On the Role of the Arctic and Antarctic Oscillations in Polar Climate

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1. Introduction

The Arctic Oscillation (AO) and its Southern Hemisphere counterpart, the Antarctic Oscillation (AAO) are recurrent spatial patterns that play an important role in the climatic variability on time scales of seasons and longer. They are defined as the leading empirical orthogonal function (EOF1) of the sea-level pressure field (SLP) in their respective hemispheres. Because they tend to be somewhat concentric about the poles, they are frequently referred to in the scientific literature as the Northern and Southern Hemisphere annular modes (NAM and SAM). The AO is closely related to the North Atlantic Oscillation (NAO) (Hurrell 1995). The term "oscillation" is something of a misnomer, since neither of these patterns exhibits periodic or quasi-periodic fluctuations in the time domain. It is best to think of them simply as preferred spatial patterns of SLP anomalies that may appear, with either polarity, in conjunction with equally distinctive patterns in temperature, wind, and other climatic variables.

Intimations of the existence of the AO/NAO date back over several centuries (van Loon and Rogers 1978, Stephenson 2002. Exner (1913) published correlation maps of SLP and surface air temperature (SAT), as shown in Fig.1, which presage patterns that appear in much more recent studies. Kidson (1988) was arguably the first to point out the existence of the AAO, which he referred to as the "high latitude mode". The terms

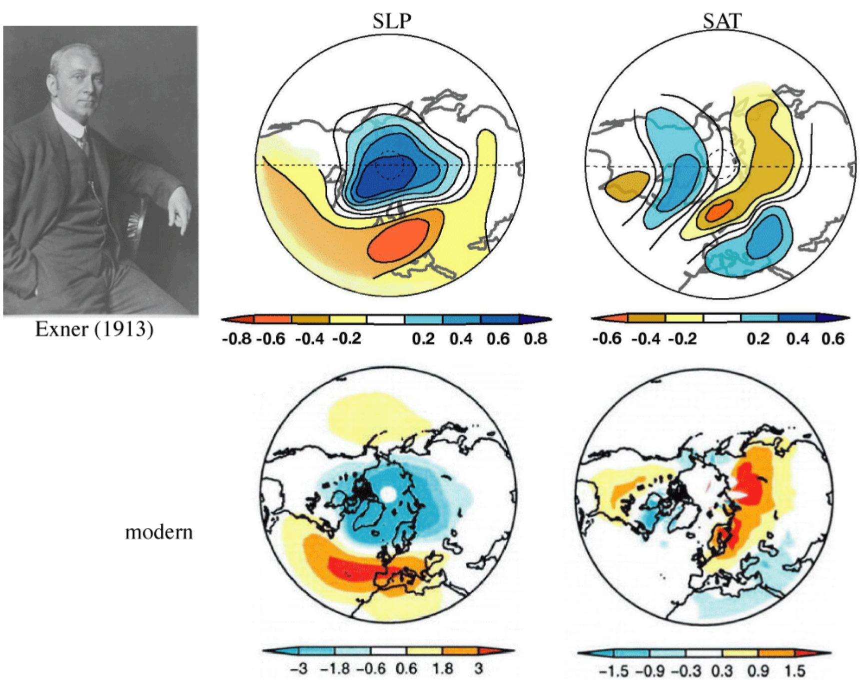

Figure 1 Representations of the sea-level pressure (left) and surface air temperature (right) fields associated with the AO presented by Exner (1913) shown in the top panels are remarkably similar to regression maps based on data for recent decades shown in the bottom panels. Courtesy of Kevin Wood, JISAO.

AO and AAO were first used in studies of Thompson and Wallace (1998, 2000) and Gong and Wang (1999). The structure of the AO and AAO are documented in Fig. 2. Both are characterized by north-south "see-saws" in the SLP field, with nodal lines ~55 latitude, as shown in the lower panels. The corresponding zonal wind anomalies tend to be strongest at 35 and 55 degrees latitude, with a node ~45 degrees, as shown in the upper panels of Fig. 2. The zonal wind perturbations extend upward from the Earth's surface into the lower stratosphere and they amplify with increasing height. The so-called "high index" polarity of the annular modes (i.e., the SLP pattern observed when the leading principal component of the SLP field is positive) is characterized by anomalously low SLP over the poles and enhanced westerlies in the 55 degree latitude belt, consistent with the sign conventions in Fig. 2. The AO is most clearly defined during the boreal winter and early spring months; during summer it shrinks to a more regional pattern centered over the Arctic. The seasonality of the AAO is not as pronounced.

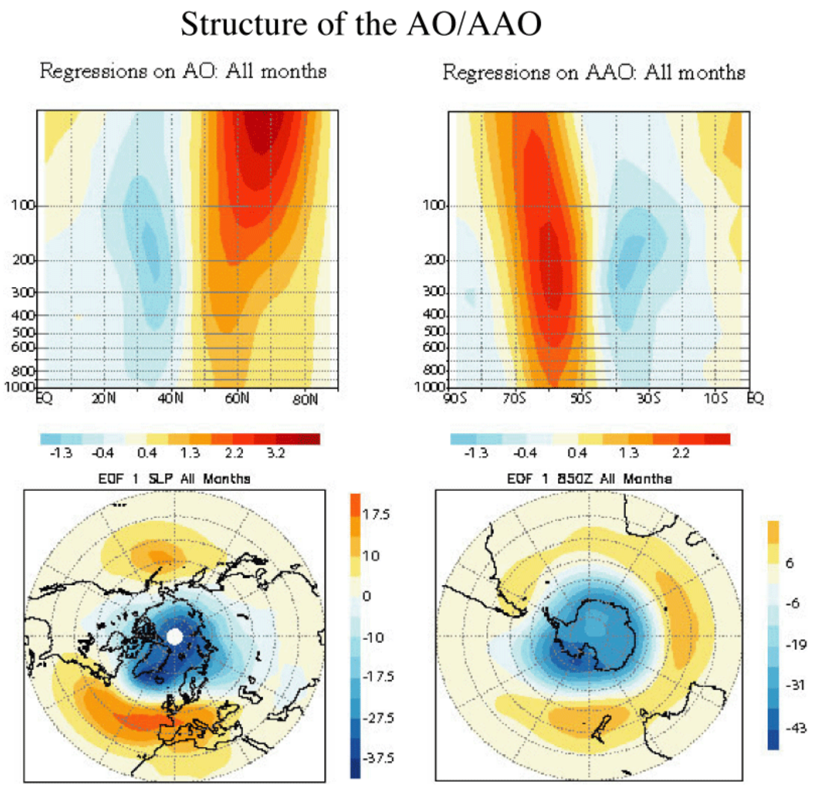

Figure 2 Structure of the AO (left) and AAO (right) as revealed by regression maps. The top panels show vertical cross sections of zonally-averaged zonal wind and the lower panels show sea-level pressure for the AO and 850-hPa height for the AAO. The amplitudes in the figure correspond to the anomalies corresponding to a value of +1 of the standardized AO or AAO index. From Thompson and Wallace (2000).

The high index polarity of the AO and AAO may also be interpreted in terms of a poleward displacement of the storm tracks and the associated belts of maximum westerly surface winds relative to their climatological-mean positions near 45 degrees latitude (e.g., see Lorenz and Hartmann 2003 and Codron 2005). In the case of the AO this description applies mainly to the North Atlantic sector; the AO signature in the Pacific sector is quite weak. Wallace (2000), Ambaum et al. (2001) and Wallace and Thompson (2002) debated the question of whether there exists an annular mode of variability, as distinct from the more sectorial NAO, focused over the Atlantic sector. They agreed that the NAO can be described as a linear combination of the two leading EOFs of the SLP field, as depicted in Fig. 3. Ambaum et al. prefer to think of the EOFs as linear combinations of the more regional NAO and Pacific/North American (PNA) patterns. Regardless of whether one prefers to think of the AO or the NAO as the more fundamental pattern of variability, it is clear that the AO and its Southern Hemisphere counterpart are closely linked to their respective stratospheric polar vortices and to a variety of high latitude phenomena and processes. The AO label is perhaps more appropriate for this conference because it emphasizes the link with high latitude phenomena and the many parallels between it and the AAO.

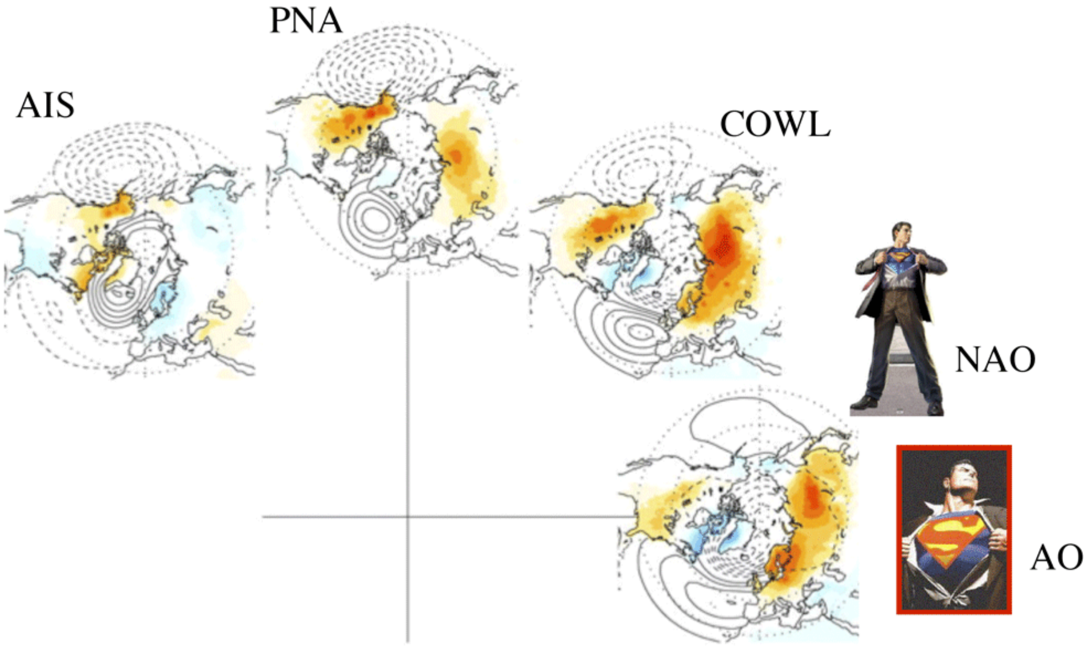

Figure 3 Patterns of sea-level pressure (contours) and surface air temperature (colored shading) observed in association with a various linear combinations of the leading principal components (PC1 and PC2) of the Northern Hemisphere SLP field. The four patterns shown in the figure are samples at 0, 45, 90 and 135 degrees in a two-dimensional phase space in which PC1 is plotted on the x-axis and PC2 on the y-axis. By definition, the pattern along the x-axis near the Superman logo corresponds to the AO. The NAO (represented by the Clark Kent logo) corresponds to an angle of 15 degrees in the phase space. The PNA pattern lies at an angle of around 105 degrees and the cold ocean - warm land (COWL) pattern (Wallace et al. 1995) and the Aleutian - Icelandic seesaw (AIS) (Honda and Nakamura (2001) at angles of around 45 and 135 degrees, respectively. After Quadrelli and Wallace (2004). It should be noted that not everyone agrees with the assignment of the Superman logo to the AO and the Clark Kent logo to the NAO.

2. The temperature signature of the AO/AAO

The surface air temperature patterns of temperature anomalies observed in association with the high index polarity of the AO/AAO can be inferred by regressing the surface air temperature field upon the AO-index, defined as the leading principal component of SLP (or 850-hPa height in the case of the AAO). Figure 4 shows the temperature pattern for the AO during the months January through March on a map projection that emphasizes the western Arctic. Note the similarity to Exner's pattern (Fig. 1) published nearly a century ago: the only place where the patterns in Figs. 1 and 4 don't match up well is over western North America where the temperatures are only weakly correlated with the AO and where Exner's analysis must have been limited to just a few stations with short periods of record. From an inspection of Fig. 4 it is evident that the high index polarity of the AO is marked by above normal temperatures over the high latitude continents with the exception of sparsely populated regions of eastern Canada, Alaska and far eastern Siberia. Such intervals are marked by an absence of major Northern Hemisphere cold air outbreaks (Thompson and Wallace 2001) and would be expected to be marked by an anomalously low demand for home heating fuels on the world market.

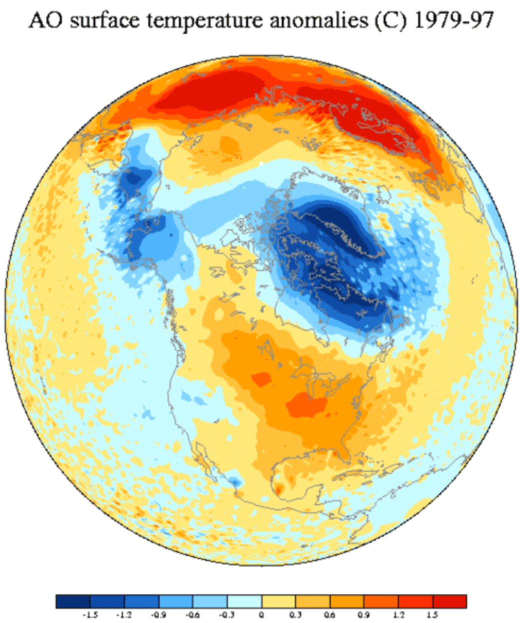

Figure 4 Surface air temperature pattern associated with the AO as derived from regression analysis. The pattern over lower latitudes is based on the NCEP Reanalyses, but the analysis over the Arctic was enhanced using data from drifting buoys. (Courtesy of Ignatius Rigor)

It is shown in Fig. 5 that spatial patterns of temperature anomalies very much like the one for the AO can be obtained by regressing the hemispheric surface air temperature field upon temperature time series at grid-points or stations near the respective centers of action of the AO regression pattern in Fig. 4. The marked similarity between the one-point regression patterns for widely separated sties and the AO regression pattern

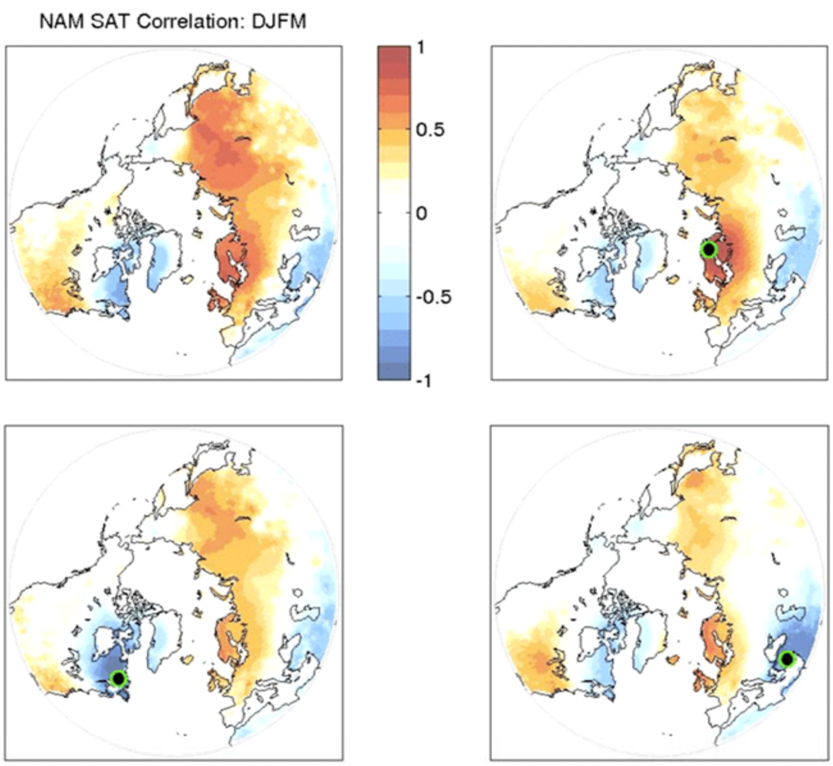

Figure 5 Upper left panel: Surface air temperature pattern associated with the AO, as in previous figures. Other panels: One-point correlation maps for surface air temperature at grid points corresponding to the three primary centers of action of the AO. (Courtesy of Justin Wettstein)

confirms that the AO is truly a hemispheric pattern and not just a statistical construct. It also suggests that temperature time series from certain favored sites (or a linear combination thereof) might serve as a useful proxy time series for the AO. It is evident from Fig. 4 that one of these favored sites is Ellesmere Island for which there are prospects of an extended ice core record. The pattern of temperature anomalies observed in association with the high index polarity AAO is marked by weak negative anomalies over the Antarctic continent and large positive anomalies over the Antarctic peninsula, as shown in Fig. 6. The positive anomalies over the peninsula are attributable to a strengthening of the westerlies at those latitudes, which enhances the advection of relatively warm marine air on the upwind side of the peninsula and the frequency of occurrence of adiabatically warmed, downslope flows on the leeward side (Orr et al. 2004).

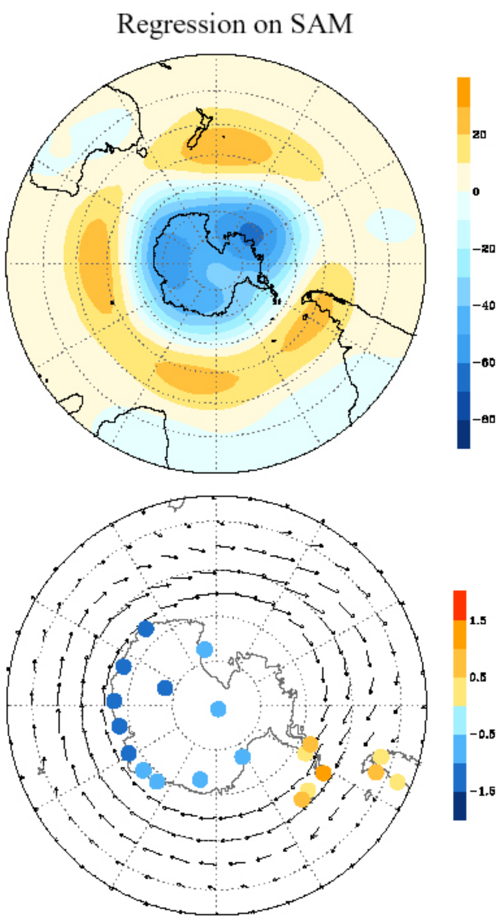

Figure 6 Surface air temperature pattern associated with the AAO as derived from NCEP reanalyses (upper panel) and from station data (lower panel) for the period of record 1979-2001. From Thompson and Solomon (2002).

3. Impact on surface winds and ocean currents

The surface wind signature associated with the AAO lies directly over the Antarctic Circumpolar Current (ACC). High-index conditions of the AAO are marked by anomalously strong surface winds and vice versa. Alternatively, the AAO may be viewed as influencing shifting the belt of strongest westerly surface winds poleward during high-index conditions and vice versa. On the basis of quantitative estimates of the wind stress over the Southern Hemisphere, Hall and Visbeck (2002) concluded that the robustness of the mechanisms relating the SAM to ocean variability suggests that the SAM is an important source of large-scale variability in the Southern Hemisphere ocean. Toggweiler et al. (2006) have proposed that the AAO response to orbitally-induced global warming and cooling may have been instrumental in producing the large changes in atmospheric carbon dioxide concentrations observed in association with transitions between glacial and interglacial states. They argue that under present (interglacial) conditions, the AAO is in a relatively ‘high-index’ state and the Southern Hemisphere westerly wind belt is centered directly over the ACC. Under these conditions the wind-driven vertical mixing in this belt penetrates deep enough to ventilate the Antarctic cell of the thermohaline circulation, which is characterized by sinking in the Ross and Weddell Seas, the northward flow of Antarctic bottom water, and mid-level return flow. Citing paleoclimatic evidence that during the ice ages, the AAO was in low-index state relative to today, they argue that the vertical mixing during glacial epochs isn't strong enough to ventilate the Antarctic cell. When the ventilation stops, the cell weakens, allowing organic matter falling from the euphotic zone to accumulate, thereby removing carbon from the atmosphere. With the onset on interglacial conditions, the winds over the ACC strengthen, ventilation resumes, and the stored carbon is returned to the atmosphere.

4. Connections with the stratosphere

The upward extension of the AO and AAO into the stratosphere in vertical cross sections shown in Figure 2 reflects a tendency for a dynamical coupling between tropospheric and stratospheric circulations that is manifested at the Earth's surface in patterns that project strongly upon the AO/AAO. That the amplitude of these regression increases with height and the associated correlations are very strong suggests that phenomena or processes that perturb the wintertime stratospheric polar vortex should produce distinctive AO/AAO signatures at the Earth's surface. This section provides several examples. Baldwin and Dunkerton (2001) considered the pattern of circulation anomalies observed in association with what they refer to as "weak and strong stratospheric polar vortex events", as defined by geopotential height anomalies over the polar cap region at the 10-hPa-level. In some of these events the geopotential height anomalies extend downward all the way to the Earth's surface, whereas in others they are largely confined to stratospheric levels, as illustrated in Fig. 7. Composites based on large numbers of events, shown in Fig. 8, exhibit a pronounced downward propagation of the anomalies into the troposphere, where they persist for about 2 months, much longer than the conventional 2-3 week predictability limit of tropospheric weather systems. During these extended intervals, the observed SLP anomalies shown in Fig. 9 bear a striking resemblance to the AO. Midwinter and spring (or final) stratospheric warmings, which are characterized by abrupt weakenings or entire eliminations of the wintertime stratospheric polar vortex tend to be followed by extended intervals of low-index AO and vice versa. In a similar manner, the springtime breakdown of the Antarctic stratospheric polar vortex in November or December tends to be followed by an extended interval of low-index AAO conditions. The stratospheric polar vortex is subject to a number of external influences that include the quasi-biennial oscillation (QBO) in equatorial stratospheric zonal wind, which influences

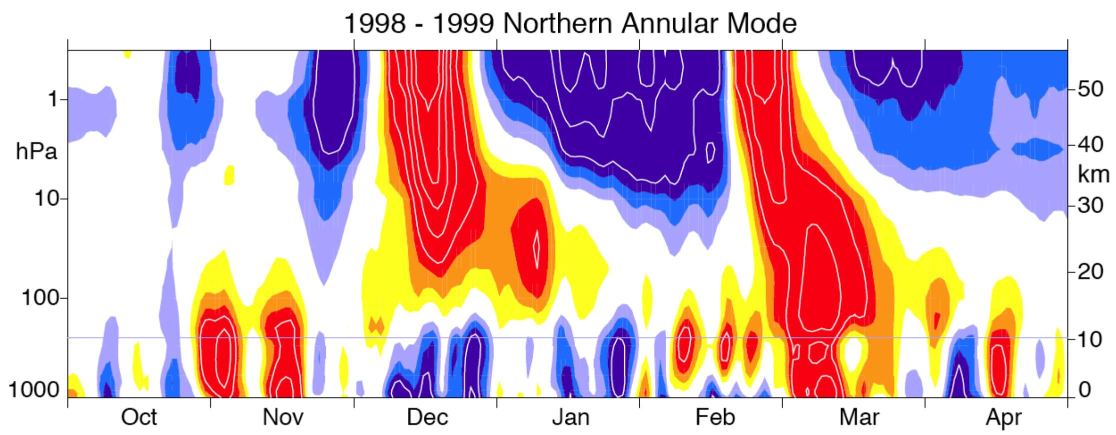

Figure 7 Time-height section of geopotential height anomalies over the polar cap region. At the upper levels the anomalies are indicative of the strength of the stratospheric polar vortex, with dark blue indicative of lower than normal heights and a stronger than normal vortex. At the lower levels they are indicative of the polarity of the AO, with blue indicative of high-index. After Baldwin and Dunkerton (2001).

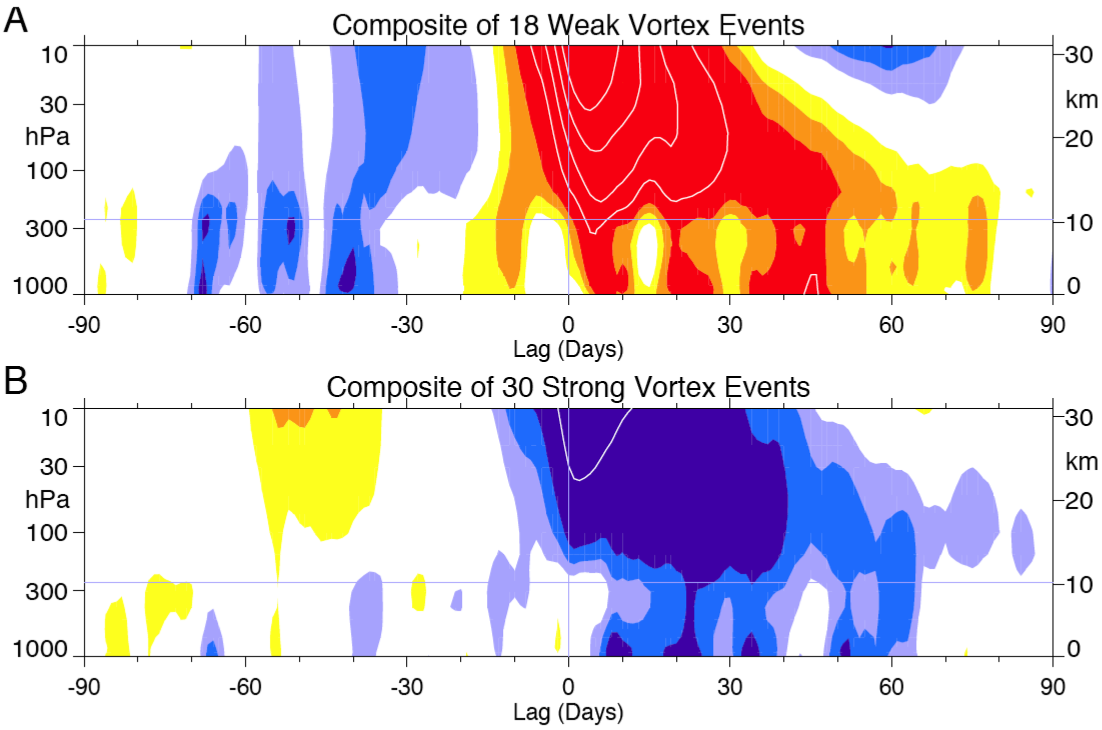

Figure 8 As in Fig. 7, but for composites of weak and strong polar vortex events, as indicated, based on the geopotential height anomalies at the 10-hPa-level. The composite shown in the top panel corresponds to midwinter sudden stratospheric warmings, which are generally marked by a pronounced weakening or complete breakdown of the polar night jet, a belt of strong westerly winds at stratospheric levels that encircles the pole at a latitude of ~65 N. After Baldwin and Dunkerton (2001).

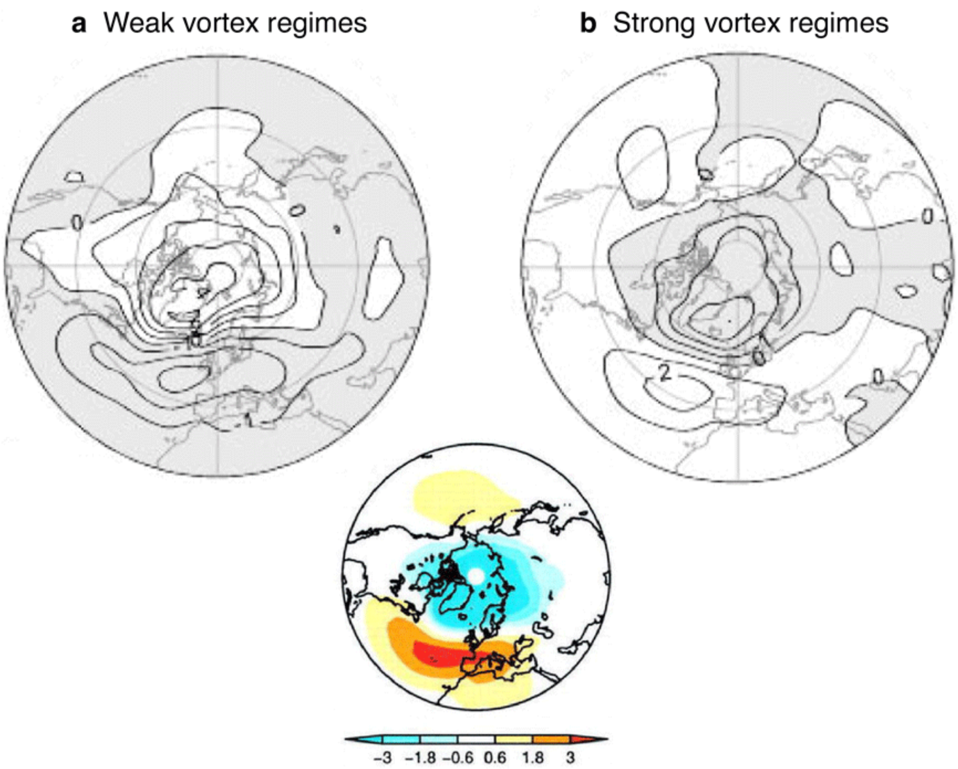

Figure 9 Composite sea-level pressure charts for the 60 days following weak and strong index events. After Baldwin and Dunkerton (2001)

lateral planetary-wave propagation, and solar activity and volcanic eruptions, both of which are capable of imposing meridional heating gradients on the stratospheric circulation. An AO-like circulation is observed in association with the QBO: winters in which the winds over the equator at the 50-hPa level less prone to midwinter warmings and are accordingly biased toward high-index AO and vice versa, as shown in Fig. 10. Winters following volcanic eruptions are characterized by an anomalously strong meridional heating gradient at stratospheric levels because of the presence of sulfate aerosols, which enhances the absorption of solar radiation at subpolar latitudes. In response to the stronger heating gradient, the stratospheric polar vortex tends to be stronger and less prone to midwinter warmings, resulting in high-index AO conditions at the Earth's surface (Robock and Mao 1995).

Though there remain questions as to whether the AO and AAO are true "modes" of variability in a strict dynamical sense of the term (e.g., see Feldstein 2000, Cash et al, 2002), the fact that these patterns emerge in composites based on stratospheric sudden warmings, the QBO and volcanic eruptions provides reassurance that they are important patterns of variability from a climate perspective. They are of particular importance from the perspective of high latitude climate, as discussed in the next two sections.

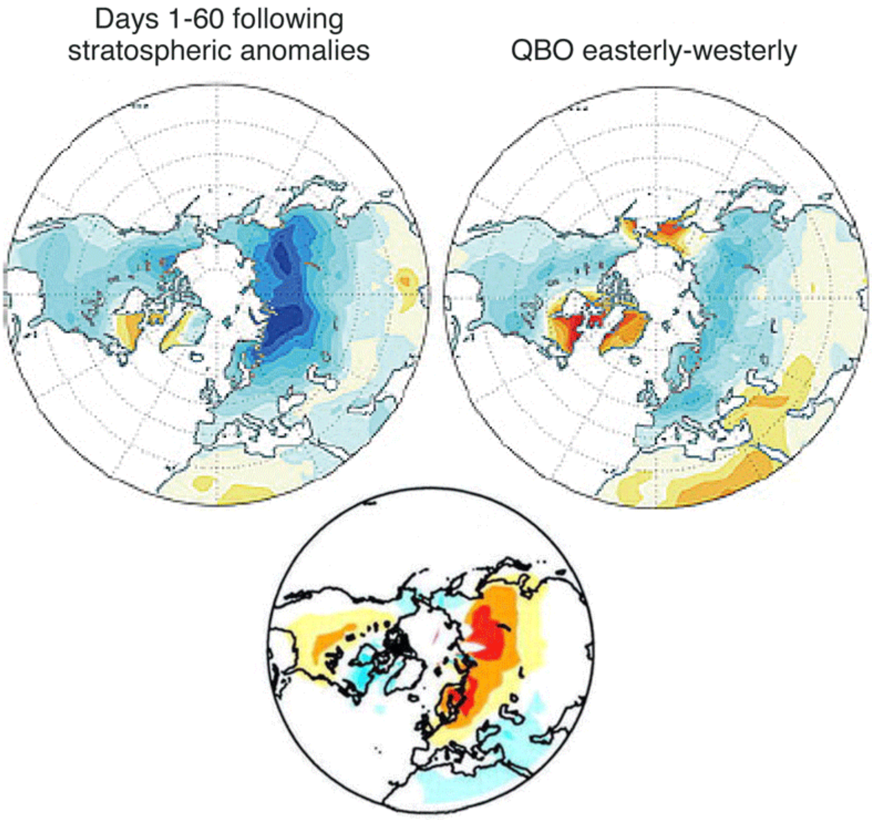

Figure 10 Difference between surface air temperature over the Northern Hemisphere in easterly and westerly winters of the QBO, based on winds at the 50-hPa-level over the equator. After Thompson et al. (2002). The AO pattern is shown for reference at the bottom.

5. The AO and Arctic sea-ice extent

During wintertime the largest variability of Arctic sea-ice tends to be along the climatological-mean ice edge at subpolar latitudes, while the Arctic Ocean itself remains ice-covered. Along the climatological-mean ice edge, the AO impacts sea-ice extent directly, by advecting warm air and driving ice northward in regions of anomalously southerly surface winds and vice versa. During episodes of high-index polarity of the AO, sea-ice concentrations tend to be enhanced in the Davis Strait - Labrador Sea region, in response to the northerly wind anomalies that prevail in that sector, and suppressed in the Greenland Sea, where the wind anomalies are southerly (Fang and Wallace (1994)). Sea ice anomalies tend to lag the AO anomalies by a week or two. The effect of the AO on summertime sea-ice concentration is more indirect. It consists largely of a delayed response to the anomalous AO-forcing during the previous winter. The response is concentrated in coastal regions where offshore winds tend to drive the existing pack ice off shore, exposing open water that quickly freezes to form first-year ice. Coastal regions characterized by anomalous offshore flow during the winter months tend to experience anomalously low sea-ice concentrations during the following summer because the thin first-year ice formed in those regions during the previous winter is much more prone to melting than thicker multi-year ice. These relationships are illustrated by the linear regression maps in Fig. 11, which show AO-related year-to-year variations in wintertime surface winds and sea-ice motions and anomalies in sea-ice concentrations during the following summer. Figure 12 compares the patterns shown in the previous figure with the corresponding patterns for the differences from the decade of the 1980s to the decade of the 1990s. From this figure it is evident that the linear relationships that prevail on the year-to-year time scale are also evident in the decade-to-decade variability. However, the trends in Arctic sea-ice concentrations since

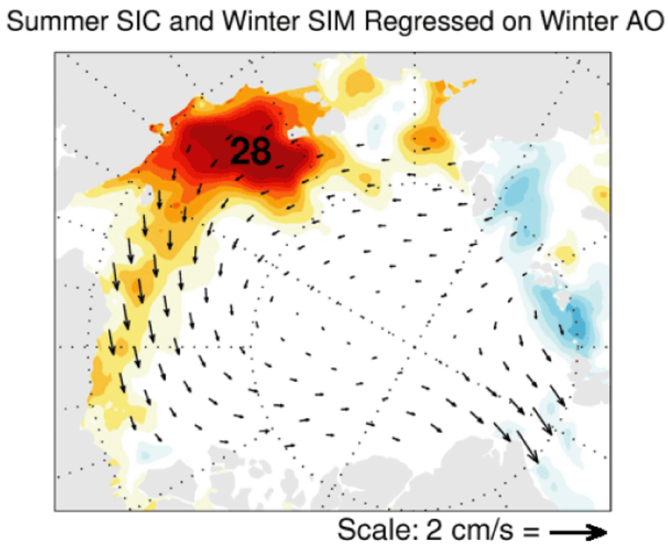

Figure 11 Anomalies in wintertime sea ice motion (arrows) and sea ice concentrations during the following summer (colored shading) that tend to occur in association with high-index wintertime AO, as inferred from lag-regression analysis. The sea-ice motion field is based on an objective analysis of buoy drift and the concentrations are based on satellite observations. The analysis is based on the period of record 1979-2001. After Rigor et al. (2002).

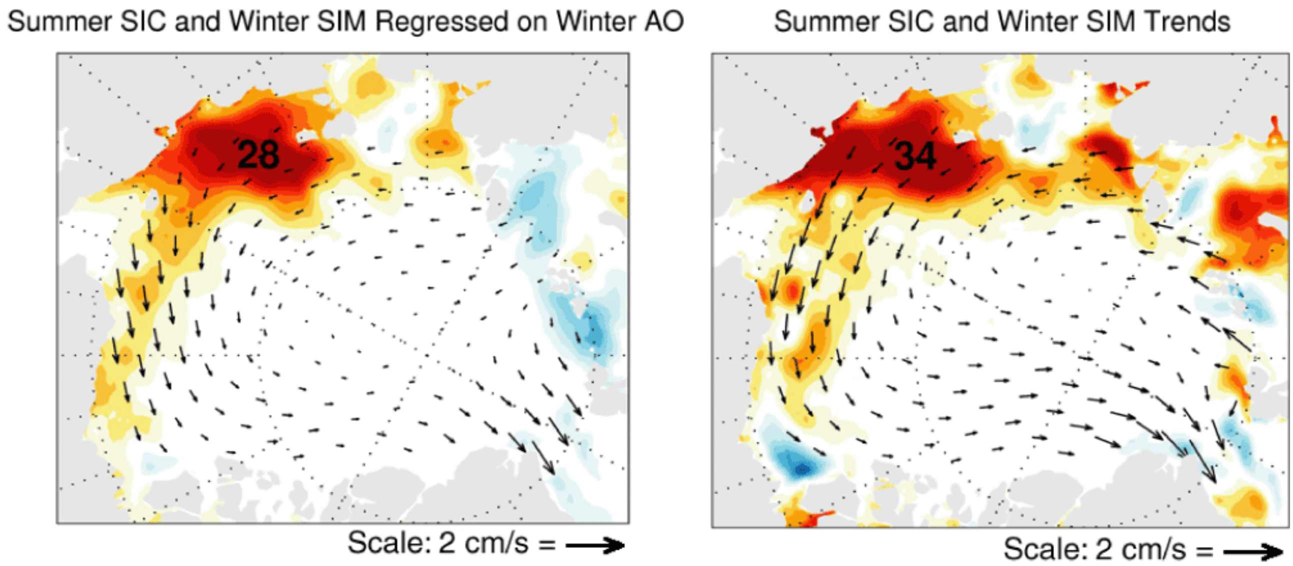

Figure 12 Left panel: The change wintertime in sea-ice motions (arrows) and summertime sea ice concentrations (colored shading) from the 1980s to the 1990s From Rigor et al. (2002). Right panel: Fig. 11 repeated.

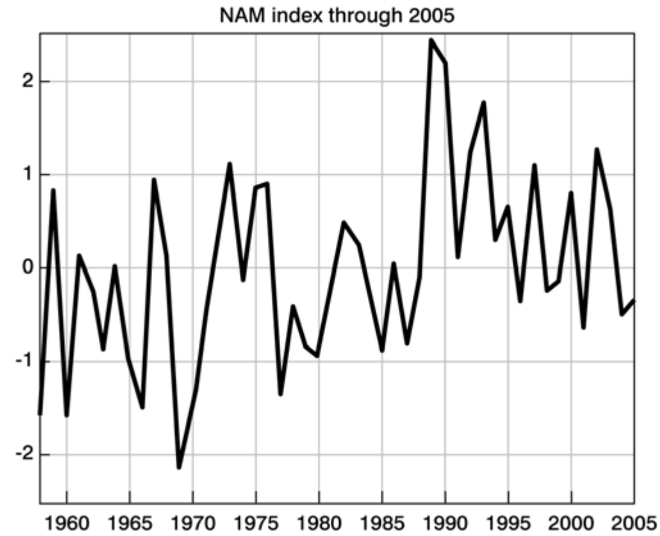

Figure 13 Time series of the wintertime (DJF) AO, 1979-2005. Courtesy of David Thompson. Note the cessation of the positive trend after 1995.

the summers of the mid-1990s are at odds with this simple linear model. During this later interval the trend in the AO has reversed, as shown in Fig. 13, while summertime sea ice concentrations have continued to decline. The spatial pattern of the recent trends in summertime sea ice concentrations is also quite different from the patterns in Fig. 12: the decreases have been greatest, not along the coast of Siberia, but along the coast of Alaska. Rigor and Wallace (2004) argue that the recent declines are, in part, a delayed reaction to the extended episode of high-index AO that prevailed from 1989 to 1995 that flushed most of the thicker multi-year ice out of the Arctic, leaving more of the basin covered by younger ice that is thinner and more susceptible to melting during the summer. That's not to say that global warming might not also be contributing to the decline.

6. The AO and the biospheric uptake of atmospheric carbon dioxide

Each year the atmospheric carbon dioxide concentration drops abruptly from May to July in response to the greening of the biosphere over the high latitude Northern Hemisphere continents, as illustrated by the segment of Mauna Loa time series shown in Fig. 14. The magnitude of this drawdown varies from year to year in response to variations in biospheric productivity. Joellen Russell has made careful estimates of the summer drawdown at 9 Northern Hemisphere monitoring stations and regressed hemispheric patterns of SLP

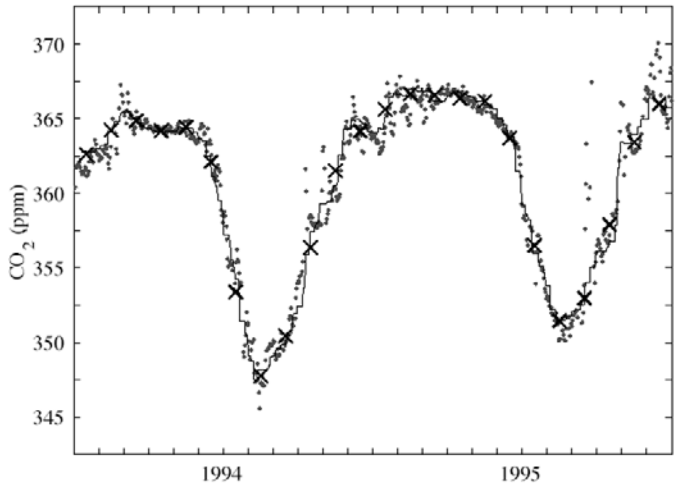

Figure 14 Measurements of atmospheric carbon dioxide concentrations by NOAA/CMDL at Mauna Loa showing the early summer drawdown that occurs each year. After Russell and Wallace (2004).

anomalies for each calendar month upon the resulting time series of yearly values. The most robust regression patterns that emerged were those for the winter months January-March and the spatial pattern for those months, shown in Fig. 15, bears a strong resemblance to the AO. Hence, Northern Hemisphere biological productivity tends to be enhanced following high-index AO winters. A possible explanation for this finding is that winters in which the AO is in its high-index polarity, with below normal SLP over the polar cap region, tend to be warmer than normal over most of the regions of the hemisphere covered by the boreal forests and that a mild winter in these regions tends to be followed by an early spring, allowing for a longer and more productive growing season (Russell and Wallace 2004).

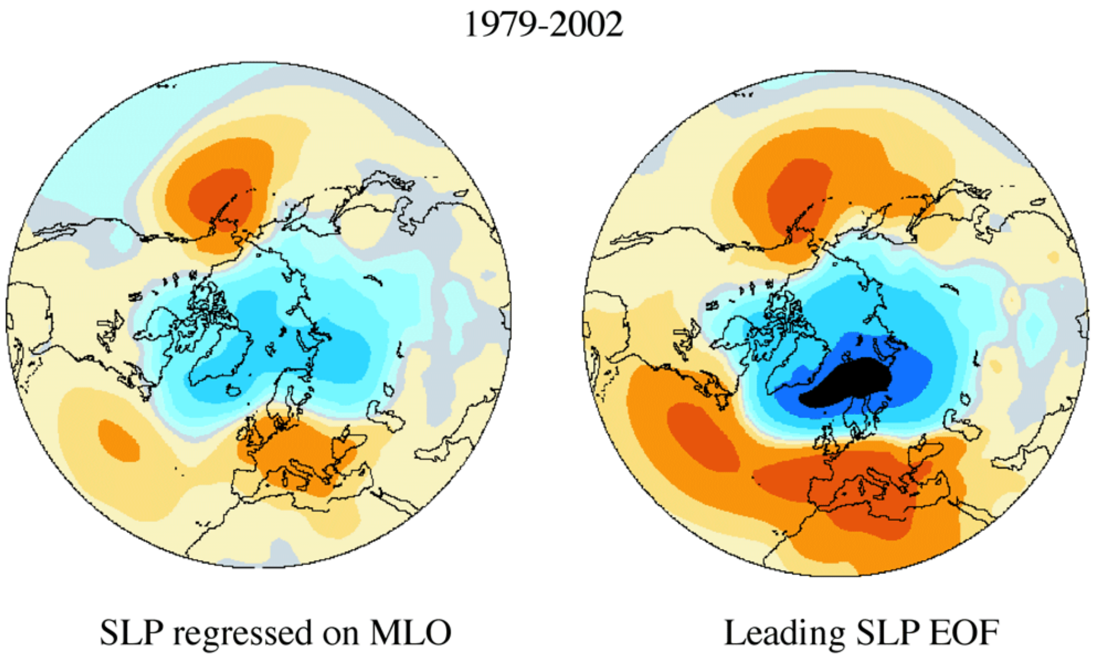

Figure 15 Left panel: Northern hemisphere sea-level pressure regressed on a time series of the annual early summer drawdown of atmospheric carbon dioxide (one data point each year), based on data from 9 Northern Hemisphere stations based on the period of record 1979-2002. Right panel: The leading EOF of Northern Hemisphere sea-level pressure based on the same period of record. After Russell and Wallace (2004).

7. Trends in the AO and the AAO

During the late 1990s it appeared as though the AO and the AAO were both exhibiting secular trends toward the high-index polarity, indicative of a strengthening of the wintertime polar vortices in both hemispheres and a poleward shift of the westerly wind belts in both hemispheres and the storm tracks (e.g., see Thompson et al. (2000), Thompson and Solomon (2002)). Shindell et al. (1999) interpreted these trends as a dynamical response to the buildup of greenhouse gases. They argued that within the layer 10-15 km above the Earth's surface the tropics were warming in synchrony with the Earth's surface while the higher latitudes were cooling in response to the increasing emissivity of the air at infrared wavelengths and that, as a result, the meridional temperature gradient at these levels was increasing, the wintertime stratospheric polar vortex was becoming stronger and more resistant to planetary-wave forcing, and the AO was shifting toward its high-index polarity. Gillett and Thompson (2002) interpreted the shift in the AAO toward its high-index polarity as a response to ozone depletion. Recently, David Thompson has revisited the trends based on the updated period of record 1979-2005 and found that the AO signature in them is much less pronounced than it was in the 1979-1997 period of record: a result that might have been anticipated on the basis of the shape of the AO time series in Fig. 13. The absence of a positive trend in the AO-index during the past decade casts doubt on the role of increasing concentrations of greenhouse gases in driving the AO toward its high-index polarity.

Thompson has also examined the seasonality of the trends and found that if the analysis is focused on the time of year when the polar vortex breaks down (March-April in the Northern Hemisphere and November-December in the Southern Hemisphere) the trends toward the high-index polarity appear to be more robust with respect to the lengthening of the period of record over which the trend is computed. In both hemispheres, the polar vortex has been persisting later into the spring in recent decades, consistent with the notion that ozone depletion is playing a role. Jones and Widmann (2003) have attempted to extend the AAO time series backward in time into the 1950s and beyond, using data from midlatitude stations as a proxy for Antarctic stations. Their reconstructed time series, shown in Fig. 16, suggests that the AO-index may have been higher during the 1960s than during subsequent decades. If their proxy time series is really representative of the AAO, their analysis would suggest that the AAO-index is capable of undergoing wide excursions independent of those caused by ozone depletion.

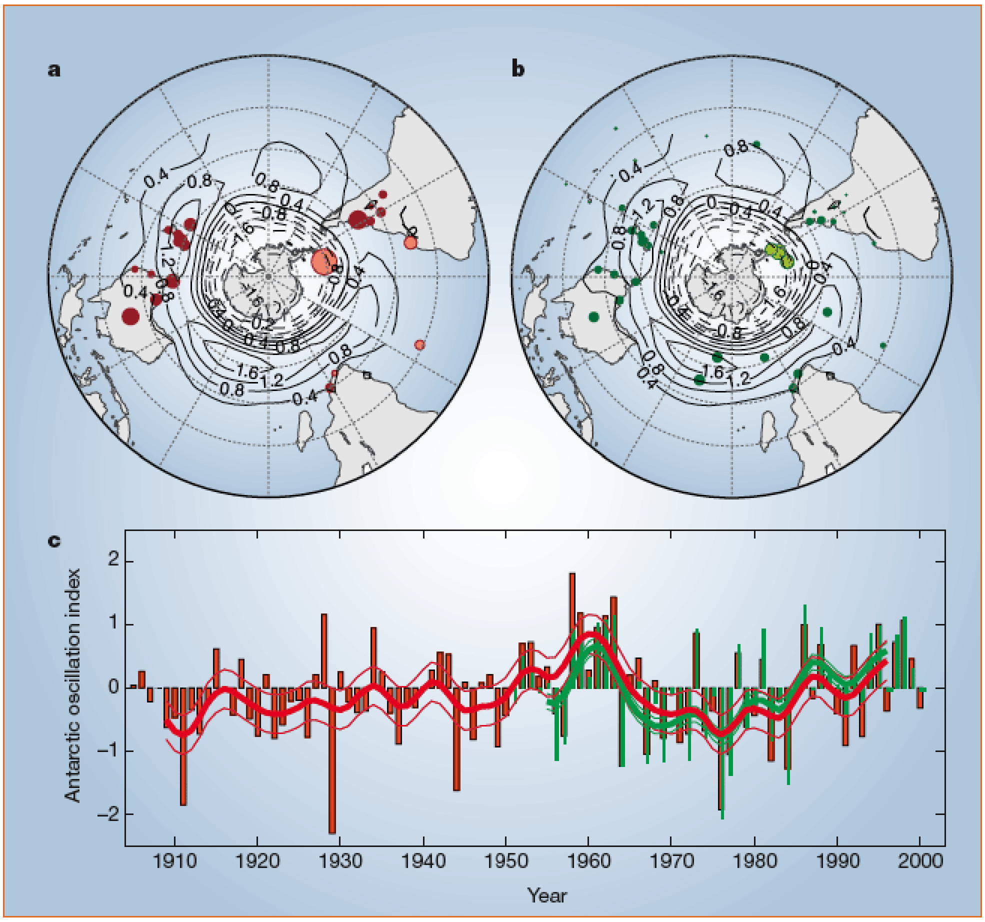

Figure 16 A reconstruction of the AAO-index based exclusively on data for stations located at subpolar latitudes that have records extending back over many decades. After Jones and Widmann (2003)

8. Conclusions

The AO and AAO are useful paradigms for framing discussions of climatic variability in the polar regions. They are particularly useful for characterizing interactions between the wintertime stratospheric polar vortex and the impact of the atmospheric circulation on the Southern Ocean, sea-ice, and the Northern Hemisphere terrestrial biosphere. They dominate the high latitude atmospheric variability on the decade-to-decade time scale. Long term trends in the AO and AAO continue to be of interest, but they are more complex, more seasonally dependent, and more sensitive to the period of record than we thought they were when these modes were first identified and popularized during the late 1990s. Until we gain a clearer understanding of the variability of the AO and the AAO over the 20th century and the reasons for it, I would be hesitant to place much reliance on what climate models tell us about they can be expected to vary over the 21st century. Variability of the AO and AAO in association with glacial- interglacial cycles is a promising new area of study that has the potential to simplify the characterization of the atmosphere-ocean interactions.

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