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The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems

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In 1992, world leaders at the historical UN Conference on Environment and Development (UNCED) recognized that the exploitation of resources in coastal oceans was becoming increasingly unsustainable, resulting in an international effort to assess, recover, and manage goods and services of large marine ecosystems (LMEs). More than $3 billion in support to 110 economically developing nations have been dedicated to operationalizing a five-module approach supporting LME assessment and management practices. An important component of this effort focuses on the effects of climate change on fisheries biomass yields of LMEs, using satellite remote sensing and *in situ* sampling of key indicators of changing ecological conditions. Warming appears to be reducing primary productivity in the lower latitudes, where stratification of the water column has intensified. Fishery biomass yields in the Subpolar LMEs of the Northeast Atlantic are also increasing as zooplankton levels increase with warming. During the current period of climate warming, it is especially important for space agency programmes in Asia, Europe, and the United States to continue to provide satellite-borne radiometry data to the global networks of LME assessment scientists.

Keywords: large marine ecosystems, primary productivity, satellite remote sensing.

Introduction

Overfishing, pollution, habitat loss, and climate change are causing serious degradation in the world's coastal oceans and a downward spiral in economic benefits from marine goods and services. Prompt and large-scale changes in the use of ocean resources are needed to overcome this downward spiral. In 1992, the world community of nations convened the first global conference of world leaders in Rio de Janeiro to address ways and means to improve the degraded condition of the global environment (Robinson *et al.*, 1992). Ten years later (2002), at a follow-up World Summit on Sustainable Development in Johannesburg (Sherman, 2006), world leaders agreed to a Plan of Implementation for several marine-related targets including achievement of:

- (i) "substantial" reductions in land-based sources of pollution by 2006;
- (ii) introduction of the ecosystems approach to marine resource assessment and management by 2010;
- (iii) designation of a network of marine protected areas by 2012; and
- (iv) maintenance and restoration of fish stocks to maximum sustainable yield levels by 2015.

More recently, in Copenhagen in 2009, world leaders agreed to non-binding actions to reduce emissions of greenhouse gases to mitigate the effects of global climate change.

For the period 2010–2020, the international community of maritime nations is pursuing solutions for recovering depleted marine fish stocks, restoring degraded habitats, controlling pollution, nutrient overenrichment, and ocean acidification, conserving biodiversity, and adapting to climate change. This effort at improving the ecological condition of the world's 64 large marine ecosystems (LMEs) is global in scope and ecosystems-orientated in approach (Sherman *et al.*, 2005). LMEs are regions of 200 000 km^2 or more, encompassing coastal areas from estuaries to the continental slope and the seaward extent of well-defined current systems along coasts lacking continental shelves (Figure 1). They are defined by ecological criteria including bathymetry, hydrography, productivity, and trophically linked populations (Sherman, 1994). The LMEs produce 80% of the world's marine fisheries yields annually and are growing sinks of coastal pollution and nutrient overenrichment. They also harbour degraded habitats (e.g. corals, seagrasses, mangroves, and oxygen-depleted dead zones). The Global Environment Facility (GEF), a financial group located in Washington, DC, supports developing countries committed to the recovery and sustainability of coastal ocean areas, by providing financial and catalytic support to projects that use LMEs as the geographic focus for

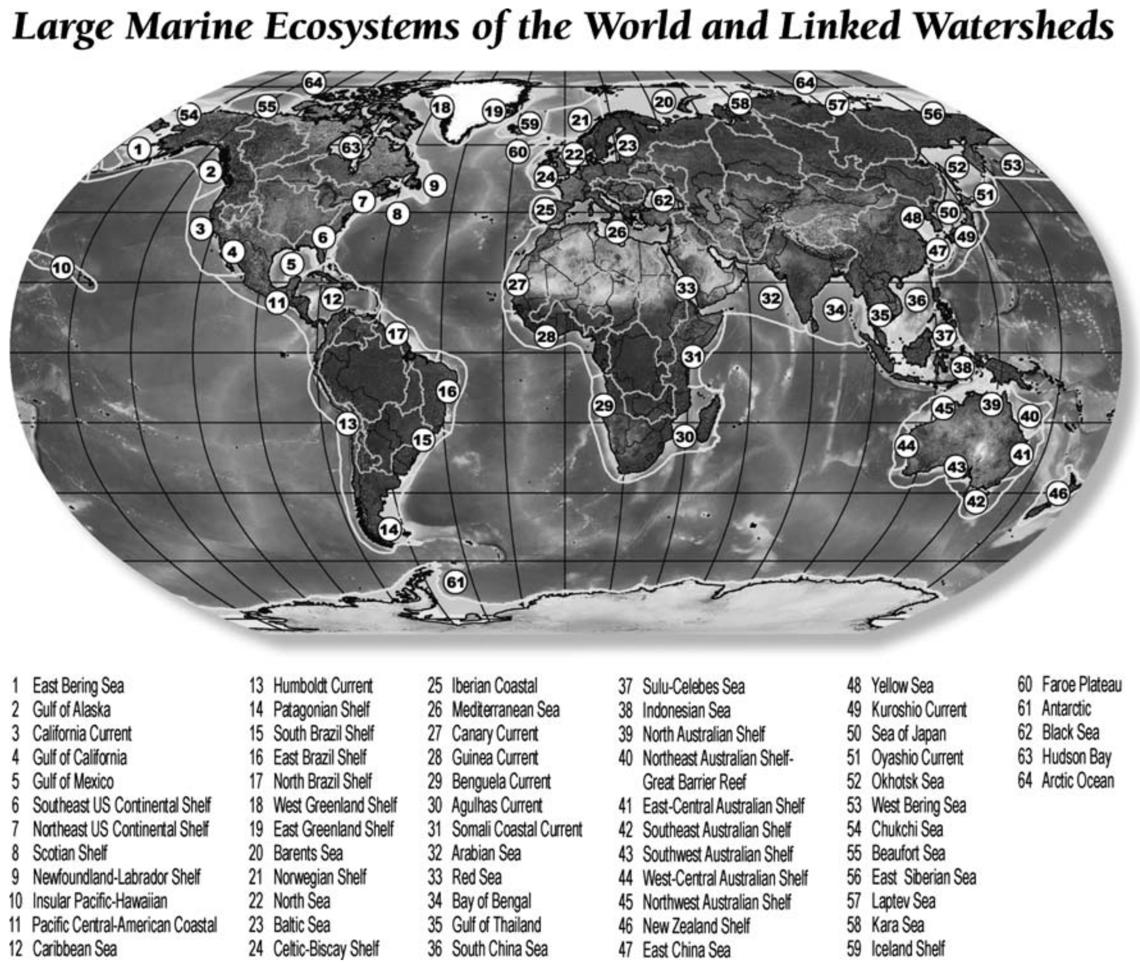

Figure 1. The 64 LMEs of the world.

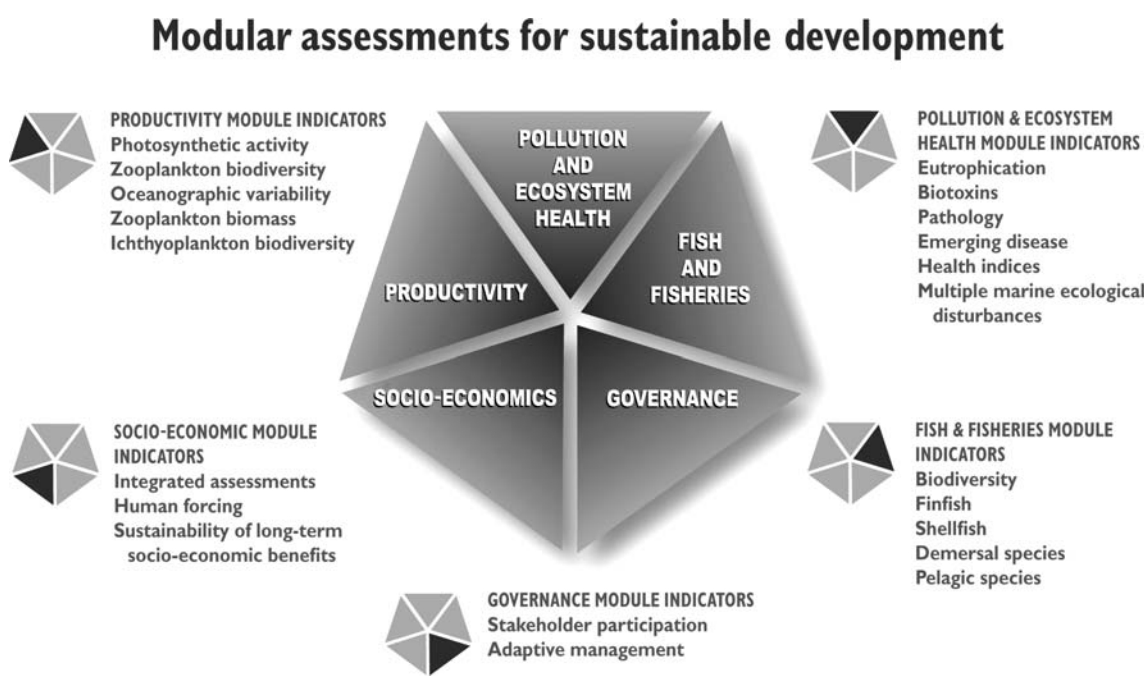

Figure 2. LME modules as suites of ecosystem indicators (first published in Sherman, 2005).

ecosystem-based strategies to reduce coastal pollution, control nutrient overenrichment, restore damaged habitats, recover depleted fisheries, protect biodiversity, and adapt to climate change (Duda and Sherman, 2002).

Modular LME assessments

A five-module indicator approach to the assessment and management of LMEs is being implemented for measuring changing states in LMEs: (i) productivity, (ii) fish and fisheries, (iii) pollution and ecosystem health, (iv) socio-economics, and (v) governance in 17 GEF-supported LME projects (Duda and Sherman, 2002; Duda, 2009). Ecosystem measurements for the first three modules provide a sound scientific foundation for decisions affecting the human dimensions of LMEs, including management policies that consider both socio-economic benefits for people and a mutually agreeable governance regime focused on sustaining LME goods and services. Time-series surveys of modules (i), (ii), and (iii) provide the scientific basis for assessments of ecosystem conditions (Figure 2). Currently, 110 countries in Africa, Asia, Latin America, and eastern Europe are engaged in LME projects. They are supported by $3.1 billion in financial assistance from the GEF and the World Bank, in partnership with five UN agencies (UNEP, UNDP, UNIDO, IOC–UNESCO, FAO), and two non-governmental organizations (International Union for the Conservation of Nature, and the World Wildlife Fund). All projects are applying country-driven LME assessment strategies developed from the bottom up, including transboundary diagnostic analyses and strategic action plans to identify the root causes of marine ecosystem deterioration and major transboundary problems. All projects specify the nature, scope, and timetable for the recovery and sustainability of degraded goods and services (Duda, 2009). Participating countries are making substantial progress in operationalizing the five-module, ecosystem-based approach for monitoring, assessing, and managing LMEs.

Satellite remote sensing and the LME productivity module

Primary productivity derived from remotely sensed satellite data can be related to the carrying capacity of an ecosystem for supporting fish resources (Pauly and Christensen, 1995; Pauly *et al.*, 2008). On a global scale, the levels of primary productivity of the world's LMEs are significantly higher than in the open ocean. Average primary productivity values, based on Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite data between September 1998 and August 1999, are depicted in Figure 3 for the US Northeast Shelf LME. The total annual average fisheries biomass from all LMEs is estimated at 1.1 billion tonnes (Christensen *et al.*, 2009). Recent levels of marine fisheries biomass yields, based on landings data, are 80 million tonnes (Pauly *et al.*, 2008). Many marine fish stocks are over-exploited and need accelerated stock-recovery efforts by responsible government ministries (Pauly *et al.*, 1998; Worm *et al.*, 2009). Measurements of ecosystem productivity can also be useful indicators of the growing problem of coastal eutrophication and hypoxia. Excessive nutrient-loading to coastal waters has been related to harmful algal blooms implicated in mass mortalities of living resources, the emergence of pathogens (e.g. cholera, vibrios, and paralytic shellfish toxins), and the explosive growth of non-indigenous species (Epstein, 1993).

The ecosystem parameters measured and used as indicators of changing conditions in the productivity module are water-column structure, transparency, chlorophyll *a* (Chl *a*), nitrite, nitrate, primary production, and zooplankton biodiversity and biomass. Satellite remotely sensed products are indispensable in measuring sea surface temperature (SST), Chl *a*, and primary production. Plankton can be measured over the large spatial extents of LMEs with continuous plankton recorders (CPRs), as deployed for the past 75 years by the Sir Alistair Hardy Foundation for Ocean Science (SAHFOS) from commercial vessels of opportunity (SAHFOS, 2009). The CPR, although limited to a fixed depth of 10 m, provides a cost-effective method for sampling the zooplankton community, and it can be fitted too with temperature and salinity sensors to provide additional information on ecosystem conditions.

An undulating vehicle for LME productivity metrics

Chlorophyll is not always uniformly distributed by depth and is found subsurface but not detectable by satellite-borne colour

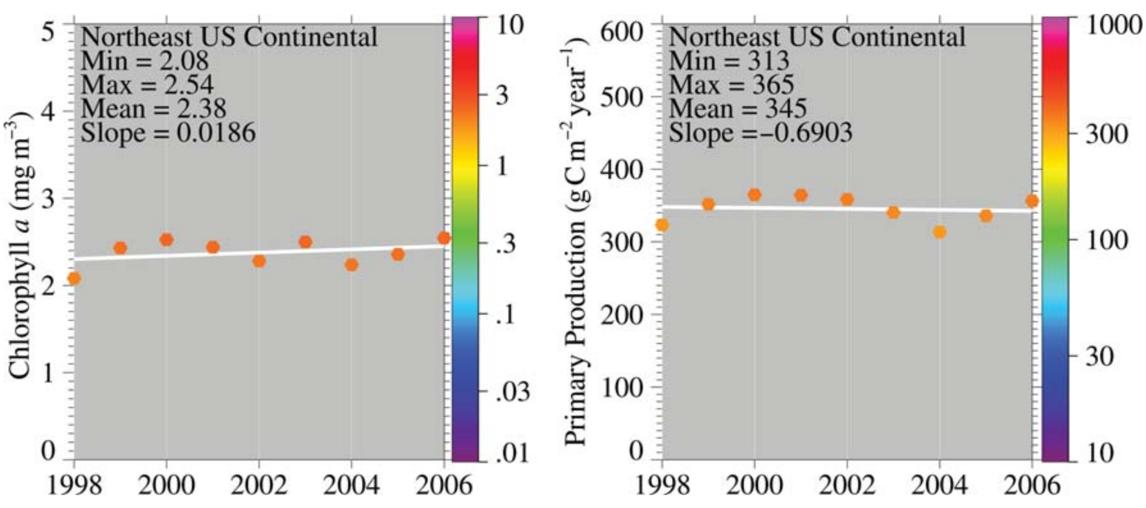

Figure 3. Northeast US continental shelf LME trends in chlorophyll *a* (left) and primary productivity (right), 1998 – 2006, from satellite ocean-colour imagery. Values are colour-coded to the right-hand ordinate.

sensors. However, subsurface data can be collected with an undulating vehicle carrying chlorophyll sensors and other sensors developed for LME projects.

A prototype undulating, towed sampling platform was developed to obtain biological, chemical, and physical measurements in the upper 70 m, with a focus on primary productivity and plankton at the base of the marine foodweb (Berman and Sherman, 2001; Melrose *et al*., 2006, 2007). The system was based on the NuShuttle (Chelsea Technologies Group) and was successfully deployed and tested in Narragansett Bay, RI, on monthly surveys from 1998 to 2008. With lessons that were learned from 10 years of field experience, the system was replaced by the Mariner Shuttle Mk II in 2009.

The Mariner Shuttle Mk II (Mk II) is based on the Acrobat towed body of Sea Sciences Inc. Instrumentation includes a Seabird 19plusV2 CTD, an autonomous plankton sampler (Chelsea Technologies Group) to sample zooplankton, a fast-repetition-rate fluorometer (Chelsea Technologies Group) with attached PAR sensor to measure photosynthesis and primary productivity, a SCUFA II fluorometer (Turner Designs) to measure chlorophyll and turbidity, a Satlantic/MBARI ISUS nitrate sensor, and a Seabird 43 dissolved-oxygen sensor. The system is towed at up to 8 knots and includes software that automatically adjusts the flight pattern to the bottom depth (Figure 4). The system is being deployed successfully during continuing monthly cruises in Narragansett Bay and elsewhere in the US Northeast Shelf LME.

The great advantage of the Mariner Shuttle is that it allows near-continuous vertical sampling on transects. This facilitates the study of subsurface chlorophyll, fronts, and horizontal features that would be missed by fixed-station sampling. The Mk II samples vertical and fine-scale horizontal structure not seen by satellites. Mk II data can be integrated with satellite data at sea (Figure 5). An example of Mariner Shuttle chlorophyll and temperature data from a recent transect across the Nantucket Shoals of the US Northeast Shelf LME is given in Figure 6.

A unique feature of the Mariner Shuttle is the fast-repetition-rate fluorometer that measures instantaneous primary productivity and photosynthetic efficiency. Historically, ^{14}C primary productivity measurements have required many and cumbersome carbon or oxygen-based incubations that limit large-scale, routine measurements for ecosystem studies. The technique correlates well with traditional ^{14}C uptake methods (Kolber and Falkowski, 1993; Suggett *et al*., 2001; Melrose *et al*., 2006), as illustrated in Figure 7.

Figure 4. The Mariner Shuttle Mk II (MS Mk II) is based on the versatile Sea Sciences Acrobat towed body. Operation and on-board instrumentation is described in text.

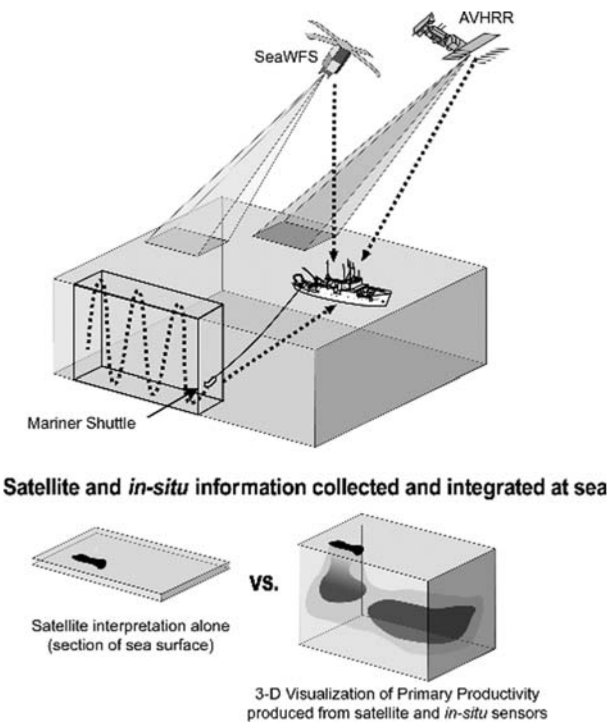

Figure 5. Satellite (SeaWiFS and AVHRR) and *in situ* information collected by the Mariner Shuttle is integrated at sea.

Satellite-based productivity, SST, and frontal gradient assessments

Primary productivity trends (1998–2006), SST, and frontal gradient assessments have been determined for each of the 64 LMEs (Sherman and Hempel, 2008). The LME primary productivity estimates are derived from satellite-borne data archived at NOAA's Northeast Fisheries Science Center, Narragansett Laboratory. These estimates originate from a large archive of near-surface chlorophyll data measured by various ocean-colour sensors and satellites, such as the Coastal Zone Colour Scanner (CZCS), SeaWiFS, Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua and MODIS-Terra), and SST from the Advanced Very High Resolution Radiometer (AVHRR) flown on various NOAA satellites. These remotely sensed data, collected daily, facilitate the quantification of spatial and seasonal variability of surface chlorophyll and SST in LMEs.

Oceanic fronts enhance productivity (Belkin *et al*., 2009), so front mapping is an important aspect of LME characterization. The first global remote-sensing survey of fronts in the world ocean LMEs was based on a unique frontal-data archive assembled

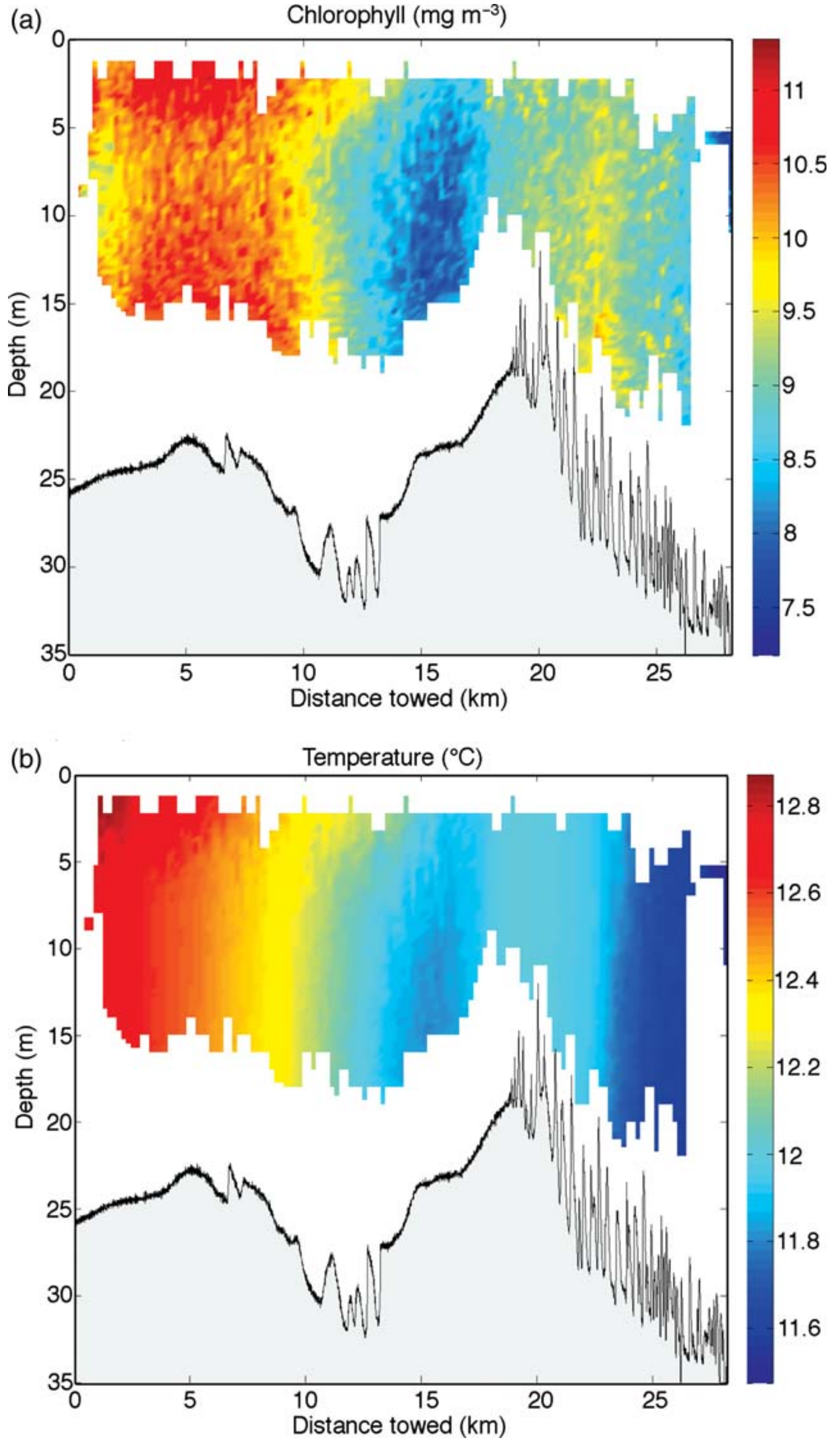

Figure 6. (a) Chlorophyll and (b) temperature measured by the Mariner Shuttle Mk II on the Nantucket Shoals.

at the University of Rhode Island. Thermal fronts were derived with a front-detection algorithm (Cayula and Cornillon, 1992, 1995, 1996; Belkin *et al*., 2009) from 12 years of twice-daily, global, 9-km-resolution SST data to produce synoptic, instantaneous frontal maps and compute long-term monthly frequencies of SST fronts and their gradients. These maps were then used to distinguish major quasi-stationary fronts and to derive frontal schematics for a provisional atlas. Because SST and chlorophyll fronts are associated (Belkin and O'Reilly, 2009), frontal paths in the digitized schematics lend themselves to time-series assessments of physical–biological correlations. Satellite-derived thermal fronts are typically co-located with hydrographic fronts determined from *in situ* subsurface data. An example of a frontal schematic for the US Northeast Shelf LME is given in Figure 8.

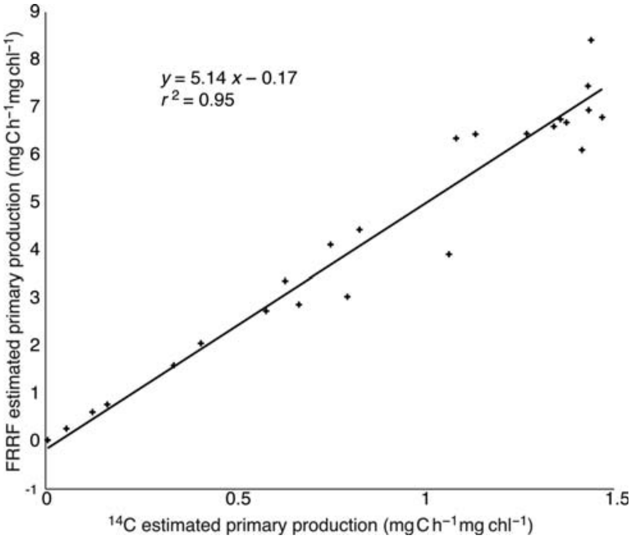

Figure 7. Correlation between the fast-repetition-rate fluorometer (FRRF) and ^{14}C uptake measured primary productivity for Narragansett Bay samples.

SST and fisheries yields

The earth's climate is warming. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), the global mean surface air temperature increased by 0.74°C, whereas the global mean SST rose by 0.67°C over the past century. Global warming has already affected marine ecosystems significantly (Richardson and Schoeman, 2004; Behrenfeld *et al.*, 2006; Halpern *et al.*, 2008); with the current accelerated warming rate, this impact is expected to increase soon (IPCC, 2007). From a global perspective, marine ecosystem-based management can be significantly improved through a better understanding of how large-scale oceanic and atmospheric circulation variability affects specific LMEs. In particular, it is important to establish how global warming translates into patterns of climate change at the LME scale of ocean management. To meet this goal, a study of climate change in the world ocean LMEs was conducted, based on the UK Meteorological Office Hadley Centre's SST climatology, and a 50-year (1957–2006) SST time-series was calculated (Belkin, 2009).

Reflecting a global trend, warming in most LMEs accelerated in the late 1970s and early 1980s (Belkin, 2009). Of the 63 LMEs, 61

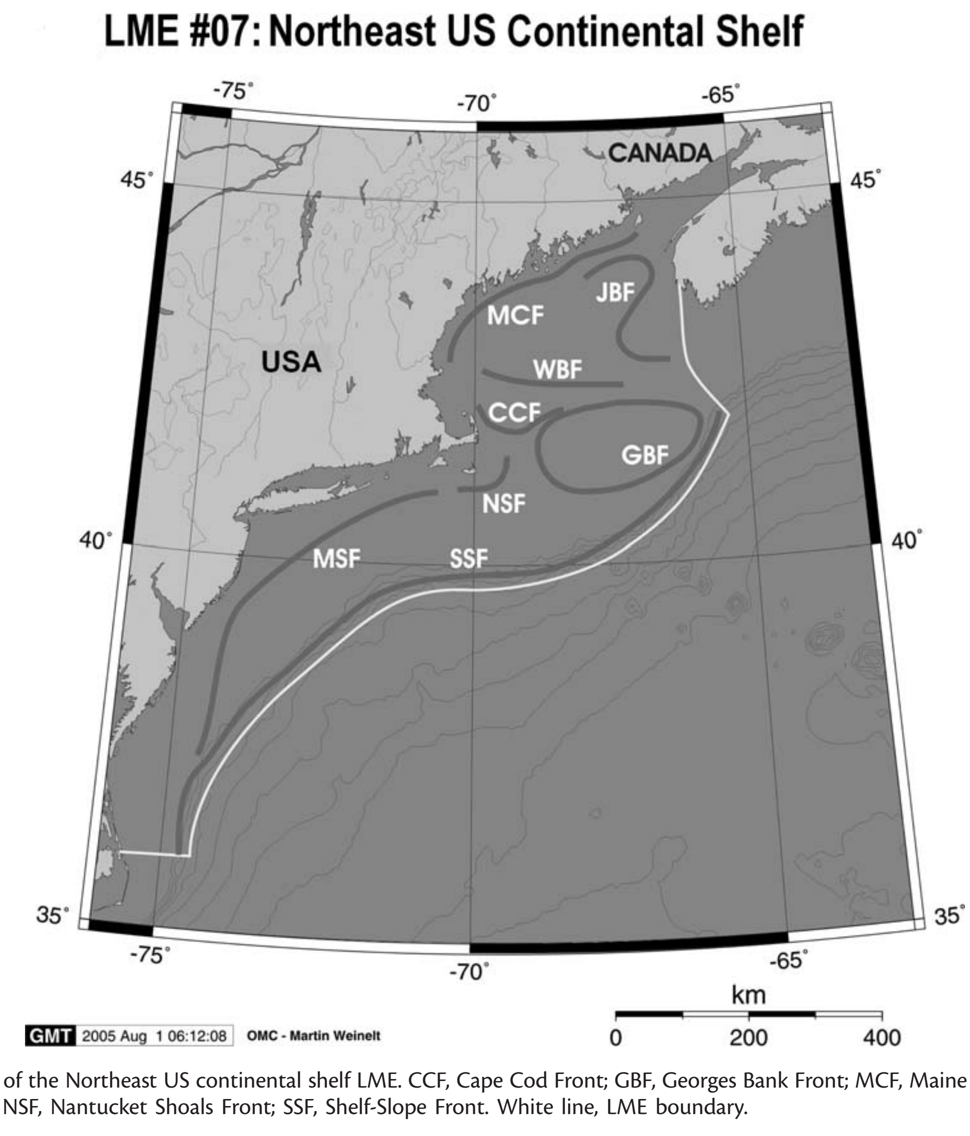

Figure 8. Fronts of the Northeast US continental shelf LME. CCF, Cape Cod Front; GBF, Georges Bank Front; MCF, Maine Coastal Front; MSF, Mid-Shelf Front; NSF, Nantucket Shoals Front; SSF, Shelf-Slope Front. White line, LME boundary.

warmed; only two cooled during the period 1982–2006, the upwelling California Current and the Humboldt Current LMEs. The Arctic Ocean LME was not included in the analysis because of ice cover. The warming trend for the US Northeast Shelf LME is illustrated in Figure 9.

Spatial distribution of SST warming rates reveals a distinct global pattern of rapid warming around the Northeast Atlantic and in the East Asian LMEs (Figure 10). From 1981 to 2004 in the Northeast Atlantic, in the fast-warming Norwegian Shelf, Faroe Plateau, and Iceland Shelf LMEs, fisheries yields increased with warming. In contrast, in the more southern areas of the Northeast Atlantic, in the North Sea, Celtic–Biscay shelf, and the Iberian Coastal LMEs (also fast-warming), fisheries biomass yields decreased with warming (Figure 11). The increases in fisheries yields were attributed to the growing production of zooplanktivorous fish species [e.g. herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*), and capelin (*Mallotus villosus*)] coincident with population rises in an expanding prey field of zooplankton (Sherman *et al*., 2009).

Increasing water stratification and declining plankton: the productivity reduction hypothesis

Declines in fisheries yields in the North Sea, Celtic–Biscay shelf, and Iberian Coastal LMEs were related to declines in plankton levels caused by increased water stratification and the resulting reduction in seasonal nutrient mixing (Sherman *et al*., 2009). These observations are supported by time-series plankton assessments conducted by several European researchers (Beaugrand *et al*., 2002; Beaugrand and Ibañez, 2004; Richardson and Schoeman, 2004).

Theoretical studies of latitudinal changes in primary productivity attributable to global warming suggest that ocean productivity will decline in warmer latitudes (30°N–30°S) and increase in Subpolar waters (Behrenfeld and Falkowski, 1997). These changes are attributed to increasing stratification and decreasing nutrient supply to the upper water column in southern areas, and the extension of the annual production cycle in Subpolar waters (Sarmiento *et al*., 2004; Behrenfeld *et al*., 2006). The results of six different coupled climate models (Sarmiento

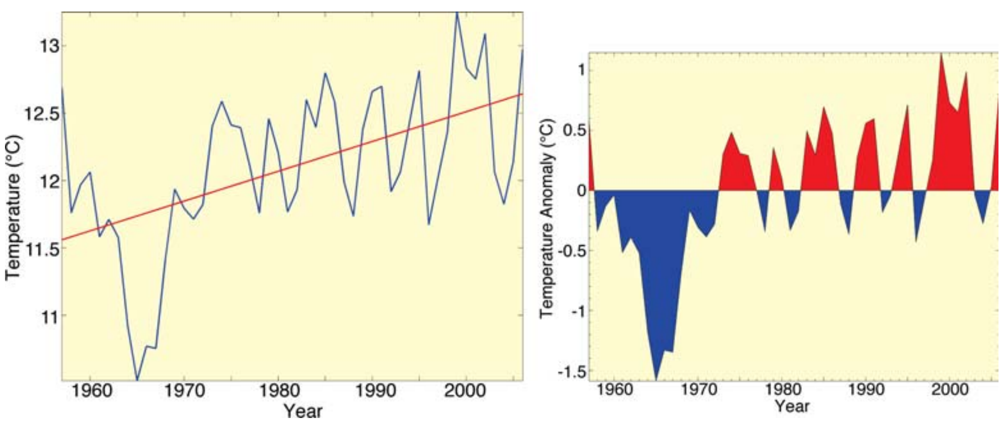

Figure 9. Northeast US continental shelf annual mean SST (left) and SST anomalies (right), 1957–2006, based on the climatology of the UK Meteorological Office's Hadley Centre.

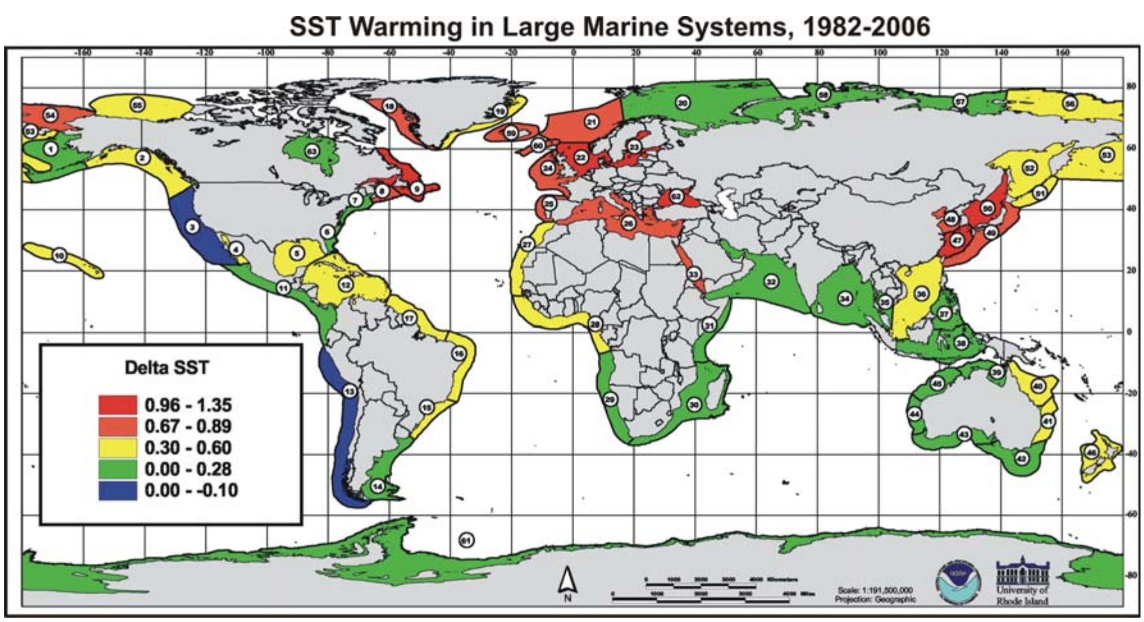

Figure 10. SST trends in the world ocean LMEs, 1982–2006.

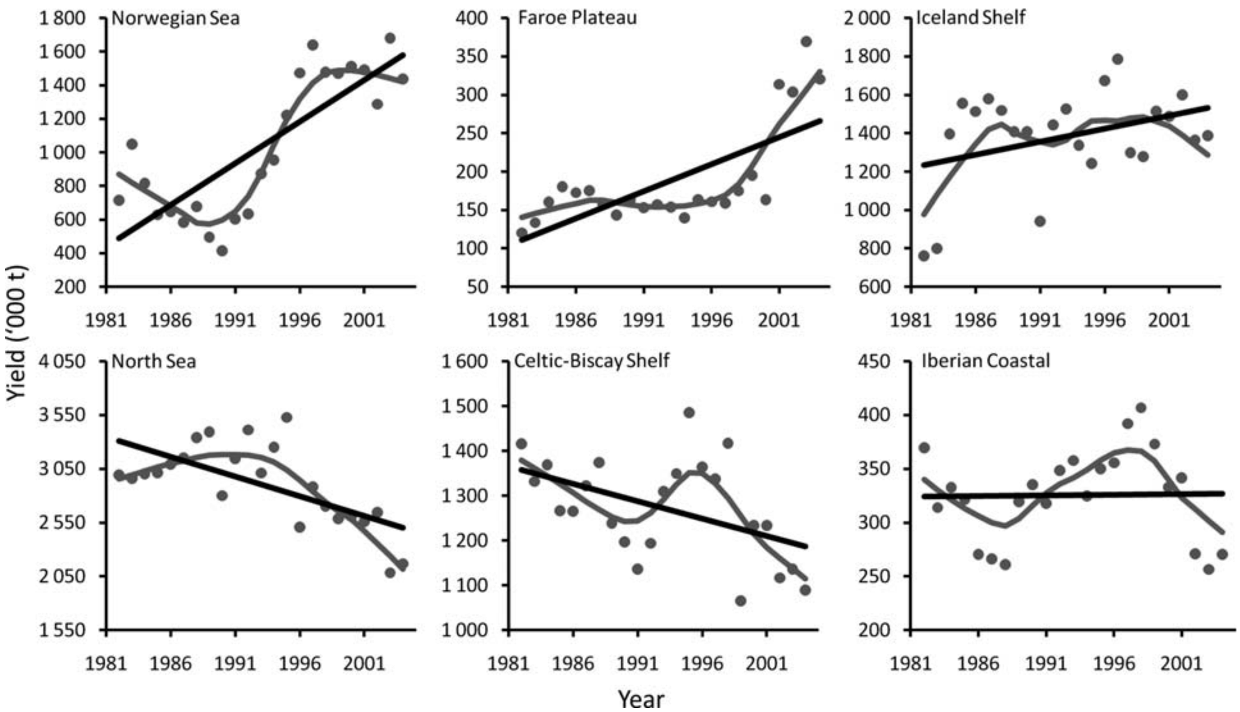

Figure 11. Increasing fisheries biomass yield trends for the Norwegian Sea, Faroe Plateau, and Iceland shelf LMEs (above). Declining fisheries biomass yield trends for North Sea, Celtic – Biscay, and Iberian coastal (below).

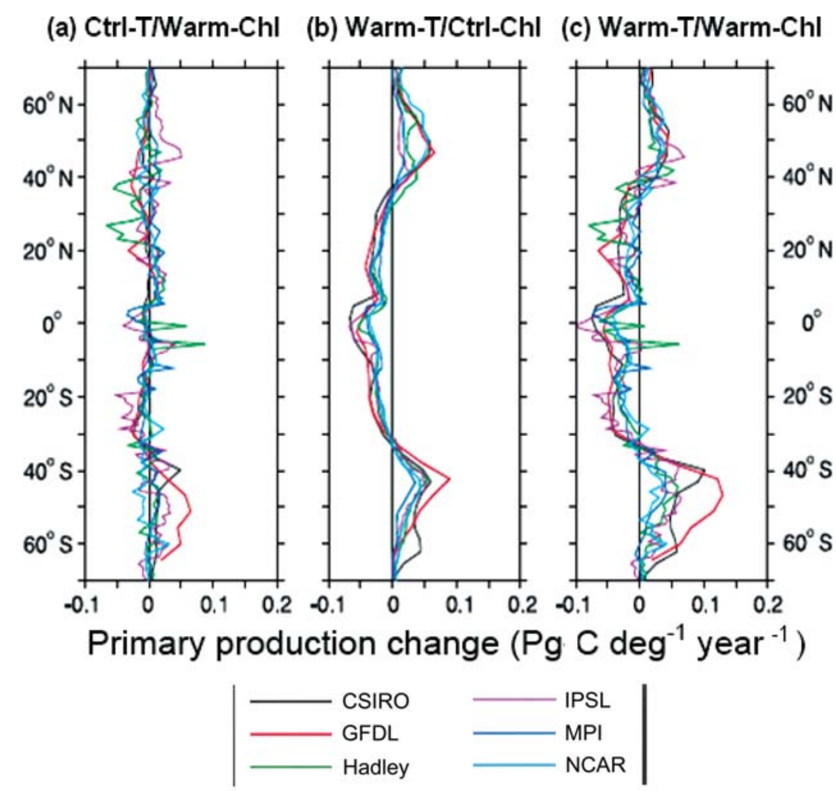

Figure 12. Zonally integrated response of primary production calculated with the Behrenfeld and Falkowski, 1997 algorithm using chlorophyll calculated from the empirical model [Equation (2)]. The difference between the warming and the control simulation for each of the six AOGCMs is shown, averaged over the period 2040 – 2060 (except for MPI, which is for the period 2040 – 2049). The increase in primary production in response to (a) chlorophyll change only, with temperature kept constant at the control scenario, (b) temperature increase only, with chlorophyll kept constant at the control scenario, and (c) the combined effect of the chlorophyll change and temperature increase.

et al., 2004) estimating latitudinal changes in annual primary productivity levels for the years 2040–2060 support this conclusion (Figure 12), as does a retrospective, Atlantic–meridional model analysis of the last ice age (Schmittner, 2005).

Rebuilding and future catch potential

Exploited, overexploited, and collapsed stocks, as defined by Pauly and Pitcher (2000), can be recovered in LMEs where the principal driver is overfishing and where primary productivity, zooplankton production, and other ecosystem services are not seriously impaired. The principal pelagic and groundfish stocks in the slowly warming US Northeast Shelf LME 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 analyses of data from multi-decadal productivity and fisheries assessment surveys, it was concluded that the principal driver of the declining trend in biomass yield was overfishing (Murawski, 1999). Reductions in foreign fishing effort in the 1980s resulted in the recovery of herring and mackerel (*Scomber scombrus*) stocks (Sherman *et al.*, 2003). Further reductions in US fishing effort since 1994 initiated recovery of the spawning-stock biomass of haddock (*Melanogrammus aeglefinus*), yellowtail flounder (*Limanda ferruginea*; Sherman *et al.*, 2002), and sea scallops (*Placopecten magellanicus*; Hart and Rago, 2006). Similar fish stock rebuilding efforts are underway in all 11 of the LMEs in US coastal waters (NMFS, 2007).

Projections by Cheung *et al.* (2007) for 20 EEZs from 2005 to 2050 indicate that increased catches can be expected in coastal waters of northern hemisphere countries including the United States, Norway, Greenland, Alaska, Russia, Iceland, and Canada. Conversely, lower catches and increased risk of food security loss are expected off the coasts of economically developing countries in the warmer parts of the global ocean, including Indonesia, Brazil, and Mexico.

Conclusions

Clearly, LME- and global-scale studies of the effects of global warming, including projections of productivity changes and their verification through direct observation, require synoptic and global observational capabilities. Satellite-based monitoring of SST, chlorophyll, and fronts within the boundaries of the world's LMEs is crucial in this regard. It is particularly important off the coasts of developing countries bordering the LMEs of Africa, Asia, and Latin America, where survey-vessel operations are severely limited and where the potential for losses in food security is greatest. The productivity metrics from satellite remote sensing are important measures of the effects of climate change. Marine scientists, policy experts, and managers should be considering ways and means to support and apply colour radiometry to improve spatial and temporal monitoring and assessment of the levels of chlorophyll and primary productivity in the LMEs.

References

Beaugrand, G., and Ibañez, F. 2004. Monitoring marine plankton ecosystems. 2. Long-term changes in North Sea calanoid copepods in relation to hydro-climatic variability. Marine Ecology Progress Series, 284: 35–47.

Beaugrand, G., Reid, P. C., Ibañez, F., Lindley, J. A., and Edwards, M. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. Science, 296: 1692–1694.

Behrenfeld, M., and Falkowski, P. G. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceangraphy, 42: 1–20.

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., *et al.* 2006. Climate-driven trends in contemporary ocean productivity. Nature, 444: 752–755.

Belkin, I. 2009. Rapid warming of large marine ecosystems. Progress in Oceanography, 81: 207–213.

Belkin, I. M., Cornillon, P. C., and Sherman, K. 2009. Fronts in large marine ecosystems. Progress in Oceanography, 81: 223–236.

Belkin, I. M., and O'Reilly, J. E. 2009. An algorithm for oceanic front detection in chlorophyll and SST satellite imagery. Journal of Marine Systems, 78: 319–326.

Berman, M. S., and Sherman, K. 2001. A towed body sampler for monitoring marine ecosystems. Sea Technology, 42: 48–52.

Cayula, J-F., and Cornillon, P. 1992. Edge detection algorithm for SST images. Journal of Atmospheric and Oceanic Technology, 9: 67–80.

Cayula, J-F., and Cornillon, P. 1995. Multi-image edge detection for SST images. Journal of Atmospheric and Oceanic Technology, 12: 821–829.

Cayula, J-F., and Cornillon, P. 1996. Cloud detection from a sequence of SST images. Remote Sensing of Environment, 55: 80–88.

Cheung, W. W. L., Watson, R., Morato, T., Pitcher, T. J., and Pauly, D. 2007. Change of intrinsic vulnerability in the global fish catch. Marine Ecology Progress Series, 333: 1–12.

Christensen, V., Walters, C. J., Ahrens, R., Alder, J., Buszowski, J., Christensen, L. B., Cheung, W. W. L., *et al.* 2009. Database-driven models of the world's large marine ecosystems. Ecological Modelling, 220: 1984–1996.

Duda, A. M. 2009. GEF support for the global movement toward the improved assessment and management of large marine ecosystems. *In* Sustaining the World's Large Marine Ecosystems, pp. 1–12. Ed. by K. Sherman, M. C. Aquarone, and S. Adams. International Union for Conservation of Nature and Natural Resources (IUCN), Gland, Switzerland. 140 pp.

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

Epstein, P. R. 1993. Algal blooms and public health. World Resource Review, 5: 190–206.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., *et al.* 2008. A global map of human impact on marine ecosystems. Science, 319: 948–949.

Hart, D., and Rago, P. J. 2006. Long-term dynamics of US Atlantic sea scallop *Placopecten magellanicus* populations. North American Journal of Fisheries Management, 26: 490–501.

IPCC. 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller, *et al.* Cambridge University Press, Cambridge, UK. 1000 pp.

Kolber, Z. S., and Falkowski, P. G. 1993. Use of active fluorescence to estimate phytoplankton photosynthesis *in situ*. Limnology and Oceanography, 38: 1646–1665.

Melrose, D. C., Oviatt, C. A., and Berman, M. S. 2007. Hypoxic events in Narragansett Bay, Rhode Island, during the summer of 2001. Estuaries and Coasts, 30: 47–53.

Melrose, D. C., Oviatt, C. A., O'Reilly, J. E., and Berman, M. S. 2006. Comparisons of fast repetition rate fluorescence estimated primary production and ^{14}C uptake by phytoplankton. Marine Ecology Progress Series, 311: 37–46.

Murawski, S. A. 1999. New England groundfish. *In* Our Living Oceans: Report on the Status of US Living Marine Resources, 1999. NOAA Technical Memorandum NMFS-F/SPO-41.

NMFS (National Marine Fisheries Service). 2007. Magnuson–Stevens Fishery Conservation and Management Act, as amended through January 12, 2007 (Public Law 109–479). www.nmfs.noaa.gov/msa2005/docs/MSA_amended_msa%20_20070112_FINAL.pdf.

Pauly, D., Alder, J., Booth, S., Cheung, W. W. L., Christensen, V., Close, C., Sumaila, U. R., *et al.* 2008. Fisheries in large marine ecosystems: descriptions and diagnoses. *In* The UNEP Large Marine Ecosystems Report: a Perspective on Changing Conditions in LMEs of the World's Regional Seas, pp. 23–40. Ed. by K. Sherman, and G. Hempel. UNEP Regional Seas Report and Studies, 182. 872 pp.

Pauly, D., and Christensen, V. 1995. Primary production required to sustain global fisheries. Nature, 374: 255–257.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. 1998. Fishing down marine food webs. Science, 279: 860–863.

Pauly, D., and Pitcher, T. J. 2000. Assessment and mitigation of fisheries impacts on marine ecosystems: a multidisciplinary approach for basin-scale inferences, applied to the North Atlantic. *In* Methods for Evaluating the Impacts of Fisheries on North Atlantic Ecosystems, pp. 1–12. Ed. by D. Pauly, and T. J. Pitcher. Fisheries Centre Research Reports, 8.

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

Robinson, N. A., Hassan, P., and Burhenne-Guilmin, F. (eds). 1992. Agenda 21 & the UNCED Proceedings. Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3–14 June 1992. Oceana Publications, New York.

SAHFOS. 2009. Annual Report 2008. Ed. by M. Edwards, A. W. G. John, D. G. Johns, and A. McQuatters-Gollop. Sir Alistair Hardy Foundation for Ocean Science, Plymouth, UK. 32 pp.

Sarmiento, J. L., Slater, R., Barber, R., Bopp, L., Doney, S. C., Hirst, A. C., Kleypas, J., *et al.* 2004. Response of ocean ecosystems to climate warming. Global Biogeochemical Cycles, 18: doi:10.1029/2003GB002134, 2004.

Schmittner, A. 2005. Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation. Nature, 434: 628–633.

Sherman, K. 1994. Sustainability, biomass yields, and health of coastal ecosystems: an ecological perspective. Marine Ecology Progress Series, 112: 277–301.

Sherman, K. 2005. The large marine ecosystem approach for assessment and management of ocean coastal waters. *In* Sustaining Large Marine Ecosystems: The Human Dimension, pp. 3–16. Ed. by T. A. Hennessey, and J. G. Sutinen. Elsevier B. V., Amsterdam. 380 pp.

Sherman, K. 2006. The large marine ecosystem network approach to WSSD targets. Ocean and Coastal Management, 49: 640–648.

Sherman, K., Belkin, I. M., Friedland, K. D., O'Reilly, J., and Hyde, K. 2009. Accelerated warming and emergent trends in fisheries biomass yields of the world's large marine ecosystems. Ambio, 38: 215–224.

Sherman, K., and Hempel, G. (eds). 2008. The UNEP Large Marine Ecosystem Report: a Perspective on Changing Conditions in LMEs of the World's Regional Seas. UNEP Regional Seas Report and Studies, 182. 872 pp.

Sherman, K., Kane, J., Murawski, S., Overholtz, W., and Solow, A. 2002. The US Northeast shelf large marine ecosystem: zooplankton trends in fish biomass recovery. *In* Large Marine Ecosystems of the North Atlantic: Changing States and Sustainability, pp. 195–215. Ed. by K. Sherman, and H. R. Skjoldal. Elsevier, Amsterdam. 449 pp.

Sherman, K., O'Reilly, J., and Kane, J. 2003. Assessment and sustainability of the Northeast Shelf ecosystem. *In* Large Marine Ecosystems of the World: Trends in Exploitation, Protection, and Research, pp. 93–120. Ed. by G. Hempel, and K. Sherman. Elsevier, Amsterdam. 423 pp.

Sherman, K., Sissenwine, M., Christensen, V., Duda, A., Hempel, G., Ibe, C., Levin, S., *et al.* 2005. A global movement toward an ecosystem approach to marine resources management. Marine Ecology Progress Series, 300: 275–279.

Suggett, D. J., Kraay, G., Holligan, P., Davey, M., Aiken, J., and Geider, R. 2001. Assessment of photosynthesis in a spring cyanobacterial bloom by use of a fast repetition rate fluorometer. Limnology and Oceanography, 46: 802–810.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., *et al.* 2009. Rebuilding global fisheries. Science, 325: 578–585.