Interpretation of recent Antarctic sea ice variability

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[1] Trends in the satellite-derived Antarctic sea ice concentrations (1979–2002) show pronounced increase (decrease) in the central Pacific sector (Bellingshausen/western Weddell sector) by ~4–10% per decade. Confidence levels for these regional trends exceed 95%. Positive polarities of the Antarctic Oscillation (AAO) lead to more (less) ice in the eastern Ross/Amundsen sector (Bellingshausen/northern Weddell sector), which are qualitatively opposite to the impacts of positive polarities of the El Niño-Southern Oscillation (ENSO). The mechanisms responsible for the covariability between the ice and the (a) AAO and (b) ENSO are demonstrated. Over the last 24 years, a positive AAO trend and a slightly negative ENSO trend produce a spatial pattern of ice changes similar to the regional ice trends. However, the magnitude of the ice changes associated with the AAO and ENSO is much smaller than the regional ice trends. More local (or less understood large) scale processes should be investigated for the explanations. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504). **Citation:** Liu, J., J. A. Curry, and D. G. Martinson (2004), Interpretation of recent Antarctic sea ice variability, *Geophys. Res. Lett.*, *31*, L02205, doi:10.1029/2003GL018732.

1. Introduction and Questions

[2] Hypotheses, models and observations suggest that the Antarctic sea ice plays an important role in the state and variability of regional and global climate through the ice albedo feedback, insulating effect, deep water formation and fresh water budget [e.g., *Fletcher*, 1969; *Walsh*, 1983; *Curry et al.*, 1995; *Rind et al.*, 1995]. In the context of greenhouse warming, there are two classic views on Antarctic sea ice changes: (1) sea ice cover would decrease with warmer surface temperature, and (2) sea ice cover would increase with warmer climate. The latter viewpoint assumes that increased precipitation with warmer atmosphere in the Antarctic would result in more snowfall on sea ice (which enhances the positive ice-albedo feedback) and lower salinity in the surface ocean layer (which reduces the contribution of heat from the relatively warm deep water into the surface layer).

[3] Undoubtedly, as a sensitive indicator of global climate change, a detailed understanding of the nature and causes of recent Antarctic sea ice variability is necessary.

[4] Sea ice concentrations retrieved from the scanning multichannel microwave radiometer (SMMR) on the Nimbus 7 satellite and the spatial sensor microwave/imager (SSMI) on several defense meteorological satellites provide so far the longest, quality-controlled record for studying the intraseasonal, interannual and even decadal Antarctic sea ice variability. Using the above ice data from 1979 to 1996 (1998), *Cavalieri et al.* [1997] and *Zwally et al.* [2002] reported that the total Antarctic sea ice extent and area increased by ~14,300 km^2/yr and ~13,800 km^2/yr (~11,180 km^2/yr and ~10,860 km^2/yr). Regionally, the trends are positive in the Pacific Ocean, Ross and Weddell Seas and negative in the Indian Ocean, Bellingshausen and Amundsen Seas. However, the ice data used in these studies is inadequate for covering one full, and potentially important, solar cycle (~22 years). Additionally, because these time series are relatively short, a single unusual year might substantially affect the estimated trends as well. For example, *Cavalieri and Parkinson* [2003] recently showed that the Antarctic sea ice extent decreased dramatically over 1973–1977, before gradually increased from 1977 to 2002. However, there is a concern about the quality of the satellite-derived ice data prior to 1979, and they did not discuss regional ice trends. Do these ice trends (total and regional) persist in the longer quality-controlled satellite-based ice record (1979–2002)?

[5] During the last two decades, a pronounced warming in the eastern Pacific sector of the Antarctic has occurred, in contrast to a cooling at plateau of East and West Antarctica [e.g., *Comiso*, 2000]. The signatures of atmospheric teleconnections (i.e., El Niño-Southern Oscillation (ENSO), Antarctic Oscillation (AAO), Semi-Annual Oscillation, Pacific-South American Pattern) involving in the Antarctic have been revealed in many studies [e.g., *Jacobs and Comiso*, 1997; *Bromwich et al.*, 2000; *Thompson and Wallace*, 2000; *Kwok and Comiso*, 2002; see *Carleton*, 2003 for a review]. Clearly, the control of the Antarctic sea ice trends is determined by the interactions of physical processes at a variety of spatial and temporal scales. This paper investigates the extent to which the relatively well-understood large scale phenomena: AAO and ENSO can account for the recent Antarctic sea ice variability.

2. Data Sets

[6] The monthly Antarctic sea ice concentrations retrieved from the SMMR/SSMI over the period 1979–2002 [based on a bootstrap algorithm, see *Zwally et al.*, 2002] were used in this study. The monthly Antarctic sea ice drifts derived from the SMMR/SSMI over 1979–2000 [*W. Emery et al.*, personal communication, 2001], and the

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monthly mean 850 hpa geopotential height (GPH), air temperature at 2 m (T), surface zonal (U) and meridional (V) winds south of 45°S from the National Centers for Environmental Prediction (NCEP) reanalysis over 1979–2002 were also used to facilitate the analysis. This period (1979–2002) covers one full solar cycle, different stages of the AAO, and several ENSO events.

3. Results

[7] A linear least-squares fit regression was applied to both the total Antarctic sea ice extent and area, and the Antarctic sea ice concentration anomaly time series (after removing the seasonal cycle) in each grid cell over 1979–2002 to capture the trends. Overall, the total Antarctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown an increasing trend (~4,801 km^2/yr). This is smaller than previous studies have suggested, and is not statistically significant. However, the total Antarctic sea ice area (the cumulative area of the ocean actually covered by at least 15% ice concentrations) has increased significantly by ~13,295 km^2/yr, exceeding the 95% confidence level. The upward trends in the total ice extent and area are robust for different cutoffs of 15, 20, and 30% ice concentrations (used to define the ice extent and area). Regionally, as shown in Figure 1a, the Antarctic sea ice has exhibited a pronounced increasing trend in the central Pacific sector and a markedly decreasing trend in the Bellingshausen/western Weddell sector by ~4–10% per decade. Confidence levels for these regional trends exceed 95% [*Weatherhead et al.*, 1998]. The maximum positive trend (+9.6% per decade, mark P in Figure 1a) arises from the trends in autumn (+15.8%), winter (+6.7%) and spring (+13.6%), since the ice is reduced to the continents in summer. By contrast, the maximum negative trend (−14.3% per decade, mark N in Figure 1a) arises from the trends in summer (−29%), autumn (−18.1%) and spring (−7.5%), since ice cover is almost complete in winter. In addition, the strong out of phase ice trends between the central Pacific sector and the Bellingshausen/western Weddell sector are persistent in seasonal analyses.

[8] Are recent regional ice changes related to well-documented large-scale processes: the AAO and ENSO?

[9] The atmospheric circulation of the southern high latitudes is dominated by a westerly circumpolar vortex that extends from the surface to the stratosphere, which is called the AAO [*Thompson and Wallace*, 2000]. Here, we defined the AAO index as the leading principle component of the empirical orthogonal function analysis of the monthly NCEP 850 hpa GPH anomalies south of 45°S, which explains ~27% of the total variance. The changes in the Antarctic sea ice concentrations based on the linear regression with the AAO index are presented in Figure 2a. A wave-number 3 pattern is visible, with a pronounced dipole pattern between the eastern Ross/Amundsen Sea and the Bellingshausen/northern Weddell Sea. Associated with one positive unit of deviation change in the AAO index, sea ice increases (decreases) by ~3–7% in the eastern Ross/Amundsen Sea (the Bellingshausen/northern Weddell Sea), which is consistent with the surface cooling (warming) on the magnitude of ~0.5–2°C there congruent with the positive phases of the AAO.

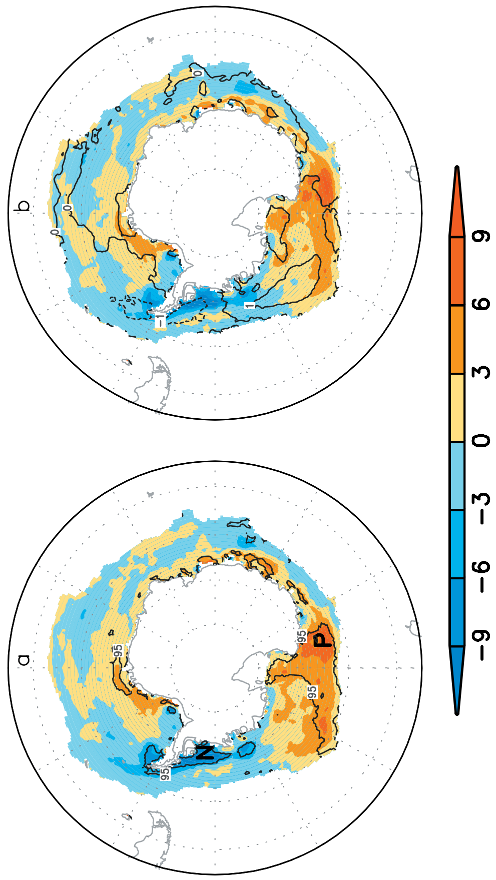

Figure 1. (a) The spatial trends of the Antarctic sea ice concentrations (%, shaded) spanning 1979–2002 derived from the SMMR/SSMI. Contours give the trends above the 95% confidence level. The maximum positive (negative) ice trend is marked by P (N). (b) The spatial trends of the residual Antarctic sea ice concentrations after removing the impacts of the AAO and ENSO (%, shaded). Contours give the trends due to the impacts of the AAO and ENSO.

[10] How does the AAO manifest itself in the aforementioned ice changes? It appears that the response of the Antarctic sea ice to the AAO is a consequence of a combination of the anomalous mean surface heat flux and ice advection. During the high-index polarities of the AAO, an anomalous strong cyclonic circulation in the southeast Pacific leads to an anomalous equatorward (poleward) mean heat flux at the surface in the Ross/Amundsen Sea (the Bellingshausen/Weddell Sea), which encourages (limits) sea ice growth (Figure 3a). In the Ross/Amundsen sector, an anomalous strong intensification of the surface westerlies associated with the positive phases of the AAO (Figure 3a) induces an enhanced Ekman drift to the north. The enhanced northward Ekman drift transports cold water equatorward, reducing the oceanic poleward heat transport. The enhanced northward Ekman drift also leads to enhanced equatorward ice advection especially during the cold season (because the ice is reduced to the Antarctic continents in summer, Figure 3b). The northward dispersion of ice decreases ice thickness and provides more open water for new ice formation in the southern Ross Sea. The newly-formed ice is then advected northward by the enhanced

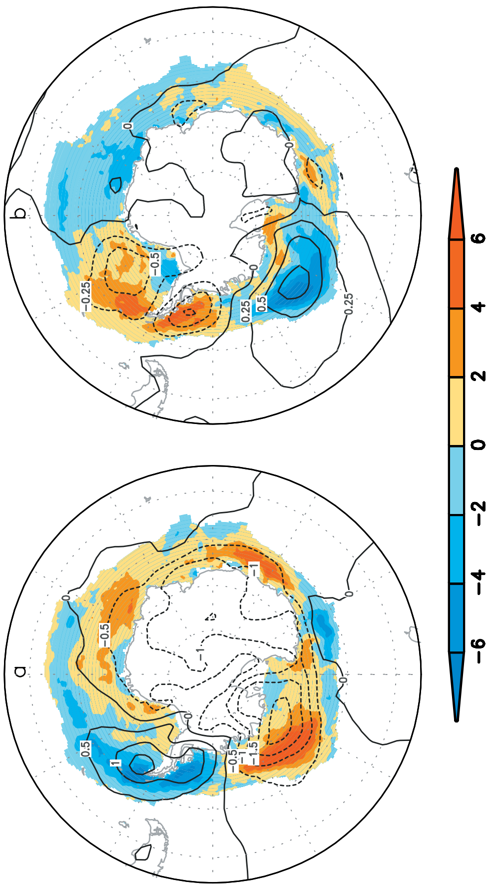

Figure 2. The regression maps of the satellite-based Antarctic sea ice concentrations (shaded) and the NCEP air temperature at 2 m (contour) anomalies on the standardized (a) AAO and (b) ENSO indices (1979–2002). The regression coefficients indicate changes in the ice concentration (%) and air temperature (°C) corresponding to one standard deviation change in the indices.

Ekman drift, thereby increasing ice cover and thickness further north (the northeast Ross Sea, Figure 2a). There is also ice divergence away from both sides of the Antarctic Peninsula (particularly the west side, Figure 3b). The contribution of the strong anomalous poleward mean surface heat flux and ice divergence west of the Antarctic Peninsula explain why the maximum warming associated with the positive AAO index occurs there.

[11] Associated with one positive unit of deviation change in the Niño3 index [www.cdc.noaa.gov/ClimateIndices], a wave-number 2 pattern is visible, and the increase (decrease) of sea ice in the eastern Ross/Amundsen Sea (the Bellingshausen/Weddell Sea) are of similar magnitude (∼3–7%) to the AAO response (Figure 2b) [the Antarctic Dipole, *Yuan and Martinson*, 2001]. The interesting feature is that the positive polarity of the AAO and ENSO indices produces quite opposite sea ice changes in the eastern Pacific and Atlantic Ocean.

[12] Our previous work has demonstrated how the ENSO manifests itself in the Antarctic sea ice [*Liu et al.*, 2002]. Briefly, this mechanism works as follows. During El Niño events, (i) the intensification (relaxation) of the Hadley Cell in the eastern equatorial Pacific (tropical Atlantic) due to an increased (decreased) pole-to-equator meridional temperature gradient leads to (ii) an equatorward (poleward) shift of the subtropical jet. This results in an equatorward (poleward) shift of the storm track in the Ross/Amunden Seas (the eastern Bellingshausen/Weddell sector). The reduced (enhanced) storm activity in the Ross/Amunden sector (the eastern Bellingshausen/Weddell sector) leads to (iv) a strengthening (weakening) of the poleward segment of the regional Ferrel Cell and a weakening (strengthening) of the equatorward regional Ferrel Cell there indirectly by (a) changing the meridional eddy heat flux convergence/divergence, and (b) shifting the latent heat release zone. The changes of the regional Ferrel Cell cause anomalous southward (northward) mean meridional heat flux into the sea ice zone in the Ross/Amunden sector (the eastern Bellingshausen/Weddell sector), which limits (encourages) sea ice growth there. Furthermore, a shift or change of tropical general circulation related to the ENSO variability could perturb the regional mean meridional circulation, thus communicating the changes to high southern latitudes. This might explain the observed phase shift that occurred around 1990 between the ENSO and West Antarctic precipitation [*Bromwich et al.*, 2000; *Genthon et al.*, 2003] and Amundsen sea ice extent (not shown). Interestingly, no phase shift is observed between the ENSO (the Niño3 index) and sea ice extent in the Ross Sea (where an out of phase relationship has persisted) and in the Bellingshausen Sea (where an

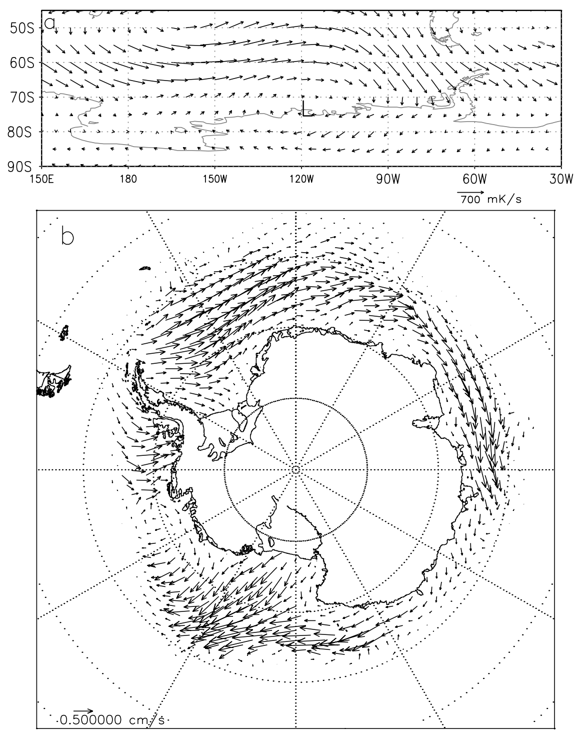

Figure 3. The regression maps of (a) the NCEP mean surface zonal and meridional heat flux anomalies (UT and VT, mK/s) (1979–2002) and (b) the satellite-based Antarctic sea ice drift anomalies (cm/s) derived from the SMMR/SSMI (1979–2000) on the standardized AAO index.

in phase relationship has continued) [*S. Stammerjohn*, personal communication, 2003].

[13] Therefore, the AAO and ENSO do influence the Antarctic sea ice greatly. Considering the variations of the AAO and ENSO are seasonal in nature, we also conducted seasonal regression analyses. The aforementioned spatial signatures based on anomalies for all months in association with the AAO and ENSO are robust in the seasonal analyses, though the magnitude of the responses varies with seasons (not shown). The logical question is whether the recent decadal regional ice trends are due to the AAO and ENSO variability. For the last 24 years, the AAO index has moved toward high-index polarity; the trend for 1979–2002 is 0.18/decade. This indicates a drift toward a spatial pattern with more ice in the eastern Ross/Amundsen sector and less ice in the Bellingshausen/northern Weddell sector. The Niño3 index has a slightly negative trend for 1979–2002 (−0.09/decade). Over the 24-year period, the correlation between the AAO and ENSO is −0.19, which suggests the weak linear relationship between them. As a first approximation, we can consider the AAO and ENSO as relatively independent physical processes.

[14] Employing that assumption, we removed the linearly-regressed impacts of the AAO and ENSO from the original Antarctic sea ice concentration anomaly time series in each grid cell. Trend analysis of the residual Antarctic sea ice concentration anomaly time series shows a spatial pattern extremely similar to the original regional trends (Figure 1b). More specifically, the maximum increasing (decreasing) trend changes from +9.6% and −14.3% (Figure 1a, original) to +9.7% and −12.8% (Figure 1b, residual) respectively. Therefore, the AAO and ENSO can not explain the recent regional Antarctic sea ice trends, though they do influence sea ice dramatically on the intraseasonal (AAO) and interannual (AAO and ENSO) time scales, as illustrated by the regression maps.

4. Discussion and Conclusion

[15] To summarize, we have presented an analysis of the increasing trends in the total Antarctic sea ice extent and area obtained from the satellite-based sea ice record (1979–2002) that is robust for different ice concentration cut-offs and consistent with previous studies. More specifically, the Antarctic sea ice has increased in the central Pacific sector and decreased in the Bellingshausen/western Weddell sector by ~4–10% per decade. These regional trends exceed the 95% confidence level. Our study also demonstrated the manner in which the Antarctic sea ice changes are related to the AAO and ENSO. Positive phases of the AAO result in more (less) ice in the eastern Ross/Amundsen sector (the Bellingshausen/northern Weddell sector) by a combination of the anomalous mean surface heat flux and ice advection. These changes are qualitatively opposite to the signatures of positive phases of the ENSO, which modulates the mean meridional heat flux through the control of the changes in the regional mean meridional circulation. At decadal time scales, the upward (slightly downward) AAO (ENSO) trend during 1979–2002 did indeed lead to more (less) ice in the eastern Ross/Amundsen sector (the Bellingshausen/northern Weddell sector) (Figure 1b). However, the AAO and ENSO cannot explain the recent regional ice trends.

[16] Therefore, to understand these trends, we need to consider less understood large-scale processes such as the Semi-Annual Oscillation, Pacific-South American Pattern [e.g., *Carleton*, 2003] and the potentially complex nonlinear coupling among large-scale processes, and local-scale processes such as katabatic winds. Locally, the meteorology of the Ross Sea sector - which shows significantly positive sea ice trends - is profoundly influenced by katabatic winds. These winds are driven by the regional topography of the Antarctic ice sheet and adjacent transantarctic mountains, which transport cold air across the Ross ice-shelf and through the Ross Sea [*Bromwich*, 2001]. In order to better understand how sea ice may change as climate warms, we need to understand how these processes affect sea ice.

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