Climate, ocean regimes and biomass yields of five North Atlantic large marine ecosystems

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ABSTRACT
From west to east across the North Atlantic, the influence of climate forcing on the biomass yields of large marine ecosystems (LMEs) varies. The US Continental Shelf ecosystem on the western margin of the North Atlantic basin is strongly influenced by the climate of the North American land mass. A pattern of relative stability emerges from an analysis of multi-decadal time-series of chlorophyll, primary productivity, zooplankton and temperature. In contrast, significant population declines in demersal fish stocks including cod, haddock, and flounder, were not attributed to any climate or oceanographic signal. Their declining population trends were linked to excessive fishing mortality of the 1970s through the early 1990s. Mandated reductions in fishing effort in 1994 resulted in significant increases in spawning stock biomass and recruitment of several important demersal fish stocks. Northward, around the margins of the Atlantic basin, declining trends in demersal species of the Scotian Shelf LME and Newfoundland-Labrador LME are attributed to a combination of excessive fishing mortality and cooling of shelf waters. Further northward and eastward, variable climatology and oceanographic conditions are shown to be influencing changes in chlorophyll, primary productivity, zooplankton and growth of cod and other fish stocks of the Iceland Shelf and Faroe Plateau LMEs. From west to east across the North Atlantic, climate and ocean forcing have increasingly greater impact.
on biomass yields of LMEs than the relatively stable climate and oceanographic regime of the US Northeast Shelf LME on the southwest margin of the North Atlantic ocean.

Key Words: climate, regime, ecosystem differences

1. Northeast Shelf Ecosystem
The Northeast Shelf Large Marine Ecosystem extends over 260,000 km² from the Gulf of Maine to Cape Hatteras, North Carolina (Figure 1). Dominant meteorological forces affecting the ecosystem move from the west, southeast, and northwest, steered by the westerly flow of the troposphere. The climatology of the NE Shelf ecosystem is characterized by a wide range of temperatures during an annual thermal cycle. The amplitudes of the annual temperature cycles are two to four times the range of coastal temperatures as recorded at Portland, Maine; New York City, New York; and Norfolk, Virginia (Figure 2). In addition to seasonal atmospheric heating and cooling, the periodic advection of cool water from the Labrador Current (Pershing et al. 2001), and warm-core-ring water of Gulf Stream origin (Brooks 1996), affect the mean-annual temperature conditions of the Northeast Shelf (NES) ecosystem.

MARMAP time-series of mean-annual surface temperature data for the NES-LME is indicative of interannual variability. Examination of decadal trends in temperature were not suggestive of an oceanographic regime-shift, and revealed no persistent long-term upward or downward trend in temperature of the NES ecosystem (Figure 3). Over the past two decades, the long-term estimated biomass level of the zooplankton in the NES ecosystem has been close to the 27-year mean of 39 cc/100m³ (Figure 4). The mean annual total abundance levels of the three dominant zooplankters—Pseudocalanus spp, Calanus finmarchicus, and Centropages typicus—were also close to long-term mean levels (Figure 5). Values of chlorophyll a and productivity of surface waters of the Northeast Shelf ecosystem as measured by the Sea WiFs (1998-2002) ocean color sensor are not significantly different from the long term time-series estimates of 350 G/C/m²/yr calculated for Coastal Zone Color Scanner data (1979-1985) based on comparisons made with MARMAP in situ data and with reprocessed data and modified algorithms (O’Reilly and Zetlin 1998; Sherman et al. 2002).

The MARMAP zooplankton time-series was examined for shifts in species composition using the annual time-series of standardized mean abundance of four zooplankton species—Calanus finmarchicus, Centropages typicus, Metridia lucens, and Centropages hamatus. The abundance of these four relatively large copepod species was stable through the time-series, while the numbers of the smaller copepod fraction sampled, including Pseudocalanus spp, Temora longicornis, and Centropages hamatus, show some evidence of increasing trends during recent years (Figure 6). However, total zooplankton biomass during the same period was close to the long-term mean or higher.

From the mid-1960s through the 1990s the biomass of the principal groundfish species within the ecosystem declined significantly from overfishing of the spawning stock biomass (Murawski et al. 1999). The decline was measured in both a trend in reduced
commercial landings and a parallel decline in catches (kg/tow) from the fisheries independent bottom trawl surveys of the Northeast Shelf ecosystem conducted by the Northeast Fisheries Science Center of NOAA’s National Marine Fisheries Service (Figure 7).

The declining trends in catch and spawning stock biomass of the demersal fish stocks are the subject of considerable effort to “turn the corner” from overfishing to a rebuilding campaign based on significant reductions in fishing effort. Four areas representing 5000 NM of former principal fishing grounds were closed in 1994 to fishing gears capable of catching groundfish. In addition, in 1994, the days-at-sea time allowed for commercial fishery operations was reduced to 50 percent of pre-1994 levels. New regulations were also implemented to increase minimum net mesh sizes, to initiate a moratorium on new vessel entrants, and to mandate vessel and dealer reporting of catches. New regulation limited catches of species designated as “depleted,” and total allowable catch levels (TACs) were implemented. To further reduce fishing effort on the depleted groundfish species, the U.S. Congress approved a plan for “buying-out” 79 groundfishing vessels from fishing license and vessel owners. These management actions have resulted in significant reductions in exploitation rates and a positive biological response in increasing spawning stock biomass (ssb) and in recruitment levels of haddock and yellowtail flounder. Since the 1994 reductions in exploitation rate, the passage of the Sustainable Fisheries Act of 1996 has placed additional requirements for rebuilding the depleted groundfish stocks of the Northeast Shelf ecosystem including cod, hake, pollock and several flounder species.

In addition to the initiation of the recovery process for groundfish stocks, good progress has been made in the recovery of the large pelagic fish biomass of Atlantic herring and mackerel stocks inhabiting the Northeast Shelf ecosystem. Prior to 1967, both species were the targets of very heavy fishing mortality by European factory class vessels operating within the boundary of the ecosystem. Following the passage of the Magnusson Fishery Conservation Management Act of 1976, foreign vessels were excluded from fishing off the northeast coast of the United States with the exception of several joint venture operations with US fishing interests. Since 1976, in the absence of any heavy market demand in the United States for mackerel or herring as a table-food-fish, the stocks of both species have recovered from a state of depletion to robust spawning stock levels constituting an estimated combined biomass of 5.5 million metric tons.

From a fisheries perspective, the zooplankton biomass, chlorophyll $a$ and primary productivity levels remain relatively high and stable. The plankton component of the NES ecosystem continues to provide a robust zooplankton prey field for early life stages of the growing pelagic fish stocks (mackerel, herring) and recovering flounder and haddock stocks (Figure 8). The interannual variability in mean-annual temperature and zooplankton biomass levels are not indicative of any consistent long-term oceanographic regime change. The Northeast Shelf ecosystem appears to be more strongly influenced by interannual perturbations in regional climatology than by any persistent long-term change in oceanographic conditions effecting the ecosystem.
2. Scotian Shelf LME

To the eastward, the Scotian Shelf large marine ecosystem is undergoing a cooling trend. Temperature trends since 1983 show below-average bottom temperatures indicative of an oceanographic driving force. In contrast to the US Northeast Shelf ecosystem, the Scotian Shelf fisheries have been characterized by an increased abundance of cold-water fish (capelin, turbot) and invertebrates (snow crab and northern shrimp). Other changes observed in the ecosystem are the increases in growth rates of demersal species of fish and increases in the CPR phytoplankton “greenness” index and the index of total copepods showing earlier spring peak times in contrast to the 1960s (Zwanenburg et al. 2002). The shifting trend in 50 year temperature time series at 100m for the eastern Scotian Shelf ecosystem is shown in Figure 9.

Changes in the landings of the fisheries in the eastern and western areas of the Scotian Shelf ecosystem show a dramatic decline in demersal and pelagic species from the late 1960s to the early 1990s, and important increases in pelagic and invertebrate species catches since the mid-1990s. In the western Scotian shelf ecosystem during the last three decades, the pelagic species abundance levels fluctuated between a high approaching 160,000 mt in the early 1970s and late 1980s to low levels of 8000 mt in the late 1990s, while demersal species declined from the early 1990s, and invertebrate landings peaked in the late 1980s and mid-1990s (Figure 10).

3. Newfoundland – Labrador Shelf LME

Much has been published on the decline of the fisheries of the Newfoundland-Labrador Shelf LME. Rice (2002) provides a comprehensive analysis of the causes for the declines during two periods of approximately 20 years each—1958 to 1977, the decades prior to extended jurisdiction, and 1978 onwards to 1997 following Canadian jurisdiction over the spatial extent of the LME. The collapse of the cod, haddock, red fish, American plaice, Greenland halibut, yellowtail flounder, and witch flounder stocks and fisheries during the first period is attributed to excessive fishing mortality. The conclusion by Rice (2002) that, “all the circumstantial evidence supports the view that the ecosystem productivity did not change markedly over the period of collapse of these stocks” is especially instructive in relation to overfishing as the principal driving force I the decline of the demersal fisheries. The collapses in groundfish stocks for both periods are shown in Figure 11.

Following significant reductions in fishery effort resulting from the exclusion in 1977 of foreign fleets from the Newfoundland-Labrador LME, increases in catches of all demersal species were observed. However, as the fishery effort of Canadian fishing fleets increased in the 1980s, evidence of stock declines leading to the second phase collapse was reported. The cause of the second collapse, 1985-1993, of cod and other commercially important demersal fish species is more problematic. Evidence suggests that in addition to excessive fishing effort, the ecosystem was stressed from a cooling trend influenced by structural changes in predator-prey interactions and by the presence of a cold intermediate layer (CIL) of water, favoring the growth and survival of northern shrimp, snow crab, and arctic
cod. Also to be considered in relation to the depressed state of demersal fish species is the predation pressure on fish stocks by a growing population of harp seals (Rice 2002).

4. Iceland Shelf LME

The ecological relationships between fish, the food web, and oceanographic variability have been described for the Iceland Shelf LME. The productivity of the Iceland Shelf LME is principally driven by changes in the movements of Atlantic water, mixed Atlantic/Arctic water, and Arctic water. Variations in the abundance levels of cod, capelin, and zooplankton have been linked to variability in the spatial extent of each of the three water masses within the Iceland Shelf LME (Astthorsson and Vilhjálmsson 2002). The linkages are shown in three figures by Astthorsson and Vilhjálmsson (2002). The linkages between zooplankton biomass and capelin biomass are shown in Figure 12. A time-series growth relationship between capelin biomass and mean weight of 6 yr. old cod is depicted in Figure 13. The conceptual model of association put forward by Astthorsson and Vilhjálmsson (2002) linking Atlantic water and Polar (Arctic) water to cod growth-cod biomass yield is given in Figure 14, underscoring the importance for continual monitoring and assessment of the productivity, oceanography, and fisheries of the Iceland Shelf LME.

5. Faroe Shelf LME

The Faroe Shelf LME is another of the Atlantic Ocean ecosystems in which the monitoring and assessment of key ecosystem indicators provides an important body of information to be applied in ecosystem LME management practice (Gaard et al. 2002). Although the data base on productivity and fish and fisheries data are limited to a 10-year period (1990-1999), the addition of sea birds to the monitoring effort is of interest. Within the decadal time-series it is interesting to note the agreement in relative variability in the mid 1990s of the primary productivity index, with sea bird abundance (guillemots), two-year old cod and haddock recruits and weight of cod and haddock at ages 2-5 (Figure 15).

6. North Atlantic West to East Climatology and Biomass Yields

Examination of LME case studies across the North Atlantic over the past two decades suggests a gradient of increasing climatological and oceanographic influence on changing ecological conditions and biomass yields of LMEs (Table 1). At the western margin of the North Atlantic, the US Northeast Shelf LME is strongly influenced by the annual heating and cooling and a climatology that is driven principally from the prevailing tropospheric westerlies over the continental landmass. Principal oceanographic signals are the periodic incursions of cool Labrador Shelf water and warm Gulf Stream water. The primary driver of fisheries biomass yields has been overfishing. Mandatory reductions in fishing effort are contributing to the recovery of yellowtail flounder, haddock, herring, mackerel, scallop and other stocks. Primary productivity, chlorophyll and zooplankton at the base of the food web, with the exception of several annual increases in the abundance of the smaller-sized zooplankton species, are in a robust condition, with no apparent multidecadal departures from the mean annual zooplankton biomass estimates of the past two decades.
Moving north and eastward, changes in climatology and oceanography appear to have generated cooling trends in temperatures from the eastern Scotian Shelf through the spatial extent of the Newfoundland Labrador LMEs. The temperature cooling, along with indications of an emergence of excessive predation on demersal fish stocks by harp seal populations, are considered as secondary and tertiary effects respectively on the depleted stocks of demersal fish. However, the primary source of decline in the fish stocks of the Scotian Shelf and Newfoundland-Labrador Shelf LMEs is considered to be driven by overfishing.

In the North Central-North Atlantic, the Iceland Shelf and Faroe Shelf LMEs appear to be located in transition zones between the relatively cool and low productivity polar water masses and the warmer, more productive Atlantic water, influencing the variability in biomass yields of the demersal fish stocks from the base of the food web to the apex predators of the LMEs. Evidence of ecosystem-level changes in primary productivity, zooplankton, increase in demersal fish growth and, in the case of the Faroe Shelf LME, marine bird growth—all are linked to years of predominance of Atlantic water. The drivers and periodicity and residence times of shifting water masses, although not well understood, appear to occur on a frequency of less than a decade.

In the Northern Atlantic, two principal areas of stress include the southern approach to the Norwegian Sea LME and the North Sea LME from where the Atlantic teleconnections studies of Continuous Plankton Recorder (CPR) plankton data (Reid et al.1998; Reid and Beaugrand 2002) and oceanographic climatological data have been analyzed. The results of both studies indicate strong correlations between climate driven oceanographic events triggering periodic incursions of warm ocean water masses into the North Sea LME and concomitant reductions in abundance levels of the cool water copepod Calanus finmarchicus, and increases in abundance levels of the warm water congeneric Calanus helgolandicus, along with increases in phytoplankton color, horse mackerel catch, benthos, and oceanic lusitanian plankton to the North Sea. The effects of climatology of the North Atlantic Ocean on the European continental shelf is underscored by Taylor, who argues that interannual variations in the movement of the north wall of the Gulf Stream are climatically induced rather than due to “natural fluctuations of the marine ecosystems,” effecting the abundance of zooplankton of the central and northern areas of the North Sea LME and the Celtic-Biscay Bay Shelf LME, and part of the Norwegian Sea LME. Taylor’s analyses suggest that changes in abundance of the zooplankton of the central and northern North Sea are more consistent with background climatic variability than with any persistent oceanographic regime shift.

The LME case studies investigated across the North Atlantic showed a good deal of variation in the numbers of different ecological indicators measured and in the frequency and extent of monitoring activities. A summary of indicators of change and the conclusions drawn on principal, secondary and tertiary forces during changes in biomass yields with the five LMEs examined and conditions of several LMEs of continental Europe is given in Table 1. In recognition of the need to fill gaps and overcome the fragmentation of important ecological indicators, several investigators have developed lists of indicators
that they consider important as governments move toward ecosystem-based management of marine resources and environments.

Based, in part, on Scotian Shelf analyses, Zwanenburg (2003) lists a series of individual species, community, and ecosystem level indices. Cognizant of the importance of informing decision-makers on the changing conditions among the indices, he has developed a “traffic-light” approach for describing the condition of selected indicators for the Scotian Shelf LME, using a red, green, and yellow color code (Zwanenburg 2003, p.88). More recently, Hall and Mainprize (2004) published a list of ecosystem related indicators and performance measurements that are useful in defining principal drivers of changes in fisheries stocks and biomass yields.

We conclude from the case studies examined that it is important for stewardship agencies and collaborating scientific institutions to minimize gaps in time series measurement of critical ecosystem indicators. The ocean community should move to support efforts to maintain effective monitoring activities and extend the frequency and spatial extent of the monitoring of climate and oceanographic conditions in an effort to more effectively assess effects of changing conditions at the base of the marine food web on the sustainability of biomass yields.

REFERENCES


**Table 1. INDICATORS OF LME CHANGE**

*No significant change (0); information indicators not available (–); Information on indicators available (+)

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Suggested forcing: +++ primary ++ secondary + tertiary

Changes in biomass

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*CPR ocean color  ^ zooplankton numbers
FIGURES LIST

**Figure 1.** The Northeast Shelf Large Marine Ecosystem

**Figure 2.** Monthly mean temperatures (degrees F) at Norfolk, Virginia (solid squares); New York city, JFK Airport, NY (crosses); and Portland, Maine (open circles). (Data from Quayle and Presnell 1991.) Freezing (0°C) is denoted by a dash-dot line; 10°C (50°F) by a dotted line (Hertzman 1996).

**Figure 3.** Annual mean surface temperature of NES waters from 1977 to 2003. Measurements taken simultaneously with each of the 20,820 zooplankton samples.

**Figure 4.** Trend in annual median zooplankton biomass of the Northeast Shelf ecosystem (displacement volumes in cc/100m³ of water), 1977-2003 (N= 21,732). The trend line is a fitted polynomial and r value.

**Figure 5.** Trends in the total abundance of the three dominant zooplankton species inhabiting the northeast Shelf ecosystem (mean annual log number per 100 m³ of water), 1977-2002.

**Figure 6.** Annual Time series of standardized mean abundance of *Centropages hamatus, Temora longicornis,* and *Pseudocalanus* spp. from MARMAP zooplankton time series 1977 to 2002 (N=19,441).

**Figure 7.** Landings in metric tons (t) and abundance index of principal groundfish and flounders, 1960-2000.

**Figure 8.** Late 1990s George’s Bank yellowtail flounder and haddock recovery trends in spawning stock biomass (ssb) and recruitment in relation to reductions in exploitation rates (NOAA, NEFSC 2002).

**Figure 9.** Monthly (dashed) and 5-year running means (solid line) of the temperature anomalies at 100 m on Misaine Bank in the eastern Scotian Shelf (from Zwanenburg 2002).

**Figure 10.** Landings of fish and invertebrates from the eastern and western Scotian Shelf for the period 1970 – 1997 (from Zwanenburg 2003).

**Figure 11.** Time series of catches of major targeted groundfish stocks in Newfoundland - Labrador Shelf area. Top panel - 2J3KL cod (squares), 3NO cod (diamonds). Second panel - 3NO Haddock (squares), 3Ps cod (diamonds), 3LN redfish (circles), 2+3K redfish (x’s), 3LNO American plaice (thick dashed line), Greenland halibut (whole area - thin dotted line). Third panel - 3LNO yellowtail (squares), 2J3KL witch (diamonds), 3O redfish (dashed line). Bottom panel - 2+3K American plaice (squares), 3Ps haddock (diamonds), 3Ps witch (stars), 3NO witch (thin solid line), 3Ps American plaice (dashed line). Panel groupings based on similar magnitudes of maximum catches (in tonnes) over time series. Data from most recent assessment research document of CSAS or NAFO (from Rice 2002).

**Figure 12.** Changes in capelin abundance and zooplankton biomass north of Iceland 1980-1997. Redrawn from Astthorsson and Gislason (1994) and additional data (Astthorsson 2002).

**Figure 13.** Changes in capelin biomass and mean weight of Icelandic cod at age of 6 years. Redrawn from Vilhjálmsdóttir (1997) and additional data.

**Figure 14.** A conceptual model of how climatic conditions in Icelandic waters may affect production at lower trophic levels and eventually the yield from the Icelandic cod stock (Astthorsson and Vilhjálmsdóttir 2002).

**Figure 15.** Relative variability in calculated new primary production, number of attending guillemots, recruitment of 2 years old cod and haddock and mean weight of 2-5 years old cod and haddock during 1990-1999 (from Gaard et al. 2002).
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Figure 9. Monthly (dashed) and 5-year running means (solid line) of the temperature anomalies at 100 m on Misaine Bank in the eastern Scotian Shelf (from Zwanenburg 2002).
Figure 10. Landings of fish and invertebrates from the eastern and western Scotian Shelf for the period 1970 – 1997 (from Zwanenburg 2003).
Figure 11. Time series of catches of major targeted groundfish stocks in Newfoundland - Labrador Shelf area. Top panel - 2J3KL cod (squares), 3NO cod (diamonds). Second panel - 3NO Haddock (squares), 3Ps cod (diamonds), 3LN redfish (circles), 2+3K redfish (x’s), 3LNO American plaice (thick dashed line), Greenland halibut (whole area - thin dotted line). Third panel - 3LNO yellowtail (squares), 2J3KL witch (diamonds), 3O redfish (dashed line). Bottom panel - 2+3K American plaice (squares), 3P haddock (diamonds), 3Ps witch (stars), 3NO witch (thin solid line), 3Ps American plaice (dashed line). Panel groupings based on similar magnitudes of maximum catches (in tonnes) over time series. Data from most recent assessment research document of CSAS or NAFO (from Rice 2002 ).
Figure 13. Changes in capelin biomass and mean weight of Icelandic cod at age of 6 years. Redrawn from Vilhjálmsson (1997) and additional data.

Figure 14. A conceptual model of how climatic conditions in Icelandic waters may affect production at lower trophic levels and eventually the yield from the Icelandic cod stock (Astthorsson and Vilhjálmssson 2002)
Figure 15. Relative variability in calculated new primary production, number of attending guillemots, recruitment of 2 years old cod and haddock and mean weight of 2-5 years old cod and haddock during 1990-1999 (from Gaard et al. 2002).