JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. C9, 3136, doi:10.1029/2000JC000491, 2002

Modeling dense water production and salt transport from Alaskan coastal polynyas

Sergio R. Signorini
Science Applications International Corporation, Beltsville, Maryland, U

Donald J. Cavalieri
Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Abstract

A three-dimensional primitive equation model was used to assess the effects of dense water formation from winter (1996/1997) polynyas on the ambient stratification, salt transport, and circulation in the vicinity of Barrow Canyon. The model, which includes ambient stratification and bottom topography, is forced by time-varying surface heat flux, surface salt flux, and coastal flow. The influence of sea ice drift on the circulation and salt transport is also analyzed by prescribing ice water stress at the sea surface. The surface fluxes and ice drift are derived from satellite observations (Special Sensor Microwave Imager (SSM/I) and NASA scatterometer (NSCAT) sensors). The coastal flow (Alaska coastal current), which is an extension of the Bering Sea throughflow, is formulated in the model by using a wind-transport regression. One set of experiments was forced by strong and persistent polynyas, simulated by 20-day averaged heat and salt fluxes originating from the largest events. In this set of experiments both strong and weak steady coastal currents were imposed. The amount of salt exported from the generation area depended on the strength of the current. Another set of experiments was forced by weaker and less persistent polynyas using time-varying forcing. The experiments with time-varying polynya forcing were conducted with two ambient vertical stratifications, one representing fall conditions and one representing winter conditions. The amount of salt retained on the shelf was found to be quite sensitive to the initial stratification. Weaker vertical stratification promotes a deeper mixed layer, which develops 20 times faster than the horizontal advective timescale of the coastal current, thus increasing the residence time of the salt generated by the polynya on the shelf. The time-varying northeastward coastal current, combined with the offshore Ekman transport, can export 29–73% of the salt produced by polynyas upstream of Barrow Canyon, depending upon the ambient vertical stratification. The inclusion of ice water stress in the model makes the coastal current much wider due to the resulting offshore Ekman transport and also doubles the amount of salt exported.

Published 27 September 2002.

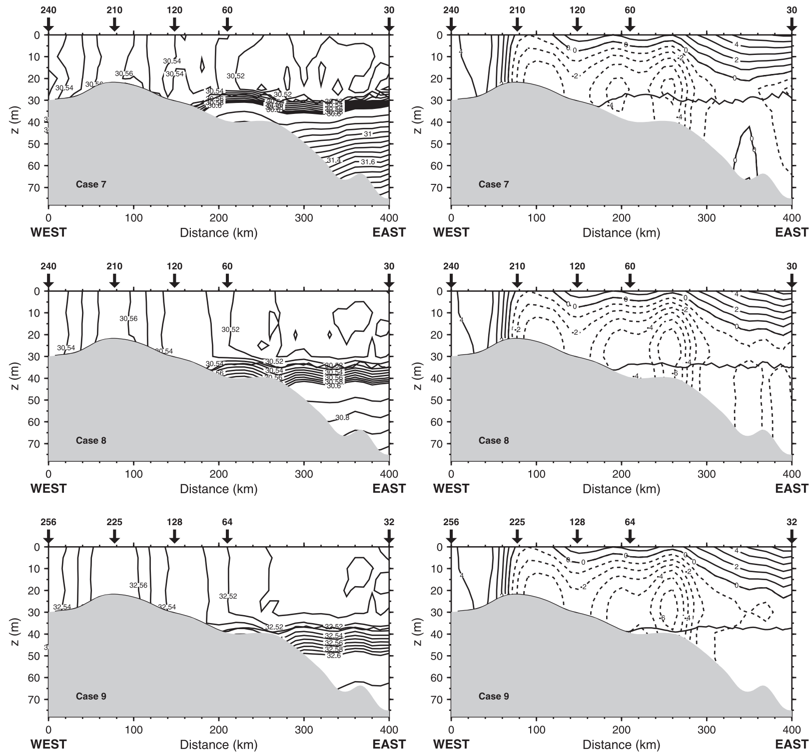

Figure 13. Snapshots of salinity and the *v* velocity component (offshore positive/onshore negative) for a transect parallel to the coast (~85 km from shore). The transect goes through the center of the polynya where the salt production reached a maximum on 17 February 1997. The salinity (left panels) and *v* velocity component (right panels) are shown for cases 7 (top tier), 8 (middle tier), and 9 (bottom tier). The salinity contour intervals for cases 7 and 8 are 0.01 for $S < 30.6$ and 0.1 for $S \geq 30.6$. For case 9, for which the initial mixed layer salinity is 32.5, the contour interval is 0.01 for $S < 32.6$ and 0.1 for $S \geq 32.6$. The salt production at the time of the snapshot (17 February 1997) is indicated by the black arrows at the surface along the transect in units of 10^6 kg d^{-1} pixels^{-1}. The thick line is the mixed layer depth.

penetration depth of the salt produced by the polynya is shown by the thick lines representing the mixed layer depth. As was shown in Figure 13, the mixed layer depth increases progressively from case 7 to case 9. The mixed layer for case 7 is the shallowest, with values ranging from 20 to 35 m. In contrast, the mixed layer depths for case 9 range from 30 to 55 m. The vertical mixing timescale, defined as MLD^2/K_v, is much smaller than the horizontal advection timescale, defined as L/U, where L is the alongshore distance and U is the coastal current velocity. Using typical values for these parameters, i.e., MLD = 30 m, K_v = 900 m^2 d^{-1}, L = 300 km (the approximate distance from the maximum polynya salt production in Figure 13 to the mouth of Barrow Canyon), and U = 15 km d^{-1} (~17 cm s^{-1}), the resulting timescales for vertical mixing and horizontal advection are 1 and 20 days, respectively. Therefore salt is mixed much more rapidly vertically than it is transported by the alongshore current. In addition, the mixed layer gets deeper with the weaker ambient vertical stratification, but the increase in mixed layer salinity is approximately the same; the end result is that more salt is retained on the shelf, as shown in Figure 9 and Table 1.

5. Summary and Conclusions

[40] Numerical experiments were conducted using a high-resolution (1–5 km) numerical model with bathymetry, ambient stratification, and ambient flow for the northeast Chukchi Sea. A total of nine numerical experiments were conducted to determine the effects of different combinations of model forcing on the salt transport, stratification, and circulation. The experiments were divided into two major categories, those conducted with time-averaged surface flux forcing and those conducted with time-varying flux forcing. Several forcing combinations were imposed under each of these two major categories. One experiment also included surface momentum forcing from ice water stresses.

[41] There are three main results from this study. First, we show that the inclusion of an ice water boundary layer in the model broadens the coastal current, thus increasing the offshore salt export from 36 to 73% of the total salt produced. Second, ambient stratification plays a major role in controlling the penetration depth of the salt produced by the polynyas. Previous modeling experiments have shown that with strong stratification, dense water is transported across the shelf break at intermediate depths (to ~150 m) [*Gawarkiewicz*, 2000]. In contrast, our results show that the dense water produced was transported from the polynya generation area at much shallower depths (~40–60 m). As noted by *Gawarkiewicz* [2000], the stratifications considered in his study where not as strong as that of the Arctic Ocean, which may explain in part the difference in penetration depth. The summer-fall melting produces a shallow

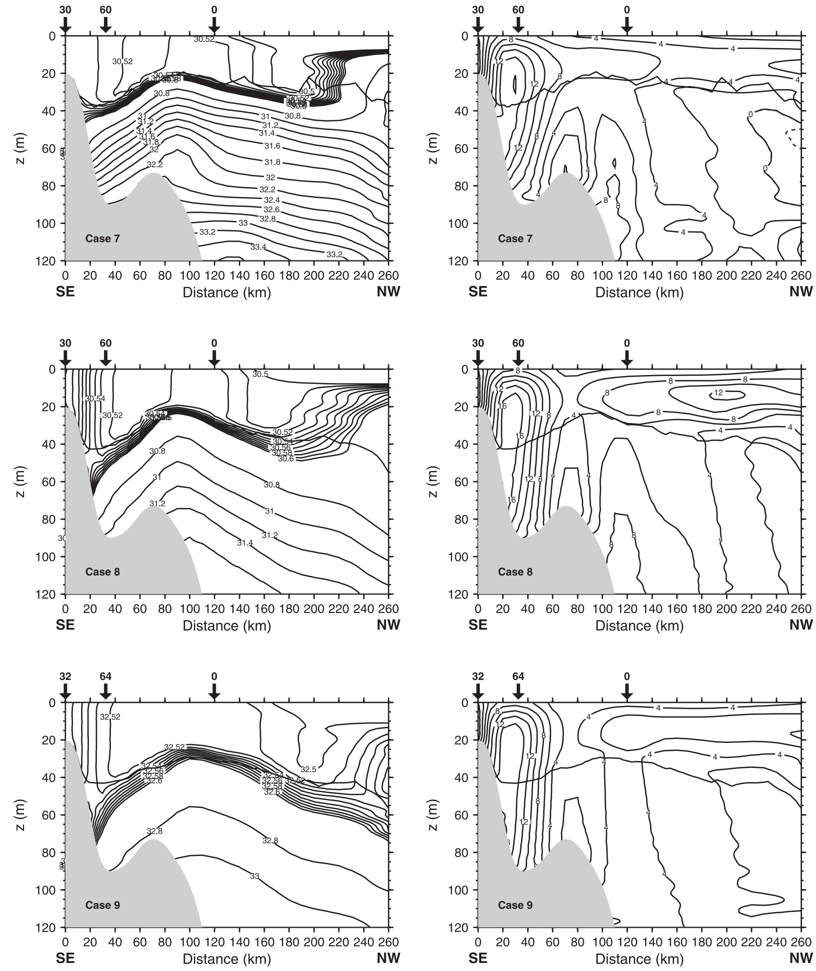

Figure 14. Snapshots of salinity and the *u* velocity component (positive eastward) for the easternmost Barrow Canyon transect. The transect goes across the downstream end of the on 17 February 1997, when the polynya center upstream from the transect reached a maximum salt production. The salinity (left panels) and *u* velocity component (right panels) are shown for cases 7 (top tier), 8 (middle tier), and 9 (bottom tier). The salinity contour intervals for cases 7 and 8 are 0.01 for $S < 30.6$ and 0.1 for $S \geq 30.6$. For case 9, for which the initial mixed layer salinity is 32.5, the contour interval is 0.01 for $S < 32.6$ and 0.1 for $S \geq 32.6$. The velocity contour interval is 5 cm s^{-1}. The salt production at the time of the snapshot (17 February 1997) is indicated by the black arrows at the surface along the transect in units of 10^6 kg d^{-1} $pixels^{-1}$. The thick line is the mixed layer depth.

($\sim$30 m) halocline in the Chukchi Sea, which provides a barrier layer for the vertical mixing of polynya-generated saltier water in the winter. During the polynya events of 1996/1997 the brine rejection did not produce water densities sufficiently high enough to erode the shallow halocline barrier layer. The only exception was the shallow ($\leq$30 m) areas of the northeastern Chukchi Sea where bottom boundary turbulence and lateral stresses from the swift Alaska coastal current produce intense mixing. Third, we also show that the alongshore coastal current significantly increases the salt transported away from the polynya from 6 to 26% for the 17 December 1996 to 7 January 1997 period. We also find that the transport is larger for a steady current than with a time-varying current with the same mean transport (0.25 Sv). The time-varying northeastward coastal current, combined with the offshore Ekman transport, was found to export 29% (with weak stratification) and 73% (with strong stratification) of the salt produced by polynyas upstream of Barrow Canyon after 26 days for the 28 January to 28 February 1997 period.

[42] The results presented in this paper for the 1996/1997 winter season do not reflect the salt production events observed by others for different years. For example, during the winter of 1991/1992, daily salt rejection from polynyas in the vicinity of Barrow Canyon peaked at $\sim$40–50 $\times$ 10^9 kg [*Weingartner et al.*, 1998], a value 5 times larger than the peak daily salt rejection encountered in this study. *Weingartner et al.* [1998] reported salinities >34 upstream of Barrow Canyon. Even higher salinities were found by *Aagaard et al.* [1985] during winter 1982 in a section seaward from Point Lay, where salinities within $\sim$20 km of the coast exceeded 36.5, and the 35 isohaline extended seaward at least 40 km in a near-bottom layer. These observational studies suggest a very large interannual variability in ice and salt production, a characteristic noted in the more recent modeling work of *Winsor and Björk* [2000].

Given this large interannual variability, we plan to extend the Chukchi Shelf modeling effort to other years for the purpose of capturing a more complete range of forcing conditions.

[43] **Acknowledgments.** We are thankful to J. Humphreys of SAIC General Sciences Corporation and X. Zhang of Science Systems and Applications, Inc. for providing the heat and salt fluxes derived from SSM/I data. We are also thankful to A. Liu of the NASA-GSFC Laboratory for Hydrospheric Processes and Y. Zhao of CAELUM for providing the ice drift data derived from SSM/I and NSCAT data. This work was sponsored by the Office of Naval Research under contract N00014-98-C-0022 MOD P00003 and NASA's Cryospheric Sciences Research Program. The SSM/I radiances were obtained from NSIDC.

References

Aagaard, K., and E. Carmack, The Arctic Ocean and climate: A perspective, in *The Polar Oceans and Their Role in Shaping the Global Environment*, *Geophys. Monogr. Ser.*, vol. 85, edited by O. M. Johannessen et al., pp. 5–20, AGU, Washington D. C., 1994.

Aagaard, K., L. K. Coachman, and E. C. Carmack, On the halocline of the Arctic Ocean, *Deep Sea Res.*, *29*, 529–545, 1981.

Aagaard, K., A. T. Roach, and J. D. Schumacher, On the wind-driven variability of the flow through Bering Strait, *J. Geophys. Res.*, *90*, 7213–7221, 1985.

Björk, G., A one-dimensional time-dependent model for the vertical stratification of the upper Arctic Ocean, *J. Phys. Oceanogr.*, *19*, 52–67, 1989.

Cavalieri, D. J., A microwave technique for mapping thin ice, *J. Geophys. Res.*, *99*, 12,561–12,572, 1994.

Cavalieri, D. J., and S. Martin, The contribution of Alaskan, Siberian, and Canadian coastal polynyas to the cold halocline layer of the Arctic Ocean, *J. Geophys. Res.*, *99*, 18,343–18,362, 1994.

Chapman, D. C., Dense water formation beneath a time-dependent coastal polynya, *J. Phys. Oceanogr.*, *29*, 807–820, 1999.

Chapman, D. C., The influence of an alongshelf current on the formation and offshore transport of dense water from a coastal polynya, *J. Geophys. Res.*, *105*, 24,007–24,019, 2000.

Chapman, D. C., and G. Gawarkiewicz, Offshore transport of dense shelf water in the presence of a submarine canyon, *J. Geophys. Res.*, *100*, 13,373–13,387, 1995.

Coachman, L. K., and K. Aagaard, On the water exchange through Bering Strait, *Limnol. Oceanogr.*, *11*, 44–59, 1966.

Coachman, L. K., and K. Aagaard, Transports through Bering Strait: Annual and interannual variability, *J. Geophys. Res.*, *93*, 15,535–15,539, 1988.

Coachman, L. K., and C. A. Barnes, The contribution of Bering Sea water to the Arctic Ocean, *Arctic*, *14*, 147–161, 1961.

Coachman, L. K., K. Aagaard, and R. B. Tripp, *Bering Strait: The Regional Physical Oceanography*, 172 pp., Univ. of Washington Press, Seattle, Wash., 1975.

Eby, M., and G. Holloway, Sensitivity of a large scale ocean model to a parameterization of topographic stress, *J. Phys. Oceanogr.*, *24*, 2577–2588, 1994.

Gawarkiewicz, G., Effects of ambient stratification and shelf break topography on offshore transport of dense water on continental shelves, *J. Geophys. Res.*, *105*, 3307–3324, 2000.

Gawarkiewicz, G., and D. C. Chapman, A numerical study of dense water formation and transport on a shallow, sloping continental shelf, *J. Geophys. Res.*, *100*, 4489–4507, 1995.

Hibler, W. D., III, A dynamic thermodynamic sea ice model, *J. Phys. Oceanogr.*, *9*, 815–846, 1979.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Killworth, P. D., and J. M. Smith, A one-and-a-half dimensional model for the Arctic halocline, *Deep Sea Res.*, *31*, 271–293, 1984.

Liu, A. K., and D. J. Cavalieri, On sea ice drift from the wavelet analysis of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) Data, *Int. J. Remote Sensing*, *19*, 1415–1423, 1998.

Liu, A. K., Y. Zhao, and S. Y. Wu, Arctic sea ice drift from wavelet analysis of NSCAT and special sensor microwave imager data, *J. Geophys. Res.*, *104*, 11,529–11,538, 1999.

Martin, S., and P. Kaufman, A field and laboratory study of wave damping by grease ice, *J. Glaciol.*, *27*, 283–314, 1981.

Martin, S., R. Drucker, and K. Yamashita, The production of ice and dense shelf water in the Okhotsk Sea polynyas, *J. Geophys. Res.*, *102*, 27,771–27,782, 1998.

Millero, F. L., Freezing point of sea water, 8th report of the Joint Panel of Oceanographic Tables and Standards, Appendix 6, *UNESCO Tech. Pap. Mar. Sci.*, *28*, 29–31, 1975.

Münchow, A., and E. C. Carmack, Synoptic flow and density observations near an Arctic shelf break, *J. Phys. Oceanogr.*, *27*, 1402–1419, 1997.

Overland, J. E., and C. H. Pease, Modeling ice dynamics of coastal seas, *J. Geophys. Res.*, *93*, 15,619–15,637, 1988.

Pacanowski, R. C., and G. H. Philander, Parameterization of vertical mixing in numerical models of tropical oceans, *J. Phys. Oceanogr.*, *11*, 1443–1451, 1981.

Roach, A. T., K. Aagaard, C. H. Pease, S. A. Salo, T. Weingartner, V. Pavlov, and M. Kulakov, Direct measurements of transport and water properties through the Bering Strait, *J. Geophys. Res.*, *100*, 18,443–18,457, 1995.

Signorini, S. R., A. Münchow, and D. Haidvogel, Flow dynamics of a wide Arctic canyon, *J. Geophys. Res.*, *102*, 18,661–18,680, 1997.

Song, Y., and D. Haidvogel, A semi-implicit ocean circulation model using a generalized topography-following coordinate system, *J. Comp. Phys.*, *115*, 228–244, 1994.

Steele, M., R. Morley, and W. Ermold, PHC: A global hydrography with a high quality Arctic Ocean, *J. Clim.*, *14*, 2079–2087, 2001.

Stigebrandt, A., The North Pacific: A global scale estuary, *J. Phys. Oceanogr.*, *14*, 464–470, 1984.

Weingartner, T. J., D. J. Cavalieri, K. Aagard, and Y. Sasaki, Circulation, dense water formation, and outflow on the northeast Chukchi shelf, *J. Geophys. Res.*, *103*, 7647–7661, 1998.

Winsor, P., and G. Björk, Polynya activity in the Arctic Ocean from 1958 to 1997, *J. Geophys. Res.*, *105*, 8789–8803, 2000.

D. Cavalieri, Code 971, Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (don@cavalieri.gsfc.nasa.gov)

S. R. Signorini, Science Applications International Corporation, 4600 Powder Mill Road, Beltsville, MD 20705-2675, USA. (sergio@bluefin.gsfc.nasa.gov)