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Freshening of the upper ocean in the Arctic: Is perennial sea ice disappearing?

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Abstract. During the Surface Heat Budget of the Arctic (SHEBA) deployment in October, 1997, multiyear ice near the center of the Beaufort Gyre was anomalously thin. The upper ocean was both warmer and less saline than in previous years. The salinity deficit in the upper 100 m, compared with the same region during the Arctic Ice Dynamics Joint Experiment (AIDJEX) in 1975, is equivalent to surface input of about 2.4 m of fresh water. Heat content has increased by 67 MJ m^{-2}. During AIDJEX the change in salinity over the melt season implied melt equivalent to about 0.8 m of fresh water. As much as 2 m of freshwater input may have occurred during the 1997 summer, possibly resulting from decreased ice concentration from changes in atmospheric circulation early in the summer , in the classic albedo-feedback scenario. Unchecked, the pattern could lead to a significantly different sea-ice regime in the central Arctic.

Introduction

Polar amplification and feedback as major factors in climate change are persistent themes in both numerical climate modeling studies [*Manabe and Stouffer*, 1993; *Rind et al.*, 1995], and from ice-core records [*Cuffey et al.*, 1995]. Significant changes are occurring in the Arctic. Satellite observations indicate a decrease in areal ice extent of nearly 3% per decade since the late 1970s, accelerating in this decade [*Cavalieri et al.*, 1997]. There is an upward trend in surface temperature [*Chapman and Walsh*, 1993] and evidence that atmospheric circulation is changing, including reduction of the surface pressure over the central Arctic [*Maslanik et al.*, 1996; *Serreze et al.*, 1997; *Thompson and Wallace*, 1998]. Results from several oceanographic cruises [*Morison et al.*, 1997; *Carmack et al.*, 1997] indicate that the Arctic Ocean has undergone related significant changes since about 1990, including an increase in the temperature and a decrease in depth of the Atlantic Water temperature maximum and a shift in the frontal circulation between eastern and western water types.

Sea ice plays a central role in most climate change scenarios because it (i) changes drastically the albedo of the ocean; (ii) presents a formidable barrier to sensible and latent heat exchange between the atmosphere and ocean; and (iii) depends for its existence on a rather precarious balance among several large energy sources and sinks. SHEBA is a major effort now underway to study the surface energy balance of polar oceans in the perennial ice pack north of Alaska, using instruments deployed on or near the Canadian Coast Guard icebreaker *Des Groseilliers* as it drifts passively with the surrounding sea ice from October, 1997, through September, 1998. For both logistical and scientific reasons, the region chosen for initial deployment is near the center of the Beaufort Gyre, an anticyclonic feature of the ocean circulation centered over the Canadian Basin, which has traditionally included some of the oldest and most compact concentrations of multiyear pack ice found in the Arctic. It is also where the last major US effort to maintain continuous drifting sea ice stations for more than a year occurred, in 1975-1976 (AIDJEX).

During the icebreaker transit into the prospective SHEBA site this past September, we were struck by the lack of thick ice. Where we expected the *mean* thickness to be between 2 and 3 m, we were hard pressed to find floes more than a 1.5 m thick. Even on the comparatively thick floe chosen for the SHEBA site, the thickest unridged ice rarely exceeded 1.8 m. With the first ocean measurements, we found the upper ocean to be less saline and warmer than we had expected, and surmised that this indicated excessive melting. The ocean measurements broaden the scope of the sampling significantly. An ice station established on a particular floe nearly always continues to drift with a patch of surrounding ice at least tens of kilometers across, which will retain many of its gross characteristics for an extended time. In contrast, the upper ocean is always "new" in the sense that the ice and mixed layer move differentially, often in nearly perpendicular directions. Constantly sheared by Ekman drift currents, the upper ocean tends to be more horizontally uniform.

Results

The station trajectory during the first five weeks of the SHEBA drift is shown along with positions of STD casts from AIDJEX manned stations in Plate 1. The AIDJEX deployment was in March and April of 1975, with the array drifting southeast over the following summer. From early October, 1997, through the first part of November, *Des Groseilliers* has drifted mainly to the northwest over much the same area covered by the initial deployment and drift of the AIDJEX array. The juxtaposition provides an unprecedented opportunity for comparing conditions in the mid-1970s with the present using comparatively high resolution data. A comparison of temperature and salinity of the upper 500 m of the ocean at the same location 22 years apart is shown in Figure 1. Above about 70 m, the water is now much warmer and less saline than two decades ago. The two sets of profiles are in different seasons (SHEBA day 312 is 8 Nov 1997; AIDJEX day 201 is 20 Jul 1975), thus need to be compared in light of expected seasonal changes. By October, 1975, the entire AIDJEX array had drifted well south of the SHEBA location, across a frontal feature in the main pycnocline [*Maykut and McPhee*, 1995], precluding a direct seasonal comparison with the initial SHEBA data.

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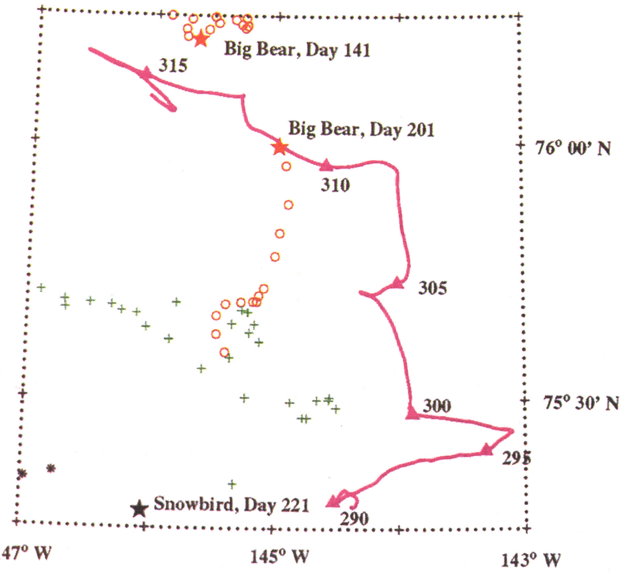

Plate 1. Trajectory of the SHEBA drift in Oct-Nov, 1997, along with locations of the AIDJEX STD stations in 1975. Numbers on the drift track refer to year days of 1997 (day 290 is 17 Oct 97). Pentagrams mark the positions and year days (1975) of the AIDJEX casts shown in Figures 2 and 3.

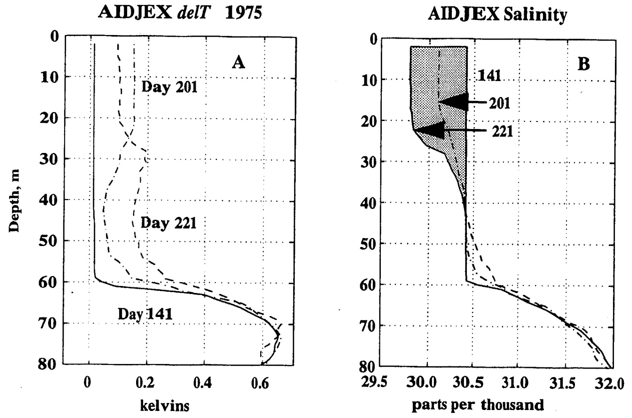

Figure 2. Progression of δT (departure of temperature from freezing) and salinity within the box of Plate 1 over the AIDJEX summer. Day 141 is 21 May 75; day 221 is 9 Aug 75. The shaded area represents salinity deficit from freshwater input.

To interpret SHEBA measurements made during the fall, it is useful first to consider the progression of upper ocean salinity and temperature during the AIDJEX summer (Figure 2). For heat transfer in a coupled ice/ocean system, the thermodynamically important water temperature is departure from freezing, $\delta T = T - T_f(S)$, where T is the actual water temperature and T_f is its freezing temperature for salinity S at surface pressure. Three AIDJEX profiles, all located reasonably close to the SHEBA trajectory, were chosen for display. The first, on day 141 (21 May 1975), typifies late winter conditions with a relatively deep well mixed layer near it freezing temperature. There is a hint of warming from insolation in leads, which may occur even during times of rapid ice growth [*McPhee and Stanton,* 1996]. The heat is thoroughly mixed by boundary layer turbulence. After two months (spanning the summer solstice) the profile on day 201 shows significant warming through the entire mixed layer and freshening due to melt water introduced at the surface. By day 221 (9 August 1975), the upper 50 m is well above freezing but a distinct seasonal halocline has formed between 25 and 30 m. This presents a significant barrier to turbulent mixing and caps the "remnant" mixed layer, trapping heat stored there until released by winter convective mixing (during AIDJEX the trapped heat was never entirely recovered [*Maykut and McPhee*, 1995]). Note that in the seasonal mixed layer above about 25 m, δT is smaller than in the remnant mixed layer below. As sun angle decreases in August, solar heating cannot keep pace with melting and the mixed layer temperature relaxes back to freezing. Solar heating during AIDJEX is described in detail by *Maykut and McPhee* [1995; *viz.*their Plate 2]. They estimated ocean-to-ice heat flux from mixed-layer δT and ice velocity, and found its average over the entire summer (days 140 to 300) to be slightly more than 10 W m^{-2} for stations Caribou and Snowbird, amounting to a total heat transfer from the ocean of around 140 MJ m^{-2}. This coincided closely with their estimate of insolation to the ocean through leads and thin ice.

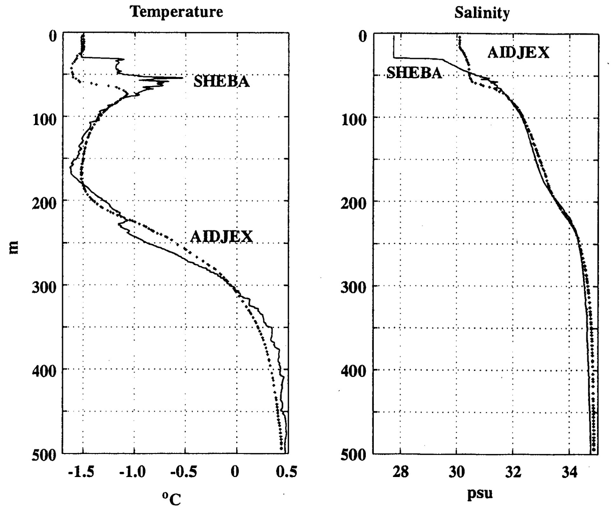

Figure 1. Comparison of temperature and salinity profiles for day 201 (20 Jul) of 1975 (AIDJEX Big Bear) with SHEBA SeaCat cast on day 312 (8 Nov) of 1997. The two casts were made only a few kilometers apart.

The shaded portion of Figure 2B indicates the total salinity deficit from freshwater input over the first 80 days of the AIDJEX melt season. Once the seasonal halocline becomes established, isolating the intermediate (remnant) mixed layer from surface turbulence, there is little mechanism for mixing there, implying that vertical flux of heat or salt near its center (depth 43 m in this case) would be small. Provided that vertical mixing processes dominate horizontal advection, the salinity deficit may thus be interpreted as the time integral of upward salinity flux near the surface. It may be expressed in terms of an equivalent thickness of freshwater input, Δh_f. Freshwater input includes contributions from basal and surface melting, along with percolation from internal melting plus any summer imbalance in precipitation and evaporation. The change at AIDJEX from day 141 to 221 implies an equivalent freshwater input of 0.54 m, but there was still a fair amount of melting after day 221. *Maykut and McPhee* [1995] estimated that ocean heat transfer by day 221 at AIDJEX was two-thirds of the entire amount. If total melting followed basal melting, this implies a seasonal value for Δh_f of about 0.8 m and total ice melt was about 1 m, consistent with observational estimates of the amplitude of the seasonal signal in Arctic mixed layer salinity [*Morison and Smith*, 1981; *McPhee*, 1986]. Oceanic heat transfer at stations

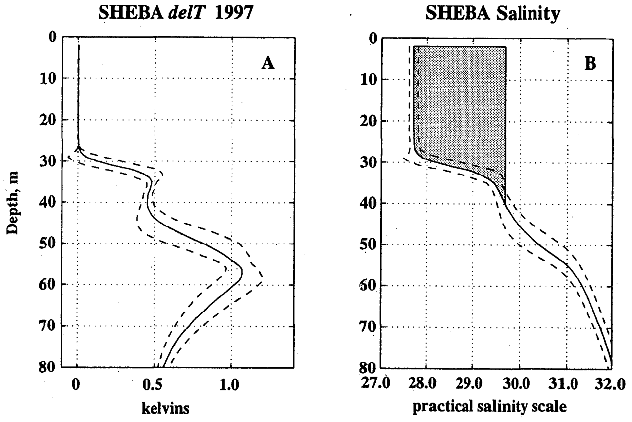

Figure 3. Mean values of δT and salinity for station SHEBA from 14 Oct to 14 Nov 97. Dashed lines represent ± one standard deviation of twice daily samples. The shaded area is the hypothesized salinity deficit from the mixed layer that existed at the start of this (or some recent) melt season.

Caribou and Snowbird (140 MJ m^{-2}) implied a basal melting of about 0.5 m, i.e., half the total.

Mean temperature and salinity profiles over the SHEBA drift track about 110 km in length, spanning days 287-318, are shown in Figure 3. The standard-deviation envelope illustrates that changes have been relatively minor. Note that the abscissa scales are doubled from the corresponding AIDJEX plots (Figure 2).

A comparison of the August temperature profile from AIDJEX (Figure 2A, labeled 221) with the mean October profile from SHEBA (Figure 3A) shows two distinct δT maxima in each. Both are much larger in the SHEBA profile. *Maykut and McPhee* [1995], interpeted the upper δT maximum at AIDJEX to be the temperature to which the mixed layer was heated at around the time of the solstice, prior to the meltwater "cap" which began forming about mid-July. By early October, most of the available heat was gone from the AIDJEX mixed layer, but there was still 15-20 MJ m^{-2} of residual heat stored in the remnant layer below. We have no data from the 1997 summer, but the temperature profile suggests a similar scenario: a mixed layer initially around 40-45 m thick heated by solar radiation early in the summer, then later capped by a shallower meltwater mixed layer which had by October given up most of its available heat. The remnant mixed layer δT is almost $2^1/_2$ times as large as in 1975, suggesting that oceanic heat flux was considerably greater during the 1997 summer.

Discussion

By analogy with the AIDJEX observations, the inflection point occurring in the SHEBA salinity profile (Figure 3B) at around 40 m indicates the mixed layer salinity at the start of the melt season. The shaded curve then represents the total salinity deficit, and implies freshwater equivalent thickness input of about 2 m, which is $2^1/_2$ times the AIDJEX estimate. Where did all the additional fresh water originate? Besides melting sea ice, other possible sources include a large imbalance between precipitation and evaporation, or a major change in advection of continental runoff into the region. Neither provides a satisfactory explanation. There was little evidence for a major change in precipitation. The surface area encompassed by the Beaufort Gyre is of order half a million square kilometers. By early November, the SHEBA station had traversed enough of the region to infer that the freshening was widespread. A 1.2-m thick layer of fresh water, representing the change from a "normal" expected seasonal variation of 0.8 m, spread over the entire region would comprise something like 600 km^3, over twice the annual total discharge of the Mackenzie River, about 280 km^3 [*Dümenil et al.*, 1997]. If our interpretation of the remnant mixed layer from the start of the melt season is correct, this occurred ***in one season.*** Even if a mechanism for diverting the entire outflow of the Mackenzie from its previous paths and spreading it more or less uniformly across the upper 50 m of the Beaufort Gyre could be imagined, it would still take years to accomplish the observed freshening.

Is it physically possible to accomplish the freshening by sea ice melt alone? There is the obvious drawback that from a one-dimensional viewpoint, a 2.5-m melt in one season would eliminate most of the ice pack. In 1997 the ice edge was farther north than its historical mean autumn position [*R. Moritz*, pers. comm., 1997], hence net advection into the region of ice grown elsewhere could satisfy local continuity. The more important issue may be in the energetics, and here the "wild card" of the albedo feedback is relevant. In 1975 the cumulative observed net surface input of shortwave radiation was approximately 1800 MJ m^{-2} [*Pautzke and Hornof,* 1978]. Of this, about 155 MJ m^{-2}, or 8.6%, made its way into the mixed layer, with 140 MJ m^{-2} eventually returning to the ice as oceanic heat flux [*Maykut and McPhee*, 1995]. From the difference in albedo between sea ice and ocean, we surmise that open water occupied roughly 9-10% of the surface during the AIDJEX melt season. Suppose this were tripled. We would still see an ice cover in excess of 7/10s coverage, but the ocean-to-ice heat transfer would be close to 430 MJ m^{-2}, melting about 1.5 m of ice from below. From *McPhee's* [1992] heat flux parameterization, this would require an average mixed layer δT over the entire season of about 0.12 K. This is not implausible, given evidence that mixed layer δT may have reached almost 0.5 K before the seasonal halocline formed (Figure 3B).

It is possible, of course, that the "remnant mixed layer" identified here was not formed during the 1997 season, and that the seasonal cycle had already subsumed this year's summer halocline by the time we arrived in early October. A radioactive isotope, ^{7}Be, was measured in the upper ocean during the SHEBA deployment [*D. Kadko*, pers. comm., 1997]. Because of its meteoric source and relatively short half life, ^{7}Be serves as a tracer for water that has been in contact with the surface over the past season [*Kadko and Olson*, 1996]. Kadko's results indicate that water below the October mixed layer had in fact been in contact with the surface during the 1997 summer.

Regardless of whether the upper ocean freshening occurred in one season or over several recent melt seasons, it may signal a significant shift in the ice/ocean heat budget toward a markedly different sea-ice regime. It bears emphasizing that the hypothesized enhanced melting is not directly related to recent ocean warming found elsewhere in the Arctic. Mixed layer freshening since AIDJEX has more than doubled the strength of an already strong pycnocline, effectively decoupling the mixed-layer/sea-ice system from the deep ocean. It seems likely that enhanced ice melting, especially if it follows the albedo-feedback scenario described above, would have to originate with changes in atmospheric circulation. These changes include a sharp increase in extra-tropical cyclone activity since the 1980s, with associated reduction in surface pressure [*Serreze and Maslanik*, 1997], which may indicate a long term shift in Arctic circulation [*Thompson and Wallace*, 1998]. The mean anticyclonic high pressure dome that maintains the Beaufort Gyre is also critical in maintaining the high ice concentrations found there— by Ekman dynamics sea ice tends to converge under anticyclonic systems and diverge under cyclones. Specifically, if the high pressure dome breaks down earlier in the summer, allowing more cyclones to track across the region at the time of maximum solar input, the albedo feedback mechanism is most effective. Events during the AIDJEX summer hint at how strong this effect can be [*Maykut and McPhee*, 1995]. In mid-to-late August, oceanic heat flux at station Blue Fox was approximately twice as large as at the other stations for a period of about 10 days. There was about twice as much open water in the area around Blue Fox (~25%) compared with the AIDJEX triangle as a whole. This one event raised the cumulative ocean-to-ice energy transfer at Blue Fox to nearly 200 MJ m^{-2}, about 40% greater than at Caribou and Snowbird. By late August the incoming shortwave radiation had fallen to about 40% of its peak at the summer solstice. Had the opening occurred over a wider area earlier in the summer, it could easily have doubled the basal melting.

Much in this note is conjectural. The horizontal extent of the freshening is unknown, and from the fall temperature and salinity structure we can only guess at the events which occurred during the 1997 summer, based on previous experience. Still, a plausible argument may be made that the total ice mass in the Beaufort Gyre has been significantly reduced, and is susceptible to even greater reduction next summer. The SHEBA project is well poised to investigate if and how the ice pack will re-establish equilibrium. The possibility that the ice is thinning rapidly lends a sense of urgency to our measurements over the next melt season.

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