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Recent Arctic Climate Change and Its Remote Forcing of Northwest Atlantic Shelf Ecosystems

BY THE MARINE ECOSYSTEM RESPONSES TO CLIMATE IN THE NORTH ATLANTIC (MERCINA) WORKING GROUP | CHARLES H. GREENE, BRUCE C. MONGER, LOUISE P. McGARRY, MATTHEW D. CONNELLY, NEESHA R. SCHNEPF, ANDREW J. PERSHING, IGOR M. BELKIN, PAULA S. FRATANTONI, DAVID G. MOUNTAIN, ROBERT S. PICKART, RUBAO JI, JAMES J. BISAGNI, CHANGSHENG CHEN, SIRPA M.A. HAKKINEN, DALE B. HAIDVOGEL, JIA WANG, ERICA HEAD, PETER SMITH, AND ALESSANDRA CONVERSI

ABSTRACT. During recent decades, historically unprecedented changes have been observed in the Arctic as climate warming has increased precipitation, river discharge, and glacial as well as sea ice melting. Additionally, shifts in the Arctic's atmospheric pressure field have altered surface winds, ocean circulation, and freshwater storage in the Beaufort Gyre. These processes have resulted in variable patterns of freshwater export from the Arctic Ocean, including the emergence of great salinity anomalies propagating throughout the North Atlantic. Here, we link these variable patterns of freshwater export from the Arctic Ocean to the regime shifts observed in Northwest Atlantic shelf ecosystems. Specifically, we hypothesize that the corresponding salinity anomalies, both negative and positive, alter the timing and extent of water-column stratification, thereby impacting the production and seasonal cycles of phytoplankton, zooplankton, and higher-trophic-level consumers. Should this hypothesis hold up to critical evaluation, it has the potential to fundamentally alter our current understanding of the processes forcing the dynamics of Northwest Atlantic shelf ecosystems.

ARCTIC CLIMATE FORCING OF NORTHWEST ATLANTIC ECOSYSTEMS DURING THE 1990s

In 1989, sea level pressure dropped precipitously in the central Arctic, leading to the most positive Arctic Oscillation (AO) Index of the twentieth century and the emergence of a strongly cyclonic atmospheric circulation anomaly (Figure 1a, Technical Note 1*; Dickson, 1999). This anomaly persisted as a strong cyclonic circulation regime until 1996 and coincided with a reorganization of upper-ocean circulation patterns in the Arctic Ocean (Figure 2a), including a spinning down of the Beaufort Gyre, as quantified by the Arctic Ocean Oscillation (AOO) Index (Figure 1b, Technical Note 1; Proshutinsky and Johnson, 1997; Dukhovskoy et al., 2006; McLaughlin et al., 2011), and an increase in the Arctic Ocean's freshwater export into the North Atlantic (Steele et al., 2004). In 1996, this cyclonic circulation regime weakened and an anticyclonic one replaced it. Characterized by a strengthened Arctic High over the Canada Basin, this new regime resulted in a spinning up of the Beaufort Gyre, an accumulation of liquid freshwater in the Arctic Ocean, and a reduction of liquid freshwater export into the North Atlantic (Figure 1a,b).

Although the AO is considered a natural mode of climate variability, there is some evidence that its behavior from the late 1980s to the mid-1990s was altered by anthropogenic climate change. Greenhouse warming of the troposphere results in cooling of the stratosphere, and modeling studies suggest that such stratospheric cooling can amplify positive AO conditions (Shindell, 2003). The extremely positive AO conditions from 1989 to 1995 were associated with two large pulses of low-salinity water discharged from the Arctic Ocean into the North Atlantic. These freshwater pulses from the Arctic Ocean were the latest in a series of great salinity anomalies (GSAs; Technical Note 3) that have been documented since the late 1960s (Belkin et al., 1998; Belkin, 2004; Greene et al., 2008). All of these GSAs have involved the export of ice or low-salinity liquid water from the Arctic Ocean into the North Atlantic via either Fram Strait or the Canadian Arctic Archipelago (Figure 2a). Recent modeling results suggest that one consequence of anthropogenic climate change may be an increase in liquid freshwater export out of the Canadian Arctic Archipelago (Koenigk et al., 2007).

The first GSA pulse of the early 1990s sequentially affected shelf ecosystems downstream from the Labrador Sea, and its leading edge of low-salinity water was first observed in the Scotian Shelf/Gulf of Maine/Georges Bank region by 1991 (Figures 1c, 2b; Greene and Pershing, 2007; Greene et al., 2008). The propagation speed of the pulse's leading edge was too rapid to be explained by advective transport alone (Technical Note 4).

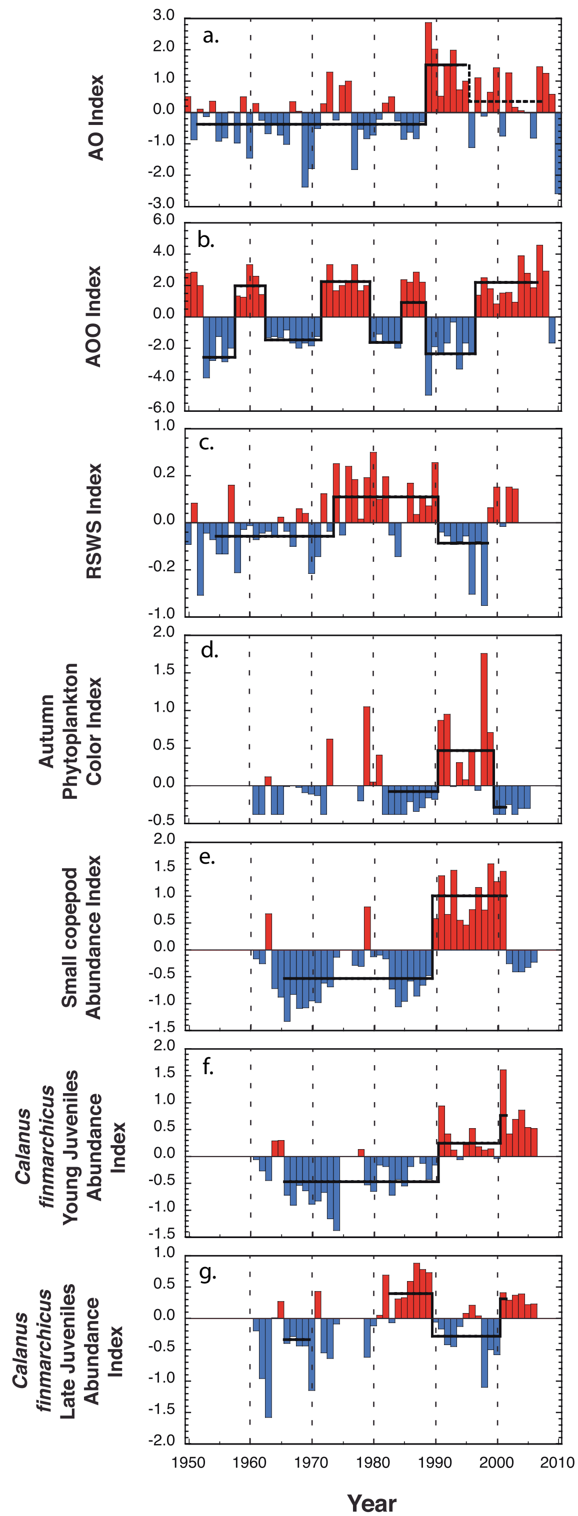

Figure 1. Time series from the Arctic and North Atlantic Oceans. (a) Annual values of the Arctic Oscillation (AO) Index. (b) Annual values of the Arctic Ocean Oscillation (AOO) Index. (c) Annual values of the Regional Shelf Water Salinity (RSWS) Index. (d) Annual values of the Autumn Phytoplankton Color Index. (e) Annual values of the Small Copepod Abundance Index. (f) Annual values of the *Calanus finmarchicus* Early Juveniles Abundance Index. (g) Annual values of the *C. finmarchicus* Late Stages Abundance Index. Positive values of indices above the climatological means are shaded in red; negative values below the climatological means are shaded in blue. Regime shifts significant at the $p = 0.05$ level are shown by solid black lines (Technical Note 2). The regime shift for the AO Index starting in 1996 was significant at the $p = 0.10$ level and is shown by a dashed black line. The AO Index is the first mode from an empirical orthogonal function (EOF) analysis of the Northern Hemisphere's winter (DJFM) sea level pressure field above 20°N (Thompson and Wallace, 1998). Positive (negative) values of the AO Index correspond to an anomalously high (low) atmospheric pressure gradient. The AOO Index is the first mode from an EOF analysis of simulated annual sea-surface heights generated by a coupled ice-ocean circulation model forced with buoy observations of the wind field near the center of the Arctic Basin (Proshutinsky and Johnson, 1997; Dukhovskoy et al., 2006; McLaughlin et al., 2011). Positive (negative) values of the AOO Index correspond to anticyclonic (cyclonic) ocean circulation. The RSWS Index is the first mode from a principal components analysis (PCA) of shelf-water salinity data from the Scotain Shelf/Gulf of Maine/Georges Bank region. Positive (negative) values of the RSWS Index correspond to higher (lower) salinity conditions. The Autumn Phytoplankton Color Index is the mean autumn color index anomaly calculated from Gulf of Maine Continuous Plankton Recorder (GOM CPR) survey data (Greene and Pershing, 2007). The Small Copepod Abundance Index is the first mode from a PCA of annual small copepod abundance anomalies calculated from GOM CPR survey data (Technical Note 6; Pershing et al., 2005). The *C. finmarchicus* Abundance Index is the mean abundance anomaly calculated each year from GOM CPR survey data; it is calculated separately for early juveniles (copepodites 1–4) and late stages (copepodite 5 and adults) of this species (Pershing et al., 2005).

*TECHNICAL NOTES

The Technical Notes for this article have been posted online at http://www.tos.org/oceanography/archive/25-3_mercina_notes.pdf.

Rather, it appears that the increased volume flux into the North Atlantic remotely forced the movement of fresher water masses and fronts downstream well in advance of the arrival of any Arctic-derived water. At an advective speed of 4 cm s^{-1}, Arctic-derived waters would have reached the Scotian Shelf/Gulf of Maine/Georges Bank region by 1993 or 1994. These years during the first half of the 1990s are when the lowest salinities were observed as boundary fluxes into the Gulf of Maine from the western Scotian Shelf (Smith et al., 2001).

A second GSA pulse brought even lower-salinity water into the region several years later (Figure 1c). This subsequent pulse, although propagating downstream from the Labrador Sea as well, appears to have had a more significant contribution from Fram Strait than from the Canadian Arctic Archipelago (Belkin, 2004). Atmospheric pressure conditions, strongly influenced by the Arctic Dipole Anomaly (Technical Note 5), favored winds that generated a meridional transport of sea ice and upper-ocean waters across the Arctic Ocean and into the North Atlantic's Greenland Sea through Fram Strait (Wu et al., 2006; Wang et al., 2009). Once in the Greenland Sea, this salinity anomaly would likely have followed the propagation pathway of the 1970s GSA, initially along the East Greenland Current, around the southern tip of Greenland, and subsequently along the West Greenland Current to the northern reaches of the Labrador Sea (Figure 2a).

Regardless of their Canadian Arctic Archipelago or Fram Strait origins, both GSA pulses of the 1990s resulted in significant freshening of shelf waters from the Labrador Sea to the Mid-Atlantic Bight (Figure 1c; Smith et al., 2001; Loder et al., 2001; Hakkinen, 2002; Mountain, 2003). This freshening increased water-column stability, especially during the autumn and winter, and has been hypothesized to be largely responsible for the ecosystem regime shifts observed in the Scotian Shelf, Gulf of Maine, and Georges Bank ecosystems during the 1990s (Greene and Pershing, 2007). During a typical seasonal cycle in the Northwest Atlantic, thermal stratification of the water column breaks down during autumn, and phytoplankton primary production becomes light limited until thermal stratification returns during the subsequent spring. However, during the 1990s, the fresher waters appear to have provided the buoyancy necessary to maintain water-column stability and extend the phytoplankton growing season throughout the autumn and sometimes far into the winter (Figure 1d; Pershing et al., 2005; Greene and Pershing, 2007; Greene et al., 2008). It

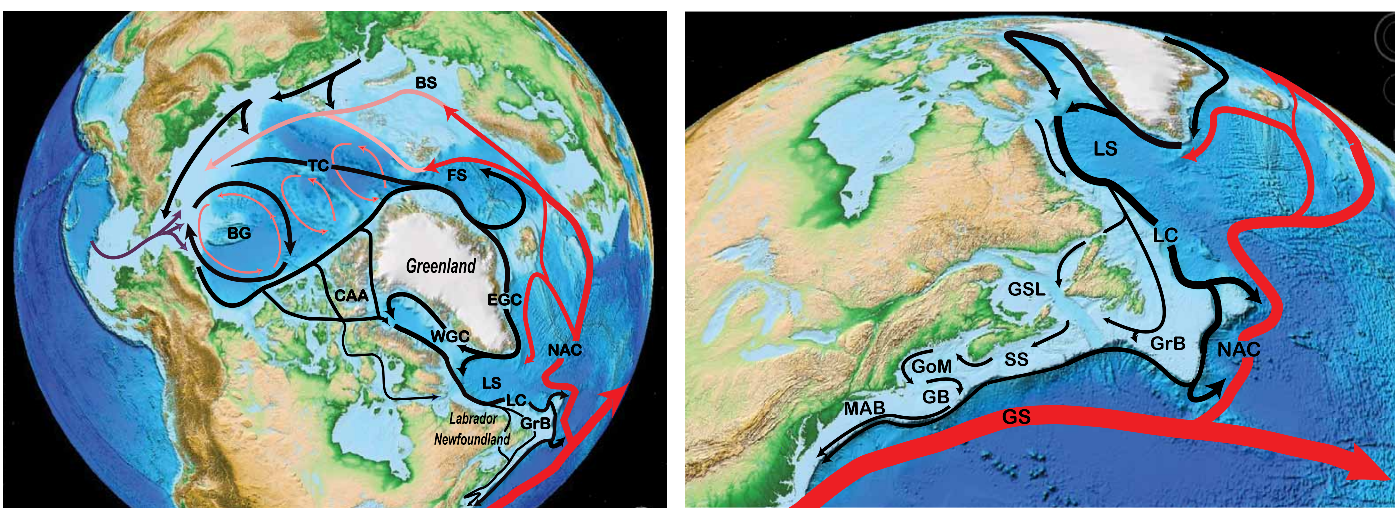

Figure 2. Circulation patterns for Arctic and Northwest Atlantic Oceans. (a) Map of Arctic Ocean circulation patterns emphasizes upper-ocean inflows and outflows with North Pacific and North Atlantic Oceans. Arctic Ocean geographic features, water masses, and currents are labeled for the following: Barents Sea (BS), Beaufort Gyre (BG), Canadian Arctic Archipelago (CAA), East Greenland Current (EGC), Fram Strait (FS), Grand Banks (GrB), Labrador Current (LC), Labrador Sea (LS), North Atlantic Current (NAC), Transpolar Current (TC), and West Greenland Current (WGC). (b) Map of Northwest Atlantic Ocean circulation patterns emphasizes the Gulf Stream and Labrador Current systems. Northwest Atlantic geographic features, water masses, and currents are labeled for the following: Georges Bank (GB), Grand Banks (GrB), Gulf of Maine (GoM), Gulf of St. Lawrence (GSL), Gulf Stream (GS), Labrador Current (LC), Labrador Sea (LS), Middle Atlantic Bight (MAB), North Atlantic Current (NAC), and Scotian Shelf (SS). Colder and fresher currents with large components of Arctic and/or more northern North Atlantic origin are shown in black; warmer and saltier currents with large components of more southern North Atlantic origin are shown in red.

has been hypothesized that the extended phytoplankton growing season resulted in more favorable feeding conditions for a zooplankton assemblage dominated by small copepod species like *Centropages typicus*, *Metridia lucens*, *Oithona* spp., and *Pseudocalanus* spp. These smaller copepod species were observed to increase in abundance, as did the younger stages of *Calanus finmarchicus*, a considerably larger species (Figure 1e,f; Technical Note 6; Pershing et al., 2005). Paradoxically, the older stages of *C. finmarchicus* declined in abundance as its younger stages increased (Figure 1f,g). Size-selective predation by herring on the larger and older stages of *C. finmarchicus* may explain this apparent paradox (Pershing et al., 2005).

NORTHWEST ATLANTIC ECOSYSTEM CHANGES DURING THE 2000s: EVALUATING ALTERNATIVE HYPOTHESES

The remote climate-forcing hypothesis described previously provides an alternative to the trophic-cascade hypothesis proposed by Frank et al. (2005, 2011). These authors hypothesized that the regime shift observed in the Northwest Atlantic during the 1990s could be attributed to a top-down trophic cascade initiated by the overfishing of cod and other demersal predatory fish. While some of the direct effects of reduced demersal fish predation on higher trophic levels seem likely, Greene and Pershing (2007) suggest that climate-associated, bottom-up processes offer a more parsimonious explanation for the observed changes in nutrients, phytoplankton, and zooplankton. More recent observations provide new insights for resolving the differences between these alternative interpretations.

With the decline of the persistent and strongly positive AO conditions during the late 1990s, the Beaufort Gyre entered an extended period of increased freshwater storage that has persisted throughout the first decade of the 2000s (Figure 1a,b; Proshutinsky et al., 2009, 2011; Rabe et al., 2011; Giles et al., 2012; Morison et al., 2012). The corresponding reduction in freshwater export from the Arctic Ocean has resulted in elevated salinities throughout Northwest Atlantic shelf waters (Figure 1c). During 2000–2001, the plankton in shelf ecosystems from the Scotian Shelf to Georges Bank shifted back to resemble the assemblage characteristic of the 1980s regime, with reduced phytoplankton and small copepod abundance during autumn and a resurgence of *C. finmarchicus* abundance during the spring and summer (Figure 1d–g). As pointed out by Frank et al. (2011), populations of

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planktivorous forage fish, such as herring, capelin, and sand lance, collapsed around the middle of the first decade of the 2000s from their earlier increase during the mid-1990s. However, the resurgence of *C. finmarchicus* began during the peak abundance of these planktivore populations in the early 2000s (see Figure 2a in Frank et al. 2011) rather than after their collapse several years later (Figure 1f,g). These findings are inconsistent with the trophic cascade hypothesis, which would predict that the population of this large-bodied copepod species would only increase after it is released from the size-selective predation pressure of planktivorous fish. In fact, the ecosystem changes observed during the 2000s lacked the coordinated, alternating trophic-level responses expected in a trophic cascade and observed during the previous decade. Instead, the lower trophic levels shifted first, in a coordinated response to remote climate forcing, while some of the higher trophic levels, including many commercially exploited fish and crustacean populations, exhibited little change and have not returned to the abundance levels observed prior to the cod collapse of the early 1990s. These findings may be explained in part by the longer life cycles and slower response times of these higher-trophic-level species and in part by the complex food web interactions resulting from the lingering and ongoing impacts of multispecies fisheries (Frank et al., 2005, 2011; Greene et al., 2009).

PROSPECTS FOR THE FUTURE

Despite the complex interplay between bottom-up forcing by climate and top-down forcing by multispecies fisheries, it is possible to make several predictions about the likely impacts of Arctic climate change on Northwest Atlantic shelf ecosystems during the next few years. Between 1997 and 2008, Arctic Ocean circulation was in an extended anticyclonic regime (Figure 1b), and no GSAs were observed to emerge from the Canadian Arctic Archipelago. Furthermore, freshwater storage in the Beaufort Gyre during recent years has been at or near record high levels (McPhee et al., 2009; Proshutinsky et al., 2009; Giles et al., 2012; Morison et al., 2012). After two years of extreme anticyclonic conditions during 2007 and 2008, Arctic Ocean circulation shifted into a cyclonic state in 2009 (Figure 1b). Although these conditions were potentially favorable for a release of some freshwater (Timmermans et al., 2011), the circulation regime shifted back to anticyclonic in 2010 (Figure 1a). This extreme variability, superimposed on the unusual atmosphere-ocean-cryosphere interactions emerging in the Arctic during recent years (Technical Note 7), makes it difficult to predict the exact timing of the next GSA. Nevertheless, when atmospheric forcing becomes favorable for a major release of this stored freshwater, the resulting GSA may be comparable to or exceed the ones observed since the 1960s (McLaughlin et al., 2011; Morison et al., 2012).

If an especially large GSA does occur in the near future, we predict it will force a regime shift in the lower trophic levels of Northwest Atlantic shelf ecosystems comparable to the one observed at the beginning of the 1990s. Using that regime shift as a guide, we would expect enhanced water-column stratification to extend the phytoplankton growing season later into the autumn and winter. In turn, this extended growing season would provide more favorable feeding conditions for the late-season zooplankton assemblage and lead to an increase in the abundance of small copepod species.

The impacts at higher trophic levels are more difficult to predict due to the slower response times of longer-lived species and the complex food web interactions associated with multispecies fisheries described previously. There is increasing evidence that cod stocks are beginning to recover in several Northwest Atlantic shelf ecosystems, and we agree with the conclusions of Frank et al. (2011) that these ecosystems appear to be more resilient to perturbations than previously believed. However, we offer the additional caveat that changing climate plays a role of comparable importance to overfishing in challenging the resiliency of these ecosystems.

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