Accelerated Warming and Emergent Trends in Fisheries Biomass Yields of the World's Large Marine Ecosystems

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Introduction

The heavily exploited state of the world's marine fisheries has been well documented (FAO 2004; Garcia and Newton 1997; González-Laxe 2007). Little, however, is known of the effects of climate change on the trends in global fisheries biomass yields. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change stated with "high confidence" that changes in marine biological systems are associated with rising water temperatures affecting shifts in pelagic algae and other plankton, and fish abundance in high latitudes (IPCC 2007). The Report also indicated that adaptation to impacts of increasing temperatures in coastal systems will be more challenging in developing countries than in developed countries due to constraints in adaptive capacity. From a marine resources management perspective, the 8 regions of the globe examined by the IPCC (i.e. North America, Latin America, Europe, Africa, Asia, the Australia and New Zealand region and the two Polar regions), are important fisheries areas but at a scale too large for determination of temperature trends relative to the assessment and management of the world's marine fisheries biomass yields produced principally in 64 large marine ecosystems (LMEs) (Figure 1). These LMEs, in coastal waters around the globe, annually produce 80% of the world's marine fisheries biomass (Figure 2).

Large Marine Ecosystems are areas of an ecologically based nested hierarchy of global ocean biomes and ecosystems (Watson et al. 2003). Since 1995, LMEs have been designated by a growing number of coastal countries in Africa, Asia, Latin America, and eastern Europe as place-based assessment and management areas for introducing an ecosystems approach to recover, 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). The approach is part of an emerging effort by the scientific community to relate the scale of place-based ecosystem assessment and management of marine resources to policy making and to tighten the linkage between applied science and improved management of ocean resources within the natural boundaries of LMEs (COMPASS 2005; Wang 2004).

Since 1995, international financial organizations have extended explicit support to developing coastal countries for assessing and managing goods and services using the modular approach at the LME scale. At present, 110 countries are engaged in LME projects along with 5 UN agencies and $1.8 billion in financial support from the Global Environment Facility (GEF) and the World Bank. Sixteen LME projects are presently focused on introducing an ecosystems approach to the recovery of depleted fish stocks, restoration of degraded habitats, reduction and control of pollution, conservation of biodiversity, and adaptation to climate change. In recognition of the observational evidence of global warming from the 4th Assessment Report of the (IPCC 2007) and the lack of information on trends in global warming at the LME scale where most of the world's marine fisheries biomass yields are produced, we undertook a study of the physical extent and rates of sea surface temperature trends in relation to fisheries biomass yields and SeaWiFS derived primary productivity of the world's LMEs.

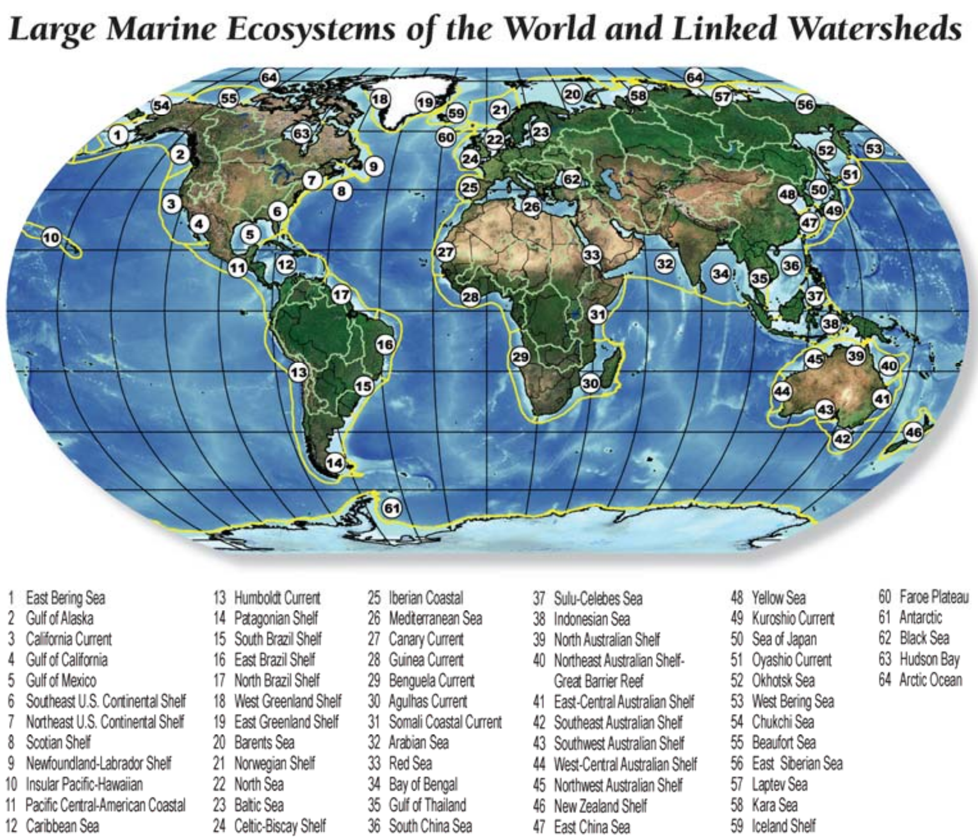

Figure 1. Large Marine Ecosystems of the World

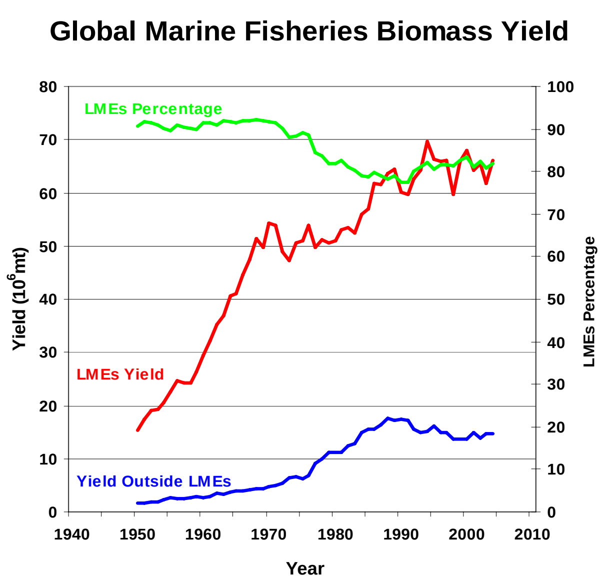

Figure 2. **Annual global marine fisheries biomass yields in metric tons of the world's LMEs. From the University of British Columbia's Sea Around us Project (SAUP).**

METHODS

Fisheries biomass yields are not presented here as representative of individual fish stock abundances. They are representative of fisheries catches and are used here to compare the effects of global warming on the fishery biomass yields of the World's LMEs. The comparative analysis of global temperature trends, fisheries biomass yields, and primary productivity is based on available time-series data at the LME scale on sea surface temperatures, marine fisheries biomass yields, and Sea WiFS derived primary productivity values.

LME Sea Surface Temperatures (SST)

Sea surface temperature (SST) data is a thermal parameter routinely measured worldwide. Subsurface temperature data, albeit important, are limited in the spatial and temporal density required for reliable assessment of thermal conditions at the Large Marine Ecosystem (LME) scale worldwide. The U.K. Meteorological Office Hadley Center SST climatology was used in this analysis (Belkin 2009), as the Hadley data set has resolution of 1 degree latitude by 1 degree longitude globally. A detailed description of this data set has been published by Rayner et al. (2003). Mean annual SST values were calculated for each 1° x 1° cell and then were area-averaged by 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. Annual anomalies of annual LME-averaged SST were calculated. 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. Annual SST anomalies were calculated by subtracting the long-term mean SST from the annual SST. Both SST and SST anomalies were plotted using adjustable temperature scales for each LME to depict temporal trends. Comparisons of fisheries biomass yields were examined in relation to intervals of 0.3°C of increasing temperature.

LME Primary Productivity

The LME primary productivity estimates are derived from satellite borne data of NOAA's Northeast Fisheries Science Center, Narragansett Laboratory. These estimates originate from SeaWiFS (satellite-derived chlorophyll estimates from the Sea-viewing Wide Field-of-view Sensor), Coastal Zone Color Scanner (CZCS), a large archive of *in situ* near-surface chlorophyll data, and satellite sea surface temperature (SST) measurements to quantify spatial and seasonal variability of near-surface chlorophyll and SST in the LMEs of the world. Daily binned global SeaWiFS chlorophyll *a* (CHL, mg m^{-3}), normalized water leaving radiances, 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's Ocean Biology Processing Group. Daily global 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 global primary productivity (PP, gC m^{-2} d^{-1}) were calculated using the Ocean Productivity from Absorption and Light (OPAL) model, a derivative of the model first formulated in Marra et al. (2003). The OPAL model generates profiles of chlorophyll estimated from the SeaWiFS chlorophyll using the algorithm from Wozniak et al. (2003) that uses the absorption properties in the water column to vertically resolve estimates of light attenuation in approximately 100 strata within the euphotic zone. Productivity is calculated for the 100 layers in the euphotic zone and summed to compute the integral daily productivity (gC m^{-2} d^{-1}). Monthly and annual means of primary productivity (PP) were extracted and averaged for each LME. Significance levels (alpha=0.01 and 0.05) of the regression coefficients of the nine years of Sea WiFS mean annual primary productivity data were determined using a t-test according to Sokal and Rohfl (1995). Time series trends plotted for each LME are available online (www.lme.noaa.gov).

Fisheries Biomass Yield Methods

Prior to the Sea Around Us Program, projections of marine fisheries yields at the LME scale, were largely defined by the range of vessels exploiting a given resource (Pauly and Pitcher 2000). The need for countries to manage fisheries within EEZ's under UNCLOS initiated efforts to derive fisheries yields at the national level(Prescott-Allen 2001) and consistent with the emergence of ecosystem-based management at the LME scale(Sherman et al. 2003) (Pauly et al. 2008). The time series of fisheries biomass yields (1950-2004) used in this study are based on the time-series data provided at the LME scale by the Sea Around Us Project at the University of British Columbia (Pauly et al. 2008) The method used by the Sea Around Us Project to map reported fishery catches onto 180,000 global spatial cells of ½ degrees latitude and longitude was applied to produce profiles of 54-yr. mean annual time-series of catches (biomass yields) by 12 species or species groups for the world's LMEs (Pauly et al. 2008; Watson et al. 2003). In addition, plots on the status of the stocks within each of the LMEs according to their condition (e.g. undeveloped, fully exploited and overexploited) in accordance with the method of Froese and Kesner-Reyes (2002), and illustrated by Pauly et al. (2008), were used to examine trends in yield condition among the LMEs. Fisheries biomass yields were examined in relation to warming trends for 63 LMEs for the period 1982 to 2004. Fisheries biomass yield trends were plotted for each LME using the LOESS smoothing method (tension=0.5) and the emergent increasing and decreasing patterns examined in relation to LME warming data (Cleveland and Devlin 1988). Observed trends were compared to earlier studies for emergent spatial and temporal global trends in LME fishery biomass yields.

RESULTS

Comparative SST Clusters

The LME plots of SST and SST anomalies are presented in 2 sets of 4 plates, with each set containing a total of 63 figures: four plates for SST and four plates for SST anomalies 1957-2006. These can be viewed at www.lme.noaa.gov. The Arctic Ocean LME was not included in this analysis because of the perennial sea ice cover. 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 however, the long-term SST variability since 1957 was not linear over the period. Specifically. most LMEs underwent a cooling between the 1950s and the 1970s, replaced by a rapid warming from the 1980s until the present. Therefore we re-calculated SST trends using only the last 25 years of data (SST data available at www.lme.noaa.gov, where SST anomalies are calculated for each LME. Net SST change in each LME between 1982 and 2006 based on SST trends is summarized in Table 1 (after Belkin 2009).

The most striking result is the consistent warming of LMEs, with the notable exceptions of two, the California Current and Humboldt Current. These LMEs experienced cooling over the last 25 years. Both are in large and persistent upwelling areas of nutrient rich cool water in the Eastern Pacific. The SST values were partitioned into 0.3°C intervals to allow for comparison among LME warming rates. The warming trend observed in 61 LMEs ranged from a low of 0.08°C for the Patagonian Shelf LME to a high of 1.35°C in the Baltic Sea LME (Table 1). The relatively rapid warming exceeding 0.6°C 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 (IPCC 2007). The warming in low-latitude LMEs is several times slower than the warming in high-latitude LMEs (Table 1). In addition to the Baltic Sea, the most rapid

Table 1. SST change in each LME, 1982-2006 (sorted in descending order)

LME#	SST Change (°C) 1982-2006	Slope of Linear Regression (°C/year)	Standard Error of Slope (°C/year)
LME23='BALTIC SEA';	1.35	0.0563	0.0151
LME22='NORTH SEA';	1.31	0.0544	0.0099
LME47='EAST CHINA SEA';	1.22	0.0509	0.0077
LME50='SEA OF JAPAN'/'EAST SEA';	1.09	0.0453	0.0098
LME9='NEWFOUNDLAND-LABRADOR SHELF';	1.04	0.0435	0.0108
LME62='BLACK SEA';	0.96	0.0401	0.0124
LME8='SCOTIAN SHELF';	0.89	0.0370	0.0105
LME59='ICELAND SHELF	0.86	0.0360	0.0091
LME21='NORWEGIAN SEA';	0.85	0.0356	0.0072
LME49'KUROSHIO CURRENT';	0.75	0.0312	0.0062
LME60='FAROE PLATEAU';	0.75	0.0311	0.0078
LME33='RED SEA';	0.74	0.0309	0.0048
LME18='WEST GREENLAND SHELF';	0.73	0.0304	0.0064
LME24='CELTIC-BISCAY SHELF';	0.72	0.0301	0.0076
LME26='MEDITERRANEAN SEA';	0.71	0.0294	0.0055
LME54='CHUKCHI SEA';	0.70	0.0290	0.0087
LME25='IBERIAN COASTAL';	0.68	0.0283	0.0072
LME48='YELLOW SEA';	0.67	0.0279	0.0097
LME17='NORTH BRAZIL SHELF';	0.60	0.0252	0.0049
LME51='OYASHIO CURRENT';	0.60	0.0250	0.0086
LME15='SOUTH BRAZIL SHELF';	0.53	0.0221	0.0068
LME27='CANARY CURRENT';	0.52	0.0217	0.0082
LME12='CARIBBEAN SEA';	0.50	0.0208	0.0050
LME19='EAST GREENLAND SHELF';	0.47	0.0197	0.0074
LME28='GUINEA CURRENT';	0.46	0.0194	0.0063
LME10='INSULAR PACIFIC HAWAIIAN';	0.45	0.0187	0.0056
LME36='SOUTH CHINA SEA';	0.44	0.0182	0.0063
LME53='WEST BERING SEA';	0.39	0.0162	0.0064
LME2='GULF OF ALASKA';	0.37	0.0154	0.0081
LME40='NE AUSTRALIAN SHELF-GREAT BARRIER REEF';	0.37	0.0153	0.0101
LME56='EAST SIBERIAN SHELF';	0.36	0.0149	0.0092
LME41='EAST-CENTRAL AUSTRALIAN SHELF';	0.35	0.0145	0.0056
LME55='BEAUFORT SEA';	0.34	0.0140	0.0066
LME46='NEW ZEALAND SHELF';	0.32	0.0135	0.0105
LME4='GULF OF CALIFORNIA';	0.31	0.0130	0.0069
LME5='GULF OF MEXICO';	0.31	0.0130	0.0161
LME52='SEA OF OKHOTSK';	0.31	0.0129	0.0053
LME16='EAST BRAZIL SHELF';	0.30	0.0126	0.0062
LME63='HUDSON BAY';	0.28	0.0117	0.0076
LME1='EAST BERING SEA';	0.27	0.0113	0.0070
LME32='ARABIAN SEA';	0.26	0.0110	0.0048
LME29='BENGUELA CURRENT';	0.24	0.0100	0.0072
LME34='BAY OF BENGAL';	0.24	0.0098	0.0061
LME38='INDONESIAN SEA';	0.24	0.0098	0.0067
LME45='NORTHWEST AUSTRALIAN SHELF';	0.24	0.0098	0.0049
LME7='NORTHEAST U.S. CONTINENTAL SHELF';	0.23	0.0096	0.0043
LME37='SULU-CELEBES SEA';	0.23	0.0096	0.0125
LME30='AGULHAS CURRENT';	0.20	0.0085	0.0079
LME42='SOUTHEAST AUSTRALIAN SHELF';	0.20	0.0084	0.0042
LME31='SOMALI COASTAL CURRENT';	0.18	0.0074	0.0059
LME39='NORTH AUSTRALIAN SHELF';	0.17	0.0070	0.0068
LME6='SOUTHEAST U.S. CONTINENTAL SHELF';	0.16	0.0067	0.0061
LME35='GULF OF THAILAND';	0.16	0.0067	0.0064
LME58='KARA SEA';	0.16	0.0066	0.0065
LME11='PACIFIC CENTRAL-AMERICAN COASTAL';	0.14	0.0059	0.0101
LME20='BARENTS SEA';	0.12	0.0051	0.0092
LME57='LAPTEV SEA';	0.12	0.0048	0.0088
LME43='SOUTHWEST AUSTRALIAN SHELF';	0.09	0.0039	0.0057
LME44='WEST-CENTRAL AUSTRALIAN SHELF';	0.09	0.0038	0.0093
LME14='PATAGONIAN SHELF';	0.08	0.0034	0.0059
LME61='ANTARCTIC';	0.00	0.0001	0.0011
LME3='CALIFORNIA CURRENT';	-0.07	-0.0030	0.0119
LME13='HUMBOLDT CURRENT';	-0.10	-0.0042	0.0112
LME64='ARCTIC OCEAN';			

warming exceeding 0.96°C over 25 years is observed in the North Sea, East China Sea, Sea of Japan/East Sea, and Newfoundland-Labrador Shelf and Black Sea LMEs. Comparisons of warming were made among three temperature clusters of LMEs. 1) Super fast warming LMEs with D(SST) between >0.96°C -1.35°C are combined with fast warming LMEs .67°C – 0.84°C. Moderate warming LMEs have D(SST) between >0.3-0.6°C; slow warming LMEs, have D(SST) between 0.0°C-0.28°C. Of the fast warming LMEs (0.67°C to 1.35°C), 18 are warming at rates 2x to 4x times higher than the global air surface temperature increase of 0.74°C for the past 100 years as reported by the IPCC (2007) (Figure 3).

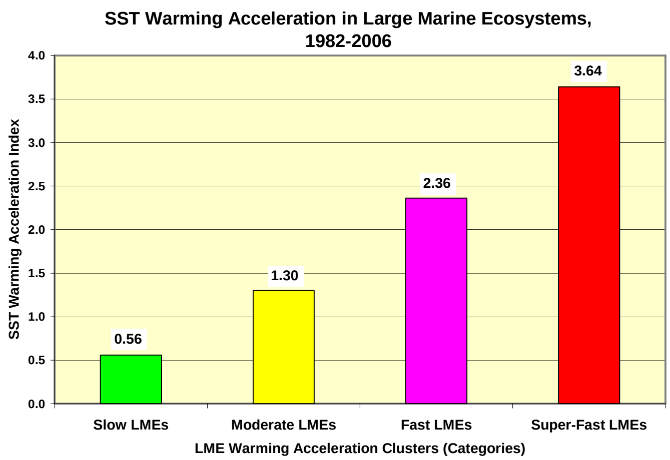

Figure 3. Accelerated warming of sea surface temperature in Large Marine Ecosystems, 1982-2006. Shown is the Warming Acceleration Index (WAI) for four clusters of LMEs grouped according to their net SST change between 1982 and 2006, categorized as slow (0.0-0.3°C, net SST change), moderate (0.3-0.6°C), fast (0.6-0.9°C) and super-fast (>0.9°C) (Table 1). The WAI (shown at the top of each bar) is calculated as the ratio of the cluster's average SST warming rate (Belkin 2009) to the IPCC-2007 global average SST warming rate of 0.133±0.047°C/decade (Trenberth et al. 2006).

Primary Productivity

No large scale consistent pattern of either increase or decrease in primary productivity was observed. Of the 64 LMEs examined, only four 9-year trends were significant (P<.05) (Figure 4). Primary productivity declined in the Bay of Bengal, and increased in the Hudson Bay, Humboldt Current and Red Sea LMEs). The general declining trend in primary productivity with ocean warming reported by Behrenfeld (2006) was limited to the Bay of Bengal LMEs. No consistent trend among the LMEs was observed (Table 2). However, as previously reported (Chassot et al. 2007; Nixon et al. 1986; Ware and Thomson 2005) fisheries biomass yields did increase with increasing levels of primary productivity (P<.001) in all 63 LMEs, and for LMEs in each of the warming clusters (Figure 5A and 5B).

Table 2. Test results of primary productivity regression analysis for 9 years of mean annual Sea WiFS Primary Productivity (PP) data; +*P<0.05

LME	PP
Bay of Bengal	- *
Hudson Bay	+ *
Humboldt Current	+ *
Red Sea	+ *

Fisheries biomass yield trends

The effects of warming on global fisheries biomass yields were non-uniform in relation to any persistent global pattern of increasing or decreasing yields. The relationship between change in LME yield and SST change was not significant; the slight suggestion of a trend in the regression, was influenced by the data for the Humbolt LME (Figure 6). Partitioning of the results into LMEs with increasing trends in fisheries biomass yields, and those with declining trends divided the trends into two groups. Increasing yields were observed in 31 (49.2%) and decreasing trends in 32 (50.8%) of LMEs. Differences

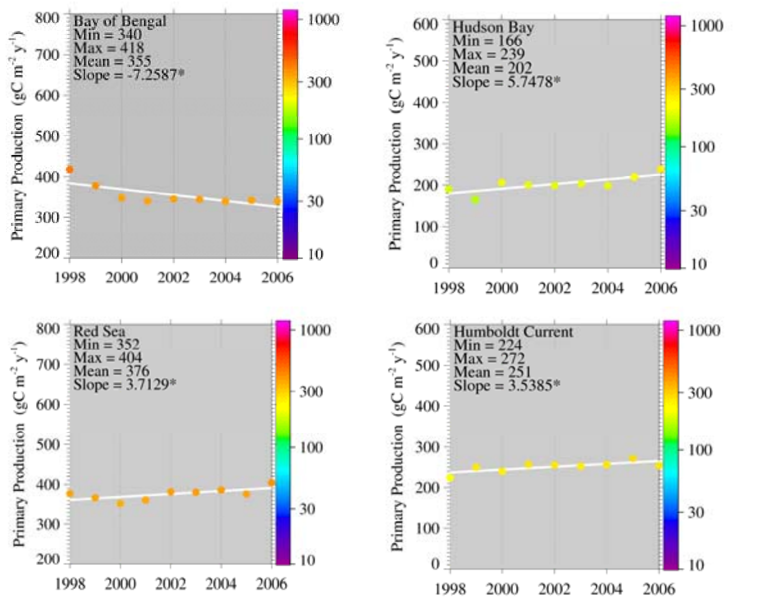

Figure 4. Primary productivity trends (1998-2006): Bay of Bengal, Hudson Bay, Humboldt Current and Red Sea.

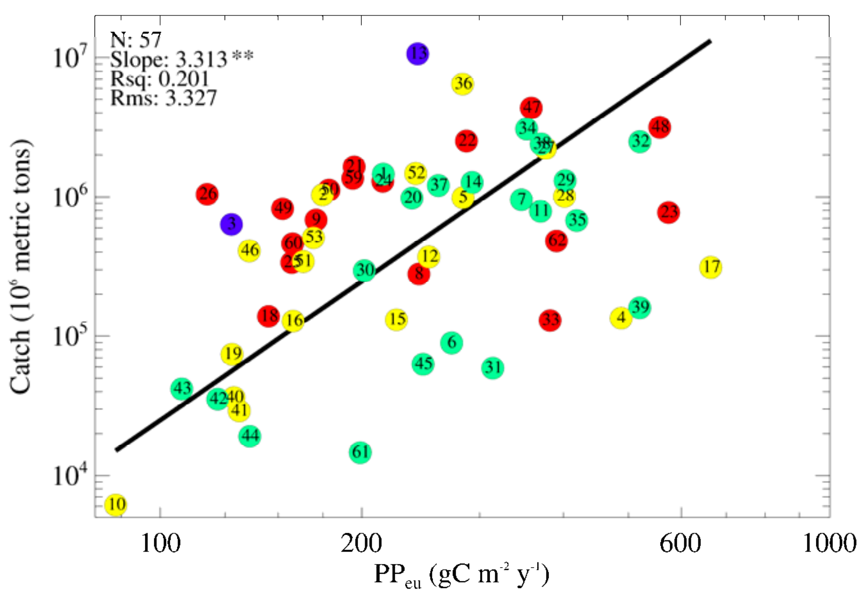

Figure 5A. Positive correlation of 5-yr. mean annual fisheries biomass yield with 9-yr. mean annual primary production in fast warming (red), moderately warming (yellow) and slower warming (green) LMEs. The two blue circles represent cooling LMEs. P<0.001.

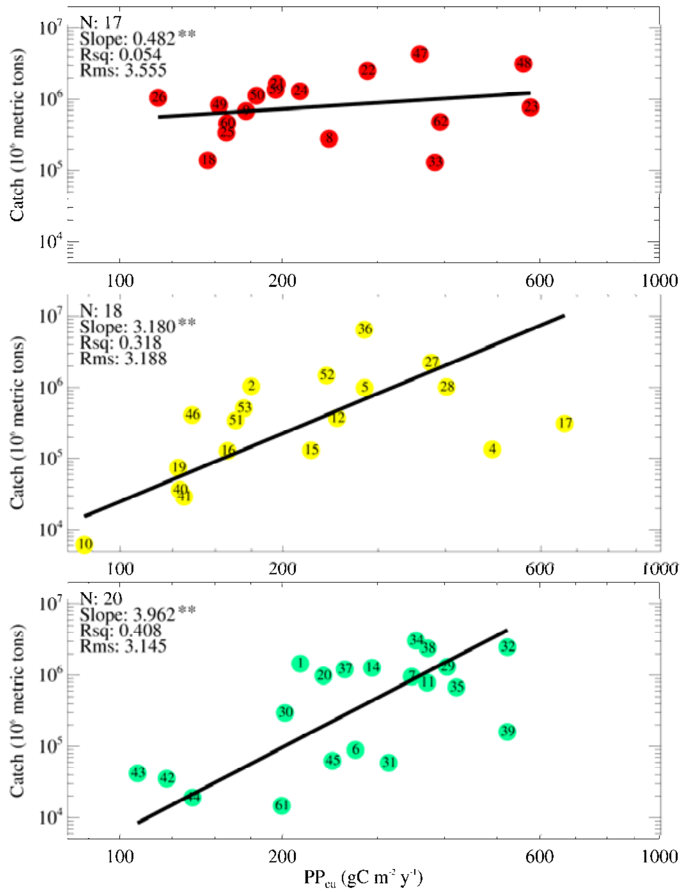

Figure 5A. P<0.001

Figure 5B. Comparison of 5-yr mean annual fisheries biomass yield with 9-yr mean annual primary production in fast warming (red), moderately warming (yellow) and slower warming (green) LMEs.

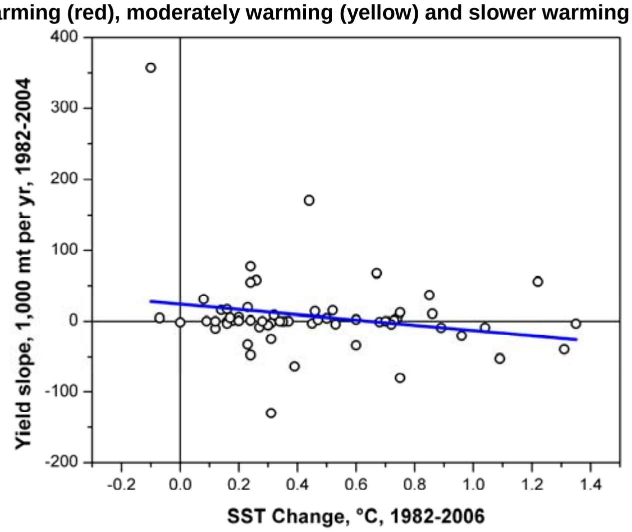

Figure 6. The relationship (shown with blue trend line) between LME yield trend slope and net SST change was not significant; the slight suggestion of a trend in the regression, was influenced by the data for the Humbolt LME.

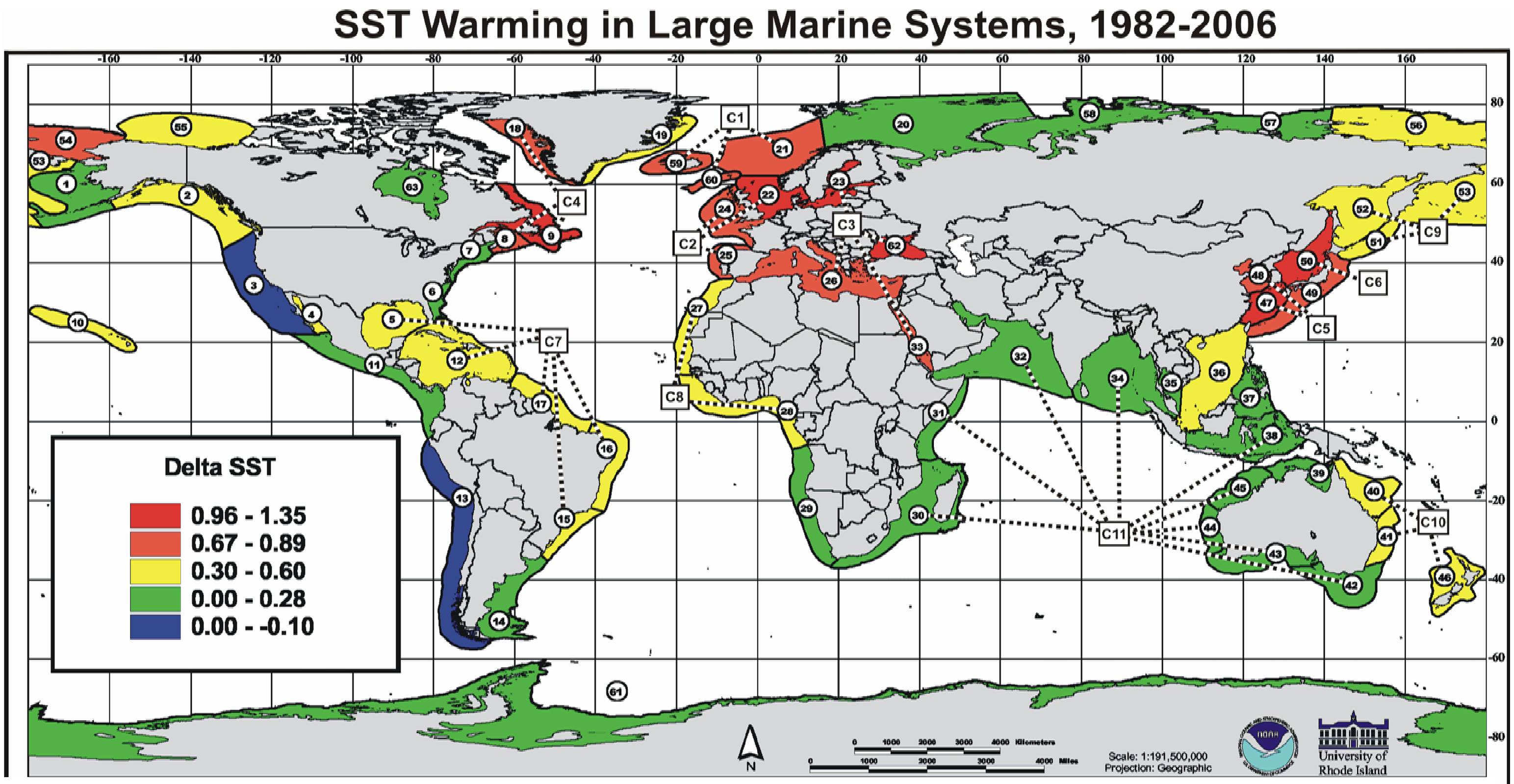

Figure 7. Warming Clusters of LMEs in Relation to SSTs, 1982-2006:

FAST WARMING:

C1 Northern European Cluster; **C2** Southern European; **C3** Semi-Enclosed European Seas; **C4** of the NW Atlantic; **C5** Fast Warming East Asian LMEs; **C6** Kuroshio Current and Sea of Japan/East Sea LMEs.

MODERATE WARMING:

C7 Western Atlantic LMEs; **C8** Eastern Atlantic LMEs; **C9** NW Pacific; **C10** SW Pacific. Several **Non-Clustered, Moderate Warming LMEs** are moderate warming: NE Australia, Insular Pacific Hawaiian, Gulf of Alaska, Gulf of California; South China Sea, East Greenland Shelf;

SLOW WARMING:

C11 Indian Ocean and Adjacent Waters.

Non-clustered, Slow Warming LMEs include the U.S. Northeast Shelf, the U.S. Southeast Shelf, the Barents Sea, East Bering Sea; Patagonian Shelf, Benguela Current and Pacific Central American Coastal LMEs.

were similar in Fast Warming (8 increasing, 10 decreasing) and Moderate Warming LMEs (10 increasing, 8 decreasing). In the Slower Warming LMEs, most (14) were undergoing increasing biomass yields and 6 were in a decreasing condition (Table 3**).** Linear warming trends from 1982 to 2006 for each LME were distributed in distinct global clusters, (i) the Fast Warming LME clusters were in the Northeast Atlantic, African and Southeast Asian waters; (ii) the Moderate Warming LMEs were clustered in the Atlantic and North Pacific waters; and (iii) the Slow Warming LME clusters were located principally in the Indian Ocean, and also in locations around the margins of the Atlantic and Pacific Oceans (Figure 7). Comparisons of fisheries biomass yield trends for eleven LME warming clusters were examined.

Table 3. Fisheries biomass trends in LMEs adjacent to developing and developed countries.

Fisheries biomass trend	**Status of adjacent countries**	**Fisheries biomass in million metric tons**	**Percentage of total**
Increasing fisheries (20 LMEs)	Developing countries	32.0	49%
Decreasing fisheries (9 LMEs)	Developing countries	6.2	9%
Increasing fisheries (11 LMEs)	Developed countries	4.4	6%
Decreasing fisheries (15 LMEs)	Developed countries	11.0	17%
California Current, Humboldt Current, and 7 Arctic LMEs (9 LMEs)		11.4	19%
Total fisheries biomass	All categories	65.0	100%

Comparative fisheries biomass yields in relation to warming: Fast warming European LMEs

In the **Norwegian Sea, Faroe Plateau, and Iceland Shelf,** the fisheries biomass yield is increasing. These three LMEs account for 3.4 million tons, or 5% of the world biomass catch, (Figure 8A). This cluster of LMEs is influenced from bottom-up forcing of increasing zooplankton abundance and warming hydrographic conditions in the northern areas of the North Atlantic, where stocks of herring, blue whiting and capelin are benefiting from an expanding prey field of zooplankton (Beaugrand and Ibanez 2004; Beaugrand et al. 2002) supporting growth and recruitment of these three species. The warming trend in the Norwegian Sea driving the increase in biomass of herring, capelin and blue whiting yields has been reported by (Skjoldal and Saetre 2004). On the Faroe Plateau LME, Gaard et al. (2002) indicate that the increasing shelf production of plankton is linked to the increased production of fish and fisheries in the ecosystem. Astthorsson and Vilhjálmsson (2002) have shown that variations of zooplankton in Icelandic waters are greatly influenced by large scale climatic factors and that warm Atlantic water inflows favor zooplankton that supports larger populations of capelin that serve as important prey of cod. The productivity and fisheries of all three LMEs are benefiting from the increasing strength of the sub-Polar gyre bringing warmed waters to the LMEs of the region generally in the northern northeast Atlantic and contributing to decreasing production and fisheries yields in the relatively warmer southern waters of the northeast Atlantic (Richardson and Schoeman 2004).

In southern Europe three LMEs, the **North Sea, Celtic Biscay, and Iberian Coastal LMEs** in fast warming clusters are experiencing declines in biomass trends representing 4.1 mmt (6.4%) of the mean annual global biomass yield (Figure 8B). It has been

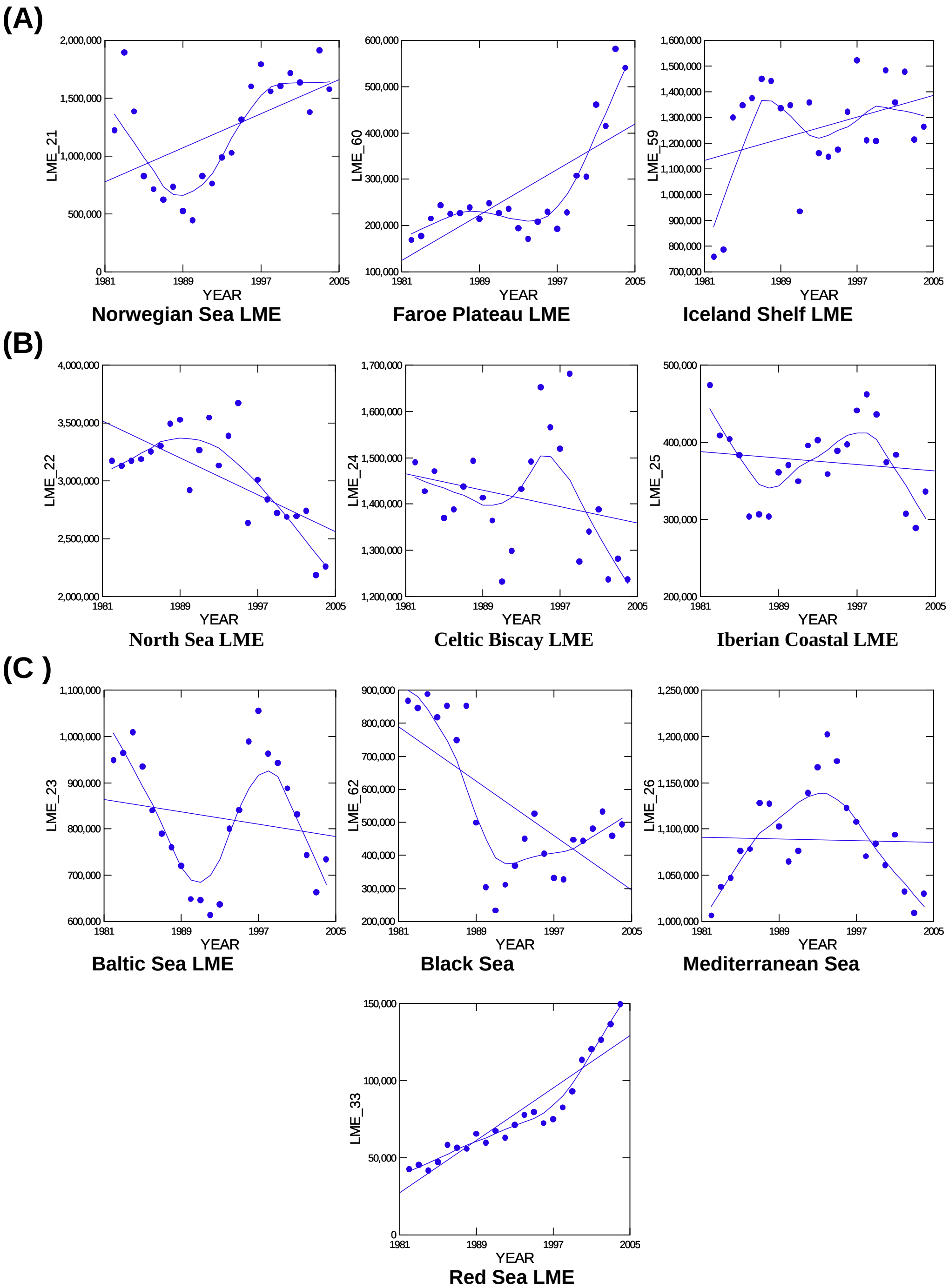

Figure 8. Fisheries biomass yield trends (metric tons) in fast warming clusters A. Norwegian, Faroe Plateau and Iceland Shelf LMEs (C1) B. North Sea, Celtic Biscay and Iberian Coastal LMEs (C2) and C. Baltic Sea, Black Sea, Mediterranean Sea and Red Sea (C3) LMEs

reported that zooplankton abundance levels in the three LMEs are in decline, reducing the prey field for zooplanktivores (Beaugrand et al. 2002; Valdés and Lavin 2002; Valdés et al. 2007). Although we did not detect any significant decline in primary productivity in the three LMEs, the declining phytoplankton level in the region (Richardson and Schoeman 2004) is consistent with the declines in primary productivity in warming ocean waters reported by Behrenfeld (2006). The fisheries biomass yields of 80% of the targeted species are in an overexploited or fully exploited condition (Table 4), suggesting that the observed decline in biomass yield of pelagic species is related to both heavy exploitation and warming.

The three semi-enclosed European LMEs, the **Mediterranean, the Black Sea, and the Baltic Sea,** and the adjacent area of the **Red Sea** **(**Figure 8C**)**, are surrounded by terrestrial areas and are fast warming, with heavy fishing as a dominant feature. The four LMEs contribute 2.4 mmt (3.7%) of the mean annual global biomass yield. In three European LMEs, the fisheries biomass trend is decreasing, while in the Red Sea it is increasing. In the case of the **Black Sea**, the fisheries biomass is severely depleted, with 85% of fisheries stocks overexploited due to heavy fishing and a trophic cascade (Daskalov 2003). In the Baltic Sea, Red Sea and Mediterranean Sea LMEs, 78% of the stocks are in a fully exploited condition. Mixed species dominate in the **Red Sea,** where 88% of the species fished are fully exploited and 10% are overexploited (Table 4). It appears that heavy exploitation is the dominant driver of the biomass trends observed in all four LMEs.

Comparative fisheries biomass yields (in metric tons) in the fast warming clusters of the Northwest Atlantic (C4) LMEs and the Asian (C5, C6) LMEs

The three LMEs in this region contribute 1.1 mmt (1.7%) to the global biomass yield. In two LMEs of the Northwest Atlantic, the downward trends in fisheries yield have been attributed to the cod collapse in the **Newfoundland-Labrador Shelf** (Rice 2002), and to the cod collapse and collapse of other demersal fisheries in the **Scotian Shelf** LME from excessive fishing mortality (Choi et al. 2004; Frank et al. 2005). In the **West Greenland Shelf LME,** where the cod stock has collapsed from excessive fishing mortality, there is a recent increase in the landings of shrimp and other species (Aquarone and Adams 2008b) (Figure 9A).

Biomass yields of the fast warming LMEs of East Asian Seas

The 7.5 million metric tons (mmt) biomass yields of the **Yellow Sea and East China Sea LMEs** constitute 11% of the global yield. In both LMEs, yields are increasing (Figure 9B). The principal driver of the increase is food security to accommodate the needs of the People's Republic of China and Korea (Tang 2003; Tang 2006; Tang and Jin 1999; Zhang and Kim 1999). Biomass yields are dominated by heavily fished “mixed” species. Seventy percent or more of the species constituting the yields are fully exploited or overexploited (Table 3), suggesting that the principal driver of increased biomass yields is full exploitation rather than global warming.

The fast warming **Kuroshio Current and Sea of Japan/East Sea LMEs** show declining fisheries trends (Figure 9B). They contribute 1.9 mmt (2.9%) to the global marine fisheries yield. For these two LMEs, exploitation levels are high with 90% of the species in a fully exploited to overexploited condition (Table 4). The fisheries are also subjected to periodic oceanographic regime shifts affecting the abundance of biomass yields (Chavez et al. 2003). Among the fast warming East Asian Seas LMEs, no analysis has been conducted for the ice-covered **Chukchi Sea LME**, as the data is limited and of questionable value.

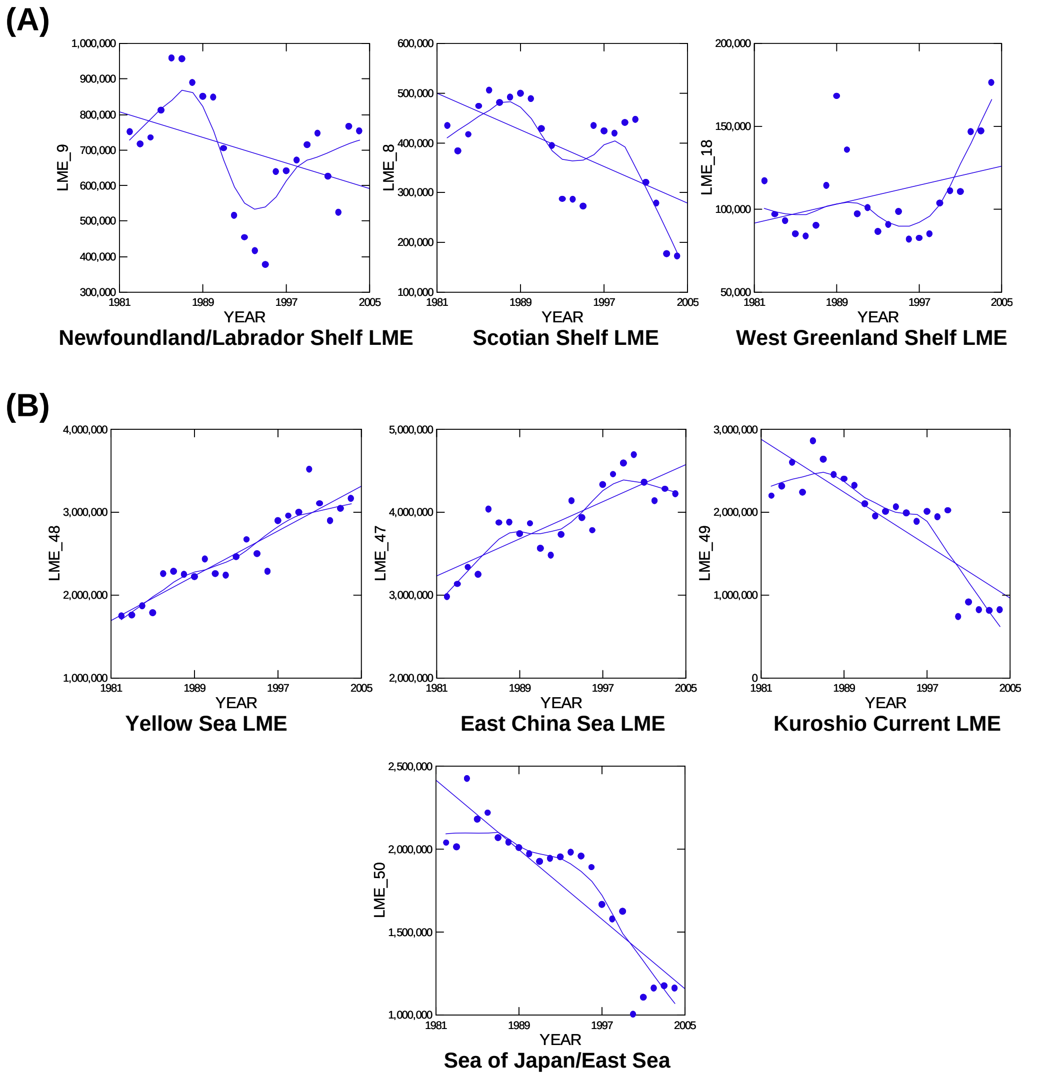

Figure 9. Comparative fisheries biomass yields (in metric tons) in the fast warming clusters of the (A) Northwest Atlantic (C4) LMEs and the(B) Asian (C5, C6) LMEs

Comparative Fisheries Biomass Yields (in metric tons) in Moderate Warming Western Atlantic LMEs (C7), Eastern Atlantic (C8) LMEs, and LMEs of the Asian Northwest Pacific region

A large cluster of moderately warming LMEs can be found in the Trade Winds region of the Atlantic Ocean. This is an important cluster of LMEs contributing 5.1 mmt (7.9%) to the mean annual global biomass yield. Five LMEs are clustered in the Western Atlantic, and two in the Eastern Atlantic. In the West Atlantic Ocean, the **Gulf of Mexico LME** fisheries biomass yields are decreasing, while in the **Caribbean, North Brazil, East Brazil, and South Brazil Shelf LMEs** fisheries biomass yields are increasing (Figure 10A).

The fisheries biomass yield trends in the Atlantic Ocean region appear to be driven principally by heavy exploitation rather than climate warming. The Caribbean, North Brazil, and East Brazil Shelf LMEs are in a fully exploited and over-exploited fisheries condition equal to or greater than 88% of the stocks. In the South Brazil Shelf, 60% of fisheries are fully exploited or overexploited (Table 4). The East Brazil Shelf and South Brazil Shelf LMEs are dominated by small pelagics and/or “mixed species”

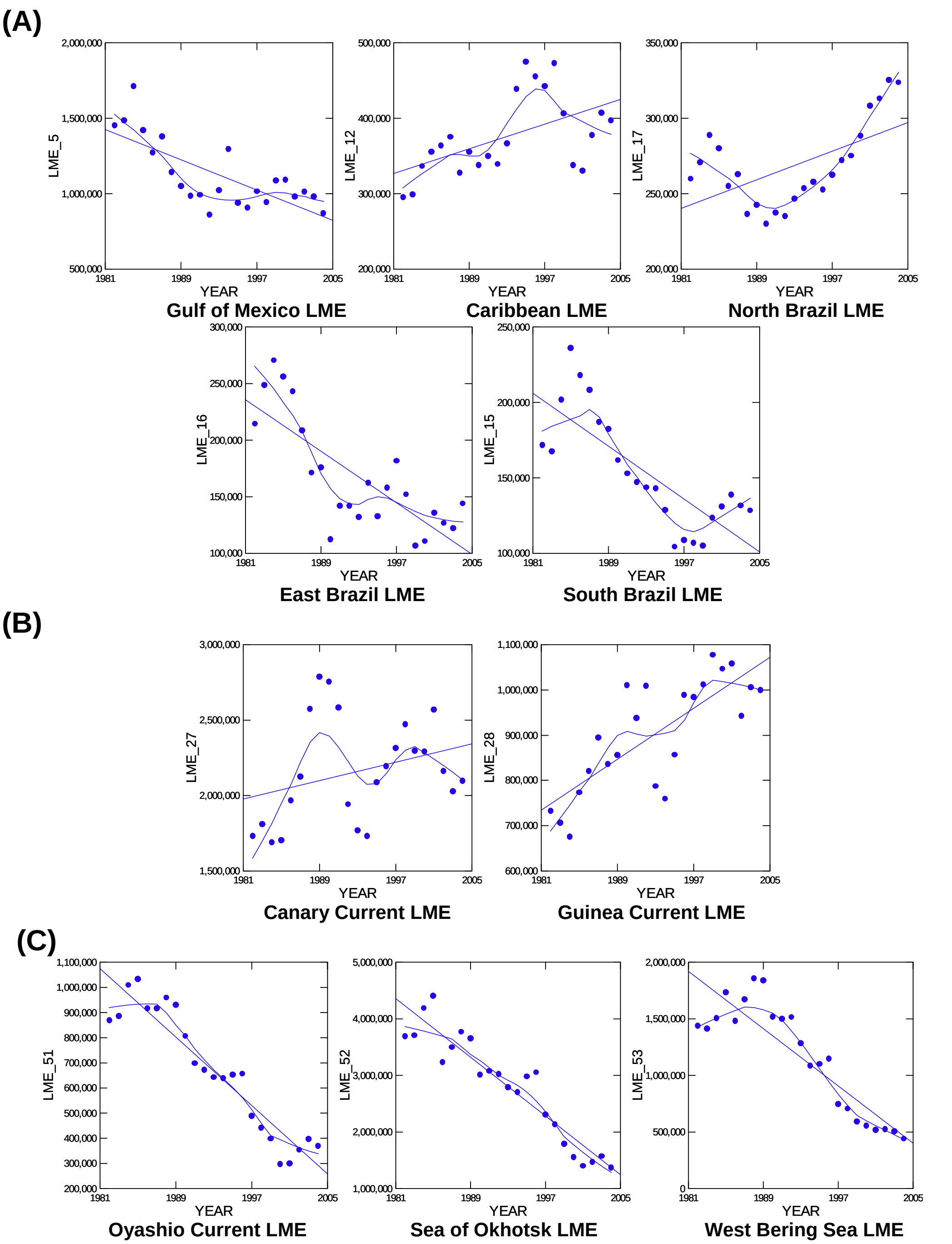

Figure 10. Comparative Fisheries Biomass Yields (in metric tons) in Moderate Warming (A) Western Atlantic LMEs (C7), (B) Eastern Atlantic (C8) and (C) Pacific LMEs

The two LMEs of the Eastern Atlantic are important sources of food security to the over 300 million people of West African countries adjacent to the LMEs. The **Canary Current and the Guinea Current** are showing increasing trends in biomass yield with "mixed species" dominant (Heileman 2008) (Figure 10 B&C. The fisheries stocks in both LMEs are at risk. Oceanographic perturbations are also a source of significant variability in biomass yields in the Guinea Current (Hardman-Mountford and McGlade 2002; Koranteng and McGlade 2002) and in the waters of the Canary Current LME (Roy and Cury 2003)(www.thegef.org, IW Project 1909).

Three LMEs, the **Sea of Okhotsk,** the **Oyashio Current,** and the **West Bering Sea**, contribute 2.3 mmt (3.5%) to the mean annual global biomass yield. They are in a condition where 78% of the fisheries stocks are overexploited (Table 4). The **Oyashio Current** and the **West Bering Sea LMEs** show decreasing trends in fisheries yields (Figure 10C. In the Sea of **Okhotsk**, the biomass yields are dominated by targeted table fish including pollock and cod. The increasing yield trend in the **Sea of Okhotsk LME** is related principally to a high level of overexploitation (Shuntov et al. 1999).

Comparative Fisheries biomass yields in Moderately Warming Southwest Pacific LMEs (C10) and other Non-clustered, Moderately Warming LMEs

The three moderately warming LMEs, two on the east coast of Australia **(Northeast and East Central Australia LMEs)** and the **New Zealand Shelf LME,** contribute 0.4 mmt (0.7%) to the mean annual global biomass yield. Biomass yields are decreasing in the Australian LMEs, whereas they are increasing in the New Zealand Shelf LME (Figure 11) under the present condition of full exploitation (Table 4). Whether their conditions are the result of top down or bottom up forcing is not clear. However, Individual Transferable Quota (ITQ) management to promote the recovery and sustainability of high priority fisheries stocks is in place. Stewardship agencies in Australia and New Zealand have implemented management actions for the recovery and sustainability of the overexploited species.

Six moderately warming LMEs occur in separate locations. Taken together they contribute 7.7 mmt (11.8%) to the mean annual global biomass yields. In the **Pacific,** landings are too low in the moderately warming **Insular Pacific Hawaiian LME** to draw any conclusion on biomass yield. In the moderate warming **Gulf of Alaska LME**, the overall 25-yr. fisheries biomass trend is decreasing. However, this LME shows evidence of a relatively recent upturn in yield, attributed to increases in biomass of Alaska Pollock and Pacific salmon populations in response to climate warming (Overland et al. 2005).

The biomass of the moderately warming **Gulf of California LME** is in a declining trend (Figure 11). The dominant biomass yield in this LME is from small pelagics and "mixed species," suggestive of top down fishing as the principal driver of the decline. The **South China Sea** fisheries biomass yields are increasing. The dominant biomass yield of the LME is of "mixed species" and the level of exploitation is high with 83% fully exploited and 13% overexploited (Table 3). In this case, high population demand for protein by the adjacent countries contributes to drive the biomass yield upward.

The **Arctic** region's **Beaufort Sea LME**, landings data are unavailable. The moderate warming **East Greenland Shelf** fisheries biomass yields are increasing with capelin, redfish and shrimp dominant; following the earlier collapse of cod and other demersal species. The role of global warming in relation to cause and effect of increasing yields is not known.

Table 4. LMEs, rates of warming, 5-yr. mean fisheries biomass yields, adjacent to developing or developed countries, status of stocks exploitation

FAST WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
East China Sea LME	developing	increasing	4,339,890	77% fully exploited, 21% overxploited
Red Sea LME	developing	increasing	129,206	88% fully exploited, 10% overexploited
Yellow Sea LME	developing	increasing	3,147,211	70% fully exploited, 18% overexploited
FAST WARMING LMEs	**Adjacent countries developing**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Mediterranean Sea LME	developing	decreasing	1,045,214	78% fully exploited, 22% overexploited
Baltic Sea LME	developing	decreasing	771,911	88% fully exploited, 12% overexploited
Black Sea LME	developing	decreasing	481,699	0% fully exploited, 85% overexploited
MODERATELY WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Brazil Shelf LME	developing	increasing	311,848	70% fully exploited, 29% overexploited
Canary Current LME	developing	increasing	2,229,215	72% fully exploited, 6% overexploited
Caribbean Sea LME	developing	increasing	370,231	40% fully exploited, 58% overexploited
Guinea Current LME	developing	increasing	1,010,453	71% fully exploited, 24% overexploited
East Brazil Shelf LME	developing	increasing	127,969	40% fully exploited, 48% overexploited
South Brazil Shelf LME	developing	increasing	130,669	20% fully exploited, 40% overexploited
Sea of Okhotsk LME	developing	increasing	1,472,394	10% fully exploited, 78% overexploited
South China Sea LME	developing	increasing	6,454,043	83% fully exploited, 13% overexploited
MODERATELY WARMING LMEs	**Adjacent countries developing**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Gulf of Mexico LME	developing	decreasing	987,865	36% fully exploited, 60%overexploited
West Bering Sea LME	developing	decreasing	508,804	1% fully exploited, 79% overexploited
Gulf of California LME	developing	decreasing	134,297	45% fully exploited, 48% overexploited
SLOWER WARMING LMEs	**Adjacent countries developing**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Arabian Sea LME	developing	increasing	2,486,227	84% fully exploited, 11% overexploited
Bay of Bengal LME	developing	increasing	3,062,147	83% fully exploited, 15% overexploited
Indonesian Sea LME	developing	increasing	2,392,818	88% fully exploited, 12% overexploited
Gulf of Thailand	developing	increasing	676,304	37% fully exploited, 50% overexploited
Sulu Celebes LME	developing	increasing	1,207,946	82% fully exploited, 17% overexploited
Agulhas Current LME	developing	increasing	295,364	30% fully exploited, 32% overexploited
Somali Current LME	developing	increasing	58,961	45% fully exploited, 50% overexploited
Pacific Central American LME	developing	increasing	788,191	42% fully exploited, 18% overexploited
Patagonian Shelf LME	developing	increasing	1,269,644	30% fully exploited, 69%overexploited
SLOWER WARMING LMEs	**Adjacent to developing countries**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Antarctic LME	developing	decreasing	14,553	0----------0---------- 0
Barents Sea LME	developing	decreasing	980,781	0% fully exploited, 60% over exploited
Benguela Current LME	developing	decreasing	1,307,649	50% fully exploited, 8% overexploited
FAST WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
Norwegian Sea LME	developed	increasing	1,643,808	2% fully exploited, 23% overexploited
Iceland Shelf LME	developed	increasing	1,359,767	0% fully exploited, 80% overexploited
Faroe Plateau LME	developed	increasing	460,686	83% fully exploited, 10% overexploited
West Greenland Shelf LME	developed	increasing	138,369	90% fully exploited, 0% overexploited

FAST WARMING, declines in fisheries biomass yields	adjacent countries developed	decreasing fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Sea	developed	decreasing	2,513,263	19% fully exploited, 63% overexploited
Newfoundland/Labrador Shelf	developed	decreasing	683,480	55% fully exploited, 10% overexploited
Scotian Shelf	developed	decreasing	279,470	29% fully exploited, 55% overexploited
Kuroshio Current	developed	decreasing	823,035	48% fully exploited, 42% overexploited
Sea of Japan/East Sea	developed	decreasing	1,121,826	45% fully exploited, 49% overexploited
Celtic-Biscay Shelf	developed	decreasing	1,296,762	65% fully exploited, 30% overexploited
Iberian Coastal	developed	decreasing	338,049	30% fully exploited, 61% overexploited
MODERATE WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
New Zealand Shelf LME	developed	increasing	408,913	77% fully exploited, 21% overexploited
East Greenland Shelf LME	developed	increasing	73,932	6% fully exploited, 23% overexploited
MODERATE WARMING LMEs	**Adjacent countries developed**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited, collapsed
Oyashio Current LME	developed	decreasing	343,734	08% fully exploited, 85% overexploited
Insular Pacific Hawaiian	developed	decreasing	6,121	01% fully exploited, 54% overexploited
Gulf of Alaska	developed	decreasing	1,035,005	80% fully exploited, 18%overexploited
East Central Australian	developed	decreasing	29,095	18% fully exploited, 64% overexploited
Northeast Australian Shelf/ Great Barrier Reef	developed	decreasing	36,310	46% fully exploited, 30% overexploited
SLOWER WARMING LMEs	**Adjacent countries developed**	**increasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
North Australian Shelf	developed	Increasing	159,572	78% fully exploited, 18% overexploited
Northwest Australian Shelf	developed	Increasing	62,842	59% fully exploited, 18% overexploited
West Central Australian Shelf	developed	increasing	19,079	75% fully exploited, 10% overexploited
Southeast Australian Shelf	developed	increasing	35,339	50% fully exploited, 40% overexploited
Southwest Australia Shelf	developed	increasing	41,844	51% fully exploited, 27% overexploited
SLOWER WARMING LMEs	**Adjacent countries developed**	**decreasing** fisheries biomass yield trend	5-yr. mean fisheries biomass in metric tons	Fisheries biomass yield status from SAUP: Fully exploited, overexploited
East Bering Sea	developed	decreasing	1,454,881	62% fully exploited, 28% overexploited
U.S. Northeast Shelf	developed	decreasing	955,948	33% fully exploited, 45% overexploited
U.S. Southeast Shelf	developed	decreasing	89,216	54% fully exploited, 26% overexploited
Arctic LMEs yields are too low for trend analysis				
Chukchi			0	
East Siberian			0	
Beaufort Sea			8	
Hudson Bay			50	
Kara Sea			295	
Laptev Sea			0	
Arctic Ocean			242,913	
2 upwelling LMEs, cooling, adjacent to developed countries				
Humboldt Current LME			10,617,103	
California Current LME			634,669	

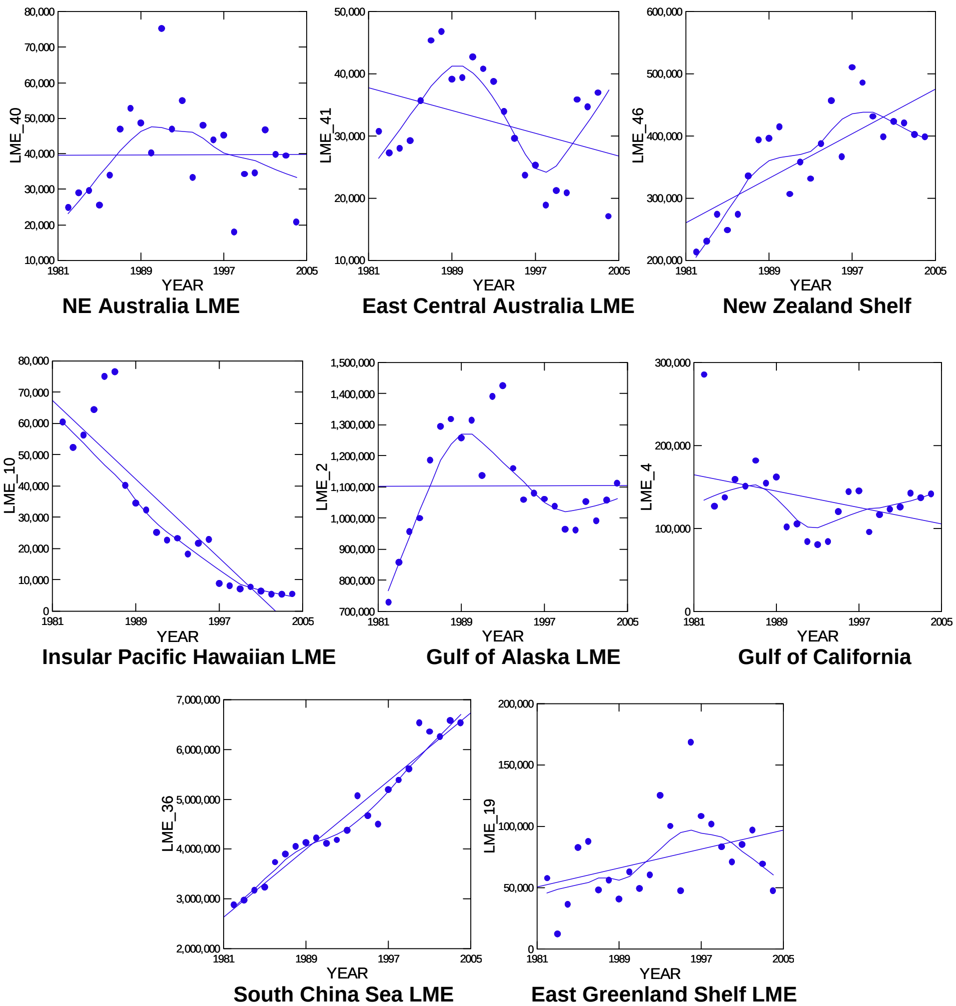

Figure 11. Comparative Fisheries Biomass Yields (in metric tons) in Moderately Warming Southwest Pacific LMEs (C10) and other Moderately Warming LMEs

Comparative Fisheries Biomass Yields in Slow Warming Indian Ocean and Adjacent LMEs (C11)

The 10 LMEs of the Indian Ocean, **Arabian Sea, Bay of Bengal, Agulhas Current, Somali Current, Indonesian Sea, North Australia, Northwest Australia, West Central Australia, Southwest Australia and Southeast Australia LMEs** are in the slow range of climate warming and their biomass trends are all increasing. This group of LMEs contributes 8.6 million metric tons, or 13.2% of the global biomass yield. The slow warming is consistent with the IPCC forecast of slow but steady warming of the Indian Ocean in response to climate change (IPCC 2007). While biomass yields are increasing, the landings adjacent to developing countries are composed primarily of mixed species and small pelagics (Heileman 2008) and the stocks are predominantly fully exploited and/or overexploited (Table 3), suggesting that top down fishing is the predominant influence on the condition of biomass yield. In the adjacent Southwest Pacific waters, the slow warming Sulu-Celebes and Gulf of Thailand LMEs contribute 1.8 mmt (2.8%) to the mean annual global biomass yield. The consistent pattern of increasing yields of the Indian Ocean LMEs adjacent to developing countries is driven principally by the demand for fish protein and food security (Ahmad et al. 1998; Dwivedi and Choubey 1998). In the case of the 5 LMEs adjacent to Australia, the national and provincial stewardship agencies are promoting stock recovery and sustainable management through ITQs. The fisheries stocks in the LMEs adjacent to developing countries are under national pressure to further continue to expand the fisheries to provide food security for the quarter of the world's population inhabiting the region. Given the demands on fisheries for food security for the developing countries bordering the Indian Ocean, there is a need to control biomass yields and sustain the fisheries of the bordering African and Asian LMEs.

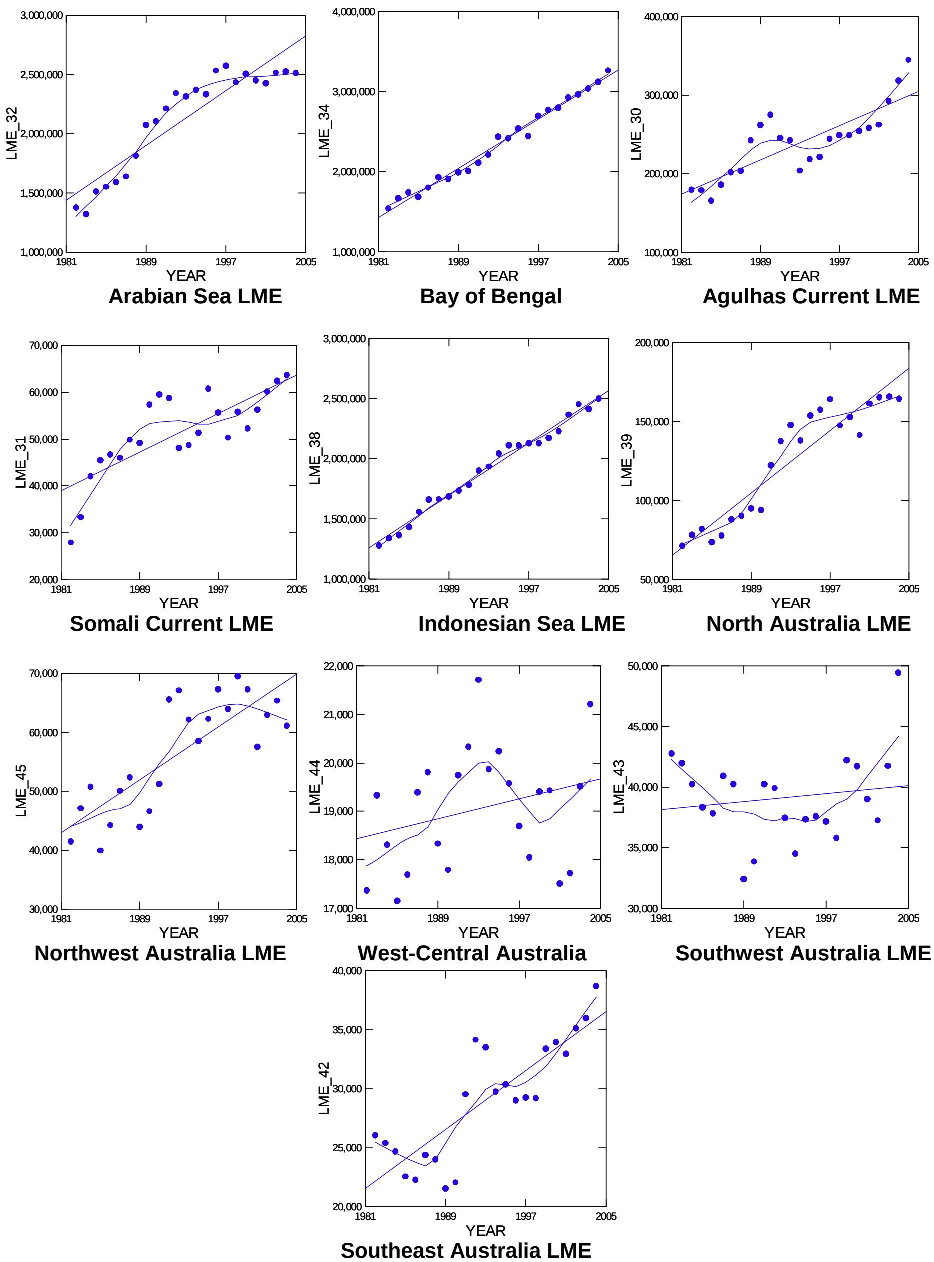

Figure 12. Comparative Fisheries Biomass Yields (in metric tons) in Slow Warming Indian Ocean and Adjacent LMEs (C11)

The biomass yields of other slow warming LMEs of the Northwest Atlantic and the United States East Coast, Barents Sea, East Bering Sea, Patagonian Shelf, Benguela Current, and Pacific Central American Coastal LMEs

There is slow warming taking place in the Northeast US Shelf and in the Southeast US Shelf. The LMEs contribute 1.0 mmt (1.6%) to the mean annual global marine biomass yield. For both LMEs, the declines are attributed principally to overfishing (NMFS 2006) For these two LMEs and the Gulf of Mexico, the Gulf of Alaska, the East Bering Sea, Chukchi Sea, Beaufort Sea, Insular Pacific Hawaiian Islands, and the Caribbean, the United States has underway a fisheries stock rebuilding program for increasing the spawning stock biomass of overfished species(NMFS 2007).

Biomass yields of the slow warming LMEs of the Arctic region

For several of the slow warming LMEs bordering the Arctic including the Laptev Sea, Kara Sea, East Siberian Sea and Hudson Bay, biomass yield data is at present incomplete and is not included in the trend analyses. In the case of the **Barents Sea LME**, there is a decreasing biomass trend attributed to the over-exploited condition of many fish stocks inhabiting the LME (Table 4)(Figure 13). During the present warming condition, variability in ice cover has an important influence on biomass yields (Matishov et al. 2003)

Biomass yields of other LMEs

Four widely separated LMEs, the **East Bering Sea**, the **Patagonian Shelf**, **Benguela Current,** and **Pacific Central American LMEs** are located in slow warming waters (Figure 13). Together they contribute 3.3 mmt (5.1%) to the mean annual global biomass yield. In the North Pacific Ocean, the slow warming East Bering Sea has an overall decline in fisheries biomass yield. However, in recent years there has been an upturn in yield, attributed to climate warming and increases in biomass of Alaska Pollock and Pacific Salmon populations (Overland et al. 2005). In the Southwest Atlantic Ocean Patagonian Shelf LME, increasing biomass yields are reflective of a very high level of fisheries exploitation, overshadowing any climate change effects, where 30% of fisheries are fully exploited, and 69% are overexploited (Table 4). The increasing biomass trends of the Pacific Central American Coastal LME are the result of high levels of exploitation (Table 4) driven principally by the need for fish protein and food security of the adjacent developing countries and secondarily by oceanographic regime shifts (Bakun et al. 1999).

The biomass yields of the Benguela Current (BCLME), southwest African coast are in a declining trend (Figure 13). The living resources of the BCLME have been stressed by both heavy exploitation and environmental perturbations during the past 25 years (van der Lingen et al. 2006) The southwestward movement of sardines (Sardinella) populations from the coastal areas off Namibia to southeastern South Africa has been attributed to recent warming. The southerly migration has disrupted the Namibian fisheries. A further southerly movement of sardines and anchovies from the vicinity of island colonies of African penguins off South Africa led to a decrease in availability of small pelagic fish prey of penguins resulting in a 40% penguin population decline (Koenig 2007).

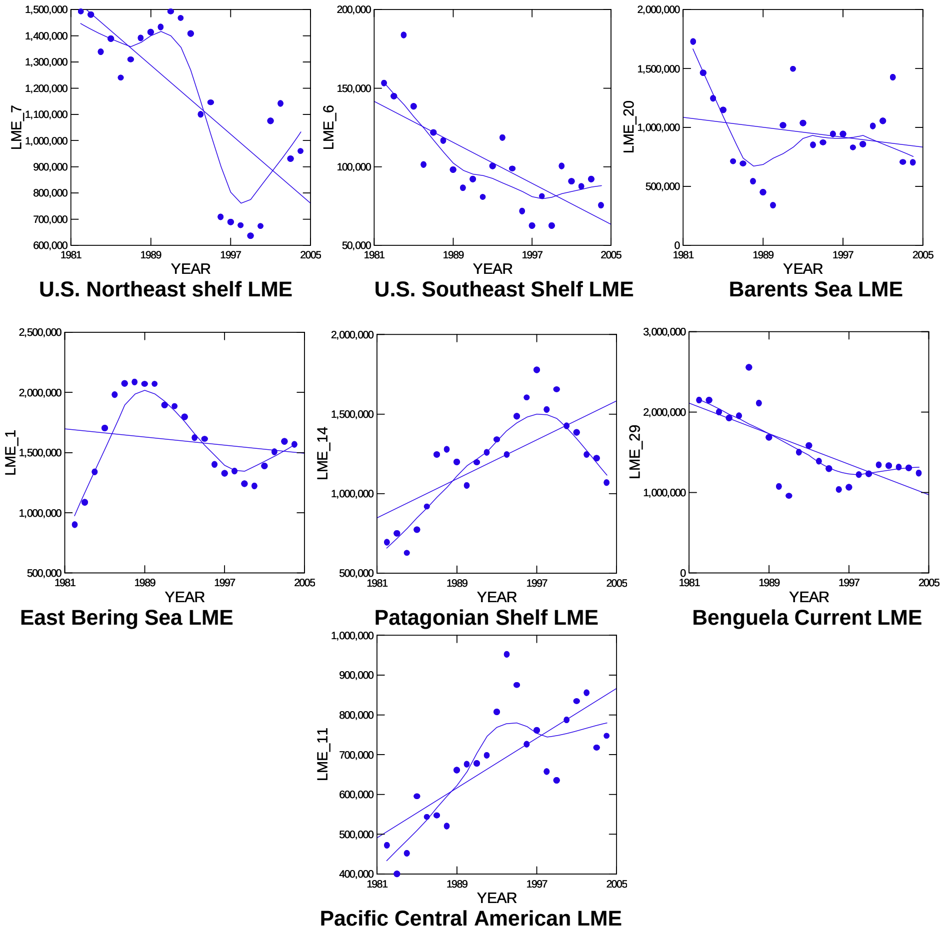

Figure 13. Comparative Fisheries Biomass Yields (in metric tons) in <u>Slow Warming LMEs</u> of the United States East Coast, Barents Sea, East Bering Sea, Patagonian Shelf, Benguela Current and Pacific Central American Coastal LMEs

Discussion

Emergent trends

From the analysis, we conclude that in four LME cases the warming clusters of LMEs are influencing 7.5 mmt or 11.3% of the world's fisheries biomass yields. The first and clearest case for an emergent effect of global warming on LME fishery yields is in the increasing biomass yields of the fast warming temperature clusters affecting 3.4 mmt (5.0%) of global yields for the Iceland Shelf, Norwegian Sea, and Faroe Plateau LMEs in the northern Northeast Atlantic. Warming in this region has exceeded levels expected from entering the warm phase of the Atlantic Multi-decadal Oscillation (Trenberth and Shea 2006). The increase in zooplankton is related to warming waters in the northern areas of the Northeast Atlantic (Beaugrand et al. 2002) leading to improved feeding conditions of three zooplanktiverous species that are increasing in biomass yields. Herring, blue whiting, and capelin yields are increasing in the Iceland Shelf and Norwegian Sea LMEs, and blue whiting yields are increasing in the Faroe Plateau LME.

The second case is in the contrasting declines in biomass yields of the fast warming cluster of more southern Northeast Atlantic waters including the North Sea, the Celtic-

Biscay Shelf, and Iberian Coastal LME where declines in warm water plankton (Valdés et al. 2007) and northward movement of fish (Perry et al. 2005) are a negative influence on 4.1 mmt (6.3%) of the mean annual global biomass yields. Recent investigations have found that SST warming in the northeast Atlantic is accompanied by increasing zooplankton abundance in cooler more northerly areas, and decreasing phytoplankton and zooplankton abundance in the more southerly warmer regions of the northeast Atlantic in the vicinity of the North Sea, Celtic-Biscay Shelf and Iberian Coastal LMEs (Richardson and Schoeman 2004). Due to tight trophic coupling fisheries are adversely affected by shifts in distribution, reduction in prey and reductions in primary productivity generated by strong thermocline stratification inhibiting nutrient mixing (Behrenfeld et al. 2006).

In the third case, recent moderate warming of the Gulf of Alaska, and slow warming of the East Bering Sea are supporting increasing levels of zooplankton production and recent increasing biomass yields of Alaska Pollock and Pacific Salmon (Grebmeier et al. 2006; Hunt et al. 2002; Overland et al. 2005).

The biomass yields of the fourth case are more problematic. Biomass yields of all 10 LMEs (8.6 mmt) (13.2%) around the western and central margin of the **Indian Ocean** are increasing (Figure 12). The increasing yields of the five LMEs adjacent to developing countries, the Agulhas Current, Somali Current, Arabian Sea, Bay of Bengal and Indonesian Sea are dominated by mixed species and small pelagic species, driven by the fish protein and food security needs of nearly one quarter of the world's population inhabiting the bordering countries of Africa and Asia (Heileman and Mistafa 2008). The overexploited condition of most species is at present masking any gains in biomass yield that may be attributed to the slow and steady warming of waters predicted for the Indian Ocean by the IPCC (2007) and observed during the present study. In contrast, the slow warming five Australian LMEs on the eastern margin of the Indian Ocean are driven principally by economic considerations and are closely monitored by governmental stewardship agencies that practice an adaptive management system of Individual Transferable Quotas (Aquarone and Adams 2008a). Taken together, the 8.6 mmt mean annual biomass yield of the Indian Ocean LMEs are critical for food security of the heavily populated adjacent countries. In this region there is a need to exercise a precautionary approach (FAO 1995) to recover and sustain the fisheries in the LMEs of east Africa and Asia, in the slow warming clusters.

Precautionary Cap and Sustain Action

From a global perspective 38.2 mmt or 58% of the mean annual 2001-2006 biomass yields are being produced in 29 LMEs adjacent to developing countries (Table 3). This vital global resource is at risk from serious overexploitation (Table 4). Given the importance for sustaining 58% of the world's marine fisheries biomass yield, it would be prudent for the GEF supported LME assessment and management projects to immediately cap the total biomass yield at the annual 5-year mean (2000-2004) as a precautionary measure and move toward adoption of more sustainable fisheries management practices.

The management strategies for protecting the 26.8 mmt or 42% of global marine biomass yields in LMEs adjacent to the more developed countries (Table 3) have had variable results ranging from highly successful fisheries biomass yield recovery and sustainability actions for stocks in LMEs adjacent to Australia, New Zealand, the United States, Norway, and Iceland to the less successful efforts of the European Union and LMEs under EU jurisdiction in the Northeast Atlantic (Gray and Hatchard 2003). An ecosystem-based cap and sustain adaptive management strategy for groundfish based on an annual overall total allowable catch level and agreed upon TACs for key species is proving successful in the management of the moderately warming waters of the Gulf of Alaska LME and slow warming East Bering Sea LME Alaska Pollock and Pacific Salmon stocks, providing evidence that cap and sustain strategies can serve to protect fisheries biomass yields (NPFMC 2002; Witherell et al. 2000).

In LMEs where primary productivity, zooplankton production and other ecosystem services are not seriously impaired, exploited, overexploited and collapsed stocks as defined by Pauly and Pitcher (2000) can be recovered where the principal driver is excessive fishing mortality and the global warming rates are moderate or slow. The principal pelagic and groundfish stocks in the slow warming US Northeast Shelf ecosystem have been targeted for rebuilding from the depleted state of the 1960s and 1970s by the New England Fisheries Management Council and the Mid Atlantic Fisheries Management Council. In collaboration with NOAA-Fisheries and the results of productivity and fisheries multi-decadal assessment surveys it was concluded that the principal driver of the declining trend in biomass yield was overfishing. Reductions in foreign fishing effort in the 1980s resulted in the recovery of herring and mackerel stocks.

Further reductions in US fishing effort since 1994 initiated recovery of spawning stock biomass of haddock, yellowtail flounder and sea scallops. Similar fish stock rebuilding efforts are underway in all 10 of the LMEs in the US coastal waters (NMFS 2007).

From our analysis, it appears that the emerging increasing trends in biomass yields can be expected to continue in fast warming LMEs of the northern North Atlantic (Iceland Shelf, Faroe Plateau, Norwegian Sea) and the moderate and slow warming LMEs of the northeast Pacific (Gulf of Alaska, East Bering Sea and the U.S. Northeast Shelf). The countries bordering these LMEs (U.S., Norway, Faroes Islands) have in place sufficiently advanced ecosystem-based capacity to support adaptive assessment and management regimes for maintaining sustainable levels of fishery biomass yields.

In the absence of the capacity for conducting annual assessments for a large number of marine fish species in many developing countries, and in recognition of the uncertainties of effects of climate warming, in the observed slow warming and increasing fisheries biomass yields of LMEs adjacent to east Africa and south Asia along the margins of the Indian Ocean, it would be prudent for the bordering countries to implement precautionary actions to protect present and future fishery yields with a cap and sustain strategy aimed at supporting long term food security and economic development needs.

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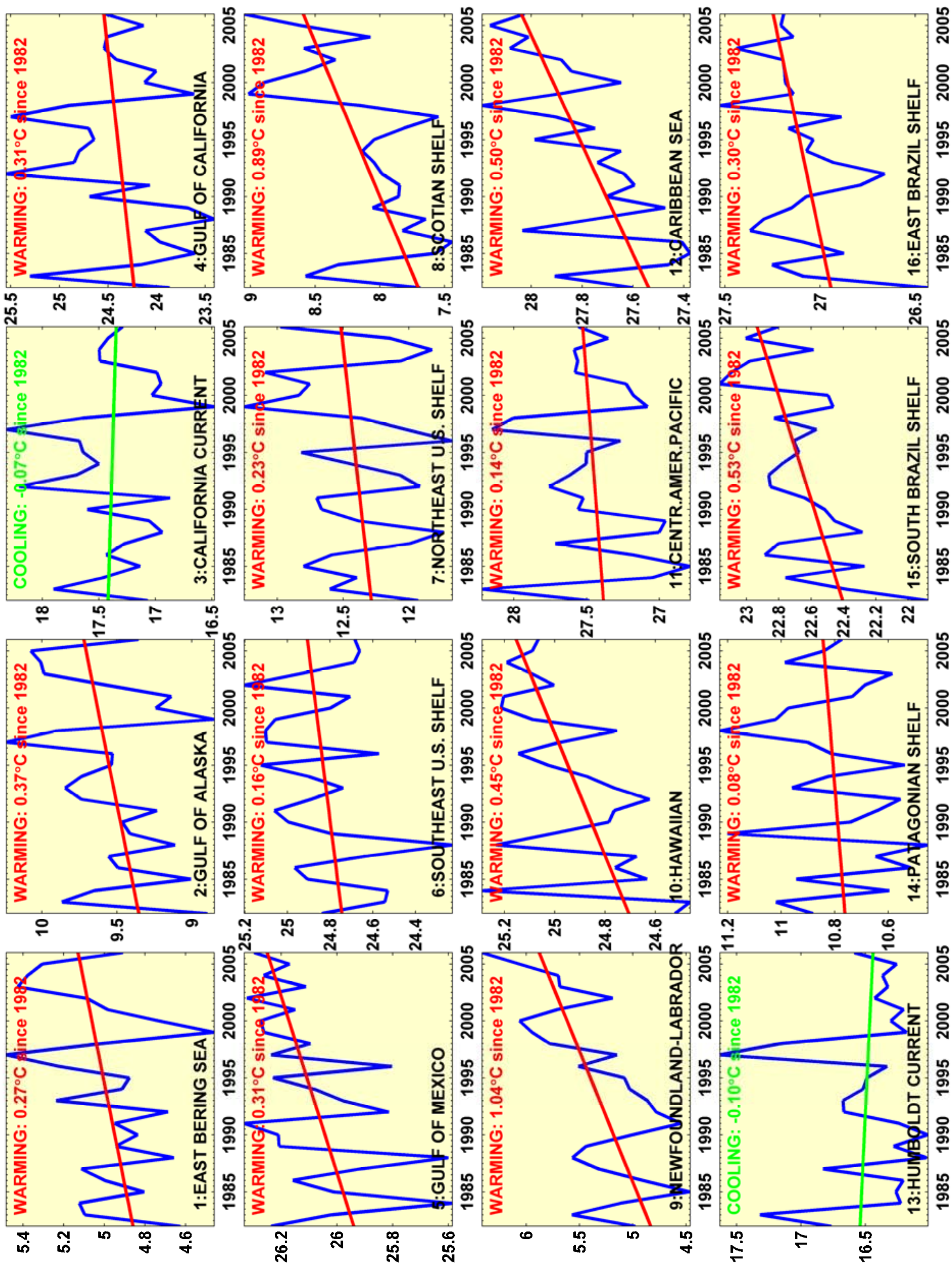
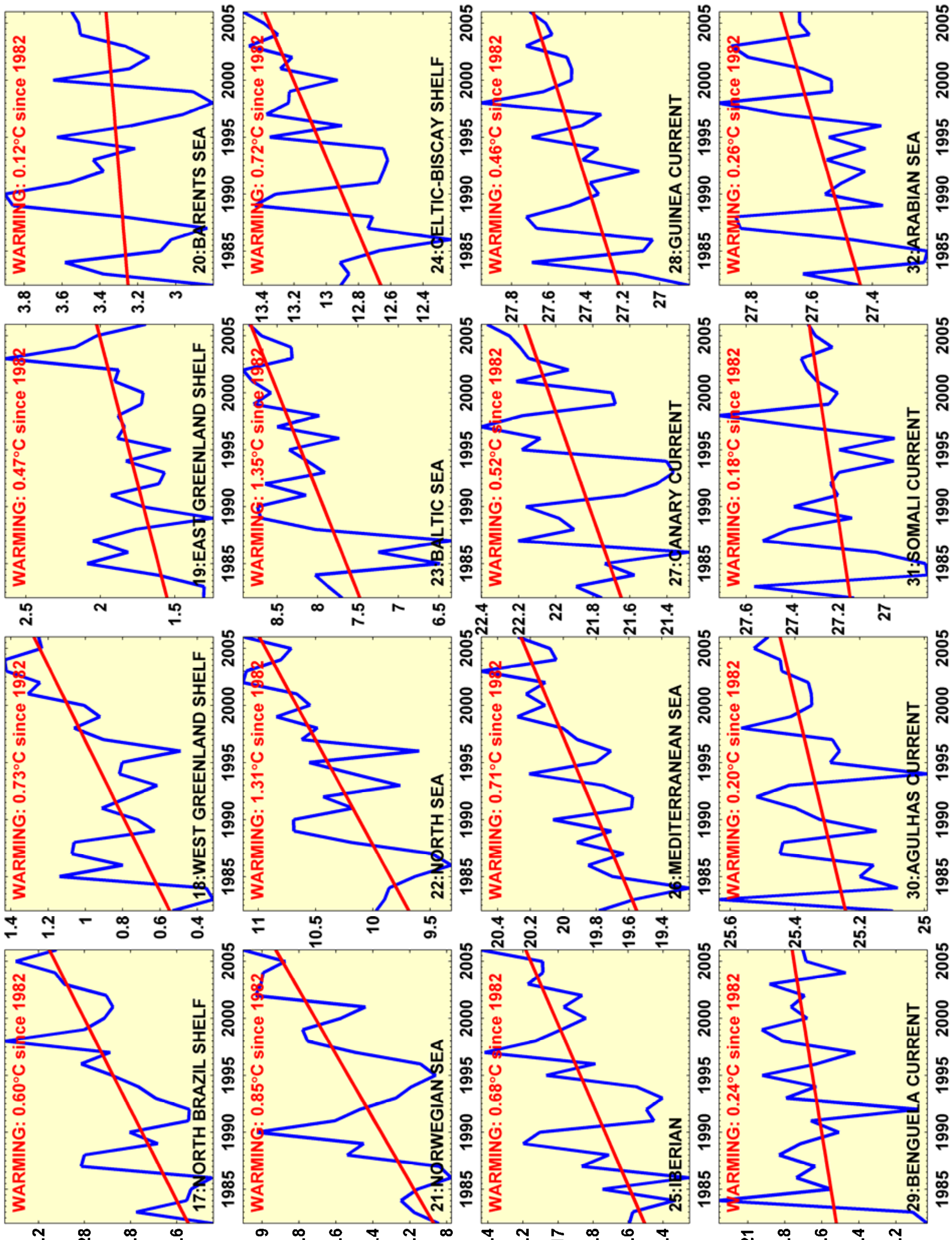
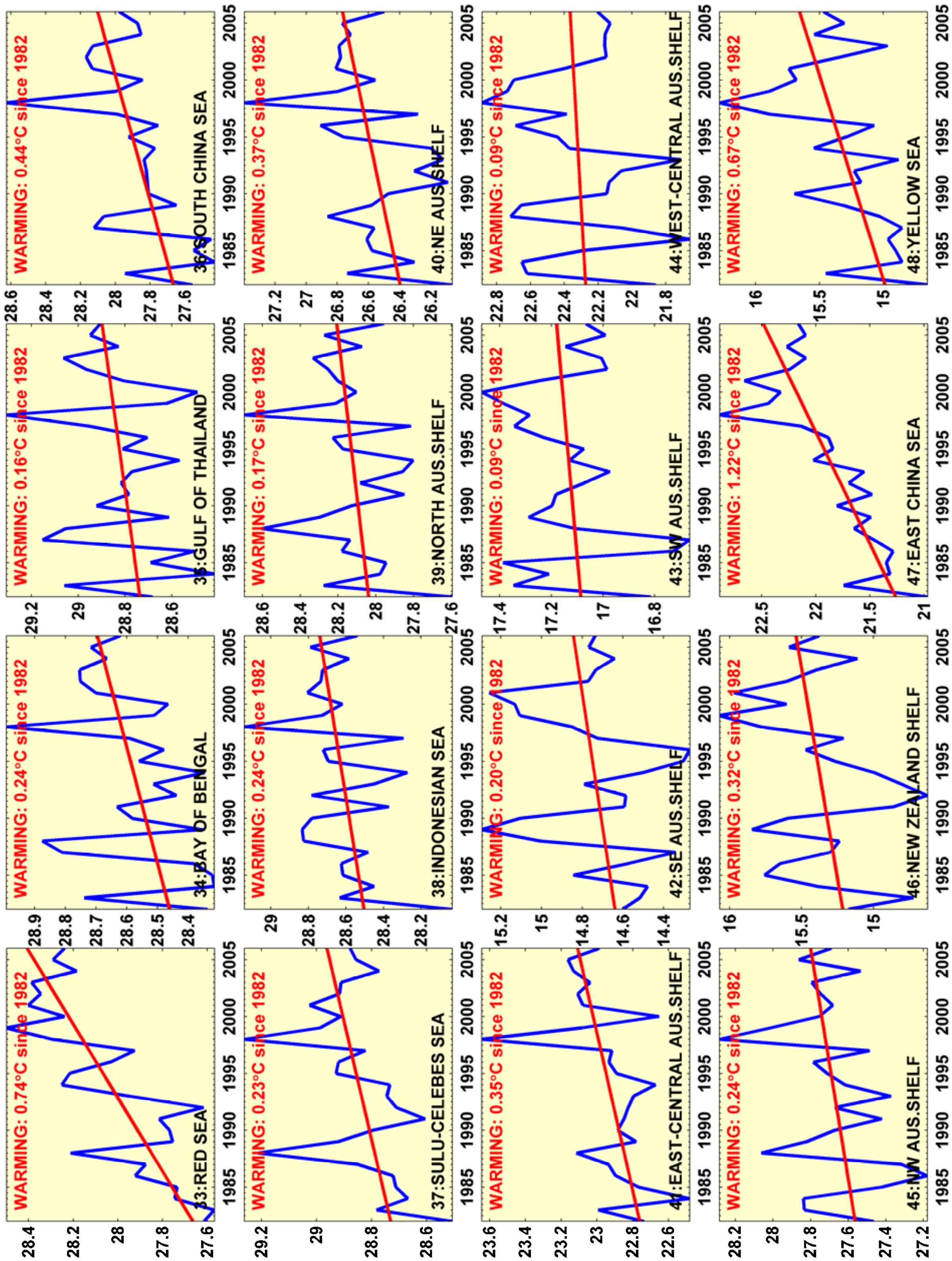
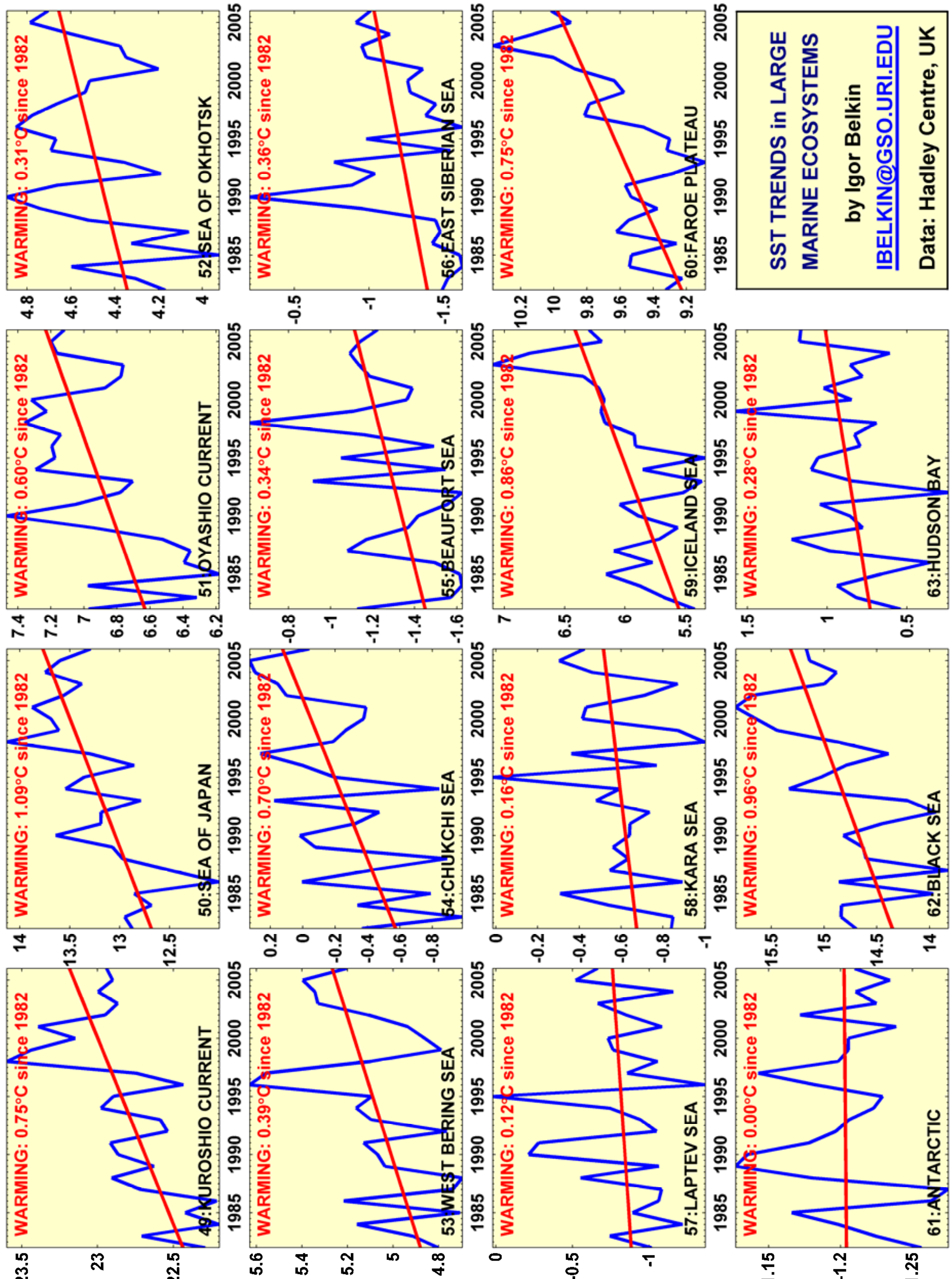
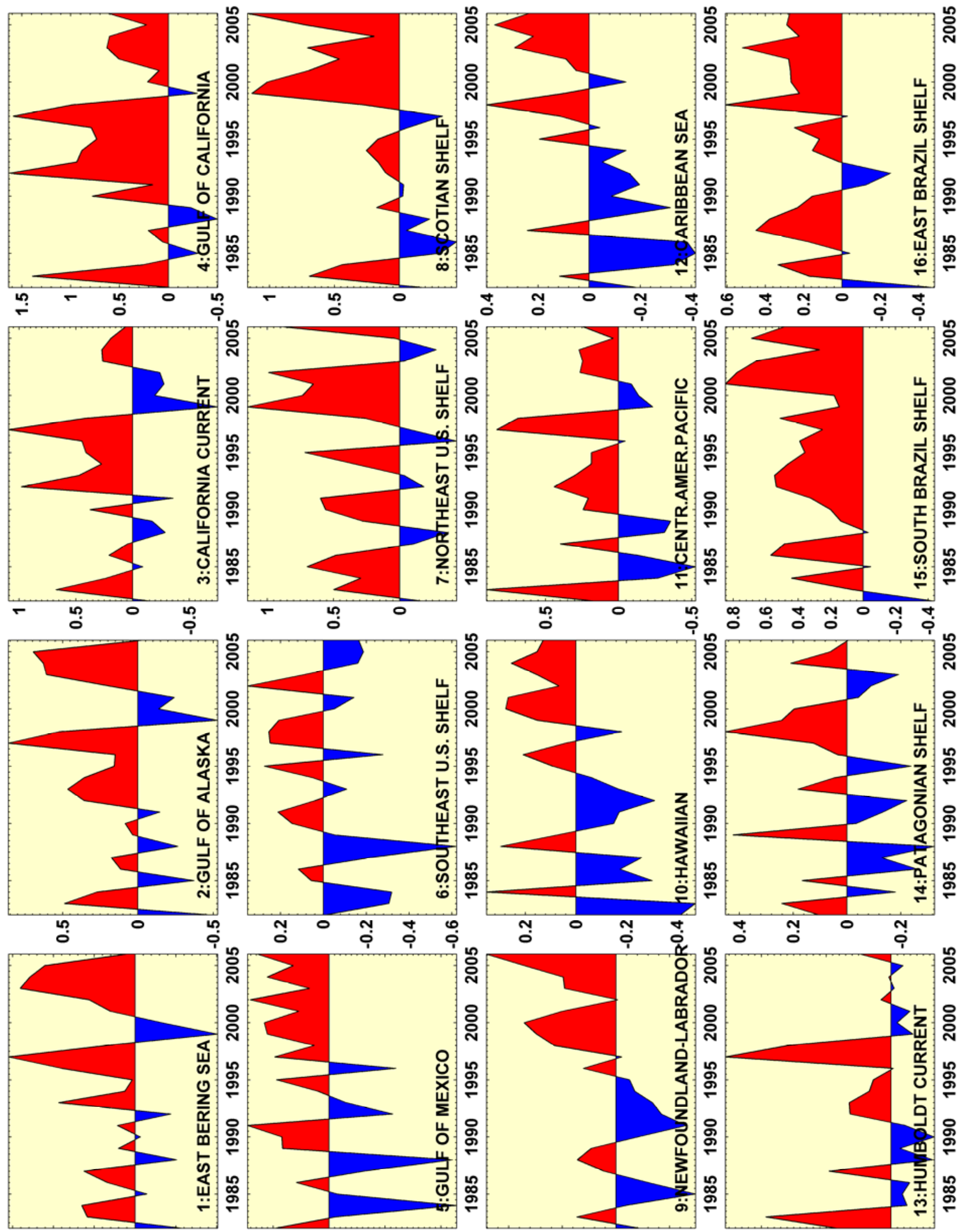
APPENDIX 1. Mean annual SST for all LMEs and SST anomalies, 1982-2006**.**




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


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


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
1985 1990 1995 2000 2005
SST TRENDS in LARGE
MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK


1:EAST BERING SEA
2:GULF OF ALASKA
3:CALIFORNIA CURRENT
4:GULF OF CALIFORNIA
5:GULF OF MEXICO
6:SOUTHEAST U.S. SHELF
7:NORTHEAST U.S. SHELF
8:SCOTIAN SHELF
9:NEWFOUNDLAND-LABRADOR
10:HAWAIIAN
11:CENTR.AMER.PACIFIC
12:CARIBBEAN SEA
13:HUMBOLDT CURRENT
14:PATAGONIAN SHELF
15:SOUTH BRAZIL SHELF
16:EAST BRAZIL SHELF
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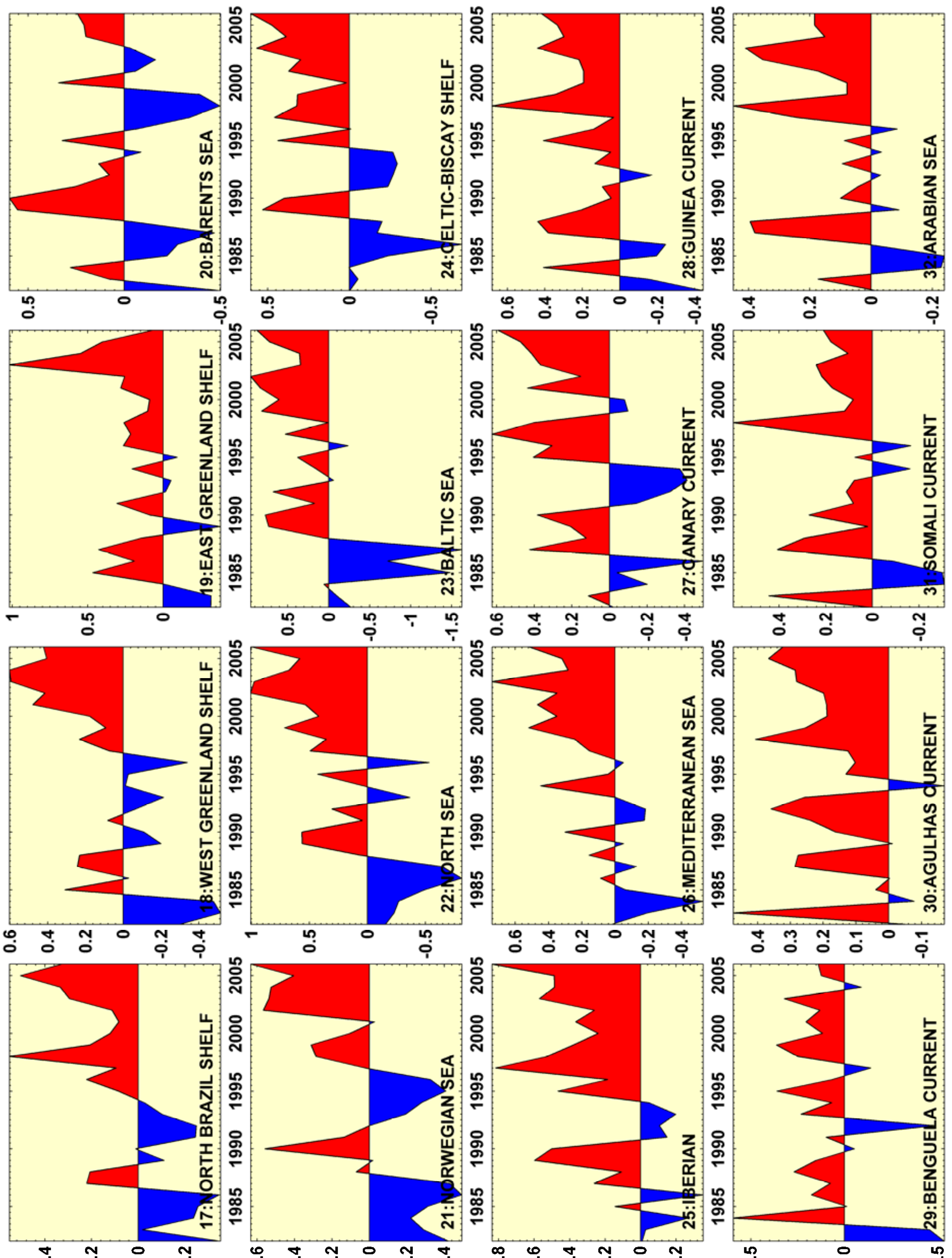
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18:WEST GREENLAND SHELF
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20:BARENTS SEA
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23:BALTIC SEA
24:CELTIC-BISCAY SHELF
25:IBERIAN
26:MEDITERRANEAN SEA
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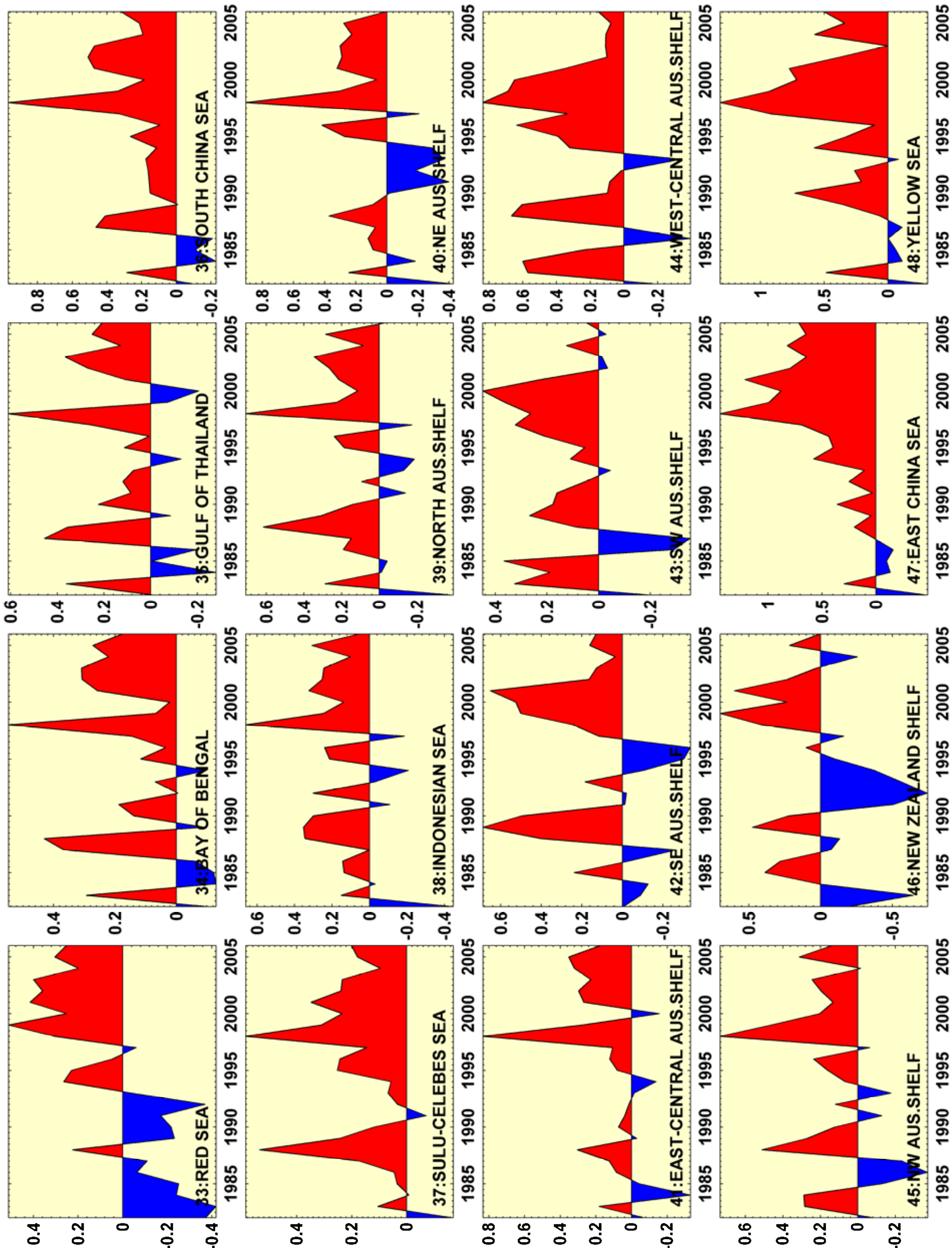
28:GUINEA CURRENT
29:BENGUELA CURRENT
30:AGULHAS CURRENT
31:SOMALI CURRENT
32:ARABIAN SEA


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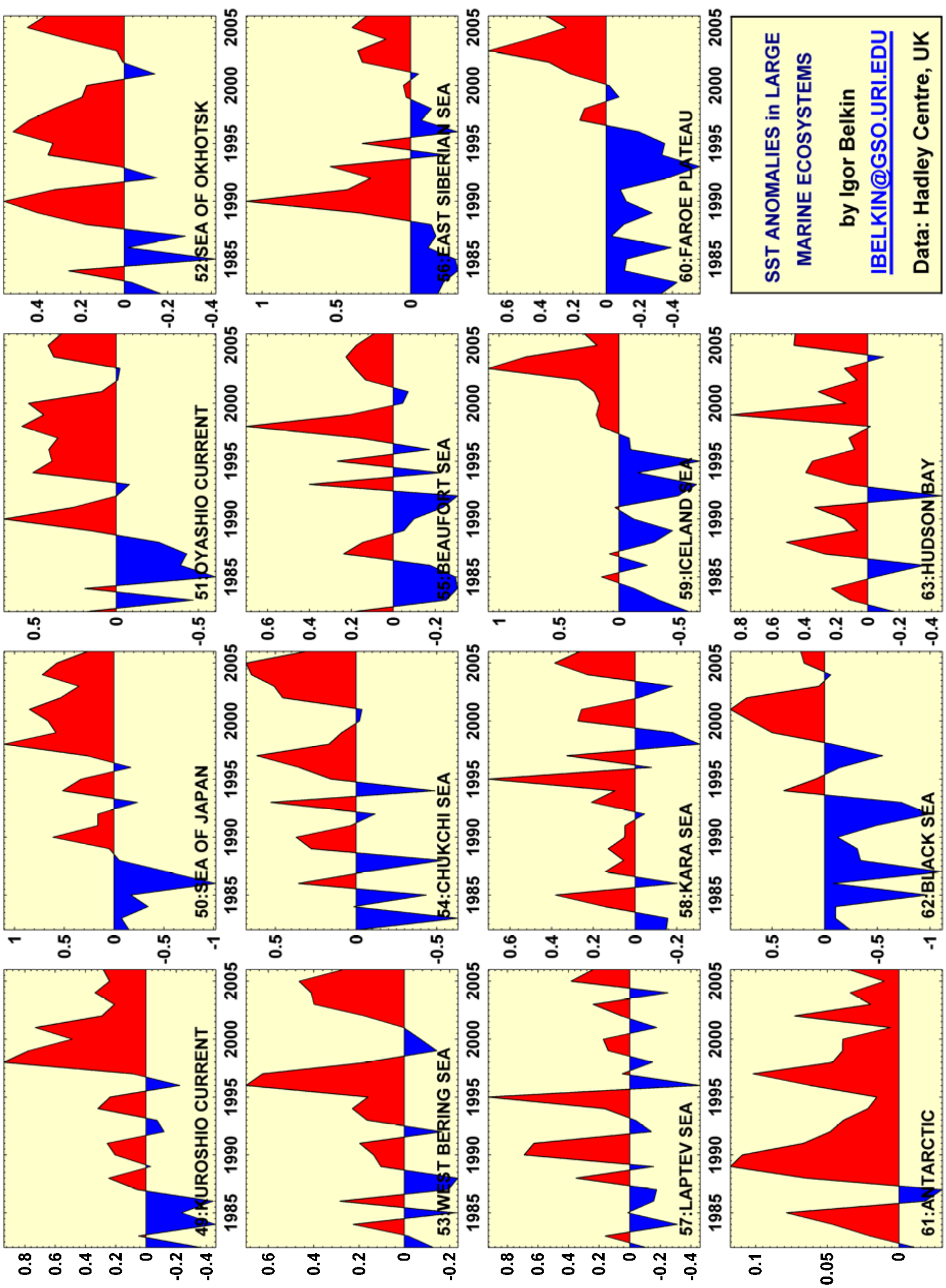
49:KUROSHIO CURRENT
50:SEA OF JAPAN
51:OYASHIO CURRENT
52:SEA OF OKHOTSK
53:WEST BERING SEA
54:CHUKCHI SEA
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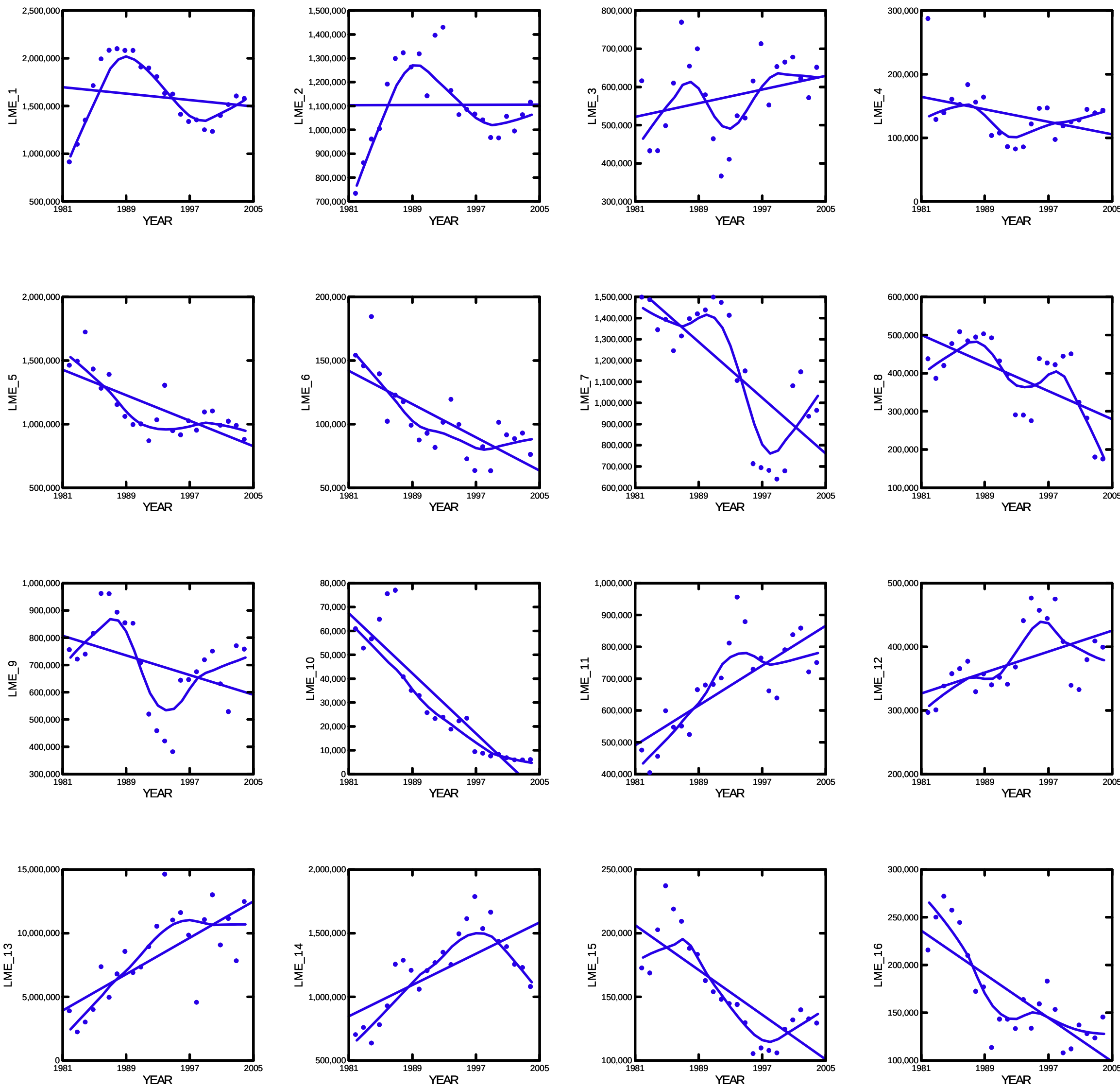
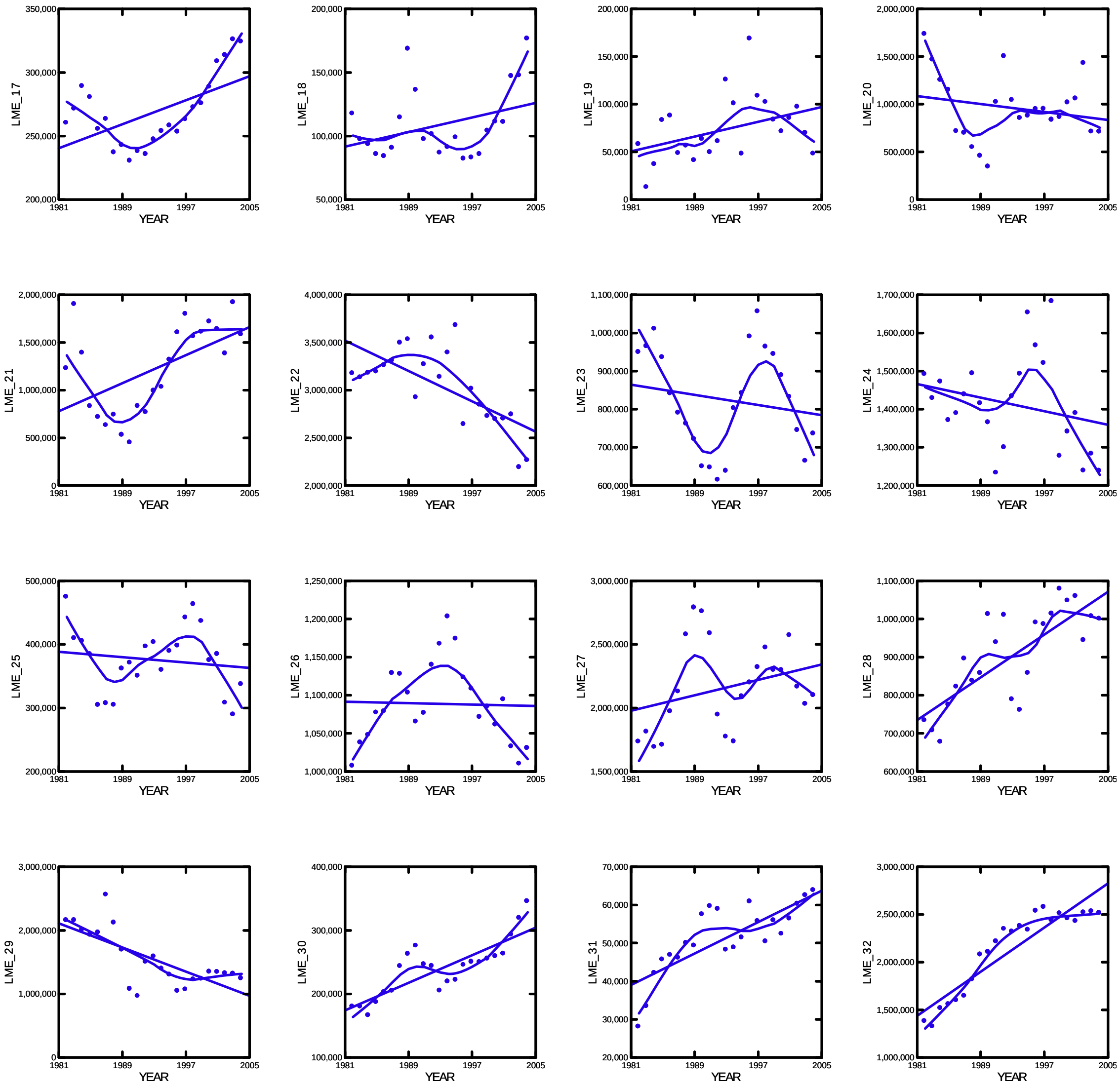
56:EAST SIBERIAN SEA
57:LAPTEV SEA
58:KARA SEA
59:ICELAND SEA
60:FAROE PLATEAU
61:ANTARCTIC
62:BLACK SEA
63:HUDSON BAY
SST ANOMALIES in LARGE
MARINE ECOSYSTEMS
by Igor Belkin
IBELKIN@GSO.URI.EDU
Data: Hadley Centre, UK

APPENDIX 2. Fishery biomass yields by year for Large Marine Ecosystems, linear regression lines cover the period 1982-2004, smoothing curves are LOWESS smoothers at tension=0.5. LME numbers correspond to the LME numbers in Figure 1, p.42 (this volume).

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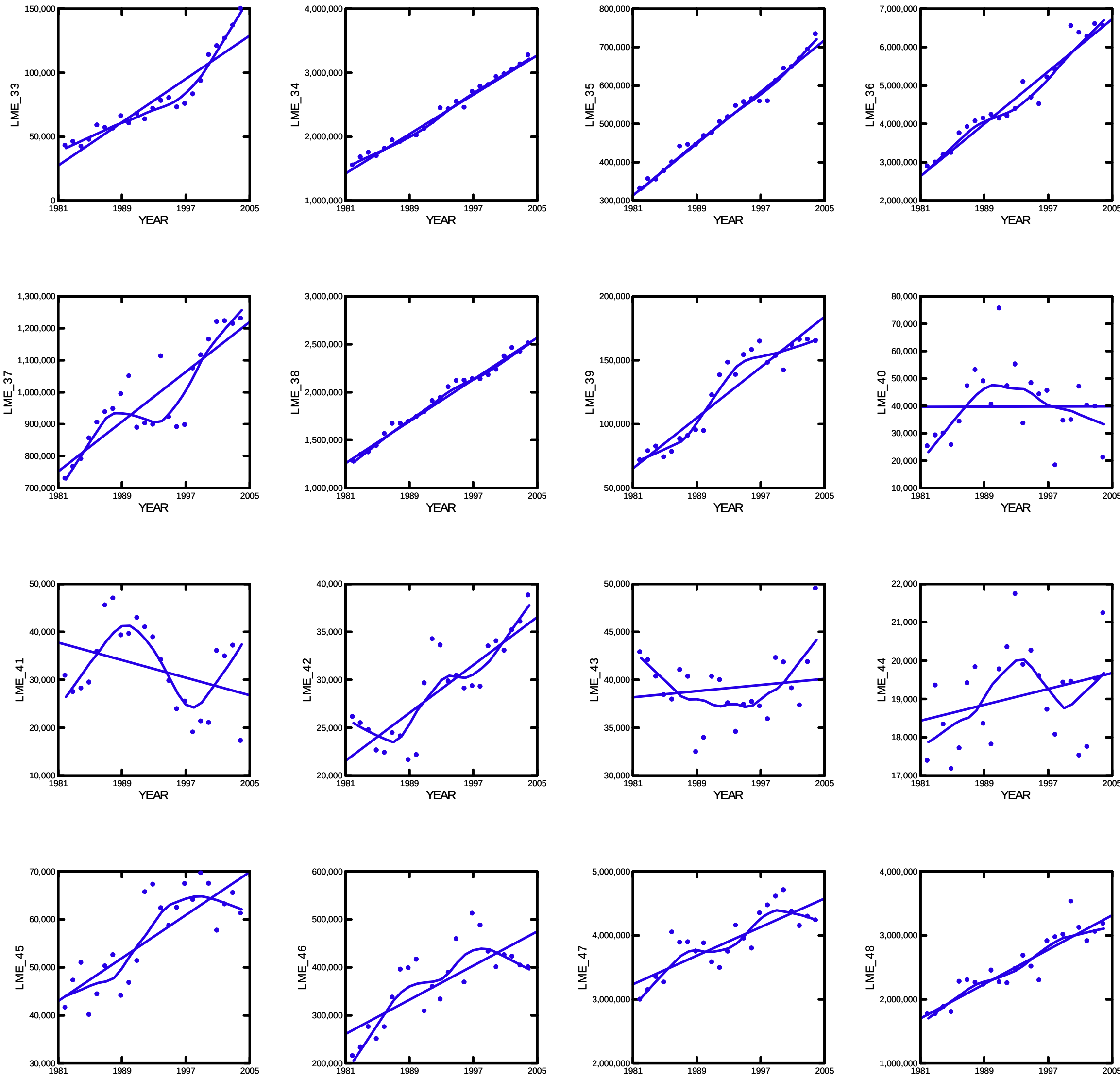
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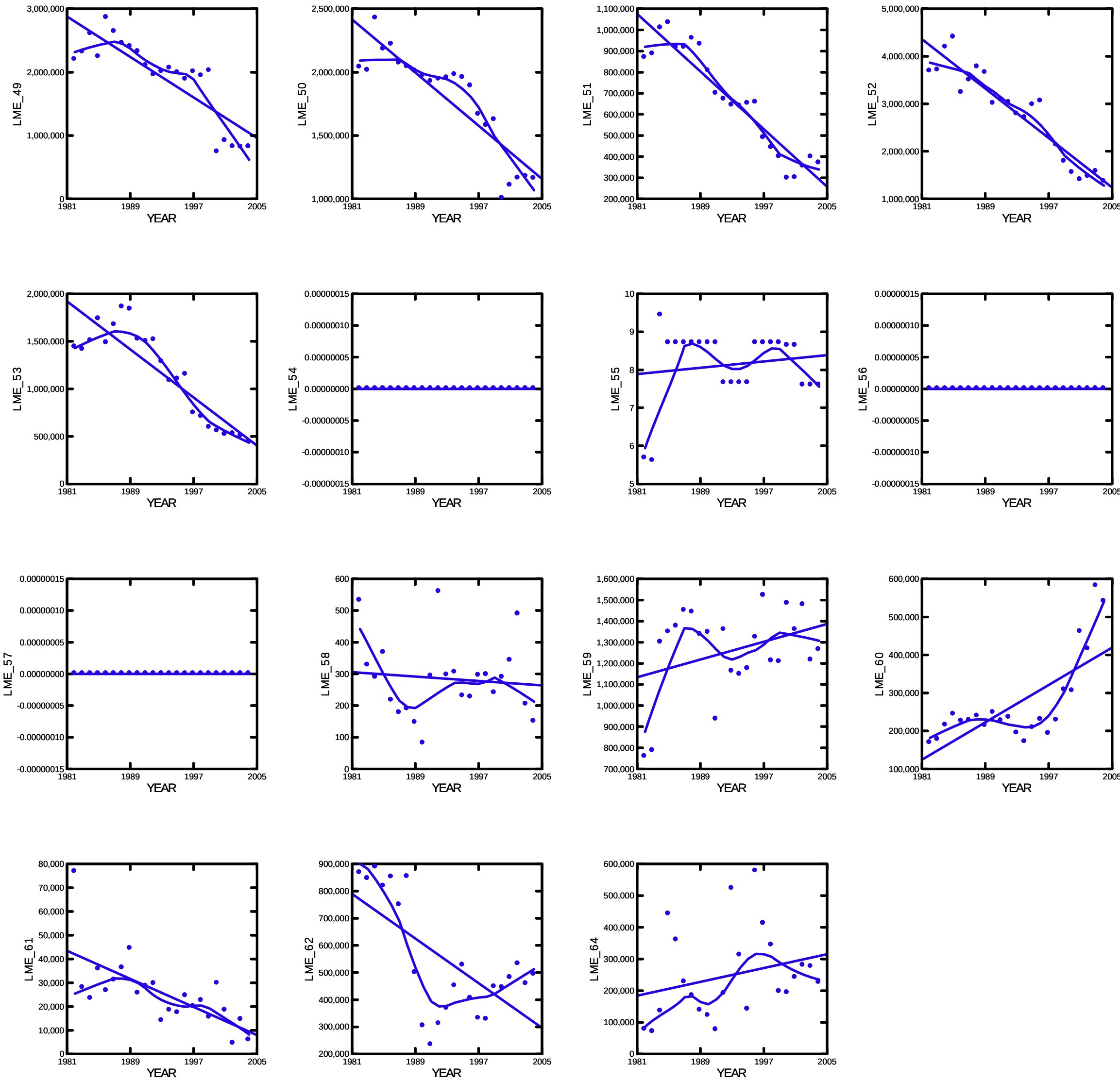
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