ARCTIC SEA ICE SPATIAL BEHAVIOUR AND CLIMATE TRENDS

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Principal components analysis of 30 years of Arctic monthly sea ice concentration data (1979 – 2009) for both the winter maximum period (JFMA) and summer minimum period (JASO) reveals 3 primary ice concentration spatial patterns (each with an arbitrary ‘positive’ and ‘negative’ phase) for each season. The study data set spans a period during which summer sea ice extent declines by 27%, and winter extent declines by 9%. Climate data extracted for the years with high loadings of the individual patterns provide insight into the underlying circulation and air temperature conditions for each of the patterns. Several of the patterns show changes in prevalence over the 3 decades of the analysis period, suggesting ongoing shifts in climatic conditions leading to sea ice loss. The first component pattern for summer, in its positive phase, appears to be related to anomalously high air temperatures in the Arctic basin; this pattern shows high positive phase loadings in recent years. The second summer component pattern is primarily related to the strength of the trans-polar drift and air circulation anomalies, and its negative phase, with strong transpolar drift, is more common over time. For the winter season, the primary component pattern is closely tied to the Arctic Oscillation, and both were dominantly positive in the mid-1980s and early 1990s. The second winter pattern appears to be related again to strong Arctic warming, and its negative phase, associated with warm years, has increased in prevalence over the study period.

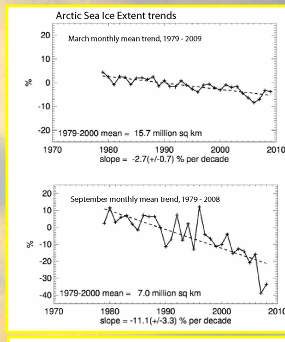

Figure 1. Arctic sea ice extent changes, 1978 – 2009 for March (a) and 1979 – 2008 for September (b).

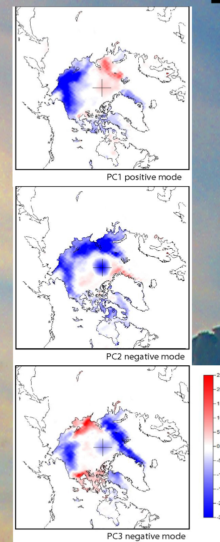

Figure 2. The three extracted summer sea ice patterns from the 1978 – 2006 sea ice concentration data, shown in the mode (positive or negative) that has become more prevalent over time. The opposite mode for each principal component is the reverse of the patterns shown.

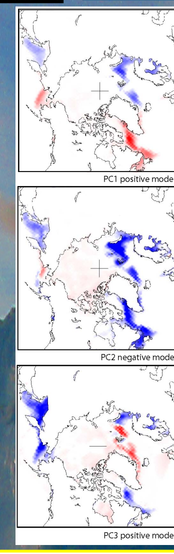

Figure 3. The three extracted winter sea ice patterns from the 1978 – 2007 sea ice concentration data, shown in the mode (positive or negative) that has become more prevalent over time. The opposite mode for each principal component is the reverse patterns shown.

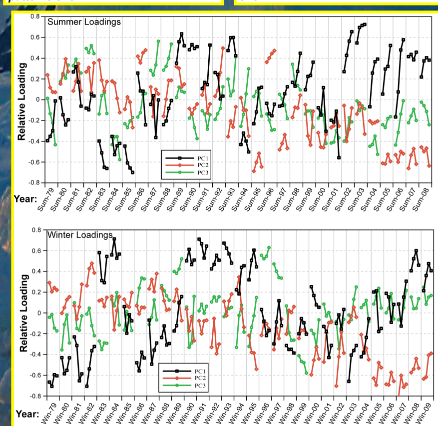

Figure 4. Upper panel: Loadings for the 3 summer principal component patterns; Low panel: Loadings for the 3 winter principal component patterns.

Extracted Summer Climate Patterns associated with sea ice decline

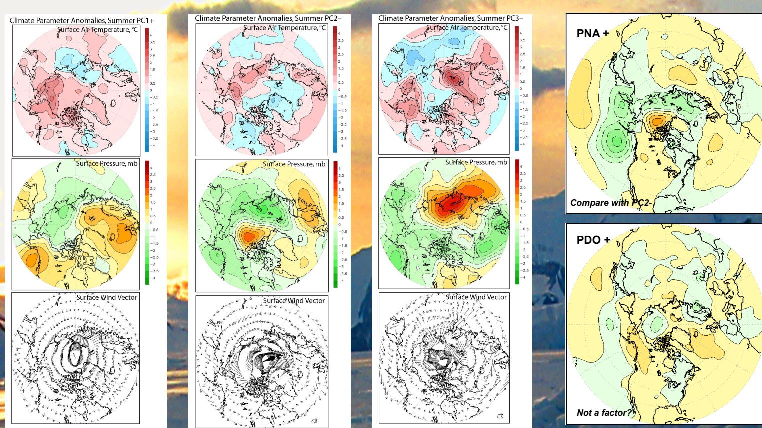

Figure 5. Surface temperature, pressure, and wind anomaly patterns associated with the three leading principal components of the summer patterns of ice concentration (in the phase associated with ice decline).

The climate patterns directly associated with summertime sea ice decline appear be related to three trends: broad increasing warmth throughout the Arctic, with no clear associated pressure pattern (PC1+); a stronger PNA pattern, in particular the ‘dipole anomaly’ and increased high pressure over the Beaufort Sea (PC2-); and an increased tendency for very warm surface temperatures and high pressure anomalies over the Kara and Barents Seas. The latter pattern is presumably a result of increased delivery or increased temperature of the warm water pool of the northernmost North Atlantic. The Pacific Decadal Oscillation (PDO) appears not to be a factor in the decline.

Extracted Winter Climate Patterns associated with sea ice decline

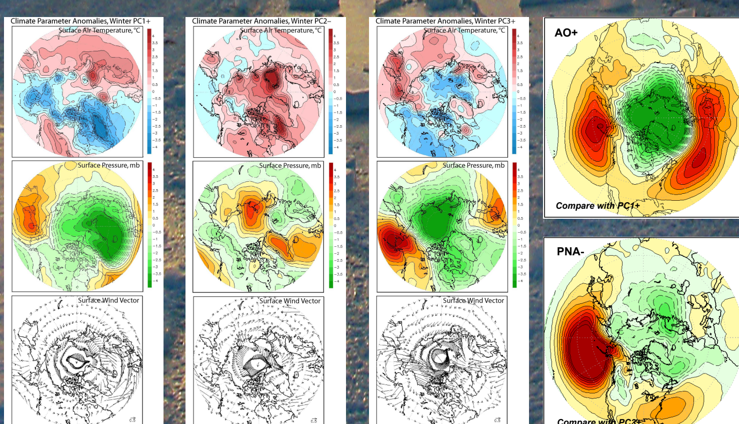

Figure 6. Surface temperature, pressure, and wind anomaly patterns associated with the three leading principal components of the winter patterns of ice concentration (in the phase associated with ice decline).

Winter climate patterns extracted from the sea ice trends of winter ice decline are closely tied to the Arctic Oscillation (AO; linked to the PC1 pattern), the Pacific North American pattern in its negative phase (PNA-, associated with the PC3+ ice and climate patterns) and a pattern associated with the strong warming anomaly along the retreating ice edge of the northern North Atlantic and Baffin Bay.

While the AO is the most widely recognized pattern in Arctic climatology, our analysis indicates it has little to do with winter sea ice decline. It appears that this pattern simply creates differently located, roughly equal anomalies in ice concentration and extent. Instead the first and second principal component of the summer patterns and the second principal component of the winter pattern appear to be most directly associated with the general trend towards reduced sea ice.

That Arctic climate changing is of course obvious, but our study has identified several specific climate patterns that appear to be responsible for much of the change. Moreover, a specific combination of relative loadings of the patterns and modes, favoring lower ice concentration, appears to be dominating climate in the past few years. Summer seasons (JASO) since 2002 have consistently seen strong loadings of PC1+ that increase through the summer months (to +0.4 to +0.75), and low to moderate loadings of PC2- and PC3- (near 0 to –0.6). Winter seasons since 2004 have had a repetitive pattern of strong PC2- loadings (-0.6 for 2005, 2006, and 2007) and near-zero to mildly positive loading of PC1+ and PC3+. In other words, the Arctic is now exhibiting persistent climate patterns that were formerly only a component of a more variable climate system. The new organization of the atmosphere is apparently related to much lower extent and concentration of sea ice. No other period within the study years shows a similarly consistent arrangement of pattern modes and loadings.

Are these trends in climate causing, or a result of, the loss of sea ice? The recent-year summer patterns lead to large areas of open water by September/ October; several studies show this consistently leads to anomalously warm late summer and autumn SAT, and in turn this has been shown to be affecting patterns of autumn and winter climate throughout the northern temperature and polar latitudes (Francis et al., 2009). Other studies have pointed out that Arctic sea ice has become younger and thinner over the study period, particularly since the late 1990s (Drobot et al, 2008; Kwok et al., 2009). This thinning is due to both circulation patterns that favor old ice export through Fram Strait, and the trend towards complete summer ice loss in the southern portions of the Beaufort Gyre (Nghiem et al., 2007; Maslanik et al., 2007). Wind anomalies in the dominant winter patterns, PC2- and PC3+, favor export. The dominant summer pattern (PC2+) includes southerly wind anomalies and warm conditions over the Alaskan coast. Thus it is likely that the climate patterns are causal for much of the sea ice anomaly. But, there is also evidence of warm water intrusions into the Arctic that may lead to basal melt; and it is clear that open water areas inherently lead to SAT warm anomalies (since the surface-air interface is being buffered by latent heat at near the freezing point). To the extent that ocean circulation changes and warm-water intrusions are forcing sea ice concentration and extent anomalies, it is possible that the sea ice trends are causal to the climate pattern change. Evidence for this would be a climate pattern where the wind anomaly is inconsistent with the sea ice pattern; for example, a place where the wind anomaly should be pushing the ice south, but the ice anomaly is negative in that region.