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Variability of Large Marine Ecosystems in response to global climate change

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Abstract:
A fifty year time series of sea surface temperature (SST) and time series on fishery yields are examined for emergent patterns relative to climate change. More recent SeaWiFS derived chlorophyll and primary productivity data were also included in the examination. Of the 64 LMEs examined, 61 showed an emergent pattern of SST increases from 1957 to 2006, ranging from mean annual values of 0.08°C to 1.35°C. The rate of surface warming in LMEs from 1957 to 2006 is 4 to 8 times greater than the recent estimate of the Japan Meteorological Society's COBE estimate for the world oceans. Effects of SST warming on fisheries, climate change, and trophic cascading are examined. Concern is expressed on the possible effects of surface layer warming in relation to thermocline formation and possible inhibition of vertical nutrient mixing within the water column in relation to bottom up effects of chlorophyll and primary productivity on global fisheries resources.

1. Background

Large Marine Ecosystems (LMEs) are an important component of a hierarchical scientifically-founded marine geographical construct published in 2003 (Watson et al., 2003). Since 1995, the LMEs have been designated by a growing number of coastal countries in Africa, Asia, Latin America and eastern Europe as place-specific assessment and management areas for introducing an ecosystem based approach to recover or develop and sustain marine resources. The LME approach to the assessment and management of marine resources is based on the operationalization of five modules with suites of indicators for monitoring and assessing changing conditions in ecosystem: (i) productivity, (ii) fish and fisheries (iii) pollution and ecosystem health, (iv) socioeconomics and (v) governance (Duda and Sherman, 2002). As part of an emerging effort by the scientific community to relate ecosystem-based management to policy makers, 220 marine scientists and policy experts released a statement in support of matching natural ecological units of ocean space, including LMEs, to scientific studies on the structure and function of marine ecosystems in an effort to tighten the linkage between applied science and improved management of ocean resources (COMPASS, 2005).

A recent paper published in the National Academy of Science Proceedings (Essington et al., 2006), along with a growing number of LME case study volumes and reports (Table 1), including the recent controversial biodiversity loss paper in *Science* (Worm et al., 2006), have made good use of the LMEs as ecologically derived units of ocean space that are directly related to the assessment and management of marine resources around the globe.

Since 1995, explicit support has been extended by international financial organizations to developing coastal countries for assessing and managing LMEs and their goods and services using an LME approach. At present 110 countries are engaged in LME projects along with 5 UN agencies, the Global Environment Facility and the World Bank. The countries are supported by $1.8 billion in financial assistance to 16 LME projects focused on introducing an ecosystems approach to the recovery of depleted fish stocks, restoration of degraded habitats, reduction and control of pollution and conservation of biodiversity (Sherman et al., 2007).

The LME approach advances ecosystem-based management (EBM) with a long-term assessment strategy that measures "core" suites of indicators from primary productivity in relation to LME carrying capacity for fish and fisheries to the socioeconomic benefits of sustainable development of ecosystem goods and services. One of the growing issues in the management of LMEs is the effect of global climate change and warming on the fish and fisheries of the LMEs. In this report we provide the results of our initial examination of the physical extent and rates of sea surface temperature trends, chlorophyll, and primary productivity of the world's 64 LMEs.

2. LME Chlorophyll and Primary Productivity

Daily binned global SeaWiFS chlorophyll *a* (CHL, mg m^{-3}) and photosynthetically available radiation (PAR, Einsteins m^{-2} d^{-1}) scenes at 9 km resolution for the period January 1998 through December 2006) were obtained from NASA OBPG. Daily global sea surface temperature (SST, ^{o}C) measurements at 4 km resolution were derived from nighttime scenes composited from the AVHRR sensor on NOAA's polar-orbiting satellites and from NASA's MODIS TERRA and MODIS

AQUA sensors. Daily estimates of primary productivity (PP, gC m^{-2} d^{-1}) were generated using a vertically generalized productivity model (VGPM2) that calculates the daily amount of carbon fixed based on the maximum rate of chlorophyll-specific carbon fixation in the water column (P^b_{opt}, mgC $mgChl^{-1}$ h^{-1}); daily sea surface PAR; the euphotic depth (Z_{eu}, m); CHL; and the number of daylight hours (DL, h). The VGPM2 is similar to the Behrenfeld and Falkowski (1997) VGPM, but uses an exponential model relating P^b_{opt} (mgC $mgChl^{-1}$ h^{-1}) to SST (Eppley, 1972) as modified by Antoine et al. (1996) Estimates of the euphotic depth (1% surface PAR) were derived from CHL according to Morel and Berthon (1989). Monthly and annual means of CHL and PP were extracted and time series trends plotted for each LME (Figures 1 and 2). A simple linear regression of the annual CHL and PP was used to determine the rate of change over time. The significance (alpha+0.01 and 0.05) of the regression coefficient was calculated using a t-test according to Sokal and Rohfl (Sokal and Rohlf, 1995). The results were statistically significant for chlorophyll trends in only 8 LMEs, and in 5 LMEs for primary productivity (Table 2)

3. LME Sea Surface Temperatures (SST)

Sea surface temperature (SST) data is the only thermal parameter routinely measured worldwide that can be used to characterize thermal conditions in each and every LME. Subsurface hydrographic data, albeit important, lack spatial and temporal density required for reliable assessment of thermal conditions at the LME scale worldwide. The U.K. Meteorological Office Hadley Center SST climatology was used in the analysis as the Hadley data set has the best resolution, 1 degree latitude by 1 degree longitude globally and, since the project goal was to assess thermal conditions over the last 49 years, we needed a data set that goes as far back as 1957. The Hadley data set meets this condition. A highly detailed, research-level description of this data set has been published by (Rayner et al., 2003).

The Hadley data set consists of monthly SSTs calculated for each 1° x 1° rectangular cell (spherical trapezoid, to be exact) between 90°N-90°S, 180°W-180°E. Our goal was to calculate and visualize **annual** **SSTs** for **each LME**. We have calculated annual SST for each 1° x 1° cell and then have **area-averaged** annual 1° x 1° SSTs within each LME. Since the square area of each trapezoidal cell is proportional to the cosine of the middle latitude of the given cell, 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 that is by the sum of the cosines.

The next step was to calculate annual anomalies of annual LME-averaged SST. To this goal, the long-term LME-averaged SST was computed for each LME by a simple long-term averaging of the annual area-weighted LME-averaged SSTs. Then, annual SST anomalies were calculated by subtracting the long-term mean SST from the annual SST. Both SST and SST anomalies were visualized using adjustable temperature scales for each LME in order to bring out details of temporal variability that otherwise would be hardly noticeable if a unified temperature scale were used. The resulting plots of SST and SST anomalies are presented in 2 sets of 4 plates, each set containing a total of 63 figures: four plates for SST and four plates for SST anomalies (Figures 3 and 4). The Arctic Ocean LME was not included in this analysis because of the perennial sea ice cover that prevents meaningful assessment of the LME-averaged SST. Other Arctic LMEs also feature sea ice cover that essentially vanishes in summer, thus making summer SST assessment possible.

The 1957-2006 time series revealed a global pattern of long-term warming (Figures 3 and 4). At the same time, the long-term SST variability since 1957 was neither statistically stationary nor uniform. Most LMEs underwent a prolonged cooling between the 1950s and the 1970s, replaced by a rapid warming until present. Therefore we re-calculated SST trends using only the last 25 years of data (Figures 5 and 6), where SST anomalies are calculated relative to the 1957-2006 mean SST, for each LME. Net SST change in each LME between 1982 and 2006 based on SST trends shown in Figure 5 is summarized in Table 3 and Figure 7.

The most striking result is the wide-spread, global pattern of warming, with the notable exceptions of two LMEs, the California Current and Humboldt Current. These LMEs experienced cooling over the last 25 years. Both LMEs are in the largest and most persistent upwelling areas in the Eastern Pacific.

The average warming rate of LMEs (Table 3) is several times the global SST warming rate (Yoshida et al., 2006). Since most LMEs are located within the coastal ocean realm, our results reveal that the coastal ocean is warming much faster than the deep ocean.

Rapid warming exceeding 0.6°C (or roughly 1°F) over 25 years is observed almost exclusively in moderate- and high-latitude LMEs. This pattern is generally consistent with the model-predicted *polar-and-subpolar amplification* of global warming. Low-latitude LMEs' warming is several times slower than the high-latitude warming. The most rapid warming exceeding 1.0°C over 25 years is only observed in the Baltic Sea, North Sea, Black Sea, Sea of Japan/East Sea, East China Sea and Newfoundland-Labrador Shelf LMEs.

Comparison of LME SST levels versus global SST warming

Warming was observed in 61 LMEs, whereas slight cooling was only observed in two LMEs located in the Eastern Pacific. We divided the 61 warming LMEs into four groups according to their warming rates (Table 3; Figure 7):

(a) Super-fast warming LMEs (red), with D(SST)>0.9°C;
(b) Fast warming LMEs (pink), with D(SST) between 0.6-0.9°C;
(c) Moderate warming LMEs (yellow), with D(SST) between 0.3-0.6°C;

(d) Slow warming LMEs (green), with D(SST) between 0.0-0.3°C.

The LME warming rates were compared to *in situ* SST global data of the Japan Meteorological Society and their estimate of a global ocean warming rate of +0.5°C/100 yr (Yoshida et al., 2006).

The "red" LMEs were warming with an average rate exceeding 1°C over 25 years, equivalent of 4°C over a century. This rate is **eight** times the global SST warming rate of 0.5°C over the last century determined from *in situ* data (Yoshida et al., 2006). Even the moderate-rate "yellow" LMEs were warming with a rate of 0.45°C over the last 25 years or approximately **four** times the global SST warming rate over the last century.

It must be stressed that the above comparisons are warranted since (a) the global SST warming rate was determined from ***in situ*** data, thus being completely independent from satellite SST data that are sometimes questioned; and (b) the global SST warming since 1910 is well-described by a ***linear*** trend, unlike the global ***surface air temperature*** trend; the latter having distinct breakpoints, including a sharp acceleration since 1976-1977 (Yoshida et al., 2006).

4. .Fish and Fisheries

Examination of the fish and fisheries of the Red Zone LMEs revealed that considerable ecological stress has been reported for all six LMEs. Two of the semi-enclosed LMEs—the Baltic and the Black Sea—are in degraded condition from overfishing and eutrophication. Ecosystem effects of overfishing are reported by Daskalov (2003) for the Black Sea LME who also describes the impact of non-indigenous coelenterates and eutrophication on the ecosystem. Both stressors are considered secondary to the overfishing depletion of top predators causing a cascading change in dominance of the pelagic food web after 1970 (Daskalov, 2003).

In the case of the Baltic Sea, large scale decreases in cod, herring, eel, and salmon biomass and an increase in sprat are cause for concern (Jansson, 2003), as is the frequency and extent of coastal eutrophication events (HELCOM, 2001). The effects of relatively rapid increase in SST on the ecosystem are being studied and will undoubtedly be addressed by the GEF supported projects in both LMEs, with oversight by the Black Sea Commission, and HELCOM and ICES for the Baltic LME.

Temperature increases in the North Sea LME are of concern based on earlier reports of northward extensions of North Sea zooplankton (Beaugrand and Ibanez, 2004; Beaugrand et al., 2002) and fish species and incursions of southern zooplankton species and fish species advancing northward (Perry et al., 2005), and the continuing decline in the abundance of demersal fish species. In the Northeast Atlantic SST warming leads to increasing phytoplankton abundance in nutrient-rich cooler areas and decreasing phytoplankton in warmer areas (Richardson and Schoeman, 2004). Their findings raise the question of the relative importance of stratification in the annual biological production cycle of plankton in the North Sea LME, suggesting that warmer waters may lead to stratification that will inhibit nutrient missing and thereby limit plankton production. The argument is brought forward further by Schmittner, who argues based on projections with climate models that a disruption of the Atlantic meridional overturning circulation could lead to a collapse of North Atlantic plankton to less than half of their initial biomass, owing to rapid shoaling of winter mixed layers and their subsequent discontinuity from nutrient-rich deeper waters (Schmittner, 2005). Examination of LME chlorophyll and primary productivity SeaWiFS time series showed no significant differences for waters of the North Sea (Table 2). At this point in time our observations suggest that further investigation of the seasonal nutrient cycle will need to be closely examined to test the Schmittner hypothesis.

Two Asian LMEs have experienced high temperature increases—the East China Sea and the Sea of Japan/East Sea. The fisheries of the East China Sea have undergone a major shift from dominance of herring, croaker, cuttlefish and jellyfish in the 1960s and 1970s to a shift in species dominance of shrimp, crab, mackerel, filefish and hairtail in the 1980s (Chen and Shen, 1999) and 1990s coincident to the major shift in SST anomalies from a cooling period from the 1960s to 1980s followed by positive anomalies in the 1990s.

In the Sea of Japan/East Sea, a major shift in biomass yields occurred in the late 1970s with a reduction of anchovy, and increases of herring (Terazaki, 1999). The SST temperature anomalies following a negative period in the mid 1980s, turned positive in the late 1980s through the early 1990s coincident with increases in yields of yellowtail, herring and anchovy (Terazaki, 1999).

The collapse of the cod stocks in the Newfoundland-Labrador Shelf LME is well documented. Rice (2002) reports on the importance of excessive fishing mortality as a primary cause, and considers that “harsh environmental conditions” including extreme cold also contributed “in some manner” to the population collapses” (Rice, 2002). It is not clear at present what effect the SST warming trend may have on the altered structure of the LME.

In the case of the Iceland Shelf LME, it has been argued that during periods of incursions of warm Atlantic waters, the ecosystem responds positively with increased Cod growth and yield; whereas in years of polar water incursions, cod growth and yield are reduced (Astthorsson and Vilhjalmsson, 2002). The onset of SST positive increases since 1999 does not appear to be reflected by significant increasing trends in mean annual chlorophyll or primary production levels (Table 2).

In the Norwegian Sea LME, Skjoldal and Saetre (2004) report that since 1995 the warming trend is related to the dominant presence of warm-high salinity Atlantic waters. This has been accompanied by an increase in the abundance of the zooplanktiverous blue whiting, with recruitment pattern and landings of nearly 1.6 million metric tons in 2002 (Skjoldal and Saetre, 2004), and northward spatial increases in herring abundance during the late 1990s beginning with a strong 1983 year class which coincides with the SST increase in mean annual temperature from 8°C following a relatively cold period in the 1970s and a shift in the NAO index from low to high (Skjoldal and Saetre, 2004). Increases in biomass of the Northeast Atlantic mackerel stock have also been reported). The SeaWiFS chlorophyll and primary productivity time series for the Norwegian Sea were not significantly different (Table 2).

The response to temperature increases observed in the Faroe Plateau LME is not known at this time. Earlier studies suggest a close coupling between increases in primary productivity and cod, haddock, and marine bird biomass, productivity (Gaard et al., 2002). SeaWiFS mean annual Chlorophyll and primary productivity levels for the Faroe Plateau LME, over the nine year time series (1998-2006) were not significantly different (Table 2) .

In the West Greenland Shelf LME (Pedersen and Rice, 2002), reported catch levels of cod, redfish, Greenland halibut and shrimp have been related to excessive fishing mortality. Cod and redfish landings declined from the 1960s to the early 1970s. In contrast, catches of Greenland Halibut increased from the early 1970s through the 1990s. No significant mean annual differences in chlorophyll or primary productivity levels were detected in the SeaWiFS time series (Table 2).

In the case of the Scotian Shelf LME, the reports by Choi et al. (2004) and Frank et al. (Frank et al., 2005) document the collapse of the cod and other demersal fish components of the ecosystem as viable economic resources. The effect of temperature on the decline of the Cod and other demersal stocks appears as secondary to overfishing and the trophic cascade effects on the ecosystem. The increases in SST temperatures have not resulted in a significant positive feedback in the SeaWiFS chlorophyll levels or in primary productivity over the nine year time series.

The warming trend in the Biscay Bay subarea of the Celtic-Biscay Shelf LME were investigated by Valdes and Lavin (2002). They relate surface warming to increased thermal stratification and in turn link this focus to a "linear decreasing relationship to the number of copepod species observed in the Bay of Biscay, due to a reduction in nutrients to the surface layers. However, the effects of temperature increasing the important anchovy stocks of the Biscay subarea are not included in the Valdez and Lavin report. They do note, however, increased presence of tropical fish species in the southeast shelf area of the Bay of Biscay; along with a subtropical copepod, *Temora stylifera*.

The mean annual catches of the fisheries of the Mediterranean Sea LME since the mid 1980s have remained at a level of one million metric tons through 2003; however, since 1985 a decline has been observed for the mean annual trophic level of the catch (SAUP, 2007). The period of trophic level change is coincident to the post 1980s doubling of the "other" taxa category of species that are apparently dominated by lower trophic level species. During the past 9 years, however, there have been no concomitant significant increases in mean annual chlorophyll levels. However, primary productivity levels in the Mediterranean appear to be in a declining trend (Table 2).

In the Red Sea annual average catches have been increasing since the mid 1970s as in the Mediterranean, the mean annual biomass yields of unidentified taxa increased from 1990 through 2003 coincident with the SST mean annual warming accompanied by significant increases in chlorophyll ($P< 0.01$; Table 2) but not in primary productivity. The post 1993 unidentified species are likely to include smaller species lower in the food chain as the mean trophic index declined from 3.8 in 1993 to 3.6 in 2000 (SAUP, 2007).

The fisheries of the Iberian Coastal LME underwent a shift in species composition in the 1970s. The principal shift from cold to warming of SST was initiated in 1984. During the period 1984 through 2003, the mean annual level of catch ranged between 400,000mt and 500,000 mt. Approximately 50% of the catch is listed as "other" taxa (SAUP, 2007). During this period, chlorophyll and primary production Sea WiFS time series levels were not significantly different.

Around the margins of the North Pacific, two LMEs are in the Red Zone of SST change: the Chukchi Sea and the Yellow Sea. The important living marine resources of the Chukchi Sea LME are salmon and herring, halibut and pollock. The warming trend depicted in figure 5 is not accompanied by any significant recent evidence of SeaWiFS derived chlorophyll or primary productivity increases (Table 2). It is likely that with increasing ice melt, that the biomass of renewable resources within the LME will undergo significant growth.

The Yellow Sea LME has undergone major changes in fisheries biomass yields. Important demersal species were depleted by the mid 1970s and replaced by fast growing smaller pelagic herring and anchovies in the 1990s (Tang, 2003). Since 1984, the LME has been in a warming period, that has not, as yet, resulted in any significant increase in chlorophyll or primary productivity (Table 2). In an effort to recover depleted demersal fish stocks, China has closed the Yellow Sea to fishing by Chinese registered vessels to protect juvenile stages (Tang, 2003).

5.. LMEs in yellow and green zones in relation to Changing Ecological Conditions

The high rate observed of SST warming of LMEs in the Red Zone indicates that the deeper waters of the ocean basins are responding more slowly to climate change. The global extent of the Red, Yellow, and Green Zones where SSTs are increasing are all areas of LMEs with relatively higher chlorophyll and primary productivity levels than open ocean areas, and where 95% of the world's annual marine fisheries are produced, coastal habitats are seriously degraded, biodiversity is stressed, and coastal pollution is concentrated (Figure 7).

It is important for marine resource scientists, policy experts, and managers to maintain close monitoring of ecological conditions effecting an estimated $12.6 trillion in annual value to the global economy (Costanza et al., 1997). Although we found a limited number of significant trends in examination of SeaWiFS chlorophyll and primary productivity changes (Table 2), it is important to maintain cognizance of possible temperature responses affecting primary productivity as in the cases of the Humboldt Current and California Current LMEs where values are increasing in contrast to the Bay of Bengal, Caribbean Sea, Kuroshio Current and Mediterranean Sea LMEs where mean annual primary productivity levels are decreasing. The Humboldt Current chlorophyll is also in an increasing trend, as are the chlorophyll levels of the Barents Sea, Hudson Bay and Red Sea LMEs. Negative correlations in the chlorophyll time series were observed for the East Siberian Sea, the East China Sea, and the Bay of Bengal, where primary productivity values were also decreasing. It is interesting to note that primary productivity increases in the Humboldt Current and California Current where mean annual SST values were negative. Both LMEs are in the world's strongest marine upwelling areas suggesting that strong vertical mixing reduces thermocline discontinuities and promotes nutrient enrichment of biologically active photic zone surface layers. The Red Zone LMEs, in contrast, are at risk of greater thermal stratification of surface waters inhibiting nutrient exchanges with deeper layers and thereby limiting chlorophyll and primary production (Li, 2002; Roemmich and McGowan, 1995)(Richardson and Schoeman, 2004; Schmittner, 2005).

In the Yellow and Green Zones, where the SST changes are less than in the Red Zone, policy and management experts should be aware that changes affecting fish and fisheries are already being reported for the areas of significant oceanographic regime shifts. In the Yellow Zone, oceanographic regime changes have been reported as important drivers of biomass variability within the Guinea Current LME (Koranteng, 2002a; Koranteng, 2002b; Roy et al., 2002).

In the Green Zone of the North Pacific for the Gulf of Alaska LME, biomass increases have been reported for zooplankton, related to an oceanographic regime shift in the North Pacific in the mid 1970s (Brodeur et al., 1999). More recently, changes have been reported for the East Bering Sea LME, where fisheries are increasing in biomass yields for salmon and Alaska Pollock

(Overland et al., 2005). The major oceanographic shift occurred in the mid 1970s as can be seen in the shift in SST trends from a cooling period from the 1960s to the warming from 1975 through 2006 (Figure 7).

In the Atlantic Green Zones, changing oceanographic conditions in the Benguela Current have been reported (Lingen et al., 2006). Recently, a southward shift in clupeid distribution has severely impacted the fisheries of Namibia by separating fish processing plants in Namibia from pilchard biomass moving south along the coast of South Africa and toward the east in the vicinity of the Agulhas Banks off southeast South Africa The southward moving pilchard are an important food species for penguins inhabiting the Islands off Namibia. In search of the pilchards, penguin colonies are also moving southward in the Benguela LME, leaving the protection of the islands where they are less exposed to predation to occupy coastal areas of South African coast where they are more vulnerable to predation (Koenig, 2007).

From a trophodynamic perspective, two of the Asian LMEs—the Yellow Sea LME (YSLME) and the Gulf of Thailand LME (GoTLME) are in a stressed ecosystem condition. In both cases, evidence of “fishing-down-the-food-web” has been brought forward. For the YSLME, Tang has demonstrated the loss of important demersal stocks and the subsequent dominance of small fast-growing pelagic species (Tang, 1989; Tang, 1993; Tang, 2003). Pauly and Chuenpagdee (2003) provide a comprehensive time series analysis of the seriously overfished GoTLME, and recommend a “drastic reduction of fishing” effort to recover depleted stocks. As noted previously, China has taken measures to reduce fishing effort by Chinese fishermen in the YSLME (Tang, 2003). In both cases, the influence of increasing temperatures on the management efforts to recover depleted fish stocks should be taken into consideration in stock rebuilding plans.

We express concerns over the accelerated rate of SST increases that can lead to increased productivity at the base of the food web in vertically mixed cool upwelling waters. However, in shoal warm coastal waters, the influence of surface water heating results in a strengthened pycnocline, thermoclyne and reduced nutrient mixing within the water column. This can lead to a reduction in plankton-zooplankton population growth (Li, 2002; Richardson and Schoeman, 2004; Roemmich and McGowan, 1995; Schmittner, 2005). Current LME and reproductive leading to secondary limits in fish growth and survival.

The next phase of our investigation is directed to an examination of the effects of warming on the entire water column within each of the LMEs in an effort to monitor and assess the effects of warming on chlorophyll and primary productivity in relation to bottom up effects on fish and fisheries stock recovery and sustainability.

References

Antoine, D., Andre, J.-M. and Morel, A., 1996. oceanic primary production 2. Estimation at global scale from satellite (coastal zone color scanner) chlorophyll. Global Biogeochemical Cycles, 10((1)): 57-69.

Astthorsson, O.S. and Vilhjalmsson, H., 2002. Iceland Shelf large marine ecosystem. In: K. Sherman and H.R. Skjoldal, eds (Editors), Large marine ecosystems of the North Atlantic: Changing states and sustainability. Elsevier Science, Amsterdam, pp. 219-244. 449p.

Beaugrand, G. and Ibanez, F., 2004. Monitoring marine plankton ecosystems. II: Long-term changes in North Sea calanoid copepods in relation to hydro-climatic variability. Mar Ecol Prog Ser, 284(December 21): 35-47.

Beaugrand, G., Reid, P.C., Ibanez, F., Lindley, J.A. and Edwards, M., 2002. Reorganization of North Atlantic Marine Copepod Biodiversity and Climate. Science, 296(): 1692-1694.

Behrenfeld, M.J. and Falkowski, P.G., 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography, 42((1)): 1-20.

Brodeur, R., Frost, B., Hare, S., Francis, R. and Ingraham, J., 1999. Interannual Variations in Zooplankton Biomass in the Gulf of Alaska, and Covariation with California Current Zooplankton Biomass. In: K. Sherman and Q. Tang (Editors), Large Marine Ecosystems of the Pacific Rim. Large Marine Ecosystems. Elsevier, pp. 106-138.

Chen, Y.-Q. and Shen, X.-Q., 1999. Changes in the biomass of the East China Sea ecosystem. In: K. Sherman, eds and Q. Tang, eds (Editors), Large marine ecosystems of the Pacific Rim: Assessment, sustainability and management. Blackwell Science, Malden, MA, pp. 221-239. 465p.

Choi, J.S., Frank, K.T., Leggett, W.c. and Drinkwater, K., 2004. Transition to an alternate state in a continental shelf ecosystem. Can. J. Fish. Aquat. Sci., 61: 505-510.

COMPASS, 2005. Communication Partnership for Science and the Sea: Scientific Consensus Statement on Marine Ecosystem-Based Management Released 21 March 2005. For full text of the Consensus Statement, www.compassonline.org/pdf_files/EBM_Consensus_Statement_v12.pdf.

Costanza, R. et al., 1997. The value of the world's ecosystem services and natural capital. Nature, 387: 253-260.

Daskalov, G.M., 2003. Overfishing drives a trophic cascade in the Black Sea. In: G. Hempel and K. Sherman (Editors), Large Marine Ecosystems of the World: Trends in Exploitation, Protection, and Research. Elsevier Science, the Netherlands, pp. 171-191.

Duda, A.M. and Sherman, K., 2002. A new imperative for improving management of large marine ecosystems. Ocean & Coastal Management, 45(2002): 797-833.

Eppley, R.W., 1972. Temperature and phytoplankton growth in the sea. Fishery Bulletin, 70((4)): 1-20.

Essington, T.E., Beaudreau, A.H. and Wiedenmann, J., 2006. Fishing through marine food webs. PNAS, 103(9): 3171-3175.

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.

Gaard, E., Hansen, B., Olsen, B. and Reinert, J., 2002. Ecological Features and Recent Trends in the Physical Environment, Plankton, Fish Stocks, and Seabirds in the Faroe Shelf Ecosystem. In: K. Sherman and H.R. Skjoldal (Editors), Large marine Ecosystems of the North Atlantic. Large Marine Ecosystems. Elsevier, pp. 245-266.

HELCOM, 2001. Environment of the Baltic Sea area, Baltic Sea Environment Proceedings No. 82A. Helsinki Commission, pp. 23p.

Jansson, B.-O., 2003. The Baltic Sea. In: G. Hempel and K. Sherman (Editors), Large Marine Ecosystems of the World. Elsevier Science, The Netherlands, pp. 145-170.

Koenig, R., 2007. African Penguin Populations Reported in a Puzzling Decline. Science, 315(2 March): 1205.

Koranteng, K., 2002a. Fish Species Assemblages on the Continental Shelf and Upper Slope off Ghana. In: J. McGlade, P. Cury, K. Koranteng and N. Hardman-Mountford (Editors), The Gulf of Guinea Large Marine Ecosystem. Large Marine Ecosystem. Elsevier, pp. 173-188.

Koranteng, K., 2002b. Status of Demersal Fishery Resources on the Inner Continental Shelf off Ghana. In: J. McGlade, P. Cury, K. Koranteng and N. Hardman-Mountford (Editors), The Gulf of Guinea Large Marine Ecosystem. Large Marine Ecosystem. Elsevier, pp. 261-274.

Li, W.K.W., 2002. Nature, 419.

Lingen, C.v.d. et al., 2006. Resource and ecosystem variability, including regime shifts, in the Benguela Current system. In: V. Shannon, G. Hempel, P. Malanotte-Rizzoli, C. Moloney and J. Woods (Editors), Benguela: Predicting a Large Marine Ecosystem. Large Marine Ecosystems. Elsevier, pp. 147-184.

Morel, A. and Berthon, J.-F., 1989. Surface pigments, algal biomass profiles, and potential production of the euphotic layer: Relationships reinvestigated in view of remote sensing applications. Limnology and Oceanography, 34((8)): 1545-1562.

Morgan, J.R., 1989. Large marine ecosystems in the Pacific Ocean. In: K. Sherman and L.M. Alexander, eds (Editors), Biomass yields and geography of large marine ecosystems. AAAS Selected Symposium 111. Westview Press, Inc., Boulder, CO, pp. 377-394.

Overland, J.E., Boldt, J. and Stabeno, P.J., 2005. Multiple indicators track major ecosystem shifts in the Bering Sea., J.E. Overland, J. Boldt, P.J. Stabeno. Multiple indicators track major ecosystem shifts in the Bering Sea. ICES CM 2005/M:21, ICES CM 2005/M:21.

Pauly, D. and Chuenpagdee, R., 2003. Development of fisheries in the Gulf of thailand large marine ecosystem: Analysis of an unplanned experiment. In: G. Hempel and K.e. Sherman (Editors), Large marine ecosystems of the world: Trends in exploitation, protection and research. Elsevier Science, Amsterdam, Netherlands, pp. 337-354. 423p.

Pedersen, S.A. and Rice, J.C., 2002. Dynamics of fish larvae, zooplankton, and hydrographical characteristics in the West Greenland Large Marine Ecosystem

1950-1984. In: K. Sherman and H.R. Skjoldal (Editors), Large marine Ecosystems of the North Atlantic. Elsevier Science B.V., The Netherlands.

Perry, A.L., Low, P.J., Ellis, J.R. and Reynolds, J.D., 2005. Climate change and distribution shifts in marine fishes. Science, 308(5730): 1912-1915.

Rayner, N.A. et al., 2003. Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. J. Geophys. Res., 108(doi:10.1029/2002JD002670,2003).

Rice, J., 2002. Changes to the Large Marine Ecosystem of the Newfoundland-Labrador Shelf. In: K. Sherman and H.R. Skjoldal (Editors), Large Marine Ecosystems of the North Atlantic. Elsevier Science B.V., The Netherlands.

Richardson, A.J. and Schoeman, D.S., 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science, 305(10 September 2004): 1609-1612.

Roemmich, D. and McGowan, J., 1995. Climatic warming and the decline of zooplankton in the California Current. Science, 267(3 March): 13241326.

Roy, C., Cury, P., Freon, P. and Demarcq, H., 2002. Environmental and Resource Variability off Northwest Africa and in the Gulf of Guinea: A Review. In: J. McGlade, P. Cury, K. Koranteng and N. Hardman-Mountford (Editors), The Gulf of Guinea Large Marine Ecosystem. Large Marine Ecosystems. Elsevier, pp. 121-140.

SAUP, 2007. Sea Around Us Project at www.saup.org.

Schmittner, A., 2005. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. Nature, 434.

Sherman, K., Aquarone, M.-C. and Adams, S., 2007. Global Applications of the Large Marine Ecosystem Approach. In: U.S.D.o. Commerce (Editor). National Oceanic and Atmospheric Administration.

Skjoldal, H.r. and Saetre, R., 2004. Climate and ecosystem variability. In: H.R. Skjoldal (Editor), The Norwegian Sea Ecosystem. Tapir Academic Press, Trondheim.

Sokal, R.R. and Rohlf, F.J., 1995. Biometry: The Principals and Practical Statistics in Biological Research. W.H. Freeman and Company, New York.

Tang, Q., 1989. Changes in the biomass of the Yellow Sea ecosystems. In: K. Sherman and L.M. Alexander, eds (Editors), Biomass yields and geography of large marine ecosystems. AAAS Selected Symp. 111. Westview Press, Boulder, CO, pp. 7-35. 493p.

Tang, Q., 1993. Effects of long-term physical and biological perturbations on the contemporary biomass yields of the Yellow Sea ecosystem. In: K. Sherman, L.M. Alexander and B.D. Gold, eds (Editors), Large marine ecosystems: Stress, mitigation and sustainability. AAAS Press, Washington, DC, pp. 79-93.

Tang, Q., 2003. The Yellow Sea and mitigation action. In: G. Hempel and K. Sherman, eds (Editors), Large marine ecosystems of the world: Trends in exploitation, protection and research. Elsevier Science, Amsterdam, Netherlands, pp. 423p.

Terazaki, M., 1999. The Sea of Japan large marine ecosystem. In: K. Sherman and Q. Tang, eds (Editors), Large marine ecosystems of the Pacific Rim: Assessment, sustainability and management. Blackwell Science, Malden, MA, pp. 199-220. 465p.

Valdes, L. and Lavin, A., 2002. Dynamics and human impact in the Bay of Biscay: An ecological perspective. In: K. sherman and H.R. Skjoldal (Editors), Large Marine

Ecosystems of the North Atlantic: Changing States and Sustainability. Elsevier Science B.V., The Netherlands, pp. 293-320.

Watson, R. et al., 2003. Mapping fisheries onto marine ecosystems for regional, oceanic and global integrations. In: G. Hempel and K. Sherman, eds (Editors), Large marine ecosystems of the world: Trends in exploitation, protection, and research. Elsevier Science, pp. 423p.

Worm, B. et al., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science, 314(5800): 787-790.

Yoshida, T. et al., 2006. Operational use of newly analyzed historical SST data for climate monitoring (COBE-SST) at Japan Meteorological Agency, http://icoads.noaa.gov/marcdat2/P_Takashi_Yoshida_COBESST.pdf.

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TABLES:

Table 1. List of Large Marine Ecosystems, volumes in which case studies have appeared, and principal authors of those studies.

LME	Vol.	Author(s)
Barents Sea	2	Skjoldal & Rey
	4	Borisov
	5	Skjoldal
	10	Dalpadado et al.
	12	Matishov
Norwegian Shelf	3	Ellertsen et al.
	5	Blindheim & Skjoldal
North Sea	1	Daan
	9	Reid
	10	McGlade
	12	Hempel
Iceland Shelf	10	Astthorsson & Vilhjálmsson
Faroe Plateau	10	Gaard et al.
Antarctic	1	Scully et al.
	3	Hempel
	5	Scully et al.
California Current	1	MacCall
	4	Mullin
	5	Bottom
	12	Lluch-Belda et al.
Pacific American Coastal	8	Bakun
Humboldt Current	5	Bernal
	12	Wolff et al.
Gulf of Thailand	5	Piyakarnchana
	11	Pauly & Chuenpagdee
South China Sea	5	Christensen
Indonesian Sea	3	Zijlstra & Baars
Northeast Australian Shelf	2	Bradbury & Mundy
	5	Kelleher
	8, 12	Brodie
Gulf of Mexico	9	Shipp
	9	Gracia & Vasquez Baden
Southeast U.S. Shelf	4	Yoder
Northeast U.S. Shelf	1	Sissenwine
	4	Falkowski
	6	Anthony
	10,12	Sherman
	13	Dyer & Poggie

LME	Vol.	Author(s) cont.
	13	Edwards et al.
	13	Cho et al.
	13	Grigalunas et al
Scotian Shelf	8	Zwanenburg et al.
Caribbean Sea	3	Richards & Bohnsack
Patagonian Shelf	5	Bakun
South Brazil Shelf	12	Ekau & Knoppers
East Brazil Shelf	12	Ekau & Knoppers
North Brazil Shelf	12	Ekau & Knoppers
Baltic Sea	1	Kullenberg
	12	Jansson
Celtic-Biscay Shelf	10	Lavin
Iberian Coastal	2	Perez-Gandaras
	10	Wyatt & Porteiro
Mediterranean Sea	5	Caddy
Canary Current	5	Bas
	12	Roy & Curry
Guinea Current	5	Binet & Marchal
	11	Koranteng & McGlade
	11	Mensah & Quaatey
	11	Lovell & McGlade
	11	Cury & Roy
	11	Koranteng
Benguela Current	2	Crawford et al.
	12	Shannon & O'Toole
	14	Ahanhanzo
	14	Shillington et al.
	14	Monteiro & van der Plas
	14	Hutchings et al.
	14	Pitcher & Weeks
	14	van der Lingen et al.
	14	Fréon et al.
	14	Reason et al.
	14	Jarre et al.
	14	Bernard et al.
	14	Monteiro et al.
	14	Gründlingh et al.
	14	Brundrit et al.
Black Sea	5	Caddy
	12	Daskalov

Volume No.	Volume Description
1	1986. *Variability and Management of Large Marine Ecosystems.* Sherman and Alexander, eds. AAAS Symposium 99. Westview Press, Boulder, CO. 319p
2	1989. *Biomass Yields and Geography of Large Marine Ecosystems.* Sherman and Alexander, eds. AAAS Symposium 111. Westview Press, Boulder, CO. 493p
3	1990. *Large Marine Ecosystems: Patterns, Processes, and Yields.* Sherman, Alexander and Gold, eds. AAAS Symposium. AAAS. Washington, DC. 242p
4	1991. *Food Chains, Yields, Models, and Management of Large Marine Ecosystems.* Sherman, Alexander and Gold, eds. AAAS Symposium. Westview Press, Boulder, CO. 320p
5	1992. *Large Marine Ecosystems: Stress, Mtigation and Sustainability.* Sherman, Alexander and Gold, eds. AAAS Press, Washington, DC. 376p
6	1996. *The Northeast Shelf Ecosystem: Assessment, Sustainability and Management.* Sherman, Jaworski and Smayda, eds. Blackwell Science, Cambridge, MA. 564p
7	1998. Large marine Ecosystems of the Indian Ocean: Assessment, Sustainability and Management. Sherman, Okemwa and Ntiba, eds. Blackwell Science, Malden, MA. 394p
8	1999. *Large Marine Ecosystems of the Pacific Rim: Assessment, Sustainability and Management.* Sherman and Tang, eds. Blackwell Science, Malden, MA. 455p
9	1999. *The Gulf of Mexico Large Marine Ecosystem: Assessment, Sustainability and Management.* Kumpf, Steidinger and Sherman, eds. Blackwell Science, Malden, MA 736p
10	2002. *Large Marine Ecosystems of the North Atlantic: Changing States and Sustainability.* Skjoldal and Sherman, eds. Elsevier Science, New York, and Amsterdam. 449p
11	2002. *Gulf of Guinea Large Marine Ecosystem: Environmental Forcing and Sustainable Development of Marine Resources.* McGlade, Cury, Koranteng, Hardman-Mountford, eds. Elsevier Science, Amsterdam and New York. 392p
12	2003. Large marine Ecosystems of the World: Trends in Exploitation, Protection and Research. Hempel and Sherman, eds. Elsevier Science, New York and Amsterdam. 423p.
13	2005. Sustaining Large Marine Ecosystems: The Human Dimension. Hennessey and Sutinen, eds. Elsevier Science, New York and Amsterdam. 368p
14	2006. Benguela: Predicting a Large Marine Ecosystem. Shannon, Hempel, Malanotte-Rizzoli, Moloney, Woods, eds. Elsevier Science, New York and Amsterdam. 401p

Table 2. Tests results of chlorophyll and primary productivity regression analysis

LME	Chl	PPD
Humboldt Current	+ *	+ **
Barents Sea	+ *	
Red Sea	+ **	
Bay of Bengal	- **	- *
NE Australian Shelf	- *	
East China Sea	- *	
East Siberian Sea	- *	
Hudson Bay	+ *	
Caribbean Sea		- *
Mediterranean Sea		- *
Kuroshio Current		- *

Significance of T test on chlorophyll (Chl) and primary productivity (PPD) regression coefficients. Only cases where $p<.05$ are listed. All other comparisons were non-significant. Plus and minus signs are used to designate the direction of the slope of the trend line. * Indicates $P<.05$ ** Indicates $P<.01$

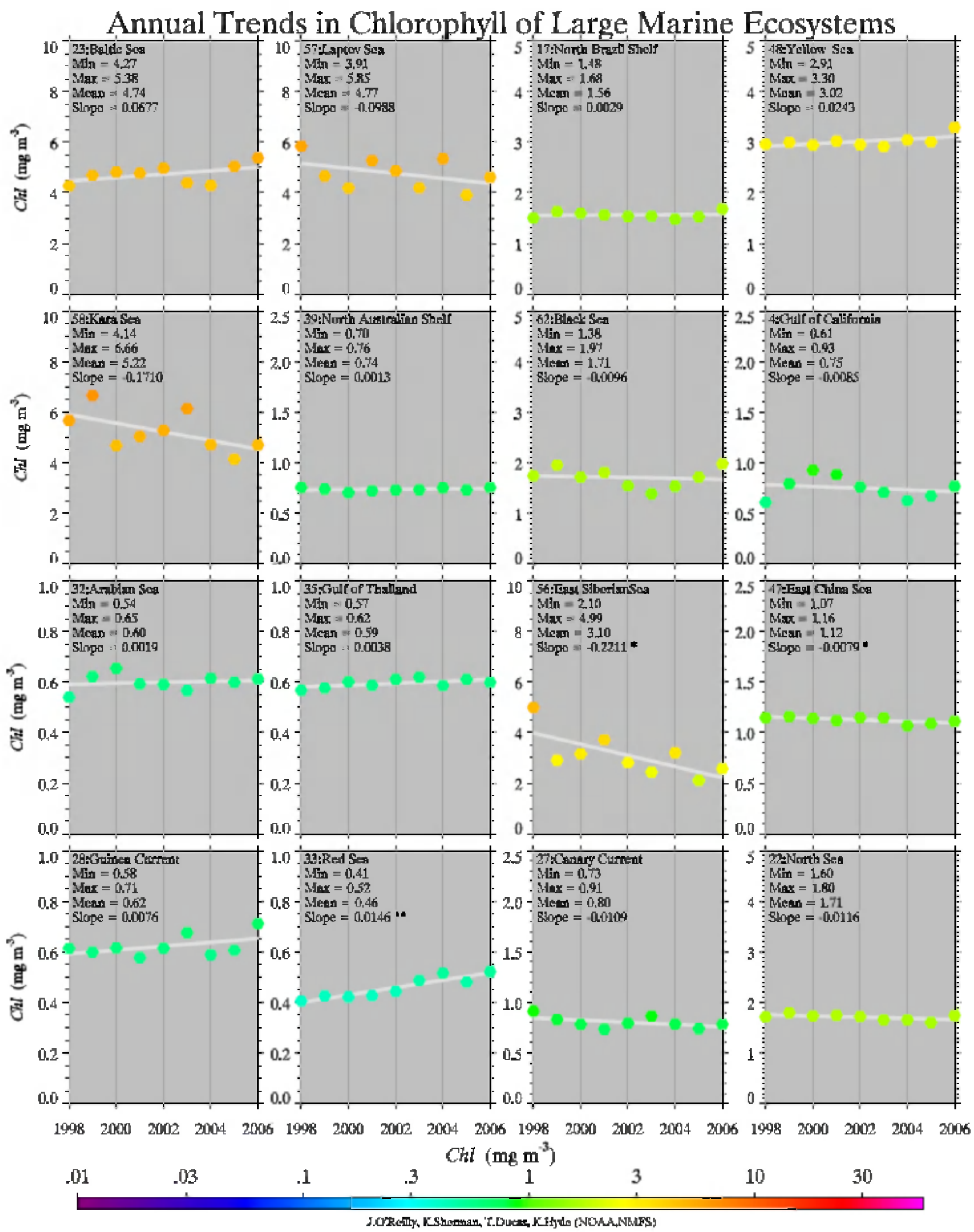
Table 3. SST change in each LME, 1982-2006 (sorted in descending order)

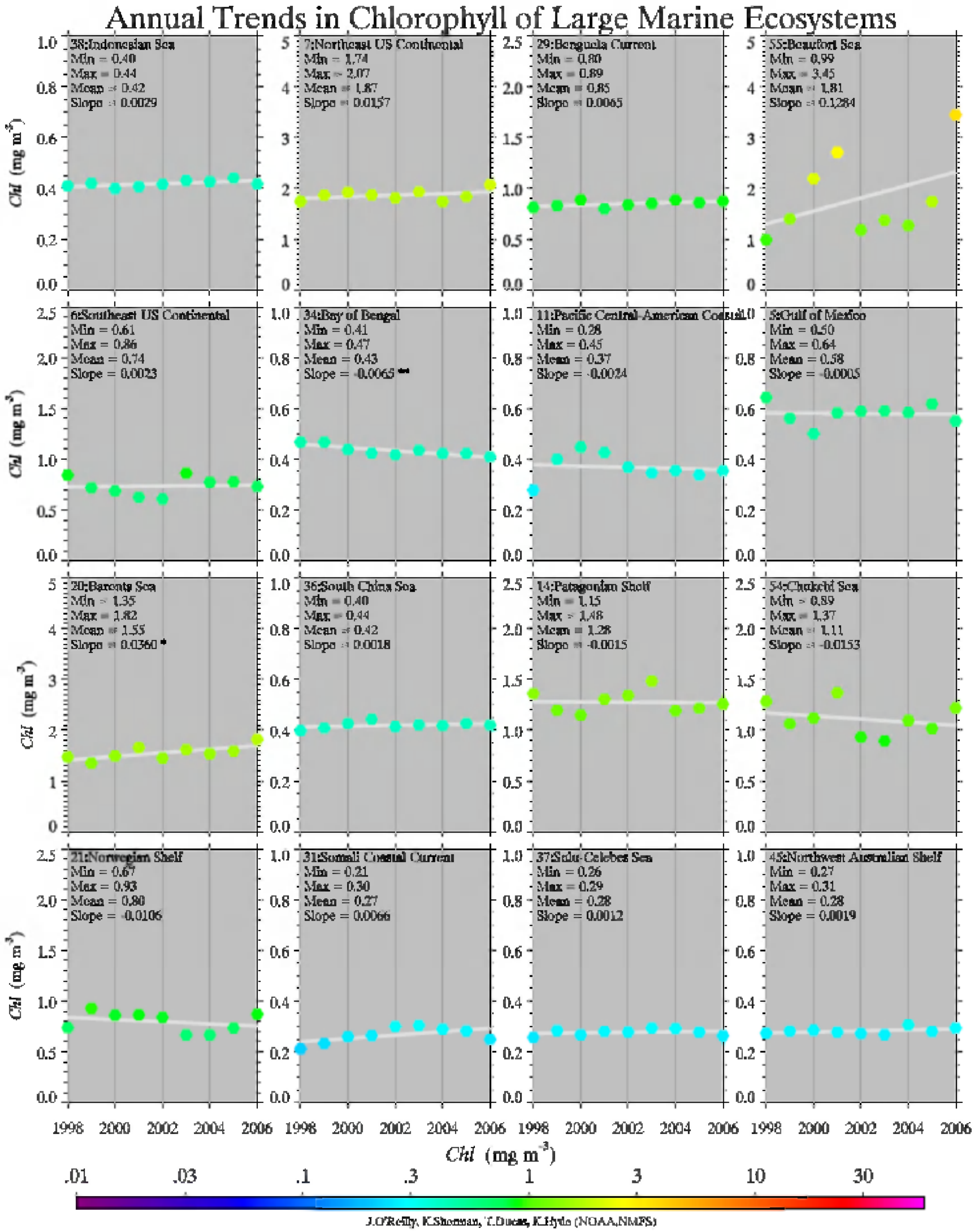
LME23='BALTIC SEA';	1.35
LME22='NORTH SEA';	1.31
LME47='EAST CHINA SEA';	1.22
LME50='SEA OF JAPAN';	1.09
LME(Morgan)='NEWFOUNDLAND-LABRADOR SHELF';	1.04
LME62='BLACK SEA';	0.96
LME(Morgan)='SCOTIAN SHELF';	0.89
LME59='ICELAND SEA';	0.86
LME21='NORWEGIAN SEA';	0.85
LME49'KUROSHIO CURRENT';	0.75
LME60='FAROE PLATEAU';	0.75
LME33='RED SEA';	0.74
LME18='WEST GREENLAND SHELF';	0.73
LME24='CELTIC-BISCAY SHELF';	0.72
LME26='MEDITERRANEAN SEA';	0.71
LME54='CHUKCHI SEA';	0.70
LME25='IBERIAN COASTAL';	0.68
LME48='YELLOW SEA';	0.67
LME17='NORTH BRAZIL SHELF';	0.60
LME51='OYASHIO CURRENT';	0.60
LME15='SOUTH BRAZIL SHELF';	0.53
LME27='CANARY CURRENT';	0.52
LME12='CARIBBEAN SEA';	0.50
LME(Morgan)='EAST GREENLAND SHELF';	0.47
LME28='GUINEA CURRENT';	0.46
LME10='INSULAR PACIFIC HAWAIIAN';	0.45
LME36='SOUTH CHINA SEA';	0.44
LME53='WEST BERING SEA';	0.39
LME2='GULF OF ALASKA';	0.37
LME40='NE AUSTRALIAN SHELF-GREAT BARRIER REEF';	0.37
LME56}='EAST SIBERIAN SEA';	0.36
LME41='EAST-CENTRAL AUSTRALIAN SHELF';	0.35
LME55='BEAUFORT SEA';	0.34
LME46='NEW ZEALAND SHELF';	0.32
LME4='GULF OF CALIFORNIA';	0.31
LME5='GULF OF MEXICO';	0.31
LME52='SEA OF OKHOTSK';	0.31

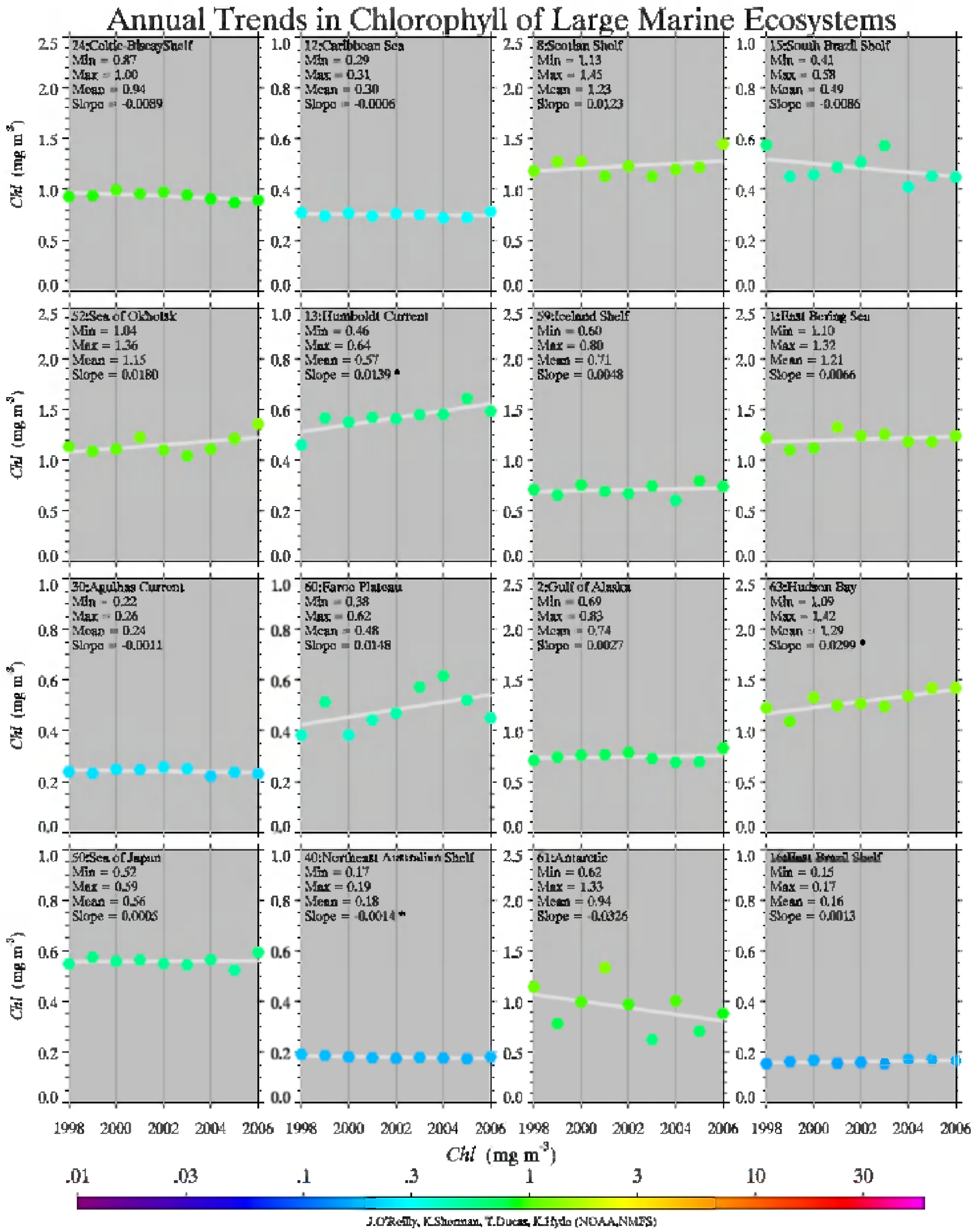
LME16='EAST BRAZIL SHELF';	0.30
LME63='HUDSON BAY';	0.28
LME(Morgan)='EAST BERING SEA';	0.27
LME32='ARABIAN SEA';	0.26
LME29='BENGUELA CURRENT';	0.24
LME34='BAY OF BENGAL';	0.24
LME38='INDONESIAN SEA';	0.24
LME45='NORTHWEST AUSTRALIAN SHELF';	0.24
LME7='NORTHEAST U.S. CONTINENTAL SHELF';	0.23
LME37='SULU-CELEBES SEA';	0.23
LME30='AGULHAS CURRENT';	0.20
LME42='SOUTHEAST AUSTRALIAN SHELF';	0.20
LME31='SOMALI COASTAL CURRENT';	0.18
LME39='NORTH AUSTRALIAN SHELF';	0.17
LME6='SOUTHEAST U.S. CONTINENTAL SHELF';	0.16
LME35='GULF OF THAILAND';	0.16
LME58='KARA SEA';	0.16
LME11='PACIFIC CENTRAL-AMERICAN COAST';	0.14
LME20='BARENTS SEA';	0.12
LME57='LAPTEV SEA';	0.12
LME43='SOUTHWEST AUSTRALIAN SHELF';	0.09
LME44='WEST-CENTRAL AUSTRALIAN SHELF';	0.09
LME14='PATAGONIAN SHELF';	0.08
LME61='ANTARCTIC';	0.00
LME3='CALIFORNIA CURRENT';	-0.07
LME13='HUMBOLDT CURRENT';	-0.10
LME64='ARCTIC OCEAN';	

FIGURES:

Figure 1. Trends of mean annual chlorophyll levels derived from 1998 to 2006 data




Annual Trends in Chlorophyll of Large Marine Ecosystems
38:Indonesian Sea Min = 0.40 Max = 0.44 Mean = 0.42 Slope = 0.0029
7:Northeast US Continental Min = 1.74 Max = 2.07 Mean = 1.87 Slope = 0.0157
29:Benguela Current Min = 0.80 Max = 0.89 Mean = 0.85 Slope = 0.0065
55:Beaufort Sea Min = 0.99 Max = 3.45 Mean = 1.81 Slope = 0.1284
6:Southeast US Continental Min = 0.61 Max = 0.86 Mean = 0.74 Slope = 0.0023
34:Bay of Bengal Min = 0.41 Max = 0.47 Mean = 0.43 Slope = -0.0065 **
11:Pacific Central-American Coastal Min = 0.28 Max = 0.45 Mean = 0.37 Slope = -0.0024
5:Gulf of Mexico Min = 0.50 Max = 0.64 Mean = 0.58 Slope = -0.0005
20:Barents Sea Min = 1.35 Max = 1.82 Mean = 1.55 Slope = 0.0360 *
36:South China Sea Min = 0.40 Max = 0.44 Mean = 0.42 Slope = 0.0018
14:Patagonian Shelf Min = 1.15 Max = 1.48 Mean = 1.28 Slope = -0.0015
54:Chukchi Sea Min = 0.89 Max = 1.37 Mean = 1.11 Slope = -0.0153
21:Norwegian Shelf Min = 0.67 Max = 0.93 Mean = 0.80 Slope = -0.0106
31:Somali Coastal Current Min = 0.21 Max = 0.30 Mean = 0.27 Slope = 0.0066
37:Sulu-Celebes Sea Min = 0.26 Max = 0.29 Mean = 0.28 Slope = 0.0012
45:Northwest Australian Shelf Min = 0.27 Max = 0.31 Mean = 0.28 Slope = 0.0019
Chl (mg m-3)
Chl (mg m-3)
.01 .03 .1 .3 1 3 10 30
J.O'Reilly, K.Sherman, T.Ducas, K.Hyde (NOAA,NMFS)


Annual Trends in Chlorophyll of Large Marine Ecosystems
24:Celtic-Biscay Shelf
Min = 0.87
Max = 1.00
Mean = 0.94
Slope = -0.0089
12:Caribbean Sea
Min = 0.29
Max = 0.31
Mean = 0.30
Slope = -0.0006
8:Scotian Shelf
Min = 1.13
Max = 1.45
Mean = 1.23
Slope = 0.0123
15:South Brazil Shelf
Min = 0.41
Max = 0.58
Mean = 0.49
Slope = -0.0086
52:Sea of Okhotsk
Min = 1.04
Max = 1.36
Mean = 1.15
Slope = 0.0180
13:Humboldt Current
Min = 0.46
Max = 0.64
Mean = 0.57
Slope = 0.0139 *
59:Iceland Shelf
Min = 0.60
Max = 0.80
Mean = 0.71
Slope = 0.0048
1:East Bering Sea
Min = 1.10
Max = 1.32
Mean = 1.21
Slope = 0.0066
30:Agulhas Current
Min = 0.22
Max = 0.26
Mean = 0.24
Slope = -0.0011
60:Faroe Plateau
Min = 0.38
Max = 0.62
Mean = 0.48
Slope = 0.0148
2:Gulf of Alaska
Min = 0.69
Max = 0.83
Mean = 0.74
Slope = 0.0027
63:Hudson Bay
Min = 1.09
Max = 1.42
Mean = 1.29
Slope = 0.0299 *
50:Sea of Japan
Min = 0.52
Max = 0.59
Mean = 0.56
Slope = 0.0005
40:Northeast Australian Shelf
Min = 0.17
Max = 0.19
Mean = 0.18
Slope = -0.0014 *
61:Antarctic
Min = 0.62
Max = 1.33
Mean = 0.94
Slope = -0.0326
16:East Brazil Shelf
Min = 0.15
Max = 0.17
Mean = 0.16
Slope = 0.0013
Chl (mg m-3)
1998 2000 2002 2004 2006
Chl (mg m-3)
.01 .03 .1 .3 1 3 10 30
J.O'Reilly, K.Sherman, T.Ducas, K.Hyde (NOAA,NMFS)

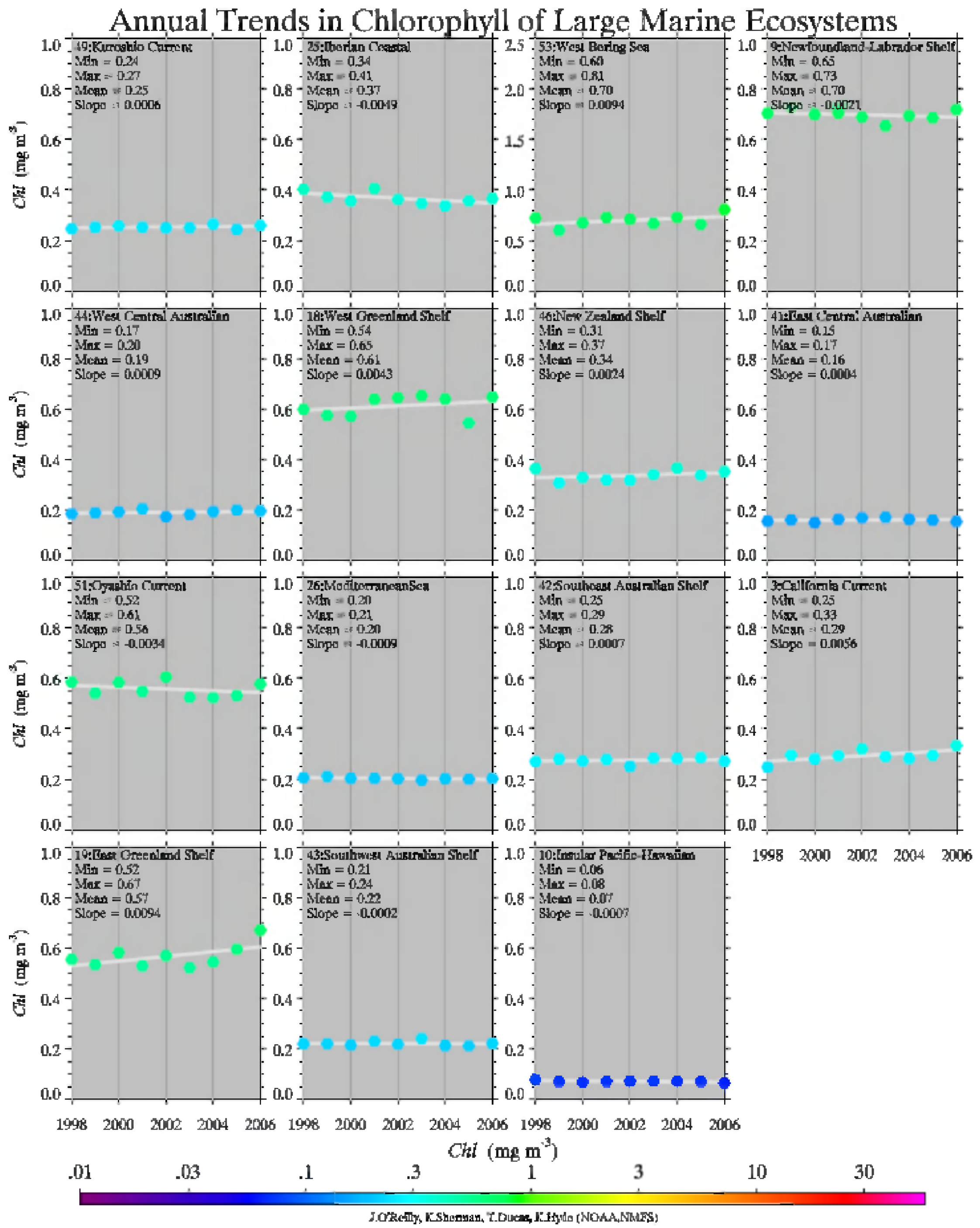
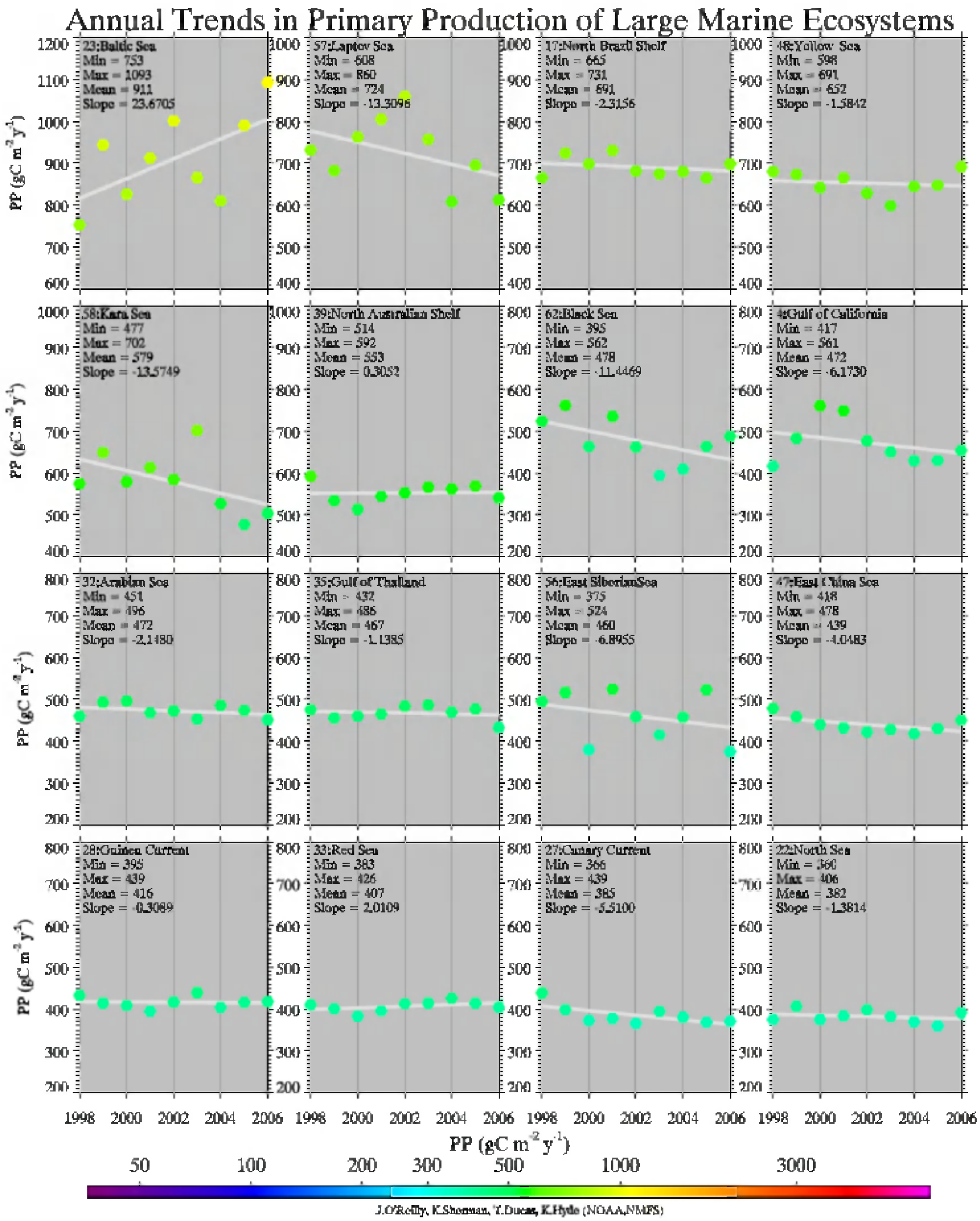
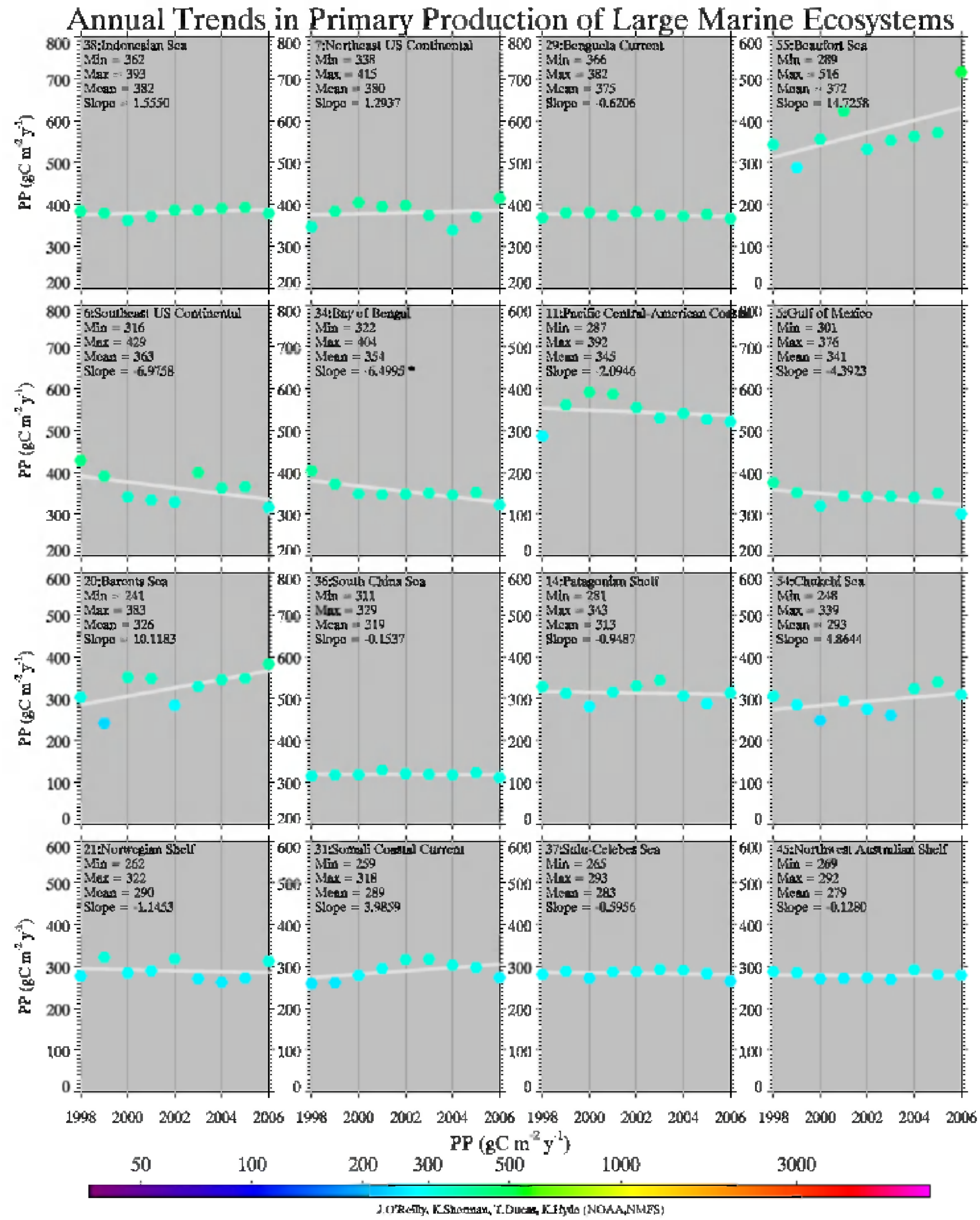
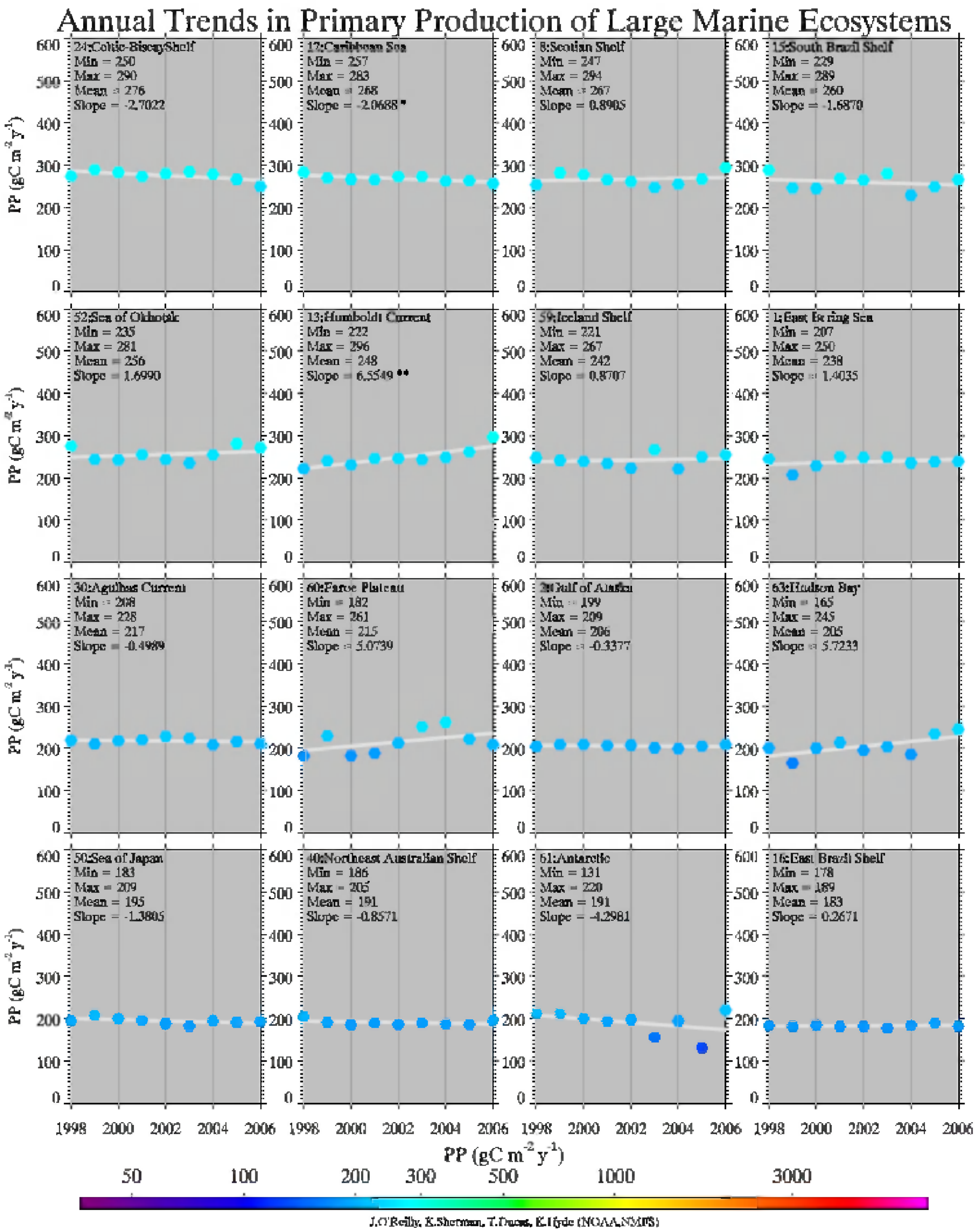

Annual Trends in Chlorophyll of Large Marine Ecosystems
49:Kuroshio Current Min = 0.24 Max = 0.27 Mean = 0.25 Slope = 0.0006
25:Iberian Coastal Min = 0.34 Max = 0.41 Mean = 0.37 Slope = -0.0049
53:West Bering Sea Min = 0.60 Max = 0.81 Mean = 0.70 Slope = 0.0094
9:Newfoundland-Labrador Shelf Min = 0.65 Max = 0.73 Mean = 0.70 Slope = -0.0021
44:West Central Australian Min = 0.17 Max = 0.20 Mean = 0.19 Slope = 0.0009
18:West Greenland Shelf Min = 0.54 Max = 0.65 Mean = 0.61 Slope = 0.0043
46:New Zealand Shelf Min = 0.31 Max = 0.37 Mean = 0.34 Slope = 0.0024
41:East Central Australian Min = 0.15 Max = 0.17 Mean = 0.16 Slope = 0.0004
51:Oyashio Current Min = 0.52 Max = 0.61 Mean = 0.56 Slope = -0.0034
26:MediterraneanSea Min = 0.20 Max = 0.21 Mean = 0.20 Slope = -0.0009
42:Southeast Australian Shelf Min = 0.25 Max = 0.29 Mean = 0.28 Slope = 0.0007
3:California Current Min = 0.25 Max = 0.33 Mean = 0.29 Slope = 0.0056
19:East Greenland Shelf Min = 0.52 Max = 0.67 Mean = 0.57 Slope = 0.0094
43:Southwest Australian Shelf Min = 0.21 Max = 0.24 Mean = 0.22 Slope = -0.0002
10:Insular Pacific-Hawaiian Min = 0.06 Max = 0.08 Mean = 0.07 Slope = -0.0007
Chl (mg m-3)
1998 2000 2002 2004 2006
.01 .03 .1 .3 1 3 10 30
J.O'Reilly, K.Sherman, T.Ducas, K.Hyde (NOAA,NMFS)

Figure 2. Trends of primary productivity levels derived from 1998-2006 data




Annual Trends in Primary Production of Large Marine Ecosystems
38:Indonesian Sea
Min = 362
Max = 393
Mean = 382
Slope = 1.5550
7:Northeast US Continental
Min = 338
Max = 415
Mean = 380
Slope = 1.2937
29:Benguela Current
Min = 366
Max = 382
Mean = 375
Slope = -0.6206
55:Beaufort Sea
Min = 289
Max = 516
Mean = 372
Slope = 14.7258
6:Southeast US Continental
Min = 316
Max = 429
Mean = 363
Slope = -6.9758
34:Bay of Bengal
Min = 322
Max = 404
Mean = 354
Slope = -6.4995 *
11:Pacific Central-American Coastal
Min = 287
Max = 392
Mean = 345
Slope = -2.0946
5:Gulf of Mexico
Min = 301
Max = 376
Mean = 341
Slope = -4.3923
20:Barents Sea
Min = 241
Max = 383
Mean = 326
Slope = 10.1183
36:South China Sea
Min = 311
Max = 329
Mean = 319
Slope = -0.1537
14:Patagonian Shelf
Min = 281
Max = 343
Mean = 313
Slope = -0.9487
54:Chukchi Sea
Min = 248
Max = 339
Mean = 293
Slope = 4.8644
21:Norwegian Shelf
Min = 262
Max = 322
Mean = 290
Slope = -1.1453
31:Somali Coastal Current
Min = 259
Max = 318
Mean = 289
Slope = 3.9859
37:Sulu-Celebes Sea
Min = 265
Max = 293
Mean = 283
Slope = -0.5956
45:Northwest Australian Shelf
Min = 269
Max = 292
Mean = 279
Slope = -0.1280
PP (gC m-2 y-1)
1998 2000 2002 2004 2006
PP (gC m-2 y-1)
50 100 200 300 500 1000 3000
J.O'Reilly, K.Sherman, T.Ducas, K.Hyde (NOAA,NMFS)


Annual Trends in Primary Production of Large Marine Ecosystems
24:Celtic-BiscayShelf
Min = 250
Max = 290
Mean = 276
Slope = -2.7022
12:Caribbean Sea
Min = 257
Max = 283
Mean = 268
Slope = -2.0688 *
8:Scotian Shelf
Min = 247
Max = 294
Mean = 267
Slope = 0.8905
15:South Brazil Shelf
Min = 229
Max = 289
Mean = 260
Slope = -1.6870
52:Sea of Okhotsk
Min = 235
Max = 281
Mean = 256
Slope = 1.6990
13:Humboldt Current
Min = 222
Max = 296
Mean = 248
Slope = 6.5549 **
59:Iceland Shelf
Min = 221
Max = 267
Mean = 242
Slope = 0.8707
1:East Bering Sea
Min = 207
Max = 250
Mean = 238
Slope = 1.4035
30:Agulhas Current
Min = 208
Max = 228
Mean = 217
Slope = -0.4989
60:Faroe Plateau
Min = 182
Max = 261
Mean = 215
Slope = 5.0739
2:Gulf of Alaska
Min = 199
Max = 209
Mean = 206
Slope = -0.3377
63:Hudson Bay
Min = 165
Max = 245
Mean = 205
Slope = 5.7233
50:Sea of Japan
Min = 183
Max = 209
Mean = 195
Slope = -1.3805
40:Northeast Australian Shelf
Min = 186
Max = 205
Mean = 191
Slope = -0.8571
61:Antarctic
Min = 131
Max = 220
Mean = 191
Slope = -4.2981
16:East Brazil Shelf
Min = 178
Max = 189
Mean = 183
Slope = 0.2671
PP (gC m-2 y-1)
0 100 200 300 400 500 600
1998 2000 2002 2004 2006
PP (gC m-2 y-1)
50 100 200 300 500 1000 3000
J.O'Reilly, K.Sherman, T.Ducas, E.Hyde (NOAA,NMFS)

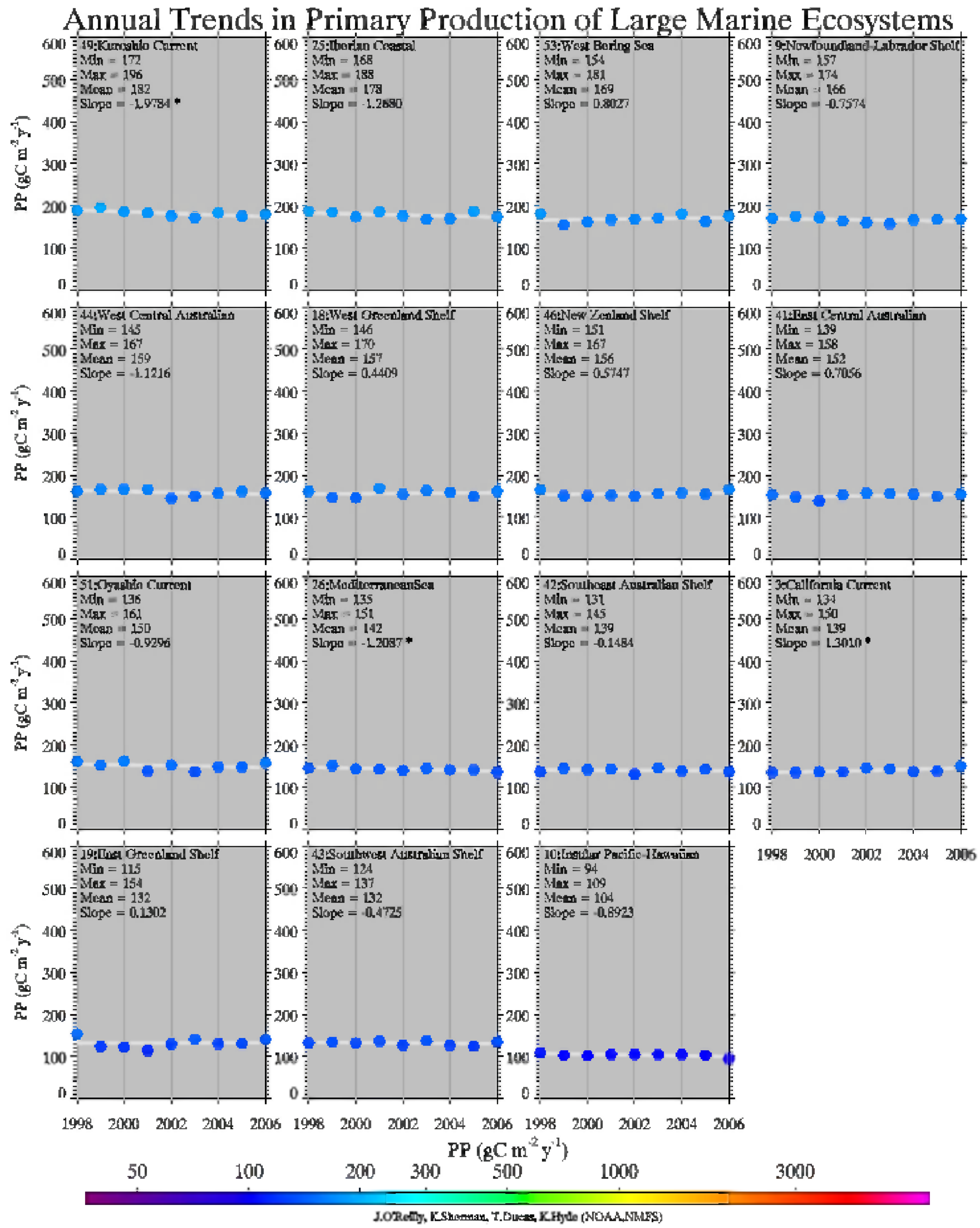
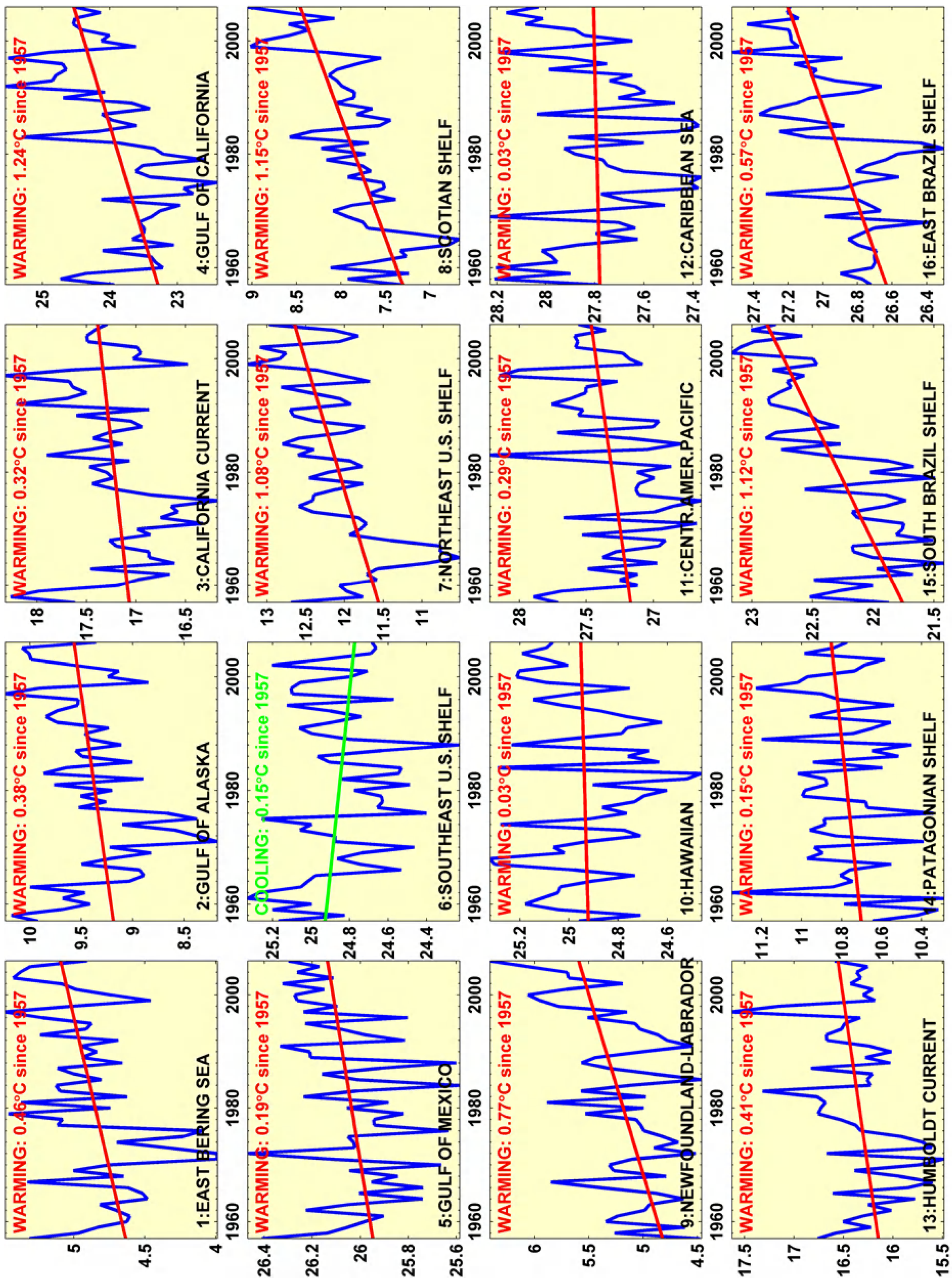
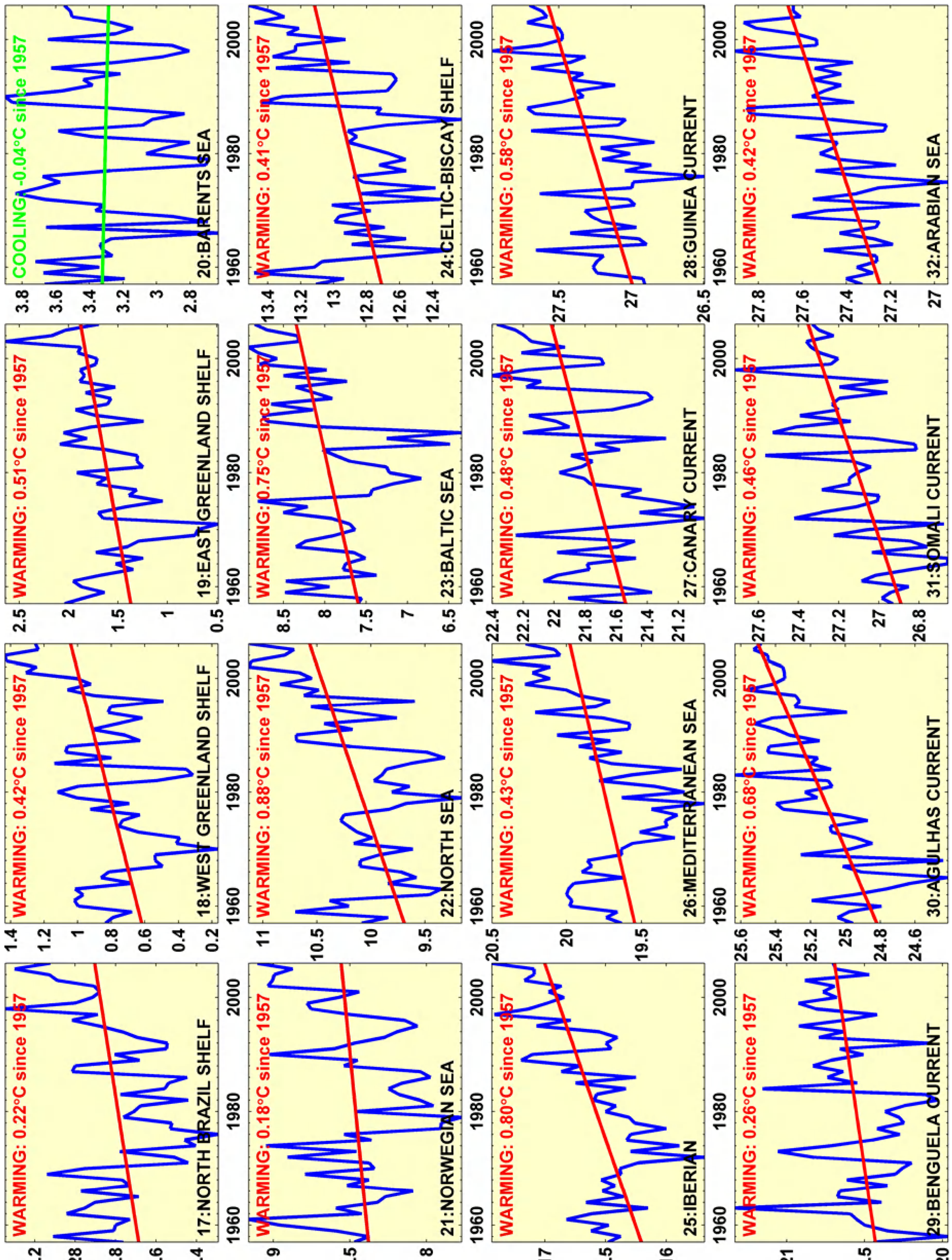
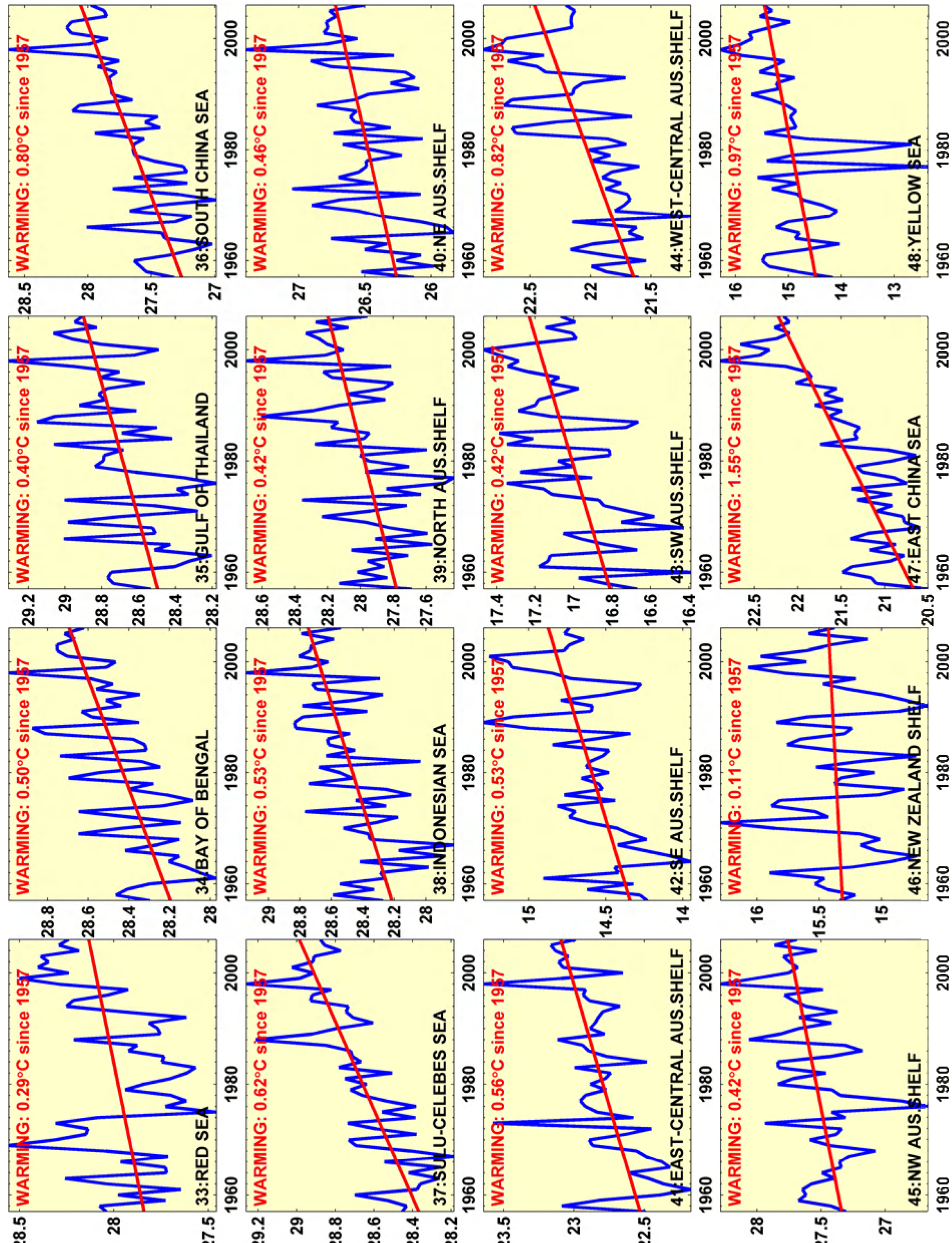

Annual Trends in Primary Production of Large Marine Ecosystems
49:Kuroshio Current
Min = 172
Max = 196
Mean = 182
Slope = -1.9784 *
25:Iberian Coastal
Min = 168
Max = 188
Mean = 178
Slope = -1.2680
53:West Bering Sea
Min = 154
Max = 181
Mean = 169
Slope = 0.8027
9:Newfoundland-Labrador Shelf
Min = 157
Max = 174
Mean = 166
Slope = -0.7574
44:West Central Australian
Min = 145
Max = 167
Mean = 159
Slope = -1.1216
18:West Greenland Shelf
Min = 146
Max = 170
Mean = 157
Slope = 0.4409
46:New Zealand Shelf
Min = 151
Max = 167
Mean = 156
Slope = 0.5747
41:East Central Australian
Min = 139
Max = 158
Mean = 152
Slope = 0.7056
51:Oyashio Current
Min = 136
Max = 161
Mean = 150
Slope = -0.9296
26:MediterraneanSea
Min = 135
Max = 151
Mean = 142
Slope = -1.2087 *
42:Southeast Australian Shelf
Min = 131
Max = 145
Mean = 139
Slope = -0.1484
3:California Current
Min = 134
Max = 150
Mean = 139
Slope = 1.3010 *
19:East Greenland Shelf
Min = 115
Max = 154
Mean = 132
Slope = 0.1302
43:Southwest Australian Shelf
Min = 124
Max = 137
Mean = 132
Slope = -0.4725
10:Insular Pacific-Hawaiian
Min = 94
Max = 109
Mean = 104
Slope = -0.8923
PP (gC m-2 y-1)
0
100
200
300
400
500
600
1998
2000
2002
2004
2006
PP (gC m-2 y-1)
50
100
200
300
500
1000
3000
J.O'Reilly, K.Sherman, T.Ducas, K.Hyde (NOAA,NMFS)

Figure 3. SST trends in Large Marine Ecosystems, 1957-2006




WARMING: 0.22°C since 1957
17:NORTH BRAZIL SHELF
WARMING: 0.42°C since 1957
18:WEST GREENLAND SHELF
WARMING: 0.51°C since 1957
19:EAST GREENLAND SHELF
COOLING: -0.04°C since 1957
20:BARENTS SEA
WARMING: 0.18°C since 1957
21:NORWEGIAN SEA
WARMING: 0.88°C since 1957
22:NORTH SEA
WARMING: 0.75°C since 1957
23:BALTIC SEA
WARMING: 0.41°C since 1957
24:CELTIC-BISCAY SHELF
WARMING: 0.80°C since 1957
25:IBERIAN
WARMING: 0.43°C since 1957
26:MEDITERRANEAN SEA
WARMING: 0.48°C since 1957
27:CANARY CURRENT
WARMING: 0.58°C since 1957
28:GUINEA CURRENT
WARMING: 0.26°C since 1957
29:BENGUELA CURRENT
WARMING: 0.68°C since 1957
30:AGULHAS CURRENT
WARMING: 0.46°C since 1957
31:SOMALI CURRENT
WARMING: 0.42°C since 1957
32:ARABIAN SEA


WARMING: 0.29°C since 1957
33:RED SEA
WARMING: 0.50°C since 1957
34:BAY OF BENGAL
WARMING: 0.40°C since 1957
35:GULF OF THAILAND
WARMING: 0.80°C since 1957
36:SOUTH CHINA SEA
WARMING: 0.62°C since 1957
37:SULU-CELEBES SEA
WARMING: 0.53°C since 1957
38:INDONESIAN SEA
WARMING: 0.42°C since 1957
39:NORTH AUS.SHELF
WARMING: 0.46°C since 1957
40:NE AUS.SHELF
WARMING: 0.56°C since 1957
41:EAST-CENTRAL AUS.SHELF
WARMING: 0.53°C since 1957
42:SE AUS.SHELF
WARMING: 0.42°C since 1957
43:SW AUS.SHELF
WARMING: 0.82°C since 1957
44:WEST-CENTRAL AUS.SHELF
WARMING: 0.42°C since 1957
45:NW AUS.SHELF
WARMING: 0.11°C since 1957
46:NEW ZEALAND SHELF
WARMING: 1.55°C since 1957
47:EAST CHINA SEA
WARMING: 0.97°C since 1957
48:YELLOW SEA
1960
1980
2000

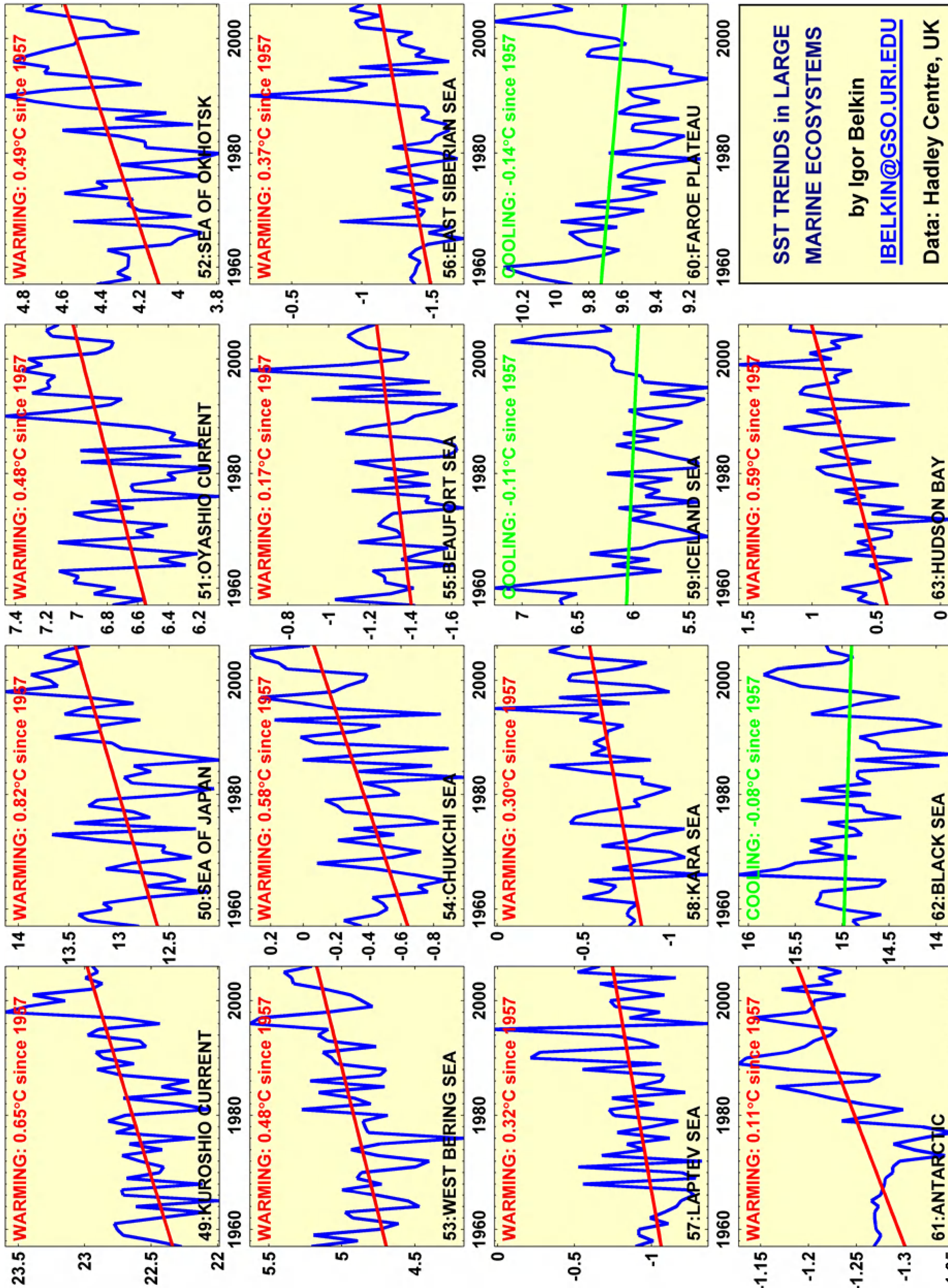
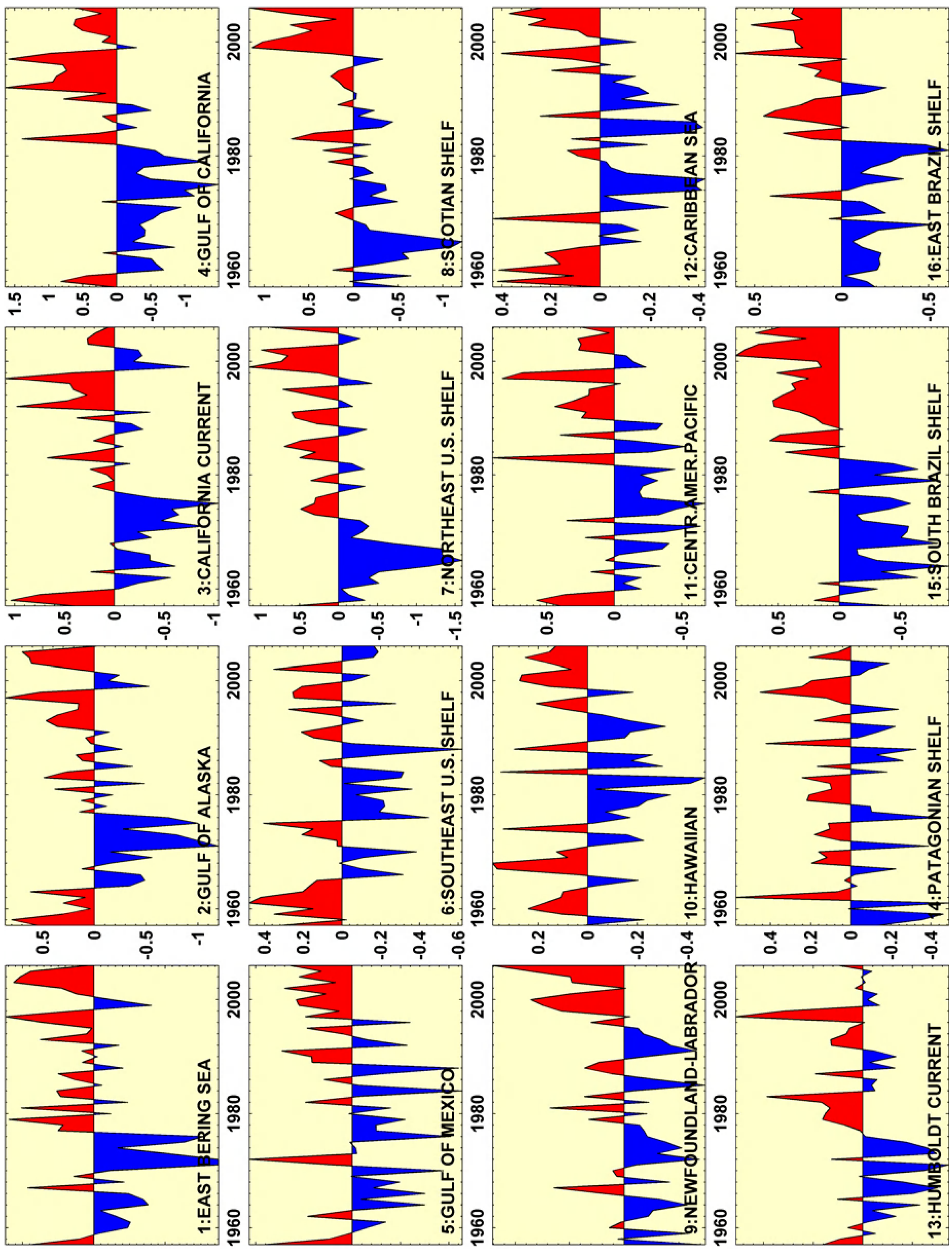
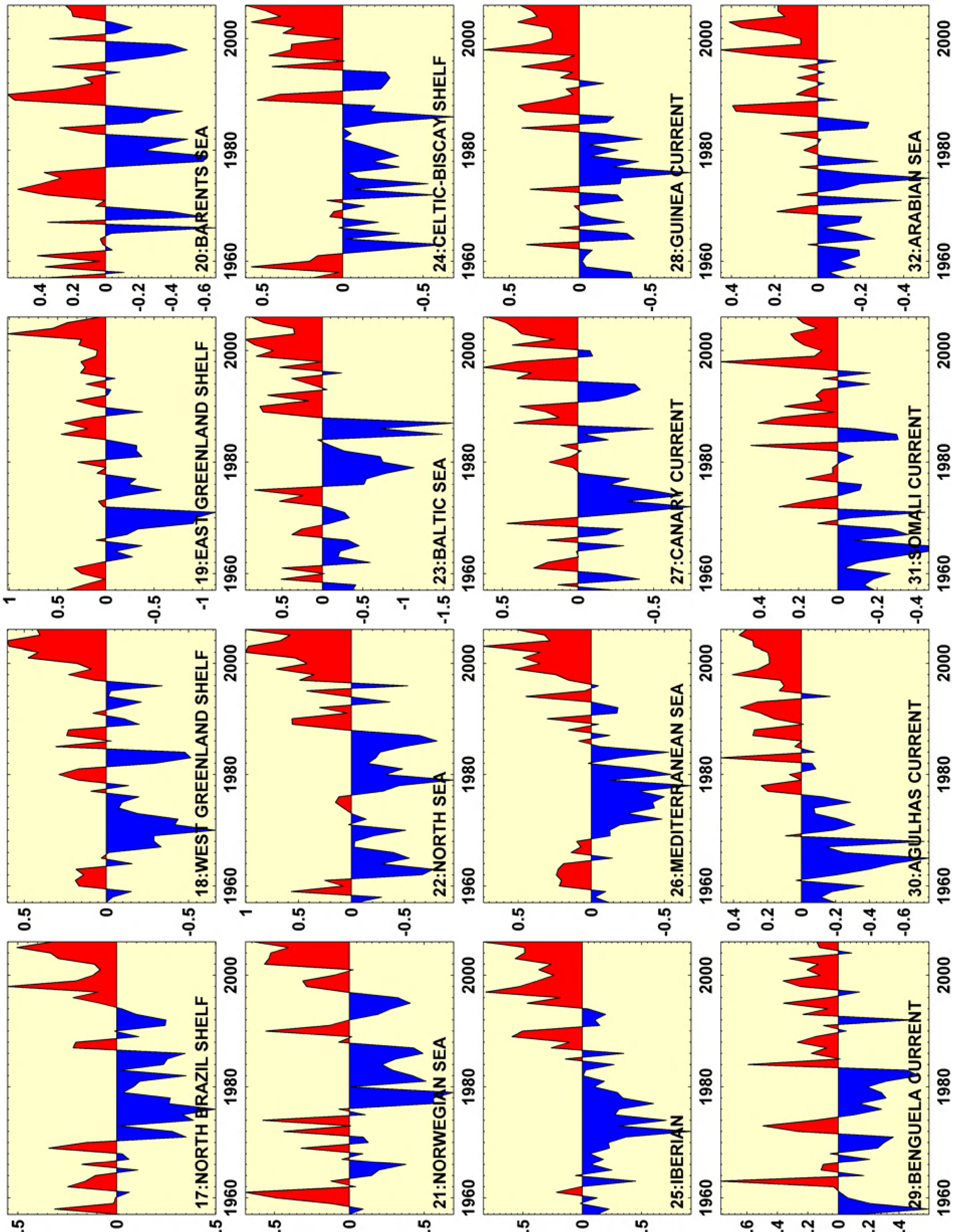
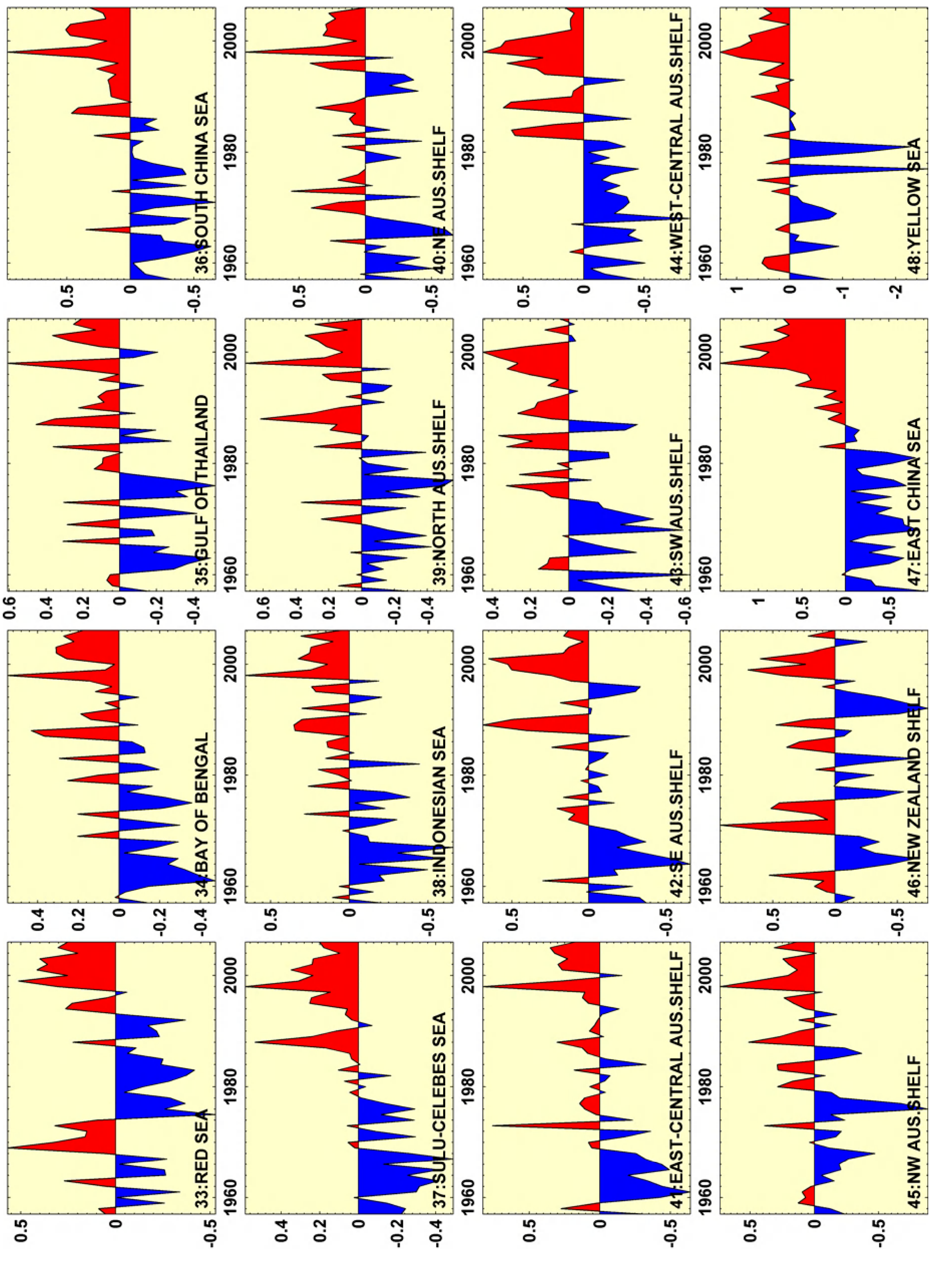

49:KUROSHIO CURRENT
WARMING: 0.65°C since 1957
50:SEA OF JAPAN
WARMING: 0.82°C since 1957
51:OYASHIO CURRENT
WARMING: 0.48°C since 1957
52:SEA OF OKHOTSK
WARMING: 0.49°C since 1957
53:WEST BERING SEA
WARMING: 0.48°C since 1957
54:CHUKCHI SEA
WARMING: 0.58°C since 1957
55:BEAUFORT SEA
WARMING: 0.17°C since 1957
56:EAST SIBERIAN SEA
WARMING: 0.37°C since 1957
57:LAPTEV SEA
WARMING: 0.32°C since 1957
58:KARA SEA
WARMING: 0.30°C since 1957
59:ICELAND SEA
COOLING: -0.11°C since 1957
60:FAROE PLATEAU
COOLING: -0.14°C since 1957
61:ANTARCTIC
WARMING: 0.11°C since 1957
62:BLACK SEA
COOLING: -0.08°C since 1957
63:HUDSON BAY
WARMING: 0.59°C since 1957
SST TRENDS in LARGE MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

Figure 4. SST anomalies in Large Marine Ecosystems, 1957-2006




17:NORTH BRAZIL SHELF
18:WEST GREENLAND SHELF
19:EAST GREENLAND SHELF
20:BARENTS SEA
21:NORWEGIAN SEA
22:NORTH SEA
23:BALTIC SEA
24:CELTIC-BISCAY SHELF
25:IBERIAN
26:MEDITERRANEAN SEA
27:CANARY CURRENT
28:GUINEA CURRENT
29:BENGUELA CURRENT
30:AGULHAS CURRENT
31:SOMALI CURRENT
32:ARABIAN SEA


33:RED SEA
34:BAY OF BENGAL
35:GULF OF THAILAND
36:SOUTH CHINA SEA
37:SULU-CELEBES SEA
38:INDONESIAN SEA
39:NORTH AUS.SHELF
40:NE AUS.SHELF
41:EAST-CENTRAL AUS.SHELF
42:SE AUS.SHELF
43:SW AUS.SHELF
44:WEST-CENTRAL AUS.SHELF
45:NW AUS.SHELF
46:NEW ZEALAND SHELF
47:EAST CHINA SEA
48:YELLOW SEA
1960
1980
2000

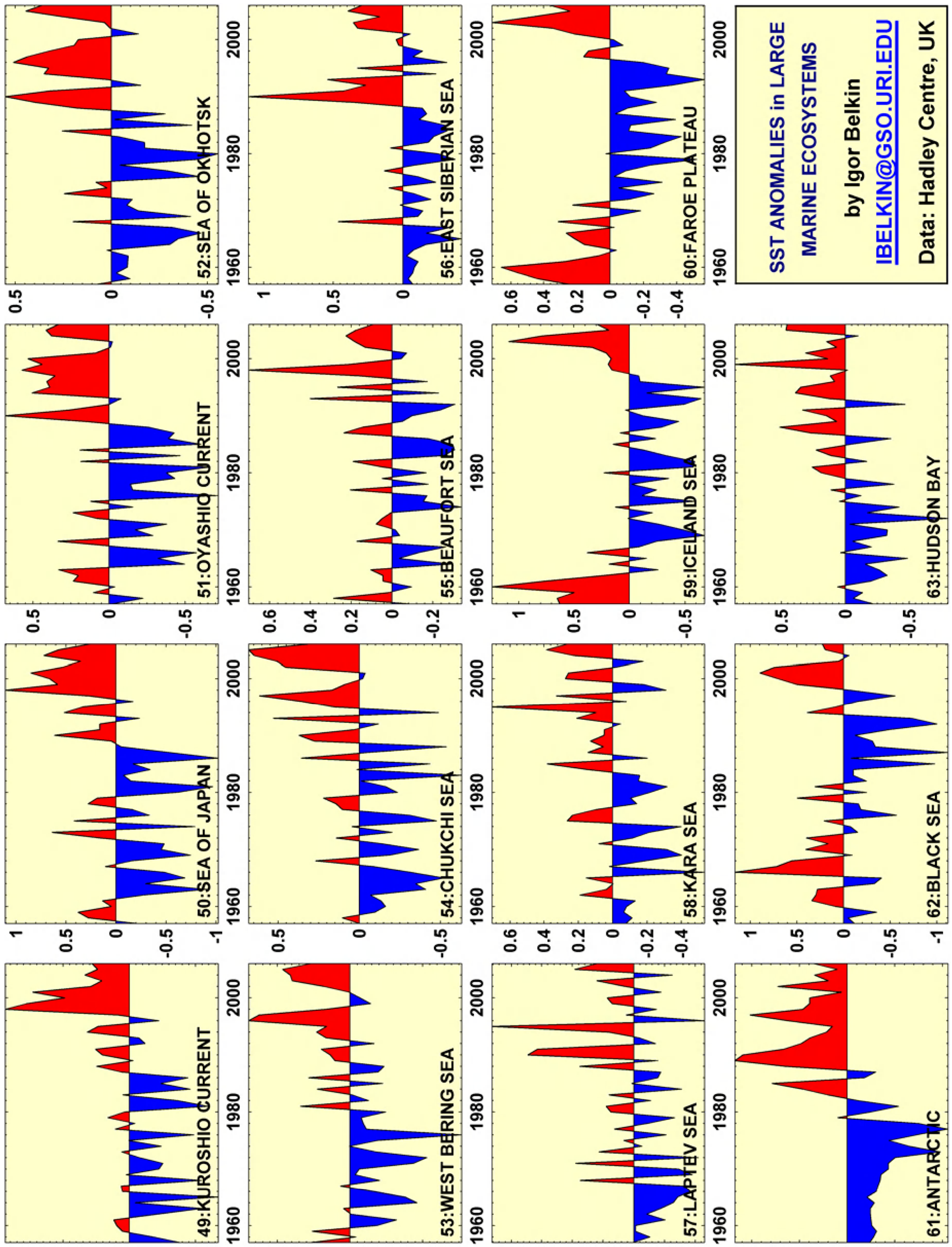
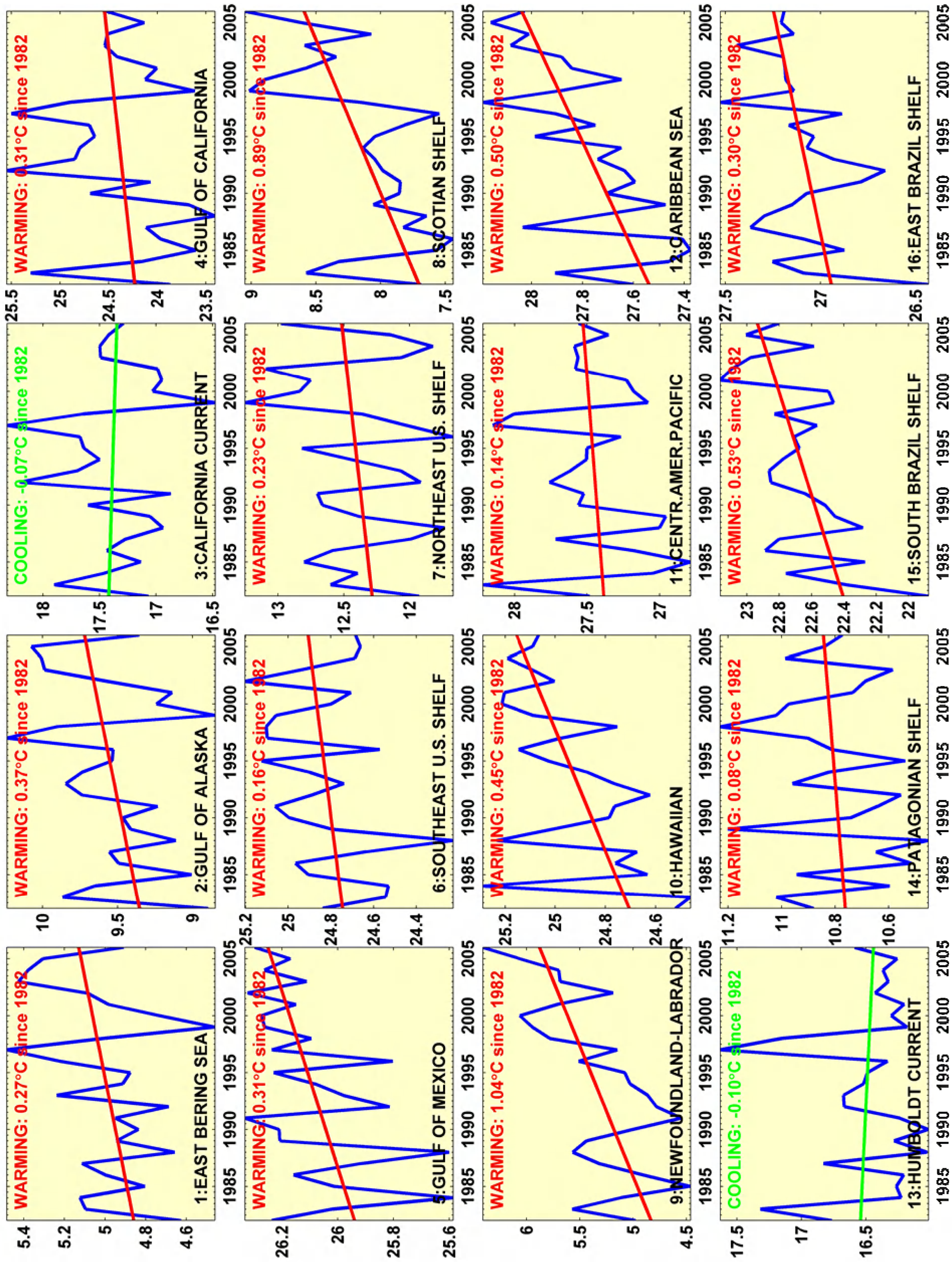
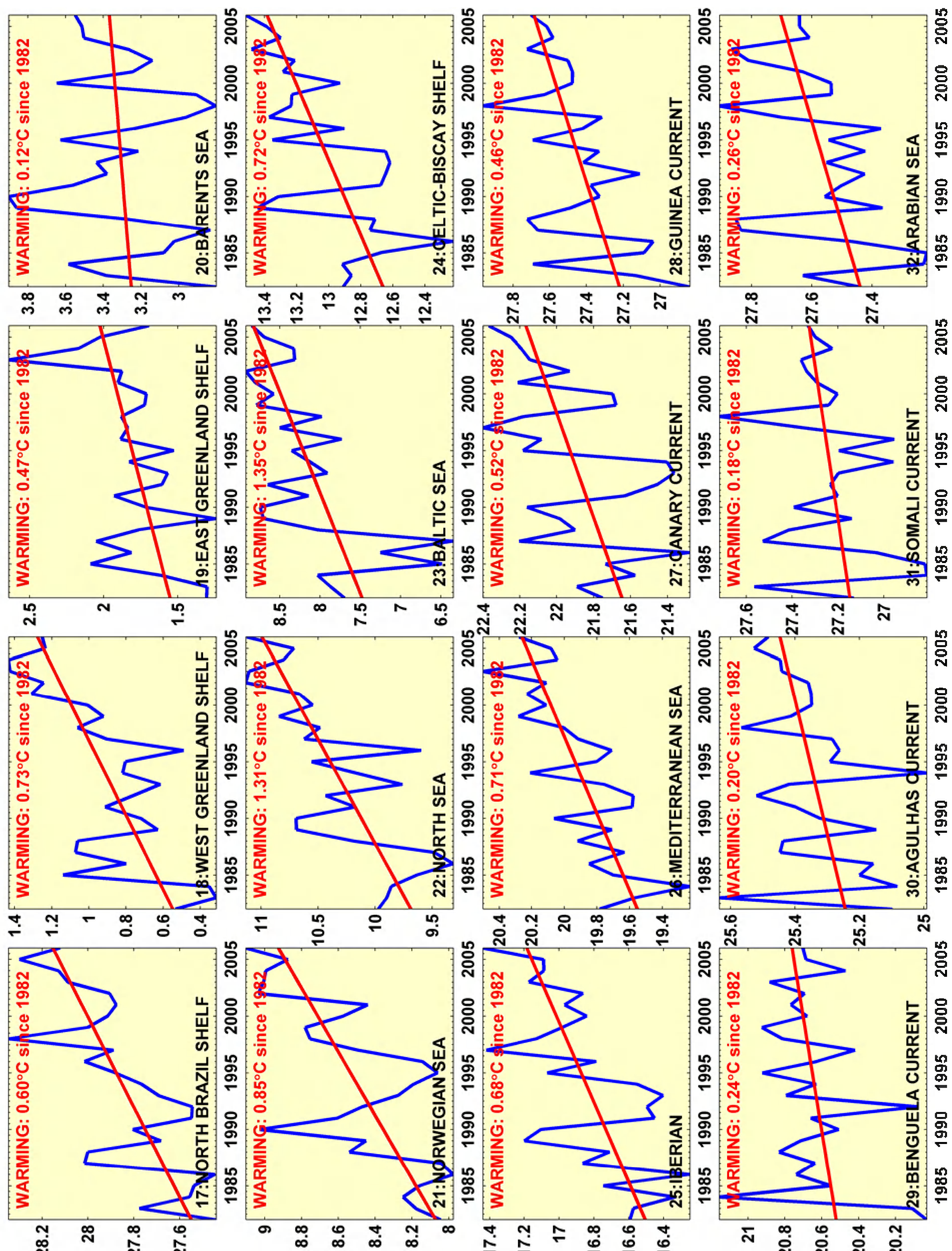
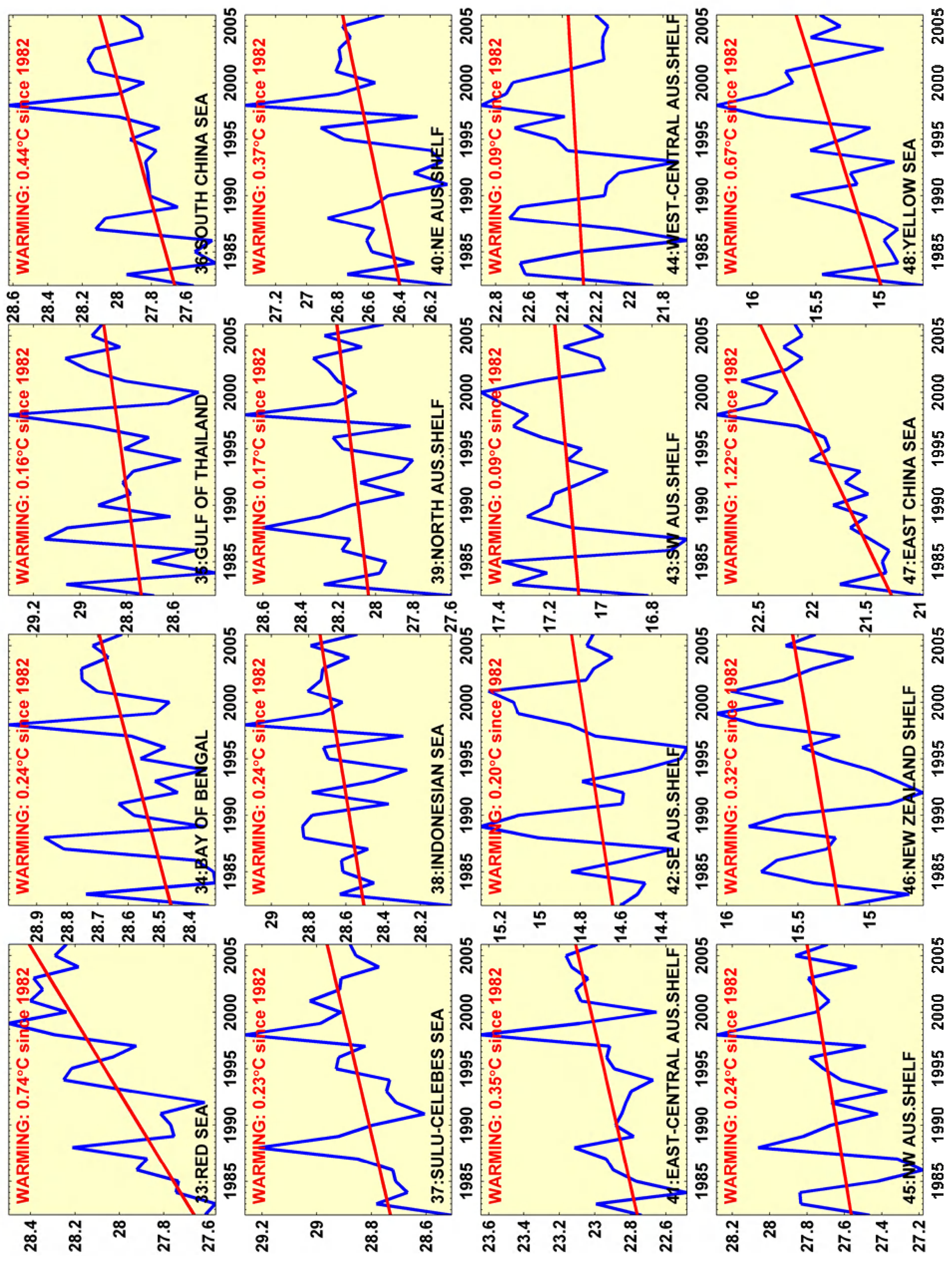

49:KUROSHIO CURRENT
50:SEA OF JAPAN
51:OYASHIO CURRENT
52:SEA OF OKHOTSK
53:WEST BERING SEA
54:CHUKCHI SEA
55:BEAUFORT SEA
56:EAST SIBERIAN SEA
57:LAPTEV SEA
58:KARA SEA
59:ICELAND SEA
60:FAROE PLATEAU
61:ANTARCTIC
62:BLACK SEA
63:HUDSON BAY
SST ANOMALIES in LARGE MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

Figure 5. SST trends in Large Marine Ecosystems, 1982-2006




WARMING: 0.60°C since 1982
17:NORTH BRAZIL SHELF
WARMING: 0.73°C since 1982
18:WEST GREENLAND SHELF
WARMING: 0.47°C since 1982
19:EAST GREENLAND SHELF
WARMING: 0.12°C since 1982
20:BARENTS SEA
WARMING: 0.85°C since 1982
21:NORWEGIAN SEA
WARMING: 1.31°C since 1982
22:NORTH SEA
WARMING: 1.35°C since 1982
23:BALTIC SEA
WARMING: 0.72°C since 1982
24:CELTIC-BISCAY SHELF
WARMING: 0.68°C since 1982
25:IBERIAN
WARMING: 0.71°C since 1982
26:MEDITERRANEAN SEA
WARMING: 0.52°C since 1982
27:CANARY CURRENT
WARMING: 0.46°C since 1982
28:GUINEA CURRENT
WARMING: 0.24°C since 1982
29:BENGUELA CURRENT
WARMING: 0.20°C since 1982
30:AGULHAS CURRENT
WARMING: 0.18°C since 1982
31:SOMALI CURRENT
WARMING: 0.26°C since 1982
32:ARABIAN SEA


33:RED SEA
WARMING: 0.74°C since 1982
34:BAY OF BENGAL
WARMING: 0.24°C since 1982
35:GULF OF THAILAND
WARMING: 0.16°C since 1982
36:SOUTH CHINA SEA
WARMING: 0.44°C since 1982
37:SULU-CELEBES SEA
WARMING: 0.23°C since 1982
38:INDONESIAN SEA
WARMING: 0.24°C since 1982
39:NORTH AUS.SHELF
WARMING: 0.17°C since 1982
40:NE AUS.SHELF
WARMING: 0.37°C since 1982
41:EAST-CENTRAL AUS.SHELF
WARMING: 0.35°C since 1982
42:SE AUS.SHELF
WARMING: 0.20°C since 1982
43:SW AUS.SHELF
WARMING: 0.09°C since 1982
44:WEST-CENTRAL AUS.SHELF
WARMING: 0.09°C since 1982
45:NW AUS.SHELF
WARMING: 0.24°C since 1982
46:NEW ZEALAND SHELF
WARMING: 0.32°C since 1982
47:EAST CHINA SEA
WARMING: 1.22°C since 1982
48:YELLOW SEA
WARMING: 0.67°C since 1982

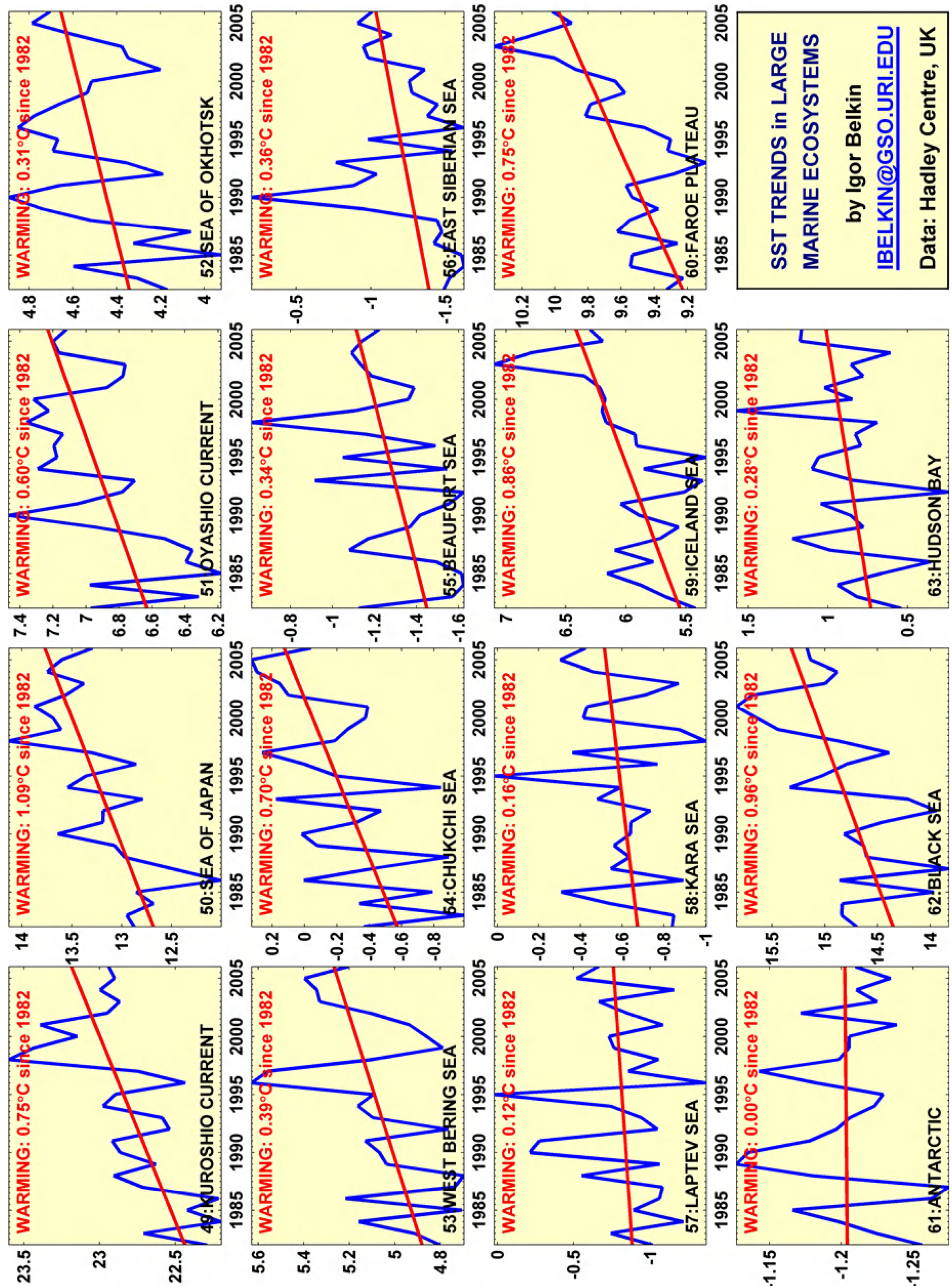
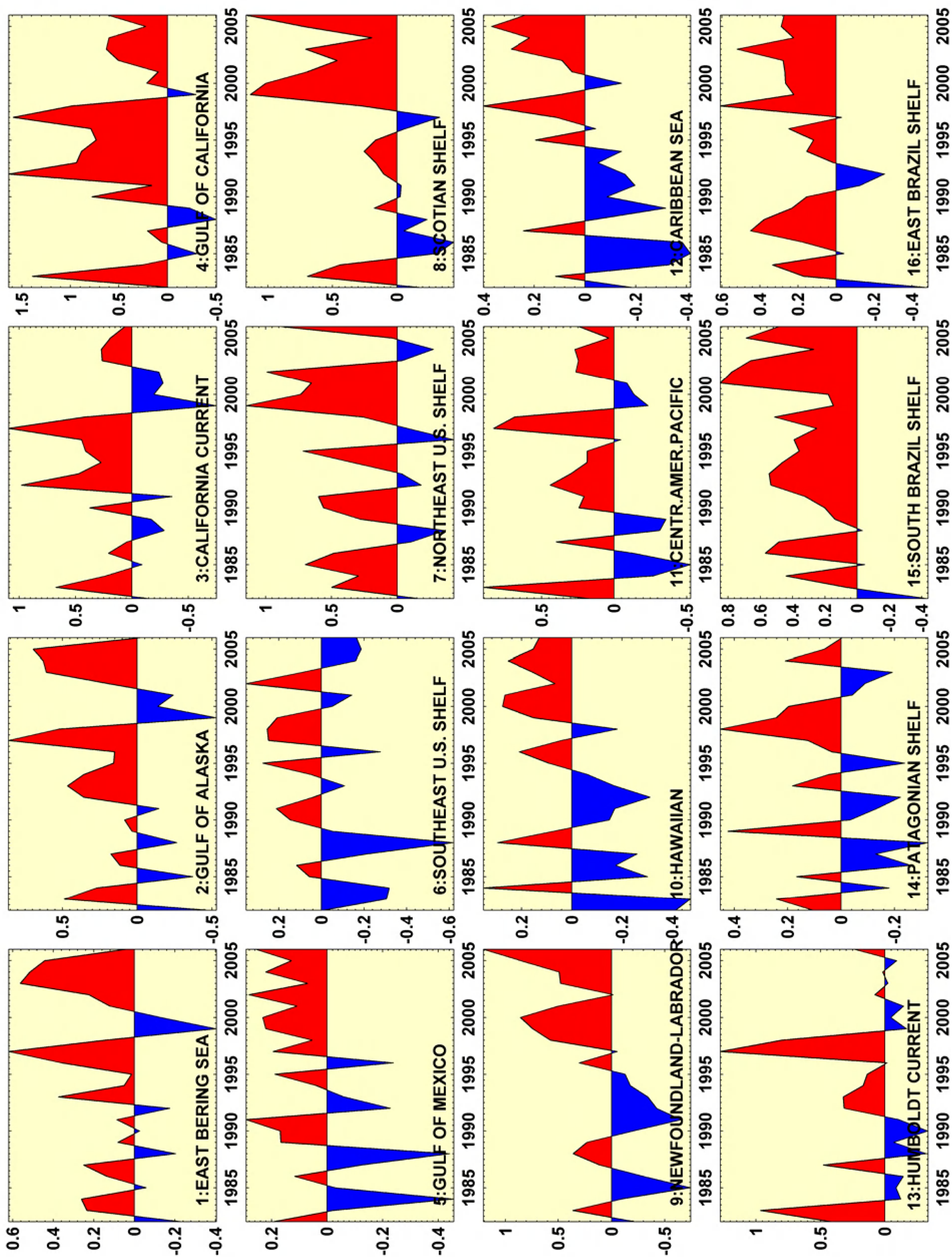
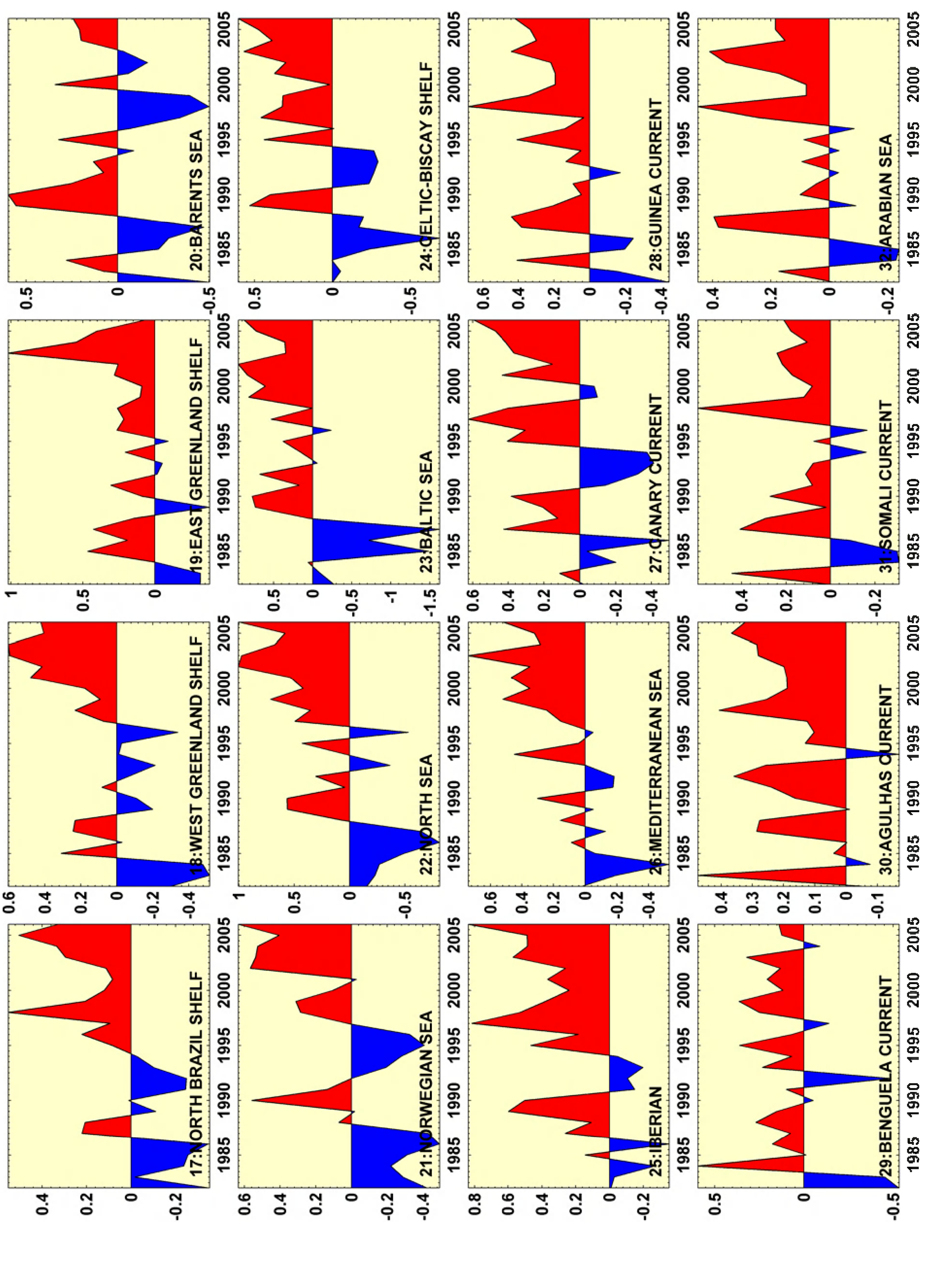
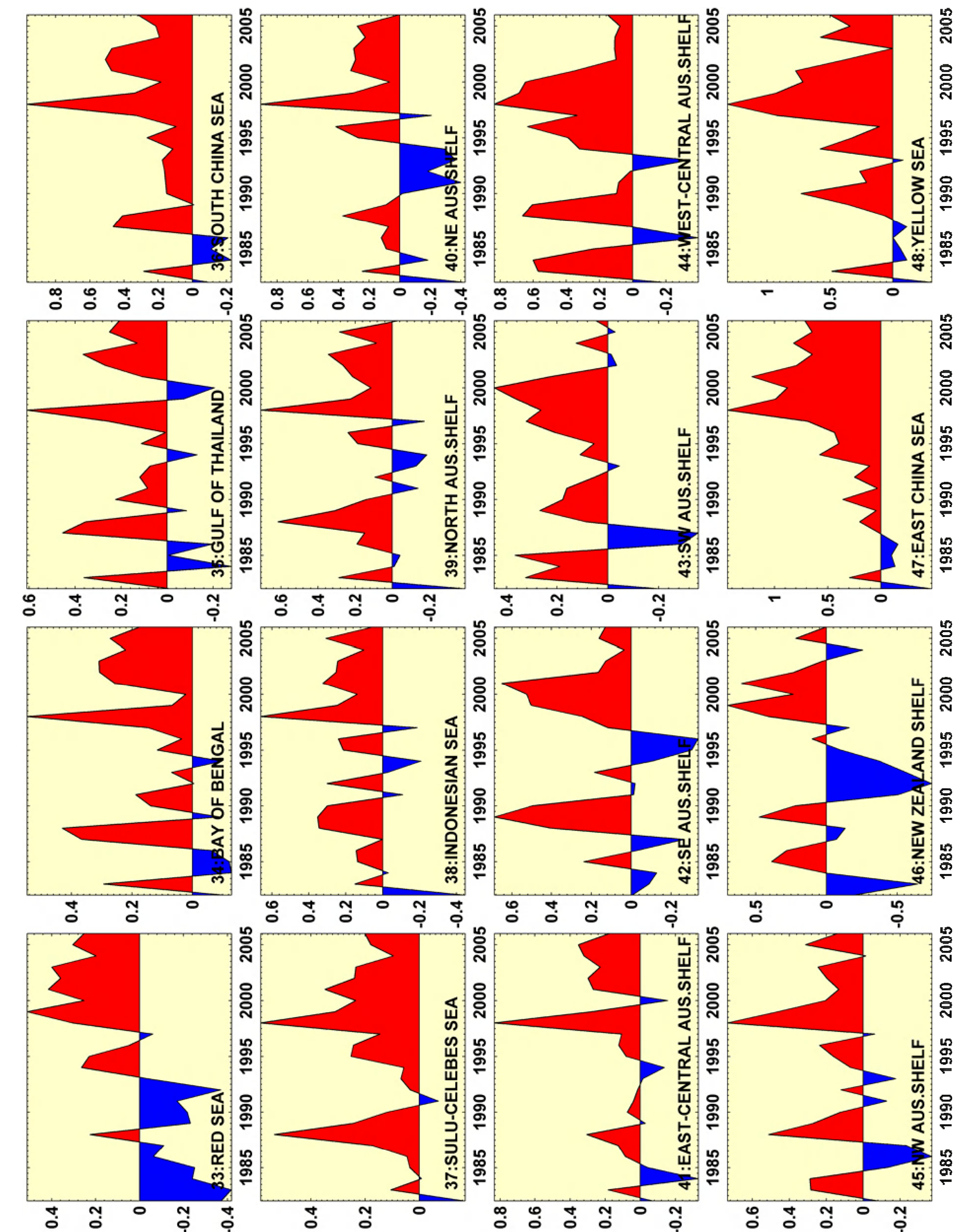
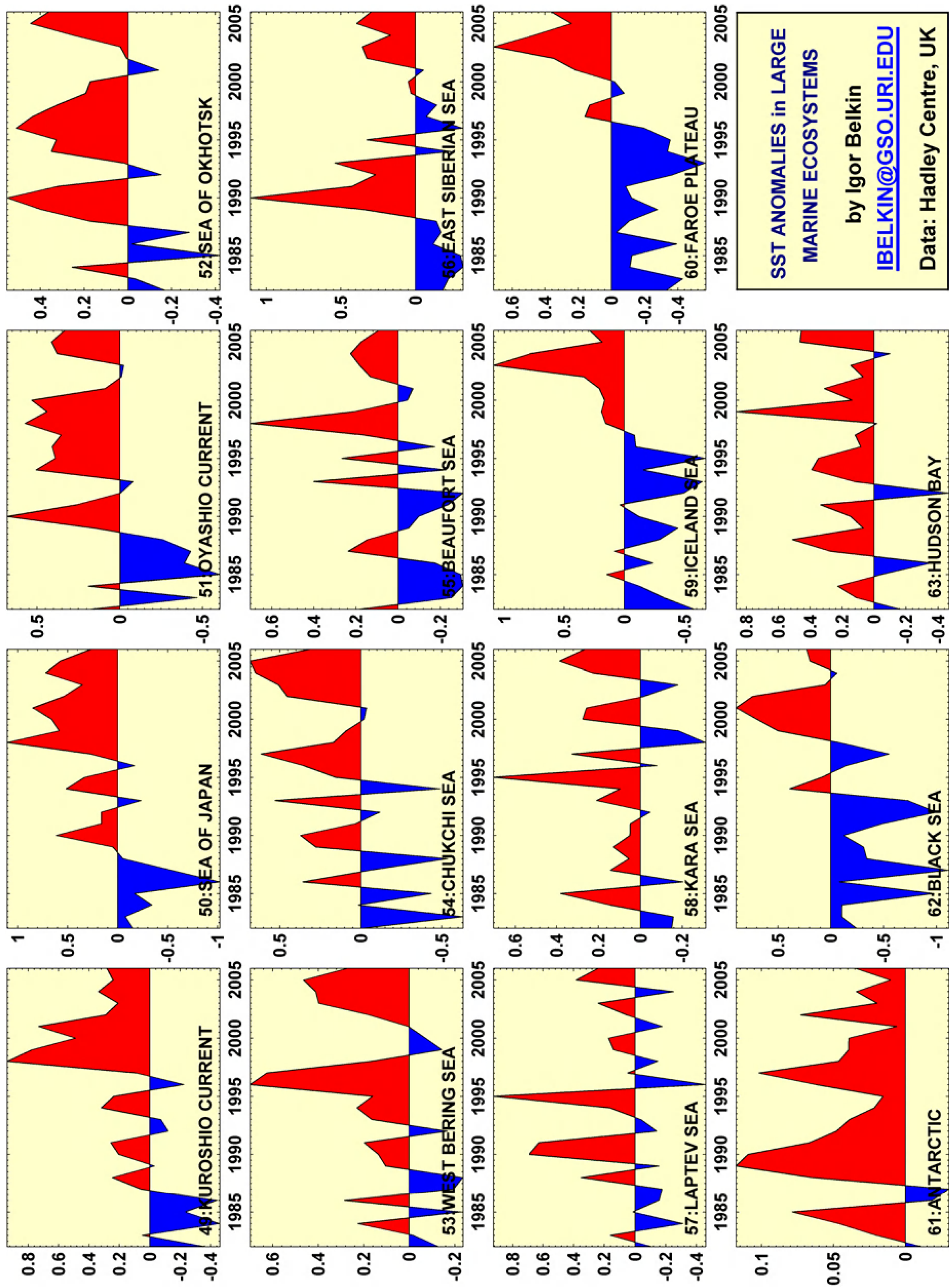

WARMING: 0.75°C since 1982
49:KUROSHIO CURRENT
WARMING: 1.09°C since 1982
50:SEA OF JAPAN
WARMING: 0.60°C since 1982
51:OYASHIO CURRENT
WARMING: 0.31°C since 1982
52:SEA OF OKHOTSK
WARMING: 0.39°C since 1982
53:WEST BERING SEA
WARMING: 0.70°C since 1982
54:CHUKCHI SEA
WARMING: 0.34°C since 1982
55:BEAUFORT SEA
WARMING: 0.36°C since 1982
56:EAST SIBERIAN SEA
WARMING: 0.12°C since 1982
57:LAPTEV SEA
WARMING: 0.16°C since 1982
58:KARA SEA
WARMING: 0.86°C since 1982
59:ICELAND SEA
WARMING: 0.75°C since 1982
60:FAROE PLATEAU
WARMING: 0.00°C since 1982
61:ANTARCTIC
WARMING: 0.96°C since 1982
62:BLACK SEA
WARMING: 0.28°C since 1982
63:HUDSON BAY
SST TRENDS in LARGE
MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

Figure 6. SST anomalies in Large Marine Ecosystems, 1982-2006




17:NORTH BRAZIL SHELF
18:WEST GREENLAND SHELF
19:EAST GREENLAND SHELF
20:BARENTS SEA
21:NORWEGIAN SEA
22:NORTH SEA
23:BALTIC SEA
24:CELTIC-BISCAY SHELF
25:IBERIAN
26:MEDITERRANEAN SEA
27:CANARY CURRENT
28:GUINEA CURRENT
29:BENGUELA CURRENT
30:AGULHAS CURRENT
31:SOMALI CURRENT
32:ARABIAN SEA
1985 1990 1995 2000 2005


33:RED SEA
34:BAY OF BENGAL
35:GULF OF THAILAND
36:SOUTH CHINA SEA
37:SULU-CELEBES SEA
38:INDONESIAN SEA
39:NORTH AUS.SHELF
40:NE AUS.SHELF
41:EAST-CENTRAL AUS.SHELF
42:SE AUS.SHELF
43:SW AUS.SHELF
44:WEST-CENTRAL AUS.SHELF
45:NW AUS.SHELF
46:NEW ZEALAND SHELF
47:EAST CHINA SEA
48:YELLOW SEA


49:KUROSHIO CURRENT
50:SEA OF JAPAN
51:OYASHIO CURRENT
52:SEA OF OKHOTSK
53:WEST BERING SEA
54:CHUKCHI SEA
55:BEAUFORT SEA
56:EAST SIBERIAN SEA
57:LAPTEV SEA
58:KARA SEA
59:ICELAND SEA
60:FAROE PLATEAU
61:ANTARCTIC
62:BLACK SEA
63:HUDSON BAY
SST ANOMALIES in LARGE
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Data: Hadley Centre, UK

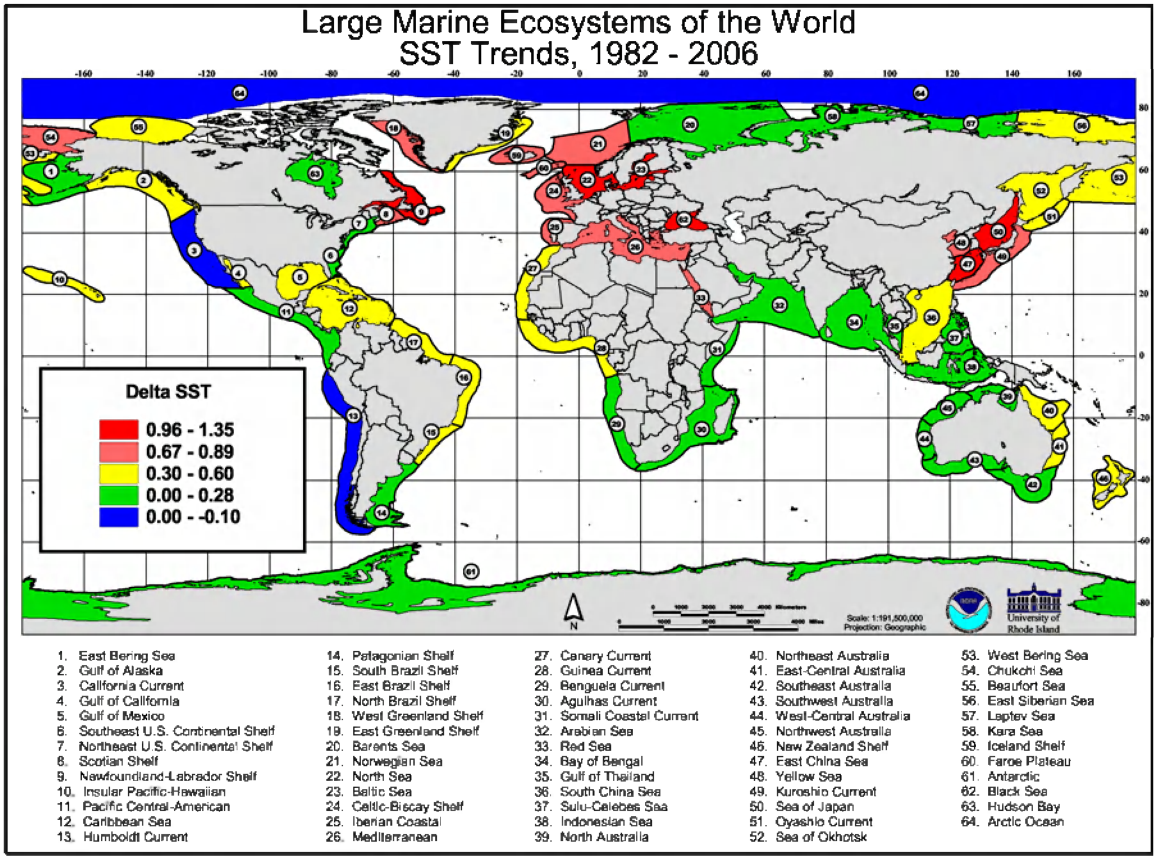

Figure 7. Net SST change in Large Marine Ecosystems based on a linear trend between 1982-2006.

Figure 8. Regime Shift of 1976-1977 in the West Bering Sea

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