Origins of the SHEBA freshwater anomaly in the Mackenzie River delta

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[1] The formation of a low salinity anomaly observed in the southern Beaufort Gyre in fall 1997 is examined, using output from a numerical sea - ocean climate model. The anomaly forms from locally reduced fall ice growth and from advection of river water. With regard to the latter, we find anomalous northwestern advection of water from the Mackenzie River delta (MRD) during 1997–1999, which fed a low salinity anomaly that circulated and deepened in the Beaufort Gyre until summer 2002, when it dissipated. The MRD salinity anomaly was especially fresh in 1997 because unusually convergent sea ice the previous summer and fall 1996 suppressed fall ice growth. The model shows a high correlation between advection from the MRD and salinity anomalies in the southern Beaufort Gyre until about 2002, when the correlation weakens as local sea ice melt/growth becomes the dominant forcing. Citation: Steele, M., A. Porcelli, and J. Zhang (2006), Origins of the SHEBA freshwater anomaly in the Mackenzie River delta, Geophys. Res. Lett., 33, L09601, doi:10.1029/2005GL024813.

1. Introduction

[2] What caused the anomalously fresh Beaufort Sea surface mixed layer observed at the beginning of the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment in fall 1997? McPhee et al. [1998] measured salinities ∼2 lower than previous observations over a mixed layer ∼20–30 m deep, concluding that the main forcing was sea ice melt. Subsequently, Macdonald et al. [1999, hereinafter referred to as M99, 2002, hereinafter referred to as M02] used oxygen isotope data to determine that the major factor was Mackenzie River discharge, with a secondary contribution from ice melt. In this study, we use a numerical model to focus on the origins of the freshwater anomaly in the Mackenzie River delta (MRD) and its evolution in the Beaufort Gyre.

2. The Model

[3] We used an eight-category thickness and enthalpy distribution sea-ice model coupled to an ocean model [Zhang and Rothrock, 2003]. The domain covers the northern hemisphere to an open boundary at 48.9°N, at which inflow is specified from a global simulation [Zhang et al., 2004]. Mean horizontal resolution in the Arctic Ocean is 31 km. Vertical resolution is 10 m down to 45 m depth, with decreasing resolution below. The model assimilates satellite observations of ice concentration as was done by Lindsay

and Zhang [2006] except that here, ice-ocean salt flux is not affected by assimilation, in order to avoid occasionally unphysical fluxes described in that study. The model is driven by daily NCEP/NCAR reanalysis fields over 1978–2004, while river discharge is climatological with a simple seasonal cycle [Hibler and Bryan, 1987]. Salinity below 200 m is restored to Levitus [1982] climatology with a 5-year time scale.

3. Results

3.1. The SHEBA Salinity Anomaly

[4] Figure 1 shows the evolution of the modeled SHEBA sea surface salinity (SSS) anomaly in six bimonthly averages. In summer (July/August) 1997, MRD SSS is fresher than the long-term mean by more than 2.5, or about 3 standard deviations. The MRD anomaly forms over the previous winter of 1996/1997, as discussed in the following section.

[5] In fall (September/October) 1997, the SSS anomaly suddenly spreads westward. Modeled ocean currents of ∼5 cm s⁻¹ are sufficient to transport this water from the MRD to the SHEBA deployment site, but not beyond. (Note that the model places the anomaly a bit south of the observed position.) Thus the westward extension beyond SHEBA, although considerably weaker than at SHEBA (Figure 1b), must have other origins. Figure 2 shows a local source: anomalously low ice growth during fall 1997, forced by a warm surface air temperature anomaly of over 4°C. The freshwater flux anomalies from MRD advection and from low fall growth are similar at ∼40 cm if spread over the anomaly’s area in fall 1997 (Figure 1b), and can fully account for the average SSS anomaly of about −2. Thus both advective and local freshwater sources influenced the fall 1997 anomaly, in keeping with M99.

[6] Over the SHEBA year (October, 1997–October, 1998), the modeled salinity anomaly recirculates within the Beaufort Gyre. New freshwater anomalies form in the Chukchi and East Siberian Seas, but either dissipate locally or are advected away from the SHEBA anomaly. The anomaly deepens within the Gyre during the next three years (Figure 3), receiving additional freshwater from the MRD through 1999 (see also Section 3c) and dissipating completely by summer 2002. Figure 3 shows that the model’s salinity anomaly is comparable to observations, although too shallow.

[7] Some low salinity water from the MRD is also drawn eastward by the surface currents over winter 1997/1998 into M’Clure Strait and the Canadian Archipelago (Figures 1b and 1c). However, this anomaly is completely erased by ice growth during the winter of 1998/1999.

3.2. Origins of the MRD Anomaly

[8] Figure 4 shows conditions during summer and fall 1996, when the salinity anomaly first appeared. At this time,
there was a cold surface air temperature (SAT) anomaly associated with an unusually thick sea ice cover (Figure 4a). The cold temperatures forced strong fall sea ice growth along the Alaskan coast (Figure 4b), but not in the MRD, where growth rates were reduced by a thick ice cover to values very close to zero. So what created this thick ice? The answer is ridging, forced by anomalous convergence into the MRD. Modeled and observed sea ice drift (Figure 4c) during the summer and fall of 1996 was from the northwest, directly toward the MRD. The result was unusually thick ice, which prevented the usual fall ice growth and its associated salt flux to the ocean. A low salinity anomaly was thus created.

What about meteoric freshwater sources? Our climatological river discharge cannot create interannual anomalies. Mackenzie River discharge time series available from the University of New Hampshire (http://www.r-arcticnet.sr.unh.edu/v3.0/) show anomalously low discharge in summer 1996, and slightly above average values in summer 1997. Thus this was not a major source of positive freshwater anomalies in the real ocean. Figure 4d shows a small positive anomaly of net marine precipitation less evaporation (P-E) from the NCEP reanalysis data in the MRD, similar to the anomaly computed from the European Centre for Medium-range Weather Forecasts 40-year reanalysis (not shown).
Note, however, that the P-E anomaly is ten times smaller than the sea ice growth anomaly.

Anomalies of ice divergence, ice growth, and P-E are all relatively small over the 1996/1997 winter. The upper 20-30 m ocean currents are also small and somewhat anomalously eastward. Thus the MRD salinity anomaly that formed in the fall of 1996 remained stationary over the winter, moving slowly toward the closed Amundsen Gulf. In summer and fall 1997, the anomaly was advected into the SHEBA deployment area by anomalously north-westward ocean advection. Some Mackenzie River water also moved northeastward into M’Clure Strait and the Canadian Archipelago (Figure 1).

3.3. Historical Context

How unusual were the conditions that led to the creation of a MRD low salinity anomaly over 1996/1997? Figure 5 shows that six years during 1978–2004 had anomalous summer/fall convergence, leading to thick ice and low rates of fall ice growth. Of these years, only 1996 was followed the next year by anomalously westward ocean surface currents, which swept the low salinity anomaly into the Beaufort Gyre.

In general, any westward ocean currents will advect fresh MRD water into the Beaufort Gyre. This is illustrated in Figure 5 by the high correspondence between MRD currents and SSS in the southern Beaufort Gyre. This effect would have been amplified in 1997 because of unusually low salinities in the MRD, created over the previous winter by anomalously low sea ice growth. However, it was moderated by the secondary pathway that MRD waters took through M’Clure Strait in the Canadian Archipelago (Figure 1b), which reduced the anomaly seen in the southern Beaufort Gyre in 1997. Nonetheless, anomalous westward currents during the following three years 1997–99 continued to feed low MRD salinity water into the Beaufort Gyre. Conditions started to return toward the 1978–2004 mean in 2000, when these currents declined.

Figure 5 addresses the conjecture of M02 that westward currents in this area might have been more prevalent in the late 1990s. In the model, this is true for the mid-late 1990s, but then the trend reverses in the 2000s. There are also strong westward currents in the late 1970s. Thus the model does not support any long term trend in ocean advection direction in this area. However, Figure 5 does show a major shift in the last 3 simulation years, in which anomalously fresh waters in the southern Beaufort Gyre are not linked to advection from the MRD. Instead, this freshening is caused by strong summer sea ice melting and suppression of fall growth. This is not surprising, given the recent large decreases in summertime sea ice extent in this area [e.g., Stroeve et al., 2005]

4. Conclusions

The model confirms previous observational studies showing that the SHEBA freshwater anomaly was created by local ice melt/growth processes and by advection of riverine waters from the MRD. With regard to the latter, we find that the MRD was particularly fresh in the summer of 1997 because ice convergence led to low sea ice growth during the previous fall. We also find that anomalous ocean advection from the MRD into the Beaufort Gyre continued for about three years, feeding the gyre with fresh waters. When this ceased, the anomaly dissipated within another two and a half years.

The cause of freshwater anomalies in the southern Beaufort Gyre appears to have shifted in recent years, with ice melting playing a more dominant role, relative to riverine water advection. This is in keeping with recent observations of dramatically reduced summer sea ice extent.

This study shows the complexity of near-shore processes in the Arctic Ocean. The SHEBA case provides an example when the freshwater fluxes from river discharge, sea ice melt and growth, and P-E are all additive, creating an anomalously low surface salinity. We note that our model, like most large-scale sea ice - ocean models, does not accurately represent many of the more interesting near-shore processes such as stamukhi and over-ice flooding. These

Figure 3. Fall salinity anomaly profiles (relative to 1978–2004 bimonthly means) averaged over the red dotted areas in Figure 1. Also shown is the mean observed salinity profile at SHEBA during fall 1997, minus a climatological salinity profile from the same area [Steele et al., 2001]. Model depth levels are marked on the right axis.

Figure 2. Mean fall 1997 anomalies of ocean velocity at 5 m depth (relative to 1978–2004 fall mean), only plotted where they exceed 2 cm s$^{-1}$ (vectors), net ice growth minus melt (color contours), and surface air temperature (contour lines, interval = 2°C).
Figure 4. Conditions in 1996, when the SHEBA freshwater anomaly first formed. (a) Summer anomalies of surface air temperature (contour lines) and ice thickness (color contours), (b) fall anomalies of net sea ice growth minus melt, (c) ice velocity (not anomaly) and ice thickness divergence anomaly over summer and fall, and (d) P-E anomaly over fall. Also shown in Figure 4c is the drift of ice buoy 26693 (magenta track starting at the diamond) [Rigor and Heiberg, 1997].
clearly influence the ocean on short (~weekly) and possibly longer time scales. Further, the absence of tracers in the model to distinguish various freshwater sources is an impediment to both analysis and comparison with observations.

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