, and system shifts under climate change around Australia. ICES Journal of Marine Science, 68: 1329–1342.

Garcia, S. M., and Rosenberg, A. A. 2009. UK Future Foresight: Food Security and Marine Capture Fisheries: Characteristics of the Sector and Perspectives on Emerging Issues. Defra, London. 52 pp.

Genner, M. J., Sims, D. W., Wearmouth, V. J., Southall, E. J., Southward, A. J., Henderson, P. A., and Hawkins, S. 2004. Regional climate warming drives long-term community changes of British marine fish. Proceedings of the Royal Society B: Biological Sciences, 271: 655–661.

Gibson, G. A., and Spitz, Y. H. 2011. Impacts of biological parameterization, initial conditions, and environmental forcing on parameter sensitivity and uncertainty in a marine ecosystem model for the Bering Sea. Journal of Marine Systems, 88: 214–231.

Gnanadesikan, A., Dunne, J. P., and John, J. 2011. What ocean biogeochemical models can tell us about bottom-up control of ecosystem variability. ICES Journal of Marine Science, 68: 1030–1044.

Godfray, H. C. 2011. Food for thought. Proceedings of the National Academy of Sciences of the USA, 108: 19845–19846.

Godfray, H. C., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., *et al.* 2010. Food security: the challenge of feeding 9 billion people. Science, 327: 812–818.

Greene, C. H., and Pershing, A. J. 2007. Climate drives sea change. Science, 315: 1084–1085.

Gutierrez, N. L., Hilborn, R., and Defeo, O. 2011. Leadership, social capital and incentives promote successful fisheries. Nature, 470: 386–389.

Halpern, B. S., Longo, C., Hardy, D., McLeod, K. L., Samhouri, J. F., Katona, S. K., Kleisner, K., *et al.* 2012. An index to assess the health and benefits of the global ocean. Nature, 488: 615–620.

Haltuch, M. A., Punt, A. E., and Dorn, M. W. 2009. Evaluating the estimation of fishery management reference points in a variable environment. Fisheries Research, 100: 43–56.

Handegard, N. O., du Buisson, L., Brehmer, P., Chalmers, S. J., De Robertis, A., Huse, G., Kloser, R., *et al.* 2012. Towards an acoustic-based coupled observation and modeling system for monitoring and predicting ecosystem dynamics of the open ocean. Fish and Fisheries, doi:10.1111/j.1467-2979.2012.00480.x.

Hare, J. A., Alexander, M. A., Fogarty, M. J., Williams, E. H., and Scott, J. D. 2010a. Forecasting the dynamics of a coastal fishery species using a coupled climate-population model. Ecological Applications, 20: 452–464.

Hare, J. A., Manderson, J., Nye, J., Alexander, M., Auster, P. J., Borggaard, D., Capotondi, A., *et al.* 2012a. Cusk (*Brosme brosme*) and climate change: assessing the threat to a candidate marine fish species under the U.S. Endangered Species Act. ICES Journal of Marine Science, 69: 1753–1768.

Hare, J. A., Wuenschel, M. J., and Kimball, M. E. 2012b. Projecting range limits with coupled thermal tolerance - climate change models: an example based on gray snapper (*Lutjanus griseus*) along the U.S. east coast. PLoS One, 7: e52294.

Hare, S. R., and Mantua, N. J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47: 103–145.

Hashioka, T., and Yamanaka, Y. 2007. Ecosystem change in the western North Pacific associated with global warming using 3D-NEMURO. Ecological Modelling, 202: 95–104.

Hátún, H., Payne, M. R., Beaugrand, G., Reid, P. C., Sandø, A. B., Drange, H., Hansen, B., *et al.* 2009. Large bio-geographical shifts in the north –eastern Atlantic Ocean: from the subpolar gyre, via plankton, to blue whiting and pilot whales. Progress in Oceanography, 80: 149–162.

Haynie, A. C., and Pfeiffer, L. 2012. Why economics matters for understanding the effects of climate change on fisheries. ICES Journal of Marine Science, 69: 1160–1167.

Hawkins, E., and Sutton, R. 2009. The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society, 90: 1095–1107.

Helser, T. E., Lai, H-l., and Black, B. A. 2012. Bayesian hierarchical modeling of Pacific geoduck growth increment data and climate indices. Ecological Modelling, 247: 210–220.

Hofstede, T. R., Hiddink, J. G., and Rijnsdorp, A. D. 2010. Regional warming changes fish species richness in the eastern North Atlantic Ocean. Marine Ecology Progress Series, 414: 1–9.

Hofstede, T. R., and Rijnsdorp, A. D. 2011. Comparing demersal fish assemblages between periods of contrasting climate and fishing pressure. ICES Journal of Marine Science, 68: 1189–1198.

Hollowed, A. B., Barange, M., Ito, S., Kim, S., and Loeng, H. 2011. Effects of climate change on fish and fisheries: forecasting impacts, assessing ecosystem responses, and evaluating management strategies Preface. ICES Journal of Marine Science, 68: 984–985.

Hollowed, A. B., Bond, N. A., Wilderbuer, T. K., Stockhausen, W. T., A'mar, Z. T., Beamish, R. J., Overland, J. E., *et al.* 2009. A framework for modelling fish and shellfish responses to future climate change. ICES Journal of Marine Science, 66: 1574–1594.

Hollowed, A. B., Curchitser, E., Stock, C., and Zhang, C. I. in press a. Trade-offs associated with different modeling approaches for assessment of fish and shellfish responses to climate change. Climatic Change, doi:10.1007/s10584-012-0641-z.

Hollowed, A. B., Planque, B., and Loeng, H. in press b. Potential movement of fish and shellfish from the Sub-Arctic to the Arctic ocean. Fisheries Oceanography, doi:10.1111/fog.12027.

Holt, J., Butenschon, M., Wakelin, S. L., Artioli, Y., and Allen, J. I. 2012. Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. Biogeosciences, 9: 97–117.

Howard, J., Babij, E., Griffis, R., Helmuth, B., Himes-Cornell, A., Niemier, P., Orbach, M., *et al.* 2013. Oceans and marine resources in a changing climate. Oceanography and Marine Biology: An Annual Review, 51: 71–192.

Hsieh, C-H., Kim, H. J., Watson, W., Di Lorenzo, E., and Sugihara, G. 2009. Climate-driven changes in abundance and distribution of larvae of oceanic fishes in the southern California region. Global Change Biology, 15: 2137–2152.

Huse, G., and Ellingsen, I. 2008. Capelin migrations and climate change – a modeling analysis. Climatic Change, 87: 177–197.

Ianelli, J., Hollowed, A., Haynie, A., Mueter, F. J., and Bond, N. A. 2011. Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment. ICES Journal of Marine Science, 68: 1297–1304.

IPCC, and . 2007. Climate Change 2007: Synthesis Report. *In* Contribution of Working Groups I, II and III to the fourth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by R. K. Pachauri, A. Reisinger, and Core Writing Team. IPCC, Geneva, Switzerland. 104 pp.

Ito, S., Okunishi, T., Kishi, M. J., and Wang, M. This volume. Modeling ecological responses of Pacific saury (*Cololabis saira*) to future climate change and its uncertainty. ICES Journal of Marine Science.

Ito, S., Rose, K. A., Miller, A. J., Drinkwater, K., Brander, K. M., Overland, J. E., Sundby, S., *et al.* 2010. Ocean ecosystem responses to future global change scenarios: a way forward. *In* Global Change and Marine Ecosystems, pp. 287–322. Ed. by M. Barange, J. G. Field, R. H. Harris, E. Hofmann, R. I. Perry, and F. Werner. Oxford University Press. 440 pp.

Jang, C. J., Park, J., Park, T., and Yoo, S. 2011. Response of the ocean mixed layer depth to global warming and its impact on primary production: a case for the North Pacific Ocean. ICES Journal of Marine Science, 68: 996–1007.

Jones, M.C., Dye, S.R., Pinnegar, J.K., Warren, R., and Cheung, W. W. L. 2012. Modelling commercial fish distributions: prediction and assessment using different approaches. Ecological Modeling, 225: 133–145.

Jørgensen, C., Peck, M. A., Antognarelli, F., Azzurro, E., Burrows, M. T., Cheung, W. W. L., Cucco, A., *et al.* 2012. Conservation physiology of marine fishes: advancing the predictive capacity of models. Biology Letters, 8: 900–903.

Kim, S. 2010. Fisheries development in northeastern Asia in conjunction with changes in climate and social systems. Marine Policy, 34: 803–809.

King, J. R., Agostini, V. N., Harvey, C. J., McFarlane, G. A., Foreman, M. G. G., Overland, J. E., Di Lorenzo, E., *et al.* 2011. Climate forcing and the California Current Ecosystem. ICES Journal of Marine Science, 68: 1199–1216.

Kingsolver, J. G. 2009. The well-temperatured biologist. The American Naturalist, 174: 755–768.

Kristiansen, T., Drinkwater, K. F., Lough, R. G., and Sunby, S. 2011. Recruitment variability in North Atlantic cod and match–mismatch dynamics. PLoS One, 6: e17456.

Last, P. R., White, W. T., Gledhill, D. C., Hobday, A. J., Brown, R., Edgar, G. J., and Pecl, G. 2011. Long-term shifts in abundance and distribution of a temperate fish fauna: a response to climate change and fishing practices. Global Ecology and Biogeography, 20: 58–72.

Laurenti, G. (comp.). 2007. 1961–2003 Fish and fishery products: world apparent consumption statistics based on food balance sheets. FAO Fisheries Circular No.i821, rev.9. FAO, Rome. 429 pp.

Lehodey, P., Senina, I., Calmettes, B., Hampton, J., and Nicol, S. 2012. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Climatic Change, doi:10.1007/s10584-012-0595-1.

Levin, L. A., Fogarty, M. J., Murawski, S. A., and Fluharty, D. 2009. Effects of natural and human-induced hypoxia on coastal benthos. Biogeosciences, 6: 2063–2098.

Lindegren, M., Diekmann, R., and Mollmann, C. 2010. Regime shifts, resilience and recovery of a cod stock. Marine Ecology Progress Series, 402: 239–253.

Link, J. S., Ihde, T. F., Harvey, C. J., Gaichas, S. K., Field, J. C., Brodziak, J. K. T., Townsend, H. M., *et al.* 2012. Dealing with uncertainty in ecosystem models: the paradox of use for living marine resource management. Progress in Oceanography, 102: 102–114.

Loeng, H., and Drinkwater, K. 2007. An overview of the ecosystems of the Barents and Norwegian Seas and their response to climate variability. Deep Sea Research II, 54: 2478–2500.

Loukos, H., Monfray, P., Bopp, L., and Lehodey, P. 2003. Potential changes in skipjack tuna (*Katsuwonus pelamis*) habitat from a global warming scenario: modeling approach and preliminary results. Fisheries Oceanography, 12: 474–482.

Lucey, S. M., and Nye, J. A. 2010. Shifting species assemblages in the northeast US continental shelf large marine ecosystem. Marine Ecology Progress Series, 415: 23–33.

Mackas, D. L., Batten, S., and Trudel, M. 2007. Effects on zooplankton of a warmer ocean: recent evidence from the North Pacific. Progress in Oceanography, 75: 223–52.

MacKenzie, B. R., Meier, H. E. M., Lindegren, M., Neuenfeldt, S., Eero, M., Blenckner, T., Tomczak, M., *et al.* 2012. Impact of climate change on fish population dynamics in the Baltic Sea – a dynamical downscaling investigation. Ambio, 41: 626–646. doi:10.1007/s13280-012-0325-y.

Maunder, M. N., Harley, S. J., and Hampton, J. 2006. Including parameter uncertainty in forward projections of computationally intensive statistical dynamic models. ICES Journal of Marine Science, 63: 969–979.

Megrey, B. A., Link, J. S., Hunt, G. L., Jr, and Moksness, E. 2009. Comparative marine ecosystem analysis: applications, opportunities, and lessons learned. Progress in Oceanography, 81: 2–9.

Meier, H. E. M., Andersson, H. C., Arheimer, B., Blenckner, T., Chubarenko, B., Donnelly, C., Eilola, K., *et al.* 2012. Comparing reconstructed past variations and future projections of the Baltic

Sea ecosystem—first results from multi-model ensemble simulations. Environmental Research Letters, 7: 034005 (8pp).

Merino, G., Barange, M., Blanchard, J., Harle, J., Holmes, R., Allen, I., Allison, E. H., *et al.* 2012. Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? Global Environmental Change, 22: 795–806.

Miller, K., Anthony, C., Barange, M., Brander, K., Gallucci, V. F., Gasalla, M. A., Khan, A., *et al.* 2010. Climate change, uncertainty, and resilient fisheries: institutional responses through integrative science. Progress in Oceanography, 87: 338–346.

Morán, X. A. G., López-Urrutia, Á., Calvo-Díaz, A., and Li, W. K. W. 2010. Increasing importance of small phytoplankton in a warmer ocean. Global Change Biology, 16: 1137–1144.

Mueter, F. J., Bond, N. A., Ianelli, J. N., and Hollowed, A. B. 2011. Expected declines in recruitment of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea under future climate change. ICES Journal of Marine Science, 68: 1284–1296.

Mueter, F. J., and Litzow, M. A. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecological Applications, 18: 309–320.

Mueter, F. J., Peterman, R. M., and Pyper, B. J. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. Canadian Journal of Fisheries and Aquatic Sciences, 59: 456–463.

Muhling, B. A., Lee, S-K., Lamkin, J. T., and Liu, Y. 2011. Predicting the effects of climate change on bluefin tuna (*Thunnus thynnus*) spawning habitat in the Gulf of Mexico. ICES Journal of Marine Science, 68: 1051–1052.

Murawski, S. A. 2007. Ten myths concerning ecosystem approaches to marine resources management. Marine Policy, 31: 681–690.

Murawski, S. A., *et al.* 2010. Why compare marine ecosystems? ICES Journal of Marine Science, 67: 1–9.

Nye, J. A., Link, J. S., Hare, J. A., and Overholtz, W. J. 2009. Changing spatial distribution of fish stocks in relation to climate and population size in the Northeast United States continental shelf. Marine Ecology Progress Series, 393: 111–139.

OECD. 2008. OECD Environmental Outlook to 2030. Paris, France, www.oecd.org/env.

OECD-FAO. 2009. OECD-FAO Agricultural Outlook 2009–2018. OECD, FAO, Paris, Rome. 95 pp. http://www.fao.org/docrep/x5738e/x5738e0g.htm.

Okunishi, T., Ito, S., Hashioka, T., Sakamoto, T. T., Yoshie, N., Sumata, H., Yara, Y., *et al.* 2012. Impacts of climate change on growth, migration and recruitment success of Japanese sardine (*Sardinops melanostictus*) in the western North Pacific. Climatic Change, doi:10.1007/s10584-012-0484-7.

Ottersen, G., Hjermann, D., and Stenseth, N. C. 2006. Changes in spawning stock structure strengthens the link between climate and recruitment in a heavily fished cod stock. Fisheries Oceanography, 15: 230–243.

Overland, J. E., and Wang, M. 2007. Future climate of the North Pacific Ocean. EOS Transactions of the AGU, 88: 182.

Overland, J. E., Alheit, J., Bakun, A., Hurrell, J. W., Mackas, D. L., and Miller, A. J. 2010. Climate controls on marine ecosystems and fish populations. Journal Marine Systems, 79: 305–315.

Peck, M. A., and Hufnagl, M. 2012. Can IBMs explain why most larvae die in the sea? Model scenarios and sensitivity analyses reveal research needs. Journal of Marine Systems, 93: 77–93.

Perrette, M., Yool, A., Quartly, G. D., and Popova, E. E. 2011. Near – ubiquity of ice edge bloom in the Arctic. Biogeosciences, 8: 515–524.

Perry, A. L., Low, P. J., Ellis, J. R., and Reynolds, J. D. 2005. Climate change and distribution shifts in marine fishes. Science, 308: 1912–1915.

Perry, R. I., Ommer, R. E., Barange, M., Jentoft, S., Neis, B., and Sumaila, U. R. 2011. Marine social–ecological responses to environmental change and the impacts of globalization. Fish and Fisheries, 12: 427–450.

Petitgas, P., Alheit, J., Peck, M. A., Raab, K., Irigoien, X., Huret, M., van der Kooij, J., *et al.* 2012. Anchovy population expansion in the North Sea. Marine Ecology Progress Series, 444: 1–13.

Petitgas, P., Rijnsdorp, A. D., Dickey-Collas, M., Engelhard, G. H., Peck, M. A., Pinnegar, J. K., Drinkwater, K., *et al.* 2013. Impacts of climate change on the complex life cycles of fish. Fisheries Oceanography, 22: 121–139.

Plagányi, É. E., Bell, J. D., Bustamante, R. H., Dambacher, J. M., Dennis, D. M., Dichmont, C. M., Dutra, L. X. C., *et al.* 2011. Modelling climate-change effects on Australian and Pacific aquatic ecosystems: a review of analytical tools and management implications. Marine and Freshwater Research, 62: 1132–1147.

Planque, B., Bellier, E., and Loots, C. 2011. Uncertainties in projecting spatial distributions of marine populations. ICES Journal of Marine Science, 68: 1045–1050.

Polovina, J. J., Dunne, J. P., Woodworth, P. A., and Howell, E. A. 2011. Projected expansion of the subtropical biome and contraction of the temperate and equatorial upwelling biomes in the North Pacific under global warming. ICES Journal of Marine Science, 68: 986–995.

Pörtner, H. O. 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. Journal of Experimental Biology, 213: 881–893.

Pörtner, H. O., and Peck, M. A. 2010. Climate change impacts on fish and fisheries: towards a cause and effect understanding. Journal of Fish Biology, 77: 1745–1779.

Prince, E. D., *et al.* 2010. Ocean scale hypoxia-based habitat compression of Atlantic Istiophorid billfishes. Fisheries Oceanography, 19: 448462.

Rabalais, N. N., Diaz, R. J., Levin, L. A., Turner, R. E., Gilbert, D., and Zhang, J. 2010. Dynamics and distribution of natural and human-caused hypoxia. Biogeosciences, 7: 585–619.

Racherla, P. N., Shindell, D. T., and Faluvegi, G. S. 2012. The added value to global model projections of climate change by dynamical downscaling: A case study over the continental U.S. using the GISS-ModelE2 and WRF models. Journal of Geophysical Research, 117: 1–8.

Reichler, T., and Kim, J. 2008. How well do coupled models simulate today's climate? Bulletin American Meteorological Society, 89: 303–311.

Ressler, P. H., De Robertis, A., Warren, J. D., Smith, J. N., and Kotwicki, S. 2012. Developing an acoustic survey of euphausiids to understand trophic interactions in the Bering Sea ecosystem. Deep Sea Research II, 65–70: 184–195.

Rice, J. 2001. Implications of variability on many time scales for scientific advice on sustainable management of living marine resources. Progress in Oceanography, 49: 189–209.

Rice, J. C., and Garcia, S. M. 2011. Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. ICES Journal of Marine Science, 68: 1343–1353.

Richardson, A. J. 2008. In hot water: zooplankton and climate change. ICES Journal of Marine Science, 65: 279–295.

Richardson, A. J., and Schoeman, D. S. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science, 305: 1609–1612.

Ries, J. B., Cohen, A. L., and McCorkle, D. C. 2009. Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geology, 37: 1131–1134.

Rijnsdorp, A. D., Peck, M. A., Engelhard, G. H., Möllmann, C., and Pinnegar, J. K. (Eds). 2010. Resolving Climate Impacts on Fish Stocks. ICES Cooperative Research Report, 301.

Rochet, M-J., and Rice, J. C. 2009. Simulation-based management strategy evaluation: ignorance disguised as mathematics? ICES Journal of Marine Science, 66: 754–762.

Rogers, L. A., Stige, L. C., Olsen, E. M., Knutsen, H., Chan, K. S., and Stenseth, N. C. 2011. Climate and population density drive changes in cod body size throughout a century on the Norwegian coast. Proceedings of the National Academic of Sciences of the USA, 108: 1961–1966.

Rose, G. A. 2005. On distributional responses of North Atlantic fish to climate change. ICES Journal of Marine Science, 62: 1360–1374.

Ruckelshaus, M., Doney, S. C., Glindo, H. M., Barry, J., Chan, F., Duffy, J. E., English, C. A., *et al.* 2013. Securing ocean benefits for society in the face of climate change. Marine Policy, 40: 154–159.

Rykaczewski, R. R., and Dunne, J. P. 2010. Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model. Geophysical Research Letters, 37: L21606.

Salinger, M. J., Bell, J. D., Evans, K., Hobday, A. J., Allain, V., Brander, K., Dexter, P., *et al.* in press. Climate and oceanic fisheries: Cook Islands 2011 Workshop conclusions and recommendations. Climatic Change.

Shoji, J., Toshito, S., Mizuno, K., Kamimura, Y., Hori, M., and Hirakawa, K. 2011. Possible effects of global warming on fish recruitment: shifts in spawning season and latitudinal distribution can alter growth of fish early life stages through changes in daylength. ICES Journal of Marine Science, 68: 1165–1169.

Shuntov, V. P., and Temnykh, O. S. 2011. Pacific salmon in marine and oceanic ecosystems. V. 2. TINRO-Center: Vladivostok, 2011. 473 pp. (In Russian).

Skud, B. E. 1982. Dominance in fishes: the relation between environment and abundance. Science, 216: 144–149.

Southward, A. J., Boalch, G. T., and Maddock, L. 1988. Fluctuations in the herring and pilchard fisheries of Devon and Cornwall linked to change in climate since the 16th century. Journal of the Marine Biological Association of the UK, 68: 423–445.

Spencer, P. D. 2008. Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. Fisheries Oceanography, 17: 396–410.

Steinacher, M., Joos, F., Frolicher, T. L., Bopp, L., Cadule, P., Cocco, V., Doney, S. C., *et al.* 2010. Projected 21st century decrease in marine productivity: a multi-model analysis. Biogeosciences, 7: 979–1005.

Stenseth, N. C., Mysterud, A., Ottersen, G., Hurrell, J. W., Chan, K-S., and Lima, M. 2002. Ecological effects of climate fluctuations. Science, 297: 1292–1296.

Stewart, J. S., Hazen, E. L., Foley, D. G., Bograd, S. J., and Gilly, W. F. 2012. Marine predator migration during range expansion: Humboldt squid *Dosidicus gigas* in the northern California Current System. Marine Ecology Progressive Series, 471: 135–150.

Stock, C. A., Alexander, M. A., Bond, N. A., Brander, K. M., Cheung, W. W. L., Curchister, E. N., Delworth, T. L., *et al.* 2011. On the use of IPCC-class models to assess the impact of climate on Living Marine Resources. Progress in Oceanography, 88: 1–27.

Stramma, L., Prince, E. D., Schmidtko, S., Luo, J., Hoolihan, J. P., Visbeck, M., Wallace, D. W. R., *et al.* 2011. Expansion of oxygen minimum zone may reduce available habitat for tropical pelagic fishes. Nature Climate Change, 2: 33–37.

Su, N-J., Sun, C-L., Punt, A. E., Yeh, S-Z., and DiNardo, G. 2011. Modelling the impacts of environmental variation on the distribution of blue marlin, *Makaira nigricans*, in the Pacific Ocean. ICES Journal of Marine Science, 68: 1072–1080.

Sundby, S., and Nakken, O. 2008. Spatial shifts in spawning habitats of Arcto-Norwegian cod related to multidecdal climate oscillations and climate change. ICES Journal Marine Science, 65: 953–962.

Taucher, J., and Oschlies, A. 2011. Can we predict the direction of marine primary production change under global warming? Geophysical Research Letters, 38: 6.

Tseng, C-T., Sun, C-L., Yeh, S-Z., Chen, S-C., Su, W-C., and Liu, D-C. 2011. Influence of climate-driven sea surface temperature increase on potential habitats of the Pacific saury (*Colobais saira*). ICES Journal of Marine Science, 68: 1105–1113.

UN-DESA. 2009. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision and World Urbanization Prospects: the 2009 Revision, http://esa.un.org/wup2009/unup/index.asp.

UN-WHO. 2002. Protein and amino acid requirements in human nutrition: report of a joint WHO/FAO/UNU Expert Consultation. WHO Technical Report Series, 953. 284 pp.

Valdés, L., Peterson, W., Church, J., Brander, K., and Marcos, M. 2009. Our changing oceans: conclusions of the first International Symposium on the Effects of climate change on the world's oceans. ICES Journal of Marine Science, 66: 1435–1438.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., *et al.* 2011. The representative concentration pathways: an overview. Climatic Change, 109: 5–31.

Vaquer-Sunyer, R., and Duarte, C. M. 2008. Thresholds of hypoxia for marine biodiversity. Proceedings of the National Academy of Sciences of the USA, 105: 15452–15457.

Wang, M., and Overland, J. E. 2009. A sea ice free summer Arctic within 30 years? Geophysical Research Letters, 36: L07502.

Wang, M., Overland, J. E., and Stabeno, P. 2012. Future climate of the Bering and Chukchi Seas projected by global climate models. Deep Sea Research II, 65–70: 46–57.

Welch, D. W., Ishida, Y., and Nagasawa, K. 2001. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Canadian Journal of Fisheries and Aquatic Sciences, 55: 937–948.

Whitney, F. A., Freeland, H. J., and Robert, M. 2007. Persistently declining oxygen levels in the interior waters of the eastern Subarctic Pacific. Progress in Oceanography, 75: 179–199.

Wiese, F. K., Wiseman, W. J., Jr, and Van Pelt, T. I. 2012. Bering Sea linkages. Deep Sea Research II: Topical Studies in Oceanography, 65–70: 2–5.

Worm, B., and Branch, T. A. 2012. The future of fish. Trends in Ecology and Evolution, 27: 594–599.

Worm, B., Hilborn, R., Baum, J. K., Branch, T., Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding Global Fisheries. Science, 325: 578–585.

Yatsu, A., Chiba, S., Yamanaka, Y., Ito, S., Shimizu, Y., Kaeriyama, M., and Watanabe, Y. 2013. Climate forcing and the Kuroshio/Oyashio ecosystem. ICES Journal of Marine Science.

Handling editor: Jason Link