Chapter 5.2. Sea surface temperature trends in large marine ecosystems

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5.2 Sea surface temperature trends in large marine ecosystems

SUMMARY

Sea surface temperature (SST) affects ocean primary productivity through its physical effect on water stratification (which in turn affects nutrient availability) and its biological effect on plankton metabolic rates. Global mean SST has risen over the past century, and this is linked with both decreases and increases in primary productivity, depending on the time period and the region. Although many studies address global climate variability, studies on LME-scale climate variations based on a uniform, spatially, and temporally consistent methodology have been lacking until recently. This report extends and updates previous work at the LME scale with the aim of improving understanding of how global-scale climate changes translate into LME-scale changes.

SST is the only oceanic variable measured worldwide since the 19th century, providing the longest instrumental record of ocean climate change. Hadley Centre global climatology data were used to construct long-term SST time-series in 66 LMEs and the Western Pacific Warm Pool (WPWP). Long-term trends were calculated from annual SSTs for each LME. Warming rates between 1957 and 2012 were calculated on the basis of these SST trends. LMEs and the WPWP were then divided into five categories based on the rate of warming. Overall confidence in the results is rated as very high.

KEY MESSAGES

1. **Between 1957 and 2012, SST in all but two LMEs increased.** SST change varied widely between regions, from -0.28°C to +1.57°C in 55 years.
    - LMEs with highest rates of warming: East China Sea, Scotian Shelf, and Northeast US Continental Shelf;
    - LMEs that cooled over this period: Barents Sea and Southeast US Continental Shelf.
2. **The LMEs with the largest increases in SST are mainly in three regions: Northwest Atlantic, eastern North Atlantic, and the Western Pacific.** LMEs with high rates of seawater warming:
    - Northwest Atlantic: US Continental Shelf, Scotian Shelf, and Faroe Plateau LMEs;
    - Eastern North Atlantic: Celtic-Biscay Shelf, North Sea, and Baltic Sea LMEs;
    - Western Pacific: South China Sea, East China Sea, Yellow Sea, and Sea of Japan LMEs.
3. **The observed long-term global ocean warming from 1957 to 2012 was not steady, especially in the North Atlantic and North Pacific.** In these regions, SST tends to alternate between cooling and warming epochs, separated by abrupt regime shifts. In the North Atlantic, the most typical regime shift was a transition from cooling to warming in the 1970s to the 1980s. In the North Pacific, the most conspicuous regime shift from cooling to warming occurred around 1976 to 1977.
4. **After 1998, most LMEs in the North Pacific experienced slowdowns, and even reversals, of late 20th century warming.**
    - LMEs with slowed or reversed rates of warming since about 1998: East China Sea, Yellow Sea, Kuroshio Current, West Bering Sea, East Bering Sea, Aleutian Islands, Gulf of Alaska, California Current, and Gulf of California;
    - Three LMEs in the subarctic Northwest Pacific with no signs of slowed warming since 1998: Sea of Japan, Oyashio Current, and Sea of Okhotsk.

5.2.1 Introduction

Sea surface temperature (SST) is placed in the Productivity module because of its effects on ocean productivity. A growing body of knowledge suggests that changes in phytoplankton biomass and productivity are related to ocean warming (Lewandowska *et al*. 2014; Polovina *et al*. 2011 and 2008; Boyce *et al*. 2010; Behrenfeld *et al*. 2006). At least two distinct mechanisms are implicated: a physical effect of warming on vertical stratification and nutrient flux, and a biological effect on plankton metabolic rates. For example, rising SSTs are linked to an overall global decline in phytoplankton productivity since the late 1990s through changes in ocean circulation and stratification of water layers, restricting nutrient availability in surface waters (Behrenfeld *et al*. 2006). On the other hand, increased primary production observed in some temperate areas is largely a response of increased phytoplankton growth to warming surface waters (Polovina *et al*. 2011).

The Earth's climate has become substantially warmer since the 19th century. Based on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, the global mean surface air temperature increased by 0.74°C while the global mean SST rose by 0.67°C over the last century (Trenberth *et al.*, 2007). The most recent global assessment (Hartmann *et al*. 2013) discusses estimates of SST trends based on specific data sets and time periods selected for trend analysis. These estimates are generally consistent with Trenberth *et al.* (2007). The world ocean's mean temperature in the layer from the surface to 3 000 m deep increased by 0.037°C between 1955 and 1998 (Levitus *et al.*, 2005). The heat content of the top 2 000 m of the world ocean increased by 24.0±1.9 x 10^{22} Joules (±2 standard errors) between 1955 and 2010, corresponding to a rate of increase of 0.39 watts per m^2 and a rise in temperature of this layer of water of 0.09°C, when averaged over its entire volume (Levitus *et al.*, 2012).

The nature and extent of changes to the Earth's climate in the near and distant future is uncertain. As the CO_2 concentration in the Earth's atmosphere rises, the greenhouse effect must lead to an increase in the atmosphere's temperature and, after a time lag, to a further ocean temperature increase. The IPCC-2007 report projected that the rate of climate warming will increase. This trend is obviously non-sustainable. However, recent data, especially from the period after the 1998 El Niño, revealed a slowdown of the 20th century warming rate as the world entered the 21st century. In some regions, this slowdown has turned into cooling. For example, surface layers of the East China Sea and Taiwan Strait have cooled by 1°C since 1998 (Belkin and Lee, 2014). Clearly, re-assessment of the current climate trends based on the most recent data is needed.

LME-based management can be significantly improved through a better understanding of oceanic and atmospheric circulation and physical-biological interactions at the LME scale (Sherman *et al.* 2009, 2011, 2013, 2014a and 2014b; Belkin *et al.* 2009; Sherman *et al.*, 2005; Duda and Sherman 2002). It is therefore crucial to make clear the various mechanisms that translate global-scale climate changes into LME-scale changes

Great efforts have been made to document global climate variability (Trenberth *et al.* 2007), but studies of LME-scale climate variations based on a uniform, spatially, and temporally consistent methodology were lacking until recently (Belkin, 2009). This report extends and updates our previous study by adding six years of recent data (2007 to 2012). This addition has turned out to be critically important, as the most recent data has confirmed a slowdown, and even reversal of, late 20th century warming in some regions (Kosaka and Xie 2013; England *et al.* 2014. Our goal is to document these most recent changes and put them in a historical perspective with comparisons with earlier trends.

5.2.2 Main findings, discussion and conclusions

Table 5.2 lists net SST changes from 1957 to 2012 for 66 LMEs plus the WPWP. These changes were estimated from linear regressions of annual mean SST. Plots of annual mean SST and accompanying narratives for each LME are available on the TWAP LME website and data portal (onesharedocean.org) and in the author's report to IOC/UNESCO (Belkin 2014).

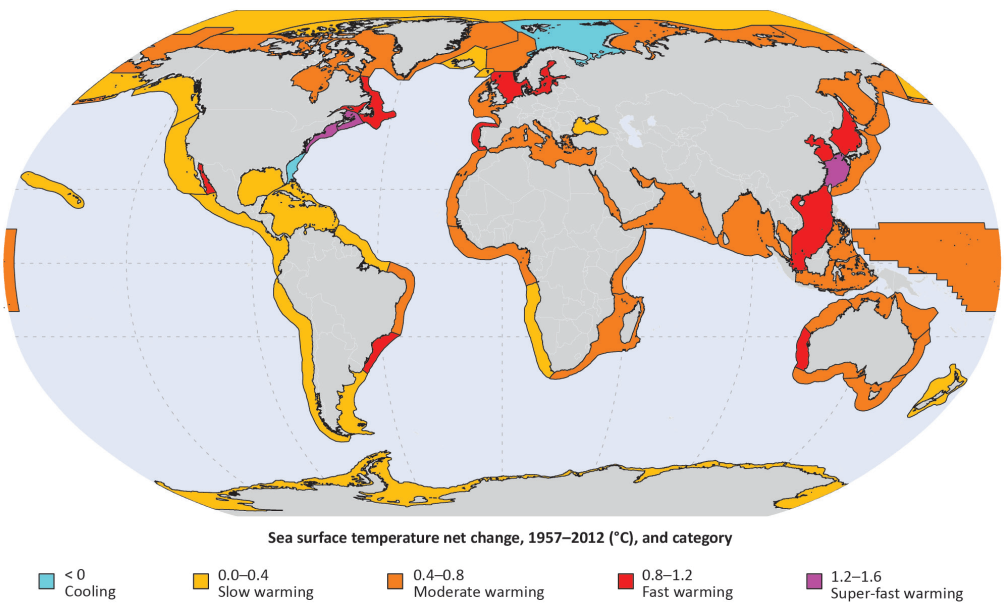
Table 5.2 Net sea surface temperature changes in LMEs and the WPWP, 1957–2012. Colour codes are used to map the distribution of SST change in Figure 5.8.

SST change category and colour code	LME	Change in SST (°C)
Super-fast warming	East China Sea	1.57
	Scotian Shelf	1.46
	Northeast US Continental Shelf	1.40
Fast warming	Gulf of California	1.13
	South Brazil Shelf	1.07
	Sea of Japan	1.05
	Newfoundland-Labrador Shelf	1.04
	West-Central Australian Shelf	0.96
	North Sea	0.93
	Baltic Sea	0.93
	Yellow Sea	0.93
	Iberian Coastal	0.90
	South China Sea	0.80
Moderate warming	Agulhas Current	0.72
	Kuroshio Current	0.70
	Oyashio Current	0.68
	Mediterranean	0.66
	Guinea Current	0.66
	Northern Bering-Chukchi Seas	0.65
	Sulu-Celebes Sea	0.64
	Southeast Australian Shelf	0.61
	Kara Sea	0.60
	Hudson Bay Complex	0.60
	East Brazil Shelf	0.59
	Canary Current	0.59
	East-Central Australian Shelf	0.58
	Sea of Okhotsk	0.57
	Norwegian Sea	0.55
	Somali Coastal Current	0.55
	Indonesian Sea	0.54
	Southwest Australian Shelf	0.54
	Bay of Bengal	0.53
	Northeast Australian Shelf	0.53
	Greenland Sea	0.51
	Celtic-Biscay Shelf	0.51
	Canadian Eastern Arctic-West Greenland	0.50
	Northwest Australian Shelf	0.50
	Arabian Sea	0.48
	West Pacific Warm Pool Province	0.48
	West Bering Sea	0.47
	Beaufort Sea	0.47
	Laptev Sea	0.47
	North Australian Shelf	0.44
	East Siberian Sea	0.44
	Gulf of Thailand	0.42
	Red Sea	0.40
	Aleutian Islands	0.40

SST change category and colour code	LME	Change in SST (°C)
Slow warming	North Brazil Shelf	0.38
	Iceland Shelf and Sea	0.36
	Black Sea	0.31
	Pacific Central-American Coastal	0.27
	Benguela Current	0.27
	East Bering Sea	0.24
	Humboldt Current	0.24
	Gulf of Mexico	0.16
	Caribbean Sea	0.15
	Canadian High Arctic-North Greenland	0.13
	Insular Pacific-Hawaiian	0.12
	Antarctic	0.12
	Faroe Plateau	0.10
	Central Arctic	0.10
	New Zealand Shelf	0.09
	Gulf of Alaska	0.06
	Patagonian Shelf	0.06
	California Current	0.02
Cooling	Barents Sea	-0.06
	Southeast US Continental Shelf	-0.28

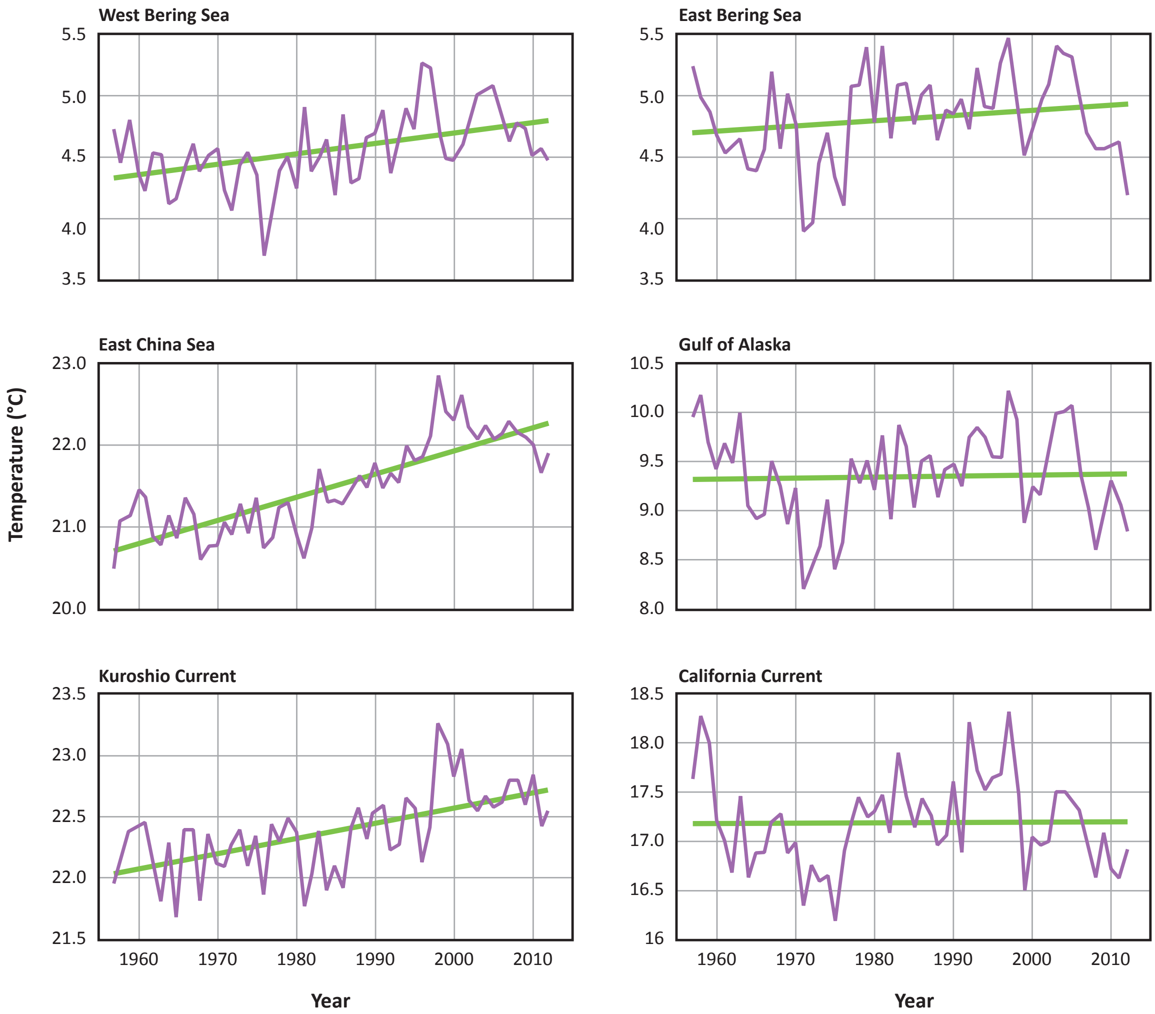
All but two LMEs warmed between 1957 and 2012 (Table 5.2 and Figure 5.8). Temperature change ranged from -0.28°C to 1.57°C over 55 years, varying widely between different regions and even between adjacent LMEs. The long-term warming between 1957 and 2012 was not steady in the great majority of LMEs. Instead, their thermal history consisted of alternating cooling and warming epochs, separated by regime shifts (Figure 5.9 to Figure 5.11). For example, the Southeast US Continental Shelf LME cooled by almost 0.3°C, while the nearby Northeast US Continental

Figure 5.8 Long-term sea surface temperature trends (net changes) in 66 LMEs, 1957–2012. The LMEs with the greatest increases in SST are concentrated in three regions: Northwest Atlantic, Northeast Atlantic, and Western Pacific. Long-term net cooling over this period was observed in two LMEs only: Barents Sea LME and Southeast US Continental Shelf LME. See Table 5.2 for sea surface temperature net change for each LME.



Calculated from linear regressions of annual SSTs for each LME.

Figure 5.9 Sea surface temperature time series in selected LMEs of the North Pacific. The regime shift of 1976–1977 in the Bering Sea, Gulf of Alaska, and California Current marked a transition from cooling to warming. The post-1997/1998 cooling is evident in these LMEs.

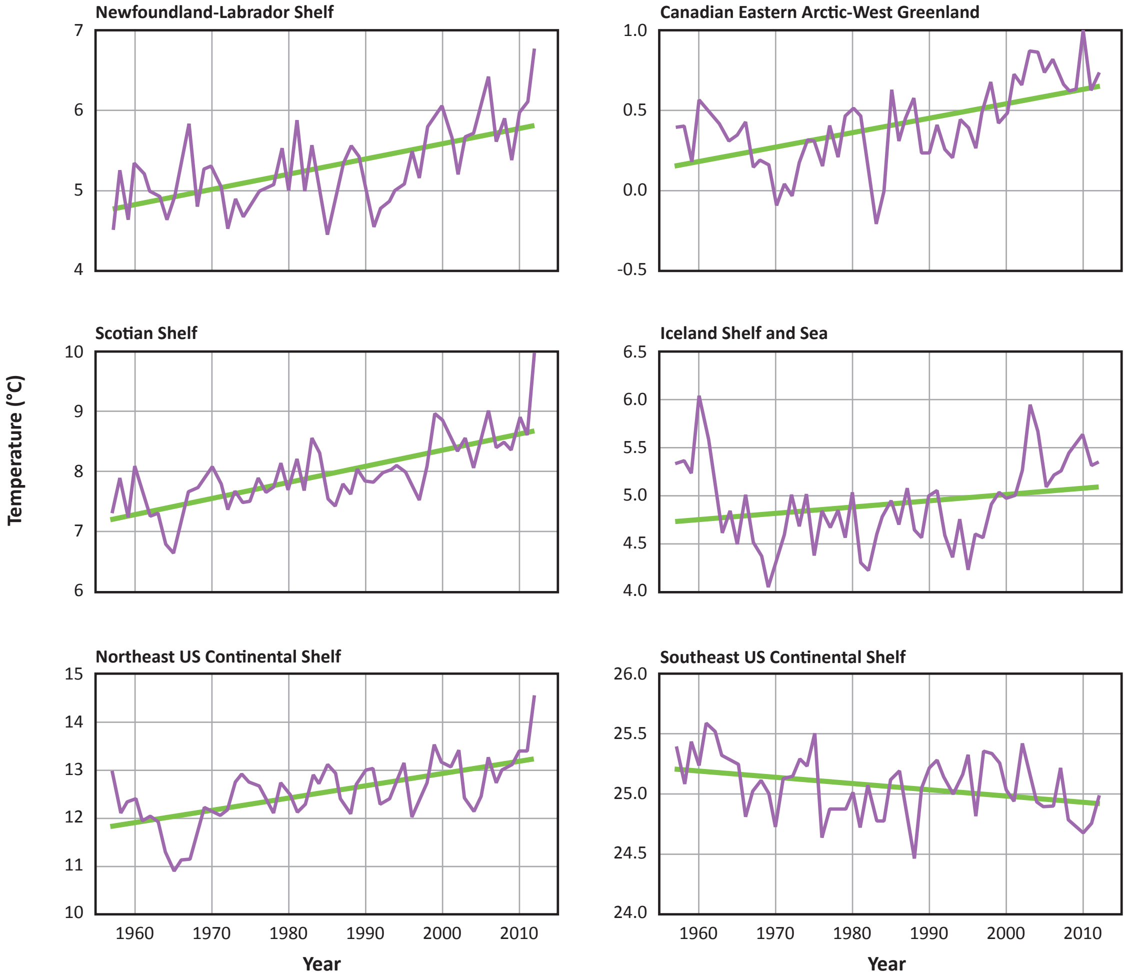


Note the variation in scales for temperature.

Shelf LME was one of the fastest warming LMEs in the world ocean, with a 1.4°C increase in SST over 55 years. In the North Atlantic, the most conspicuous regime shift in the 1970s to 1980s has marked a transition from cooling to warming (Figure 5.10 and Figure 5.11). In the North Pacific, the most conspicuous regime shift in SST occurred around 1976 to 1977, while the regime shift of 1988 to 1989 was not evident in the SST records (Figure 5.9; Hare and Mantua 2000).

The post-1998 data revealed a slowdown, and even a reversal, of the late 20th century warming in many North Pacific LMEs (Figure 5.9**;** Belkin and Lee 2014). Some LMEs in other regions also showed signs of this change. This is a global-scale phenomenon, with the annual mean global temperature showing no increase during the twenty-first century (Kosaka and Xie 2013). This phenomenon has recently become a focus of observational and modelling studies (Chen and Tung 2014; Drijfhout *et al.* 2014; England *et al.* 2014; Kosaka and Xie 2013). As pointed out by Easterling and Wehner (2009), "*…the climate over the 21st century can and likely will produce periods of a decade or two where the globally averaged surface air temperature shows no trend or even slight cooling in the presence of longer-term warming*." The global SST can be expected to exhibit variations similar to global air temperature on the same time scales, approximately 10 to 20 years. Any long-term climate change adaptation and mitigation policies should consider this variability.

Figure 5.10 Sea surface temperature time series in selected LMEs of the Western North Atlantic. The Northwest Atlantic experienced a steady warming, which abruptly accelerated after 2010. In the Canadian Eastern Arctic-West Greenland and off Iceland, cooling episodes in the late 1960s to early 1970s and early 1980s were linked to salinity anomalies accompanied by negative anomalies of SST. The Southeast US Continental Shelf LME is the only LME showing a steady decline of SST over the 1957–2012 period.



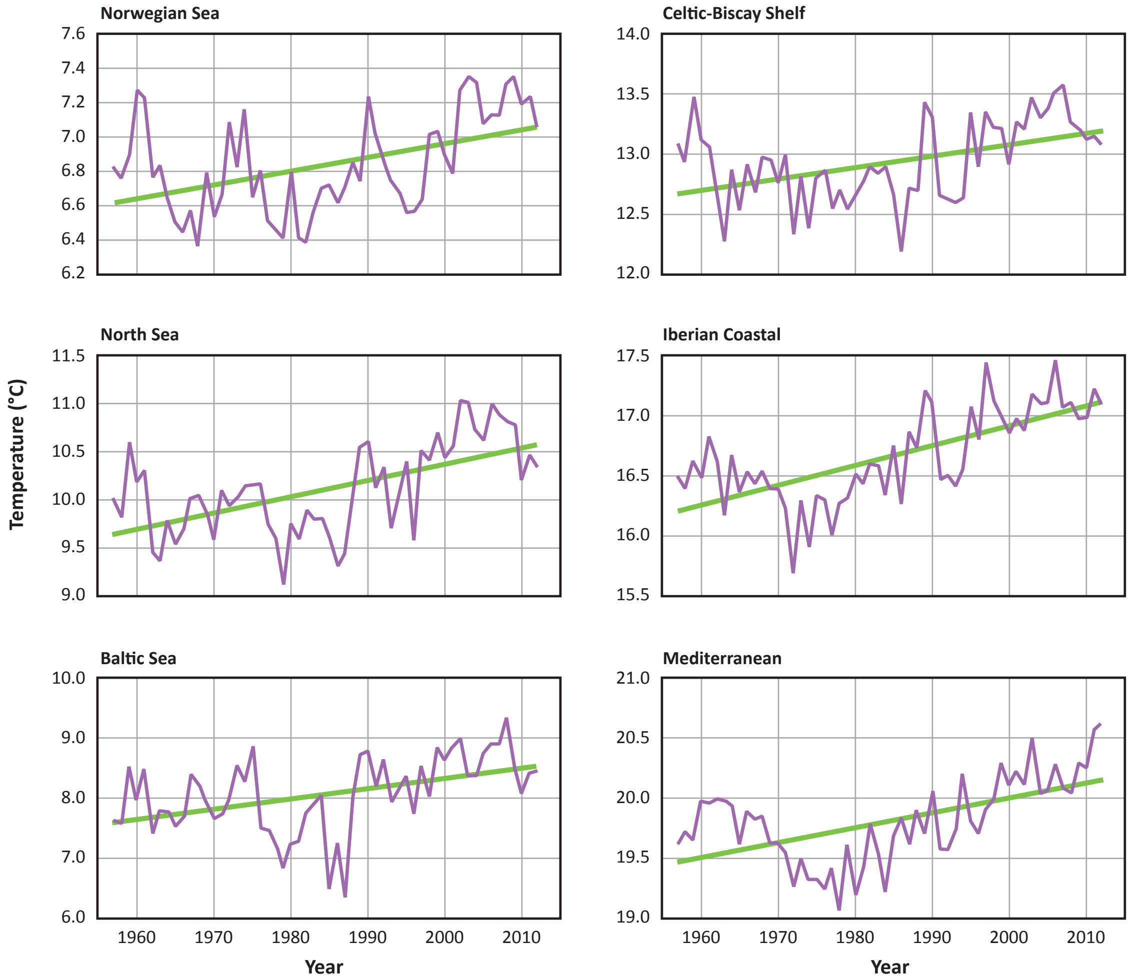
Note the variation in scales for temperature.

The global map of warming rates (Figure 5.8) illustrates regional variations of net changes. The full range of net changes in SST was divided into five intervals or categories (an optimum number for visual rendering of global distribution of net changes), with each interval encompassing a range of 0.4°C and consistent with the terminology introduced by Belkin (2009) (Table 5.3). Colour codes were used to represent the five categories to which the LMEs were assigned based on their net change in SST.

Table 5.3 Classification of LMEs based on net change in sea surface temperature, 1957–2012

Category and colour code		Range of changes in SST (°C)
Super-fast warming		1.2–1.6
Fast warming		0.8–1.2
Moderate warming		0.4–0.8
Slow warming		0.0–0.4
Cooling		-0.4–0.0

Figure 5.11 Sea surface temperature time series in selected LMEs of the Eastern North Atlantic (European seas). The fast warming in this region was not a regular progression – it was interrupted by cooling epochs. The most pronounced cooling episodes were linked to the low-temperature, low-salinity, high-sea-ice-cover salinity anomalies in the 1970s, 1980s, and 1990s. The Iberian Coastal and Mediterranean LMEs experienced sharp regime shifts in the 1970s, switching from rapid cooling to rapid long-term warming through the rest of the 1957–2012 period, over which SST has risen by approximately 1.5°C in both LMEs.



Note the variation in scales for temperature.

The above classification does not imply any natural (data-driven) clustering of LMEs. The analysis shows that all 66 LMEs are distributed rather evenly across the SST warming rate variability range and do not form any clusters (classes) of values.

The East China Sea LME warmed the most of all the LMEs (1.57°C between 1957 and 2012). The Southeast US Continental Shelf and the Barents Sea LMEs were the only two to cool during that period (by 0.28°C and 0.06°C respectively). In three large-scale regions, the long-term warming between 1957 and 2012 exceeded 0.8°C: (1) Western North Atlantic off the North American coast (Northeast US Continental Shelf, Scotian Shelf, and Newfoundland-Labrador Shelf LMEs); (2) Western Pacific (South China Sea, East China Sea, Yellow Sea, and Sea of Japan LMEs); and (3) Northeastern Atlantic (North Sea, Baltic Sea, and Mediterranean LMEs) as shown in Figure 5.9 to Figure 5.11. Three additional LMEs (Gulf of California, South Brazil Shelf, and West Australian Shelf) also experienced rapid warming (exceeding 0.8°C) between 1957 and 2012.

The SST time series shows long-term (decadal and multi-decadal) trends, separated by regime shifts between warming and cooling epochs. These trends show different patterns and time lines in different oceans. The North Atlantic's main trend pattern is characterized by cooling from the late 1950s to the early 1970s, continuing into the 1980s in some places, followed by warming up to the present time. Trends are punctuated by cold anomalies associated with the 'great salinity anomalies' that propagated around the North Atlantic Ocean in the 1970s, 1980s, and 1990s (Belkin *et al.* 1998; Belkin 2004). In the North Pacific, the most dramatic regime shift was around 1976 to 1977, followed by another regime shift in 1988/1989 (Hare and Mantua 2000). However, the impact of the 1988 to 1989 regime shift on the thermal state (characterized by SST) of the North Pacific LMEs was significantly less than the impact of the earlier regime shift. Somewhat surprisingly, the Arctic Ocean and its coastal seas, as a whole, have not experienced the accelerated warming that has been observed in air temperature over Arctic landmasses.

5.2.2.1 Impacts on marine ecosystems and services and socio-economic and policy implications

Global warming has already affected marine ecosystems significantly (Cheung *et al.* 2013; Sherman *et al.* 2009, 2011, 2013, 2014a and 2014b; Halpern *et al.* 2008). This impact is projected to increase (Trenberth *et al.* 2007). Warming may affect fish or other biota at a global scale (Klyashtorin and Lyubishin, 2007), although the mechanisms at work are not clear. The global warming signal translates down to ocean-scale, basin-scale, and LME-scale signals that affect ecosystems and marine living organisms through changes in ambient temperature. Long-term consequences of global warming will be LME-specific (Sherman *et al.*, 2009, 2011, 2013, 2014a, 2014b), therefore LME-scale estimates and projections of SST warming and cooling rates are especially important. There is no consistent link between SST trends and environmental risks. Sherman *et al.* (2011 and 2013) have shown that the ongoing warming is beneficial for many LMEs, but detrimental to others. Sherman *et al*. (2009) recommended protecting current and future fisheries yields with a cap-and-sustain strategy in certain LMEs as a precautionary action in the light of the uncertainties around climate warming effects. Climate warming is associated with non-linear changes in fish stock abundance that are difficult to predict.

5.2.2.2 Confidence levels

The overall confidence level of the main results and conclusions is very high. The confidence levels of individual results, which are summarized in the key messages section at the beginning of this chapter, vary from high to very high. Confidence in the conclusion that all but two LMEs have warmed since 1957 is high, while very high confidence is assigned to conclusions about regional and temporal patterns of warming, and about the post-1999 slowdown of warming in most North Pacific LMEs.

5.2.3 Data and methodology

This analysis uses the same data set and methodology as Belkin (2009). The main reason for choosing SST to represent ocean climate is that SST is the only oceanic variable that has been routinely measured worldwide since the 19th century, thereby providing the longest instrumental record of ocean climate change compared to other oceanic observables. Of the few global SST climatologies available, we have chosen the UK Met Office Hadley Centre SST climatology designated as HadISST1 (Rayner *et al.* 2003 and 2006). This includes data as far back as 1870. It has the best spatial and temporal resolution (1°x 1° and monthly, respectively) compared with other data sets. Overall, the Hadley climatology appears to be the best choice and was therefore used in the IPCC-2007 Report (Trenberth *et al.*, 2007).

For each LME, annual mean SST was calculated from monthly SSTs in 1° x 1° cells, area-averaged within the given LME. The square area of each spherical trapezoidal 1° x 1° cell is proportional to the cosine of the middle latitude of the given cell, thus all SSTs were weighted by the cosine of the cell's middle latitude. After integration over the given LME area, the resulting sum of weighted SSTs was normalized by the sum of the weights (cosines). For each LME, long-term LME-averaged SSTs were computed by long-term averaging of annual area-weighted LME-averaged SSTs. Anomalies of annual LME-averaged SST were calculated by subtracting the long-term mean SST from the annual SSTs. Long-term trends based on linear regression were calculated from annual SSTs for each LME. Net SST changes (warming rates) between 1957 and 2012 were calculated based on the linear SST trends.

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