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Synoptic Storms and the Development of the 1997 Warming and Freshening Event in the Beaufort Sea

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Abstract. The climatic state in the Beaufort Sea in 1997 was characterized by warmer atmosphere, smaller areal coverage of sea ice in summer than average, and an oceanic mixed layer with a relatively low salinity that persisted into fall and and early winter. The most remarkable change occurred near the end of 1997 when both salinity and temperature in the upper layer varied dramatically in a short-time period. The evolution of the air-sea-ice condition was observed by an autonomous buoy. The buoy observation revealed that deep mixing that penetrated through the Arctic halocline occurred in response to enhanced wind-stress forcing associated with an intense storm and was mainly responsible for the abrupt change of temperature and salinity in the mixed layer near the end of 1997. Similar events were inferred from storms in the Eurasian basin in 1994. We postulate that synoptic storms plays a very important role in the variations of the heat and salt budgets in the upper Arctic Ocean.

Introduction

Satellite observations indicate that the areal coverage of sea ice in summer has decreased considerably in the last two decades (e.g., Parkinson et al., 1999). An important process that has a direct impact on sea-ice distribution is the heat flux to the ocean mixed layer. The solar radiation in the summer season has been recognized as the primary heat source. Heat flux from deeper ocean is often considered to be small since the a strongly stratified halocline layer, between 30m to 50m in depth, effectively insulates the mixed layer from the thermocline (Aagaard et al., 1981). However, deep mixing events have been observed in the Arctic Ocean and shown to be important for the heat flux to the mixed layer (Steele and Morison, 1993).

Data collected by an autonomous buoy system, drifted in the Beaufort Sea between April and December of 1997, provide a rare opportunity to study the atmosphere-ice-ocean interaction and the evolution of a major climate event in the Arctic Ocean. The observation shows that deep vertical mixing events that penetrated through the halocline occurred in response to wind stress forcing associated with synoptic storms and they played an important role in the development of the 1997 warming and freshening event in the Beaufort Sea.

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The warming and freshening of the Beaufort Sea mixed layer in 1997

The Ice-Ocean Environmental Buoy (IOEB) was designed to acquire and transmit coherent multi-variable environmental data while drifting in the Arctic pack ice through all seasons for several years (Krishfield et al., 1993). Most instruments and sensors take data at hourly intervals, and are matched in space with locations determined by Argos satellites. The IOEB has been deployed and re-deployed in various regions in the Arctic Ocean. The IOEB in the Beaufort Sea was recovered on April 8, 1997, at 79.60° N, 130.62° W, refurbished, and re-deployed. Its trajectory in 1997 after being refurbished is shown in Fig.1(a).

The buoy-observed salinity and temperature at 3 depths, 8m (red), 45m (green) and 76m (blue), are shown in Fig.2(a)-(b). The salinity in the halocline (45m) has greater high-frequency variations than in the other two depths. The surface salinity at 8m started a slow decrease in June (about 180th day) around 29.5 psu and dropped more than 1 psu in about two months (designated as period A). A brief reversal occurred in late August when S_{8m} jumped about 0.5 psu between the 230th and 240th day (period B). Afterward the surface salinity underwent a two-month steep decline, by as much as 2 psu in September and October (period C), only to encounter an even more dramatic drop in early November when S_{8m} fell about 2.5 psu in just a few days (indicated in Figure 2 as D). This negative salinity anomaly, however, was quickly removed in December when S_{8m} jumped more than 5 psu between the 330th and 345th day (marked as period E). The variation at 76m was much smaller in amplitude.

The gradual freshening in the summer and the fall (from period A to C) was likely due to the melting of sea ice. The freshening in the period from A to C continued for almost another month after the sea ice reached the minimum in September. This was likely due to the delay response of the salinity to the surface forcing. What is puzzling is that the surface salinity dropped sharply in November (period D) when freezing should have already been underway in a

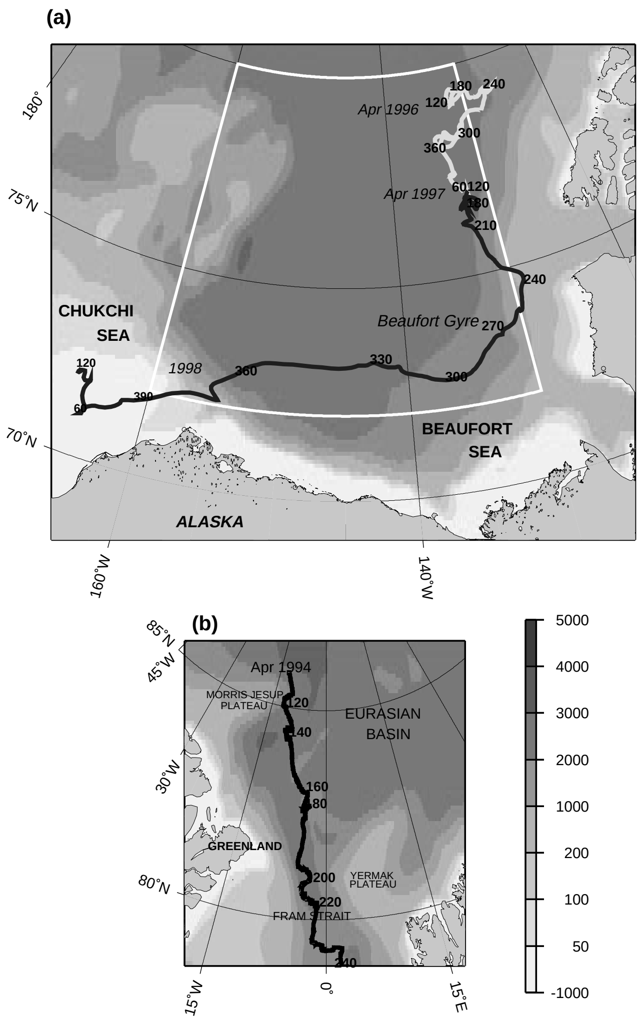

Figure 1. (a) The IOEB trajectory (dark line) in the Beaufort Sea in 1997 after being refurbished. The number marked on the dark line is the calendar day to indicate the position of the buoy. The background color shows the bathymetry; (b) The trajectory of the Transpolar Drift IOEB in 1994.

normal seasonal cycle. Even more fascinating is the rapid removal of the freshwater cap in December 1997 (period E).

Air temperature (T_{air}) averaged over a broad region, shown by the box in Fig.1a, from the International Arctic Buoy Program confirmed that T_{air} during most of 1997 was anomalously higher than its 19-year (1979-97) average, e.g., about 4.5° warmer in November 1997 (Fig.3a). The sea-ice concentration, derived from SSM/I data (Comiso, 1995), was lower in the fall and early winter in 1997 than the previous 3 years in the Beaufort Sea (Figure 3b). The ice thickness, inferred from IOEB's set of ice thermisters, thinned from 4.1m to about 3.75m during the summer, and stayed thin for the rest of the year (Fig.4a). It indicates that ice growth in the underside of the ice was either absent or small from October to December when freezing normally takes place in the Arctic.

The water temperatures at 45m and 76m were both considerably warmer than the freezing point (T_f) (Fig.2b), indicating that the Arctic halocline was either thinner or absent. This is consistent with the hypothesis that the Arctic halocline may have retreated in recent years (Steele and Boyd, 1998), and such changes may occurred in both Eurasian and Canadian basins. The near surface temperature T_{8m} was above T_f in the summer season (Fig.5a) as expected from its seasonal variation. It typically cools down to T_f when ice freezing starts. However, $\Delta T = T_{8m} - T_f$ shows that two warming events occurred, one near the 300th day and the other near the 340th day (Fig.5a), coinciding in time with the large salinity changes in periods D and E as marked in Fig.2a.

Because these two warming events occurred in winter season, the most likely cause would be vertical mixing with warmer thermocline water. Such mixing events can be driven either by brine rejection (buoyancy flux) or by mechanical stirring associated with enhanced air-water or ice-water stresses. Both the wind speed recorded by the IOEB and the ice drift speed inferred from the buoy position were dramatically higher in these two periods, indicating some intense changes in surface wind field, likely associated with synoptic storms. The input of kinetic energy can be estimated from the speeds of wind and ice movement. The energy for the wind-stress stirring in the open-water areas is calculated using the bulk formula. The formula developed by McPhee (1979) is used to calculate the kinetic energy input from sea ice to water. The percentage of sea-ice cover (from SSM/I) in the vicinity of the buoy, shown in Figure 4b, is used to partition air-water and ice-water fluxes.

The kinetic energy flux, shown in Fig.5b (thin line and thick line for the 5-day running mean), was high around the 300th day and after the 340th day, coinciding well with periods D and E when both salinity and temperature at 8m and 45m changed significantly. The entrainment of heat into the mixed layer from the thermocline water, estimated from a simple turbulent mixed-layer model (Lemke et al., 1990), shows that the heat flux was enhanced significantly in this period. The model results support our hypothesis that the warming in November and December 1997 was related to the enhanced vertical mixing driven by storms.

While one would expect that a stronger vertical mixing would lead to higher salinity in the surface (such as what occurred during period E), the salinity at 8m depth actually dropped considerably in period D. Here we will try to explain this discrepancy. When sea ice melts, a thin layer of fresh water is usually formed on the surface. This thin fresh-

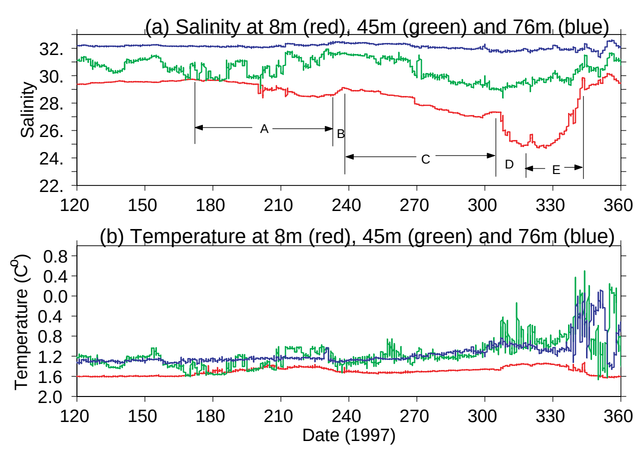

Figure 2. The IOEB observed salinity (a) and temperature (b) at three depths: 8m (red), 45m (green) and 76m (blue)

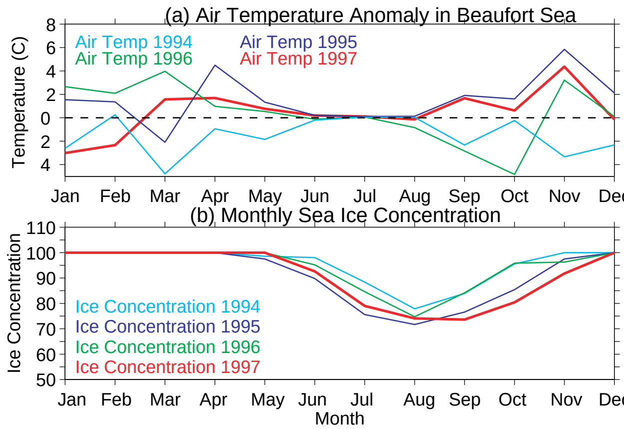

Figure 3. (a) The air temperature anomaly (from the International Arctic Buoy Program) in 1994, 1995, 1996 and 1997 averaged over an area bounded by 72°N and 80°N latitudes, and 130°W and 170°W. (b) the SSM/I sea-ice concentration, averaged over the same area.

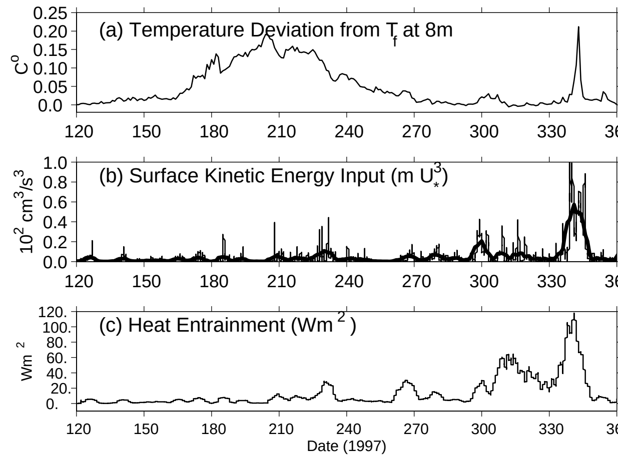

Figure 5. (a) The deviation of 8m temperature from the freezing point (determined by IOEB salinity at the same depth); (b) the surface kinetic energy input (thick line represents the 5-day running mean); (c) the entrainment of heat into the mixed layer calculated from an one-dimensional turbulent mixed-layer model.

water layer is usually eliminated when ice freezing resumes in early winter. The freezing was delayed as shown in Fig.3 and thus this thin fresh layer might survive longer into the fall. When a moderate storm hit the Beaufort Sea in late October and early November (period D), this surface fresh layer was mixed with the subsurface water. Consequently, the salinity beneath the fresh layer at the 8m was diluted. A much more powerful (with wind speed over 20 ms^{-1}) and longer-lasting (about 2 weeks) storm developed in December 1997 (Fig.5b). The oceanic mixed layer deepened substantially, and entrained warm and salty water upward. Both T and S in all three depths increased following the storm, indicating that the mixing penetrated deeper than 76m. Fig.5a shows that the initial warming was quickly cooled down to the freezing point within a few days. Due to the heat entrainment and also likely due to the ice divergence forced by the storm, the satellite SSM/I data show that the sea-ice concentration near the site of the buoy was reduced by more than 6% (Fig.4b) during this storm period.

We have examined other possible causes for the dramatic change of salinity in period D and E. Our budget calculations of heat and freshwater fluxes indicate that melting/freezing alone was unlikely to cause such rapid changes. Another possible cause that has been examined is that the IOEB went across a low-salinity front, such as a plume associated with Mackenzie River runoff. The IOEB had drifted for more than 10° in longitude (see Fig.1a) between 300th and 340th day, indicating that the change was large in spatial scale. Meanwhile, McPhee et al. (1998) who used data collected from SHEBA ice camp also reported a large freshening in Beaufort Sea in 1997. The same finding from these two spatially-separate platforms suggests that the freshening indeed occurred on a large scale and the salinity change did not merely result from drifting across a low-salinity front.

To demonstrate that this type of storm-driven mixing also occurred in other regions in the Arctic, we analyzed data collected from the Transpolar Drift IOEB, which was deployed northeast of Morris Jesup Plateau in April 1994. This buoy drifted southward across the Fram Strait into the Greenland Sea (Fig.1b for the trajectory). We will show data between Julian days 100 and 190 only since after the later, the IOEB had crossed the Fram Strait and entered an oceanographic regime that is very different. The temperature and salinity at four depths (8m, 43m, 75m and 110m)

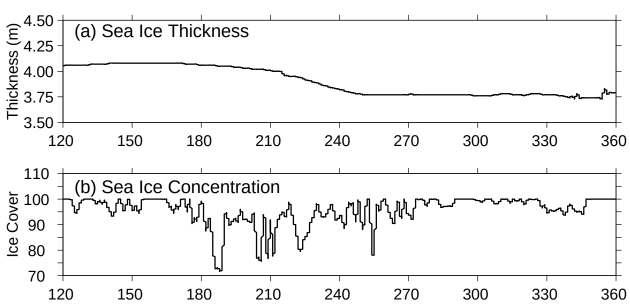

Figure 4. (a) The ice thickness inferred from ice temperature measured by the IOEB; (b) the SSM/I sea-ice concentration in the vicinity of the buoy.

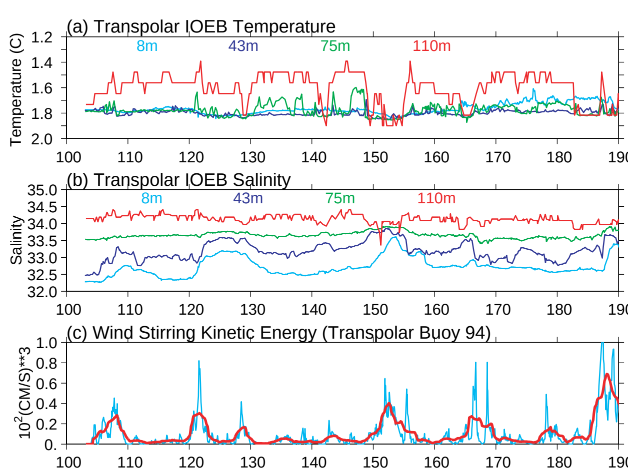

Figure 6. (a) Temperature, (b) salinity and (c) the kinetic energy input from wind stirring for the Transpolar Drift IOEB.

are shown in Fig.6(a)-(b), and the kinetic energy input computed from IOEB observed wind speed is shown in Fig.6(c). The hydrography data indicate that intensive mixing (characterized by rapid increases of salinity in the surface layer and cooling in the sub-surface layer) occurred around 105th, 120th, 150th, 165th, and 185th day. The wind speed data showed that the kinetic energy input was enhanced in these periods (Fig.6c).

Discussion

The evolution of the warming and freshening event in the Beaufort Sea in 1997 has been discussed based on oceanographic, meteorological and sea-ice observations from an autonomous drifting buoy and from satellite sensors. While large-scale processes, such as the Arctic Oscillation (AO), has been recognized for its profound impacts on basin-scale changes, our analyses indicate that smaller and shorter time scale synoptic events, such as intense storms, play crucial roles for the heat and salt balances in the upper Arctic Ocean. IOEB data indicated that the storm in December 1997 was powerful enough to drive a deep mixing that penetrated the halocline. The entrainment of warmer and saltier thermocline water reversed the trend for salinity anomaly and re-initiated the mixed layer condition. We also showed that this type of storm-driven mixing also occurred in the Transpolar Drift region in the spring and the summer seasons. The 1994 Transpolar IOEB was deployed in the Eurasian Basin, and the buoy observed several deep mixing events and most of them were associated with enhanced surface wind speed, as what happened in the Beaufort Sea in 1997. It indicates that this type of storm-driven mixing may occur over the whole Arctic Ocean in different seasons.

Whenever deep mixing occurs, as can happen during a storm, the surface mixed layer gains heat and salt from the deeper ocean. It not only affects the air-sea and ice-sea heat fluxes but also changes the stratification in the upper ocean and thus may alter the sensitivity of the Arctic Ocean to other types of forcing. Important questions that arise from this study are the following: How much do such synoptic events affect the overall heat and salt budgets in the upper Arctic Ocean? How do they affect air–water, air–ice and ice–water interfacial fluxes? What role do they play in longer time scale climate changes? More in-situ measurements and more detailed analysis are needed in order to address these issues. Meanwhile, numerical models with sufficient representations of small-scale mixing as described in this study, should be developed for more accurate budget calculations.

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