Summer retreat of Arctic sea ice: Role of summer winds

Masayo Ogi,[1,2] Ignatius G. Rigor,[1,3] Miles G. McPhee,[4] and John M. Wallace[5]

[1] The unprecedented retreat of first-year ice during summer 2007 was enhanced by strong poleward drift over the western Arctic induced by anomalously high sea-level pressure (SLP) over the Beaufort Sea that persisted throughout much of the summer. Comparison of the tracks of drifting buoys with monthly mean SLP charts shows a substantial Ekman drift. By means of linear regression analysis it is shown that Ekman drift during summer has played an important role in regulating annual minimum Arctic sea-ice extent in prior years as well. In combination, the preconditioning by events in prior years, as represented by an index of May multi-year ice, and current atmospheric conditions, as represented by an index of July–August–September SLP anomalies over the Arctic basin account for ~60% of the year-to-year variance of September sea-ice extent since 1979. **Citation:** Ogi, M., I. G. Rigor, M. G. McPhee, and J. M. Wallace (2008), Summer retreat of Arctic sea ice: Role of summer winds, *Geophys. Res. Lett.*, *35*, L24701, doi:10.1029/2008GL035672.

1. Introduction

[2] Sea ice extent (SIE) in the Arctic Ocean reached record low levels in September 2007, following upon previous record lows in September 2002 [*Serreze et al.*, 2003; *Stroeve et al.*, 2005], and a near record low in 2005. Factors that may have contributed to the record low in 2007 can be grouped into two categories: those that contributed to reducing the thickness of the ice at the beginning of the melt season, hereafter referred to collectively as *preconditioning*, and anomalous atmospheric conditions during the summer of 2007 that might have enhanced the retreat of the ice edge beyond what would have been expected, given the thickness distribution at the beginning of the melt season. Discussion of putative causes of year-to-year variations in September SIE during prior years can be framed in a similar manner. Here we assess the role of anomalous summer wind patterns over the Arctic in enhancing the retreat of the ice edge in 2007 and, more generally, as a factor that contributes to year-to-year variability in September SIE.

[3] *Ogi and Wallace* [2007] (hereinafter referred to as OW) showed that summer (July–August–September (JAS)) sea-level pressure (SLP) over the Arctic is signifi-

cantly correlated with detrended September SIE: positive SLP anomalies over the Arctic during JAS, indicative of anticyclonic surface wind anomalies, favor anomalously low September SIE. OW interpreted this result as indicating that anticyclonic circulation anomalies should induce an anomalous Ekman drift of the sea-ice toward the central Arctic, which would increase the areal coverage of open water over the marginal seas and thereby reduce the SIE over the Arctic Ocean as a whole.

[4] The mechanism proposed by OW requires a right-ward Ekman drift of the ice relative to the geostrophic wind. Although it has been well established since Nansen's observations [*Ekman*, 1905] that Arctic pack ice drifts to the right of surface wind, it has also often been observed that drifting buoys tend to follow atmospheric isobars [see, e.g., *Colony and Rigor*, 1993], particularly when responding to anticyclonic winds during winter. Newly processed measurements from the Advanced Satellite Microwave Radiometer (AMSR) of the NASA Earth Observing System (EOS) [*Kwok*, 2008] also indicate that the summer ice motion during 2007 was closely aligned with the SLP isobars. On the other hand, a substantial Ekman drift to the right of the geostropic wind has been observed on some occasions in field measurements [see, e.g., *McPhee*, 1980; *Albright*, 1980] and in comparisons of buoy drifts with geostrophic winds [*Rigor et al.*, 2002; *Inoue and Kikuchi*, 2007].

[5] A critical element in the dynamical interpretation of Ekman drift is the requirement that the sea ice be in *free drift*; i.e., that the gradient of internal ice stress be negligible in the balance of forces acting on the ice pack. The cross-isobar flow in the direction of an inertia circle follows from elemental consideration of the three forces comprising the free-drift balance: wind stress on the surface, τ_a; water stress on the ice undersurface, τ_w; and the Coriolis force acting upon the ice column, $mf\mathbf{k} \times \mathbf{V}_{ice}$ where m is ice mass per unit area, f the Coriolis parameter, $\mathbf{k}$ the unit vector in the vertical (opposite to gravity) direction and $\mathbf{V}_{ice}$ ice velocity relative to the undisturbed ocean

$$\boldsymbol{\tau}_a - mf\mathbf{k} \times V_{ice} = \boldsymbol{\tau}_w$$

If the pack ice is thick and dense enough to support internal stresses, the rightward Coriolis force will be opposed by a leftward force exerted by the surrounding ice floes and the ice will drift in the direction of the geostrophic wind. It follows that ice may or may not tend to drift toward the center of an anomalous anticyclone in the SLP field, depending on whether it is in a state of free drift.

2. Role of Wind-Induced Drift in Summer 2007

[6] Here we show evidence of Ekman drift of sea ice during summer 2007 based on tracks of drifting buoys and

---
[1]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington, USA.
[2]Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan.
[3]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, Washington, USA.
[4]McPhee Research Company, Naches, Washington, USA.
[5]Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.
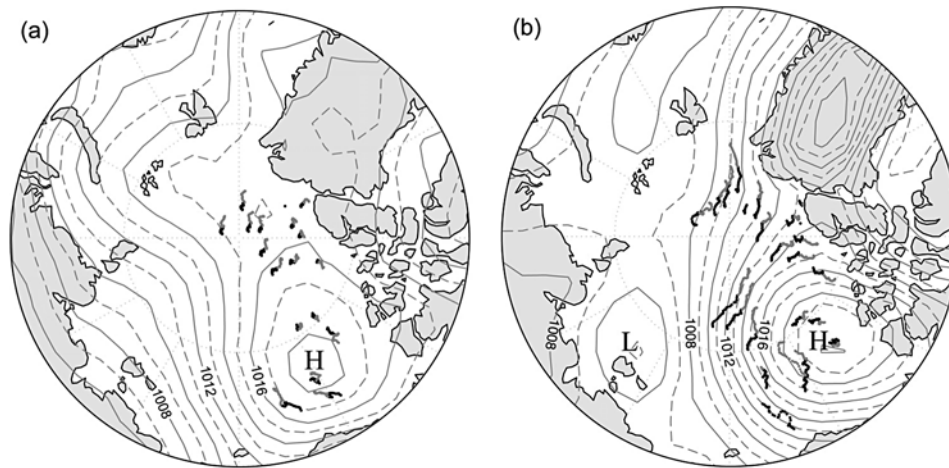
Figure 1. Mean sea-level pressure (contours) and tracks of International Arctic Buoy Programme (IABP) drifting buoys during summer 2007. (a) June–July; (b) August–September. The black segment of each buoy track corresponds to the first month and the gray segment to the second month.

we assess the contribution of the drift to the precipitous decline in the areal extent of ice over the summer. Figures 1a and 1b show buoy tracks superimposed on the mean SLP distribution for (*a*) early summer (June, July) and (*b*) late summer (August, September) 2007. Cross-isobar drift of the buoys is apparent in both periods, but the motions are stronger in late summer when the SLP gradients near the buoys are stronger (Figure 1b). Figures 2a and 2b show buoy tracks superimposed on the month-by-month position of the ice edge, as defined by the 15% ice concentration contour for early (June–July) and late (August–September) summer 2007. In this study ice concentration is based on the "bootstrap" ice concentration analysis described by *Comiso and Nishio* [2008] which combines Advanced Microwave Scanning Radiometer (AMSR-E) brightness temperatures, with brightness temperatures from the Special Scanning Microwave Imager and Scanning Multichannel Microwave Radiometer sensors that have been normalized to be consistent with AMSR-E. Comparing the buoy-inferred ice drift in late summer (Figure 2b) with the monthly positions of the ice edge, it is evident that it's was in the sense as to advect the ice northward in the Siberian sector, where the retreat of the ice edge was most rapid.

[7] To estimate the contribution of advection to the retreat of the sea ice edge, we selected a sea ice concentration isoline at the start of each month and estimated the drift of this line during the month using the gridded fields of ice motion based on buoy drift [*Rigor et al.*, 2002]. We then compared the areas bounded by this estimated shift of the isoline, with the observed sea ice extent line at the end of the month, which also includes retreat of the isoline due to melt. The estimated importance of advection depends somewhat upon the choice of ice concentration contour that is used to define the ice edge. For the 15% isoline, we find that advection accounts for about 10, 19, 25, 37% of the retreat for June, July, August, and September, respectively for the entire Pacific sector of the Arctic extending from $90°$ to $270°E$, whereas for the 50% isoline the corresponding contributions are 13, 21, 30 and 85%. The first set of estimates is similar to the results of *Kwok* [2008] who estimated a total contribution

of 15% for June through August using drifts inferred from AMSR-E retrievals.

3. Analysis of Data for Prior Years

[8] In this section we assess and compare the roles of preconditioning and atmospheric conditions during the concurrent summer as controls on September SIE (i.e., the 15% sea ice concentration contour) based on a statistical analysis of year-to-year variations from 1979 onward. To assess the role of preconditioning requires an estimate of the thickness distribution at the beginning of each year's melt season. For this purpose we use the ice age model described by *Rigor and Wallace* [2004], which estimates the age of the sea ice on an array of grid points with ∼50 km spacing based on the past history of the buoy motions together with the observed field of ice concentration in September of each year. For each month, the model provides fields of first year ice and multi-year ice. We use the areal coverage of
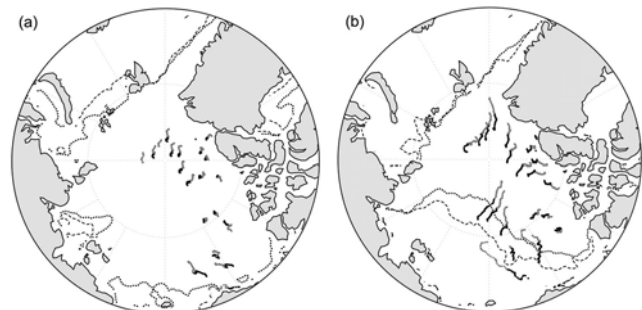

Figure 2. Monthly mean positions of the ice edge as defined by the 15% ice concentration, based on the bootstrap described by *Comiso and Nishio* [2008], as indicated by the dashed contours (first month) and dotted contours (second month) and tracks of IABP drifting buoys during summer 2007. (a) June–July; (b) August–September. The black segment of each buoy track corresponds to the first month and the gray segment to the second month.
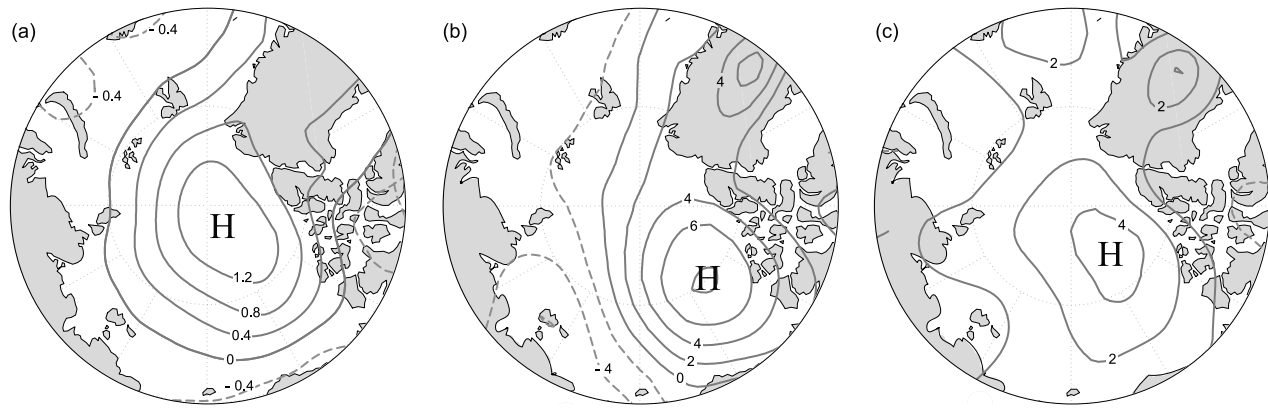
Figure 3. (a) Summer seasonal (July–August–September) mean SLP anomalies regressed on standardized index of May minus September sea ice extent over the Arctic basin as defined by the 15% ice concentration contour based on the period of record 1979–2006. (b) Summer seasonal (July–August–September) mean SLP anomalies for 2007. (c) Same as in Figure 3b but for 2008.

multi-year ice in May (henceforth referred to as May MYI) to represent the preconditioning of the ice by events in previous years. Concurrent summer conditions are represented by the July–August–September SLP field in the NCEP Reanalyses [*Kalnay et al.*, 1996].

[9] To obtain an annual index to represent the influence of the summertime SLP field on SIE, we used the following procedure:

[10] (1) At each grid point the time series of JAS-mean SLP is linearly regressed upon the time series of May minus September SIE for each calendar year (1979 – 2006). The regression coefficients are plotted in Figure 3a. The regression pattern resembles the JAS 2007 anomaly pattern shown in Figure 3b. Both are characterized by positive SLP anomalies, indicative of anticyclonic surface wind anomalies over the Arctic, which would produce Ekman drift of sea ice out of the marginal seas and into the central Arctic. The resemblance between the patterns in Figure 3 serves as a verification of the (1979–2006) regression pattern based on independent (2007) data.

[11] (2) The pattern of JAS-mean SLP anomalies for each year is projected onto the regression coefficient pattern obtained in step 1 (weighting each grid point by the cosine of latitude to ensure equal areal representation in the summation) to obtain a "score" for each year, a measure of how closely the SLP anomaly pattern for that year resembles the regression pattern in Figure 3a.

[12] The "score" for the jth year is given by $\Sigma P_{ij}R_i \cos \phi$, where P_{ij} is the JAS SLP anomaly at the ith grid point in the jth year, R_i is the regression coefficient derived in (1), ϕ is the latitude of the grid point, and the summation is carried out over all grid points poleward of 65°N.

[13] (3) The time series obtained in (2) is standardized.

[14] The resulting yearly SLP index is shown in Figure 4a, together with the time series of May minus September sea ice extent from which it was derived. The SLP index is a measure of the similarity between each year's SLP pattern and the regression pattern in Figure 3a. That the value of the SLP index for 2007 is the highest on record is notable, considering that 2007 data were not used in deriving the algorithm on which the index is based. The correlation coefficient between the time series of this SLP

index and May minus September SIE (1979–2007) is 0.72 ($p <$. 001 based on the Monte Carlo test described by OW).

[15] The procedure used in obtaining the SLP index was the same as employed by OW except that May minus September SIE was used as a reference time series (rather than inverted, detrended September SIE) based on the expectation that it should be less subject to the influence of preconditioning by events in prior years, and therefore more complementary to May MYI as a predictor of September SIE. Another advantage of using the May minus September time series rather than the September SIE time series is that it doesn't have such a strong linear trend and hence, its decorrelation time is shorter and it contains more statistical degrees of freedom. In this case, it was possible to perform the analysis without the detrending that was done by OW. The statistical significance of the correlation coefficient between the reference time series and the SLP index proved to be much higher than obtained by OW ($p <$. 001 versus $p < 0.08$).

[16] Having shown that JAS wind anomalies influence the evolution of SIE anomalies over the course of the summer, we will now consider the relative importance of the preconditioning of the ice pack, as reflected in the areal coverage of multi-year ice in May, versus JAS winds in determining year-to-year variations of September SIE. As a basis for this comparison, we develop a simple, linear, least squares best fit model that "predicts" September SIE each year from 1979 onward using May MYI and the JAS SLP index (Figure 4b) as linear "predictors"; i.e., $y = \alpha_1 \chi_1 + \alpha_2 \chi_2$ where y is predicted September SIE, χ_1 is May MYI, χ_2 is the JAS SLP index, and all three terms are expressed as anomalies about their respective time means for the 1979–2007 period of record. Strictly speaking, this is a "hindcast model" because JAS SLP is specified *a posteriori* on the basis of observations rather than predictions. The regression coefficients for May MYI and JAS SLP (i.e., α_1 and α_2) are 0.58 and −0.60 respectively. Time series of observed and hindcast September SIE are shown together in Figure 4c. The fact that the regression coefficients for May MYI and JAS SLP are nearly equal suggests that the preconditioning and summer atmospheric conditions lend roughly comparable levels of skill to the
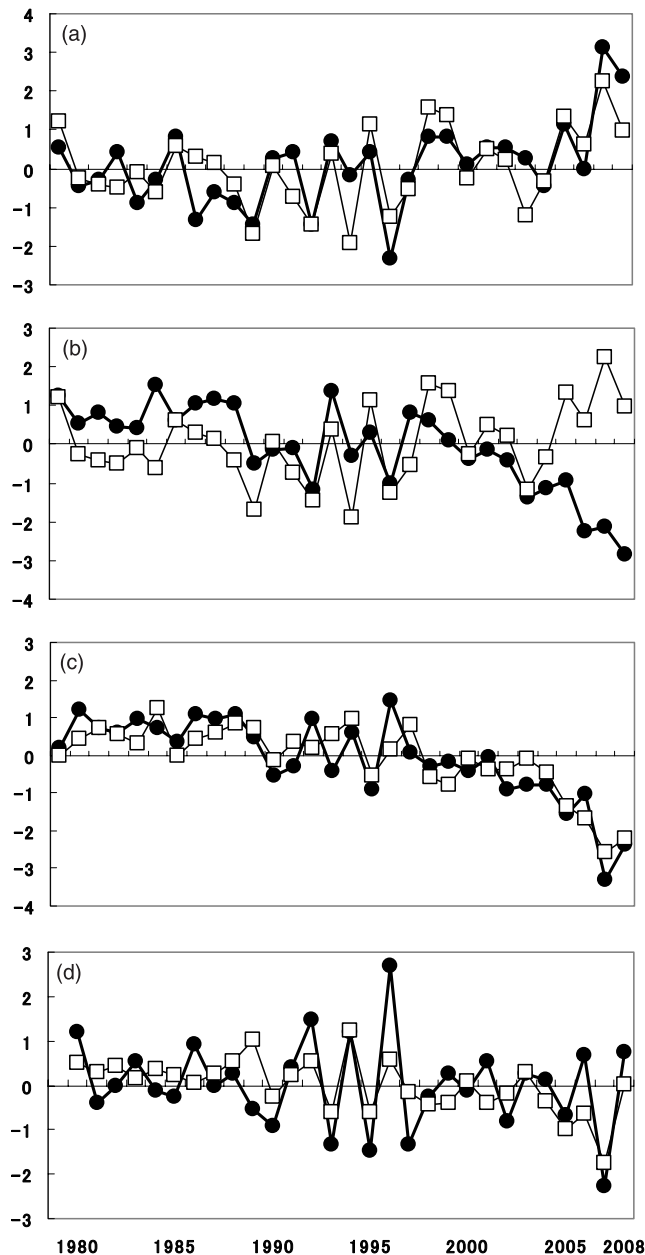
Figure 4. Time series of the standardized indices discussed in Section 3. (a) May minus September SIE (black circles) and JAS SLP (open squares) [Correlation coefficients (1979–2007), r=0.72]. (b) May MYI (black circles) and JAS SLP (open squares) [r=0.03]. (c) Observed (black circles) and "predicted" (open squares) September SIE based on the multivariate linear regression model using May MYI and the JAS SLP index [r=0.82]. (d) Observed (black circles) and "predicted" (open squares) one-year difference of September SIE based on the multivariate linear regression model [r=0.61].

prediction. Together the two "predictors" account for 67% of the variance of the time series of September SIE (60% with cross validation, withholding data for one year at a time in developing the hindcast model and hindcasting September SIE for the withheld year).

[17] Inspection of the time series of May MYI, JAS SLP and September SIE in Figures 4a, 4b, and 4c suggests that May MYI is responsible for most of the hindcast skill on the decadal time scale, while JAS SLP is responsible for much of the skill in hindcasting the change in September SIE from one year to the next. To quantify this impression, a linear model was developed to hindcast the change in September SIE from the previous to the current summer using, as "predictors", the change in MYI from the previous May to the current May and, as before, JAS SLP for the current year. The resulting regression coefficients are 0.32 for the one year change in (May-to-May) MYI and −0.41 for JAS SLP, with the hindcast model (Figure 4d) accounting for 37% of the variance of the change in September SIE from the previous year (27% with cross-validation).

4. Update for Summer 2008

[18] Summer 2008 witnessed sea ice concentrations almost as low as in the previous summer. The May 2008 MYI was at record low levels, raising expectations that a new record might be set, given summer atmospheric conditions favoring a rapid or retreat of the first year ice, either by melting or Ekman drift. The JAS SLP index proved to be positive (i.e., conducive to sea ice retreat), but the anomalies were not as strong as in 2007, as documented in Figures 3b and 3c. The predicted September 2008 SIE and the predicted change in it from the previous year, based on the schemes described in the previous section, proved fairly accurate, as indicated in Figures 4c and 4d. Had the positive SLP anomalies over the Arctic been even a few tens of percent stronger in summer 2008, the previous summer's record low minimum in SIE might well have been tied or broken.

5. Discussion

[19] Observational evidence presented here supports the conclusion of OW that the prevalence of anomalous anticyclonic surface wind anomalies over the Arctic, as observed during the summer of 2007, tends to reduce SIE by producing an anomalous Ekman drift of ice out of the marginal seas and toward the central Arctic. Our JAS SLP index, a measure of the strength of the late summer anticyclonic surface wind anomalies over the Arctic, was more extreme during the record-low ice year 2007 than during any prior year from 1979 onward.

[20] Summertime SLP anomalies over the Arctic can reduce also SIE through their influence on the surface radiation budget: positive SLP anomalies over the Arctic favor reduced cloudiness and enhanced downward fluxes of solar radiation, which accelerates melting. Based on experiments with an ice-ocean model, *Schweiger et al.* [2008] concluded that the anomalously clear skies over much of the Arctic during summer 2007 were not the cause of that year's record low September SIE. We considered the relative importance of this causal linkage by repeating the analysis in Section 3, but using JJA cloudiness, as inferred from the NCEP 2 Reanalysis in place of SLP. The resulting cloudiness index also proved to be a reasonably good "predictor" of summer SIE when used in conjunction with May MYI, but the skill was not as high as for SLP (cross-validated $R^2 =$

0.52 for May MYI and cloudiness versus 0.60 for May MYI and SLP). The regression pattern for cloudiness (i.e., the analog of the SLP regression pattern Figure 3a (not shown)) exhibits a complex structure with anomalies of mixed sign over the region of interest, and it bears little resemblance to the anomalies in JJA 2007. These results, though not entirely conclusive, suggest that summer SLP anomalies mediate September SIE primarily through the wind-induced Ekman drift, rather than through cloudiness.

[21] We have shown that summertime SLP anomalies over the Arctic are as important as preconditioning by events in prior years in determining the variations in September SIE from one year to the next, and our analysis suggests that they are even more important than preconditioning in determining how September SIE will change relative to conditions observed during the previous year.

[22] The six summers that exhibited highest values of the SLP index (1995, 1998, 1999, 2005, 2007 and 2008) were all in the last half of the record. September SIE reached record lows in three of these years (1995, 2005, and 2007), and it nearly tied the record in 2008. Yet it is clear from Figure 4c that the precipitous decline in September SIE in recent years is mainly due to the cumulative loss of multi-year ice: summertime SLP anomalies have played an important role in setting the timing of record lows, but the long term trend is mainly due to preconditioning.

References

Albright, M. (1980), Geostrophic wind calculations for AIDJEX, in *Sea Ice Processes and Models*, edited by R. S. Pritchard, pp. 402–409, Univ. of Wash. Press, Seattle.

Colony, R. L., and I. G. Rigor (1993), International Arctic Buoy Program data report for 1 January 1992–31 December 1992, *Tech. Memo. APL-UW TM29-93*, 215 pp., Appl. Phys. Lab., Univ. of Wash., Seattle.

Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, 113, C02S07, doi:10.1029/2007JC004257.

Ekman, V. W. (1905), On the influence of the Earth's rotation on ocean currents, *Ark. Mat. Astron. Fys.*, 2, 1–52.

Inoue, J., and T. Kikuchi (2007), Outflow of summertime Arctic sea ice observed by ice drifting buoys and its linkage with ice reduction and atmospheric circulation patterns, *J. Meteorol. Soc. Jpn.*, 85, 881–887.

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

Kwok, R. (2008), Summer sea ice motion from the 18 GHz channel of AMSR-E and the exchange of sea ice between the Pacific and Atlantic sectors, *Geophys. Res. Lett.*, 35, L03504, doi:10.1029/2007GL032692.

McPhee, M. G. (1980), An analysis of pack ice drift in summer, in *Sea Ice Processes and Models*, edited by R. S. Pritchard, pp. 62–75, Univ. of Wash. Press, Seattle.

Ogi, M., and J. M. Wallace (2007), Summer minimum Arctic sea ice extent and the associated summer atmospheric circulation, *Geophys. Res. Lett.*, 34, L12705, doi:10.1029/2007GL029897.

Rigor, I. G., and J. M. Wallace (2004), Variations in the age of Arctic sea-ice and summer sea-ice extent, *Geophys. Res. Lett.*, 31, L09401, doi:10.1029/2004GL019492.

Rigor, I. G., J. M. Wallace, and R. L. Colony (2002), Response of sea-ice to the Arctic Oscillation, *J. Clim.*, 15, 2648–2663.

Schweiger, A. J., J. Zhang, R. W. Lindsay, and M. Steele (2008), Did unusually sunny skies help drive the record sea ice minimum of 2007?, *Geophys. Res. Lett.*, 35, L10503, doi:10.1029/2008GL033463.

Serreze, M. C., J. A. Maslanik, T. A. Scambos, F. Fetterer, J. Stroeve, K. Knowles, C. Fowler, S. Drobot, R. G. Barry, and T. M. Haran (2003), A record minimum arctic sea ice extent and area in 2002, *Geophys. Res. Lett.*, 30(3), 1110, doi:10.1029/2002GL016406.

Stroeve, J. C., M. C. Serreze, F. Fetterer, T. Arbetter, W. Meier, J. Maslanik, and K. Knowles (2005), Tracking the Arctic's shrinking ice cover: Another extreme September minimum in 2004, *Geophys. Res. Lett.*, 32, L04501, doi:10.1029/2004GL021810.

————————————

M. G. McPhee, McPhee Research Company, 450 Clover Springs Road, Naches, WA 98937, USA.

M. Ogi, Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Kanazawa-ku, Yokohama, Kanagawa 236-0001, Japan. (masayo.ogi@jamstec.go.jp)

I. G. Rigor, Polar Science Center, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA.

J. M. Wallace, Department of Atmospheric Sciences, University of Washington, 408 ATG Building, Box 31640, Seattle, WA 98195, USA.