J1.10 ATMOSPHERIC FORCING OF THE ROSS SEA POLYNYA DURING SUMMER

David H. Bromwich*, Andrew J. Monaghan, Aric N. Rogers
Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, Columbus, Ohio

Michael L. Van Woert
NOAA/NESDIS Office of Research and Applications, Camp Springs, Maryland

Kevin R. Arrigo
Department of Geophysics, Stanford University, Stanford California

1. INTRODUCTION

Literature in recent years has stressed the significance of polynyas. Brine rejected by the production of ice in polynyas contributes to the formation of Antarctic Bottom Water, and is thought to effect ocean circulation on a global scale (e.g. Gordon and Comiso, 1988). This has generated research into the physical processes that control the size and distribution of these phenomena. Several one-dimensional, wind-driven coastal polynya models examine the wintertime behavior of polynyas with some success (Pease, 1987; Ou, 1988; Darby et al., 1995; Van Woert, 1999). *Gallee* (1997) and *Dare et al*, (1999) couple polynya and atmospheric models, distinguishing the unique atmospheric conditions that exist as a result of open water adjacent to land and sea ice. Other (non-modeling) work investigating the relation of polynyas to atmospheric and oceanographic forcing includes *Kurtz and Bromwich* (1985), *Cavalieri and Martin* (1985), *Zwally et al.* (1985), *Bromwich et al.* (1998), and *Jacobs and Comiso* (1989).

The impact of polynyas is thought to be greatest in winter due to increased heat loss between the ocean and atmosphere. In the case of latent heat (wind-driven) polynyas, this creates an ideal environment for large-scale ice production. Strong offshore winds cause evaporative heat loss to the atmosphere, and ice forms as a result. The winds remove the ice, and the cycle repeats. The brine rejected by the production of huge quantities of ice contributes significantly to the density of surface and underlying water masses (Gordon and Comiso, 1988; Zwally et al, 1985).

This is one reason studies and modeling efforts to date have concentrated mainly on winter months. Another is the simplification of winter conditions. The input of shortwave energy from the sun can be neglected (this is a difficult term to estimate due to the lack of quality cloud cover data in the high latitudes). Furthermore, terms for the melting of edge and frazil ice (processes that are not fully understood) can be neglected in winter. However, understanding the *year-round* behavior and climatic/oceanographic impacts of polynyas is essential to the improvement of modeling efforts. For example, the spatial extent of the Ross Sea (RS) Polynya is greater during the spring/summer seasons than winter (Fig. 1). This is expected, as increased shortwave radiation and higher temperatures occur in summer and inhibit the production of ice.

* Corresponding Author Address: David H. Bromwich, Polar Meteorology Group, Byrd Polar Research Center, The Ohio State University, 1090 Carmack Road, 108 Scott Hall, Columbus, OH 43210-1002; e-mail: bromwich@polarmet1.mps.ohio-state.edu

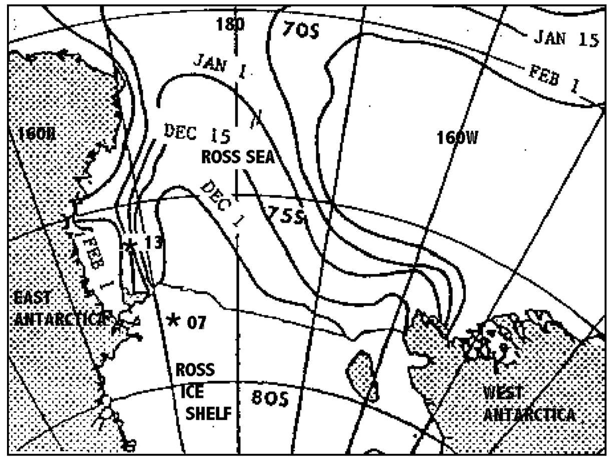

Figure 1. Area where RS Polynya usually forms. Curves labeled with dates indicate typical progression of RS polynya expansion through the summer. Asterisks are used to indicate the position of Ferrell (07) and Whitlock (13) AWS. Adapted from *Naval Polar Oceanography Center* (1987), and *Rogers et al* (1999).

Therefore, as a part of the ROAVERRS (Research on Ocean-Atmosphere Variability and Ecosystem Response in the Ross Sea) program, the spring and summer dynamics of the RS Polynya are investigated. Located to the to the east of Ross Island approximately between 170° E and 170° W, this polynya is bounded to the south by the Ross Ice Shelf (RIS). *Rogers et al*. (1999) examined the springtime opening conditions surrounding the RS. This study is an extension of that work into the summer months. A simple, one-dimensional, wind-driven coastal polynya model is used to examine the forcing of the RS Polynya in summer.

2. THE MODEL

The one-dimensional coastal polynya model used in this study is adapted from the models of *Pease* (1987), *Ou* (1988), *Darby* (1995), and *Van Woert* (1999). Assuming that the frazil ice drifts downwind much faster than the polynya expands, the state of a polynya with respect to time is (Pease, 1987),

$$\mathrm{U_i}(t) = \frac{\mathrm{DL}(t)}{\mathrm{D}t} + \frac{\mathrm{PL}(t)}{\mathrm{H_i}} \tag{1}$$

where $U_i(t)$ is the ice drift velocity, $L(t)$ is width of the polynya, P is the ice production rate, and H_i is the frazil ice collection depth. The value of U_i is generally taken as 3% of the 10 m wind speed (U_{10}) (e.g. Martinson and

Wamser, 1990; Van Woert, 1999). In this model U_{10} is a function of prevailing wind direction at Ferrell AWS (~195°), and is given by,

$$U_{10} = -V_{10}\cos(\theta - 15°) \tag{2}$$

where V_{10} is the wind speed at Ferrell AWS, after modifying from 3 m to 10 m and reflecting a decrease in surface roughness over open water, and θ is the wind direction at Ferrell AWS. Generally, V_{10} is greater than the 3 m wind speed at Ferrell by about 1.5. Equation (2) allows for a wind contribution based on how near to the prevailing SSW wind the actual wind direction is. Note that northerly winds in this equation cause U_{10} to become negative, contributing to a lessening of the polynya width given in (1).

The ice production rate is (Pease, 1987),

$$P = \frac{Q_{net}}{L_f \rho_i} \tag{3}$$

where Q_{net} is the net upward heat flux, L_f is the latent heat of fusion (3.34 X 10^5 J/kg) and ρ_i is the ice density (950 kg/m^3). Q_{net} is given by,

$$Q_{net} = Q_{lw} + Q_{sw} + Q_{le} + Q_s \tag{4}$$

where Q_{lw} is the longwave radiation, Q_{sw} is the shortwave radiation, Q_{le} is the latent (evaporative) heat flux, and Q_s is the sensible heat flux. All fluxes are positive upward. Q_{sw} is estimated based on the solar constant and the position of the earth with respect to the sun (Allen et al., 1998). Cloud cover observations are considered in the calculation of Q_{lw} and Q_{sw}. For the purpose of brevity, the heat flux terms will not be elaborated on in this text.

3. INPUT DATA

Data from Ferrell AWS (77.93° S, 170.82° E) are used as model input. Ferrell AWS is chosen for its proximity to the RS Polynya, as well as the consistent southerly winds recorded there. These winds are thought to have a major controlling impact on the behavior of the RS Polynya (Bromwich et al., 1998; Rogers et al., 1999). In addition to the data at Ferrell, cloud cover data is taken from observations at McMurdo and multiplied by a factor of 1.2 to account for the increase in cloud amount over open water.

The period chosen for the model run spans Winter 1993 through Winter 1998. These years have good data continuity and capture five consecutive melt seasons. In general, more than 90% of the possible data is available for each month during this time. Furthermore, this period captures interannual variability in weather parameters and polynya size, especially during the weak La Nina (1996-97) and strong El Nino (1997-98) years (Ledley et al., 1997; Bromwich et al., 2000).

It is appropriate to discuss the effectiveness of Ferrell AWS in representing the wind and temperature conditions over the RS Polynya. Indeed, when the extent is not far from the face of the Ross Ice Shelf, the winds over the polynya may be similar to those at Ferrell AWS. However, with northward expansion in summer (Fig. 1), there is most likely significant spatial variability in wind speed and direction over the polynya. Additionally, strong temperature gradients exist between the continentality of the Ross Ice Shelf and the maritime conditions over the polynya. Therefore, when using Ferrell AWS (or any single-point data) to predict the extent of the RS Polynya, it should be considered that a decrease in both temporal and spatial accuracy of the model will occur as the polynya expands.

In the future, the model will be driven by gridded output from the Polar MM5, a hybrid version of the Pennsylvania State / NCAR Mesoscale Model 5, modified to represent parameterizations over extensive ice sheets (Bromwich et al., 2001). It is anticipated that these data will better capture the variable conditions that result as the polynya grows. In addition, this data should represent the maritime setting present over the polynya.

4. MODEL VERIFICATION

Special Sensor Microwave Imager (SSM/I) passive microwave satellite data is used as a means of comparing modeled output to actual ice conditions in the Ross Sea. The surface area of the RS polynya is calculated in the area bounded by 165° E to 140° W, 70°S to the Ross Ice Shelf (around 78° S). The satellite information is processed via the "NASA TEAM" algorithm (Gloerson and Cavalieri, 1986). This algorithm uses the 19 and 37 gigahertz (GHz) vertical and 19 GHz horizontal polarization data. In order to calculate the size of the RS polynya (which is generally indicative of the total open water area of the domain defined above), the processed microwave satellite data are projected onto a latitude/longitude grid and pixels of the grid are then classified according to the percentage of sea ice each contains. In this study, we use pixels that are classified as having zero percent ice cover for the purpose of gauging the springtime expansion of the RS polynya.

Due to limitations, the satellite derived *width* of the polynya cannot be calculated with this particular version of data. Therefore, the SSM/I derived polynya size is based on ice-free *area*, whereas the modeled output is based on *width*. For the purpose of comparison, it is assumed that the area of the polynya remains proportional to the width. The Byrd Polar Research Center has just obtained an updated version of the SSM/I data that will enable the explicit measurement of the RS Polynya width. A comparison using these results will be published at a later date.

5. RESULTS

Figure 2 shows a plot of the modeled RS Polynya width vs. the SSM/I derived ice-free area for Winter 1993 through Winter 1998. Two variables are used to compare the curves: *interannual variability* and *timing* (lag). A comparison of the magnitude of the curves is not given at this phase of the study, as it is impractical to associate the modeled width (one-dimensional) with the satellite-derived area (two-dimensional).

***Interannual variability*:** According to the satellite analysis, there is little interannual variability in ice coverage in the first three seasons of the study. However, the modeled data suggest otherwise - a large difference is observed between these three years. The final two years of modeling (1996-97 and 1997-98 – coincidentally La Nina and El Nino years) compare reasonably with the SSM/I derived data. Using these two seasons as a gauge, the modeled 1994-95 season also reasonably captures interannual variation. This leaves the 1993-94 (1st year – too low) and 1995-96 (3rd year - too high) unexplained by the model.

On the low model-predicted 1993-94 season: An examination of monthly averaged data at Ferrell AWS (not shown), indicates the December 1993 average temperatures are the lowest of the period (~2C^{o} lower). This would increase the upward heat loss, Q_{net} (4), extending ice production (3) into the summer. Wind speeds are also lower in November and December 1993 when compared to other melt seasons. This would contribute directly to lower outward edge velocity caused by southerly winds (1). In January 1994, the winds are further reduced by an average departure of 30 degrees from the prevailing wind direction (195°), the largest departure seen in any of the years. This would lessen wind speed from that at 195^{o} by about 13%, as given in (2). These three factors may contribute to the low model prediction in 1993-94. However, as discussed in Section 3, the more likely cause of difference is due to the use of a single AWS site to represent conditions that cover a large spatial area.

On the high model-predicted 1995-96 season: Winds in 1995-96 are generally higher when compared to the other years. This leads to greater outward edge velocity, perhaps over-predicting polynya expansion. Again however, the use of one site to represent a large region is the most likely source of discrepancy. Also, as mentioned in Section 4, the SSM/I data currently used covers the entire Ross Sea, not just the RS Polynya. All of this poses the question: does the model perform deficiently in these two seasons, or are atmospheric conditions near the RS Polynya during these years much different from the rest of the Ross Sea? Hopefully, this will be answered in the near future when 1) satellite-derived polynya widths are explicitly measured and compared to the modeled widths, and 2) the Polar MM5 output is used to drive the model.

Timing-upward leg: The temporal offset of the spring/summer polynya expansion (upward leg in Fig. 2) in relation to the SSM/I (lagging) data may be partly explained by the coarse data resolution of the SSM/I data. Only pixels that are 100% ice free are used to determine polynya size, and therefore a large percentage of open water may exist early in the melt season that is not accounted for in the SSM/I data. However, as the season progresses, the error introduced by not including these pixels becomes insignificant with respect to polynya size. Another explanation may be that the winds at Ferrell AWS, while capturing the opening conditions satisfactorily, are too strong to represent the polynya once it expands northward.

Timing-downward leg: The temporal offset of the autumn polynya contraction (downward leg in Fig. 2) when compared with the SSM/I data is most likely due to the lack of oceanic heat storage in the model. In the future, a heat loss term will be added in an attempt to improve the downward leg. However, this is a fairly complicated, 3-dimensional mechanism, that may be difficult to account for realistically in a model of this simplicity.

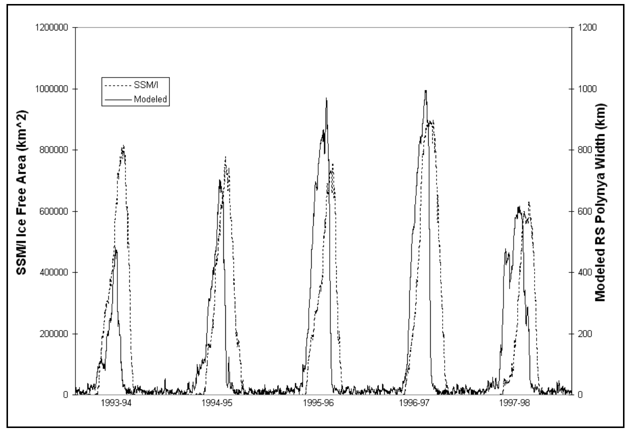

Figure 2. Modeled RS Polynya width vs. SSM/I derived ice-free area.

6. CONCLUSIONS

This summary provides an overview of progress to date. In the future we plan to:

1) Better assess the model performance by explicitly measuring the polynya width using satellite-derived data
2) Perform simulations using data derived from the Polar MM5, a mesoscale model developed for use over extensive ice sheets. These data may better capture conditions over open water which are not explained by AWS data.
3) Determine what mechanisms force the dynamics of the Ross Sea Polynya during summer.

7. ACKNOWLEDGMENTS

This research is supported by the National Science Foundation under grant OPP-9420681. We would like to thank Jodi Humphreys from the Goddard Space Flight Center of the National Aeronautics and Space Administration for supplying the processed RS polynya data. Thanks also to Raytheon Polar Services for providing cloud cover observations from McMurdo.

8. REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, M. Smith, 1998: *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and Drainage paper 56*, 300 pp., Food and Agriculture Organization of the United Nations, Rome.

Bromwich, D. H., Z. Liu, A. N. Rogers, and M. L. Van Woert, 1998: Winter atmospheric forcing of the Ross Sea Polynya, in *Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin, Antarct. Res. Ser.*, **75**, edited by S. S. Jacobs and R. F. Weiss, pp. 101-133, AGU, Washington, D. C.

Bromwich, D. H., A. N. Rogers, P. Kallberg, R. I. Cullather, J. W. C. White, K. J. Kreutz, 2000: ECMWF Analyses and Reanalyses depiction of ENSO signal in Antarctic precipitation, *J. of Clim.*, **13**, 1406-1420.

Bromwich, D. H., J. J. Cassano, T. Klein, G. Heinemann,

K. M. Hines, K. Steffen, and J. E. Box, 2001: Mesoscale modeling of katabatic winds over Greenland with the Polar MM5, *Mon. Wea. Rev*., accepted.

Cavalieri, D. J., and S. Martin, 1985: A passive microwave study of polynyas along the Antarctic Wilkes Land Coast, *in Oceanology of the Antarctic Continental Shelf, Antarct. Res. Ser.*, **43**, edited by S. S. Jacobs, pp. 177-201, AGU, Washington, D.C.

Darby, M. S., A. J. Willmott, and T. A. Somerville, 1995: On the influence of coastline orientation on the steady state width of a latent heat polynya*, J. Geophys. Res.*, **100**, 13625-13633.

Dare, R. A., and B. W. Atkinson, 1999: Numerical modeling of atmospheric response to polynyas in the Southern Ocean sea ice zone, J. Geophys. Res., **104**(D14), 16,691-16,708.

Gallee, H., 1997: Air-sea interactions over Terra Nova Bay during winter: Simulation with a coupled atmosphere-polynya model, *J. Geophys. Res*., **102**, 13835-13849.

Gloersen, P., and D. J. Cavalieri, 1986: Reduction of weather effects in the calculation of sea ice concentration from microwave radiances, *J. Geophys. Res*., **91**, 3913-3919.

Gordon, A. L., 1981: Seasonality of southern ocean sea ice, *J. Geophys. Res*., **86**(C5), 4193-4197.

Gordon, A. L., and J. C. Comiso, 1988: Polynyas in the southern ocean, *Sci. Am.*, **258**(6), 90-97.

Jacobs, S. S., and J. C. Comiso, 1989: Sea ice processes on the Ross Sea Continental Shelf, *J. Geophys. Res*., **94**, 18195-18211.

Kurtz, D. D., and D. H. Bromwich, 1985: A recurring, atmospherically forced polynya in Terra Nova Bay, *in Oceanology of the Antarctic Continental Shelf, Antarct. Res. Ser.*, **43**, edited by S. S. Jacobs, pp. 177-201, AGU, Washington, D.C.

Ledley, T. S., and Z. Huang, 1997: A possible ENSO signal in the Ross Sea, *Geophys. Res. Lett*., **24**, 3253-3256.

Martinson, D. G., and C. Wamser, 1990: Ice drift and momentum exchange in winter Antarctic pack ice, *J. Geophys. Res*., **95**, 1741-1755.

Naval Polar Oceanography Center, 1987: U.S. Navy-NOAA joint ice center seasonal outlook western Ross Sea and McMurdo Sound, 7pp. [Available from Commanding Officer, Naval Polar Oceanography Center, Navy Department, 4301 Suitland Road, Washington, DC 20390.]

Ou, H. W., 1988: A time-dependent model of a coastal polynya, *J. Phys. Oceanogr*., **18**, 584-590.

Pease, C. H., 1987: The size of wind-driven coastal polynyas, *J. Geophys. Res*., **92**, 7049-7059.

Rogers, A. N., D. H. Bromwich, and K. Arrigo, 1999: Atmospheric forcing of the Ross Sea Polynya during spring, *5th Conference on Polar Meteorology and Oceanography*, 10-15 January 1999, American Meteorological Society, Boston, USA, 448-451.

Van Woert, M. L., 1999: Wintertime dynamics of the Terra Nova Bay polynya*, J. Geophys. Res.*, **104**(C4), 7753-7769.

Zwally, H. J., J. C. Comiso, and A. L. Gordon, 1985: Antarctic offshore leads and polynyas and oceanographic effects, in *Oceanology of the Antarctic Continental Shelf, Antarct. Res. Ser.*, **43**, edited by S. S. Jacobs, pp. 203-226, AGU, Washington, D. C.