surface to buckle out into the third dimension. On the unstretched disc, the shortest distance between A and B is a straight line, the blue path. On the cone, however, the red path is connected and shorter than the blue path. The cone is flat except at the vertex, where there is intrinsic, or Gaussian, curvature. That is precisely what happens in these gel discs. Although a bug on the stretched surface and on the cone will observe the same two-dimensional, intrinsic geometry, our extrinsic view from outside the surface will be different.

In general relativity, there is no need for our four-dimensional, curved space-time to be embedded in a higher-dimensional space, but when it comes to materials, we see that this buckling into more dimensions enables Klein *et al.* to create, control, and manipulate surfaces, containers, and actuators. Moreover, controlling the geometry of sheets should make it possible for layered systems to self-assemble with intrinsic curvature, as shown in the bottom panel of the figure. These base units would come together to form triply periodic structures and, if mixed and matched properly with diblock copolymer architectures, can stabilize new and yet unseen morphologies. It may even be possible to assemble structures that are known for their useful photonic properties (*5*). This beautiful control of geometry only scratches the surface of how to create complex topologies and structures.

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Climate Drives Sea Change

Changes in Arctic climate have contributed to shifts in abundances and seasonal cycles of a variety of species in the northwest Atlantic.

Charles H. Greene and Andrew J. Pershing

Ecosystems can shift rapidly from one state to another as a result of natural environmental variability, human activities (such as overfishing or human-induced climate change), or both. Recently, Frank *et al.* reported such an ecosystem regime shift in the northwest Atlantic during the early 1990s (*1*). To understand the likely causes for this shift, we here consider changes in the climate system that occurred at the same time.

Changes in climate beginning in the late 1980s resulted in an enhanced outflow of low-salinity waters from the Arctic (*2*) and a general freshening of shelf waters from the Labrador Sea to the Mid-Atlantic Bight (*3–5*). This freshening altered circulation and stratification patterns on the shelf and has been linked to changes in the abundances and seasonal cycles of phytoplankton, zooplankton, and fish populations (*6, 7*).

In recent decades, the Arctic has experienced a period of historically unprecedented changes (*2, 8*). In 1987, atmospheric pressure at the sea surface began to decline in the central Arctic. Two years later, this sea level pressure dropped precipitously, and a strongly cyclonic atmospheric regime emerged. This cyclonic regime increases the delivery of warmer, higher-salinity Atlantic water into the Arctic Ocean, mainly via the Barents Sea (see the first figure).

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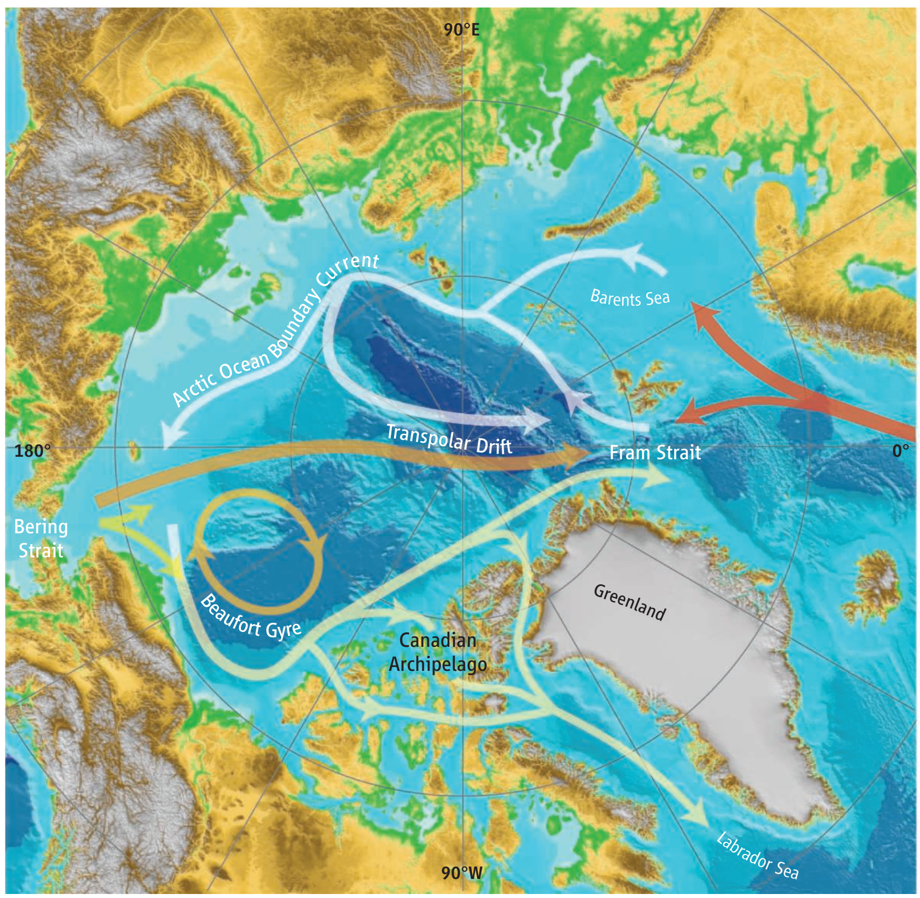


The ocean responds. Between the late 1980s and early 1990s, upper-ocean circulation in the Arctic Ocean changed substantially after an atmospheric regime shift. These changes included an increased inflow of relatively warm high-salinity Atlantic water into the Arctic Ocean through the Barents Sea and Fram Strait, a shift of the front separating Atlantic and Pacific water masses, a weakening and deflection of the Transpolar Drift, a reduction in size and intensity of the Beaufort Gyre, a thickening and intensification of the Arctic Ocean Boundary Current, and an increased discharge of relatively low-salinity water into the North Atlantic through both the Canadian Archipelago and Fram Strait.

Associated with these changes in the atmosphere and Atlantic water inflow, circulation in the upper layers of the Arctic Ocean changed substantially between the late 1980s and early 1990s (see the first figure). From an Atlantic perspective, the most important consequence of these changes was a redirection of the shallow outflow from the Arctic Ocean. Instead of entering the North Atlantic mainly via Fram Strait as before, much of this low-salinity outflow began to exit the Canadian Basin and enter the Labrador Sea via the Canadian Archipelago.

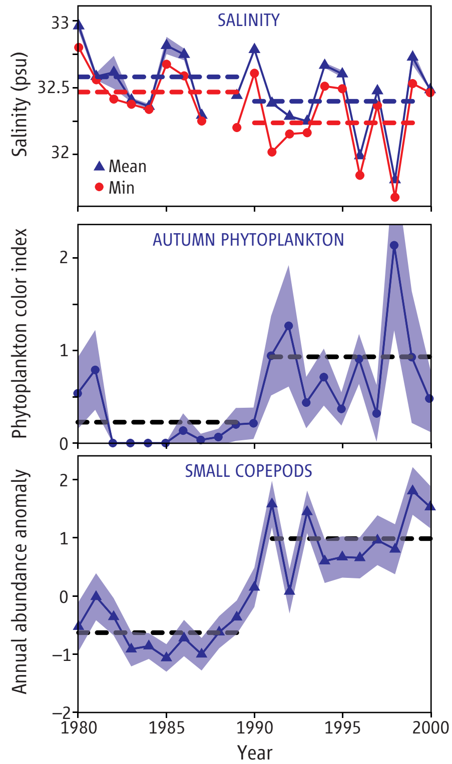
The cryosphere has also responded to changes in climate. During the past three decades, continental melting of permafrost, snow, and ice has increased substantially, which, combined with increased precipitation, has led to greater river discharge into the Arctic Ocean (*8*). Arctic sea ice has declined in both extent and thickness, with extensive summertime ice-free conditions observed to the north of Canada and Russia since 1978. Lindsay and Zhang (*9*) recently hypothesized that the atmospheric regime shift in 1989 and its effects on Arctic Ocean circulation patterns pushed the cryosphere into a new, internally perpetuating state of accelerated sea ice melting. An ice-albedo feedback mechanism may have maintained this accelerated melting even after the atmosphere shifted out of its strongly cyclonic mode during the mid-1990s (*10*).

Although anthropogenic climate forcing is considered to be responsible for the accelerated ice melting, the relative importance of human-induced versus natural climate forcing in driving the observed changes in atmospheric and oceanic circulation has not been fully resolved (*8*). Whether forced by human-induced climate change, natural climate variability, or some combination of the two, relatively low-salinity waters began to emerge from the Canadian Archipelago during 1989 and started to affect shelf ecosystems downstream from the Labrador Sea to the Mid-Atlantic Bight.

The first pulse of low-salinity water passed Georges Bank and reached the Mid-Atlantic Bight by 1991. Several years later, a second pulse advected even lower salinity waters downstream. This second pulse, although moving downstream from the Labrador Sea as well, probably originated from Fram Strait rather than the Canadian Archipelago (*2, 11*).

Northwest Atlantic shelf ecosystems shifted rapidly as they became notably fresher during the 1990s relative to the 1980s (see the second figure, top). This freshening enhanced stratification, resulting in greater phytoplankton production and abundance during the autumn (second figure, middle), a period when primary production would otherwise be expected to decline as thermal stratification breaks down and algae are mixed deeper in the water column and become increasingly light-limited (*6*). The increase in phytoplankton abundance coincided with a reorganization of the zooplankton assemblage: The abundance of smaller, shelf-associated copepods increased markedly (second figure, bottom) (*1, 7*). The largest of these increases occurred in late autumn/early winter, a change associated with the enhanced autumn phytoplankton abundance.

Early juvenile stages of the larger copepod species *Calanus finmarchicus* also increased in abundance with these smaller species; however, older stages became less abundant (*1, 7*). Increased size-selective predation by herring populations, which became much more abundant in the 1990s, may explain these observations.



The ecosystem responds. Salinity, phytoplankton, and zooplankton data from the Gulf of Maine and Georges Bank illustrate ecosystem changes associated with regime shift. Dashed lines: mean values during 1980 to 1989 and 1990 to 1999; shaded areas: 95% confidence intervals. **(Top)** Decadal mean salinities, based on annual mean (blue) and annual minimum (red) salinities reported in (*5*), decrease after the regime shift. **(Middle)** Decadal mean autumn phytoplankton abundances, based on annual mean phytoplankton color index values reported in (*12*), increase after the regime shift. **(Bottom)** Decadal mean copepod abundances, based on annual mean small copepod abundance anomaly values reported in (*7*), increase after the regime shift.

Commercially harvested fish and crustacean populations have also undergone large changes in the northwest Atlantic since 1990 (*1, 7, 12–14*). Of particular importance is the collapse of cod stocks in the early 1990s. Overfishing is considered the main cause of this collapse, but the cold, Arctic-derived waters in the northern part of their range have probably hampered their recovery despite a decade-long fishing moratorium in the Canadian Maritime Provinces (*13*). Other fish and crustaceans have become more abundant during this period (*1, 7, 13*); for certain species, such as snow crab and shrimp, a release from cod predation appears to be the most likely explanation (*1, 14*).

In their original paper on this ecosystem regime shift, Frank *et al.* reported alternating changes in groundfish, benthic crustacean, zooplankton, and phytoplankton abundances (*1*). They attributed these observations to a "trophic cascade" initiated by the overfishing of cod. Certain prey species have indeed increased in abundance with a release from top-down control by cod, but it remains open to what extent the trophic cascade proposed by Frank *et al.* affects lower links in the food chain, especially phytoplankton and zooplankton. We suggest that, with or without the collapse of cod, a bottom-up, climate-driven regime shift would have taken place in the northwest Atlantic during the 1990s.

The resilience of northwest Atlantic shelf ecosystems is being tested by climate forcing from the bottom up and predator overexploitation from the top down. Predicting the fate of these ecosystems will be one of oceanography's grand challenges for the 21st century.

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