Recent Arctic Sea Ice Variability: Connections to the Arctic Oscillation and the ENSO

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[1] Trends in the satellite-derived Arctic sea ice concentrations (1978–2002) show pronounced decreases in the Barents/Kara Seas, between the Chukchi and Beaufort Seas, the central Sea of Okhotsk and a portion of the Hudson/Baffin Bay by ~2–8% per decade, exceeding the 95% confidence level. Qualitatively speaking, positive phases of the Arctic Oscillation (AO) and El Niño-Southern Oscillation (ENSO) produce similar ice changes in the western Arctic, but opposite ice changes in the eastern Arctic. The manner in which the ice changes are related to the AO and ENSO are demonstrated. Over the last 24 years, the magnitude of the ice changes associated with the positive AO trend and the negative ENSO trend is much smaller than the regional ice trends. Thus, more local or less understood large scale processes should be investigated for 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 Y. Hu (2004), Recent Arctic Sea Ice Variability: Connections to the Arctic Oscillation and the ENSO, *Geophys. Res. Lett.*, *31*, L09211, doi:10.1029/2004GL019858.

1. Introduction

[2] Observations and models suggest that the Arctic 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., *Barry et al.*, 1993; *Curry et al.*, 1995; *IPCC*, 2001]. The classic view on the Arctic sea ice change in the context of greenhouse warming is that the ice cover would decrease, because the positive ice albedo/temperature feedback becomes increasingly important as the surface temperature in the Arctic approaches the freezing point in a gradually warming climate. As a sensitive indicator of future climate change, a detailed understanding of the nature and causes of recent Arctic sea ice variability is necessary.

[3] Since the advent of satellite remote sensing, sea ice concentrations retrieved from the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus 7 satellite and the Special 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 Arctic sea ice variability. Using the above ice data for Oct 1978–Dec 1996 (Jan 1979–Dec 1999), *Parkinson et al.* [1999] (*Parkinson and Cavalieri* [2002]) reported that the total Arctic sea ice extent decreased by ~34,300 km^2/yr (~32,900 km^2/yr). Regionally, the trends are negative in the Arctic Ocean, the Barents/Kara Seas and the Sea of Okhotsk, and positive in the Bering Sea and the Gulf of St Lawrence. Because these time series are relatively short, a single unusual year might substantially affect the estimated trends. Recently, *Cavalieri and Parkinson* [2003] showed that the total Arctic sea ice extent decreased by ~36,000 km^2/yr for 1979–2002. However, they did not discuss regional ice trends. Do these regional ice trends persist in the longer quality-controlled satellite-based record (Oct 1978–Sep 2002)?

[4] During the last two decades, the surface air temperature trends show a warming of ~1°C per decade in the eastern Arctic, primarily in the area north of the Laptev and East Siberian Seas, whereas no significant trend is found in the western Arctic, or even a slight cooling in a portion of the Canadian Beaufort Sea [e.g., *Rigor et al.*, 2000]. The signatures of atmospheric teleconnections (i.e., El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Arctic Oscillation (AO)) involved in the Arctic have been revealed in many studies [e.g., *Gloersen*, 1995; *Hurrell*, 1995; *Thompson and Wallace*, 2000]. Clearly, the control of the Arctic sea ice trends is determined by the interactions of physical processes at a variety of spatial/temporal scales. To what extent can the relatively well-understood large scale phenomena (the AO and ENSO) explain the recent Arctic sea ice variability?

2. Data

[5] The monthly Arctic sea ice concentrations retrieved from the SMMR/SSMI over the period Oct 1978–Sep 2002 [based on a bootstrap algorithm, *Parkinson et al.*, 1999] were used. The monthly Arctic sea ice drifts derived from the SMMR/SSMI for Oct 1978–Sep 2000 [*W. Emery et al.*, personal communication, 2001] and the monthly 1000 hpa geopotential height (GPH), air temperature at 2 m (T), zonal (u), meridional (v) and vertical winds (ω) from the surface to the top of the atmosphere of the National Centers for Environmental Prediction (NCEP) reanalysis for Oct 1978–Sep 2002 were also used to

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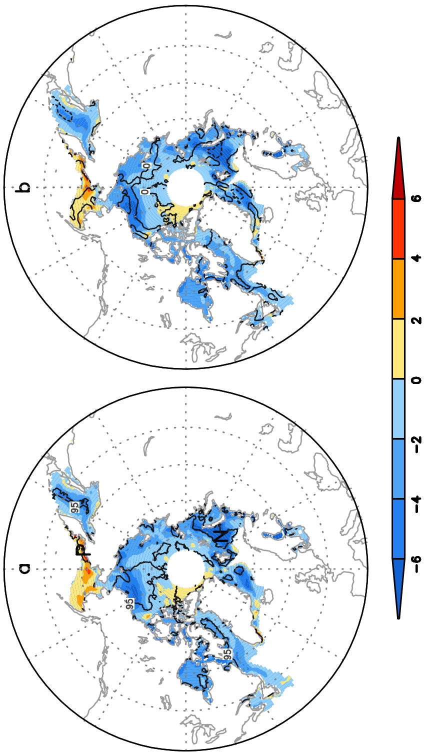

Figure 1. (a) The spatial trends of the satellite-based Arctic sea ice concentrations (%, shaded) spanning Oct 1978–Sep 2002. Contours give the ice trends above the 95% confidence level. The maximum negative (positive) ice trend is marked by N (P). (b) The spatial trends of the residual Arctic sea ice concentrations after removing the impacts of the AO and ENSO (%, shaded). Contours give the ice trends due to the impacts of the AO and ENSO.

facilitate the analysis. This period (Oct 1978–Sep 2002) covers different polarities of the AO and several ENSO events.

3. Results

[6] A linear least-squares fit regression was applied to both the total Arctic sea ice extent and area, and the Arctic sea ice concentration anomaly time series in each grid cell over the period Oct 1978–Sep 2002. Overall, the total Arctic sea ice extent (the cumulative area of grid boxes covering at least 15% ice concentrations) has shown a decreasing trend (~30,848 km^2/yr), which is slightly smaller than previous studies. The total Arctic sea ice area (the cumulative area of the ocean actually covered by at least 15% ice concentrations) has also decreased by ~35,372 km^2/yr. Both trends (total extent and area) exceed the 95% confidence level [*Weatherhead et al.*, 1998]. The significant downward trends in the total ice extent and area are robust for different cutoffs of 15, 20 and 30% ice concentrations and increases gradually with the increasing cutoffs. Regionally (Figure 1a), sea ice has exhibited pronounced decreasing trends in the Barents/Kara Seas, between the Chukchi and Beaufort Seas, the central Sea of Okhotsk and a portion of the Hudson/Baffin Bay by ~2–8% per decade, exceeding the 95% confidence level, and increasing trends in the Bering Sea and a portion of the Canadian Archipelago. The maximum negative trend (−13.7% per decade, marked N in Figure 1a) arises from the trends in winter (−20.4%), spring (−18.8%), autumn (−9.1%) and summer (−6%). The maximum positive trend (+13.6% per decade, marked P in Figure 1a) arises from the trends in winter (+36.3%), autumn (+10%) and spring (+7.7%). In addition, these regional ice trends are quite persistent in the seasonal analyses, except that more sporadic increasing trends appear in the Canadian Archipelago and the Arctic Ocean (60°E–120°E) in winter, and the decreasing trends are almost everywhere in summer.

[7] Are recent regional ice changes related to large-scale processes such as the AO and ENSO?

[8] The atmospheric circulation of the northern high latitudes is characterized by a westerly circumpolar vortex that extends from the surface to the stratosphere [called the AO, *Thompson and Wallace*, 2000]. Here the AO index is defined as the leading principal component of the empirical orthogonal function analysis of the monthly NCEP 1000 hpa GPH anomalies north of 45°N (which explains ~22% of the total variance). Figure 2a shows the changes of sea ice concentrations based on the linear regression with the AO index. Qualitatively speaking, an out of phase relationship between the eastern and western Arctic is visible. Associated with one positive unit of deviation change in the AO index, sea ice decreases (increases) in the Greenland Sea, the Barents Sea and the Sea of Okhotsk (the Bering Sea, the southern Chukchi/Beaufort Seas, and the Northwest Passage: Baffin Bay-Davis Strait-Labrador Sea) by ~2–6% per decade, which is consistent with the

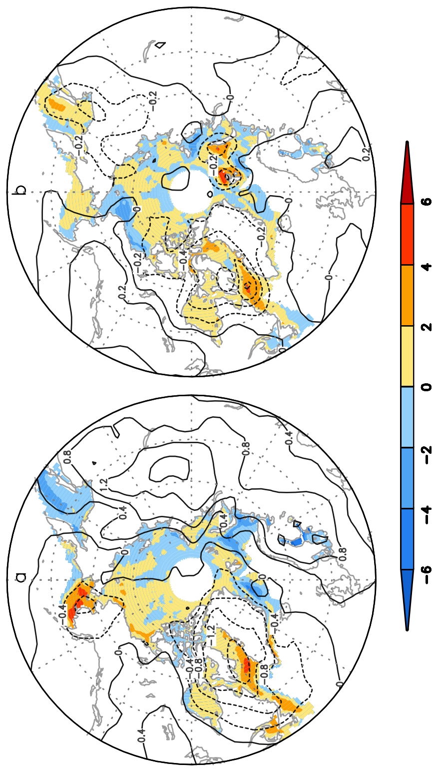

Figure 2. The regression maps of the satellite-based Arctic sea ice concentrations (shaded) and the NCEP 2 m air temperature (contour) anomalies on the standardized (a) AO and (b) ENSO indices (Oct 1978–Sep 2002).

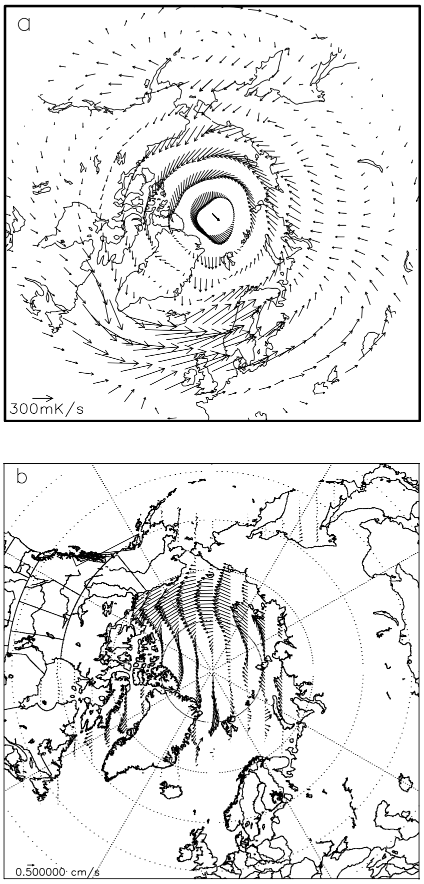

Figure 3. The regression maps of (a) the NCEP mean zonal and meridional heat flux anomalies (uT and vT, mK/s) at the surface (Oct 1978–Sep 2002) and (b) the satellite-based Arctic sea ice drift anomalies (cm/s) (Oct 1978–Sep 2000) on the standardized AO index.

surface warming (cooling) on the magnitude of ~0.4–1.2°C congruent with the positive phases of the AO.

[9] How does the AO manifest itself in the above ice changes? At the sea ice edge zones, during the positive polarities of the AO, an anomalous cyclonic circulation in the north Atlantic leads to an anomalous northeast wards surface mean heat flux in the Barents Sea (Figure 3a), which limits sea ice growth there. By contrast, there is southeast wards advection of surface mean heat flux in the Northwest Passage (Figure 3a), which encourages sea ice growth there. The climatological sea ice motions are characterized by an anticyclonic circulation in the Beaufort Sea and the Transpolar Drift Stream (the zone of high ice velocity across the Arctic Ocean toward Fram Strait). In the Arctic Ocean, an intensified southwesterly flow associated with the positive phases of the AO (Figure 3a) induces an enhanced Ekman drift to the right of the wind forcing, which leads to an anomalous cyclonic ice circulation as shown in Figure 3b. This is consistent with the results of *Rigor et al.* [2002]. The increased ice divergence from the Laptev and East Siberian Seas decreases ice thickness and provides more open water for new ice formation there, which increases latent heat release through thinner ice and more open water, contributing to the local warming (Figure 2a). The newly-formed ice is then advected by the enhanced Ekman drift to the Chukchi/Beaufort Sea, thereby increasing ice cover and thickness there (Figure 2a). In addition, there is an increased ice export from Fram Strait (Figure 3b), which is similar to the intensified ice export from Fram Strait associated with the positive phases of the NAO [*Kwok*, 2000].

[10] Associated with one positive unit of deviation change in the Niño3 index [http://www.cdc.noaa.gov], sea ice generally increases in the Arctic, except for the Chukchi and southern Beaufort Seas, the southern Barents Sea and Kara Sea by ~1–4% per decade (Figure 2b). How does the ENSO signal manifest itself in the above ice changes? During El Niño events, 1) the intensification (relaxation) of the Hadley Cell in the eastern tropical Pacific (tropical Atlantic) due to an increased (decreased) pole-to-equator meridional temperature gradient leads to 2) an equatorward (poleward) shift of the subtropical jet, which results in 3) an equatorward (poleward) shift of the storm track in *Region 1*: the northeast Pacific/northwest America sector (*Region 2*: the northeast America/northwest Atlantic sector). The shift of the storm tracks changes the regional Ferrel Cell (The mean Ferrel Cell rises in the high latitudes and sinks in the mid-latitudes). As shown in Figure 4 (the fluctuations of the regional Ferrel Cell from El Niño to La Niña), in *Region 1*, an anomalous poleward (equatorward) air advection appears near the surface north of ~40°N during the El Niño (La Niña) events, which indicates the strengthening (weakening) of the surface segment of the regional Ferrel Cell during the El Niño (La Niña) events. This anomalous poleward (equatorward) air advection extends from the surface to the top of the atmosphere. At the same time, there are a) anomalous rising (sinking) air centered ~40°N, and b) anomalous sinking (rising) air centered ~70°N. They tend to weaken (strengthen) the upper segment of the regional Ferrell Cell. In *Region 2*, the circulation patterns for the El Niño (La Niña) cases are qualitatively opposite to those described in *Region 1* for the El Niño (La Niña) cases, but the strength of the anomalies is relatively weaker. Thus, during the El Niño events, the changes of the regional Ferrel Cell cause anomalous poleward (equatorward) mean meridional heat flux into the sea ice zones in *Region 1* (*Region 2*), which increases (decreases) air temperature and limits

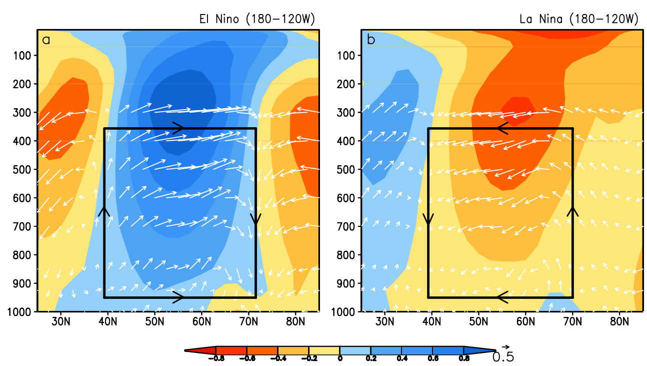

Figure 4. The 180°–120°W averaged longitude-pressure sections of meridional wind anomalies (shaded, m/s), meridional (m/s × 3) and vertical wind anomaly (Pa/s × 300) vectors for the composites of the (a) El Niño and (b) La Niña years (we average the Niño3 index from June of the first year to May of the second year to define the ENSO year).

(encourages) sea ice growth in the Chukchi and southern Beaufort Seas (the Northwest Passage).

[11] Therefore, the AO and ENSO do influence the Arctic sea ice greatly. An interesting feature is that the positive polarities of the AO and the El Niño events produce similar ice changes in the western Arctic, but opposite ice changes in the eastern Arctic. Since the variations of the AO 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 AO and ENSO are quite persistent in the seasonal analyses, though the magnitude of the responses varies with seasons (not shown).

[12] The logical question is whether the recent regional ice trends are due to the AO and ENSO variability. The AO index has a positive trend of 0.15/decade for Oct 1978–Sep 2002, which indicates a drift toward a spatial pattern with more (less) ice in the western (eastern) Arctic. The Niño3 index has a negative trend for Oct 1978–Sep 2002 (−0.12/decade), which in general produces more ice in the Arctic, except the Chukchi and southern Beaufort Seas, the southern Barents Sea and Kara Sea. Over the 24−year period, the correlation between the AO and ENSO is −0.02, which suggests no linear relationship between them. As an approximation, we can consider the AO and ENSO as independent physical processes.

[13] Employing that assumption, we removed the linearly-regressed impacts of the AO and ENSO on the ice from the original sea ice concentration anomaly time series in each grid cell. Trend analysis of the residual sea ice concentration anomaly time series shows a spatial pattern extremely similar to the original regional ice trends (Figure 1b). Specifically, the maximum decreasing (increasing) trend changes from −13.7% and +13.6% (Figure 1a, original) to −12.8% and +12.9% (Figure 1b, residual) respectively. Therefore, the AO and ENSO can not explain the recent regional ice trends, though they do influence sea ice dramatically on the intraseasonal (AO) and interannual (AO and ENSO) time scales, as illustrated by the regression maps.

4. Discussion and Conclusion

[14] To summarize, the decreasing trends in the total Arctic sea ice extent and area during Oct 1978–Sep 2002 are robust for different ice concentration cut-offs and consistent with previous studies. Specifically, sea ice has decreased in the Barents/Kara Seas, between the Chukchi and Beaufort Seas, the central Sea of Okhotsk and a portion of the Hudson/Baffin Bay and increased in the Bering Sea and a portion of the Canadian Archipelago. Our study also demonstrated the manner in which the ice changes are related to the AO and ENSO. Positive phases of the AO result in more (less) ice in the western (eastern) Arctic by a combination of the anomalous mean surface heat flux and ice advection. The El Niño events result in less (more) ice in the Chukchi/Beaufort Seas (the Northwest Passage) by changing the regional Ferrel Cell, which modulates the mean meridional heat flux. The upward (downward) AO (ENSO) trend during Oct 1978–Sep 2002 leads to more ice in the Kara, Chukchi and Beaufort Seas and the Northwest Passage, which is opposite to the regional ice trends (Figure 1b). Moreover, the magnitude of the ice changes associated with the AO and ENSO is much smaller than the regional ice trends.

[15] Therefore, to understand these regional trends and how sea ice may change as climate warms, we need to consider less understood large-scale processes and the potentially complex nonlinear coupling among large-scale processes, and local-scale processes such as river discharge into the Arctic Basin from Russia and Canada, and glacier discharge from the Greenland.

[16] **Acknowledgment.** This research was supported by the NASA.

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