

Identification of global marine hotspots: sentinels for change and vanguards for adaptation action

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Abstract Major changes consistent with the fingerprint of global warming have been reported for nearly every ecosystem on earth. Recently, studies have moved beyond correlation-based inference to demonstrate mechanistic links between warming and biological responses, particularly in regions experiencing rapid change. However, the assessment of climate change impacts and development of adaptation options that humans can undertake are at the earliest stages, particularly for marine systems. Here, we use trends in ocean temperature to characterize regions that can act as natural laboratories or focal points for early learning. These discrete marine ‘hotspots’, where ocean warming is fastest, were identified based on 50 years of historical sea surface temperature data. Persistence of

these hotspots into the future was evaluated using global climate models. This analysis provides insights and a starting point for scientists aiming to identify key regions of concern with regard to ocean warming, and illustrates a potential approach for considering additional physical drivers of change such as ocean pH or oxygenation. We found that some hotspot regions were of particular concern due to other non-climate stressors. For instance, many of the marine hotspots occur where human dependence on marine resources is greatest, such as south-east Asia and western Africa, and are therefore of critical consideration in the context of food security. Intensive study and development of comprehensive inter-disciplinary networks based on the hotspot regions identified here will allow earliest testing of management and adaptation pathways, facilitating rapid global learning and implementation of adaptation options to cope with future change.

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Introduction

Recent work has suggested that given observed emission and climate trends (Rahmstorf et al. 2007)

planning for adaptation¹ to a 4 °C temperature rise by the end of this century is prudent (Parry et al. 2009; Schneider 2009; Stafford-Smith et al. 2011). Along with the political and logistical complexity surrounding mitigation solutions, it is critical to recognize the enormity of the global adaptation challenge in socio-ecological systems. A global redistribution of species is occurring, widely recognized as a fingerprint of climate change, with species tracking environmental warming, most often by moving towards the poles (Chen et al. 2011; Sunday et al. 2012). Continued temperature increases will lead to greater re-shuffling of species assemblages, and greater challenges for sustainable natural resource management. Adaptation responses by humans to such effects of projected warming will be a complex undertaking, but one that is necessary for minimising the impacts of climate change in a warming world (Stafford-Smith et al. 2011). Our understanding of climate change impacts in the ocean has lagged behind that of terrestrial systems (Richardson and Poloczanska 2008). Likewise, adaptation efforts to date have largely focused on the human aspects of terrestrial systems (Stokes and Howden 2010), with the options for adaptation in ocean systems largely neglected.

The oceans are the earth's main buffer to climate change, absorbing up to 80 % of the heat and 50 % of the atmospheric carbon emitted (Sabine et al. 2004; Levitus et al. 2005; Domingues et al. 2008), and thus suffer the double effect of warming and ocean acidification (Cao and Caldeira 2008; Lough 2008). Changes in air and sea temperatures, rainfall, ocean chemistry, and wind patterns are all contributing to modifications in productivity, distribution and phenology of marine species, affecting ecosystem processes and altering food webs (Poloczanska et al. 2007; Brierley and Kingsford 2009; Brown et al. 2009). Given the range of existing anthropogenic threats to ocean ecosystems (e.g. Halpern et al. 2008; 2012), it is essential to develop adaptation pathways to improve outcomes for marine ecosystems, fisheries and aquaculture industries.

Catch from the world's fish stocks has been static since the 1980's (e.g. Branch et al. 2011) with 63 % of

stocks assessed as requiring rebuilding (Worm et al. 2009). Rebuilding stocks and improving yield is important as global demand for seafood products can only intensify given escalating demands in developing countries and a rapidly increasing human population (Allison et al. 2009; Bell et al. 2009). Changes in fishery catches in some of the world's large marine ecosystems have been linked to changes in ocean temperature, with a range of plausible mechanisms identified (Sherman et al. 2009). Likewise, shifts in the distribution of marine species have also been related to ocean warming with greater changes in distribution evident from regions with a greater rate of warming (Chen et al. 2011; Burrows et al. 2011). Human activities affected by large changes in the distribution or abundance of major fishery species, or those species critical to ecosystem structure and function, will need to be managed carefully and proactively to achieve the best outcomes for dependent human communities. The importance of ocean-based fisheries and aquaculture to food security and livelihoods, particularly in the world's poorest countries, is often undervalued and yet fish products provide essential nutrition for around 1.5 billion people and are a significant source of protein, income, or family stability for around 520 million people (Allison et al. 2009; Bell et al. 2009; Cochrane et al. 2009).

As a practical example of how to motivate research networking at a global scale, and to help focus adaptation efforts, we identify marine 'hotspots'—ocean regions that are warming most rapidly. Hotspots represent one of the front-line regions for climate change, and thus are prime locations for assessing impacts and evaluating adaptation options for marine ecosystems, fisheries and aquaculture. For example, data from regions with rapid warming can allow researchers to test hypotheses about the role of climate in driving the redistribution of species (Burrows et al. 2012). Identification of hotspots can enhance regional adaptation efforts and facilitate the advancement of adaptation science globally (Frusher et al. 2013; Diffenbaugh et al. 2008; Giorgi 2006), just as identification of biodiversity hotspots has focused conservation efforts in the sea (e.g. Worm et al. 2003; Renema et al. 2008; Tittensor et al. 2010) and on land (Dirzo and Raven 2003; Cardillo et al. 2006).

We define hotspots as regions where ocean surface temperatures have changed most rapidly over the past 50 years and are projected to continue to change

¹ Actions, referred to as the process of "adaptation" (e.g. Adger et al. 2005) can be taken to reduce exposure or sensitivity to climate change, or increase adaptive capacity (Stafford-Smith et al. 2011).

rapidly into the future, to demonstrate the use of trends in physical data as an approach to identify potential regions that can act as natural laboratories or focal points to facilitate our understanding. Temperature is only one physical driver of biological change, with other drivers including sea level rise, circulation changes, acidification, stratification change, salinity, upwelling and nutrient supply. In addition, regional variation, direct and indirect effects, and non-linear interactions combine to produce complex relationships between physical parameters and the associated biological responses. However, in the ocean, water temperature is the major driver of distribution, abundance, phenology and life-history of marine species (Cochrane et al. 2009; Harley et al. 2006; Byrne 2011), and consequently hotspots defined on the basis of temperature represent a constructive start to focus marine adaptation efforts.

Methods

To identify rapidly warming regions, monthly global sea surface temperature (SST) from two historical datasets HadSST2 (Rayner et al. 2006) and ERSSTv3 (Smith et al. 2008) and six GCMs used in the IPCC 4th assessment report (Randall et al. 2007) (CSIRO mk3.5, UKHadCM3, MIROCmedres, MRIcgcm, ECHAM5 and UKHadGem1) was extracted, annual averages calculated for a 50-year historical period (1950–1999, for both historical data and for the GCMs) and future period (2001–2050) using two emission scenarios (A1B and A2), and interpolated to a common grid of 1×1 degree resolution. We calculated the linear trend in temperature for each pixel, and selected the areas warming at the fastest rate (absolute rate in degrees; highest 10 %). Only spatially coherent hotspots larger than 25 square degrees were retained as hotspots, eliminating <8 % of the total selected pixels.

We used a 50-year historical period to determine the location of warming hotspots as longer periods of time are limited by variable data coverage in the historical datasets, while shorter periods limit the period over which associated biological change can be assessed, a motivation for this analysis. The end year (1999) was selected, as historical GCM simulations commonly end in the year 1999, and we wanted to make comparisons (see below). Investigation of shorter time periods showed similar trends and

regional patterns in distribution of hotspots, until the shortest period (1980–1999), which showed greater rates of warming in some of the identified regions.

We assessed agreement between datasets quantitatively (percentage of area in common) and qualitatively (occurrence of hotspots in the same general region). Differences in the scale between historical and GCM temperature fields (even though all were interpolated to the same resolution), and variation in model output at a regional scale limited the value of quantitative comparisons between the GCMs (Stock et al. 2011; Hobday and Lough 2011). The qualitative agreement in each of 24 hotspot ocean regions was assessed by overlaying the hotspot maps. We scored the confidence in the presence of each climate change hotspot region by summing the number of datasets and models that showed each regional hotspot using the two historical datasets, the six historical GCM periods, and the six future GCM predictions using the two emission scenarios (thus, with a maximum confidence score of 20 for the location of any hotspot).

Results

The two observational datasets differed slightly in the number of hotspots identified over the period 1950–1999 a total of 22 and 15 hotspots using the HadSST2 (Rayner et al. 2006) and ERSSTv3 (Smith et al. 2008) datasets respectively (Table 1). Based on a combination of the two analyses, 24 unique hotspots were identified. The qualitative overlap between the spatial location of the hotspots shows regional agreement in 13 of possible 15 ERSSTv3 locations (Table 1 and Fig. 1). At warming thresholds below 10 % (e.g. including 5 % of the fastest warming areas), fewer hotspots were located, whereas at larger thresholds, the size, rather than the number, of hotspots increased. The 10 % threshold equated to a rate of warming of 1.48 °C per 100 years for the HadSST dataset. Depending on the historical dataset, the size of individual hotspots ranged from the minimum size of 25 square degrees (e.g. south-east Australia, north-east Canada) to almost 600 square degrees (e.g. Northern Indian Ocean, Galapagos/Eastern Tropical Pacific, Fig. 1). The quantitative comparison showed only minor agreement, with low areal overlaps (16 %—data not shown) between historical hotspots despite qualitative similarity (Fig. 1). The agreement in

Table 1 Regional presence of ocean warming hotspots (>25 square degrees) in historical datasets (HadSST2 and ERSST v3), and as determined from GCMs for the historical period and future time periods based on the A2 and A1B scenario

Hemisphere	Region number	Region name	Historical period (1950–1999)			GCM historical period (1950–1999)							GCM prediction (A2) (2000–2050)						GCM prediction (A1B) (2000–2050)						Total agreement (confidence)		
			HadSST2	ERSSTv3	Total	CSIRO Mk3.5	UKHadCM3	MIROCmedres	MRICgcm	ECHAM5	UKHadGem1	Total	CSIRO Mk3.5	UKHadCM3	MIROCmedres	MRICgcm	ECHAM5	UKHadGem1	Total	CSIRO Mk3.5	UKHadCM3	MIROCmedres	MRICgcm	ECHAM5		UKHadGem1	Total
N	7	North East Canada	Y	-	1	Y	Y	Y	Y	Y	Y	6	Y	Y	Y	Y	Y	Y	6	Y	Y	Y	Y	Y	Y	6	19
N	3	Sea of Okhotsk	Y	-	1	-	Y	-	-	Y	Y	3	Y	Y	Y	-	Y	Y	5	Y	Y	Y	Y	Y	Y	6	15
N	4	Bering Sea	Y	Y	2	Y	Y	-	-	-	Y	3	-	Y	-	-	Y	Y	3	Y	Y	Y	Y	Y	Y	6	14
N	13	Sea of Japan	Y	-	1	-	Y	Y	Y	Y	Y	5	-	Y	-	-	-	Y	2	Y	Y	Y	Y	Y	Y	6	14
N	5	South California (USA)-Baja (Mexico)	Y	Y	2	-	-	Y	-	-	Y	2	Y	Y	Y	-	Y	Y	5	Y	Y	Y	-	-	Y	4	13
N	12	Indo-China	Y	Y	2	Y	-	-	-	-	1	Y	-	-	Y	-	Y	3	Y	Y	Y	Y	Y	Y	Y	6	12
N	21	Greenland Sea	Y	-	1	-	Y	Y	-	-	-	2	-	-	Y	-	Y	Y	3	Y	Y	Y	-	Y	Y	5	11
N	14	Gulf of Alaska	Y	-	1	-	Y	-	-	-	-	1	-	Y	-	-	Y	Y	3	-	Y	Y	Y	-	Y	4	9
S	1	South East Australia	Y	Y	2	Y	-	-	-	Y	-	2	Y	Y	Y	-	-	-	3	Y	-	-	-	-	-	1	8
S	6	South-Brazil Uruguay	Y	Y	2	-	Y	-	-	Y	Y	3	-	Y	Y	-	-	-	2	Y	-	-	-	-	-	1	8
S	17	South Africa	Y	Y	2	Y	-	-	Y	Y	Y	4	-	-	Y	Y	-	-	2	-	-	-	-	-	-	0	8
E	23	East of Micronesia	-	Y	1	-	-	-	-	-	0	Y	-	-	-	Y	-	2	Y	Y	Y	Y	-	-	-	4	7
S	19	Kerguelan Is (SIO)	Y	Y	2	-	-	-	Y	Y	-	2	-	-	Y	Y	-	-	2	-	-	-	-	-	-	0	6
E	22	Micronesia	Y	-	1	-	-	-	-	Y	-	1	Y	-	-	-	Y	-	2	Y	Y	-	-	-	-	2	6
N	11	Indian Ocean	Y	Y	2	Y	-	-	-	-	1	-	Y	-	-	-	-	1	-	-	Y	-	-	-	-	1	5
E	15	Galapagos (ETP)	Y	Y	2	-	-	-	-	-	0	-	Y	-	-	Y	-	2	Y	-	-	-	-	-	-	1	5
S	2	South West Australia	Y	Y	2	-	Y	-	-	Y	-	2	-	-	-	-	-	0	-	-	-	-	-	-	-	0	4
N	8	Hudson Sea	Y	-	1	Y	-	Y	-	-	-	2	-	-	Y	-	-	1	-	-	-	-	-	-	-	0	4
S	9	Angola Basin	Y	Y	2	-	-	-	-	-	Y	1	-	-	-	-	-	0	Y	-	-	-	-	-	-	1	4
S	18	Drakes Passage	Y	-	1	-	-	-	-	Y	-	1	Y	-	Y	-	-	2	-	-	-	-	-	-	-	0	4
N	20	North Sea	Y	Y	2	-	-	Y	-	-	1	-	-	-	-	-	-	0	-	-	Y	-	-	-	-	1	4
S	10	Mozambique Channel	Y	Y	2	-	-	-	-	-	0	Y	-	-	-	-	-	1	-	-	-	-	-	-	-	0	3
N	16	Russian Arctic	Y	-	1	-	-	-	-	-	0	-	-	-	-	-	-	0	-	-	-	-	-	-	-	0	1
N	24	Canadian Arctic	-	Y	1	-	-	-	-	-	0	-	-	-	-	-	-	0	-	-	-	-	-	-	-	0	1
		Total	22	15	37	7	8	6	4	10	8	43	9	10	10	4	9	8	50	13	10	11	7	6	8	55	185

Qualitative agreement for each of the hotspot regions is indicated as the number of models that showed the hotspot. Total agreement is indicated by the sum of the datasets and models identifying hotspots in each region. Numbers identifying each region are shown in Fig. 1. Each of the hotspots is classified as falling in the northern (N) or southern (S) hemisphere, or equatorial region (E)

hotspot location between the observational datasets was best represented using the qualitative method based on the presence of a hotspot in a region, rather than quantitative overlap (Table 1).

We then evaluated which of six coupled ocean–atmosphere global climate models (GCM) (CSIRO mk3.5; UKHadCM3; MIROCmedres; MRICgcm; ECHAM5; UKHadGem1) from the CIMP3 archive used for IPCC AR4 also showed these historical hotspots over the period 1950–1999 using the same

methods as for the observed data. This step was to determine which GCMs were able to replicate the historical patterns, as we planned to use only the “best” GCMs to assess likely hotspot persistence into the future (Hobday and Lough 2011; Stock et al. 2011). Overall, the performance of the GCMs in reproducing the historical hotspots was similar and poor using the quantitative approach (<8 % areal overlap, data not shown) and similar and reasonable using the qualitative approach (19 of the

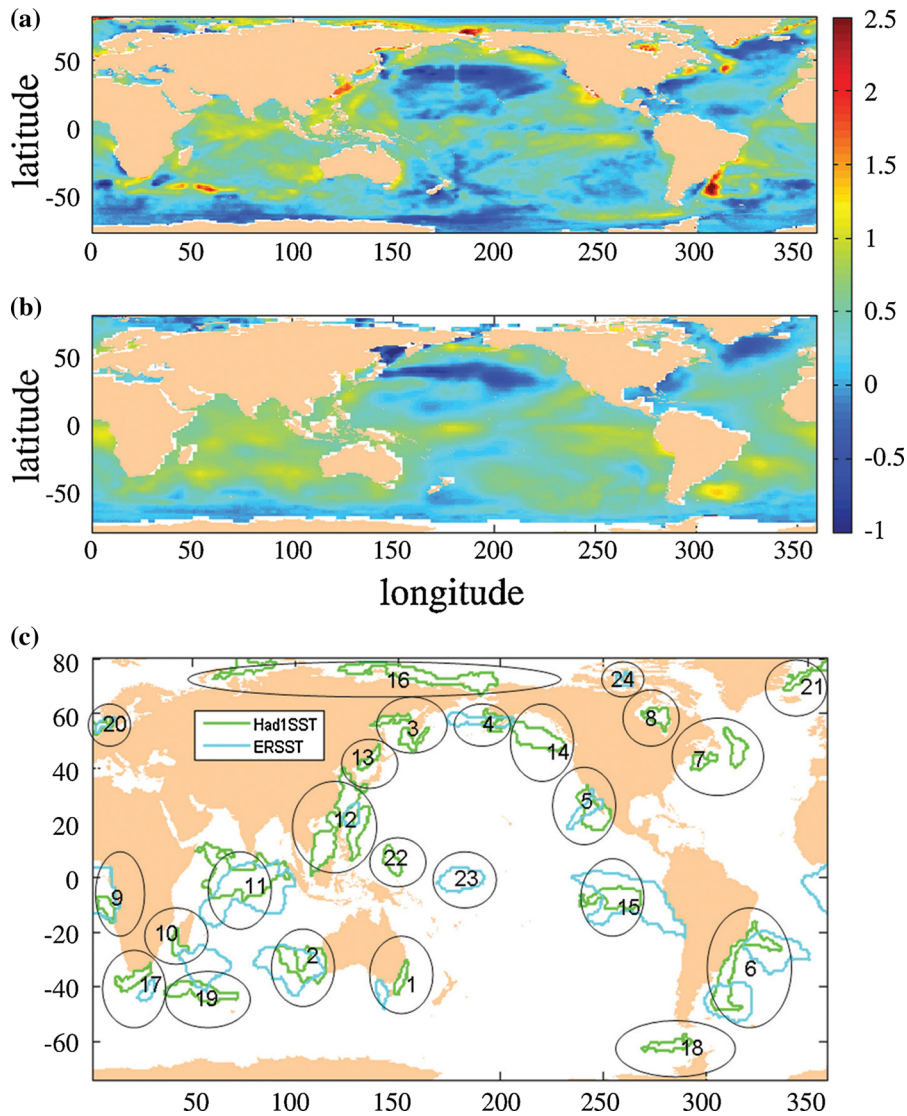


Fig. 1 Analysis of historical sea surface temperature trends over the period 1950–1999. Linear sea surface temperature trends (°C) for two historical sea surface temperature datasets (a: HadSST2, b: ERSSTv3) c: Overlap between the distribution

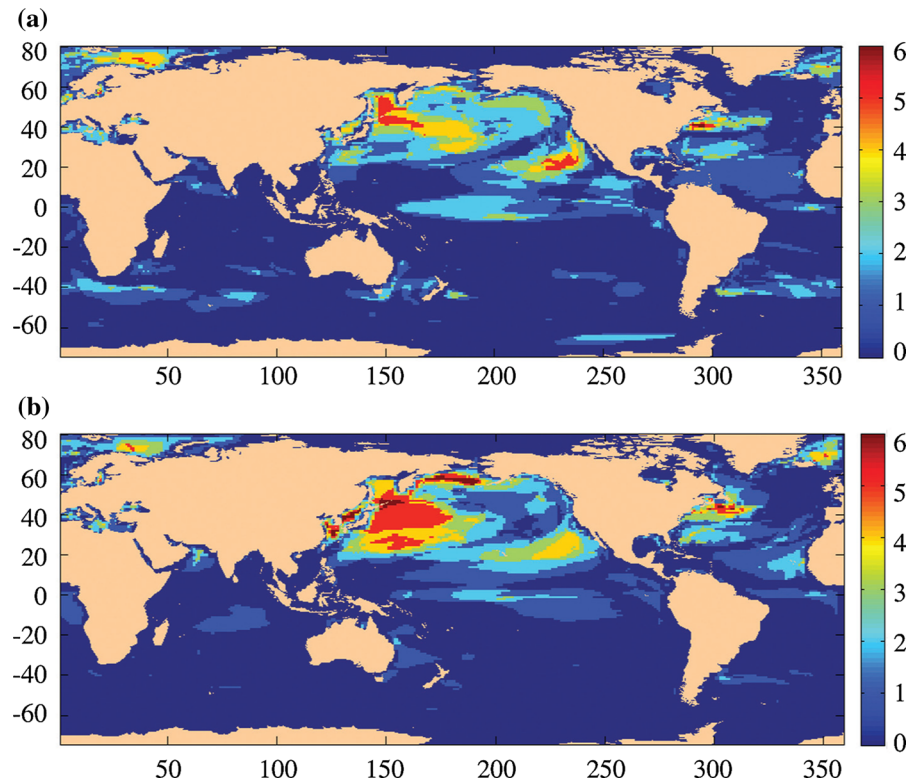
of large hotspots (>25 square degrees) from each dataset for the same period. The regions that were used for qualitative analysis are shown as the *numbered circles* and listed in Table 1

24 historical hotspots were found in at least one historical GCM; Table 1). We thus predicted future hotspots (the upper 10 % of warming regions) using all six GCMs for two SRES emission scenarios (A2—medium, and A1B—higher end, to allow for potential future differences in global emissions) for the period 2001–2050. The qualitative analysis showed variation between the GCMs in terms of hotspot locations in the future, although 19 and 16 of the 24 historical hotspots were projected by

between 1 and 6 GCMs for the A2 and A1B scenarios respectively (Table 1 and Fig. 2).

The confidence scores for the location of the regional hotspots ranged from 1 to 19 (out of 20 possible agreements; Table 1). The confidence in hotspot location was highest in the northern hemisphere; for example, north-east Canada, Sea of Okhotsk and Bering Sea. While the rate of warming differs between the A1B and A2 scenarios, our results show that hotspots are in similar locations regardless

Fig. 2 Overlap in occurrence of hotspots based on the predictions of six GCMs using the A2 (a) and A1B scenarios (b). The colour bar represents the number of GCMs with a hotspot at the pixel location. Note the higher level of agreement for the north Pacific and the lower level of agreement for the southern hemisphere



of the rate of warming (i.e. the warmest 10 % occurs in the same regions under both scenarios). However, the lower number of historical hotspots that were identified under the higher A1B scenario ($n = 16$) could be interpreted as more intense and widespread regional warming (i.e. larger hotspots).

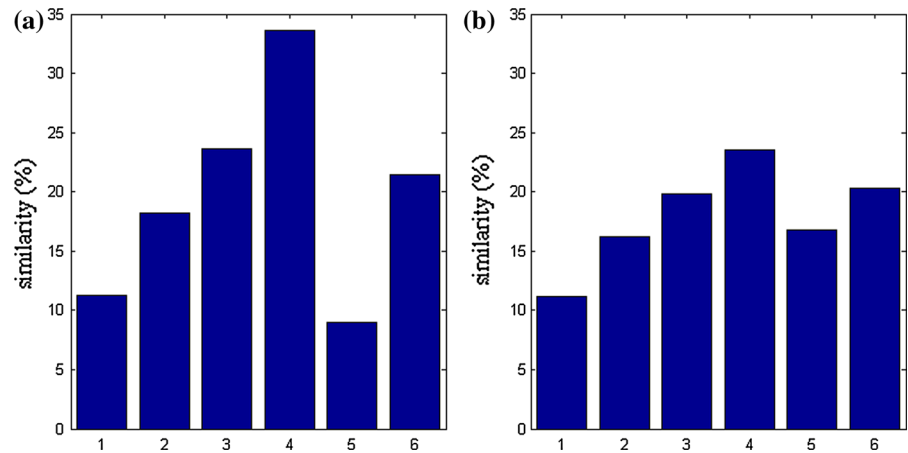
Learning from historical changes in biological response at hotspots can be useful for evaluating adaptation efforts, but particularly so if the pattern of warming is such that the historical hotspots persist into the future. Based on the quantitative analysis, the overlap between the historical and future hotspots for each GCM ranged from 9 to 34 % (Fig. 3). This persistence can also be seen in the qualitative analysis, where 21 of the 24 historical hotspots were also projected to occur into the future by at least one GCM (Table 1).

Discussion

The regional global warming ‘hotspots’ shown here, typified by above-average surface ocean temperature increases, provide a framework for early warning of

the response by natural systems to climate change. We identified 24 discrete regions that are experiencing ocean warming at a rate faster than 90 % of the rest of the oceans, and it is in these regions that many impacts of climate change on biology are being reported (see papers this volume). Our historical analysis produced similar trends in historical warming as reported by Hansen et al. (2006), but differs in that it is based on trends over the full period considered, rather than on a difference between a recent period (2001–2005) and a longer baseline period (1951–1980), and clearly identifies the fast warming regions. Other previous efforts to determine geographic variation in the rate of historical ocean warming have used pre-existing ocean regional boundaries, such as large marine ecosystems (LME), or coastal areas only, to determine the fastest warming areas (Sherman et al. 2009; Belkin 2009; Lima and Wethey 2012). Our historical analysis considers the global ocean, in contrast to Belkin 2009 and Sherman et al. 2009 who by considering LME’s, included only the coastal regions of the ocean (e.g. Exclusive Economic Zones). Although they are valuable analyses, using pre-existing boundaries such as the LMEs, and calculating a mean warming rate for

Fig. 3 The quantitative stability of hotspots for the six GCMs calculated as the areal overlap in hotspots between the period 1950–1999 and 2001–2050 for each GCM. **a** A2 scenario. **b** A1B scenario. Models from left to right in each *panel* are: 1 CSIRO mk3.5, 2 UKHadCM3, 3 MIROCmedres, 4 MRIcgm, 5 ECHAM5 and 6 UKHadGem1



each LME, means that regional variation in warming can be missed. The south-east Australian LME for example, includes both the fastest and slowest warming regions in Australia (Lough and Hobday 2011), such that this particular LME is rated with an intermediate rate of warming (Belkin 2009) that is not representative of the LME as a whole, or consistent with in situ observations e.g. south-east Australia (Ridgway 2007).

Projections to the year 2050 represent a time scale particularly relevant to adaptation efforts by marine resource users, policy makers and managers. For this period, the choice of emission scenarios is also less critical as much of the projected warming represents a “commitment” based on existing emission of greenhouse gases (IPCC 2007). While there is uncertainty in our future projections, there was high agreement for many regions, and for many of these, historical corroborating evidence of high rates of physical and biological change is available in published literature (e.g. papers in this volume, and see Poloczanska et al. 2013). Knowing where future hotspots are located is important in planning adaptation efforts, even if historical signals of impact have not yet been reported.

Many of the regions we identify here as hotspots are greatly valued regionally, and in some cases, globally. The Galapagos Islands, situated at the confluence of five ocean currents, have already experienced major biodiversity losses as a result of the synergistic impacts of changed oceanographic cycles, likely altered by climate change, and overfishing (Edgar et al. 2009). Darwin’s “cradle of evolution”, arguably the world’s most celebrated environmental treasure, looks set to continue being exposed to rapid warming.

Waters in south-eastern Australia are responsible for 50 % of Australia’s fisheries production (ABARES 2011), host a high level of endemic species and offer no coastal areas further south for species unable to cope with increasing water temperature. Forty five species, representing approximately 30 % of the inshore fish families occurring in the region, have exhibited major climate related distributional shifts in recent decades (Last et al. 2011). Range extensions linked to warming temperatures have also been recorded in barrens-forming sea urchins (Ling et al. 2009), and major declines in rock lobster recruitment have been linked to ocean warming (Pecl et al. 2009; Johnson et al. 2011). Waters around Alaska sustain the largest commercial fisheries (salmon, crab, halibut, pollock, cod and other groundfish) in the United States and support an unparalleled array of marine mammals and seabirds. Oceanographic changes linked to climate change have already dramatically reshaped the Bering Sea ecosystem (Mueter and Litzow 2008; Pfeiffer and Haynie 2012).

Traditionally, ecologists and fishery biologists have looked to the past to generate hypotheses of future species, ecosystem and fishery behavior, yet in today’s world past patterns may not be suitable predictors for the future. As we move towards no-analogue futures, the nature and pace of climate change in some respects erodes the value of historical information and we need to develop ways of capitalizing, as efficiently and rapidly as possible, on emerging information (Cochrane et al. 2009). Close scrutiny of these high-exposure, fast-changing regions may highlight metrics or approaches that are appropriate for monitoring climate change impacts in other marine ecosystems.

Additionally, as a function of the strength of the climate drivers, hotspots provide excellent foci for addressing major and complex challenges such as resolving the interaction between the synergistic stressors (e.g. climate change and fishing impacts) and validating species or ecosystem model projections against reality. An alternative viewpoint may argue that regions of high change should be left to their own devices, and we should focus our limited resources on regions that are undergoing less rapid change, and hence are potentially more resilient. However, Frusher et al. (2013) clearly demonstrate the value of intensive research focus within a rapidly warming region, identifying key challenges experienced in the development and implementation of adaptation options and suggesting constructive approaches for addressing these issues.

We considered the period 1950–1999 to locate historical hotspots, in part as we wanted to identify regions where biological change may have been observed, and this often requires long time series. Some additional regions known to have undergone considerable warming in more recent periods were not identified by our analysis. For example, we did not detect hotspots close to Antarctica (although these changes are linked to warming air temperatures e.g. Thomas et al. 2009) and in some regions of the Arctic (Reid et al. 2007). Other identified hotspots, such as the waters off south-east Australia, have multi-decadal in situ temperature records documenting warming at a much greater rate than the global average (Hill et al. 2008), and yet were only identified with medium confidence (score of 8/20). These differences may represent limitations inherent in the global climate models (Stock et al. 2011), or the period of time used, and so validating these hotspots with in situ data is an important next step. Thus, our analysis should be considered as a first step towards identifying the fastest warming marine regions globally with more data urgently required to resolve this issue with greater confidence.

The temperature-based approach outlined here could be extended to include other physical (e.g. pH or oxygenation), ecological (e.g. vulnerable species) or socio-economic (e.g. resource-dependency) data. For example, coral reefs are sensitive to only small changes in temperature, and when coupled with pH changes, small temperature increases may threaten their existence (Hoegh-Guldberg et al. 2007).

Ecosystem-specific analyses of multiple drivers may be needed to identify such regions, after which networking between researchers and the other stakeholders necessary to generate adaptation options is recommended. Additional layers of complexity include identifying regions where ecosystem services from the ocean are particularly important for supporting human populations, and measures of a regions' vulnerability, such as the level of resource dependency (Allison et al. 2009) could be used to identify these. However, the concept of identifying a suite of regions with climate change challenges in common, and networking to facilitate knowledge exchange as highlighted here, can link regions with a range of capacities to respond (e.g. developed and developing countries). Temperature itself could also be explored in more dimensions by identifying regions of greatest natural seasonal or interannual variability or scaling the rate of temperature change to the annual temperature range. For example, does the low annual temperature range at the tropics and poles mean that the same absolute temperature increases have proportionally greater impact in these more thermally stable regions (see Dillon et al. 2010), or do organisms from thermally unstable environments live closer to their thermal limits (Madeira et al. 2012)? Additionally, it may be worth exploring which global regions contain areas with very low rates of warming, and the likelihood of these persisting, as these may represent 'refuges' in an otherwise warming world.

Most of the hotspot areas were associated with the eastern and western boundary currents, particularly on the east and south-east Asian coasts. Potential changes in marine resource distribution or abundance are of particular concern in these densely populated tropical regions of high biodiversity where small-scale fishers constitute more than 90 % of the world's fishers and fish traders (Badjeck et al. 2010). Additionally, in many of these areas the fisheries catch potential has been predicted to decline by 40 % by 2055 (Cheung et al. 2009). Hotspot regions like the Angola Basin, adjacent to terrestrial areas that are also expected to face major declines in food crops (Allison et al. 2009), are particular cause for alarm in terms of food security. Marine natural resources such as fisheries provide significant social and economic benefits globally, and early warning of changes in resource quality and/or availability is required to minimize social tensions (e.g. increased poverty and changes in resource

allocation) and societal costs (e.g. income redistribution and government restructuring). Prior knowledge of how resources may alter will facilitate the development, application and evaluation of adaptation options for fisheries.

The role of funding for adaptation in middle and low income countries was central in negotiations of the UNFCCC leading up to Copenhagen, in Mexico (COP 16), and at discussions in Durban (COP 17); however, the development of the expertise base for adaptation and collaboration on a global scale is also critical. We need to facilitate the development of adaptation science and accelerated learning and move beyond the “simple” provision of accurate predictions of impending impacts (Hulme 2005). Developing a network of scientists, resource managers and policy makers working in global marine hotspots, where information is integrated and synthesized, contrasted and compared across locations provides us, globally, with critical learning opportunities to address the immediate and future challenges of climate change.

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