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Rapid warming of Large Marine Ecosystems

Igor M. Belkin

Graduate School of Oceanography, University of Rhode Island, 215 South Ferry Road, Narragansett, RI 02882, USA

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ABSTRACT

The need to understand local effects of global climate change is most urgent in the Large Marine Ecosystems (LMEs) since marine ecosystem-based management requires information on the LME scale. Reported here is a study of sea surface temperature (SST) change in the World Ocean LMEs in 1957–2006 that revealed strong regional variations in the rate of SST change. The rapid warming in 1982–2006 was confined to the Subarctic Gyre, European Seas, and East Asian Seas. These LMEs warmed at rates 2–4 times the global mean rate. The most rapid warming was observed in the land-locked or semi-enclosed European and East Asian Seas (Baltic Sea, North Sea, Black Sea, Japan Sea/East Sea, and East China Sea) and also over the Newfoundland–Labrador Shelf. The Indian Ocean LMEs' warming was slow, while two major upwelling areas – California and Humboldt Currents – experienced a slight cooling. The Subarctic Gyre warming was likely caused by natural variability related to the North Atlantic Oscillation. The extremely rapid surface warming in the enclosed and semi-enclosed European and East Asian Seas surrounded by major industrial/population agglomerations may have resulted from the observed terrestrial warming directly affecting the adjacent coastal seas. Regions of freshwater influence in the European and East Asian Seas seem to play a special role in modulating and exacerbating global warming effects on the regional scale.

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1. Introduction

The Earth's climate is warming. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-2007), the global mean surface air temperature increased by 0.74 °C while the global mean sea surface temperature (SST) rose by 0.67 °C over the last century (Trenberth et al., 2007). The World Ocean's mean temperature in 0–3000 m layer increased by 0.037 °C between 1955 and 1998 (Levitus et al., 2005). Global warming has already significantly affected marine ecosystems (e.g. Richardson and Schoeman, 2004; Behrenfeld et al., 2006; Halpern et al., 2008), and this impact is expected to increase in the near future owing to the current acceleration of warming (Trenberth et al., 2007). From a global perspective, marine ecosystem-based management can be significantly improved through a better understanding of regional oceanic and atmospheric circulation and physical–biological interactions in specific Large Marine Ecosystems, LMEs (Duda and Sherman, 2002; Sherman et al., 2005; http://www.lme.noaa.gov; see also Fig. 2). Thus, it is necessary to establish how global warming translates into regional patterns of climate change and how these regional changes in climate affect regional ecosystems. And yet, as the IPCC-2007 emphasized the global nature of the most recent climate warming regime, regional analyses based on uniform methodology and uniform data base are lacking. In the meantime, it is such regional analyses on the LME scale that are needed most in marine ecosystem-based management. The aim of this study is to fill this gap. Out of the entire ensemble of climate-related oceanic and meteorological parameters, the SST was chosen as the observable with the most densely populated global data base, with the spatial and temporal resolution that warranted a study of decadal variability on the LME scale. The data and methods are described in Section 2, while results are presented in Section 3, discussed in Section 4, and summarized in Section 5.

2. Data and methods

Sea surface temperature (SST) is the only thermal parameter routinely measured worldwide that can be used to characterize thermal conditions in each LME, whereas subsurface hydrographic data lack spatial and temporal density required for reliable assessment of thermal conditions at the LME scale. The U.K. Meteorological Office Hadley Centre SST climatology (Rayner et al., 2003, 2006), which dates back to 1870, was chosen for this study because Hadley data set has the best spatial ($1^\circ \times 1^\circ$ globally) and temporal (monthly) resolution compared to other data sets. The IPCC-2007 Report (Trenberth et al., 2007) is based on the same data set.

Annual average SSTs for each LME were calculated from monthly SSTs in $1^\circ \times 1^\circ$ cells and then area-averaged within each LME. The square area of each spherical trapezoidal cell is proportional to the cosine of the middle latitude of the given cell, thus

E-mail address: igormbelkin@gmail.com

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all SSTs were weighted by the cosine of the cell's middle latitude. After integration over the LME area, the resulting sum of weighted SSTs was normalized by the sum of the weights (cosines). Long-term LME-averaged SSTs were computed for each LME 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 linear trends were estimated based on annual SSTs for each LME except for the Arctic Ocean LME, which is ice-covered most of the year. Net SST changes between 1982 and 2006 were calculated based on the linear SST trends. The 1982–2006 LME-average SST warming rates were compared with the IPCC-2007 global average SST warming rate of 0.133 ± 0.047 °C/decade (Trenberth et al., 2007).

3. Results

SST anomalies in the World Ocean LMEs over 50 years, 1957–2006, are presented in Fig. 1 (top). Conventional time series and linear trends of SST and SST anomalies for each LME, 1957–2006, are provided in Appendix (Supplementary Material). Global warming and its recent acceleration are evident in most LMEs. At the same time, the long-term SST variability since 1957 was not uniform. Only in a few LMEs, the SST rose more or less steadily. Almost all LMEs in the North Atlantic and North Pacific experienced a prolonged cooling in the 1950s–1970s, followed by a rapid warming until present. Therefore, linear SST trends were re-calculated using only the last 25 years of data (1982–2006). Also, SST anomalies were re-calculated relative to the 1982–2006 mean SSTs for each LME (Fig. 1, bottom). Conventional time series and linear trends of SST and SST anomalies for each LME, for 1982–2006, are provided in Appendix A. Net SST changes in each LME based on the linear SST trends in 1982–2006 are summarized in Table 1 and mapped in Fig. 2. All but two of the 63 LMEs experienced a warming trend in 1982–2006. The LMEs in Table 1 and Fig. 2 are sorted and grouped according to net SST changes between 1982 and 2006: cooling (net SST change <0 °C), slow warming (0.0–0.3 °C), moderate warming (0.3–0.6 °C), fast warming (0.6–0.9 °C) and super-fast warming (>0.9 °C). The above breakdown is arbitrary but uniform, with cell boundaries 0.3 °C apart.

The most striking result is the coherent global pattern of recent rapid warming (net SST change >0.6 °C) in the World Ocean's LMEs (Fig. 2) that can be represented by three clusters of LMEs. *Cluster 1* (Subarctic Gyre periphery) includes the Scotian Shelf, Newfoundland–Labrador Shelf, West Greenland Shelf, Iceland Shelf, Faroe Plateau, and Norwegian Sea LMEs. *Cluster 2* (European Seas) includes the North Sea, Baltic Sea, Black Sea, Mediterranean Sea, Iberian Coastal, and Celtic-Biscay Shelf LMEs, plus Red Sea. *Cluster 3* (East Asian Seas) includes the Yellow Sea, East China Sea, Japan/East Sea, and Kuroshio Current LME. The most rapid warming (>0.9 °C) is observed in the land-locked or semi-enclosed seas – Baltic Sea, North Sea, Black Sea, Japan Sea/East Sea, and East China Sea – and over the Newfoundland–Labrador Shelf. The cooling LMEs, # 3 (California Current) and # 13 (Humboldt Current), are two of the World Ocean's largest and most persistent upwelling areas in the Eastern Pacific.

Comparison of the above 1982–2006 results with the IPCC-2007 global SST warming estimates (Trenberth et al., 2007) is warranted since the IPCC-2007 estimates are based on the same data set (Hadley climatology) and nearly the same study period, 1979–2005. To simplify this comparison, the SST warming rates in the four warming LME groups were averaged and compared to the IPCC-2007 estimate (Fig. 3). The fast- and super-fast-warming LMEs (pink and red in Fig. 3) warmed at the rates 2–4 times the global average SST warming rate of 0.133 °C.

4. Discussion

The LME warming rates obtained in this study are consistent with numerous regional studies based on various data sets. The following discussion is focused on most recent warming periods that differ from one LME to another. Also provided are up-to-date estimates of SST trends and net SST changes from independent studies that reveal even higher warming rates in the 1990s–2000s, up to an order of magnitude the global mean SST warming rate of 0.133 ± 0.047 °C/decade (Trenberth et al., 2007). Finally, some possible albeit hypothetical explanations are given of the observed phenomenon of accelerated warming in Clusters 1–3.

4.1. Rapid warming Cluster 1: Subarctic Gyre

SST over the Newfoundland–Labrador, West Greenland, and Scotian shelves increased rapidly in the 1990s–early 2000s (Table 1 and Fig. 1). This rapid warming was associated with the large-scale Subarctic Gyre warming, which is amply documented (Stein, 2005, 2007; Hughes and Holliday, 2007; DFO, 2007; Petrie et al., 2007a,b). Time series from around the Labrador Sea suggest even faster warming than this study; e.g. the upper layer over Fyllas Bank and off Cape Desolation, West Greenland, warmed by 2.0–2.5 °C in 1982–2004 (∼1 °C/decade; Hughes and Holliday, 2007; data provided by Institut für Seefischerei, Germany), while the annual depth-averaged temperature on the Newfoundland–Labrador Shelf rose by 1.4 °C in 1991–2006 (∼1 °C/decade; Hughes and Holliday, 2007; data provided by the Northwest Atlantic Fisheries Centre, Canada). Rapid SST increase over the Scotian Shelf (DFO, 2007; Petrie et al., 2007a,b) was most likely associated with the concomitant decrease in the surface layer salinity and increase in vertical density stratification to its highest values in 50 years, likely caused by freshwater inflows from the Grand Banks (DFO, 2003) related to the "Great Salinity Anomalies" of the 1980s–1990s (Belkin et al., 1998; Belkin, 2004).

The Iceland Shelf and Faroe Plateau LMEs saw a rapid warming at a rate that matched or exceeded the NW Atlantic LMEs' warming rates. For example, SST in Flatey, Breidafjördur (Iceland) increased by 2 °C in 1993–2003 (Jonasson et al., 2007), which is comparable to the increase of 1.7 °C in 1995–2003 in the entire Iceland Shelf LME (this study; Appendix A). The offshore SST from Hadley data correlates well with the independent coastal SST north of Iceland (Hanna et al., 2006). The SST increased in synchrony with coastal air temperatures (Tair) around Iceland as Tair rose by >2 °C in 1995–2003 (Hughes and Holliday, 2007; IMO, 2008). Around the Faroe Islands, SST increased by 1 °C in 1992–2003 (Larsen et al., 2008), consistent with this study's estimate of SST rise in the Faroe Plateau LME by 1.3 °C in 1993–2003 (Appendix A) at a rate ∼10 times the global rate (Trenberth et al., 2007).

4.2. Rapid warming Cluster 2: European Seas

From daily monitoring surface data, since 1985, summer SST in the North and Baltic Seas increased at a rate 3 times the global rate, and 2–5 times faster than other seasons' SST (Mackenzie and Schiedek, 2007). From Hadley SST climatology used in this study, the post-1987 warming rate in the Baltic Sea exceeded 1.0 °C/decade (Fig. 1; Appendix A), more than 7 times the global rate. In the Mediterranean Sea, satellite SST in 1992–2005 rose at a rate of 0.061 °C/year (Criado-Aldeanueva et al., 2008), consistent with this report's estimate of SST rise by 1.4 °C in 1978–2003 (Appendix A) at a rate of 0.56 °C/decade or 4 times the global rate. The 1982–2003 warming magnitude increased eastward, from 0.5–1.0 °C in the Gulf of Lions and Ligurian Sea up to 2–3 °C in

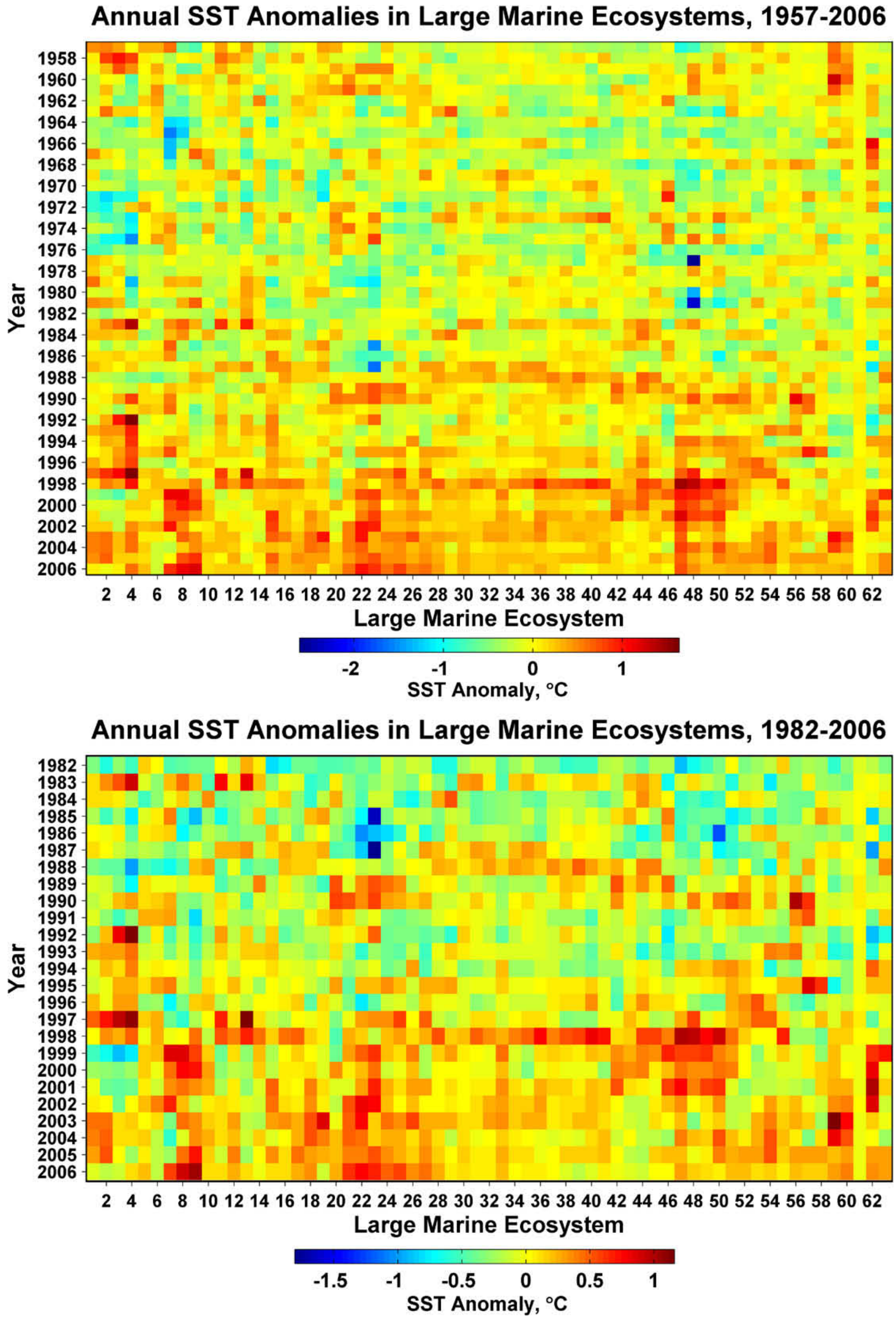

Fig. 1. Annual SST anomalies relative to the long-term annual mean SSTs, 1957–2006 (top) and 1982–2006 (bottom), computed individually for each LME. Evident is the post-1980 acceleration of global warming accentuated by El-Ninos in 1983, 1988, and 1998.

the Levantine Basin (EEA, 2007, p. 236, Map 5.9). In the Black Sea, satellite SST in 1982–2002 rose at a rate of 0.6 °C/decade; the coldest year of 1993 was a turning point after which SST rose through 2002 at a rate of >1.5 °C/decade (Ginzburg et al., 2008), consistent with this report's finding of the most rapid warming in 1992–2001 at a rate of 2 °C/decade (Appendix A).

Table 1
Net SST change in Large Marine Ecosystems (LME) between 1982 and 2006.

LME #	Large Marine Ecosystem	SST change (°C)
23	Baltic Sea	1.35
22	North Sea	1.31
47	East China Sea	1.22
50	Sea of Japan	1.09
9	Newfoundland–Labrador Shelf	1.04
62	Black Sea	0.96
8	Scotian Shelf	0.89
59	Iceland Shelf	0.86
21	Norwegian Sea	0.85
49	Kuroshio Current	0.75
60	Faroe Plateau	0.75
33	Red Sea	0.74
18	West Greenland Shelf	0.73
24	Celtic-Biscay Shelf	0.72
26	Mediterranean Sea	0.71
54	Chukchi Sea	0.70
25	Iberian Coastal	0.68
48	Yellow Sea	0.67
17	North Brazil Shelf	0.60
51	Oyashio Current	0.60
15	South Brazil Shelf	0.53
27	Canary Current	0.52
12	Caribbean Sea	0.50
19	East Greenland Shelf	0.47
28	Guinea Current	0.46
10	Insular Pacific Hawaiian	0.45
36	South China Sea	0.44
53	West Bering Sea	0.39
2	Gulf of Alaska	0.37
40	NE Australian Shelf	0.37
56	East Siberian Sea	0.36
41	East Central Australian Shelf	0.35
55	Beaufort Sea	0.34
46	New Zealand Shelf	0.32
4	Gulf of California	0.31
5	Gulf of Mexico	0.31
52	Sea of Okhotsk	0.31
16	East Brazil Shelf	0.30
63	Hudson Bay	0.28
1	East Bering Sea	0.27
32	Arabian Sea	0.26
29	Benguela Current	0.24
34	Bay of Bengal	0.24
38	Indonesian Sea	0.24
45	NW Australian Shelf	0.24
7	NE U.S. Shelf	0.23
37	Sulu-Celebes Sea	0.23
30	Agulhas Current	0.20
42	SE Australian Shelf	0.20
31	Somali Current	0.18
39	North Australian Shelf	0.17
6	SE U.S. Shelf	0.16
35	Gulf of Thailand	0.16
58	Kara Sea	0.16
11	Pacific Central-American	0.14
20	Barents Sea	0.12
57	Laptev Sea	0.12
43	SW Australian Shelf	0.09
44	West-Central Australian Shelf	0.09
14	Patagonian Shelf	0.08
61	Antarctic	0.00
3	California Current	−0.07
13	Humboldt Current	−0.10

4.3. Rapid warming Cluster 3: East Asian Seas

SST in the East China Sea rose by 2.2 °C from 1982–1998 (Appendix A at a rate of 1.4 °C/decade or >10 times the global rate. This extremely high rate is consistent with rapid warming in winter in the western East China Sea, >0.8 °C/decade (Wang, 2006); this area includes the Yangtze River estuary where warming was especially fast, up to 1 °C/decade in 1982–2003 (Ho et al., 2004). Warming in the Yellow Sea was pronounced, however its magnitude was exaggerated by a two-pronged cold spell in 1977 and 1981 (Appendix A; winter SST in the central Yellow Sea rose by >0.4 °C/decade (Wang, 2006). The Kuroshio Current LME warmed most rapidly in 1981–1998, when SST rose by 1.5 °C (∼0.9 °C/decade) (Appendix A), almost 7 times the global rate. In the Japan/East Sea, the most rapid warming occurred in 1986–1998 when SST rose by 2 °C or 1.67 °C/decade (Appendix A), >12 times the global rate. This warming was not spatially uniform across the sea since thermal histories of the northern and southern Japan Sea are decorrelated (Park and Oh, 2000) owing to a major oceanic front between them (Belkin and Cornillon, 2003).

4.4. Slow warming: Indian Ocean and Australian–Indonesian seas

The Indian Ocean LMEs and most LMEs around Australia and between Australia and Indochina experienced slow but steady warming (Fig. 2; (Appendix A)). None of them has undergone a major regime shift like many LMEs in the North Atlantic and North Pacific. The relatively slow warming rates of the Indian Ocean LMEs found in this study contradict claims of fast warming in the Indian Ocean (Alory et al., 2007; Hood et al., 2008). This apparent controversy illustrates the importance of comparative approach to trend estimations: what appeared as fast warming when considered in isolation, is in fact slow warming when compared with other LMEs.

4.5. Cooling: Eastern Pacific upwellings

The only cooling LMEs, the California Current and Humboldt Current, are both located in the Eastern Pacific upwelling areas. This collocation might be fortuitous. Alternatively, the cooling could be explained by upwelling intensification resulting from global warming as proposed by Bakun (1990) who posited that atmospheric CO_2 build-up leads to Tair increase over land compared to Tair over the ocean, thereby deepening the low pressure cell over land, increasing land–ocean pressure difference, enhancing alongshore equatorward upwelling-favorable winds, driving upwelling, and decreasing SST. This mechanism satisfactory explains the observed cooling in the Eastern Pacific. The same mechanism predicts cooling in other upwelling zones. Indeed, a rapid 20th-century increase in coastal upwelling, concomitant with a pronounced SST decrease, was observed off Cape Ghir, Northwest Africa (McGregor et al., 2007). A similar increase in 20th-century upwelling intensity was observed, for example, in the Arabian Sea (Anderson et al., 2002; Goes et al., 2005). Such observations, however, contradict to the recent slow but steady warming found in this study in most upwelling areas except for the Eastern Pacific, notably off Northwest Africa, in the Guinea Current, off Southwest Africa, in the Arabian Sea, and over the Northwest Australian Shelf (LMEs # 27, 28, 29, 32, and 45, respectively) (Figs. 1 and 2; Appendix A). These discrepancies can be explained by the fact that most paleo-oceanographic studies are usually based on a few point data (e.g. McGregor et al. (2007) analyzed two sediment cores from the same location off Cape Ghir), whereas the SST data presented in this report are obtained by LME-wide spatial averaging. Moreover, most studies of upwelling areas rely on SST time series obtained in upwelling centers close to the shore (e.g. McGregor et al., 2007), whereas the respective LMEs extend hundreds km offshore.

4.6. Rapid warming: possible causes

The recent rapid warming of Cluster 1 has likely resulted from natural climate variability. Indeed, the post-1996 warming of the Subarctic Gyre began nearly simultaneously with the North Atlantic Oscillation (NAO) index switch in 1995–1996 from strongly positive values typical of the 1973–1995 period to negative or weakly positive values afterwards. Under the positive NAO, the Subarctic

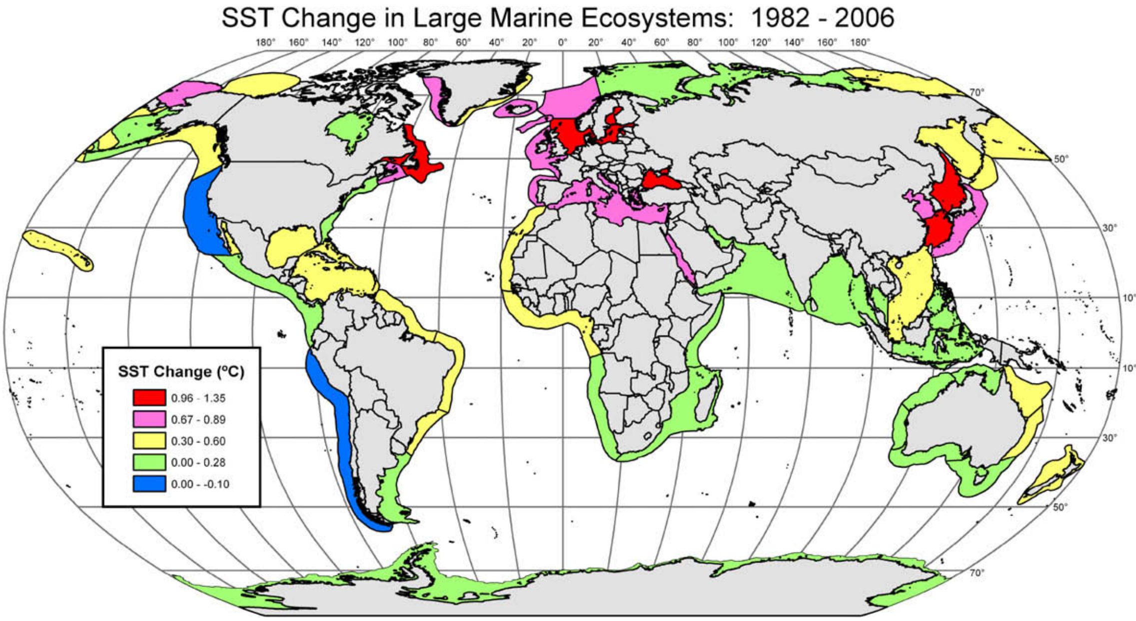

Fig. 2. Net SST change (°C) in Large Marine Ecosystems, 1982–2006. Rapid warming (red and pink) is observed around the North Atlantic Subarctic Gyre, in the European Seas, and in the East Asian Seas. The Indian Ocean LMEs and Australian–Indonesian seas warmed at slow rates. The California and Humboldt Current LMEs cooled.

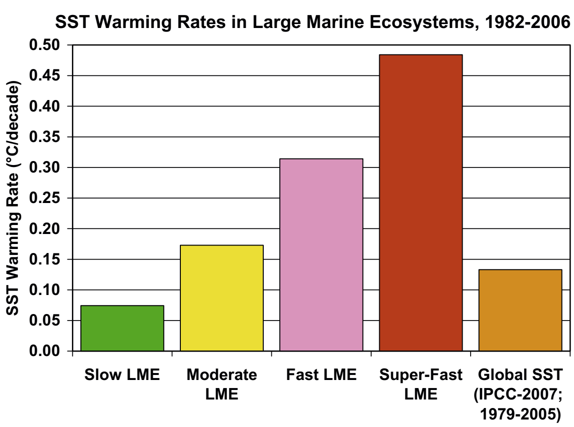

Fig. 3. Comparison of SST warming rates in Large Marine Ecosystems (this study, 1982–2006) with the IPCC-2007 global mean SST warming rate, 1979–2005 (Trenberth et al., 2007). Color palette is the same as in Fig. 2.

Gyre (Baffin Bay, Labrador Sea, and Irminger Sea) was dominated by strong and persistent cold northwestern winds from the Canadian Arctic. Once the NAO index flipped in 1995–1996, these cold winds collapsed and a milder climate set up over the Subarctic Gyre and adjacent shelves of West Greenland and Canadian Maritimes. This dramatic climate shift also affected the Iceland Shelf, Faroe Plateau, and Norwegian Sea, owing in part to advection by the Irminger Current, North Atlantic Current, and Norwegian Atlantic Current, respectively.

The rapid warming in Clusters 2 and 3 might have had a different origin. Nearly all these seas are situated between land masses that have undergone rapid warming since 1979 (Trenberth et al., 2007, p. 253, Fig. 1, bottom left). This very proximity and the semi-enclosed or land-locked nature of these seas suggest a possibility that the rapid warming in Clusters 2 and 3 might have been caused in part by the nearby land warming (natural or anthropogenic). Indeed, surface air temperature in Europe, Middle East, and East Asia increased in 1979–2005 at rates between 0.35–0.75 °C/decade or 2–4 times the global mean surface temperature warming rate of 0.177 ± 0.052 °C/decade between 1981 and 2005 (Trenberth et al., 2007, p. 253). Also, the LMEs from Clusters 2 and 3, except the Red Sea, are adjacent to heavily populated industrialized countries, suggesting that the rapid warming in the landlocked and semi-enclosed European and East Asian LMEs may in part be of direct anthropogenic origin.

4.7. Freshwater runoff and rapid warming of coastal seas

The most rapid warming in Clusters 2 and 3 occurred in those LMEs whose salinity regime is significantly affected by freshwater runoff, e.g. the North Sea, Baltic Sea, Black Sea (primarily its sizable Northwest Shelf), and East China Sea. In these LMEs, river runoff in spring–summer creates a buoyant surface layer that traps solar radiation, thereby enhancing vertical stratification through positive feedback. Therefore, SST in such LMEs is strongly affected by river runoff. For example, the Yangtze (Changjiang) River discharges ~800 Gt/year of fresh water to the East China Sea, creating a buoyant plume spreading across the sea. In summer, positive temperature differential between the warm plume and colder offshore water further enhances vertical stratification and solar heat trapping by the upper layer. The Yangtze River runoff is an important seasonal heat source to the East China Sea since (a) the river runoff peaks during summer when riverine water is warmer than offshore water (Zhang et al., 2007; Yang, in press), and (b) stream temperature in the Yangtze Estuary increased by ~2 °C since 1986 (Zhou et al., 2005), thereby contributing to the extremely rapid warming observed in the western East China Sea (Ho et al., 2004) (Fig. 4).

It is particularly important that freshwater runoff from the surrounding land masses can affect the coastal ocean SST *indirectly*, by enhancing stratification (=vertical density gradient), thereby enhancing the upper mixed layer's ability to trap solar radiation. In fact, this mechanism seems to be much more important than heat transport by river plumes. Indeed, most river plumes would only act as heat sources during a certain season, when the plume is warmer than the coastal sea. For example, the Danube River Plume acts as heat source for the Black Sea during two spring months when the Danube discharge is warmer than the surface

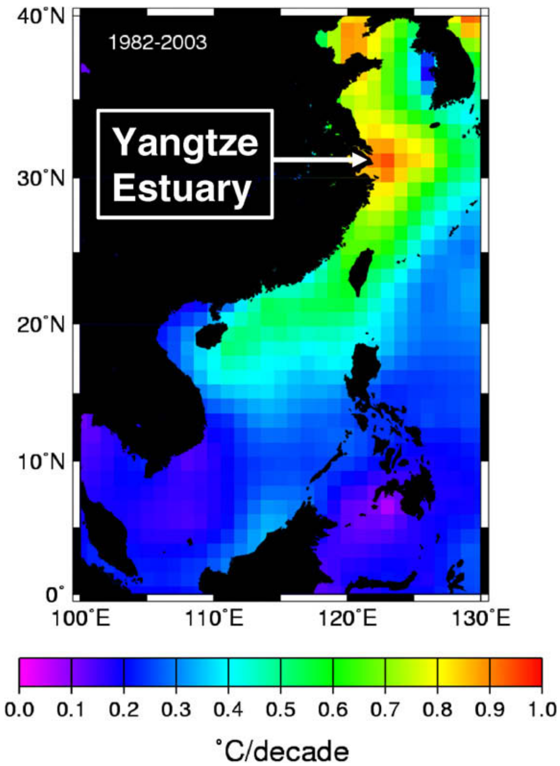

Fig. 4. Mean SST trends in the China Seas from Pathfinder AVHRR monthly data, 1982–2003 (modified after Ho et al., 2004, Fig. 4). Evident is accelerated warming off the Yangtze Estuary, at a rate of up to 1.0 °C/decade, about 8 times the global mean SST trend of 0.133 °C/decade in 1979–2005 (Trenberth et al., 2007).

waters over the Northwest Shelf; during the rest of the year, the riverine discharge is colder than the shelf waters (data courtesy of Y. Popov, personal communication, 2008).

5. Summary

The U.K. Meteorological Office Hadley Centre SST climatology was used to compute 50-year time series (1957–2006) of sea surface temperature (SST) and examine SST trends in the World Oceans' 63 LMEs. Reflecting a global trend, warming in most LMEs accelerated in late 1970s–early 1980s. Of the 63 LMEs, 61 warmed and only two cooled in 1982–2006. Linear SST trends for each LME show a distinct global pattern of rapid warming in three regions: around the Subarctic Gyre; in the European Seas; and in the East Asian Seas. Decadal rates of SST warming in these three regions are 2–4 times the global mean rate. These estimates are rather conservative as numerous independent studies based on various data sets reveal even higher rates in the 1990s–2000s, up to 10–12 times the global mean rate. The Subarctic Gyre warming is likely caused by natural variability related to the North Atlantic Oscillation. The proximity of the European and East Asian Seas to major industrial/population agglomerations suggests a possible direct anthropogenic effect. Freshwater runoff in the European and East Asian Seas likely plays a special role in modulating and exacerbating global warming effects on the regional scale.

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Appendix A. Supplementary data

Supplementary data (time series of SST and SST trends for 63 Large Marine Ecosystems) associated with this article can be found, in the online version, at doi:10.1016/j.pocean.2009.04.011.

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