Annular Modes and Climate Prediction

Links between stratospheric wind patterns and ground-based climate offer hope of improved long-range weather forecasting and provide a possible explanation for some conspicuous climate trends of the past few decades.

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When meteorologists look at the monthly or annual averages of pressure, wind speed, and temperature taken at observation stations located worldwide, and then subtract the local long-term mean values, they see certain recurrent spatial patterns. These patterns, called modes, are believed to be the signatures of distinctive dynamical interactions.

Modes are generally favored relative to other spatial patterns because they are reinforced by positive feedback. A familiar example is the El Niño–southern oscillation, the signature of the interactions between surface winds and ocean currents in the equatorial Pacific. In that case, abnormally warm, equatorial sea surface temperatures favor weak trade winds, which, in turn, favor warm sea surface temperatures. Notwithstanding that El Niño is a complicated, global pattern describing the deviations of sea surface temperature from their average values, it is well described by an index formed simply by averaging sea surface temperature deviations over the equatorial Pacific: Intervals of above normal temperatures are called El Niño events. (See the article "El Niño Dynamics" by J. David Neelin and Mojib Latif in PHYSICS TODAY, December 1998, page 32.)

The Northern Hemisphere annular mode

The west-to-east component of the surface wind averaged around 55° N latitude is a good index of the primary mode of sea-level pressure deviations: the Northern Hemisphere annular mode (NAM). Figure 1 shows the NAM and makes evident the distinctive annular features that give the NAM its name. Both the NAM, and the Southern Hemisphere annular mode (SAM), which is well indexed by the strength of the westerlies at 55° S, are signatures of a symbiotic relationship involving the meridional (north–south) profile of the westerlies in the respective hemispheres and the wavelike perturbations that are superimposed on them. The profile of the westerlies influences the shape of the embedded waves. The embedded waves, in turn, feed back on the profile of the westerlies through wave-induced meridional transports of westerly momentum.

Modes, reinforced by positive-feedback mechanisms, make a conspicuously large contribution to maps that describe the deviations from seasonally adjusted normals in climatic variables averaged over monthly or yearly time scales. So, for example, one may expand the monthly deviations in the global sea-level pressure field in terms of a complete set of empirically determined orthogonal functions.[1] Two such functions are the Northern and Southern Hemisphere annular modes, which typically make much larger contributions in their respective hemispheres than any other function in the expansion. By definition, the expansion coefficient of the NAM, suitably normalized, is the NAM's index. The index of the SAM is similarly defined and, as mentioned previously, both are well correlated with the strength of the westerlies at their respective 55° latitudes: A positive index means the westerlies are relatively strong.

Mode indices vary with time in a way that needn't be periodic, as in the case of "normal modes." Mode indices often vary randomly from one month (or year) to the next, and they may exhibit long-term trends from one algebraic sign toward the other. When a mode index changes sign, the corresponding mode is said to have changed its polarity. When the NAM is in its low-index polarity, the mode index is an appreciable negative number, and the sea-level pressure profile is opposite to that shown in figure 1: Pressure is relatively high over the polar cap and relatively low over mid-latitudes. Figure 2 shows mean temperature, pressure, and precipitation patterns over Europe and North America for high NAM-index days (that is, days on which the NAM index was more than 1.0 standard deviation above its 40-year mean over the period 1958–97) and low NAM-index days. Figure 3 shows corresponding differences between mean surface temperatures for contrasting polarities of the NAM. When the NAM index is high, the prevailing westerly winds that blow across the North Atlantic from Canada to Europe are abnormally strong, and much of the Northern Hemisphere is warmer than usual. Northern Europe bathes in mild, moist marine air. Scotland and Norway receive even more than their normally generous quota of rain and snow, while southern Europe basks in sunshine. When the NAM index is low, the westerlies are relatively weak, and cold air masses that develop over Russia more readily spill out into Europe. The weakening of the westerlies gives northern Europe a respite from wet weather, while storms passing or developing over the Mediterranean bring (usually) welcome rains to the south of the continent.

The contrasts in mean temperature associated with the NAM are not as dramatic over North America as they are in Europe. Still, temperatures tend to be colder on

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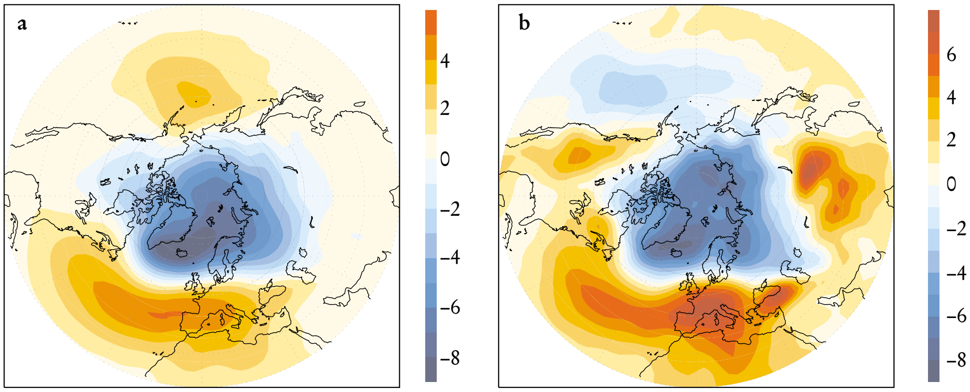

FIGURE 1. THE 30-YEAR TREND in sea-level atmospheric pressure resembles the Northern Hemisphere annular mode (NAM). **(a)** The NAM is a recurrent pattern in the deviation of sea-level pressures from their long-term averages. The figure shows the NAM on a typical high-index day, displaying relatively low pressures over the polar cap and relatively high pressures at mid latitudes. The color bar gives pressure in units of hectopascals (1 atmosphere = 1013 hPa). **(b)** The rate of change of sea-level pressure with time based on data collected from January to March over the 30-year period, 1968–97. The numbers on the color bar are in units of hPa/(30 yr), and so one may think of the figure as giving the change in sea-level pressures over the cited 30-year period. The change in the pressure field is remarkably similar to the NAM illustrated in the left panel. (Adapted from ref. 9.)

low-index days. The only notable exceptions are Canada's eastern provinces and the western coast of Greenland, where a weakening of the westerlies favors more frequent incursions of warm air masses from off the North Atlantic.

Weak westerlies lead to more than just lower mean temperatures—they also lead to a greater likelihood of extremely cold temperatures.[2] A weaker westerly jet stream aloft tends to have broader meanders that are more likely to form closed loops. These loops block the usual eastward propagation of weather systems, often setting the stage for incursions of cold, polar air masses into lower latitudes.

Notice that the see-saw between polar and mid-latitude pressure in the NAM is not perfectly symmetric but is biased toward the Atlantic sector. Because of this bias, many meteorologists view this mode as a regional phenomenon and refer to it as the North Atlantic oscillation (NAO). Most of the variability in the pressure field over the Pacific sector is associated with a mode of variability, focused over the Pacific and North American sectors, that affects the relative intensities of the semipermanent Icelandic and Aleutian lows in the wintertime sea-level pressure field.[3] Whether the regional (NAO) or hemispheric (NAM) paradigm better reflects the underlying physics has sparked a lively debate. The discussion in the box on page 31 addresses some of the arguments advanced by proponents of the competing paradigms.

The stratospheric connection

Fluctuations in the NAM at Earth's surface tend to be accompanied by a strengthening or weakening of the winter stratospheric polar night jet (PNJ), the ring of strong westerly winds that encircles the cold polar night region at latitudes around 65° N.[4] NAM-related wind fluctuations at subpolar latitudes amplify by a factor of 4–5 from Earth's surface to an altitude of 20 km near the core of the PNJ. When the NAM is in its high-index polarity, with below-normal sea-level pressure over the Arctic, the PNJ tends to be stronger than normal, the Arctic stratosphere colder than normal, and the stratospheric ozone layer abnormally thin over nearly the entire region north of 40° N. The relation between the NAM and the PNJ tends to be strongest from midwinter to the end of the winter season.

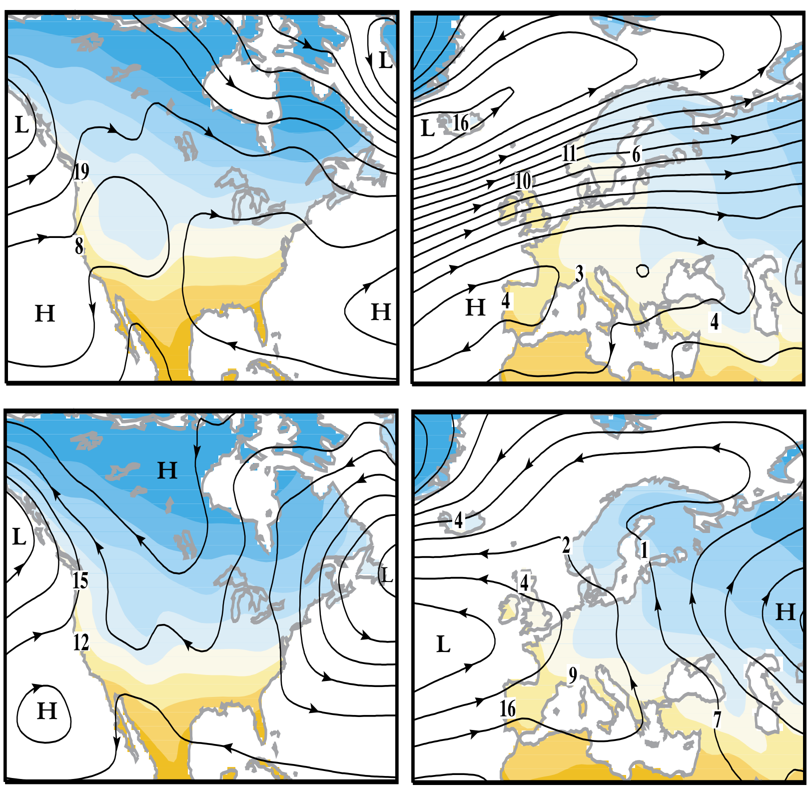

FIGURE 2. COMPOSITE MAPS of surface air temperature (shading), sea-level pressure (contours) and precipitation (the numbers indicate cm/month) for (top) high Northern Hemisphere annular mode–index days, as defined in the text, and (bottom) low NAM-index days. The maps are based on data collected from January to March over the 40-year period, 1958–1997. Contour intervals are 5°C for temperature (blue shades indicate temperatures below 0°C) and 3 hectopascals for sea-level pressure. (Adapted from ref. 2.)

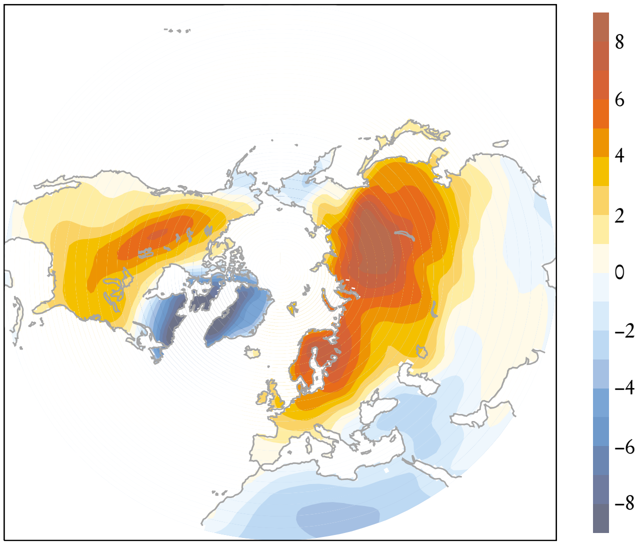

Figure 3. Air temperatures are warmer over much of the Northern Hemisphere on high-index days (as defined in the text) of the Northern Hemisphere annular mode. The map shows the difference (in °C) between mean surface air temperatures on low-index NAM days and those on high-index days. (Adapted from ref. 2.)

The PNJ develops each autumn in response to strong radiative cooling over the polar night region. The Southern Hemisphere PNJ exhibits strong circular symmetry about the pole. It is a steady, dependable feature of winter circulation with midwinter westerly wind speeds at the 20-km level of around 50 m/s.

The Northern Hemisphere PNJ is not as symmetric as its southern counterpart. It is perturbed by upward propagating velocity waves, driven by the thermal contrast between the cold continents and the warm oceans and by the deflection of the westerlies by the Rockies and the Himalayas. These velocity perturbations have wavelengths of the order of Earth's radius and are called planetary waves.

The planetary waves degrade the axial symmetry of the PNJ, deforming it into an elliptical shape centered off the pole. From time to time, the planetary waves grow enough over high latitudes to split the PNJ into pieces that drift away from the pole and dissipate. These breakdowns of the PNJ are first evident in the upper stratosphere near the 50-km level, and they propagate downward to the base of the stratosphere (at around 10 km) over the course of about two weeks. The latter part of the propagation is shown in figure 4. As warmer air replaces the cold air enclosed by the jet, the polar lower stratosphere can warm by 50°C or more over the course of just a few days. If one of these sudden warmings occurs relatively early in winter, radiative cooling over the polar cap regions gradually restores the PNJ over the course of the next month or two. But if it occurs too late in the season, the radiative cooling is terminated by the return of sunlight, and the PNJ never recovers its full intensity.

There is a growing body of evidence suggesting that during the months of January through March, the NAM might exhibit some predictability on longer time scales by virtue of its connection with the episodic weakening and strengthening of the PNJ in the lower stratosphere.

In October 2001, Mark Baldwin and Timothy Dunkerton of Northwest Research Associates in Bellevue, Washington, discussed the response of the sea-level pressure field to significant weakening and strengthening of the PNJ.[5] They found that the response, averaged over 60 days to eliminate the chaotic week-to-week variability generated in the lower atmosphere, had a spatial signature virtually identical to that of the NAM. Although the correspondence between changes in the PNJ and subsequent changes in sea-level pressure fields is far from perfect, it is strong enough to be of use in making two-month forecasts of the NAM and, by implication, the frequency of occurrence of extreme low temperatures throughout the Northern Hemisphere.[6] The winter-to-winter modulation of the strength of the PNJ by the quasi-biennial oscillation in winds over the equatorial stratosphere[7] confers more limited predictability out to a year in advance.[6]

Researchers in atmospheric dynamics had long been skeptical of the notion that changes in the circulation of the stratosphere can influence weather and climate at Earth's surface. They argued that the energy flux is in the wrong direction: The planetary waves that are ultimately responsible for the episodic weakening of the PNJ propagate upward.[4] Furthermore, given the relatively small mass of the stratosphere, the kinetic and potential energy inherent in disturbances at that level need to be substantially amplified for them to exert a perceptible influence on weather patterns at Earth's surface.

There is a way around this argument. A strengthening of the PNJ can induce a positive index NAM-like pattern at Earth's surface by diverting the planetary waves toward the equator as they propagate upward from below. A weakening of the PNJ induces a NAM-like pattern with a negative index by diverting the waves toward the pole. In either case, the PNJ harnesses the energy of planetary waves to change the winds at lower levels. Many atmospheric dynamists now accept that stratospheric changes can influence surface climate.

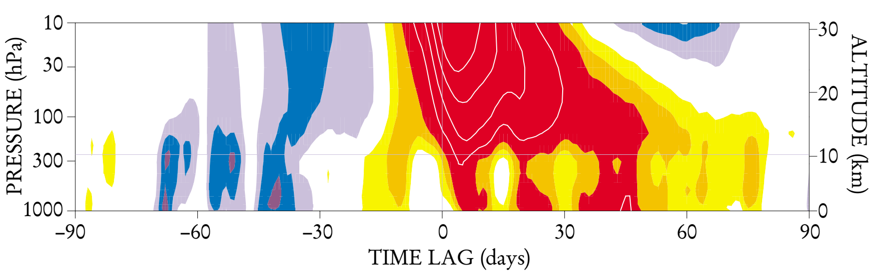

Figure 4. Time–height development of the strength of the westerlies in the 55–65° N latitude belt for 18 events, during the past 40 winters, in which the intensity of the polar night jet at the 30-km level (along the top of the diagram) dropped below a specified threshold value. Time lag in the figure is relative to the dates on which those 18 events occurred. The color shading and contours indicate the intensity of the westerlies: Blue shades denote stronger than normal intensities and warm colors denote weaker intensities than normal. The thin horizontal line indicates the base of the stratosphere. (Adapted from ref. 5.)

NAM or NAO?

While some meteorologists look at sea-level pressure patterns and see a coherent hemispheric mode—the Northern Hemisphere annular mode (NAM)—with a bias toward the Atlantic sector, others see coherence only over the Atlantic sector and speak of a mode called the North Atlantic oscillation (NAO). The two perspectives derive partially from historical precedent and partially from differing conceptions of how the polar vortex behaves.

Fragmentary evidence for the existence of the NAM/NAO based on correlations between pressure and temperature time series at small arrays of stations can be traced back well over 100 years. The first hemispheric synthesis of such correlation statistics, published in 1913 by Felix Exner,[13] was remarkably complete and accurate considering the limited data on which it is based. Exner's maps showing the correlations between pressure and temperature fields over the Northern Hemisphere and a reference time series of the sea-level pressure averaged over a group of high-latitude stations closely resemble figures 1a and 3 in the present article. More widely known are the maps establishing pressure and temperature correlations published by Sir Gilbert Walker in the 1920s and early 1930s.[14] Because Walker was more conservative than Exner in extending his analysis into regions with little data, the Arctic, Siberia, and much of the Pacific sector are left blank on his maps so that the Atlantic sector dominates to a greater degree than it does in figure 1 and in Exner's maps. It was Walker who coined the name North Atlantic oscillation (NAO), reflecting the seesaw in sea-level pressure between the regions surrounding Iceland and the Azores. In the same series of papers, Walker also coined the term southern oscillation to describe the worldwide pattern of climate variations that was later recognized as the atmospheric signature of El Niño. In both cases, the "oscillation" has proven to be something of a misnomer, because neither phenomenon exhibits quasiperiodic behavior.

Apparently unaware of Exner's and Walker's studies, Carl-Gustav Rossby and coworkers at MIT during the late 1930s and 1940s postulated the existence of a NAM that they referred to as the "zonal index cycle," where "zonal" denotes axially symmetric about the pole. The zonal index was initially defined in terms of the strength of the westerly wind component along 45° N, but Jerome Namias later redefined it as a measure of the difference between the strength of the westerlies along 55° N and 35° N.[15] Namias's definition corresponds closely to modern indices of the NAM, as does the simpler variant in which one considers only the strength of the westerlies along 55° N.

The zonal index cycle paradigm was subsequently abandoned for lack of evidence of simultaneity between climate anomalies in the Atlantic sector and other sectors of the hemisphere, but the idea of a more regional mode persisted. Influential papers by Harry van Loon and Jeffery Rogers[16] and by James Hurrell[8] drew attention to the pervasive influence of the NAO on European and eastern North American climate.

The NAM paradigm resurfaced in 1998, in part motivated by mounting evidence of coupling between variations in the intensity of the wintertime stratospheric polar vortex and circulation patterns in the lower atmosphere.[17] In addition, there was a recognition of the similarity between the NAO and the leading mode of variability of the Southern Hemisphere circulation, which is more symmetric about the pole, and verification that variations in the NAO/NAM do exert a discernible influence on climate in the east Asian, Pacific, and western North American sectors of the hemisphere.[2] The name "Northern Hemisphere annular mode" emphasizes the hemispheric scope of the mode, as does the term "Arctic oscillation," which has sometimes been used as a synonym for the NAM, particularly in the popular press.

Adherents to the NAO paradigm agree that there are important connections between the stratospheric polar vortex and weather patterns in the lower atmosphere. However, they question the extent to which the NAM behaves as a coherent entity in the lower atmosphere. Evidence in support of their position includes the lack of a strong correlation between pressure fluctuations in the Atlantic and Pacific sectors. NAO proponents also point out that Atlantic–Arctic pressure correlations are stronger than are Pacific–Arctic correlations and that the linkages between jet streams and storm tracks are stronger and in closer agreement with idealized conceptual models if they are considered within sectors of the hemisphere, rather than in the context of the NAM.[18]

Time series of NAM and NAO indices are linearly correlated at levels in excess of 0.9. Hence, advocates of both paradigms agree that sea-level pressure modes, the mildness of winters over much of the Northern Hemisphere, rainfall patterns over Europe, the strength of the polar night jet, and the thickness of the ozone layer are all related as described in this article.

Thirty-year trends

There is a widespread and well-founded perception that winters in many mid- and high-latitude regions of the Northern Hemisphere are not as severe as they were a generation ago. Global warming is partially responsible for this trend, but is not the whole story. Changes in atmospheric circulation have also contributed to the warming and, in particular, to the decreasing incidence of extreme low temperatures over the high-latitude land masses.[2] The recognition of the importance of dynamical processes in accounting for observed temperature trends is a relatively recent development.

In a 1995 paper, James Hurrell of the National Center for Atmospheric Research noted the marked similarity between the spatial patterns in surface air temperature trends during the previous 30 years and the winter-to-winter variations associated with fluctuations in the mode he called the NAO but we call the NAM. Concomitantly and independently, John Walsh and collaborators at the University of Illinois drew attention to the downward trend in sea-level pressure over the Arctic during the same 30-year period.[8] The pressure changes that Walsh et al. identified are part of a hemispheric-scale pattern that bears a striking resemblance to the NAM in its high-index polarity, as figure 1 demonstrates.

Indeed, over the past 30 years the trend in the NAM toward its high-index polarity has been quite pronounced. For example, during the winters of the decade 1958–67 there were only half as many high-index days (defined earlier) as low-index days, whereas in the decade 1988–97, high-index days outnumbered low-index days by five to one.[2] The trend of the NAM toward high index has been accompanied not only by milder winters, but also by changing rainfall patterns over Europe, a strengthening of the PNJ, and appreciable thinning of the stratospheric ozone layer north of 40° N.[9] There are indications of analogous changes over high latitudes of the Southern Hemisphere. The trend in the NAM may be a consequence of the observed trend toward a stronger PNJ and a colder, more quiescent lower polar stratosphere as reflected in the scatter plot of daily temperatures shown in figure 5.

Because the NAM describes the monthly variations in

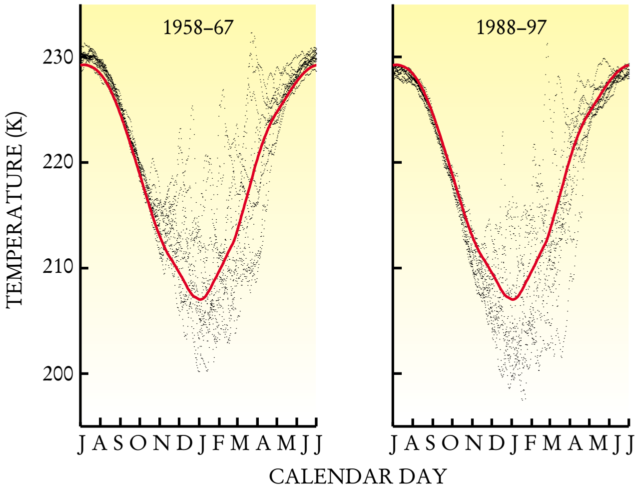

FIGURE 5. TEMPERATURE AT 20 KM over the Northern Hemisphere polar region as a function of calendar day. The horizontal axis runs from July to July. The graph in the left panel shows data for the decade 1958–67. Its companion gives data for the later decade 1988–97. The points on the scatter plots indicate daily measurements, while the solid lines give the average over the 40-year period 1958–97.

sea-level pressures from their mean values, one might worry that the overall trend toward higher index impacts its definition. Such worry is unfounded: The spatial signature of the NAM in no way depends on the trend, because the monthly variability in pressure is much larger than the variability attributable to the 30-year trend.

Possible effects of greenhouse gases

A recent series of numerical experiments by Drew Shindell and colleagues at the NASA Goddard Institute for Space Studies suggests that human activities could be responsible for the observed trend in the NAM toward higher index.[10] In their model, as in the real atmosphere, increasing concentrations of greenhouse gas molecules warm the lower atmosphere by trapping outgoing infrared radiation, and cool the stratosphere by enabling it to radiate energy to space more effectively. The lower limit of the cooling, at the base of the stratosphere, ranges from about 8 km over high latitudes to about 17 km over the tropics. The intermediate (8–17 km) layer is warmed at low latitudes, where it lies below the base of the stratosphere, and is cooled at higher latitudes, where it lies above the base.

The increasing meridional contrast in the radiative heating of the intermediate layer strengthens the equator-to-pole temperature gradient. As the gradient increases, so does the strength of the wintertime westerlies in the lower stratosphere. As the westerlies strengthen, they become more effective at refracting the upward propagating planetary waves toward the tropics before they reach the core of the PNJ. The frequency of occurrence of midwinter warmings is consequently reduced so that the polar cap region remains colder on average throughout the winter. Through this dynamical feedback, the radiative cooling induced by the buildup of greenhouse gases gets concentrated in the polar cap region and the circulation around the polar cap becomes stronger and less susceptible to the continuing barrage of planetary waves from below. The dynamical feedback thus favors a high-index NAM.

Shindell, Michael Mann (University of Virginia), and collaborators proposed that the NAM might have been at least partially responsible for Europe's "Little Ice Age."[11] Their proposed mechanism involves the reduction in the solar emission of ultraviolet radiation during the Maunder Minimum (from about 1640–1740) in sunspot activity. In their model simulations, the reduced solar UV emission alters the heating of the stratosphere in such a way as to weaken the PNJ, and the weaker PNJ, in turn, favors the low-index polarity of the NAM characterized by more severe winters throughout Europe. The results of the model agree with their analysis of historical records and temperature proxies such as tree rings and ice cores.

The hypothesis that radiative forcing in the stratosphere is capable of inducing a NAM-like signature at Earth's surface draws additional support from research results concerning the climate impacts of major volcanic eruptions.[12] An important constituent in volcanic emissions is sulfur dioxide, which is quickly converted into sulfate particles that reside in the stratosphere for a year or two. Absorption of solar radiation by these particles heats the stratosphere everywhere except in the wintertime polar night region. Hence, their presence in the stratosphere tends to strengthen the equator-to-pole temperature gradient, thereby strengthening the PNJ in a manner qualitatively similar to increasing the concentrations of greenhouse gases. The PNJ has been observed to be abnormally strong during the winters following volcanic eruptions; concomitant surface pressure and temperature variations characteristic of the high-index polarity of the NAM have also been noted.[12]

Sharing the spotlight with El Niño

Together with El Niño, the Northern and Southern Hemisphere annular modes have emerged as leading patterns of variability of the global atmosphere. El Niño is primarily a tropical phenomenon, but it influences the wintertime planetary waves at higher latitudes. The annular modes are primarily high-latitude phenomena, but their signatures in the sea-level pressure field and in the temperature field aloft extend all the way across the tropics, into the subtropics of the opposing hemisphere. El Niño and the annular modes both vary on time scales much longer than the chaotic waves and vortices that dominate the circulation of the lower atmosphere. Consequently, both are to some extent predictable well beyond the 1- to 2-week limit of conventional weather forecasts. El Niño derives its predictability from the interactions between the atmosphere and the upper layers of the equatorial Pacific Ocean, and the annular modes derive at least part of theirs from the interaction between the planetary waves and the PNJ.

Like El Niño, the NAM has emerged as an organizing theme in investigations of how climate change impacts birds, animals, fish, and susceptible human populations. Just as El Niño-related year-to-year variations in tropical rainfall and equatorial upwelling can be viewed as surrogates for longer-term climate variations such as the Pacific decadal oscillation, NAM-related year-to-year changes in winter temperatures over high northern latitudes offer insights into the potential impacts of global warming.

El Niño is viewed as an oscillatory phenomenon, whereas in the case of the NAM, it is the trend toward higher index that has been of major interest. Whether the NAM's 30-year trend is destined to continue through much of this century, or whether it is merely a segment of a multidecadal oscillation of the climate system remains to be seen. After rising for nearly three decades, the NAM

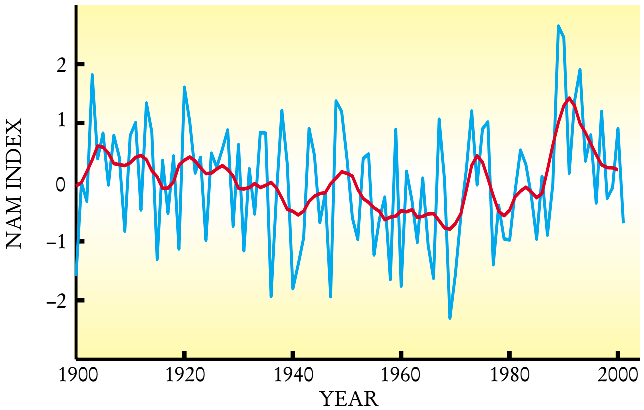

FIGURE 6. WINTERTIME INDICES of the Northern Hemisphere annular mode during the past 100 years, given in terms of standard deviations from the 100-year mean. The blue line shows January–March averages while the red line displays a five-year running average. Note that the NAM indices have significantly risen since the mid-1960s, but have fallen off somewhat in more recent years. (Adapted from ref. 9.)

index has dropped off somewhat since 1995, as shown in figure 6. If the downturn continues for another few years, the slow variations of the past few decades will begin to take on a more oscillatory appearance. On the other hand, the downturn may prove to be short lived and the NAM may resume its trend toward higher index. A continuing trend would suggest a human influence on climate at Earth's surface by way of the stratosphere.

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