Variations in the Arctic's multiyear sea ice cover: A neural network analysis of SMMR-SSM/I data, 1979–2004

Gennady I. Belchansky,[1] David C. Douglas,[2] Vladimir A. Eremeev,[1] and Nikita G. Platonov[1]

Received 10 January 2005; accepted 11 April 2005; published 10 May 2005.

[1] A 26-year (1979–2004) observational record of January multiyear sea ice distributions, derived from neural network analysis of SMMR-SSM/I passive microwave satellite data, reveals dense and persistent cover in the central Arctic basin surrounded by expansive regions of highly fluctuating interannual cover. Following a decade of quasi equilibrium, precipitous declines in multiyear ice area commenced in 1989 when the Arctic Oscillation shifted to a pronounced positive phase. Although extensive survival of first-year ice during autumn 1996 fully replenished the area of multiyear ice, a subsequent and accelerated decline returned the depletion to record lows. The most dramatic multiyear sea ice declines occurred in the East Siberian, Chukchi, and Beaufort Seas.

Citation: Belchansky, G. I., D. C. Douglas, V. A. Eremeev, and N. G. Platonov (2005), Variations in the Arctic's multiyear sea ice cover: A neural network analysis of SMMR-SSM/I data, 1979–2004, *Geophys. Res. Lett.*, *32*, L09605, doi:10.1029/2005GL022395.

1. Introduction

[2] Arctic sea ice variability and trends have been investigated in numerous studies using passive microwave satellite data and various algorithms [*Comiso*, 2002; *Parkinson and Cavalieri*, 2002; *Serreze et al.*, 2003; *Belchansky et al.*, 2004a]. Patterns of sea ice change in the Arctic indicate connections with atmospheric processes [*Deser et al.*, 2000; *Rigor et al.*, 2002; *Rigor and Wallace*, 2004]. Total sea ice cover has declined by about 3% per decade since the late 1970s [*Parkinson and Cavalieri*, 2002], but the perennial or multiyear ice (MYI) fraction (e.g. sea ice that has survived at least one melt season) has declined over twice as fast [*Comiso*, 2002]. The MYI decline has been punctuated by pronounced interannual variability; however, the past three years (2002–2004) were all extreme minima [*Stroeve et al.*, 2005], elevating scientific and societal questions about the likelihoods of future scenarios. Predicting future sea ice conditions in the Arctic remains problematic due to complex interactions and feedbacks between the ice, atmosphere, ocean, and land [*Walsh et al.*, 2002]. Predictions are further complicated by inaccuracies in the satellite measurements, inter-satellite sensor calibration and validation, and duration of the satellite records [*Belchansky et al.*, 2004b].

[1]Institute of Ecology, Russian Academy of Sciences, Moscow, Russia.
[2]USGS Alaska Science Center, Juneau, Alaska, USA.

0094-8276/05/2005GL022395$05.00

[3] A popular method for estimating MYI cover is to measure total ice cover at its minimum extent (the end of summer melt) [*Comiso*, 2002]. This proxy method avoids complications associated with estimating ice age directly, however minimum ice cover does not occur throughout all regions of the Arctic simultaneously [*Comiso*, 2002] so the estimates are partially contaminated by younger ice. In this paper, we investigate mid-winter (January) MYI trends using estimates derived from neural network (NN) analyses of multichannel passive microwave brightness temperature (T_b) data. We compare our results to the summer minimum method (SMM), and we examine interannual MYI variability with respect to prevailing atmospheric conditions.

2. Methods

[4] The development and application of NNs for estimating MYI are detailed by *Belchansky et al.* [2004a]. In general, the NNs estimate MYI concentration within each 25 km $\times$ 25 km passive microwave pixel using three SMMR-SSM/I T_b input channels (18–19H, 18–19V, and 37V). We employed NN algorithms because they accommodate important nonlinear relationships among the T_b channels without a priori assumptions about their distribution properties. For the network learning process, we used MYI estimates derived from Okean and ERS-SAR satellite data to indirectly exploit the stability of active radar MYI signatures [*Kwok et al.*, 1996]. January MYI concentrations were estimated daily, using daily-averaged SMMR-SSM/I T_b data (National Snow and Ice Data Center, Boulder, CO), and then averaged. For comparisons with summer minimum cover, we used total ice concentration estimates from the Bootstrap algorithm (BA) [*Comiso*, 1999] and the NASA Team algorithm (NTA) [*Cavalieri et al.*, 1996]. We also compare January NN results to January NTA multiyear ice estimates. Geopotential height data are from the NCEP-NCAR 40-Year reanalysis [http://www.cdc.noaa.gov]. Analyses are restricted to the Arctic Ocean, including adjacent parts of the Laptev, East Siberian, Chukchi and Beaufort Seas. The study area encompasses ~6.04×10^6 km^2, excluding a two-pixel near-shore buffer and the high-latitude void undetected by the SMMR.

3. Variability and Trends

[5] The central Arctic Ocean maintains persistent MYI cover north of Greenland and the Canadian Archipelago, while the surrounding seas experience large year-to-year fluctuations (Figure 1). During the 1980s, the MYI core was more extensive and total MYI cover in the Arctic Ocean was relatively constant. In 1990, the quasi equilibrium of

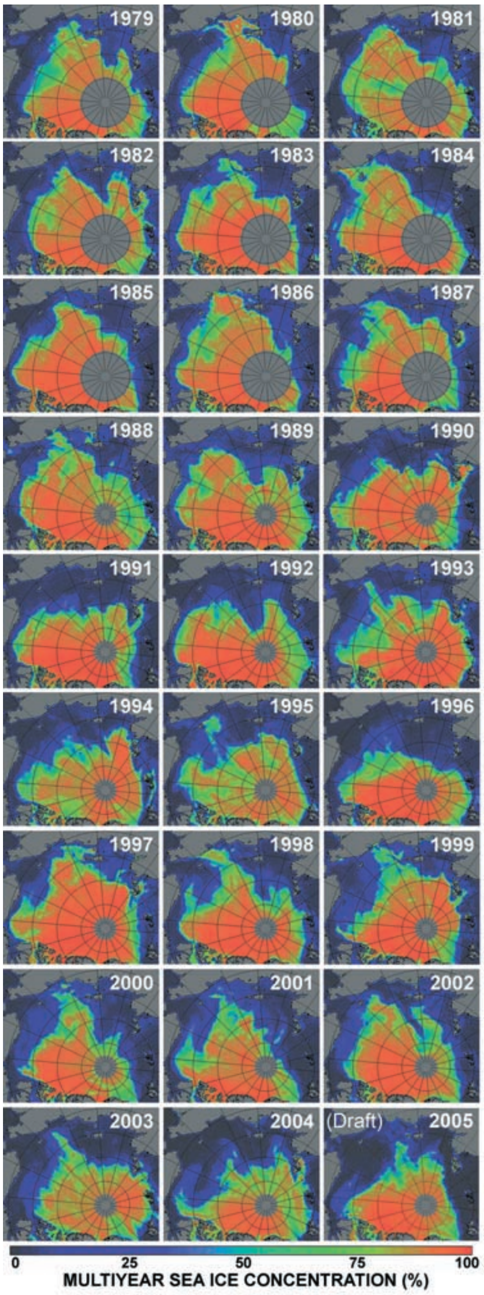

Figure 1. January multiyear sea ice distributions in the Arctic Ocean, 1979–2004, derived using neural network analyses of SMMR-SSM/I T_b data. Draft 2005 analysis used near-real-time SSM/I T_b.

the 1980s began to deteriorate. By January 1996, total MYI area had declined over 10^6 km^2, with losses primarily in the Siberian Arctic. An abbreviated melt season in 1996 [*Belchansky et al.*, 2004c] favored extensive survival of first-year ice in the Siberian Arctic that replenished the MYI cover to previous levels. The replenishment was, however, short lived. By 2000, MYI area had again diminished over 10^6 km^2, and except for a small increase in 2001–2002, continued to decline to a record low in 2004. Preliminary analyses of near-real time SSM/I T_b data indicate that January 2005 MYI area was slightly less than 2004 (-0.04×10^6 km^2), with a more compressed northward distribution over the Nansen Basin.

[6] Year-to-year fluctuations and trends in MYI area were similar between the January NN estimates and the previous year's minimum ice estimates by the BA and NTA (Figure 2). The January NN estimates were consistently lower owing to the assimilation of young ice in the SMM estimates, ice export during the intervening period, and geophysical factors that attenuate T_b signatures of MYI [*Belchansky et al.*, 2004a]. Underestimation of MYI by the NTA is a commonly observed deficiency [*Kwok et al.*, 1996]. Both the NN method and SMM yield similar rates of long-term MYI decline ($\sim 0.4 \times 10^6$ km^2 decade^{-1}). And, both methods depict similar year-to-year fluctuations, cross-validating the stability of total MYI cover in the 1980s, sharp decline in the early 1990s, replenishment in 1996, and rapid decline thereafter.

4. Atmospheric Relationships

[7] During the early 1990s, very low sea level pressure over the Arctic caused significant changes in atmospheric circulation [*Walsh et al.*, 1996] and sea ice dynamics [*Rigor et al.*, 2002]. Under low atmospheric pressure regimes, anticyclonic circulation weakens in the Beaufort Sea and cyclonic circulation intensifies in the eastern Arctic. The transition to lower sea level pressure conditions in the late 1980s is reflected by a pronounced shift in the Arctic Oscillation (AO) index [*Thompson and Wallace*, 1998], from a sustained negative phase to a strongly positive one. Average January MYI cover before and after the 1989 AO phase shift (Figures 3a and 3b) reveals substantial losses confined to one quadrant (135°E–135°W) spanning the East Siberian, Chukchi, and Beaufort Seas (Figures 3e and 3f). The marginal zone of high interannual MYI flux expanded northward after 1989 (Figures 3c and 3d), effectively eroding the central Arctic's MYI core in a manner consistent with a weakened Beaufort Gyre [*Drobot and Maslanik*, 2003].

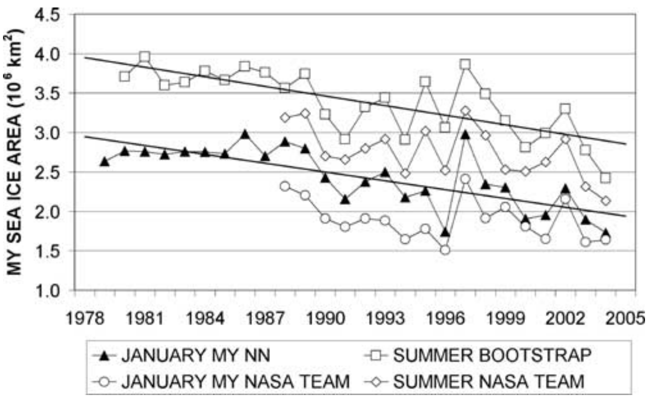

Figure 2. Interannual changes and long term trends in MYI area estimated by different methods: January neural network (1979–2004, slope = -37.3×10^3 km^2 yr^{-1}, $S >$ 99%); previous summer minimum, Bootstrap algorithm (1979–2003, slope = -40.5×10^3 km^2 yr^{-1}, $S >$ 99%); previous summer minimum, NASA Team algorithm (1987–2003); and January NASA Team MYI algorithm (1988–2004). Summer minima are plotted on subsequent years.

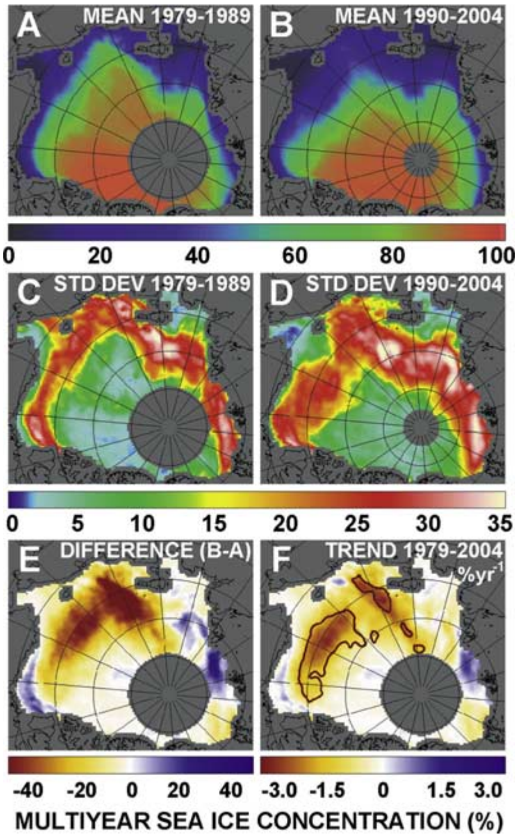

Figure 3. Mean January MYI concentrations A) before (1979–1989) and B) after (1990–2004) the Arctic Oscillation's positive phase shift; standard deviation of the mean, C) and D) respectively; E) difference between the means (1990–2004 minus 1979–1989); and F) long-term (1979–2004) linear trend (% yr^{-1}), bold contours delineate significant (S > 95%) slope.

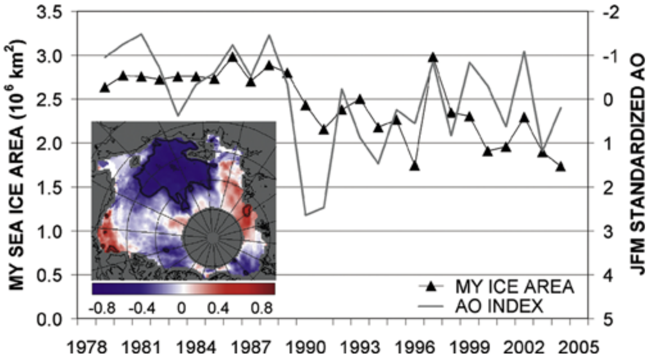

Figure 4. Relationship between January MYI area (1979–2004) and the previous winter (JFM) AO index (inverted axis), $\rho = -0.53$, S > 99%. (Inset) Spatial distribution of the Pearson correlation coefficient between January MYI concentration and the previous winter AO index, bold contours delineate significant (S > 95%) correlation.

[8] Total January MYI area was inversely correlated ($\rho = -0.53$, S > 99%) with the previous winter's AO index, however the relationship was dominated by conditions in the East Siberian Sea (Figure 4). In fact, positive correlations with the AO index were detected over smaller regions in the northern Kara and the southeastern Beaufort Sea. The opposing response between regions east (Siberian) and west (Eurasian) of the Laptev Sea is further evidenced by correlations with geopotential height anomalies (GHA). January MYI concentrations were positively correlated with the previous year's 500–1000 mb GHA in the Siberian sector, but negatively correlated in the Eurasian sector (Figure 5a). In the Siberian sector, lower (higher) than average atmospheric pressure conditions tend to export (retain) ice [*Rigor et al.*, 2002] as well as delay (advance) the onset of autumn freeze [*Belchansky et al.*, 2004c]; both mechanisms corroborate to reduce (increase) MYI concentrations the following winter. The inverse correlation in Eurasia is likely a seesaw response to ice advected from Siberia. The Eurasian correlation is more pronounced and the Siberian correlation diminished when analyses are restricted to the winter GHA (Figure 5b), and both correlations weaken with respect to summer GHA (Figure 5c).

[9] We infer that wind-driven ice motion largely determines January MYI cover in the Eurasian sector, while thermodynamic factors play a dominant role in the Siberian region through a strong dependency with the timing of autumn freeze (Figure 5d). The East Siberian Sea is a principal region of MYI recruitment, and since melt duration is critical to the fate of first-year ice, freeze dates will predicate January MYI abundance in years when the growth of first-year ice during the previous winter was enhanced by offshore ice advection.

[10] In the Beaufort Sea, January MYI concentrations were positively correlated with GHA during the previous summer (Figure 5c). Here, high (low) pressure conditions

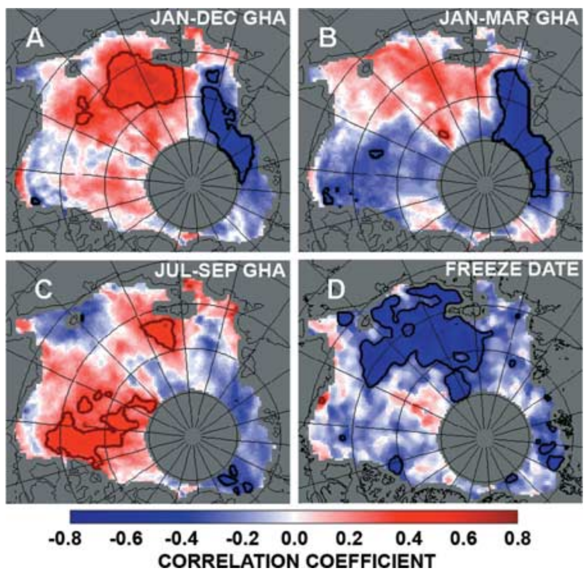

Figure 5. Spatial distribution of the Pearson correlation coefficient between January MYI concentrations (1979–2004) and 500–1000 mb geopotential height anomalies averaged over A) the previous year (Jan–Dec); B) the previous winter (Jan–Mar); C) the previous summer (Jul–Sep); and D) between January MYI area (1980–2004) and the previous year's freeze onset date from *Belchansky et al.* [2004c]. Bold contours delineate significant (S > 95%) correlation.

during summer strengthen (weaken) the Beaufort Gyre causing enhanced (diminished) easterly and northerly ice motion [*Drobot and Maslanik*, 2003] that increases (decreases) convergence in the northeastern Beaufort Sea.

5. Discussion

[11] The post-1997 MYI decline rivals that of the early 1990s, despite comparatively neutral AO conditions (Figure 4). *Rigor and Wallace* [2004] propose that residual effects of the strong positive AO phase during the early 1990s still persist. They found that much of the Arctic's oldest MYI was expelled through the Fram Strait during the high-index AO phase, leaving a younger and thinner ice pack more vulnerable to summer melt. *Fowler et al.* [2004] report a similar shift to a younger ice pack. *Serreze et al.* [2003] point out that increased heat advection into the Arctic during spring, and persistent low pressure and high temperatures during summer have exacerbated the ice retreat in recent years. These conditions also promote production and entrainment of young ice, thus perpetuating anomalous retreats in subsequent years [*Rigor and Wallace*, 2004].

[12] Predictions about future sea ice conditions are varied due to numerous interactions and feedbacks with the ocean and atmosphere [*Walsh et al.*, 2002] and underlying low-frequency oscillations [*Polyakov and Johnson*, 2000]. From a retrospective standpoint, restoring the Arctic's MYI extent and volume to that of the 1980s would likely require a sustained period of high atmospheric pressure anomalies (low-index AO) characterized by cooler air temperatures, shorter melt seasons, a strong Beaufort Gyre, reduced ice export, and a robust cold halocline layer. However, the likelihood of reestablishing a persistent low-index AO phase may be compromised by increasing greenhouse gas concentrations [*Shindell et al.*, 1999].

6. Conclusions

[13] Neural network analyses of January SMMR-SSM/I T_b data (1979–2004) show dramatic MYI declines in the Alaskan and Siberian Arctic that corroborate other studies and methodologies. Quasi equilibrium during the 1980s was clearly disrupted when altered atmospheric circulation patterns associated with a strong positive AO shift in 1989 led to substantial MYI losses in the Beaufort, Chukchi and East Siberian Seas. Despite a more neutral disposition of the AO in recent years, there is no indication that the MYI decline is reversing. Whether past sea ice conditions will return, or a new equilibrium established, remains an important topic for continued research.

[14] **Acknowledgments.** This work was supported by the International Arctic Research Center, Russian Foundation for Basic Research 04-04-49703, USGS Global Change Research Program, and NATO Grant EST.CLG.980123. We acknowledge the Alaska SAR Facility and the NSIDC for providing, respectively, ERS MYI concentrations and Daily Polar Gridded T_b and Sea Ice Concentrations. We thank S.-I. Akasofu, J. E. Walsh, I. Polyakov, and two anonymous reviewers.

References

Belchansky, G. I., D. C. Douglas, I. V. Alpatsky, and N. G. Platonov (2004a), Spatial and temporal multiyear sea ice distributions in the Arctic: A neural network analysis of SSM/I data, 1988–2001, *J. Geophys. Res.*, *109*, C10017, doi:10.1029/2004JC002388.

Belchanksy, G. I., D. C. Douglas, I. N. Mordvintsev, and N. G. Platonov (2004b), Estimating the time of melt onset and freeze onset over Arctic sea-ice area using active and passive microwave data, *Remote Sens. Environ.*, *92*, 21–39.

Belchansky, G. I., D. C. Douglas, and N. G. Platonov (2004c), Duration of the Arctic sea ice melt season: Regional and interannual variability, 1979–2001, *J. Clim.*, *17*, 67–80.

Cavalieri, D., C. Parkinson, P. Gloerson, and H. J. Zwally (1996), Sea ice concentrations from NIMBUS-7 SMMR and DMSP SSM/I passive microwave data, http://nsidc.org/data/, Natl. Snow and Ice Data Cent., Boulder, Colo.

Comiso, J. (1999), Bootstrap sea ice concentration for NIMBUS-7 SMMR and DMSP SSM/I, http://nsidc.org/data/, Natl. Snow and Ice Data Cent., Boulder, Colo.

Comiso, J. C. (2002), A rapidly declining perennial sea ice cover in the Arctic, *Geophys. Res. Lett.*, *29*(20), 1956, doi:10.1029/2002GL015650.

Deser, C., J. E. Walsh, and M. S. Timlin (2000), Arctic sea ice variability in the context of recent atmospheric circulation trends, *J. Clim.*, *13*, 617–633.

Drobot, S. D., and J. A. Maslanik (2003), Interannual variability in summer Beaufort Sea ice conditions: Relationship to winter and summer surface and atmospheric variability, *J. Geophys. Res.*, *108*(C7), 3233, doi:10.1029/2002JC001537.

Fowler, C., W. J. Emery, and J. Maslanik (2004), Satellite-derived evolution of Arctic sea ice age: October 1978 to March 2003, *IEEE Geosci. Remote Sens. Lett.*, *1*, 71–74.

Kwok, R., J. C. Comiso, and G. F. Cunningham (1996), Seasonal characteristics of the perennial ice cover of the Beaufort Sea, *J. Geophys. Res.*, *101*, 28,417–28,439.

Parkinson, C. L., and D. J. Cavalieri (2002), A 21 year record of Arctic sea-ice extents and their regional, seasonal and monthly variability and trends, *Ann. Glaciol.*, *34*, 441–446.

Polyakov, I. V., and M. A. Johnson (2000), Arctic decadal and interdecadal variability, *Geophys. Res. Lett.*, *27*, 4097–4100.

Rigor, I. G., and J. M. Wallace (2004), Variation 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.

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.

Shindell, D. T., R. L. Miller, G. A. Schmidt, and L. Pandolfo (1999), Simulation of recent northern winter climate trends by greenhouse-gas forcing, *Nature*, *399*, 452–455.

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.

Thompson, D. W. J., and J. M. Wallace (1998), The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophys. Res. Lett.*, *25*, 1297–1300.

Walsh, J. E., W. L. Chapman, and T. L. Shy (1996), Recent decrease of sea level pressure in the central Arctic, *J. Clim.*, *9*, 480–486.

Walsh, J. E., V. M. Kattsov, W. L. Chapman, V. Govorkova, and T. Pavlova (2002), Comparison of Arctic climate simulations in uncoupled and coupled global climate models, *J. Clim.*, *15*, 1429–1446.

G. I. Belchansky, V. A. Eremeev, and N. G. Platonov, Institute of Ecology, Russian Academy of Sciences, Leninsky Prospect 33, Moscow 119071, Russia. (belchans@eimb.ru)

D. C. Douglas, USGS Alaska Science Center, Juneau Field Station, 3100 National Park Rd., Juneau, AK 99801, USA. (david_douglas@usgs.gov)