Chapter 5.1. Primary productivity patterns and trends

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Chapter Citation
5.1 Primary productivity patterns and trends

SUMMARY

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production. It drives the flow of energy through food webs in LMEs and is related to the carrying capacity of LMEs for supporting biological diversity, including fisheries resources. High primary productivity is also an indicator of eutrophication (excessive addition of nutrients), which leads to harmful algal blooms and dead zones in coastal waters around the globe. Ocean primary productivity is responsive to global warming and is closely coupled to climate variability.

Satellite ocean colour data sets covering 16 years (1998 to 2013) were used to estimate average annual primary productivity and chlorophyll (the green pigment involved in photosynthesis) in the world's 66 LMEs and the Western Pacific Warm Pool (WPWP). Daily primary productivity and chlorophyll levels over the entire global ocean were estimated at a spatial resolution of approximately 9 km. Inputs to the productivity model included ocean colour data files from five satellite sensors. Results were used to rank LMEs according to their 16-year average primary productivity. LMEs were then divided into five groups based on these rankings. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. Measurements from one satellite sensor were used to estimate 11-year (2003 to 2013) trends in chlorophyll. Accurate assessments of primary productivity and chlorophyll based on satellite data were not feasible for eight high-latitude LMEs, due to low spatial coverage or low sampling frequency. Surveys from ships or airplanes provide better results for these regions.

Key messages

1. Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries. Across the entire global ocean, average annual primary productivity (1998 to 2013) ranges over three orders of magnitude, while it varies by one order of magnitude in the 66 LMEs and the WPWP (from 74 to 755 grams of carbon per m$^2$ per year). Average chlorophyll concentrations show the same pattern of global distribution.
   - LMEs with highest primary productivity: Baltic Sea (highest), Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf, and Arabian Sea.
   - LMEs with lowest primary productivity: Insular Pacific Hawaiian (lowest), Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean Sea, East Central Australian Shelf, and East Brazil Shelf, plus the WPWP.

2. No large-scale, consistent pattern of either increase or decrease in chlorophyll was observed (2003 to 2013). There are 36 LMEs with increasing trends in chlorophyll (measured as chlorophyll a) and 31 with decreasing trends. Trends are weakly correlated with latitude, and most are not statistically significant (P<0.05).
   - LMEs with significant increasing chlorophyll trends: Scotian Shelf, Patagonian Shelf, Labrador Newfoundland, and Southeast Australian Shelf LMEs (trends over 11 years of 20, 20, 13, and 1 per cent, respectively). The Baltic Sea LME had a relatively high chlorophyll increase (48 per cent), but this trend is not significant.
   - LMEs with significant decreasing chlorophyll trends: Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (trends of -16, -8, and -4 per cent over 11 years, respectively).
5.1.1 Introduction

Primary production, the photosynthesis of organic matter, supports and governs all ecosystem production and plays a pivotal role in ecosystem nutrient and carbon cycling and budgets (Hofmann et al. 2008). Primary production drives the trophodynamics (flow of energy through food webs) of LMEs and can be related to the carrying capacity of marine ecosystems for supporting fish resources (Christensen et al. 2009; Pauly and Christensen 1995).

Measurements of ecosystem primary productivity are useful indicators of the growing eutrophication problem that is leading to an increase in the frequency and extent of dead zones in coastal waters around the globe (Diaz and Rosenberg 2008). In several LMEs, excessive nutrient loadings have produced harmful algal blooms implicated in mass mortalities of marine resource species, emergence of pathogens (for example, cholera, vibrios, red tides, and paralytic shellfish toxins) and population explosions of invasive species (Epstein 2000).

Indicators of changing productivity are based on the following physical attributes and biogeochemical constituents: photosynthetically active radiation, water column transparency, chlorophyll \( \alpha \), primary production, zooplankton biomass, species biodiversity, ichthypoplankton (eggs and larvae of fish) biodiversity, oceanographic variability (for example, temperature, salinity, density, circulation, and nutrient flux) (Sherman et al. 2009; Sherman et al. 1998; Sherman 1980), and acidification (Oliver et al. 2012). Plankton can be measured over decadal time scales by deploying Continuous Plankton Recorder systems monthly across LMEs from commercial vessels of opportunity (Jossi and Kane 2013; Batten et al. 2003; Jossi et al. 2003). Advanced plankton samplers can be fitted with electronic sensors for temperature, salinity, chlorophyll, nutrients, oxygen, and light (Melrose 2006). Application of satellite-derived data, coupled with appropriate algorithms, can allow time-series visualizations of LME-scale sea surface temperature, hydrographic fronts (boundaries between water masses with different physical properties), chlorophyll concentrations, and primary productivity estimates (Sherman et al. 2011).

Chlorophyll \( \alpha \), the principal pigment in phytoplankton, can be estimated in surface water from satellite ocean colour sensors by using the blue-green part of the ocean colour spectrum (O’Reilly et al. 2000 and 1998). Chlorophyll \( \alpha \) is an index of phytoplankton abundance, and, together with light and nutrients, is among the key factors in primary productivity.

5.1.2 Data and methodologies

5.1.2.1 Chlorophyll \( \alpha \) and primary productivity estimates

The average levels of chlorophyll \( \alpha \) and primary productivity for the world’s 66 LMEs and the Western Pacific Warm Pool (WPWP) were characterized for a 16-year period (1998 to 2013) using 76 028 satellite data files at a resolution of 9 km. These data are from five sensors: 1) the Ocean Color and Thermal Sensor (OCTS); 2) Sea-viewing Wide Field-of-view Sensor (SeaWiFS); 3) Moderate Resolution Imaging Spectroradiometer on the AQUA satellite (AQUA); 4) Moderate Resolution Imaging Spectroradiometer on the TERRA satellite (TERRA); and 5) the medium-spectral-resolution imaging spectrometer (MERIS), along with the Ocean Production from the Absorption of Light (OPAL) productivity model. Primary productivity is expressed as grams of carbon per m\(^2\) per year. Measurements of primary productivity per unit volume of seawater are integrated over the upper layer of the water column to estimate grams of carbon produced per unit area of the ocean.

Satellite chlorophyll data are the standard chlorophyll products provided by the US National Aeronautics and Space Administration’s Goddard Space Flight Center (NASA-GSFC) from the most recent (2012) major data reprocessing, based on Version 6 of the OC-maximum band ratio algorithms (NASA 2013). The correlation between \textit{in situ} chlorophyll \( \alpha \) and chlorophyll \( \alpha \) estimates from SeaWiFS (0.909) and MODIS-AQUA (0.925) is relatively high, and the regression slopes between \textit{in situ} and satellite data are close to 1.0 (NASA 2013). Chlorophyll concentrations are expressed as milligrams per m\(^3\) of seawater in the surface layer (the upper metre of the ocean).
Daily estimates of global primary productivity were calculated using the OPAL model, a derivative of the model first formulated by Marra et al. (2003). Four key satellite data inputs to OPAL are: 1) the concentration of surface chlorophyll $\alpha$, 2) sea surface temperature, 3) photosynthetically active radiation striking the ocean surface, and 4) the absorption of light by coloured dissolved organic matter. Agreement is excellent between in situ $^{14}$C-based measurements from MARMAP surveys (O’Reilly et al. 1987) and productivity estimates from OPAL in the Northeast US Continental Shelf LME, where in situ productivity measurements were made throughout the ecosystem during most months (Table 5.1).

### Table 5.1 Comparison between in situ and satellite-based estimates of primary productivity for the Northeast US Continental Shelf LME.

Comparison is between long-term mean annual in situ $^{14}$C primary production estimates from MARMAP (O’Reilly et al. 1987) and productivity estimates from the OPAL model.

<table>
<thead>
<tr>
<th>Source of estimate</th>
<th>Sample size</th>
<th>Years</th>
<th>Productivity (grams of carbon per m² per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ measurements</td>
<td>1,243</td>
<td>1977–1982</td>
<td>355</td>
</tr>
</tbody>
</table>

A total of 76,028 satellite standard mapped image files from five NASA-GSFC satellite ocean colour sensors (OCTS, SeaWiFS, MODIS-AQUA, MODIS-TERRA and MERIS) were used to derive daily estimates of primary productivity over the global ocean. Merging data from these five ocean colour sensors resulted in minimal data gaps in the global productivity estimates, except in 1997. Because sampling was incomplete in 1997 and 2014, average chlorophyll $\alpha$ and primary productivity estimates are based on the 16-year period from 1998 through 2013.

Sampling by satellite ocean colour sensors is inadequate for a comprehensive characterization of chlorophyll $\alpha$ and primary productivity in the most northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements. Gregg and Casey (2007) documented the positive biases in chlorophyll data from ocean colour sensors. Nevertheless, the results for these LMEs, while biased and incomplete, are presented for comparison. In situ measurements would be required for more accurate assessment of the productivity and the timing of annual peaks and minima for these systems.

#### 5.1.2.2 Detecting time trends in chlorophyll $\alpha$

Trends in chlorophyll $\alpha$ are based on data from one sensor (MODIS-AQUA), for the 11-year period 2003 through 2013. Data from one sensor were used instead of the merged data from five sensors to minimize sensor-to-sensor biases in the trends. Trends were computed based on linear regressions of the yearly anomalies in annual mean chlorophyll $\alpha$, following the methods outlined by Gregg et al. (2005). Tests of whether linear regression slopes differ significantly from zero (no trend) at the 0.95 probability level were computed using the T-Test statistic (Sokal and Rohlf 1995). Trends in chlorophyll $\alpha$ were calculated as relative per cent change from 2003 to 2013, computed from the predicted values ($P$) from the linear regression of annual mean chlorophyll $\alpha$ versus year as follows:

$$\text{relative percentage change} = 100 \times \frac{\text{last}(P) - \text{first}(P)}{\text{first}(P)}.$$

#### 5.1.3 Major findings, discussion, and conclusions

#### 5.1.3.1 Spatial patterns in chlorophyll $\alpha$ and primary production

Mean chlorophyll $\alpha$ throughout the global ocean varies from 0.008 to 100 milligrams per m³, a range of more than four orders of magnitude (Figure 5.1). Relatively high chlorophyll $\alpha$ values (those exceeding 1 to 3 milligrams per m³) are found near shore, within LME boundaries. Mean chlorophyll $\alpha$ is less than 0.02 milligrams per m³ in the South Pacific Gyre, the Earth’s largest oceanic desert, located west of South America at about 25°S latitude (Claustre and Maritorena 2003).
Mean primary production per year (Figure 5.2) ranges over three orders of magnitude, from 1.6 grams of carbon per m² per year (at 17.92°S, 142.17°W) to 6382 grams of carbon per m² per year (at 6.00°S, 12.33°E, the Guinea Current). As with chlorophyll a, the highest primary productivity values (those exceeding 300 grams of carbon per m² per year) are found in coastal waters within LME boundaries.

5.1.3.2 Global primary production

The average annual global ocean primary production for the 16-year period 1998 to 2013, based on five sensors and estimated through OPAL, is 52 x 10¹⁵ grams of carbon per year. This is lower than the estimate by Behrenfeld et al. (2005) of 60 x 10¹⁵ grams of carbon per year, an estimate based on the Vertically Generalized Production Model and SeaWiFS data for the six-year period 1997 to 2002. The OPAL global production estimate is higher than the estimate of 36.5 to 45.6 x 10¹⁵ grams of carbon per year by Antoine et al. (1996), an estimate based on coastal zone colour data from 1978 to 1986. These global estimates are calculated by integrating primary production values (grams of carbon per m²) over the entire area of the ocean.

5.1.3.3 Classification of LMEs into five groups

It is important to know the productivity status of marine ecosystems, because the magnitude of primary productivity is related to ecosystem services such as fishery production (Rosenberg et al. 2014). High primary productivity is generally regarded as a positive ecosystem attribute, except when it results in hypoxia (low oxygen) from decomposing phytoplankton blooms stimulated by anthropogenic nutrient pollution in rivers.

The 66 LMEs and the WPWP were arranged into five groups based on their 16-year mean primary productivity values. There are no a priori criteria for grouping primary productivity into discrete ranges, and no established thresholds for indicating either impoverished or excessive levels of primary productivity in open water. Moreover, while the terms ‘oligotrophic’, ‘mesotrophic’ and ‘eutrophic’ are frequently used in the scientific literature, quantitative definitions of primary productivity levels are lacking. Consequently, a statistical approach was used to classify ecosystem primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles.
Figure 5.2 Distribution of average annual primary productivity throughout the global ocean, 1998–2013. Primary productivity, the photosynthesis of organic matter by phytoplankton that supports and governs all ecosystem production, ranges from 74 to 755 grams of carbon per m$^2$ per year in the LMEs studied. Most relatively high values of primary productivity in the global ocean are in coastal waters, within LME boundaries.

Figure 5.3 Classification of 66 LMEs and the WPWP into five groups by productivity. A statistical approach was used to classify the 16-year average primary productivity into five groups, based on the 0, 10, 25, 75, 90, and 100 percentiles. Most (33) LMEs are in the middle range of primary productivity, Group 3. Figure 5.4 maps the distribution of these productivity groups.

Values shown are mean net primary productivity per year, based on the OMF model and satellite ocean colour data; LME boundaries are outlined in white.
Most LMEs are in the middle range of primary productivity, Group 3, between the 25th and 75th percentiles (Figure 5.3). The seven LMEs with the highest primary productivity, Group 5, are the Baltic Sea, Yellow Sea, North Brazil Shelf, Black Sea, Gulf of California, North Australian Shelf and the Arabian Sea. The seven areas with the lowest primary productivity, Group 1, are six LMEs: Insular Pacific-Hawaiian, Southwest Australian Shelf, Northeast Australian Shelf, Mediterranean, East Central Australian Shelf, and East Brazil Shelf, as well as the Western Pacific Warm Pool. The global distribution of LMEs and the WPWP in these five primary productivity classification groups is mapped in Figure 5.4.

### 5.1.3.4 LME trends

No large-scale, consistent pattern of either increase or decrease in chlorophyll $\alpha$ was observed, with most chlorophyll $\alpha$ trends being near zero (Figure 5.5). There are 36 LMEs with positive chlorophyll $\alpha$ trends and 31 with negative chlorophyll $\alpha$ trends from 2003 to 2013. Trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll $\alpha$ trends at the 0.95 per cent probability level are the Scotian Shelf, Patagonian Shelf, Newfoundland-Labrador Shelf, and Southeast Australian Shelf (increases of 20, 20, 13, and 1 per cent over the 11-year period, respectively). The Baltic Sea LME shows relatively higher chlorophyll $\alpha$ increases (48 per cent), but this trend is not statistically significant. The three LMEs with statistically significant decreasing chlorophyll $\alpha$ trends are the Indonesian Sea, Oyashio Current, and Celtic-Biscay Shelf (decreases of 16, 8, and 4 per cent over 11 years, respectively). These results are similar to those presented in an earlier UNEP report (Sherman and Hempel 2008), where nine-year trends were statistically significant in only four LMEs.

There were relatively few monthly samples from ocean colour sensors in the most northerly and southerly latitudes from 1998 to 2013 (Figure 5.6). Eight LMEs had less than 60 per cent spatial coverage, or were sampled during less than 60 per cent of the 192 months from 1998 to 2013 (Figure 5.7). These LMEs are: Antarctica, Kara Sea, Laptev Sea, East Siberian Sea, Beaufort Sea, Canadian High Arctic-North Greenland, Central Arctic, and Northern Bering-Chukchi Seas. It is therefore unlikely that the status and trends in chlorophyll $\alpha$ and primary productivity described in this report for these eight LMEs are reliable or represent true ecosystem conditions. For these ecosystems, remotely-sensed ocean colour measurements, for example from aircraft (Hugo et al. 2005; Harding et al. 1992), or in situ measurements, would be required for more accurate indices of their productivity, phenology and trends.
Figure 5.5 Trends in chlorophyll a (2003–2013) in relation to latitude. No large-scale, consistent pattern of either increase or decrease in chlorophyll a was observed. There are 36 LMEs with positive chlorophyll a trends and 31 with negative chlorophyll a trends, and trends are weakly correlated with latitude. The four LMEs with statistically significant increasing chlorophyll a trends (red circles to the right of the purple line) are the Scotian Shelf (#8), Patagonian Shelf (#14), Newfoundland-Labrador Shelf, and Southeast Australian Shelf. The three LMEs with statistically significant decreasing chlorophyll a trends (red circles to the left of the purple line) are the Indonesian Sea (#38), Oyashio Current, and Celtic-Biscay Shelf.

Chlorophyll a trends (% relative change) are shown for 66 LMEs and the WPWP, based on chlorophyll a data from the AQUA sensor, 2003–2013.

Figure 5.6 Global distribution of chlorophyll a samples, 1998–2013. The confidence level of the primary productivity estimates is high where sampling is adequate, which is the case for most LMEs. However, sampling by satellite ocean colour sensors was inadequate for a comprehensive characterization of chlorophyll a and primary productivity in northern and southern LMEs with short growing seasons, persistent ice or clouds, and partial coverage by satellite sensors that rely on daylight for ocean colour measurements.

Sample numbers are over a period of 192 months; sampling was by ocean color sensors.
Trends in primary productivity would be expected to follow trends in chlorophyll $a$ since chlorophyll $a$ is a dominant input to the OPAL productivity model and their averages are correlated (correlation coefficient = 0.63).

5.1.3.5 **Limitations and qualitative confidence in the LME productivity indicators**

The overall confidence level in the primary productivity indices is high where sampling is adequate, which is the case for most LMEs. The reasons for this confidence level are:

1. The measurement consistency is high within and among LMEs.
2. Ocean colour satellite data provide a very large statistical sample size of approximately 10,000 pixels for each LME.
3. Where both in situ productivity measurements and satellite measurements were made throughout the ecosystem and during most months, such as in the Northeast US Continental Shelf, the agreement is excellent between conventional in situ 14C-based measurements of productivity and productivity indicators from the OPAL model (see Table 5.1).
4. The estimate of annual global ocean production from OPAL ($52 \times 10^{15}$ grams of carbon per year) is in agreement with the range previously reported in the scientific literature.

The major limitation of the LME productivity indicators is incomplete sampling, which is the result of inadequate spatial or seasonal coverage of the LMEs by satellite ocean colour sensors. These sensors rely on daylight and cloud-free conditions for measurements of chlorophyll and other variables in surface water. Estimates of ecosystem productivity based on satellite data, and models such as OPAL, rely heavily on these satellite ocean colour chlorophyll estimates and photosynthetically active radiation data. These estimates and models therefore have similar spatial and seasonal limitations.
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Sherman, K., O’Reilly, J., Belkin, I. and others (2011). The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world’s large marine ecosystems. ICES Journal of Marine Science 68(4), 667-676


Chapter 5.2. Sea surface temperature trends in large marine ecosystems

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Chapter Citation
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 m² 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 CO₂ 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 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.

<table>
<thead>
<tr>
<th>SST change category and colour code</th>
<th>LME</th>
<th>Change in SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Super-fast warming</strong></td>
<td>East China Sea</td>
<td>1.57</td>
</tr>
<tr>
<td></td>
<td>Scotian Shelf</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>Northeast US Continental Shelf</td>
<td>1.40</td>
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<tr>
<td><strong>Fast warming</strong></td>
<td>Gulf of California</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>South Brazil Shelf</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Sea of Japan</td>
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</tr>
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<td></td>
<td>Newfoundland-Labrador Shelf</td>
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</tr>
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<td></td>
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<td><strong>Moderate warming</strong></td>
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<td></td>
<td>Northeast Australian Shelf</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Greenland Sea</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Celtic-Biscay Shelf</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Canadian Eastern Arctic-West Greenland</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Northwest Australian Shelf</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Arabian Sea</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>West Pacific Warm Pool Province</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>West Bering Sea</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Beaufort Sea</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Laptev Sea</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>North Australian Shelf</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>East Siberian Sea</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Gulf of Thailand</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Red Sea</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Aleutian Islands</td>
<td>0.40</td>
</tr>
</tbody>
</table>
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
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.

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>
<thead>
<tr>
<th>Category and colour code</th>
<th>Range of changes in SST (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-fast warming</td>
<td>1.2–1.6</td>
</tr>
<tr>
<td>Fast warming</td>
<td>0.8–1.2</td>
</tr>
<tr>
<td>Moderate warming</td>
<td>0.4–0.8</td>
</tr>
<tr>
<td>Slow warming</td>
<td>0.0–0.4</td>
</tr>
<tr>
<td>Cooling</td>
<td>-0.4–0.0</td>
</tr>
</tbody>
</table>

Note the variation in scales for temperature.

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

### 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 episodes. 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 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.
References


Sherman, K., Sissenwine, M., Christensen, V. and others (2005). A global movement toward an ecosystem approach to management of marine resources. *Marine Ecology Progress Series* 300, 275-279


