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Warming of the Arctic Ocean by a strengthened Atlantic inflow: Model results

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Abstract. An ice-ocean model is used to examine the behavior of the Arctic Ocean in response to recent changes in Arctic climate. The model shows that, starting about 1989, there has been a significant warming and salinification in the Arctic Ocean, in agreement with recent observations. The warming and salinification occur mainly in the upper ocean owing to a sustained increase of Atlantic inflow both at Fram Strait and, most significantly, via the Barents Sea. The increased incoming warm and salty Atlantic Water "flushes" out cold and fresh Arctic Water, thus increasing the temperature and salinity of the upper ocean and resulting in more oceanic heat flux to the mixed layer and ice cover. Concomitantly, the model shows a continuing decrease in ice volume beginning in 1987.

Introduction

Significant changes in Arctic climate have been detected in the late 1980s and 1990s. During that period, there has been a substantial decrease in sea level pressure in the Arctic, characterized by a weakening of the Beaufort high pressure cell and a strengthening of the European subarctic low pressure cell and thus an altered wind circulation (Walsh et al. 1996). Meanwhile there is a noticeable downward trend in the extent of Arctic sea ice based on recent satellite data (Johannessen et al. 1995).

Moreover, recent scientific cruises aboard submarines and icebreakers provide synoptic-like hydrographic data that reveal large-scale changes in the Arctic Ocean in the 1990s. The observations indicate an increased influence of Atlantic Water (AW) in the ocean manifested by noticeable and persistent increases in temperature and salinity over a large area within various layers of the upper Arctic Ocean, particularly the Eurasian Basin (Morison et al. 1997; Carmack et al. 1995). Also, the Eurasian Basin has recently undergone such a remarkable salinification of its surface waters that the cold halocline layer has retreated from the Eurasian Basin into the Makarov Basin (Steele and Boyd 1997).

While the observations all point to pronounced and perhaps fundamental changes in the Arctic Ocean, the cause of such changes is not well established, although authors have speculated that the changes in the ocean are linked to those in the atmosphere (Morison et al. 1997; Steele and Boyd 1997). Furthermore, few model studies have provided results supporting such changes. What is a numerical model's perspective about the ongoing changes? Can a model provide evidence to link and reveal further insights into such changes? The present study addresses this question by investigating the behavior of a coupled ice-ocean model of the Arctic, under the significant climate changes of the atmospheric conditions of the period 1979-1996.

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Model description

The coupled model consists of two components: a dynamic-thermodynamic multicategory thickness distribution sea ice model (Flato and Hibler 1995) and a general circulation ocean model with an embedded mixed layer (Zhang et al. 1998). The model has a horizontal resolution of 40 km x 40 km, 21 levels vertically, 12 ice thickness categories each for ridged ice and for undeformed ice, and 12 snow thickness categories.

The model domain covers the Arctic Ocean and the Barents and Greenland-Iceland-Norwegian (GIN) Seas (Fig. 1). Besides using nonslip lateral boundary conditions along the ocean coasts, the model uses open boundary conditions across the Bering, M'Clure, Nares, and Denmark straits and the Faroe-Shetland Passage, with 0.8 Sv (1 Sv = 10^6 m^3/s) inflow at Bering Strait, 0.8 Sv outflow at M'Clure Strait, 0.7 Sv outflow at Nares Strait, 6.4 Sv outflow at Denmark Strait, and 7.1 Sv inflow at the Faroe-Shetland Passage.

Below 800 m depth, both the ocean's temperature and salinity are restored to climatology (see Zhang et al. 1998) with a 5-year restoring constant. The surface ocean salinity is similarly restored to climatology. However, the surface ocean temperature is not restored to climatology so that the ice growth, determined by the surface and oceanic heat fluxes, is not interfered by the additional heat source due to the surface temperature restoring term. This limited and weak climate restoring allows the model to approach a steady state relatively fast while still capturing the essence of the seasonal and interannual variability of the AW circulation, which occur mainly in the depth range 100-800 m.

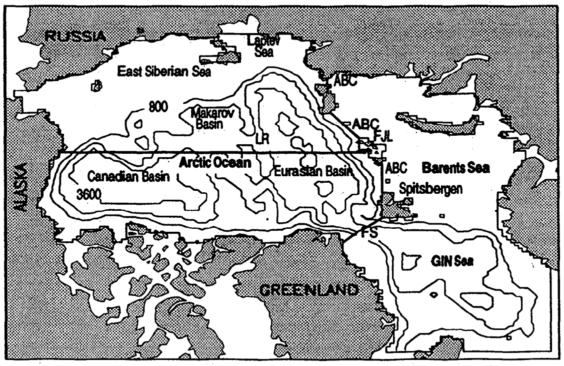

Figure 1. Model domain and bathymetry with contour interval 1400 m. A thick black line across the Arctic represents a transect for the analysis of the results. The line separating the Arctic Ocean and the GIN (Greenland-Iceland-Norwegian) Sea is defined as Fram Strait (FS); the ones separating the Barents Sea and Arctic Basin are collectively called the Arctic-Barents Connection (ABC). The Lomonosov Ridge and Franz Josef Land are marked as LR and FJL.

The ice-ocean model is driven by daily surface forcing from 1979 to 1996. It consists of geostrophic winds, surface air temperature, humidity, parameterized longwave and shortwave radiative fluxes, precipitation, and river runoff. The geostrophic winds are derived using IABP (International Arctic Buoy Program) sea level pressure fields calculated using buoy data blended with NCEP analysis data. The daily surface air temperature data are derived from buoys, manned drifting stations, and all available land stations (Rigor et al. 1997). Precipitation and river runoff are specified (see Zhang et al. 1998).

The initial conditions consist of zero ice and ocean velocities, a 2-m thick uniform ice cover, and climatological ocean temperature and salinity. A 100-year spin-up was first carried out, which consists of 20 cycles of a 5-year period integration using forcing fields of 1979-83. After the 100-year integration, the ocean approaches an approximate steady state such that the differences between the mean temperatures and salinities, averaged over the model domain, of the 19th cycle and 20th cycle are 0.000065°C and 0.0011 psu, respectively. The simulated ice volume also approaches a steady 5-year cycle. After the spin-up, the model then proceeds to simulate the whole period of 1979-96.

Recent changes in ocean circulation

Figures 2(a) and (b) show the 1979-88 mean surface ocean velocity and the difference between the 1989-96 mean and the 1979-88 mean (with a different scale). As shown in Fig. 2(a), the model captures the main surface water flows in the north polar oceans, such as the anticyclonic circulation (the Beaufort gyre) and the transpolar stream in the Arctic Basin, the East Greenland Current, the Norwegian Current, and the West Spitsbergen Current.

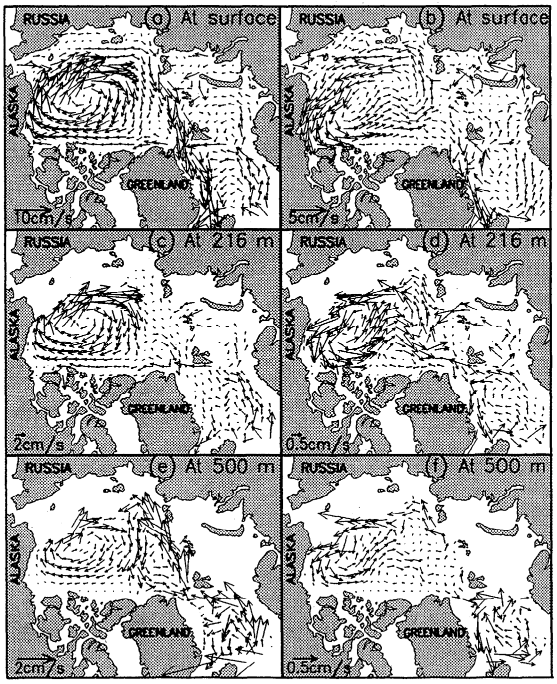

Figure 2. 1979-88 mean ocean velocities at (a) the surface, (c) 216-m depth, and (e) 500-m depth. Differences between 1989-96 mean ocean velocities and 1979-88 mean at (b) the surface, (d) 216-m depth, and (f) 500-m depth. A vector is drawn every 16 grid cells. Note the different vector scales.

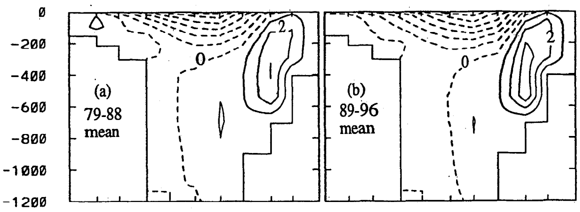

Figure 3. Velocity distributions across Fram Strait marked in Fig.1. Solid lines: flow into the Arctic; dashed lines: flow out of the Arctic. Contour interval is 1 cm/s.

The basic features of the surface ocean circulation remain in 1989-96. However, significant changes occur, as illustrated by the velocity difference field in Fig. 2(b). In the Arctic, the velocity difference field is cyclonic, indicating a substantially reduced Beaufort gyre in response to the recent decrease of the Beaufort high. In the GIN Sea, the AW flows north more strongly than before owing to an expansion of the European subarctic low. As a result, more penetrates into the Barents Sea and eventually enters the Arctic through the Arctic-Barents Connection (ABC). This increased penetration of AW into the Barents Sea is perhaps better illustrated by Figs. 2(c) and (d) which show 1979-88 mean ocean velocity and the velocity difference between 1989-96 mean and 1979-88 mean at 216 m depth (ocean level 7). All this leads to an increased Arctic Water outflow and a stronger East Greenland Current in the upper ocean (Figs. 2b, d, and f).

The circulation at 500 m depth (ocean level 10) is shown in Figs. 2(e) and (f). The 1979-88 mean ocean velocity at 500 m (Fig. 2e) shows a clear AW penetration into the Arctic at Fram Strait (FS). Once into the Arctic, the AW flows all over the Eurasian Basin, with a jet flowing from the Franz Josef Land shelf break to the Laptev Sea shelf break and then to the Lomonosov Ridge (closely following the bathymetry of the basin because of a topographic steering effect). Some AW flows out at FS and some enters the Canadian Basin. In the Canadian Basin, the model simulates an anticyclonic circulation in the intermediate layers while recent studies show a cyclonic circulation. Given that the model simulates an anticyclonic circulation at the surface, it obviously does not possess a mechanism for a circulation reversal in depth.

Again, the basic pattern of the AW circulation remains the same in 1989-96. Nevertheless, significant changes are shown by the velocity difference field in Fig. 2(f). Compared to 1979-1988, the mean 500-m AW circulation of 1988-96 shows more AW flow into the Canadian Basin at the East Siberian Sea-Laptev Sea shelf break and a considerably weakened Beaufort gyre. It also shows a slightly increased AW penetration via eastern FS and a slightly increased outflow via western FS, which is further illustrated by the velocity distributions across FS (Fig. 3).

Recent intensification of Atlantic inflow

Figure 4(a) shows the modeled annual variations in AW inflow and the outflow through FS. There is a small increase in AW penetration at FS after 1988. The mean penetration in 1979-88 is 2.4 Sv while that in 1989-96 is 2.6 Sv, a net increase of 0.2 Sv. More remarkable, however, is the increase in Arctic Water outflow after 1988. The mean outflow in 1979-88 is 2.4 Sv while that in 1989-96 is 3.1 Sv, a substantial increase of 0.7 Sv.

What causes such a large increase in Arctic Water outflow? The explanation is found by examining the AW that enters the Arctic via the Barents Sea. As shown in Fig. 4(a), the increase of

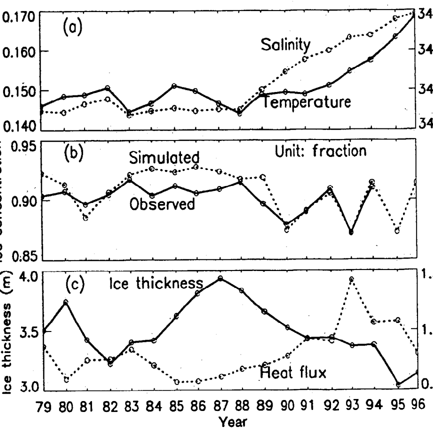

Figure 4. (a) Annual mean Atlantic inflow (solid line) and Arctic Water outflow (dotted line) at Fram Strait and Atlantic inflow via the Barents Sea (dashed line). (b) Annual mean heat carried into the Arctic Ocean by Atlantic Water at Fram Strait and via the Barents Sea.

Atlantic inflow via the Barents Sea is more prominent after 1988. The mean inflow in 1979-88 is 0.9 Sv while that in 1989-96 is 1.4 Sv, a net increase of 0.5 Sv, which is more than twice the increase at FS.

In summary, lately (1989-96) we see a more vigorous exchange of water into and out of the Arctic Ocean through its connection to the North Atlantic. The inflow increase of 0.2 Sv at FS and 0.5 Sv via the Barents Sea is balanced by an 0.7 Sv increase in the Arctic Water outflow.

Since AW is warm and salty, an increased inflow of AW leads, of course, to an increased inflow of heat and salt. Fig. 4(b) shows the heat imported by AW through FS and through ABC via the Barents Sea. Note that the heat carried in by AW via the Barents Sea is less than half that carried in by AW via FS. This is because the AW volume transport via the Barents Sea is about a third that via FS. It is also because the AW entering the Arctic via the Barents Sea is cooler than that via FS, having lost heat while crossing the Barents Sea. After 1988, a substantial increase of heat inflow occurs owing to an increased volumetric inflow of warm AW. This is also true for salt inflow (not shown).

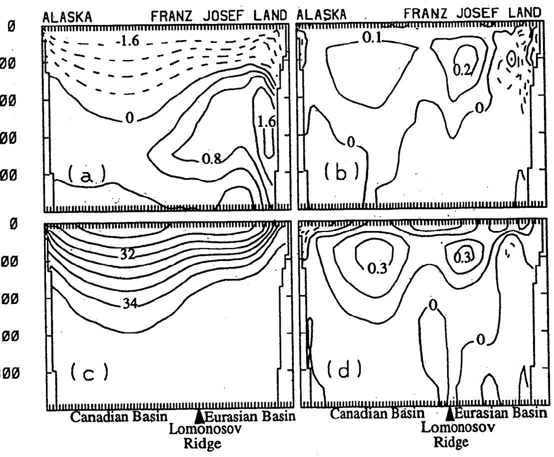

Figure 5. 1979-88 mean (a) temperature (°C) and (c) salinity (psu) on the transect in Fig. 1. Differences in (b) temperature and (d) salinity between 1989-96 mean and 1979-88 mean. Solid lines, positive; dashed lines, negative. Contour interval is 0.4°C for (a), 0.1°C for (b), 0.5 psu for (c), and 0.1 psu for (d).

Recent Arctic warming and salinification

How does the increased heat and salt inflow affect the ocean temperature and salinity structure? Fig. 5(a) shows the simulated 1979-88 mean temperature at the transect across the Arctic (see Fig. 1). The ocean temperature in the Eurasian Basin is generally warmer because of the incoming warm AW; elsewhere, particularly in the Canadian Basin, the temperature is lower because the AW has continually lost heat along its path. The depth of the temperature maximum is deeper than observed by about 100 m. Fig. 5(b) shows the difference between the mean temperature of 1989-96 and that of 1979-88 on the same transect. The 1989-96 mean temperature of the upper ocean over Lomonosov Ridge is increased considerably. The temperature in the Canadian Basin is also increased. However, in part of the Eurasian Basin off Franz Josef Land, the temperature is reduced. This is because of a more rapid increase in the Atlantic inflow via the Barents Sea (Fig. 2d) than that at FS. As mentioned before, the AW at ABC is cooler than that coming from FS but warmer than the Arctic Water over Lomonosov Ridge and in the Canadian Basin. Therefore the model simulates slightly cooled water off Franz Josef Land but warmer water elsewhere in 1989-96. Overall, more areas of the ocean are warmed than cooled by AW inflow, and generally the upper 500 m of the Arctic Ocean is warmer recently.

Figure. 5(c) shows the 1979-88 mean salinity at the transect. Similar to Fig. 5(a), the salinity in the Eurasian Basin is relatively higher because of the incoming salty AW. Again, changes occur in 1988-96. As shown in Fig. 5(d), there is a considerable salinity increase in most of the areas of the upper 500 m of the Arctic Ocean, particularly in the upper 200 m over Lomonosov Ridge and in the central Canadian Basin. The surface water off Alaskan

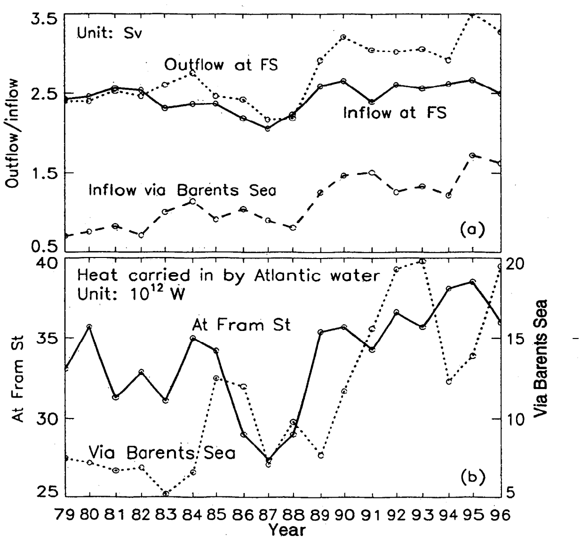

Figure 6. (a) Annual mean temperature and salinity averaged over a depth range of 80-800 m in the Arctic Ocean. (b) Satellite (the Satellite Multichannel Microwave Radiometer and the Special Sensor Microwave/Imager) observed (solid line) and model simulated (dashed line) annual mean ice concentration in the Arctic Ocean. (c) Simulated annual mean ice thickness (solid line) and upward heat flux at 80-m depth due to vertical diffusion and convective overturning in the Arctic Ocean.

coast becomes fresher because of increased ice melting and ice reduction. These simulated features generally agree with observations (Steele and Boyd 1997), particularly in the upper 200 m.

The recent Arctic warming and salinification are further illustrated in Fig. 6(a). Before 1989 the temperature and salinity in the 80-800 m depth range in the entire Arctic Ocean stay almost constant. From 1989, however, the temperature and particularly the salinity steadily increase. The temperature increases about 0.025°C, and the salinity about 0.05 psu, which is remarkable given that the period is only 8 years. Regionally, the biggest increase occurs on the Eurasian Basin side of the Lomonosov Ridge: up to 0.25°C in temperature and 0.3 psu in salinity (Fig. 5).

The simulated Arctic warming and salinification is accompanied by a decrease in ice volume and, to a lesser degree, a reduction in ice concentration in the late 1980s and 1990s, as shown in Figs. 6(b) and (c). Also shown in Fig. 6(b) are passive microwave satellite observations of ice concentration. Although the model somewhat exaggerates the recent decrease in ice concentration by overestimating the ice concentration in the mid 1980s, it generally agrees with the satellite data in capturing a slight downward trend in ice concentration lately (Johannessen et al. 1995). How is the recent ice reduction related to a warming upper Arctic Ocean? The question is addressed in Fig. 6(c) which shows the upward heat transport at 80-m depth due to oceanic processes of vertical diffusion and convective overturning. This flux is a reasonable measure of the upper ocean's thermal influence on the overlying ice cover. In the 1990s, the ocean generally delivers more heat toward the ice cover because of its higher temperature, which plays a role in modeling a decreasing ice cover.

Discussion

The model's behavior supports the recent observations of a significant increase in the temperature and salinity over a large area of the upper Arctic Ocean. It also reveals that the recent Arctic warming and salinification are largely due to a sustained intensification of AW inflow to the Arctic. The increased AW penetration drives a more robust AW circulation in the Eurasian Basin and a more wide-spread influence in the Canadian Basin, which "flushes" out colder and fresher Arctic Water and increases the upper ocean temperature and salinity. An increased influence of AW in the Arctic may have profound consequences for Arctic climate, particularly by reducing the insulating strength of the halocline and allowing more heat from the AW to reach the ice cover. In fact, the model creates an increased oceanic heat flux to the mixed layer and ice cover, which is certainly a factor for its simulation of a recent decrease in Arctic ice volume and, to a lesser degree, in ice concentration. However, we point out that the IABP surface air temperature used to drive the model shows an upswing after 1987 (not shown), which should play a more prominent role in the reduction of the Arctic ice extent.

What causes and maintains a stronger AW penetration and circulation in the Arctic and the adjacent seas? They are certainly tied to the recent weakening of the Beaufort high and expansion of the European subarctic low, which is often linked to the Icelandic low and associated with cyclonic systems that often track from the North Atlantic into the Arctic (Serreze et al. 1993), although the exact mechanism remains elusive. The changes in surface pressure and winds may enhance the air-sea heat exchange in the GIN and Barents Seas and play a role in the recent upswing of the Arctic surface air temperature. They also result in more AW flowing into the Arctic Ocean through FS. More strikingly, they increase the Barents Sea branch of AW inflow dramatically after 1988. It seems that the Barents Sea branch is more sensitive to these changes than the FS branch. Perhaps the shallow bathymetry of the Barents Sea allows the inflow in that region to respond more quickly to atmospheric forcing than the deeper FS inflow. In any case, our results confirm recent observational results of Schauer et al. (1997) and others on the important role that the Barents Sea branch plays in the formation of the hydrographic structure of the Arctic Ocean.

Are the intensified AW circulation and penetration and the resulting Arctic warming and salinification a normal interannual variation and therefore a temporary phenomenon? Or are they a permanent trend? If they are an integral part of the North Atlantic Oscillation (NAO) that has high index recently, then they will vanish when the NAO reverses. Otherwise, we speculate that a chain reaction may set a permanent trend: The intensified European subarctic low leads to a wind circulation that induces more robust AW circulation in the Arctic and the adjacent seas and more AW penetration into the Arctic, resulting in warming and salinification of the Arctic Ocean and erosion of the cold halocline layer. The erosion leads to more ice melting and more heat release from the ocean into the atmosphere, resulting in an increase in air temperature, which would further weaken the Beaufort high. If this scenario were true, then the recent warmer and more saline Arctic Ocean would not swing back to the state prior to 1988, and the Arctic ice cover will continue to shrink.

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