

# Global synchrony of an accelerating rise in sea surface temperature

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*The oceans have shown a recent rapid and accelerating rise in temperature with, given the close link between temperature and marine organisms, pronounced effects on ecosystems. Here we describe for the first time a globally synchronous pattern of pulsed short period (~1 year long) emanations of warm sea surface temperature anomalies from tropical seas towards the poles on the shelf/slope with an intensification of the warming after the 1976/1977, 1986/1987 and 1997/1998 El Niños. On the eastern margins of continents the anomalies propagate towards the poles in part by largely baroclinic boundary currents, reinforced by regional atmospheric warming. The processes contributing to the less continuous warm anomalies on western margins are linked to the transfer of warmth from adjacent western boundary currents. These climate induced events show a close parallelism with the timing of ecosystem changes in shelf seas, important for fisheries and ecosystem services, and melting of sea-ice.*

**Keywords:** sea surface temperature, principal component analysis, boundary currents, Atlantic Multidecadal Oscillation, El Niño, Atlantic Gyre Index, ecosystem synchrony, regime shift, sea-ice, earthquake

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## INTRODUCTION

There is unequivocal evidence that the world is warming rapidly and very high confidence that the warming is due to human forcing from greenhouse gas (GHG) emissions, land use changes and factors linked to economic development and population growth (Bindoff *et al.*, 2007; Hansen *et al.*, 2010). Because water can take up more than 4000 times as much heat as the same volume of air, the oceans covering more than 71% of the surface of the Earth are the major heat reservoir of our planet and play a crucial role in damping down the impact of global warming. Recently the oceans have shown a rapid and accelerating increase in temperature (Belkin, 2009; Levitus *et al.*, 2009a; Sherman *et al.*, 2009; Purkey & Johnson, 2010). Resulting changes in heat structure are profoundly affecting regional climate variability, the cryosphere, sea level and the hydrodynamics, biogeochemistry, ecosystems and living marine resources of the oceans and through feedback mechanisms exacerbate/ameliorate the effects of climate change (Brander, 2007; Beaugrand, 2009; Reid *et al.*, 2009). Biological and biogeochemical processes, including the development, reproduction, occurrence, behaviour and phenology of marine organisms, at cellular to ecosystem scales, are strongly governed by temperature (Beaugrand, 2009). Our study was prompted by the observation of a coincidence between the timing of biogeographical/phenological shifts and abrupt changes in plankton, fish and other marine organisms from different regions of the world (Perry *et al.*, 2004; Alheit & Bakun, 2010) and increasing sea surface

temperatures (SST). To investigate this apparent world-wide synchrony we analysed SST variability for January 1960 to December 2008 from the Extended Reconstructed Sea Surface Temperature, version 3 (ERSST\_V3) dataset, both globally and for the shelf/slope waters of 10 regions. We selected the shelf/slope for its importance to global fisheries, as the location of many observed changes to date and because it is likely to be strongly impacted in the future.

## MATERIALS AND METHODS

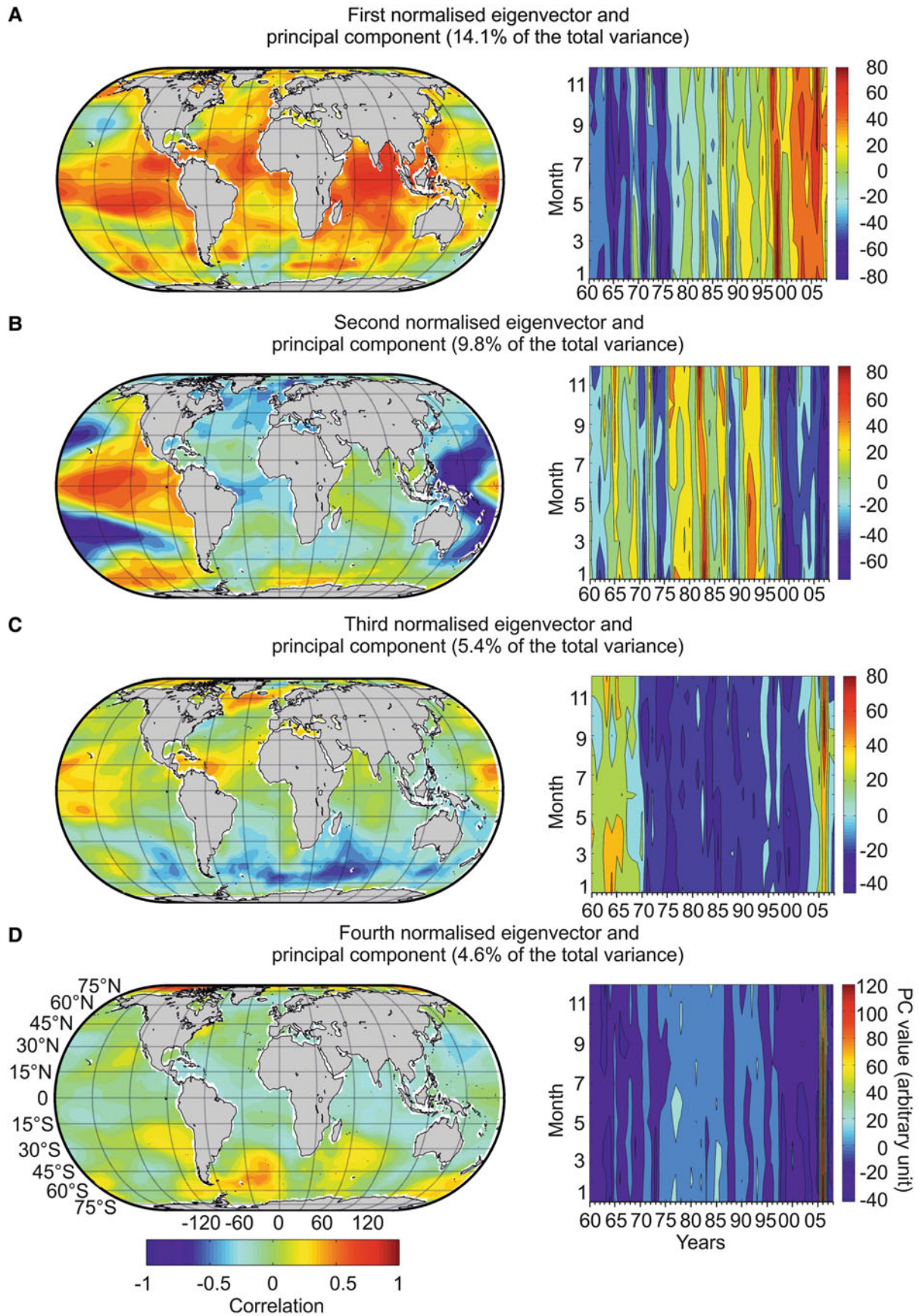
### Data

Sea surface temperature data were obtained from the Extended Reconstructed Sea Surface Temperature, version 3 (ERSST\_V3) dataset. The data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (<http://www.esrl.noaa.gov/psd/>). The ERSST\_V3 dataset is derived from a reanalysis on a  $2^\circ \times 2^\circ$  spatial grid that is based on the most recently available International Comprehensive Ocean–Atmosphere Data Set (ICOADS) SST data and has used improved statistical methods to produce a stable monthly reconstruction based on sparse data (Smith *et al.*, 2008). Bathymetry data were obtained from the global ocean bathymetry chart ( $0.1^\circ$  longitude  $\times$   $0.1^\circ$  latitude) (Smith & Sandwell, 1997). This dataset is one of the most complete high-resolution compilations of sea floor topography currently available.

### Data analyses

First we addressed the spatial and temporal variability of global SST by applying a principal component analysis

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**Fig. 1.** Principal component analysis of global sea surface temperature (January 1960–December 2008): (A) first normalised eigenvector (left) and associated principal component (right); (B) second normalised eigenvector (left) and associated principal component (right); (C) third normalised eigenvector (left) and associated principal component (right); (D) fourth normalised eigenvector (left) and associated principal component (right); normalised eigenvectors reveal the correlation of sea surface temperature with the corresponding principal component for each geographical cell.



(PCA) (Beaugrand *et al.*, 2002) to the ERSST dataset (Analysis 1; Figure 1). Prior to the analysis, data were transformed as monthly anomalies by subtracting the long-term average of the corresponding month for each geographical cell of 2° latitude × 2° longitude. Eigenvectors were normalised so that they represented the spatial correlation with the corresponding principal components.

For ‘Analysis 2’ data from ERSST\_V3 SST were interpolated on a spatial grid of 0.1° longitude × 0.1° latitude to correspond to the bathymetric grid. We then divided the marine hydrosphere into 10 regions shallower than 3500 m or 2000 m. The outer depth boundary depended on the topographic features of the areas, with the aim to

concentrate mainly on continental shelves and the adjacent shelf-edge (non-oceanic area). Maps of the regions (Figure 2) are contoured to show a division into shelf and deeper slope waters. After this data preparation SST anomalies were calculated for each latitudinal band of 0.1° of latitude. Results are presented as contour diagrams showing the latitudinal changes in SST as a function of year for the period 1960–2008.

Third (Analysis 3), to summarise the long-term changes derived from Analysis 2, we latitudinally averaged the data for the 10 shelf/slope regions. We then performed a second PCA to examine the relationships between the components and large-scale hydro-climatological indices (see text below). Probability was corrected to account for temporal autocorrelation.

### Hydro-climatological indices

Fourteen large-scale climatological indices, in addition to the 4 PCAs of Analysis 1 (Table 1) were used to examine potential relationships between sea surface temperature changes and climatological processes:

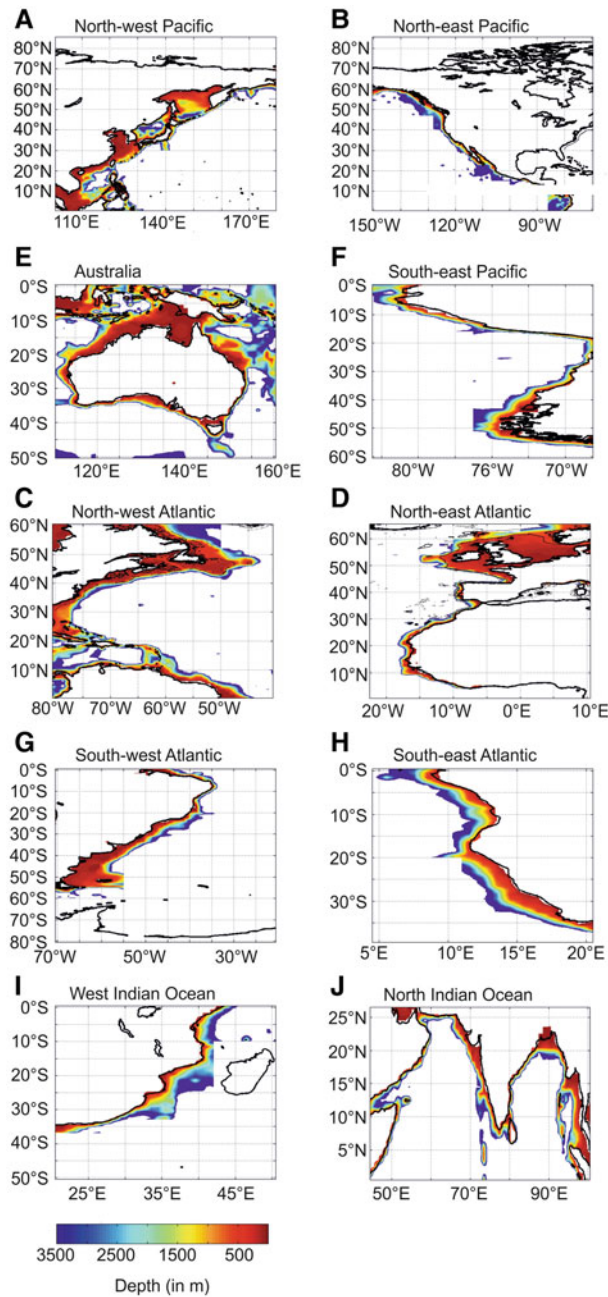
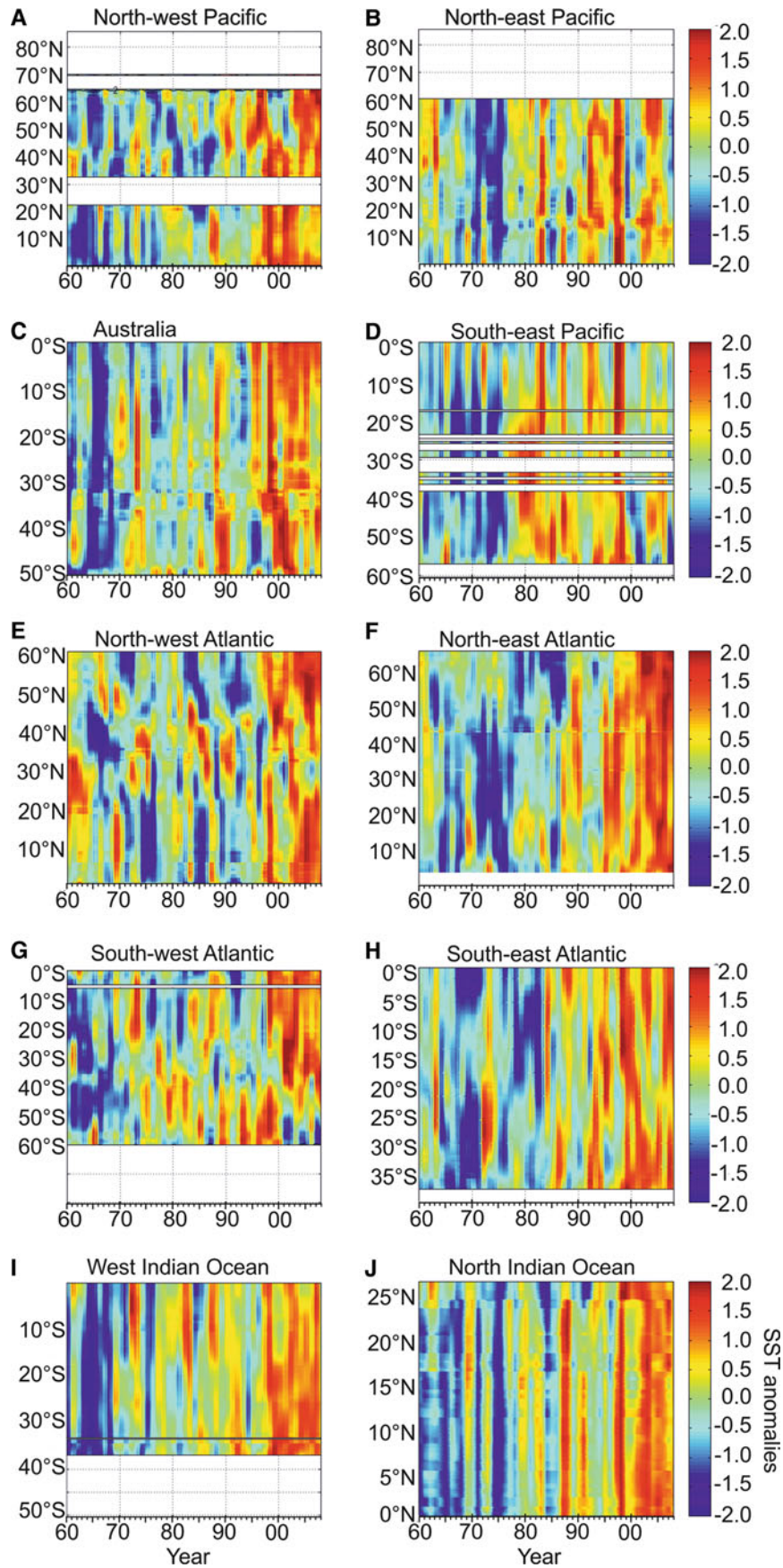


Fig. 2. Maps of the 10 geographical areas for which long-term changes in latitudinal sea surface temperature anomalies were calculated, showing the bathymetry of the shelf and slope to ~3000 m.

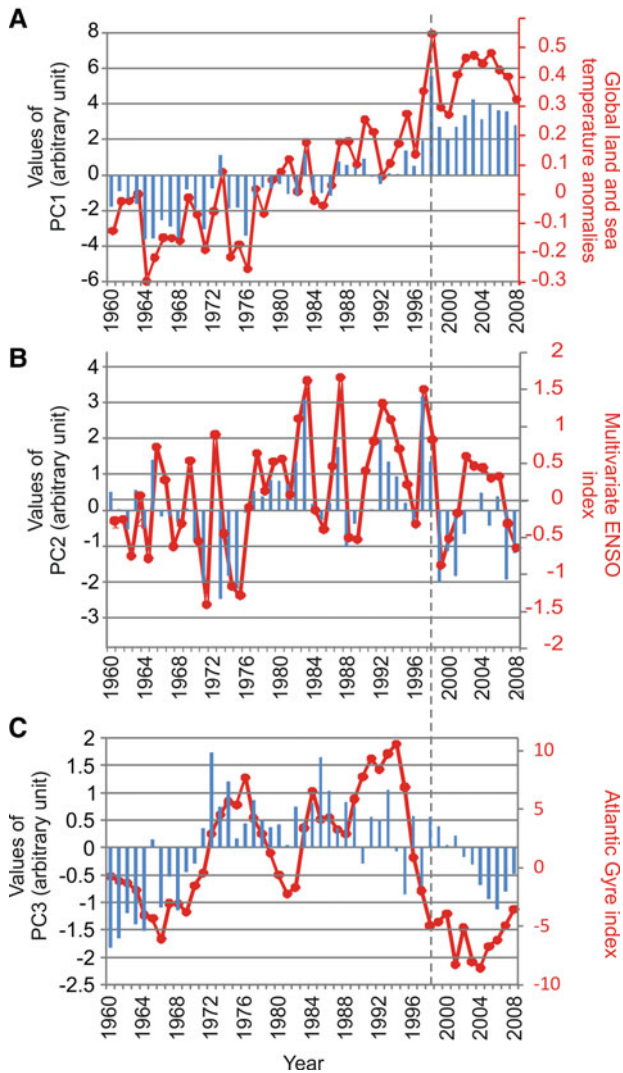
**Table 1.** Correlations between the first three principal components calculated from a principal component analysis performed on latitudinal sea surface temperature changes over the continental shelf and shelf-edge of 10 geographical regions of the world (Figures 1 & 3) and a selection of large-scale hydro-climatological indices (1960–2008) (see Figure 4). Bold numbers indicate significant correlations at  $P < 0.10$  (\*),  $P < 0.01$ (\*\*) and  $P < 0.001$ (\*\*\*). Probabilities were corrected for temporal autocorrelation. PC1–PC3, first to third principal components; HadSST2, Hadley sea surface temperature; CRUTEM3, Hadley land surface temperature anomalies; HadCRUT3, Hadley land and sea combined temperature anomalies; PC1 to PC4 SST GLO, first to fourth principal components from an analysis of global sea surface temperature (see Figure 2); SOI Darwin, Southern Oscillation Index based on sea level pressure in Darwin; SOI Tahiti, Southern Oscillation Index based on sea level pressure in Tahiti; MEI, multivariate ENSO Index; PDO, Pacific Decadal Oscillation; NPGO, North Pacific Gyre Oscillation; SASMI, South Asian Summer Monsoon Index; NAO, winter (December to March) North Atlantic Oscillation Index; AO, Arctic Oscillation Index; AGI, Atlantic Gyre Index; AMO, Atlantic Multidecadal Oscillation; AAO, Antarctic Oscillation Index (1979–2008).

	PC 1	PC 2	PC 3
HadSST2	<b>0.97**</b>	0.08	-0.05
CRUTEM3	<b>0.95**</b>	0.02	-0.11
HadCRUT3	<b>0.96**</b>	0.05	-0.07
PC1 SST GLO	<b>0.94**</b>	0.22	0.01
PC2 SST GLO	-0.37	<b>0.79**</b>	0.25
PC3 SST GLO	-0.11	0.13	<b>-0.77***</b>
PC4 SST GLO	-0.11	0.19	0.20
SOI Darwin	0.32	<b>0.77***</b>	0.00
SOI Tahiti	0.06	<b>-0.67***</b>	-0.16
MEI	0.30	<b>0.84***</b>	0.15
PDO	0.27	<b>0.68***</b>	0.25
NPGO	0.23	<b>-0.47***</b>	-0.03
SASMI	0.06	-0.18	<b>-0.54***</b>
NAO	0.27	-0.04	0.24
AO	0.18	-0.16	0.19
AGI	-0.32	0.16	<b>0.51*</b>
AMO	<b>0.73*</b>	0.05	<b>-0.59*</b>
AAO	0.11	-0.08	0.11



**Fig. 3.** Long-term changes in latitudinal sea surface temperature anomalies for the period 1960–2008 over continental oceanic areas shallower than  $\sim 3000$  m: (A) north-west Pacific; (B) north-east Pacific; (C) Australia; (D) south-east Pacific; (E) north-west Atlantic; (F) north-east Atlantic; (G) south-west Atlantic; (H) south-east Atlantic; (I) west Indian Ocean; (J) north Indian Ocean.





**Fig. 4.** Principal component analysis of long-term changes in latitudinal sea surface temperature anomalies over continental oceanic areas shallower than  $\sim 3000$  m (1960–2008): (A) long-term changes in the first principal component (in blue; 57.2% of the total variance) with respect to global land and sea temperature anomalies (in red); (B) long-term changes in the second principal component (in blue; 15.7% of the total variance) against the multivariate ENSO Index (in red); (C) long-term changes in the third principal component (in blue; 7.4% of the total variance) in relation to the Atlantic Gyre Index (in red). The explanatory variables were selected on the basis of the correlation analyses (see Table 1).

1–3. Global sea (HadSST2: Hadley sea surface temperature), land (CRUTEM3: Hadley land surface temperature anomalies), land and sea combined (HadCRUT3: Hadley land and sea combined temperature anomalies) surface temperatures were used. These data were obtained from the Hadley Centre ([www.cru.uea.ac.uk](http://www.cru.uea.ac.uk)).

4–6. Two indices of the Southern Oscillation were used (SOI Darwin and SOI Tahiti) respectively calculated from sea level pressure measured at Darwin and Tahiti. We also utilised the Multivariate ENSO Index (MEI). MEI is calculated from six variables measured by the programme: International Comprehensive Ocean–Atmosphere Data Set (ICOADS). The six variables are sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface air temperature and the

total cloudiness fraction of the sky (Wolter & Timlin, 1998).

7. The Pacific Decadal Oscillation (PDO) Index is considered to be “a long-lived El Niño-like pattern of Pacific climate variability”. The index is defined as the first principal component of North Pacific monthly SST variability north of  $20^{\circ}\text{N}$  for the period 1900–1993. Abrupt ecosystem shifts in the north-east Pacific have been related to the PDO Index (Hare & Mantua, 2000).

8. The North Pacific Gyre Oscillation (NPGO) is a climatic pattern represented by the second principal component of a PCA of sea surface height in the north-east Pacific Ocean (Di Lorenzo *et al.*, 2008) and has been correlated with temporal changes in salinity, nutrients and chlorophyll as far apart as the California Current and the Gulf of Alaska.

9. The South Asian Summer Monsoon Index (SASMI) (Li & Zeng, 2005) is defined as the intensity of the normalised seasonality of the wind field (dynamical normalised seasonality (DNS)) at the pressure level 850 hPa averaged seasonally (June to September) in the spatial domain corresponding to South Asia ( $5^{\circ}$ – $22.5^{\circ}\text{N}$   $35^{\circ}$ – $97.5^{\circ}\text{E}$ ). The index reflects both seasonal and year-to-year variability in monsoon systems for the whole world and is available from: <http://www.lasg.ac.cn/staff/ljp/data-monsoon/SASMI.htm>.

10. The North Atlantic Oscillation (NAO) is a basin scale alternation of atmospheric mass over the North Atlantic between high pressure centred on the subtropical Atlantic and low pressure around Iceland. This phenomenon, detected in all months of the year, is particularly strong in winter and explains about 37% of the variability in monthly sea level pressure (SLP) from December to February (Marshall *et al.*, 2001). The winter NAO Index used in this study is based on a PCA of SLP over the North Atlantic sector for months from December to March (Hurrell *et al.*, 2001); <http://www.cgd.ucar.edu/cas/jhurrell/>.

11–12. Both the Arctic Oscillation (AO) and the Antarctic Oscillation (AAO; 1979–2008) indices were downloaded from the Climate Prediction Center (<http://www.cpc.noaa.gov/>). These indices are constructed by projecting the daily 1000 mb height anomalies poleward of  $20^{\circ}\text{N}$  (AO) or southward of  $20^{\circ}\text{S}$  (AAO) onto the leading pattern of the AO and AAO.

13. We used the North Atlantic Subarctic Gyre Index to evaluate whether changes in SST are related to the strength of the subarctic gyre circulation. The index is the first principal component of a PCA performed on sea surface height in the North Atlantic Ocean (Häkkinen & Rhines, 2004; Hátún *et al.*, 2005).

14. The Atlantic Multidecadal Oscillation (AMO) is an index of long-term (50 to 80 years) ocean/atmosphere variability in the range of  $0.4^{\circ}\text{C}$  in many oceanic regions (Enfield *et al.*, 2001). A simple index can be constructed by calculating a running mean of Atlantic (detrended) sea surface temperature anomalies north of the equator. We used an index constructed from the Extended Reconstruction SST (ERSST) data averaged for the area  $25$ – $60^{\circ}\text{N}$  and  $7$ – $75^{\circ}\text{W}$ , minus a regression of global mean temperature (NCDC). This index was downloaded from the website <http://climexp.knmi.nl/>. The AMO has a large influence on sea surface temperature changes in the Atlantic as well as globally (Enfield *et al.*, 2001; Keenlyside *et al.*, 2008).

## RESULTS

### Analysis of global and shelf/slope patterns of SST

Mapping of the first normalised eigenvector (EV<sub>1</sub>) of global SST from the first PCA (Analysis 1) revealed areas where long-term changes were most prominent (Figure 1A). High positive values were concentrated in the tropics and especially the Indian Ocean with extratropical extensions to north and south in all oceans. The main regions with negative EVs are located in the North and South Pacific. Increasing values of the first component reflect rising temperature, that is not continuous, but increases in steps ~1977, 1987 and 1997 with the super El Niño of 1997/1998 standing out, followed by an even stronger peak in 2006/2007 at the time of an El Niño Modoki (Yeh *et al.*, 2009). The second normalised EV reflected a pattern of SST with positive correlations to the second PC over much of the central equatorial Pacific, in many cases reflecting El Niño years, and a V shaped area of negative correlations in the western Pacific (Figure 1B). The corresponding PC identified three periods: (1) lower positive anomalies in the beginning; (2) an increase that follows an abrupt change in 1976 (Guilderson & Schrag, 1998; Hare & Mantua, 2000); and (3) another sharp change after the especially strong El Niño in 1997/1998 (Takayabu *et al.*, 1999) to negative anomalies, reflecting a cooler eastern Pacific. El Niño years are evident in this last period, but with a changed sign to weak negative anomalies. For EV<sub>3</sub> (Figure 1C) three small positive areas are evident, two in the Atlantic reflecting the pattern of the North Atlantic Oscillation (NAO) tripole (Marshall *et al.*, 2001) and the North Atlantic Gyre Index (Hátún *et al.*, 2009) and one in the western tropical Pacific, with an extensive area of negative EVs in the Southern Ocean. The corresponding PC shows a change after the 1970s to negative values with an outlier of positive values throughout 2006. Both EV<sub>3</sub> and EV<sub>4</sub> reflect polar influences with, in the latter case, positive values in the Arctic (Figure 1D). The changes seen in the corresponding PC<sub>4</sub> are dominated by positive anomalies in 2006 that are possibly a precursor to the record reduction of Arctic sea-ice in the following year, 2007. In 2006 an exceptional SST anomaly from the North Atlantic resulted in the warmest year ever recorded in the Barents Sea with a mean SST that was 3.71 standard deviations above the mean in the West Spitzbergen Current and Fram Strait (Hughes *et al.*, 2010). In terms of seasonal evolution many of the anomalies start to develop in the late summer, increase in intensity from about August into the following year to decline around June.

As the second step in our analysis latitude-by-year anomaly plots of SST were produced for 10 shelf/slope regions (Figure 2). Annual mean SST anomalies were calculated and contoured by time and latitude from the equator (Figure 3). The diagrams show clear alternating periods of warm and cold finger-like anomalies extending from the tropics with for most a remarkably constant timing and persistence until ~30°N and 30°S from where some anomalies show a progressive delay in their poleward extent. In a temporal context the anomalies form and extend over distances of 100s of km relatively rapidly at monthly scales.

There is a general global synchrony in the patterns, with a progression from cooler anomalies at the start of the period to

strongly positive anomalies over the last decade, except for the eastern Pacific regions. On the eastern margins of oceans the anomalies are semi-continuous all the way from the equator towards the poles, whereas on the other side of ocean basins they are less continuous and show a different timing in the anomaly patterns between the equator and poles that reflects the proximity of adjacent warm and cold western boundary currents.

The influence of El Niño years is evident in Figure 3 and especially in the south-east Pacific, which is used as a reference for other regions. In this region, following a cold period in the early 1970s, fingers of warm anomalies extending from the equator coincide with El Niño years, with an especially pronounced and southerly persistent anomaly in 1997/1998. In the south-east and north-east Pacific and north and west Indian Oceans positive anomalies are ~centred on 1997/1998. In the north-west, south-west and south-east Atlantic and Australia the timing of the late 1990s positive anomaly is later, indicating that there is a lag in the effects of El Niño or a delay in the transport of the heat.

To further investigate mechanisms behind the changes in SST anomalies for shelf/slope seas, we averaged by latitude temporal changes in SST and performed a PCA on a table of 49 years × 10 shelf-slope regions (Analysis 3). The first three components were correlated with a number of large-scale hydro-climatological indices (Table 1; Figure 4). The patterns of change reflected in the first PC are significantly correlated with global measures of sea, air and combined land and SST (Figure 4) showing that the changes in coastal/shelf slope waters are representative of the whole globe and reflect warming from the ocean and the adjacent land. Only the Atlantic Multidecadal Oscillation (AMO) is significantly correlated with the first PC, supporting the proposal that the Atlantic Ocean is an important driver of multi-decadal variability on a global scale (Sutton & Hodson, 2007). The second PC reflects a Pacific influence acting through El Niño as seen in the significant correlation with the multivariate ENSO Index (Figure 4), reinforced by correlations with the Southern Oscillation Index, the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation (Table 1). The third PC is significantly correlated with the Atlantic Gyre Index (Figure 4) that explains recent ecosystem changes in the North Atlantic due to warming from the subtropics (Hátún *et al.*, 2009). Part of the variability is also correlated negatively with the monsoon index and AMO (Table 1), the latter, with respect to sea-ice reduction in the Arctic, reinforced by an observed correlation (Levitus *et al.*, 2009b) between SST and the AMO in the Barents Sea.

### Commentary on the latitude by year anomaly plots of SST

The finger shaped anomalies in the regional plots (Figure 3) show evidence at times for discontinuities where the extension of the anomalies becomes blurred and less clear. Differences in the width of the shelf/slope, its orientation, geography or the proportion of slope to shelf within a region contribute. There is also considerable variation in these properties between regions. Averaging by latitude for example may have contributed to some of the variability and contrasts between the results for the north-west Pacific, which is

bounded by a chain of islands with two enclosed shelf seas, and the narrow shelf/slope of the north-east Pacific. The wide shelves in the northern north-east Atlantic and to the north of Australia and regions of upwelling explain some discontinuities in the patterns. Adjacent regions to either side of the equator, e.g. the north-east and south-east Pacific (Figure 3B, D) show mirror image patterns of anomalies in the tropics.

In the north-west Pacific (Figure 3A) there is a meridional discontinuity at  $\sim 45^{\circ}\text{N}$  with a different pattern of change below and above; to the south the pattern more closely reflects that for Australia (Figure 3C) while to the north a different pattern likely reflects localised conditions in the Sea of Okhotsk. Meridional discontinuities in the north-east Pacific (Figure 3B) are evident at  $\sim 15^{\circ}$ – $20^{\circ}\text{N}$  (Gulf of California) and  $47^{\circ}\text{N}$ . The Gulf of California acts as a barrier to the movement of coastally trapped waves that propagate temperature signals (Strub & James, 2002a). Around Australia (Figure 3C) there is a meridional discontinuity at  $\sim 33$  to  $35^{\circ}\text{S}$  with different SST anomaly patterns to north and south. To the south the pattern becomes more diffuse with an indication that some of the pulses are delayed towards the pole. The north-west Atlantic (Figure 3E) can be divided into three intervals marked by meridional discontinuities; a tropical region approximately south of Cuba and to the north and south of Cape Hatteras. The pattern of anomalies in the central area to the south of Cape Hatteras appears in general to be out of phase with the areas to north and south. A meridional discontinuity is evident in the north-east Atlantic at  $\sim 50^{\circ}\text{N}$  coinciding with the entrance to the Norwegian Sea (Figure 3F). In the tropics the pattern of anomalies in the south-west Atlantic (Figure 3G) is largely a mirror image of that seen for all the other Atlantic areas; a meridional discontinuity is evident at  $\sim 23^{\circ}\text{S}$ . Until the last decade the finger-like polewards directed SST anomalies are less persistent than for other areas. In the south-east Atlantic (Figure 3H) the southern part closely coincides with the pattern in the west Indian Ocean (Figure 3I) at a similar latitude, while further north, reflecting the pattern seen in other adjacent Atlantic areas. Meridional discontinuities are evident in the plot for the west Indian Ocean at  $\sim 18^{\circ}\text{S}$  and  $35^{\circ}\text{S}$  (Figure 3I) and in the north Indian Ocean at  $\sim 25^{\circ}\text{N}$  (Figure 3J).

## DISCUSSION

### Global changes in SST

The results of Analysis 1 confirm that warming is propagating in the oceans from the tropics/subtropics and that El Niño is actively implicated, although the extent to which the latter is influenced by global warming is debated at present (Trenberth & Hoar, 1997; Yeh *et al.*, 2009; Power & Kociuba, 2011; Wolter & Timlin, 2011). One consequence is that the tropics and the subtropical gyres are expanding with important impacts on biology (Polovina *et al.*, 2008; Seidel *et al.*, 2008).

Our findings on global SST changes for the period 1960 to 2008 are consistent with earlier global and ocean scale studies (e.g. Mann *et al.*, 1998; Trenberth *et al.*, 2007), although the patterns we have discovered are clearer because of access to a larger and much improved global dataset. The first

eigenvector of our study closely corresponds with the pattern of the first empirical orthogonal function (EOF) seen in an earlier 1998 analysis (Mann *et al.*, 1998). This latter study however, used a much more limited SST dataset with large sampling gaps in many ocean areas. There is some similarity also in the pattern of their EOF2, but little for subsequent EOFs, which is likely because of the limited data coverage. The V shaped pattern of Eigenvector 2 (EV2) for the Pacific in our study (Figure 1) was shown for a shorter period in a comparative chlorophyll to temperature study, which was also correlated with the PDO (Martinez *et al.*, 2009), and is most similar to the SST anomaly pattern for the central Pacific (Modoki) El Niño (Yeh *et al.*, 2009) that is also reflected in patterns of sea level change (Behera & Yamagata, 2010). This pattern (EV2) is also similar to the first EOF of Deser *et al.* (2010), a study that is based on SST changes from 1900 To 2008. It is possible that their EOF1 evolved as the main EOF pattern over this long period as it was not dominated by the rapid global warming of the last few decades.

### Changes in SST along continental margins

The processes behind the SST anomaly patterns shown by Analysis 2 and the extent to which they are caused by oceanic advection, changes in the circulation of ocean gyres, atmospheric forcing or different combinations of these factors is still unclear. The boundary flows of the oceans have different characteristics on the eastern (poleward slope currents, boundary waves and upwelling) and western (major ocean currents) margins of ocean basins.

On the eastern margins of oceans strong candidates for the production of the anomalies in Figure 3 are poleward flowing eastern boundary shelf/slope currents (Neshyba *et al.*, 1989). Strong advective pulses of warm sea water along the shelf/slope at intraseasonal to interannual intervals are well documented from all the oceans. These largely baroclinic density driven currents follow the topography of the shelf edge and are typically  $\sim 50$  to  $100\text{ km}$  wide with a subsurface maximal flow at 50 to 400 m depth. Substantial volumes of water may be carried by these currents with for example poleward transport as high as  $5.3\text{ Sv}$  in a section off Oregon with average current speeds of  $23\text{ cm s}^{-1}$  and northerly movement of sea level height anomalies of 300 miles in 1 month (Kosro, 2002). Over large sections of coast the currents flow counter to equatorwards directed winds. It is clear however, that in some cases oceanic advection of pulsed warm anomalies are the product of distant atmospheric wind forcing, especially in equatorial regions with propagation by Kelvin waves that move poleward as coastally trapped waves after reaching the shelf edge. Local atmospheric and topographic factors may reinforce or block/delay propagation of warm pulses and the pulses may acquire additional heat from adjacent ocean gyres and the atmosphere as they progress poleward (Pingree & Le Cann, 1989; Kessler, 2006). It is assumed that negative anomalies reflect cooler conditions in the tropics, but this is not clear. In the north-east Pacific there is some evidence that negative anomalies may be associated with a reversal of the normal pattern with the propagation of cold subarctic water to the south (Kosro, 2003) and the current may also reverse off north-west Europe (Pingree, 2002).

The main distribution of heat around the world by the oceans takes place in the wind driven gyre circulations with



the subtropical gyres playing a key role. The western boundary currents of these gyres are warm, deep and fast flowing, in part along the shelf slope. While the circulation of the adjacent shelves is primarily driven by regional winds, tides and thermohaline forcing these boundary currents have a strong influence on their hydrography and thus SST through a wide variety of processes (Brink, 1998). Transport of heat by the wind driven western boundary currents contributes to the production of warm/cold anomalies on the shelf/slopes of adjacent continents as is confirmed by the close approximation between the SST patterns of offshore warm and cold gyre currents and that of adjacent shelves in satellite imagery. There is a considerable between ocean, and along shore variability in deep-sea forcing of western boundary shelves depending on topography, shelf width, obstructions, variable meandering etc, with strong advection onto the narrow shelves of the tropics by the zonal equatorial currents that feed the western boundary currents (Loder *et al.*, 1998; Lohrenz & Castro, 2004). Some regional examples of poleward flowing currents at the eastern and western margins of oceans basins that may have contributed to the SST anomalies in Figure 3 are summarised in the next section.

Reorganisation of basin-wide SST patterns due to the expansion or contraction of gyre circulations are a further contributory factor to the anomaly patterns. In the North Atlantic, for example, these alternating modes have been related to the changing states of the NAO (Pingree, 2002). When the NAO is in a high positive state, westerly winds, ocean scale wind stress curl and the Atlantic circulation are stronger and in the subtropical gyre warmer water is pulled into the centre of the gyre from the sides at the surface so that the waters closer to the continental shelves at both sides of the Atlantic become colder and the altimetry of both the shelf and the adjacent ocean are depressed. In the reverse situation of a low negative NAO, the centre of the gyre becomes shallower and colder as the wind curl reduces, surface waters flow from the centre outwards and contribute to a warming of the western and eastern edges of the basin with a noticeable rise in altimetry (Leterme & Pingree, 2007). In the eastern North Atlantic this water presses against the slope and leads in NAO negative years to an enhanced flow in the shelf/slope current (Pingree, 2002), with on the other side of the basin a more southerly penetration of Labrador Subarctic Slope Water (Greene & Pershing, 2003). Subsequent to the extremely low winter NAO of 1995/1996 the subpolar gyre in the North Atlantic contracted and allowed a northerly penetration of subtropical water and species that has further reinforced the signal propagated by the shelf/slope current in the north-east Atlantic (Figure 3F) (Hátún *et al.*, 2005, 2009).

Changes in the heat transfer between oceans, e.g. between the Pacific and Indian Oceans via the Indonesian Throughflow and between the Indian and Atlantic Oceans may also have contributed to the anomaly patterns. For example, the presence of a lag in the timing of SST anomalies between the Indian and south-east Atlantic Oceans supports an enhanced transport of warm water around the Cape of Good Hope in positive anomaly years and is reinforced by observations of a substantial increase in the leakage of warm water from the Indian to the Atlantic Oceans via the Agulhas Current (Rouault *et al.*, 2009; Beal *et al.*, 2011).

## Poleward flowing boundary currents

In the north-east Atlantic there have been a number of descriptions of pulsed northerly movement in the largely barotropic shelf/slope current, ranging from off Iberia (Garcia-Soto *et al.*, 2002; Peliz *et al.*, 2005), to the edge of the Celtic Sea (Pingree *et al.*, 1999), to the Rockall Trough (Reid *et al.*, 2001b; Holliday, 2003; Holliday *et al.*, 2008) and the Norwegian Sea (Holliday *et al.*, 2008). Eddy formation, especially 'slope water oceanic eddies' (swoddies) at abrupt changes in topography, are associated with the currents (Garcia-Soto *et al.*, 2002). Pulses of warm water off Iberia were associated with intense poleward flows in 1996 to 1998 and 2001 to 2002 (Peliz *et al.*, 2005) and the same was the case in the Rockall Trough in 1998 (Holliday, 2003). The warm currents may be seasonally reinforced. Off Iberia for example, where the current is strongest near Christmas and New Year and termed 'Navidad', it may contribute the equivalent of an extra month of summer heating to the slope region to the north (Garcia-Soto *et al.*, 2002).

El Niño events start in the western Pacific with westerly wind anomalies generating downwelling Kelvin waves that deepen the eastern thermocline and pump warm equatorial water to the east by zonal advection, which then spreads polewards to north and south when reaching the shelf in a narrow band along the coast of the Americas (Kessler, 2006). The warming is independent of local winds off the coast and is an example of remote forcing of warming by distant winds. The eastward advection spans the equator with a strengthening of the North Equatorial Counter Current as the upward bulge of the westward flowing South Equatorial Current is depressed by a flattened and deepening thermocline. In the east cool upwelling is cut off and local surface heat fluxes reinforce the warming. The poleward flows have been observed as pulses at seasonal to annual scales that can extend all the way to Oregon (Kosro, 2002), Alaska (Strub & James, 2002b; Stabeno *et al.*, 2009) and Chile (Hormazabal *et al.*, 2002) and can carry tropical water as far as the Gulf of California (Kessler, 2006). Opposing regional winds may reverse or delay the propagations and coastal topography influences the relative speed of transport of the propagating signal to north and south of the equator (Strub & James, 2002a). Off Vancouver Island, boreal and southerly plankton have been shown to alternate between warm temperature conditions and poleward transport anomalies and the reverse conditions (Mackas *et al.*, 2001) that are associated with the shelf slope (Mackas *et al.*, 2007). Further south off Oregon, enhanced northward advection, an associated depressed pycnocline and higher than normal steric height, and subsurface temperatures at ~100 m are more pronounced in El Niño years than the effects associated with the opposite southerly transport in La Niña years (Smith *et al.*, 2001). The contrast between the stronger El Niño and weaker La Niña impacts off Oregon in the 1980/1990s compared to the 1960/1970s was attributed to modulation by large scale interdecadal variability in the North Pacific.

In the equatorial Atlantic a similar sequence of events to the Pacific is believed to contribute to the formation of Benguela El Niños, which have a different timing to their Pacific counterparts (Gammelsrød *et al.*, 1998; Florenchie *et al.*, 2003). When trade winds that have piled up water at the western side of the basin relax a Kelvin wave is thought to be generated and propagates eastwards advecting warm



water towards Africa, which splits at the shelf and moves poleward as coastally trapped waves towards the poles. In the northern hemisphere this current only penetrates to  $\sim 5^{\circ}\text{N}$  where it is deflected offshore back toward South America because of the sharp change in direction of the African coastline. Other processes involved with the subtropical gyre and atmospheric forcing maintain northerly flow of warm anomalies at the eastern margin to the north of this latitude.

Both observations and modelling demonstrate that the western boundary Agulhas Current has shown a substantial increase in transport south of Madagascar and in the leakage of warm and salty water from the Indian Ocean to the Atlantic Ocean since the 1980s (Rouault *et al.*, 2009). The change is a response to enhanced warming in the Indian Ocean that is likely linked to a reduction in the shallow overturning circulation (Lee, 2004) and especially an increase in the wind stress curl in the east associated with a poleward shift in the westerly winds of the southern hemisphere (Rouault *et al.*, 2009).

In the Indian Ocean eastern boundary currents have been described from the Bay of Bengal (Suryanarayana *et al.*, 1993) and as the Leeuwin Current on the western margin of Australia (see below).

Uniquely for a continent, warm boundary currents flow polewards on either side of Australia as the Leeuwin and East Australian Currents. Changes in the strength of the Leeuwin Current are linked to El Niño with evidence from seabirds for a southward penetration of warmer water (Poloczanska *et al.*, 2007). In contrast the East Australian Current has shown a marked southerly extension of  $\sim 350$  km since 1944 and warming over the past few decades with an augmented pulse of warm subtropical waters in the summer (Ridgway, 2007).

A recent study of the western boundary Brazil Current (Matano *et al.*, 2010) has shown that the offshore characteristics of this current dominate the also southward flowing circulation of the shelf via bottom boundary layer interaction between the two systems, reinforced by intermittent cross shelf transport of eddies and meanders. The same applies to the cold Malvinas Current to the south and may explain the out-of-phase relationship of the SST anomalies for the south-west Atlantic at  $\sim 40^{\circ}\text{S}$  (Figure 3G). Reflecting adjacent subtropical and subpolar gyres, all eastern compared to western continental shelves, other than for the tropical/subtropical west Indian Ocean region (Figure 3I), show a reduced extension of positive SST anomalies from the tropics towards the poles.

## Ecosystem synchrony

Synchronous decadal changes in marine populations and ecosystems, within and between regions, and at an ocean basin scale are well documented (Perry *et al.*, 2004; Alheit & Bakun, 2010). There is a growing literature on such events, including step changes (called regime shifts or abrupt ecosystem shifts) that are a response to hydroclimatic events that simultaneously affect many biological, physical and chemical processes (deYoung *et al.*, 2008). A wide range of other responses to hydroclimatic variability over the past few decades have also been described including, biogeographical range shifts (Beaugrand *et al.*, 2002), changes in timing (phenology) (Edwards & Richardson, 2004), harmful algal blooms (Hallegraeff, 2010), ciguatera fish poisoning (Tester

*et al.*, 2010), disease (Vezzulli *et al.*, 2011), species invasions (Occhipinti-Ambrogi, 2007) and changing spatial distributions observed by satellite remote sensing in, e.g. coccolithophores (Smyth *et al.*, 2004). The underlying mechanisms behind the increasing evidence for temporal and geographical synchrony and teleconnections in biological populations and ecosystems are, however, still poorly understood. These patterns are considered to represent strong forcing by regional and global atmospheric climate variability (Alheit & Bakun, 2010), with evidence for ocean atmosphere feedbacks from SST as well as remote forcing from the SST of the tropical oceans (Overland *et al.*, 2010). Widespread changes (regime shifts/step changes/tipping points) occurred in  $\sim 1976/1977$ ,  $\sim 1988/1989$ ,  $\sim 1997/1998$  and in the 2000s and coincide well with the progressive steps and marked changes in SST seen in the components of Figure 1 and annual regional changes in Figure 3.

Step changes in ecosystems (regime shifts) (deYoung *et al.*, 2004; Alheit, 2009) that in many cases coincide with the major temporal changes seen in the temperature anomalies of Figures 1 and 3, have been described from the North Pacific (1976/1977 and 1989) (Hare & Mantua, 2000; Polovina, 2005; Field *et al.*, 2006), north-east Pacific (1976/1977) (McGowan *et al.*, 2003; Miller *et al.*, 2004) (1998/1999) (Peterson & Schwing, 2003; Lavaniegos & Ohman, 2007), north-west Pacific (1976/1977, 1988/1989 and 1998) (Kasai & Ono, 2007; Sakurai, 2007; Chiba *et al.*, 2009) the Humboldt Current (1968/1970 and 1984/1986) (Alheit & Niquen, 2004; Alheit, 2009), possibly the Benguela Current (between 1967 and 1987) (Verheye *et al.*, 1989) and the north-west Atlantic (1989/1990) (Frank *et al.*, 2005; Pershing *et al.*, 2005; Greene & Pershing, 2007) (SST 1987) (Friedland & Hare, 2007). In San Francisco Bay (Cloern *et al.*, 2010), clear concomitant changes have been observed after 1999 in phytoplankton, crabs, shrimps and demersal fish related to several hydro-climatological indices (e.g. North Pacific Gyre Index, Pacific Decadal Oscillation and Multivariate ENSO Index). Similar shifts were observed in the North Sea (Reid *et al.*, 2001a; Weijerman *et al.*, 2005), Baltic (Alheit *et al.*, 2005) and north-west European shelf seas ( $\sim 1987/1990$ ) (Beaugrand, 2004; Heath & Beare, 2008) and as synchronous changes in the Mediterranean, Adriatic and Black Sea ( $\sim 1987$ ) (Conversi *et al.*, 2010). Recent evidence indicates that an abrupt ecosystem shift might have happened in the mid- to late-1990s in the Celtic Sea and the North Sea (Beaugrand & Edwards, unpublished material) that coincides approximately with ecosystem changes in the eastern North Atlantic that have been linked to changes in the subpolar gyre (Hátún *et al.*, 2009).

Range shifts in the marine environment averaging  $19.0$  km  $\text{year}^{-1}$  were found to be an order of magnitude faster than equivalent terrestrial examples and even faster for introduced species in a recent review (Sorte *et al.*, 2010). In the north-east Atlantic range expansions by zooplankton from the mid-1980s were of the order of  $1000$  km in only 40 years (Beaugrand *et al.*, 2002, 2009). Fish have also shown a northerly range expansion and changes in depth distribution in the same region (Brander *et al.*, 2003; Perry *et al.*, 2005), with in 1988 the appearance and from then an increase in records of warm water cetaceans (MacLeod *et al.*, 2005) and plankton. Subtropical species have also been recorded off the coast of Portugal, but retreated south again in colder years (Henriques *et al.*, 2007). Some species of the rocky shore

benthos have expanded northwards (Hawkins *et al.*, 2008) and in 2004 mussels were found growing in Svalbard for the first time in over 1000 years (Berge *et al.*, 2005). Northward range expansion of fish from 1968 to 2007 (Nye *et al.*, 2009) and reef corals (Precht & Aronson, 2004) have been described from the north-west Atlantic. Benguela El Niños have been associated with mortality of fish and with a southward displacement of sardine stocks (Gammelsrød *et al.*, 1998). In eastern Australian/Tasmanian waters similar pronounced shifts in distribution have been described (Poloczanska *et al.*, 2007; Figueira & Booth, 2010; Last *et al.*, 2011), including a >1000 km range expansion of a tropical reef fish (Hobbs, 2010) all associated with a poleward advance of the East Australian Current. And a northerly movement of warmer water species has been noted in the transition zone of the Kuroshio-Oyashio Currents (Chiba *et al.*, 2009). In the Gulf of California a long (1400 years) and well dated record of foraminifera in a sediment core closely reflects global patterns of warming sea temperature, especially after the mid-1970s regime shift in the North Pacific and also shows evidence for a northerly penetration of tropical and sub-tropical species (Field *et al.*, 2006). It is clear that in the late 20th Century this region experienced unusual tropical forcing from the ocean complemented by an increase in the atmosphere-driven heat flux to the ocean. In the Bering Sea coccolithophores were recorded for the first time in 1998 (Napp & Hunt, 2001) and in the Barents Sea from 1989 (Smyth *et al.*, 2004). Tropical coccolithophores were recorded along the coast of southern Australia following an intrusion of offshore water in the summer of 1992/1993 (Blackburn & Cresswell, 1993) and a similar event was observed in Japan in 1996 (Kai *et al.*, 1999). A southerly range expansion of the coccolithophore *Emiliania huxleyi* was observed in the Southern Ocean in the early 2000s (Cubillos *et al.*, 2007). Of especial note is the trans-Arctic migration of a Pacific diatom (*Neodenticula seminae*) to the north-west Atlantic in 1998/1999 for the first time in 800,000 years (Reid *et al.*, 2007). Since 1980, on the western shelf of the Antarctic Peninsula levels of chlorophyll-*a* have declined to the north of 63°S and increased to the south of that latitude; these changes coincide with changes in krill and penguins and have been linked to reducing sea-ice (Montes-Hugo *et al.*, 2009).

Extensive coral bleaching events have been widely documented in almost all regions of the world where coral reefs form since the 1970s (Wilkinson, 2008; WMO, 2010). Most evidence indicates that the bleaching is caused by high sea temperatures that exceed the thermal limits of the corals and their endosymbiotic dinoflagellates (Hoegh-Guldberg *et al.*, 2007). Mass bleaching events have extended over many 1000 to 100,000 km<sup>2</sup> areas and have been responsible for a large loss of live coral throughout the tropical oceans, with at times a slow and poor prognosis for recovery. Coral bleaching episodes occurred in 1982/1983 (Glynn, 1984), 1987/1988, 1994/1995, 2000/2004, 2010 and were especially pronounced globally in 1997/1998 (Hoegh-Guldberg, 1999) and in 2005/2006 (Wilkinson & Souter, 2008) in the Caribbean. In some regions these phenomena are known to be associated with El Niño/La Niña events and in many cases coincide with the temperature anomalies shown in Figure 3. The differences in the timing of the SST anomalies in different ocean regions helps explain to some extent the geographical variability in the occurrence and intensity of

bleaching events. For example the timing of the exceptional bleaching events of 1997/1998 started in the Caribbean and Galapagos and moved progressively around the world and back to the Caribbean and were especially pronounced in the Indian Ocean in March/April 1998 with a relatively minor impact on the Great Barrier Reef (Hoegh-Guldberg, 1999) (see Figure 3C).

## Impacts of warm SST anomalies on the Arctic/Antarctic

The timing of reductions of sea-ice in polar seas coincides with the changing patterns of the propagating warm SST anomalies. There is however, a difference between the patterns of melting sea-ice at the two poles with widespread melting in the Arctic contrasting with a general increase in the extent of sea-ice around Antarctica other than to the west of the western Antarctic Peninsula.

In the Arctic an increased inflow of warm Atlantic water (Spielhagen *et al.*, 2011), in large part from an extension of the Slope Current, as pulses centred on 1990 and ~2004 has led to exceptional warming of the Barents Sea (Zhang *et al.*, 1998). Arctic Intermediate Water, beneath the halocline (Polyakov *et al.*, 2007, 2010), has extended along the shelf slope to the Laptev Sea (Dmitrenko *et al.*, 2008). The anomalous intrusions are seen as lagged extensions of warm temperature anomalies along the shelf slope from the Bay of Biscay to Spitzbergen (Polyakov *et al.*, 2007). There has been a marked shallowing (shoaling) of the upper surface of the inflowing Atlantic water and it is concluded that the warming has contributed through preconditioning to the large reduction of sea-ice seen in recent years (Polyakov *et al.*, 2010). Intrusion of the warm Atlantic water from a boundary current at the shelf edge onto the bottom of the Laptev Sea shelf has implications for the future stability of offshore submarine permafrost (Dmitrenko *et al.*, 2010). From the Pacific, a similar intrusion of warm Pacific Summer Water into the Bering Sea is correlated with the reduction of sea-ice that began in 1997/1998 (Shimada *et al.*, 2006).

Ocean warming to the west of Greenland since the late 1990s, due to a northward penetration of warm water in the subpolar gyre (Hughes *et al.*, 2010), may be behind the recent rapid and accelerating melting (Rignot *et al.*, 2011) of the Greenland ice sheet. The warming is strongly correlated with the acceleration and retreat of outlet glaciers in southern Greenland, although a statistical analysis of temperature changes does not support an important role for warming SST (Hanna *et al.*, 2009).

The Southern Ocean has shown one of the most rapid increases in SST in the world and has been largely linked to an intensification and southerly shift in the overlying westerly winds and a latitudinal shift in the Antarctic Circumpolar Current (ACC) although the processes behind the increase remain poorly understood (Reid *et al.*, 2009, Schofield *et al.*, 2010). A rapid increase in austral summer SST to the west of the Western Antarctic Peninsula (WAP) in the south-east Pacific (Meredith & King, 2005) and an increased delivery and southerly penetration of heat to this region has had a pronounced impact on adjacent ecosystems (Ducklow *et al.*, 2007). Heat fluxes to the peninsula, especially in winter, derive from Upper Circumpolar Deep Water (UCDW) that penetrates onto the WAP shelf from beneath the ACC due

to a north to south upward tilt of the isopycnals (Martinson, 2012) and are reinforced by higher summer temperature at the surface. Work by Meredith *et al.* (2008) shows that the region close to the Antarctic Peninsula is especially susceptible to ENSO forcing via anomalous meridional winds and that warming further east in the South Atlantic off South Georgia is associated with El Niño and the Southern Annular Mode (SAM).

Over most of the Southern Ocean sea-ice extent has shown an upward trend despite rising ocean and atmospheric temperature (Liu & Curry, 2010; Oza, *et al.*, 2011) that is still not well understood, but has markedly reduced in the Bellinghousen/Amundsen Seas to the west of the WAP (Cavalieri & Parkinson, 2008). The reduction occurred in steps with an increasing heat flux since the 1990s and a step change “regime shift” circa 1998 that was linked to El Niño by Martinson *et al.* (2008). The pattern of sea-ice reduction is closely correlated with regional SST (Schneider *et al.*, 2012) and it has been suggested coincides with a greater penetration at depth (~300m) of UCDW and upwelling of warmer water onto the shelf from the ACC (Martinson *et al.*, 2008). An alternative explanation is that a westward counterflowing shelf slope undercurrent beneath the ACC, causing uplift of the pycnocline as described for the Weddell Sea by Chavanne *et al.* (2010), is allowing warmer water with UCDW characteristics to penetrate as intrusions onto the shelf in a similar way to other shelf slope currents. Intrusion of UCDW onto the shelf may also be driven by the presence of ice shelves and overturning eddy circulation at the Antarctic Shelf Front (Nøst *et al.*, 2011) and/or by local wind forcing at the shelf edge modulated by larger scale atmospheric forcing (Steig *et al.*, 2012; Thoma *et al.*, 2008). Observations by Moffat *et al.* (2009) indicate that the warm intrusions are frequent events and may be in the form of eddies shed off the shelf edge. There are few observations of shelf slope currents around Antarctica, but modelling studies e.g. Smedsrud *et al.* (2006) have implicated them as an important contributor to rapid melting of basal ice shelves with the warmer water pulled in under the ice by an estuarine type of circulation caused by the outflowing melt-water near the surface. Warmer UCDW flows along deep bathymetric troughs to access the sub-ice shelf cavity. Pritchard *et al.* (2012) show from ICESat altimetry measurements that basal melting of ice shelves from oceanic warming is occurring in ~40% of the ice sheets of Antarctica with the most rapid changes in Western Antarctica. Modelling also suggests that the Antarctic shelf slope current is a regular feature around the whole of Antarctica (Mathiot *et al.*, 2011). The ‘Southern Boundary’ of the ACC, is a region of considerable ecological importance that supports highly productive marine ecosystems (Tynan, 1998), and coincides with the location of the shelf slope current.

### Warming sea temperature, earthquakes and other geological hazards

An enhanced sea level height above strong shelf/slope currents during warm anomalies with an increased contrast between shelf and deep offshore oceanic water and their effects on bottom pressure on the sea floor (Landerer *et al.*, 2007) might contribute to subsea earthquake and tsunami activity. The Boxing Day earthquake off Sumatra coincided with

high SST anomalies at this time (Chakravarty, 2009) (see also Figure 3). An accelerating contribution of land ice to sea level rise and regional variability in distribution patterns (Cazenave & Llovel, 2010) may also contribute to changes in bottom pressure. A wide range of geological hazards (e.g. enhanced volcanism and generation of tsunamis by submarine mass failures) that may increase with warming sea temperatures and associated melting of glaciers and ice sheets have recently been reviewed in the *Philosophical Transactions of the Royal Society* (see McGuire, 2010; Tappin, 2010; Tuffen, 2010).

### Concluding remarks

In a longer-term context global mean sea and land surface temperatures have risen substantially since 1850 (Trenberth *et al.*, 2007). In the past 50 years the rate of temperature increase has accelerated and especially so after the late 1970s with 9 of the warmest years on record in the HadCRUT3 dataset (UK Met Office) occurring post-2000; a pattern that compares well with our results. On a regional ocean scale over the past century there was considerable variability in SST with all basins clearly showing a long-term warming trend (Trenberth *et al.*, 2007). All oceans showed a more intense warm period at almost all latitudes in the past two decades, a broader scale pattern that in general agrees with our observations. For the Atlantic at least, this recent warming pattern contrasts with the warming in the 1920s to 1940s, which was largely restricted to above 30°N in the northern hemisphere (Johannessen *et al.*, 2004).

Our analysis shows that SST has developed in three progressive steps with an intensification of the warming after the 1976/1977, 1986/1987 and 1997/1998 El Niños. If this pattern continues, as seems likely from the growth of GHGs, a future intense El Niño may be followed, after a short ~one-year cool period related to La Niña, by a step growth to even higher SST and further penetration into polar waters with likely positive feedbacks from the Arctic to climate change.

We have described for the first time a globally synchronous pattern of pulsed short period (~1 year long) emanations of warm SST anomalies along the shelf slope and shelf from tropical seas towards the poles. The processes behind the anomalies and their propagation are still unclear, but poleward flowing boundary currents are strong candidates. A number of regional examples of poleward flows of warm sea temperature anomalies in boundary currents have been reported, but to our knowledge a globally synchronous pattern to their occurrence has not been previously reported or the extent of their poleward propagation widely recognised. The discovery of a new mechanism by which heat from tropical seas is being moved in a pulsating manner towards the poles along the shelf/slope margin of the oceans has major and wide ranging implications for mankind, influencing, e.g. energy consumption, weather, extreme events, the cryosphere, forest fires, heat waves, droughts and ecosystem services. Synchronous polar directed temperature anomalies propagating along the shelf/slope from the tropics/subtropics, with reinforcing en route from atmospheric, ocean gyre and other sources, provides a mechanism that explains the timing and teleconnection of a wide range of observed hydrographic, ecosystem and cryospheric events. Warm tropical waters appear to be acting like a heart, accumulating heat



and then pumping it in bursts that progressively move towards the poles, especially in eastern margin currents (Reid *et al.*, 2001b), a process that seems to be accelerating.

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## REFERENCES

- Alheit J. (2009) Consequences of regime shifts for marine food webs. *International Journal of Earth System Sciences* 98, 261–268.
- Alheit J. and Bakun A. (2010) Population synchronies within and between ocean basins: apparent teleconnections and implications as to physical–biological linkage mechanisms. *Journal of Marine Systems* 79, 267–285.
- Alheit J., Möllman C., Dutz K., Kornilovs G., Loewe P., Mohrholz V. and Wasmund N. (2005) Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. *ICES Journal of Marine Science* 62, 1205–1215.
- Alheit J. and Niquen M. (2004) Regime shifts in the Humboldt Current ecosystem. *Progress in Oceanography* 60, 201–222.
- Beal L.M., De Ruijter W.P.M., Biastoch A. and Zahn R. (2011) On the role of the Agulhas system in ocean circulation and climate. *Nature* 472, 429–436.
- Beaugrand G. (2004) The North Sea regime shift: evidence, causes, mechanisms and consequences. *Progress in Oceanography* 60, 245–262.
- Beaugrand G. (2009) Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas. *Deep-Sea Research II* 56, 656–673.
- Beaugrand G., Luczak C. and Edwards M. (2009) Rapid biogeographical plankton shifts in the North Atlantic Ocean. *Global Change Biology* 15, 1790–1803.
- Beaugrand G., Reid P.C., Ibañez F., Lindley J.A. and Edwards M. (2002) Reorganisation of North Atlantic marine copepod biodiversity and climate. *Science* 296, 1692–1694.
- Behera S. and Yamagata T. (2010) Imprint of the El Niño Modoki on decadal sea level changes. *Geophysical Research Letters* 37, L23702.
- Belkin I.M. (2009) Rapid warming of Large Marine Ecosystems. *Progress in Oceanography*, 81, 207–213.
- Berge J., Johnsen G., Nilsen F., Gulliksen B. and Slagstad D. (2005) Ocean temperature oscillations enable reappearance of blue mussels *Mytilus edulis* in Svalbard after a 1000 year absence. *Marine Ecology Progress Series* 303, 167–175.
- Bindoff N., Willebrand J., Artale V., Cazenave A., Gregory J., Gulev S., Hanawa K., Le Quéré C., Levitus S., Nojin Y., Shum C.K., Talley L.D. and Unnikrishnan A. (2007) Observations: oceanic climate change and sea level. In Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. and Miller H.L. (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press, pp. 385–432.
- Blackburn S. and Cresswell G. (1993) A coccolithophorid bloom in Jervis Bay, Australia. *Marine and Freshwater Research* 44, 253–260.
- Brander K. (2007) Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America* 104, 19709–19714.
- Brander K., Blom G., Borges M.F., Erzini K., Henderson G., MacKenzie B.R., Mendes H., Ribeiro J., Santos A.M.P. and Toresen R. (2003) Changes in fish distribution in the eastern North Atlantic: are we seeing a coherent response to changing temperature? *ICES Marine Science Symposia* 219, 261–270.
- Brink K.H. (1998) Deep-sea forcing and exchange processes. In Brink K.H. and Robinson A.R. (eds) *The sea. The global coastal ocean. Processes and methods. Volume 10*. New York: John Wiley and Sons, Inc., pp. 151–167.
- Cavaliere D.J. and Parkinson C.L. (2008) Antarctic sea ice variability and trends, 1979–2006. *Journal of Geophysical Research* 113, C07004.
- Cazenave A. and Llovel W. (2010) Contemporary sea level rise. *Annual Review of Marine Science* 2, 145–173.
- Chakravarty S.C. (2009) Case studies of SST variability derived from AQUA/AMSR-E satellite data near the Sumatra region frequently affected by under-sea earthquakes. *The Open Oceanography Journal* 3, 40–49.
- Chavanne C.P., Heywood K.J., Nicholls K.W. and Fer I. (2010) Observations of the Antarctic Slope Undercurrent in the southeastern Weddell Sea. *Geophysical Research Letters*, 37, L13601.
- Chiba S., Sugisaki H., Nonaka M. and Saino T. (2009) Geographical shift of zooplankton communities and decadal dynamics of the Kuroshio–Oyashio currents in the western North Pacific. *Global Change Biology* 15, 1846–1858.
- Cloern J.E., Hieb K.A., Jacobsen T., Sansó B., Di Lorenzo E., Stacey M.T., Largier J.L., Meiring W., Peterson W.T., Powell T.M. and Winder M. (2010) Biological communities in San Francisco Bay track large-scale climate forcing over the North Pacific. *Geophysical Research Letters* 37, L21602.
- Conversi A., Fonda Umami S., Peluso T., Molinero J.C., Santojanni A. and Edwards M. (2010) The Mediterranean Sea regime shift at the end of the 1980s, and intriguing parallels with other European basins. *PLoS ONE* 5, e10633.
- Cubillos J.C., Wright S.W., Nash G., de Solas M.F., Griffiths B., Tillbrook B., Poisson A. and Hallegraeff G.M. (2007) Calcification morphotypes of the coccolithophorid *Emiliania huxleyi* in the Southern Ocean: changes in 2001 to 2006 compared to historical data. *Marine Ecology Progress Series* 348, 47–54.
- Deser C., Alexander M.A., Xie S.-P. and Phillips A.S. (2010) Sea surface, temperature variability: patterns and mechanisms. *Annual Review of Marine Science* 2, 115–143.
- deYoung B., Barange M., Beaugrand G., Harris R., Perry R.I., Scheffer M. and Werner F. (2008) Regime shifts in marine ecosystems: detection, prediction and management. *Trends in Ecology and Evolution* 23, 402–409.
- deYoung B., Harris R., Alheit J., Beaugrand G., Mantua N. and Shannon L. (2004) Detecting regime shifts in the ocean: data considerations. *Progress in Oceanography* 60, 143–164.
- Di Lorenzo E., Schneider N., Cobb K.M., Franks P.J.S., Chhak K., Miller A.J., McWilliams J.C., Bograd S.J., Arango H., Curchitser E., Powell T.M. and Rivière P. (2008) North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* 35, L08607.

\*Michael Colebrook died peacefully at home in Plymouth on the 14th April 2012.

- Dmitrenko I.A., Kirrilov S.A., Tremblay L.B., Bauch D., Hölemann J.A., Krumpen T., Kassens H., Wegner C., Heinemann G. and Schröder D. (2010) Impact of the Arctic Ocean Atlantic water layer on Siberian shelf hydrography. *Journal of Geophysical Research* 115, C08010.
- Dmitrenko I.A., Polyakov I.V., Kirrilov S.A., Timokhov L.A., Frolov I.E., Solokov V.T., Simmons H.L., Ivanov V.V. and Walsh D. (2008) Toward a warmer Arctic Ocean: spreading of the early 21st century Atlantic Water warm anomaly along the Eurasian Basin margins. *Journal of Geophysical Research* 113, C05023.
- Ducklow H.W., Baker K., Martinson D.G., Quetin B.L., Ross M.R., Smith R.C., Stammerjohn S.E., Vernet M. and Fraser W. (2007) Marine pelagic ecosystems: the West Antarctic Peninsula. *Philosophical Transactions of the Royal Society B: Biological Sciences* 362, 67–94.
- Edwards M. and Richardson A.J. (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* 430, 881–884.
- Enfield D.B., Mestas-Nunez A.M. and Trimble P.J. (2001) The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 28, 2077–2080.
- Field D.B., Baumgartner T.R., Charles C.D., Ferreira-Bartrina V. and Ohman M.D. (2006) Planktonic Foraminifera of the California Current reflect 20th-Century warming. *Science* 311, 63–66.
- Figueira W.F. and Booth D.J. (2010) Increasing ocean temperatures allow tropical fishes to survive overwinter in temperate waters. *Global Change Biology* 16, 506–516.
- Florenchie P., Lutjeharms J.R.E., Reason C.J.C., Masson S. and Rouault M. (2003) The source of Benguela Niños in the South Atlantic Ocean. *Geophysical Research Letters* 30, 1505.
- Frank K.T., Petrie B., Choi J.S. and Leggett W.C. (2005) Trophic cascades in a formerly cod-dominated ecosystem. *Science* 308, 1621–1623.
- Friedland K.D. and Hare J.A. (2007) Long-term trends and regime shifts in sea surface temperature on the continental shelf of the northeast United States. *Continental Shelf Research* 27, 2313–2328.
- Gammelsrød T., Bartholomae C.H., Boyer D.C., Filipe V.L.L. and O'Toole M.J. (1998) Intrusion of warm surface water along the Angolan–Namibian coast in February–March 1995: the 1995 Benguela Niño. *South African Journal of Marine Science* 19, 41–56.
- García-Soto C., Pingree R.D. and Valdés L. (2002) Navidad development in the southern Bay of Biscay: climate change and swoddy structure from remote sensing and *in situ* measurements. *Journal of Geophysical Research* 107, 3118.
- Glynn P.W. (1984) Widespread coral mortality and the 1982/83 El Niño warming event. *Environmental Conservation* 11, 133–146.
- Greene C.H. and Pershing A.J. (2003) The flip-side of the North Atlantic Oscillation and modal shifts in slope-water circulation patterns. *Limnology and Oceanography* 48, 319–322.
- Greene C.H. and Pershing A.J. (2007) Climate drives sea change. *Science* 315, 1084–1085.
- Guilderson T.P. and Schrag D.P. (1998) Abrupt shift in subsurface temperatures in the tropical Pacific associated with changes in El Niño. *Science* 281, 240–243.
- Häkkinen S. and Rhines P.B. (2004) Decline of subpolar North Atlantic circulation during the 1990s. *Science* 304, 555–559.
- Hallegraeff G.M. (2010) Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology* 46, 220–235.
- Hanna E., Cappelen J., Fettweis X., Huybrechts P., Luckman A. and Ribergaard M.H. (2009) Hydrologic response of the Greenland ice sheet: the role of oceanographic warming. *Hydrological Processes* 23, 7–30.
- Hansen J., Ruedy R., Sato M. and Lo K. (2010) Global surface temperature change. *Reviews of Geophysics* 48, RG4004.
- 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.
- Hátún H., Payne M.R., Beaugrand G., Reid P.C., Sandø A.B., Drange H., Hansen B., Jacobsen J.A., and Bloch D. (2009) Large biogeographical shifts in the north-eastern Atlantic Ocean: from the sub-polar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography* 80, 149–162.
- Hátún H., Sandø A.B., Drange H., Hansen B. and Valdimarsson H. (2005) Influence of the Atlantic Subpolar Gyre on the thermohaline circulation. *Science* 309, 1841–1844.
- Hawkins S.J., Moore P.J., Burrows M.T., Poloczanska E., Mieszkowska N., Herbert R.J.H., Jenkins S.R., Thompson R.C., Genner M.J. and Southward A.J. (2008) Complex interactions in a rapidly changing world: responses of rocky shore communities to recent climate change. *Climate Research* 37, 123–133.
- Heath M.R. and Beare D.J. (2008) New primary production in northwest European shelf seas, 1960–2003. *Marine Ecology Progress Series* 363, 183–203.
- Henriques M., Gonçalves E.J. and Almada V.C. (2007) Rapid shifts in a marine fish assemblage follow fluctuations in winter sea conditions. *Marine Ecology Progress Series* 340, 259–270.
- Hobbs J.P.A. (2010) Poleward range expansion of a tropical coral reef fish (*Centropyge flavissima*) to Lord Howe Island, Australia. *Marine Biodiversity Records* 3, e118.
- Hoegh-Guldberg O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50, 839–866.
- Hoegh-Guldberg O., Mumby P.J., Hooten A.J., Steneck R.S., Greenfield P., Gomez E., Harvell C.D., Sale P.F., Edwards A.J., Caldeira K., Knowlton N., Eakin C.M., Iglesias-Prieto R., Muthiga N., Bradbury R.H., Dubi A. and Hatzioiols M.E. (2007) Coral reefs under rapid climate change and ocean acidification. *Science* 318, 1737–1742.
- Holliday N.P. (2003) Extremes of temperature and salinity during the 1990s in the northern Rockall Trough; results from the Ellett line. *ICES Marine Science Symposia Series* 219, 95–101.
- Holliday N.P., Hughes S.L., Bacon S., Beszczynska-Möller A., Hansen B., Lavin A., Loeng H., Mork K.A., Østerhus S., Sherwin T. and Walczowski W. (2008) Reversal of the 1960s to 1990s freshening trend in the northeast North Atlantic and Nordic Seas. *Geophysical Research Letters* 35, L03614.
- Hormazabal S., Shaffer G. and Pizarro O. (2002) Tropical Pacific control of intraseasonal oscillations off Chile by way of oceanic and atmospheric pathways. *Geophysical Research Letters* 29, 1081.
- Hughes S.L., Holliday N.P. and Beszczynska-Möller A. (2010) *ICES Report on Ocean Climate 2009*. International Council for the Exploration of the Sea, Report No. 67.
- Hurrell J.W., Yochanan K. and Visbeck M. (2001) The North Atlantic Oscillation. *Science* 291, 603–605.
- Johannessen O.M., Bengtsson L., Miles M.W., Kuzmina S.I., Semenov V.A., Alekseev G.V., Nagurnyi A.P., Zakharov V.F., Bobylev L.P., Pettersson L.H., Hasselmann K. and Cattle H.P. (2004) Arctic climate change: observed and modelled temperature and sea-ice variability. *Tellus A* 56, 328–341.

- Kai M., Hara T., Aoyama H. and Kuroda N. (1999) A massive coccolithophorid bloom observed in Mikawa Bay, Japan. *Journal of Oceanography* 55, 395–406.
- Kasai H. and Ono T. (2007) Has the 1998 regime shift also occurred in the oceanographic conditions and lower trophic ecosystem of the Oyashio region? *Journal of Oceanography* 63, 661–669.
- Keenlyside N.S., Latif M., Jungclaus J., Kornbluh L. and Roeckner E. (2008) Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature* 453, 84–88.
- Kessler W.S. (2006) The circulation of the eastern tropical Pacific: a review. *Progress in Oceanography* 69, 181–217.
- Kosro P.M. (2002) A poleward jet and an equatorward undercurrent observed off Oregon and northern California, during the 1997–98 El Niño. *Progress in Oceanography* 54, 343–360.
- Kosro P.M. (2003) Enhanced southward flow over the Oregon shelf in 2002: a conduit for subarctic water. *Geophysical Research Letters* 30, 8023.
- Landerer F.W., Jungclaus J.H. and Marotzke J. (2007) Ocean bottom pressure changes lead to a decreasing length-of-day in a warming climate. *Geophysical Research Letters* 34, L06307.
- 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.
- Lavaniegos B.E. and Ohman M.D. (2007) Coherence of long-term variations of zooplankton in two sectors of the California Current System. *Progress in Oceanography* 75, 42–69.
- Lee T. (2004) Decadal weakening of the shallow overturning circulation in the South Indian Ocean. *Geophysical Research Letters* 31, L18305.
- Leterme S.C. and Pingree R.D. (2007) Structure of phytoplankton (Continuous Plankton Recorder and SeaWiFS) and impact of climate in the Northwest Atlantic Shelves. *Ocean Science* 3, 105–116.
- Levitus S., Antonov J.I., Boyer T.P., Locarnini R.A., Garcia H.E. and Mishonov A.V. (2009a) Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters* 36, L07608.
- Levitus S., Matishov G., Seidov D. and Smolyar I. (2009b) Barents Sea multidecadal variability. *Geophysical Research Letters* 36, L19604.
- Li J. and Zeng Q. (2005) A new monsoon index, its interannual variability and relation with monsoon precipitation. *Climatic and Environmental Research* 10, 351–365.
- Liu J. and Curry J.A. (2010) Accelerated warming of the Southern Ocean and its impacts on the hydrological cycle and sea ice. *Proceedings of the National Academy of Sciences of the United States of America* 107, 14987–14992.
- Loder J.W., Boicourt W.C. and Simpson J.H. (1998) Overview of western ocean boundary shelves. In Robinson A.R. and Brink K.H. (eds) *The sea. The global coastal ocean. Regional Studies and Syntheses. Volume 11*. New York: John Wiley & Sons, Inc., pp. 3–27.
- Lohrenz S.E. and Castro B.M. (2004) Western ocean boundaries pan-regional overview (W). In Robinson A.R. and Brink K.H. (eds) *The Sea. The global coastal ocean: interdisciplinary studies and syntheses. Volume 14*. Cambridge, MA: Harvard University Press, pp. 3–20.
- Mackas D.L., Batten S. and Trudel M. (2007) Effects on zooplankton of a warmer ocean: recent evidence from the northeast Pacific. *Progress in Oceanography* 75, 223–252.
- Mackas D.L., Thomson R.E. and Galbraith M. (2001) Changes in the zooplankton community of the British Columbia continental margin, 1985–1999, and their covariation with oceanographic conditions. *Canadian Journal of Fisheries and Aquatic Sciences* 58, 685–702.
- MacLeod C.D., Bannon S., Pierce G., Schweder C., Learmonth J., Herman J. and Reid R. (2005) Climate change and the cetacean community of north-west Scotland. *Biological Conservation* 124, 477–483.
- Mann M.E., Bradley R.S. and Hughes M.K. (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779–787.
- Marshall J., Kushnir Y., Battisti D., Chang P., Czaja A., Dickson R., Hurrell J., McCartney M., Saravanan R. and Visbeck M. (2001) North Atlantic climate variability: phenomena, impacts and mechanisms. *International Journal of Climatology* 21, 1863–1898.
- Martinez E., Antoine D., D’Ortenzio F. and Gentili B. (2009) Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science* 326, 1253–1256.
- Martinson D.G. (2012) Antarctic circumpolar current’s role in the Antarctic ice system: an overview. *Palaeogeography, Palaeoclimatology, Palaeoecology* 335–336, 71–74.
- Martinson D.G., Stammerjohn S.E., Iannuzzi R.A., Smith R.C. and Vernet M. (2008) Western Antarctic Peninsula physical oceanography and spatio-temporal variability. *Deep-Sea Research Part II: Topical Studies in Oceanography* 55, 1964–1987.
- Matano R.P., Palma E.D. and Piola A.R. (2010) The influence of the Brazil and Malvinas Currents on the southwestern Atlantic shelf circulation. *Ocean Science Discussions* 7, 837–871.
- Mathiot P., Goosse H., Fichefet T., Barnier B. and Gallée H. (2011) Modelling the seasonal variability of the Antarctic Slope Current. *Ocean Science*, 7, 455–470.
- McGowan J.A., Bograd S.J., Lynn R.J. and Miller A.J. (2003) The biological response to the 1977 regime shift in the California Current. *Deep-Sea Research Part II: Topical Studies in Oceanography* 50, 2567–2582.
- McGuire B. (2010) Potential for a hazardous geospheric response to projected future climate changes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368, 2317–2345.
- Meredith M.P. and King J.C. (2005) Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters* 32, L19604.
- Meredith M.P., Murphy E.J., Hawker E.J., King J.C. and Wallace M.I. (2008) On the interannual variability of ocean temperatures around South Georgia, Southern Ocean: forcing by El Niño/Southern Oscillation and the Southern Annular Mode. *Deep-Sea Research Part II: Topical Studies in Oceanography* 55, 2007–2022.
- Miller A., Chai F., Chiba S., Moisan J.R. and Neilson D.J. (2004) Decadal-scale climate and ecosystem interactions in the North Pacific Ocean. *Journal of Oceanography* 60, 163–188.
- Moffat C., Owens B. and Beardsley R.C. (2009) On the characteristics of Circumpolar Deep Water intrusions to the west Antarctic Peninsula Continental Shelf. *Journal of Geophysical Research*, 114, C05017.
- Montes-Hugo M., Doney S.C., Ducklow H.W., Fraser W., Martinson D., Stammerjohn S.E. and Schofield O. (2009) Recent changes in phytoplankton communities associated with rapid regional climate change along the Western Antarctic Peninsula. *Science* 323, 1470–1473.
- Napp J.M. and Hunt G.L. (2001) Anomalous conditions in the southeastern Bering Sea 1997: linkages among climate, weather, ocean, and biology. *Fisheries Oceanography* 10, 61–68.
- Neshyba S.J., Mooers C.N.K., Smith R.L. and Barber R.T. (eds) (1989) Poleward flows along eastern ocean boundaries. Coastal and estuarine



- studies. *Volume 34*: New York, Berlin, Heidelberg: Springer-Verlag, 374 pp.
- Nøst O.A., Biuw M., Tverberg V., Lydersen C., Hattermann T., Zhou Q., Smedsrud L.H. and Kovacs K.M. (2011) Eddy overturning of the Antarctic Slope Front controls glacial melting in the Eastern Weddell Sea. *Journal of Geophysical Research* 116, C11014.
- 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 on the Northeast United States continental shelf. *Marine Ecology Progress Series* 393, 111–129.
- Occhipinti-Ambrogi A. (2007) Global change and marine communities: alien species and climate change. *Marine Pollution Bulletin* 55, 342–352.
- 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 of Marine Systems* 79, 305–315.
- Oza S.R., Singh R.K.K., Srivastava A., Dash M.K., Das J.M.L. and Vyas N.K. (2011) Inter-annual variations observed in spring and summer Antarctic sea ice extent in recent decade. *MAUSAM* 62, 633–640.
- Peliz Á., Dubert J., Santos A.M.P., Oliveira P.B. and Le Cann B. (2005) Winter upper ocean circulation in the Western Iberian Basin—fronts, eddies and poleward flows: an overview. *Deep-Sea Research Part I: Oceanographic Research Papers* 52, 621–646.
- Perry A.I., 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., Batchelder H.P., Mackas D.L., Chiba S., Durbin E., Greve W. and Verheye H.M. (2004) Identifying global synchronies in marine zooplankton populations: issues and opportunities. *ICES Journal of Marine Science* 61, 445–456.
- Pershing A.J., Greene C.H., Jossi J.W., O'Brien L., Brodziak J.K.T. and Bailey B.A. (2005) Interdecadal variability in the Gulf of Maine zooplankton community, with potential impacts on fish recruitment. *ICES Journal of Marine Science* 62, 1511–1523.
- Peterson W.T. and Schwing F.B. (2003) A new climate regime in north-east Pacific ecosystems. *Geophysical Research Letters* 30, 1896.
- Pingree R. (2002) Ocean structure and climate (Eastern North Atlantic): *in situ* measurement and remote sensing (altimeter). *Journal of the Marine Biological Association of the United Kingdom* 82, 681–707.
- Pingree R.D. and Le Cann B. (1989) Celtic and Armorican slope and shelf residual currents. *Progress in Oceanography* 23, 303–338.
- Pingree R.D., Sinha B. and Griffiths C.R. (1999) Seasonality of the European slope current (Goban Spur) and ocean margin exchange. *Continental Shelf Research* 19, 929–975.
- Poloczanska E.S., Babcock R.C., Butler A., Hobday A.J., Hoegh-Guldberg O., Kunz T.J., Matear R., Milton D.A., Okey T.A. and Richardson A.J. (2007) Climate change and Australian marine life. *Oceanography and Marine Biology: an Annual Review* 45, 407–478.
- Polovina J.J. (2005) Climate variation, regime shifts, and implications for sustainable fisheries. *Bulletin of Marine Science* 76, 233–244.
- Polovina J.J., Howell E.A. and Abecassis M. (2008) Ocean's least productive waters are expanding. *Geophysical Research Letters* 35, L03618.
- Polyakov I., Timokhov L., Dmitrenko I., Ivanov V., Simmons H., Beszczynska-Moeller A., Dickson R., Fahrbach E., Fortier L., Gascard J., Høeileman J., Holliday N.P., Hansen E., Mauritzen C., Piechura J., Pickart R., Schauer U., Steele M. and Walczowski W. (2007) Observational program tracks Arctic Ocean transition to a warmer state. *EOS, Transactions American Geophysical Union* 88, 398–399.
- Polyakov I.V., Timokhov L.A., Alexeev V.A., Bacon S., Dmitrenko I.A., Fortier L., Frolov I.E., Gascard J.C., Hansen E., Ivanov W., Laxon S., Mauritsen C., Perovich D., Shimada K., Simmons H.L., Sokolov V.T., Steele M. and Toolen J. (2010) Arctic ocean warming contributes to reduced polar ice cap. *Journal of Physical Oceanography* 40, 2743–2756.
- Power S.B. and Kociuba G. (2011) The impact of global warming on the Southern Oscillation Index. *Climate Dynamics* 37, 1745–1754.
- Precht W.F. and Aronson R.B. (2004) Climate flickers and range shifts of reef corals. *Frontiers in Ecology and the Environment* 2, 307–314.
- Pritchard H.D., Ligtenberg S.R.M., Fricker H.A., Vaughan D.G., van den Broeke M.R. and Padman L. (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves. *Nature* 484, 502–505.
- Purkey S.G. and Johnson G.C. (2010) Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: contributions to global heat and sea level rise budgets. *Journal of Climate* 23, 6336–6351.
- Reid P.C., Borges M. and Svendsen E. (2001a) A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. *Fisheries Research* 50 163–171.
- Reid P.C., Fischer A.C., Lewis-Brown E., Meredith M.P., Sparrow M., Andersson A., Antia A., Bathmann U., Beaugrand G., Brix H., Dye S., Edwards M., Furevik T., Gangstø R., Hátún H., Hopcroft R., Kendall M., Kasten S., Keeling R., Le Quércé C., Mackenzie F., Malin G., Mauritsen C., Ólafsson J., Paull C., Rignot E., Shimada K., Vogt M., Wallace C., Wang Z. and Washington R. (2009) Impacts of the oceans on climate change. *Advances in Marine Biology* 56, 1–150.
- Reid P.C., Holliday N.P. and Smyth T.J. (2001b) Pulses in the eastern margin current with higher temperatures and North Sea ecosystem changes. *Marine Ecology Progress Series* 215, 283–287.
- Reid P.C., Johns D.G., Edwards M., Starr M., Poulin M. and Snoeijis P. (2007) A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom *Neodenticula seminae* in the North Atlantic for the first time in 800,000 years. *Global Change Biology* 13, 1910–1921.
- Ridgway K.R. (2007) Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters* 34, L13613.
- Rignot E., Velicogna I., van den Broeke M.R., Monaghan A. and Lenaerts J. (2011) Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* 38, L05503.
- Rouault M., Penven P. and Pohl B. (2009) Warming in the Agulhas Current system since the 1980s. *Geophysical Research Letters* 36, L12602.
- Sakurai Y. (2007) An overview of the Oyashio ecosystem. *Deep-Sea Research Part II: Topical Studies in Oceanography* 54, 2526–2542.
- Schneider D., Deser C. and Okumura Y. (2012) An assessment and interpretation of the observed warming of West Antarctica in the austral spring. *Climate Dynamics* 38, 323–347.
- Schofield O., Ducklow H.W., Martinson D.G., Meredith M.P., Moline M.A. and Fraser W.R. (2010) How do polar marine ecosystems respond to rapid climate change? *Science*, 328, 1520–1523.
- Seidel D.J., Qiang Fu, Randel W.J. and Reichler T.J. (2008) Widening of the tropical belt in a changing climate. *Nature Geoscience* 1, 21–24.
- Sherman K., Belkin I.M., Friedland K.D., O'Reilly J. and Hyde K. (2009) Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. *AMBIO: a Journal of the Human Environment* 38, 215–224.
- Shimada K., Kamoshida T., Itoh M., Nishino S., Carmack E., McLaughlin F., Zimmerman S. and Proshutinsky A. (2006) Pacific Ocean inflow: influence on catastrophic reduction of sea ice cover in the Arctic Ocean. *Geophysical Research Letters* 33, L08605.

- Smedsrud L.H., Jenkins A., Holland D.M. and Nøst O.A.** (2006) Modelling ocean processes below Fimbulisen, Antarctica. *Journal of Geophysical Research*, 111, C01007.
- Smith R.L., Huyer A. and Fleischbein J.** (2001) The coastal ocean off Oregon from 1961 to 2000: is there evidence of climate change or only of Los Niños? *Progress in Oceanography* 49, 63–93.
- Smith T.M., Reynolds R.W., Peterson T.C. and Lawrimore J.** (2008) Improvements to NOAA's Historical Merged Land–Ocean Surface Temperature Analysis (1880–2006). *Journal of Climate* 21, 2283–2296.
- Smith W.H.F. and Sandwell D.T.** (1997) Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277, 1956–1962.
- Smyth T.J., Tyrrell T. and Tarrant B.** (2004) Time series of coccolithophore activity in the Barents Sea, from twenty years of satellite imagery. *Geophysical Research Letters* 31, L11302.
- Sorte C.J.B., Williams S.L. and Carlton J.T.** (2010) Marine range shifts and species introductions: comparative spread rates and community impacts. *Global Ecology and Biogeography* 19, 303–316.
- Spielhagen R.F., Werner K., Sørensen S.A., Zamelczyk K., Kandiano E., Budeus G., Husum K., Marchitto T.M. and Hald M.** (2011) Enhanced modern heat transfer to the Arctic by warm Atlantic water. *Science* 331, 450–453.
- Stabeno P.J., Ladd C. and Reed R.K.** (2009) Observations of the Aleutian North Slope Current, Bering Sea, 1996–2001. *Journal of Geophysical Research* 114, C05015.
- Steig E.J., Ding Q., Battisti D.S. and Jenkins A.** (2012) Tropical forcing of Circumpolar Deep Water Inflow and outlet glacier thinning in the Amudsen Sea Embayment, West Antarctica. *Annals of Glaciology* 53, 19–28.
- Strub P.T. and James C.** (2002a) The 1997–1998 oceanic El Niño signal along the southeast and northeast Pacific boundaries—an altimetric view. *Progress in Oceanography* 54, 439–458.
- Strub P.T. and James C.** (2002b) Altimeter-derived surface circulation in the large-scale NE Pacific Gyres. Part 2: 1997–1998 El Niño anomalies. *Progress in Oceanography* 53, 185–214.
- Suryanarayana A., Murty V.S.N. and Rao D.P.** (1993) Hydrography and circulation of the Bay of Bengal during early winter, 1983. *Deep-Sea Research Part I: Oceanographic Research Papers* 40, 205–217.
- Sutton R.T. and Hodson D.L.R.** (2007) Climate response to basin-scale warming and cooling of the North Atlantic Ocean. *Journal of Climate* 20, 891–907.
- Takayabu Y.N., Iguchi T., Kachi M., Shibata A. and Kanzawa H.** (1999) Abrupt termination of the 1997–98 El Niño in response to a Madden–Julian oscillation. *Nature* 402, 279–282.
- Tappin D.R.** (2010) Submarine mass failures as tsunami sources: their climate control. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368, 2417–2434.
- Tester P.A., Feldman R.L., Nau A.W., Kibler S.R. and Litaker R.W.** (2010) Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. *Toxicon* 56, 698–710.
- Thoma M., Jenkins A., Holland D., and Jacobs S.** (2008) Modelling Circumpolar Deep Water intrusions on the Amudsen Sea continental shelf, Antarctica. *Geophysical Research Letters* 35, L18602.
- Trenberth K.E. and Hoar T.J.** (1997) El Niño and climate change. *Geophysical Research Letters* 24, 3057–3060.
- Trenberth K.E., Jones P.D., Ambenje P., Bojariu R., Easterling D., Klein Tank A., Parker D., Rahimzadeh F., Renwick J.A., Rusticucci M., Soden B. and Zhai P.** (2007) Observations: surface and atmospheric climate change. In Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. and Miller H.L. (eds) *Climate change 2007: the physical science basis, contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 235–336.
- Tuffen H.** (2010) How will melting of ice affect volcanic hazards in the twenty-first century? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368, 2535–2558.
- Tynan C.T.** (1998) Ecological importance of the Southern Boundary of the Antarctic Circumpolar Current. *Nature*, 392, 708–710.
- Verheye H.M., Richardson A.J., Hutchings L., Marska G. and Gianakouras D.** (1989) Long-term trends in the abundance and community structure of coastal zooplankton in the southern Benguela system, 1951–1996. *South African Journal of Marine Science* 19, 317–332.
- Vezzulli L., Brettar I., Pezzati E., Reid P.C., Colwell R.R., Höfle M.G. and Pruzzo C.** (2011) Long-term effects of ocean warming on the prokaryotic community: evidence from the vibrios. *ISME Journal* 6, 21–30.
- Weijerman M., Lindeboom H. and Zuur A.F.** (2005) Regime shifts in marine ecosystems of the North Sea and Wadden Sea. *Marine Ecology Progress Series* 298, 21–39.
- Wilkinson C.** (2008) *Status of coral reefs of the world: 2008*. Global Coral Reef Monitoring Network Reef and Rainforest Research Centre. Townsville, QL, Australia, 304 pp.
- Wilkinson C. and Souter D.** (2008) A bad year for the Caribbean corals. In *A world of science. Volume 6*. Paris: UNESCO, pp. 20–23.
- WMO** (2010) *Climate, carbon and coral reefs*. Geneva: World Meteorological Organization, 30 pp.
- Wolter K. and Timlin M.S.** (1998) Measuring the strength of ENSO events—how does 1997/98 rank? *Weather* 53, 315–324.
- Wolter K. and Timlin M.S.** (2011) El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEIext). *International Journal of Climatology* 31, 1074–1087.
- Yeh S.-W., Kug J.-S., Dewitte B., Kwon M.-H., Kirtman B.P. and Jin F.-F.** (2009) El Niño in a changing climate. *Nature* 461, 511–514.
- and
- Zhang J., Rothrock D.A. and Steele M.** (1998) Warming of the Arctic Ocean by a strengthened Atlantic inflow: model results. *Geophysical Research Letters* 25, 1745–1748.

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