GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L07503, doi:10.1029/2009GL037274, 2009

Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent

Jennifer A. Francis,[1] Weihan Chan,[2] Daniel J. Leathers,[2] James R. Miller,[1] and Dana E. Veron[3]

Received 13 January 2009; revised 25 February 2009; accepted 11 March 2009; published 11 April 2009.

[1] The dramatic decline in Arctic summer sea-ice cover is a compelling indicator of change in the global climate system and has been attributed to a combination of natural and anthropogenic effects. Through its role in regulating the exchange of energy between the ocean and atmosphere, ice loss is anticipated to influence atmospheric circulation and weather patterns. By combining satellite measurements of sea-ice extent and conventional atmospheric observations, we find that varying summer ice conditions are associated with large-scale atmospheric features during the following autumn and winter well beyond the Arctic's boundary. Mechanisms by which the atmosphere "remembers" a reduction in summer ice cover include warming and destabilization of the lower troposphere, increased cloudiness, and slackening of the poleward thickness gradient that weakens the polar jet stream. This ice-atmosphere relationship suggests a potential long-range outlook for weather patterns in the northern hemisphere. **Citation:** Francis, J. A., W. Chan, D. J. Leathers, J. R. Miller, and D. E. Veron (2009), Winter Northern Hemisphere weather patterns remember summer Arctic sea-ice extent, *Geophys. Res. Lett.*, *36*, L07503, doi:10.1029/2009GL037274.

1. Introduction

[2] Sea ice is the primary arbiter of energy exchange between the Arctic atmosphere and ocean. Its high albedo regulates the amount of insolation entering the surface, its seasonal phase changes modulate ocean characteristics and control summer temperatures, its insulating properties retard heat exchange, and its rheology inhibits kinetic energy transfer. The large interannual variability and dramatic loss of ice coverage, therefore, is expected to have substantial effects on the climate system.

[3] Factors driving variability in sea-ice extent have been investigated [e.g., *Bitz et al.*, 2005; *Francis and Hunter*, 2006; *Deser and Teng*, 2008], but the observed effects of varying summer ice conditions on the atmospheric circulation in later months has received relatively little attention. Several recent studies have investigated the response of the atmosphere to varying sea ice conditons during winter. *Deser et al.* [2004] and *Magnusdottir et al.* [2004], for example, found that exaggerated ice losses and surface temperature increases in the N. Atlantic during winter produced a circulation response resembling the negative phase of the North Atlantic Oscillation (NAO) in the Community Climate Model (CCM3) from the National Center for Atmospheric Research. *Deser et al.* [2007] later showed that ice losses cause changes in the surface fluxes during N. Atlantic winter that affect the storm track in the region. *Alexander et al.* [2004] forced the CCM3 with observed ice extent during recent winters, finding that sea-level pressure decreased and precipitation increased in areas near the ice anomalies. They also found that ice anomalies in the Pacific sector intensified the atmospheric circulation in that region, while ice anomalies east of Greenland led to the opposite response in the N. Atlantic. *Singarayer et al.* [2006] investigated the effect of declining sea ice and warming SSTs on northern hemisphere circulation patterns in the Hadley Centre Atmospheric Model. Projections for the end of the 21st century suggest that the winter response is larger than summer, with generally lower SLP over the western Arctic and north Pacific, higher precipitation over much of the Arctic Ocean, and lower precipitation in western N. America (in accord with *Sewall* [2005]). Finally, *Bhatt et al.* [2008] forced an atmospheric general circulation model with sea ice conditions that occurred during a year with an anomalously low summer ice cover to investigate the atmospheric response from April through October. They found that the ice anomalies caused higher SLPs and upper-level heights in the N. Pacific accompanied by increased (decreased) precipitation north (south) of the Pacific storm track.

[4] All of these studies point to a substantial influence of sea ice variability on northern hemisphere circulation patterns in model simulations. In this investigation we augment recent findings by examining the relationships between the actual variability in summer sea ice extent and observed anomalies in the northern hemisphere atmosphere during the months that follow. We focus on evidence for mechanisms by which the atmosphere "remembers" summer anomalies in the ice cover, and the resulting effects on weather patterns in autumn and winter.

2. Data

[5] Observations of sea-ice concentration from the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager satellite instruments are used to calculate sea-ice extent obtained from the National Snow and Ice Data Center. Ice extent is defined as the total area with at least 15% sea ice north of 65°N [*Cavalieri et al.*, 1999]. Monthly mean fields of sea-level pressure, 500-hPa geopotential height,

[1]Institute of Marine and Coastal Sciences, Rutgers University, New Brunsick, New Jersey, USA.
[2]Department of Geography, University of Delaware, Newark, Delaware, USA.
[3]College of Marine and Earth Studies, University of Delaware, Newark, Delaware, USA.

0094-8276/09/2009GL037274$05.00

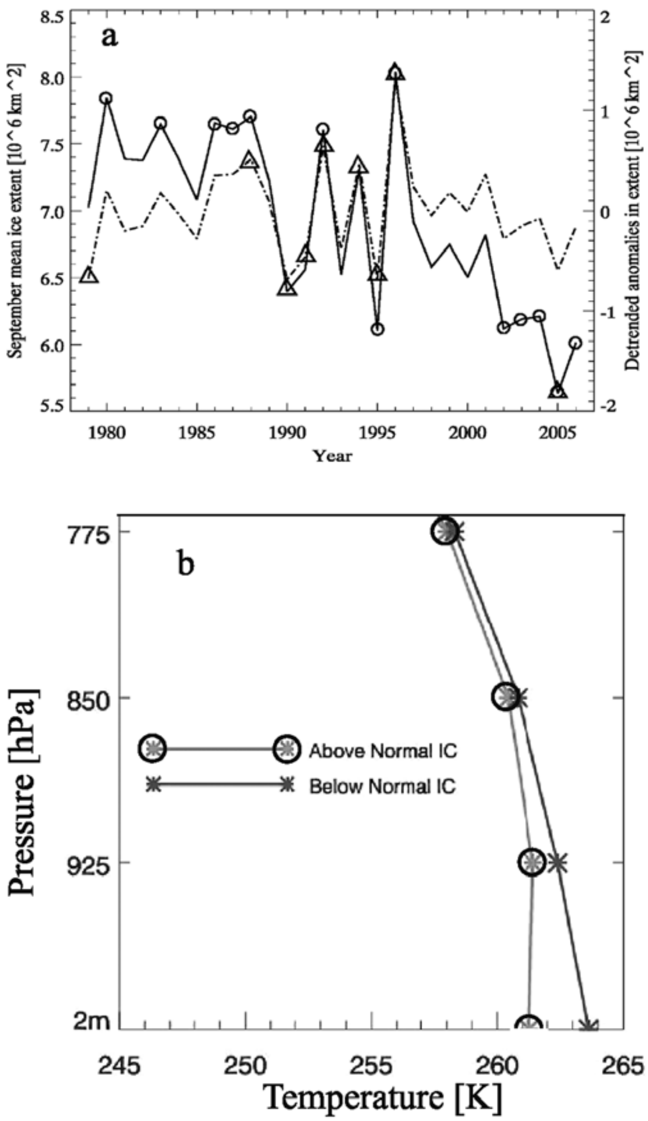

Figure 1. (a) Time-series of mean September sea-ice extent (solid) and detrended extent anomaly (dashed) [$10^6 \times km^2$] during 1979–2006. Extreme years are indicated with a circle (actual) or triangle (detrended). (b) Composites of temperature profiles from above-normal (red) and below-normal (blue) ice cover (greater than 0.5 standard deviation from mean) derived from the European Centre for Medium-range Weather Forecasts reanalysis (ERA-40) for Sept.–Nov. during 1980–2001 [from *Schweiger et al.*, 2008].

near-surface air temperature, and total-column water vapor content are obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis [*Kalnay et al.*, 1996], and monthly mean precipitation data are from the Global Precipitation Climatology Project [*Adler et al.*, 2003]. All data span 1979 to 2006, with the final winter extending into 2007.

3. Autumn/Winter Weather Following Anomalous Summer Ice Extent

[6] The decline in summer ice cover is conspicuous in time series of September-mean sea-ice extent, the month in which the minimum extent typically occurs. Both the actual and detrended ice extents north of 65°N are shown in Figure 1a, Detrended values are included to elucidate effects of the interannual variability in ice extent alone.

[7] After summers with below-normal ice extent, the fluxes of heat and moisture from the surface to the atmosphere are anomalously large, particularly near the margin where ice retreat occurs and the concentration is relatively low. The warming and additional transfer of heat into the atmosphere associated with lower-than-normal summer ice extent leads to a weakening of the near-surface stratification of the lower atmosphere (Figure 1b), accompanied by a higher boundary layer top [*Schweiger et al.*, 2008]. A deeper and less stably stratified boundary layer allows surface-released heat to be stored by a larger mass of atmosphere. Combined with the added solar energy absorbed by the ocean, the growth of sea ice in autumn will be retarded. This influence is not, however, confined to areas in close proximity to the ice edge. The difference in autumn (Oct./Nov.) mean air temperature after summers when the ice extent was less than and greater than one standard deviation from the 1979–2006 mean is shown in Figures 2a and 2c. Using both actual and detrended ice extents, the composites reveal large areas with temperature differences exceeding 3 K centered over the Pacific and Atlantic marginal ice zones, where ice loss has been most pronounced. The calculation using detrended ice extents replaces positive temperature differences over the Canadian Archipelago with negative values, suggesting the response in this area is associated with the trend in ice extent, a symptom of the large-scale warming tendency in general.

[8] A related response to varying summer ice extent is the effect on autumn clouds. Total cloud cover has been observed to increase substantially over areas of ice loss during autumn [e.g., *Levinson and Lawrimore*, 2008], which would enhance the emission of longwave radiation (LW) to the surface and further retard ice regrowth. According to estimates derived from satellite sounder retrievals [*Francis and Hunter*, 2007], LW fluxes over the Arctic and adjacent seas are indeed 10 to 40 W m^{-2} larger in autumn and winter after summers with less ice relative to those with extensive ice (not shown).

[9] A warming of the magnitude and spatial extent evident in Figures 2a and 2c would be expected to affect large-scale atmospheric circulation patterns, and ultimately influence weather over much of the northern hemisphere. This expectation is evident in the corresponding plot of composite differences in the autumn sea-level pressure (SLP) pattern during reduced-versus-extensive ice years, with and without the trend in ice extent (Figures 2b and 2d). The SLP is substantially higher over much of the Arctic Ocean and in the northeast Atlantic after summers with reduced ice. The higher SLP is compensated by lower pressure in mid-latitudes. While the pattern is similar whether actual or detrended ice extents are used to identify extreme ice years, the magnitudes of pressure differences are larger when the trend is included. The differences in the north Pacific Ocean appear to be associated primarily with the trend, suggesting that the Aleutian low during autumn is weaker following recent summers with less ice. In both cases the pattern in the north Atlantic is reminiscent of the North Atlantic Oscillation [*Hurrell*, 1995], defined concep-

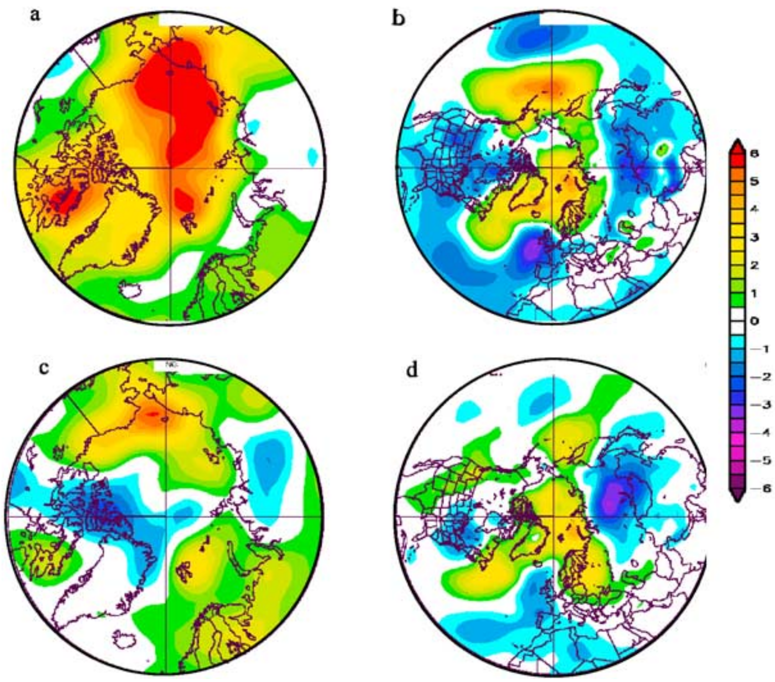

Figure 2. Difference between composites for autumns (Oct./Nov.) following Septembers with (top) actual and (bottom) detrended ice extents that are less than and greater than one standard deviation from the 1979–2006 mean. (a and c) Surface air temperature anomalies (°C); (b and d) sea-level pressure anomalies (hPa), composited for low-ice summers minus high-ice summers.

tually as the difference in pressure between the semipermanent high located near the Azores and the low centered near Iceland. When the NAO index is in a positive phase, the pressure difference is large, and the northeastern Atlantic experiences increased storminess. It appears that an anomalously small (large) ice cover during summer excites this natural mode of atmospheric behavior, resulting in a more negative (positive) NAO index during the subsequent autumn.

[10] Does the influence of extreme summer ice extent continue into winter? And if so, what are the mechanisms that provide the memory? We speculate that after low-ice summers, the additional heating of the lower troposphere increases the vertical geometric thickness of the lower atmosphere, resulting in higher geopotential heights of upper pressure surfaces in the proximity of ice loss, and a relaxation of the poleward temperature gradient between mid- and high-latitudes. This is illustrated in Figure 3, presenting the monthly evolution of the 1000-to-500 hPa thickness gradient in the approximate location of two key storm tracks: between the Azores and Iceland (Figure 3, left) and in the north Pacific (along 175°W between 30°N and 55°N; Figure 3, right) following summers with above- and below-normal ice extent. The gradient is lessened by 10 to 20% after summers with a reduced ice cover, leading to a decreased polar jet stream and a tendency for weaker semi-

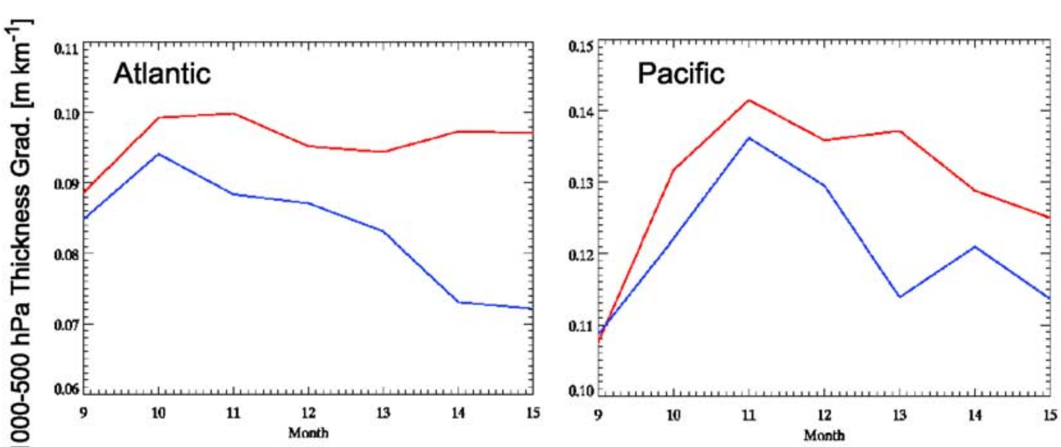

Figure 3. Poleward gradient in the geometric thickness of the 1000–500 hPa layer [m km^{-1}] in (left) the North Atlantic and (right) the North Pacific Oceans during years with above- (red) and below-normal (blue) sea ice during summer. Data extend from September of the extreme ice year to the following March.

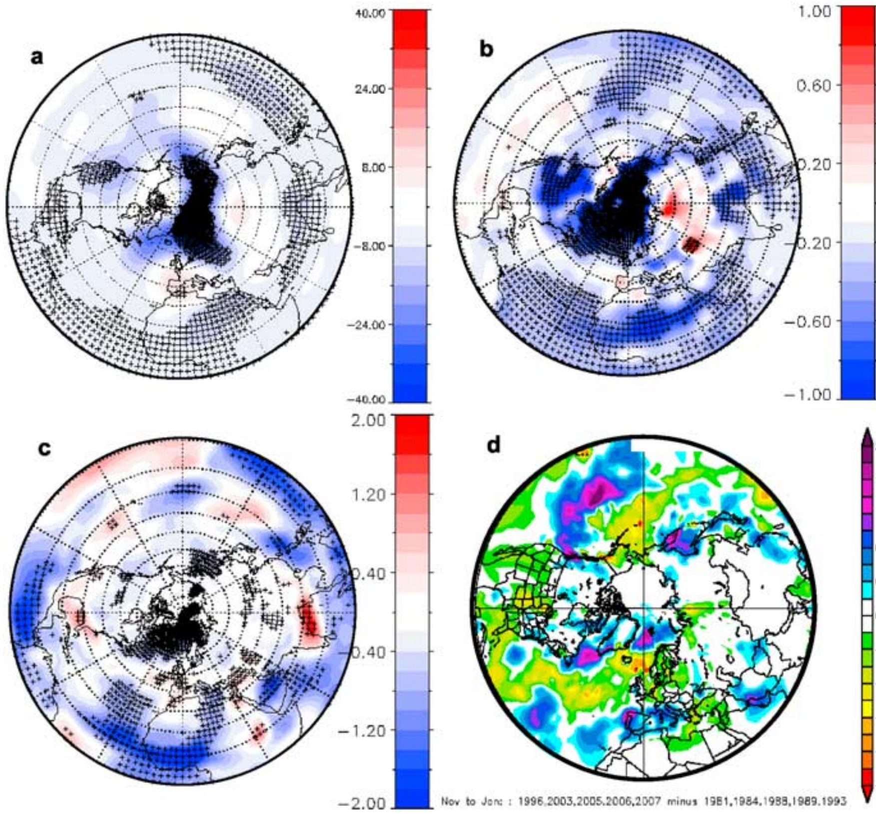

Figure 4. Linear regressions between actual September sea-ice extent and atmospheric variables during the following winter (Nov.–Jan.). (a) The 500-hPa height in m/10^6km, (b) the surface air temperature in K/10^6km, and (c) precipitable water in kg m^{-2}/10^6km. Black crosses indicate gridpoints where significance exceeds 90% confidence according to a standard f-test. (d) Difference in winter-mean precipitation (mm day^{-1}) after summers when the ice extent was less than and greater than one standard deviation from the 1979–2006 mean.

permanent low pressure centers near Iceland and the Aleutians that continue at least six months later. This mechanism was suggested by *Deser et al.* [2007] and *Peng and Whitaker* [1999] based on the modeled atmospheric response during winter to imposed ice anomalies also during winter.

[11] Further evidence of the summer-ice/winter-atmosphere relationship and the manifestations in terms of practical weather are captured in the linear regressions between Arctic-mean September ice extent and atmospheric variables during the following early winter (Nov.–Jan.; hereafter "winter") over the northern hemisphere (Figure 4). Actual summer ice extents are used so that shifts in weather patterns experienced during recent decades are revealed. Values represent a change in a variable per 10^6 km^2 change in September ice extent, and those statistically significant at or above the 90% confidence level are identified by black crosses. A large area of increased (decreased) 500 hPa heights (Figure 4a) occurs in winter over much of the Arctic Ocean after summers with less (more) ice than normal. If detrended ice extent is used in the regression (not shown), the pattern is similar, but the number of significant gridpoints in low latitudes is reduced by approximately 30%, suggesting that the relationship between summer sea ice and winter atmospheric patterns arises from a combination of forcing by fluctuations in ice extent as well as by the decline in sea ice owing to global-scale warming. Regression relationships between actual summer sea-ice extent with winter values of surface air temperature and total-column water vapor are shown in Figures 4b and 4c. The preponderance of negative values in the SAT regression indicate that low values of summer ice extent are related to higher winter SATs, not just over the Arctic, but also in concert with warming throughout the hemisphere. Water vapor content in winter also rises as summer ice declines, with large areas of significant relationships over much of the subtropical latitudes. The areas over the Arctic and Africa are significant also for the detrended ice regressions (not shown), suggesting they are driven primarily by ice variablity, while the other significant relationships arise through combined sea ice loss and hemispheric warming.

[12] Of particular interest is the influence of summer sea-ice variability and loss on northern hemisphere precipitation, as future changes in freshwater resources are a vital concern in many regions. Precipitation data are noisy by nature and tend to be less reliable, particularly in mountainous areas and high latitudes where much of it falls as snow. A regression of actual summer sea ice extent with precipitation data yields a noisy yet significant tendency for increased precipitation over much of the region north of approximately 40°N (not shown). More revealing and illustrative is the composited difference in winter-mean precipitation after summers when ice extent was less than and greater than 1 standard deviation from the 1979–2006 mean (Figure 4d). A coherent area of negative anomalies is evident over a large region of the northeast Atlantic Ocean

extending into northern Europe as well as over much of the U.S. and Alaska. A zone with wet winters extends from Spain eastward across the northern Mediterranean, over waters southwest and northeast of Greenland, and in the Sea of Okhotsk north of Japan. The North Pacific pattern is similar to those found in intraseasonal modeling studies [*Sewall*, 2005], and features are consistent with the 500 hPa height regression relationship presented in Figure 4a.

[13] It should be noted that other strong forcing mechanisms and atmospheric oscillations may obscure the relationships presented here; the summer-2007/winter-2008 being a clear example during which a relatively strong La Niña event prevailed. While sea-ice extent retreated to record lows in summer 2007, the winter 2008 precipitation pattern was reminiscent of that expected for La Niña conditions.

4. Conclusions

[14] Recognition of the relationship between summer sea-ice extent and northern hemisphere atmospheric patterns during the following months may provide a valuable long-range outlook for dominant weather patterns and for water-resource management. Scandinavia, for example, depends on hydropower for much of its electricity generation, and its winter precipitation has declined following recent summers with reduced ice. Southeast and western regions of the U.S. have been suffering a prolonged drought; widespread water restrictions are already in place and forest fires have increased [*Westerling et al.*, 2006]. If summer sea ice continues on its downward trajectory, which is likely to occur as greenhouse gases accumulate in the atmosphere [*Stroeve et al.*, 2007], then the large-scale atmospheric winter patterns associated with a below-normal summer ice cover will also likely continue. Advanced warning of persistent anomalies in winter precipitation will greatly assist water-resource managers in the affected areas by reducing uncertainty in the trajectory forward. In addition, because summers with below-normal ice extent tend to precede winters characterized by a neutral-to-negative NAO phase, the persistently positive NAO of the late 1980s and early 1990s that is blamed for removing much of the Arctic's thick sea ice [*Rigor and Wallace*, 2004] appears less likely to recur. Furthermore, a prevalence of near-neutral NAO phase may promote a rebound in the ice cover [*Serreze et al.*, 2007; *Rigor et al.*, 2002], although perhaps not enough to counteract the thermodynamic consequences of increasing greenhouse gases.

[15] **Acknowledgment.** Funding for J. Francis was provided by the National Science Foundation's Arctic System Science program (ARC 0611577).

References

Adler, R. F., et al. (2003), The version 2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, *4*, 1147–1167.

Alexander, M. A., U. S. Bhatt, J. E. Walsh, M. Timlin, and J. S. Miller (2004), The atmospheric response to realistic Arctic sea ice anomalies in an AGCM during winter, *J. Clim.*, *17*, 890–905.

Bhatt, U. S., M. A. Alexander, C. Deser, J. E. Walsh, J. S. Miller, M. S. Timlin, J. D. Scott, and R. A. Tomas (2008), The atmospheric response to realistic reduced summer Arctic sea ice anomalies, in *Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications*, *Geophys. Monogr. Ser.*, vol. 180, edited by E. T. DeWeaver, C. M. Bitz, and L.-B. Tremblay, AGU, Washington, D. C., in press.

Bitz, C. M., M. M. Holland, E. C. Hunke, and R. E. Moritz (2005), Maintenance of the sea-ice edge, *J. Clim.*, *18*, 2903–2921.

Cavalieri, D. J., C. L. Parkinson, P. Gloersen, J. C. Comiso, and H. J. Zwally (1999), Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets, *J. Geophys. Res.*, *104*, 15,803–15,814.

Deser, C., and H. Teng (2008), Evolution of Arctic sea ice concentration trends and the role of atmospheric circulation forcing, 1979–2007, *Geophys. Res. Lett.*, *35*, L02504, doi:10.1029/2007GL032023.

Deser, C., G. Magnusdottir, R. Saravanan, and A. Phillips (2004), The effects of North Atlantic SST and sea ice anomalies on the winter circulation in CCM3. Part II: Direct and indirect components of the response, *J. Clim.*, *17*, 877–889.

Deser, C., R. A. Thomas, and S. Peng (2007), The transient atmospheric circulation response to North Atlantic SST and sea ice anomalies, *J. Clim.*, *20*, 4751–4767.

Francis, J. A., and E. Hunter (2006), New insight into the disappearing Arctic sea ice, *Eos Trans. AGU*, *87*(46), doi:10.1029/2006EO460001.

Francis, J. A., and E. Hunter (2007), Changes in the fabric of the Arctic's greenhouse blanket, *Environ. Res. Lett.*, *2*, 045011, doi:10.1088/1748-9326/2/4/045011.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679.

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

Levinson, D. H., and J. H. Lawrimore (2008), State of the Climate in 2007, *Bull. Am. Meteorol. Soc.*, *89*, S1–S179, doi:10.1175/BAMS-89-7-StateoftheClimate.

Magnusdottir, G. C., C. Deser, and R. Saravanan (2004), The effects of North Atlantic SST and sea-ice anomalies on the winter circulation in CCM3. Part 1: Main features and storm track characteristics of the response, *J. Clim.*, *17*, 857–876.

Peng, S., and J. S. Whitaker (1999), Mechanisms determining the atmospheric response to midlatitude SST anomalies, *J. Clim.*, *12*, 1393–1408.

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., R. W. Linsay, S. Vavrus, and J. A. Francis (2008), Relationships between Arctic sea ice and clouds during autumn, *J. Clim.*, *21*, 4799–4810, doi:10.1175/2008JCLI2156.1.

Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's shrinking sea-ice cover, *Science*, *315*, 1533–1536.

Sewall, J. O. (2005), Precipitation shifts over western North America as a result of declining Arctic sea ice cover: The coupled system response, *Earth Interact.*, *9*, 1–23.

Singarayer, J. S., J. L. Bamber, and P. J. Valdes (2006), Twenty-first-century climate impacts from a declining Arctic sea ice cover, *J. Clim.*, *19*, 1109–1125.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze (2007), Arctic sea ice decline: Faster than forecast, *Geophys. Res. Lett.*, *34*, L09501, doi:10.1029/2007GL029703.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam (2006), Warming and earlier spring increase western U.S. forest wildfire activity, *Science*, *313*, 940–943, doi:10.1126/science.1128834.

W. Chan and D. J. Leathers, Department of Geography, University of Delaware, 216 Pearson Hall, Newark, DE 19716, USA.

J. A. Francis and J. R. Miller, Institute of Marine and Coastal Sciences, Rutgers University, 71 Dudley Road, New Brunsick, NJ 08901, USA. (francis@imcs.rutgers.edu)

D. E. Veron, College of Marine and Earth Studies, University of Delaware, 111 Robinson Hall, Newark, DE 19716, USA.