North Atlantic Oscillation / Annular Mode:
Two Paradigms - One Phenomenon

John M. Wallace
Department of Atmospheric Sciences
University of Washington

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ABSTRACT

The "North Atlantic Oscillation (NAO)" as defined in Walker and Bliss (1932) has been traditionally viewed as a teleconnection pattern with 'centers of action' in the Atlantic sector. In contrast, the "zonal index cycle", as articulated by Namias (1950), involves the interactions between a fundamentally zonally symmetric or 'annular’ mode and the eddies. The perceived dynamical significance of the NAO derives from the strength of its pointwise correlations in the sea-level pressure field, whereas the index cycle derives from the notion that the zonally symmetric component of the flow plays a unique and clearly identifiable role in the atmospheric general circulation. The annular mode has been viewed as having relevance to the leading mode of variability in the Southern Hemisphere but the Northern Hemisphere, with its stronger land sea contrasts and orography, has been regarded as dominated by more sectoral teleconnection patterns like the NAO.

It has recently been suggested that the NAO is a regional expression of the Northern Hemisphere annular mode. Here it is shown that (1) the spatial signatures of the NAO and the annular mode are virtually indistinguishable; (2) the time dependent behaviours of the NAO and the annular mode are distinguishable only if the former is defined strictly in terms of one or another of its simple station-based representations like the difference in standardized sea level pressure between Portugal and Iceland; and (3) while such simple station-based indices are capable of revealing the spatial pattern of the NAO / annular mode phenomenon, they are not particularly well suited for representing its time dependent behaviour.

The implications of the choice of paradigm that is used for diagnosing the NAO / annular mode phenomenon and interpreting it to the public are discussed, and rules of evidence are proposed for determining which of them is more appropriate.

1. Introduction

A century-long search for order in low frequency atmospheric and oceanic variability has yielded a diverse and sometimes confusing array of 'oscillations', 'modes', and ‘teleconnection patterns’, many of which are linearly dependent in space and time. The object of this ongoing search is a limited set of what I will refer to as 'dynamical modes' in the anomaly fields of primary climatic variables (notably, pressure, temperature and rainfall) whose polarity and amplitude can be shown to vary in a more rational and potentially predictable way than those of climatic anomalies at individual stations, or the amplitudes of spherical harmonics fit to anomaly fields. Dynamical modes are the imprints of fundamental processes such as instabilities of the climatological-mean flow, large scale atmosphere-ocean interaction, or interactions between the climatological mean flow and the transients.

The spatial pattern associated with what is arguably the most important Northern Hemisphere dynamical mode is undergoing something of an identity crisis. In the guise of the North Atlantic Oscillation (NAO), a name that evokes the notion of an oceanic or coupled atmosphere-ocean mode, it has long been recognized as a major player in winter-to-winter climate variability over Europe and eastern North America (van Loon and Rogers 1978; Hurrell 1995; Hurrell and van Loon 1997). The same pattern has recently come to be recognized as the tropospheric signature of the primary mode of variability of the wintertime stratospheric circulation (Perlwitz and Graf 1995; Kodera et al. 1996; Kitoh et al. 1996) and as bearing a remarkably strong resemblance to the pronounced wintertime climatic trends of the past 30-years (Hurrell 1995, 1996; Graf et al. 1995; Kodera and Koide 1997; Thompson and Wallace 1998; Thompson et al. 1999). Thompson and Wallace (1998, 1999), Gong and Wang (1999), and Thompson et al. (1999) have drawn attention to the prominence of the zonally symmetric component of this pattern and to its remarkable resemblance to the leading mode of variability of the extratropical Southern Hemisphere circulation. These new findings have elicited different reactions in different parts of the community. Some hail them as revealing the identity of a Northern Hemisphere ‘annular mode’ that transcends the NAO and the regional atmosphere / ocean focus implied by that name, while others believe that the NAO paradigm can be easily adapted to incorporate them.

This article offers a perspective on the NAO / annular mode controversy and suggests numerical experiments that might be performed to resolve it. The next section traces the historical development of these two contrasting paradigms. Section 3 offers examples illustrating some of the consequences of the choice of paradigm, and the final section proposes a series of numerical experiments that could be performed to expose and hopefully resolve the dynamical issues involved in the choice of paradigm.

2. Two paradigms: one phenomenon

The mode in question was first identified in a series of studies by Sir Gilbert Walker, culminating in the landmark paper of Walker and Bliss (1932) hereafter referred to as WB. In his global search for predictors of Indian monsoon rainfall, Walker noticed that time series of wintertime-mean sea-level pressure (SLP) and surface air temperature (SAT) time series at an array of widely dispersed stations in eastern North America and Europe were strongly correlated with each other. He hypothesized that these strong correlations are a reflection of a preferred mode of planetary-scale fluctuations that he referred to as the North Atlantic Oscillation (NAO).

In order to describe the spatial pattern and time history of the NAO, WB generated a 'first guess' index comprised of a weighted average of what Walker considered to be a representative selection of these highly correlated SLP and SAT time series, where the weights were discretized as described in Table 1. The corresponding spatial patterns for SLP and SAT were obtained by correlating this trial index with each of the station time series. A second guess index was then generated by replacing the original weights by these correlation coefficients and discretizing them. The process was then repeated with the 'second guess' index to generate a third index, and so on until successive iterations converged. The final station weights and the correlation coefficients between the index and each of the stations are shown in Table 1. Based on this same methodology, WB also identified what they referred to as the North Pacific Oscillation (NPO), which has proven to be less important than the NAO, as well as their most celebrated mode, the Southern Oscillation (SO).

Apart from the discretization, the analysis procedure employed by WB is essentially equivalent to empirical orthogonal function (EOF) analysis based on the temporal correlation matrix for their prescribed multivariate set of station time series. We have verified that this is, in fact, the case by comparing WB’s NAO and the NPO indices with the leading principal components of the respective correlation matrices for their component time series. The correlation coefficients, based on the period 1950-94, are 0.99 and 0.94, respectively. Hence, the only really subjective element in the procedure employed in WB was in the choice of station time series used to represent the NAO, NPO and SO in their analysis.

Figure 1 shows the wintertime (DJF) SLP correlation pattern associated with the NAO as published in WB together with an updated representation of the same pattern in which an NAO-index was constructed for the period of record 1950-94 by applying the weights for the locations in Table 1 to the nearest gridpoints in the UKMO SLP analyses (Basnett and Parker 1997) and the University of East Anglia SAT analyses (Jones 1994), and the SLP correlation map is based on the UKMO analyses. The remarkable similarity between the two representations attests to the robustness of both the pattern and the analysis scheme. The most pronounced differences in appearance are over the Arctic, which was not represented in WB's analysis. Note that the Arctic data have no influence on our 'updated NAO-index' as such: they only serve to fill in the correlation pattern and make it more fully hemispheric. Nonetheless, there is a notable difference in the appearance of the patterns. The prominence of the Arctic is even more apparent when the correlation pattern for the updated index is mapped in a polar stereographic projection (Fig. 2a.)

Most modern representations of WB's NAO fall into two categories: those that simplify the original formulation by reducing it to just a pair of station time series, and those derived from objective analysis of gridded SLP datasets.

The most popular simplified station-based indices are those that represent the meridional SLP gradient and the strength of the surface westerlies across the North Atlantic sector. Data for Iceland are used to represent the higher latitudes and the Azores or Portugal (depending upon the season) to represent the lower latitudes. Bjerknes (1964) has used the difference in raw SLP, which yields the mean surface geostrophic zonal wind speed in the intervening latitude belt, whereas Rogers (1984) and Hurrell (1995) have used the difference in standardized SLP in order to reduce the dominance of the Iceland station. An alternative approach employed by van Loon and Rogers (1978) was to represent the NAO in terms of the east-west contrast in the SAT anomalies across the subpolar North Atlantic using station data for Olso Norway and Jakobshavn Greenland. Correlation patterns for these two indices are shown in Fig. 2b,c and statistics for them are included in Table 2. The SLP-based index captures WB's pattern remarkably well, whereas the temperature index, being based on an east-west difference, tends to accentuate the features in the Atlantic sector, yielding a slightly more sectoral pattern with a weaker zonally symmetric component. The latter index is not very strongly correlated with the other indices in Table 2.

Kutzbach (1970), Trenberth and Paolino (1981), Wallace and Gutzler (1981), Thompson and

Wallace (1998), among others have used principal component (PC) analysis as an objective method of determining the dominant patterns of variability in the SLP field. Regardless of whether a monthly or seasonal sampling interval is used, the leading mode recovered from this analysis is well separated from the succeeding ones and can therefore be considered reliable. The correlation pattern for the leading PC based on monthly (December-March) data, shown in Fig. 2d, is very similar to WB’s NAO. It is evident from Table 2 that this PC is more strongly correlated with WB’s NAO than the index based on Portugal and Iceland SLP.

An arguably similar phenomenon was discovered by Rossby and collaborators at the Massachusetts Institute of Technology (MIT) during the 1940's, using an entirely different research approach. Following Rossby (1939), these studies were based on the premise that the low frequency variability of the atmospheric general circulation can be more clearly understood by dividing it into zonally symmetric and eddy (or stationary-wave) components. What distinguishes this particular group of studies from others in the general circulation literature is the fact that the variations in the zonally symmetric component were represented in terms of a single mode that they referred to as the 'zonal index cycle'. In most of these early MIT studies, the zonal index cycle was envisioned as characterizing variations in the strength of the midlatitude (35-55° N) surface westerlies. However, in a few of the papers that were written just before the concept of a zonal index cycle fell out of favour, it appears in a different form. Based on his experience as a synoptic meteorologist, Namias (1950) became convinced that the principal mode of variability of the zonal flow involves not so much the variations in overall strength of the surface westerlies as the meridional shifting of the belt of strongest westerlies. He defined a 'high zonal index' circulation as being characterized by a poleward displacement of the zonally averaged surface westerlies toward subpolar latitudes, and a 'low-index circulation' by a southward displacement toward subtropical latitudes. Hence, while Rossby's original index is commonly represented by the zonally averaged SLP difference between 55°N and 35°N, Namias' (1950) 'zonal index' would be more appropriately represented by the surface zonal wind difference between 55°N and 35°N.

Although it is not expressed as overtly in those papers, a similar recasting of Rossby's zonal index cycle is implicit in studies of Lorenz (1950) and Gates (1950). On the basis of a thorough examination of correlation statistics for zonally averaged SLP and zonal wind perturbations on all possible pairs of latitude circles, Lorenz concluded that the zonal wind on 55°N represents the principal mode of variability of the zonally symmetric flow at the earth's surface about as well as any of the more complicated indices that he considered. As the basis for an extensive series of correlation maps, Gates employed an index that he referred to as the 'polar pressure deficit', the zonally averaged SLP on the 45°N latitude circle minus the SLP averaged over the polar cap region poleward of 45°N. Correlation maps for monthly mean sea level pressure based on Lorenz's and Gates' indices for December-March are shown in Fig. 2e,f, respectively. The similarity between these patterns and the one based on the NAO-index of WB is quite striking, as are the correlations between the indices themselves (the numbers in plain type in Table 2). These indices are virtually identical to one another and to the leading PC of the SLP field. It follows that the PC time series can be regarded as an index of the zonal index cycle or, as I will refer to it, the “annular mode”.

The patterns in Fig. 2 are more similar to each other than might have been expected, given the modest strength of some of the correlations between the indices in Table 2. The correlations are relatively low because, unlike PC’s, the simple station-based indices are not optimal representations of the time dependent behaviour of their own associated spatial patterns. These indices are based on data for only a few stations, whereas the optimal representations (like PC’s) are derived by projecting the full hemispheric seasonal-mean SLP fields onto their spatial correlation patterns in Fig. 2a,b,c. The correlations based on these optimal indices, shown in Table 3, are much higher than their counterparts in Table 2. For example, the optimal index derived from Portugal minus Iceland standardized SLP is correlated with the leading PC of the hemispheric SLP field at a level of 0.97, compared to 0.83 for the original station-based index. Hence, the PC provides a much more faithful representation of the time dependent behaviour of the spatial pattern derived from the Portugal minus Iceland standardized SLP index than the index itself does, and the same is true of the Norway minus Greenland SAT index. It follows that the NAO can be regarded as distinct from the annular mode only if one insists upon defining it in terms of a particular station-based index, rather than the corresponding correlation or regression pattern in the SLP field. The alternative is to ignore the distinction and

- define the NAO / annular mode phenomenon in terms of the common spatial pattern in Fig. 2,
- represent its time dependent behaviour by, say, the leading PC of the SLP field or Gates’ polar pressure deficit, and
- rely on simple station-based indices for representing its time dependent variability only when gridded data are unavailable or considered unreliable.

The time series listed in Table 2 are not the only ones that have been used for representing the NAO / annular mode phenomenon. Other indices include rotated EOF's of the midtropospheric geopotential height field (Barnston and Livezey 1987; Kushnir and Wallace 1987) and the 200-hPa streamfunction field (DeWeaver and Nigam 1999a,b), the leading mode of a multi-level (1000-50-hPa) EOF analysis of the geopotential height field (Baldwin and Dunkerton 1999), and projections of monthly hemispheric SAT and precipitation fields upon the leading PC of the SLP field (Fig. 1 of Thompson et al. 1999). Indices based on zonally averaged data include the 500-hPa geostrophic zonal wind difference between 55 and 35°N (Ting et al. 1996) and the leading PC of the multi-level (1000-50-hPa) geopotential height and zonal wind fields (Thompson and Wallace 1999).

An important consideration in the interpretation of the common pattern in Fig. 2 is the fact that it is so analogous to the leading mode of variability in the Southern Hemisphere (Gong and Wang 1999; Thompson and Wallace 1999). The analogy is further illustrated in Fig. 3, which shows the two leading EOF's of global, monthly mean SLP, based on the NCEP/NCAR Reanalysis for all calendar months. This similarity has prompted the use of the terms Northern and Southern Hemisphere ‘annular modes’ to refer to the zonal index cycle and its Southern Hemisphere counterpart (Limpasuvan and Hartmann 1999; Thompson and Wallace 1999) .

Whether the phenomenon in question should be cast in terms of the NAO or annular mode paradigms remains controversial (e.g., see Kerr 1999). Historical precedence might appear to favour the former, but based on the results presented above it can be argued that if Walker had had access to a global SLP dataset (1) he would have recognized the significant involvement of the entire Arctic basin in the mode that he labeled the NAO; and (2) he would have discovered the Southern Hemisphere annular mode and recognized it as an analogue of the NAO, in which case, his global synthesis of these modes would have been quite different from the one presented in WB.

Yet the NAO paradigm endures by virtue of the undeniable predominance of the Atlantic sector in the SLP signature of this mode and the weakness of the SLP teleconnections between the Atlantic and Pacific sectors (Deser 1999). This lack of sectoral coherence, which is also characteristic of the Southern Hemisphere annular mode, was largely responsible for the decline in the popularity of the index cycle after the weather services began to make operational use of data for the entire Northern Hemisphere.

But the annular mode paradigm derives, not from pattern geometry or ‘teleconnectivity’, but from consideration of the mechanism(s) that determine its structure and time dependent behaviour on the time scales of interest, the most important of which is believed to be the interaction between the eddies and the zonally symmetric component of the flow (Yoden et al. 1987; Shiotani 1990; Karoly 1990; Robinson 1991, 1996; Yu and Hartmann 1993; Kidson and Sinclair 1995; Lee 1997; Feldstein and Lee 1998; Hartmann and Lo 1998; Kidson and Watterson 1999; von Storch 1999; Limpasuvan and Hartmann 1999). In the context of this paradigm, the meridional structure of the perturbations in the zonally symmetric component of the flow is presumed to be determined by processes that transcend the physical geography of any particular hemisphere. The bias of the Northern Hemisphere annular mode toward the Atlantic sector is attributed to the underlying land sea distribution (in particular, the presence of a warm ocean extending to high northern latitudes). Atmosphere-ocean interaction in the Atlantic sector is acknowledged as possibly enhancing the interdecadal and longer term variability of this mode through positive feedbacks, but such sectoral processes are regarded as playing a supportive, rather than a central role, except possibly on paleoclimatic time scales.

3. What difference does the choice of paradigm make?

Lest the discussion of paradigms seem overly academic, I will offer in this section, seven specific examples of how the choice affects the way observations and/or model simulations are described, interpreted, or used.

(*a*) The strong troposphere-stratosphere coupling that occurs in association with the NAO / annular mode phenomenon is not well understood. One school of thought holds that perturbations in the zonally symmetric component of the flow at stratospheric levels alter the upward propagation of the planetary-wave component of the NAO, thereby modulating its amplitude at tropospheric levels (e.g., Baldwin et al. 1994; Kodera and Yamazaki 1994; Perlwitz and Graf 1995). An alternative interpretation, suggested by Thompson and Wallace (1998), is that the vertical coupling is accomplished, not by any particular planetary-wave pattern, but by the zonally symmetric component of the flow itself, by interacting with whatever planetary-waves happen to be present at the time. These contrasting interpretations, one emphasizing the role of the waves and the other role of the zonally symmetric component of the flow, clearly reflect the distinctions between the NAO and annular mode paradigms. The latter draws support from observational results of Baldwin and Dunkerton (1999) showing anomalies in the geopotential height averaged over the entire polar cap region tend to propagate downward from the 10 hPa to the 100hPa level and from the finding of Hartley et al. (1998) that, owing to their much larger horizontal scale, potential vorticity perturbations associated with simultaneous geopotential height rises and falls over the entire polar cap region are capable of inducing circulation anomalies through a much deeper layer than those associated with planetary-waves.

(*b*) Hurrell (1995) pointed out that the trend toward the high index polarity of the NAO (stronger subpolar westerlies) since the late 1960's has had important implications for climatic change over the North Atlantic sector and western Eurasia. His analysis was based on Rogers' (1984) NAO-index: i.e., the difference between standardised SLP anomalies at Portugal and Iceland stations. The annular mode paradigm suggests a somewhat different analysis approach for dealing with these trends. Rather than using a prescribed station-based NAO index, one uses the leading natural mode(s) of variability as determined from principal component analysis of the hemispheric or global SLP field based on observations or model control runs, as appropriate. Thompson et al. (1999) have shown that the trend identified by Hurrell shows up even more clearly when his analysis is repeated using the leading PC of hemispheric SLP. The same appears to be true of those simulated responses to increasing concentrations of greenhouse gases that have proven to be statistically significant (R. Miller, NASA/GFSC; J. Fyfe, Univ. of Victoria; E. Roeckner, Max Planck Institute for Meteorology; R. McDonald, Hadley Centre; personal communication). In a similar manner, it can be argued that the expressions of this phenomenon in regions of the hemisphere remote from the North Atlantic are revealed more clearly by the leading PC of the full hemispheric SLP field or other indices based on the annular mode paradigm than by the station-based indices of the NAO discussed in the previous section. [PC's based on the SLP field over the Atlantic sector only work just about as well as well, but it's difficult to justify the use of such arbitrarily defined indices.]

(*c*) Recent atmospheric general circulation model (GCM) experiments conducted by Rodwell et al. (1999) show an apparent atmospheric response to prescribed time varying sea surface temperature (SST) anomalies over the Atlantic that qualitatively resembles the observed changes during the past 50-years. The results have been interpreted as indicating that atmosphere-ocean interaction over the Atlantic sector has been instrumental in inducing the observed trend toward the high index polarity of the NAO that has been observed since the late 1960's. An alternative interpretation is that (1) the buildup of greenhouse gases (Shindell et al. 1999, Fyfe 1999) or ozone depletion

(Volodin and Galin 1999) forced a secular trend toward the ‘high index’ polarity of the annular mode which, in turn, forced the observed SST anomalies; (2) the atmospheric ‘response’ to the SST anomalies in the experiments of Rodwell et al.(1999) is a reflection of the weak positive feedback mechanism described by Barsugli and Battisti (1998); and (3) the prominence of this weak ‘response’ was exaggerated owing to the use of ensemble averaging in the experimental design (Bretherton and Battisti 1999). The first interpretation is inspired by the NAO paradigm, whereas the second is more closely aligned the annular mode paradigm.

(*d*) Analogues are helpful in illuminating the nature and causes of phenomena. The Atlanti-centric NAO paradigm invites the expectation of a Pacific counterpart of the NAO that exhibits an analogous kind of atmosphere-ocean coupling . In contrast, the planetary annular mode paradigm looks to the Southern Hemisphere annular mode, as illuminated by the studies of Szeredzi and Karoly (1987), Yoden et al. (1987), Kidson (1988a,b), Karoly (1990), Shiotani (1990), Hartmann and Lo (1998), Kidson and Watterson (1999) and others, for the most meaningful analogue. It also exploits the extensive literature on the zonally symmetric flow in idealized planetary atmospheres (Williams 1979; Robinson 1991, 1996; Feldstein and Lee 1998). In interpreting the trends of the past few decades, the annular mode paradigm invites comparison of the behaviour of the Northern and Southern Hemisphere annular modes. There is, in fact, some indication of a trend toward the high index polarity of the Southern Hemisphere annular mode (Hurrell and van Loon 1994; Randel and Wu 1999; Thompson et al. 1999).

(*e*) The wind stress over the Arctic affects the movement of sea-ice and the thickness of the layer of relatively fresh cold water that insulates the sea-ice from the warmer, saltier waters underneath: anticyclonic stress favors a cohesive ice pack and a deep halocline and vice versa. Sea-level pressures over the Arctic have exhibited a downward trend during the past few decades (Walsh et al. 1996), which has presumably been accompanied by a tendency toward more cyclonic wind stress. Recent evidence reported by McPhee et al. (1998) and Rothrock et al. (1999) suggests that this trend has been accompanied by a marked thinning of the pack ice. In the context of the NAO paradigm this Arctic variability is interpreted as a remote response to the primary mode of variability in the North Atlantic. Alternatively, it can be viewed as constituting what is perhaps the prime example of the many regional expressions of the variability of the annular mode.

(*f*) In the context of the annular mode paradigm, it can be argued that the patterns of North Atlantic SST anomalies that deserve the greatest emphasis are the ones with distinctive shapes of their own, clearly distinguishable from the forced pattern observed in association with the NAO / annular mode. Examples include the rapid warming that occurred along the Arctic fringe of the Atlantic from Baffin Island to Russia during the 1920's and the cooling that followed several decades later (Kelly 1982) and the Great Salinity Anomaly of the 1970's (Dickson et al. 1988), both of which can be viewed as distinctively Atlantic contributions to the climate variability of the 20th century.

(*g*) This annular mode paradigm, with its greater emphasis on dynamical mechanisms as opposed to pattern geometry and teleconnectivity, is consistent with a more discriminating policy with regard to the designation of 'dynamical modes'. Among the modes that would qualify are (1) the Northern and Southern Hemisphere annular modes, which are presumably reflections of the interactions between the eddies and the mean flow, (2) the global signature of SST-induced rainfall anomalies in the tropical Pacific that occur in association with Walker's 'Southern Oscillation', and (3) the wintertime Pacific / North American (PNA) pattern, the signature of barotropic instability downstream of the core of the jetstream over east Asia (Simmons et al. 1983). But one could question the credentials of the diverse array of regional patterns that can be recovered from rotated principal component analysis (e.g., see Barnston and Livezey 1987) or from analyses conducted within arbitrarily defined regional domains.

The choice of paradigms has implications for the way scientists in different subfields communicate and interact. The NAO is listed as one of four regional foci of the DecCen component of the CLIVAR Implementation Plan (World Climate Research Programme 1998) and could be construed as falling largely within the purview of that program. The annular mode transcends such geographic, time scale or programmatic classifications, and therefore serves as a cross-cutting theme of interest to the climate prediction, Arctic, stratospheric, anthropogenic climate change and atmospheric dynamics communities. Implicit in the two paradigms are different research agendas: different prioritization of the same research questions and, in some instances, different questions entirely.

In conveying the message of what this phenomenon is about, there is no more important medium than the name by which it is known within the scientific community. Regardless of how it might be understood by the scientists themselves, the name “NAO” conveys to the public the notion of a Northern Hemisphere, Atlanti-centric phenomenon, whereas “Northern Hemisphere annular mode (NAM)” portrays it as a more generic, planetary-scale phenomenon. The alternative name “Arctic Oscillation (AO)” suggested by Thompson and Wallace (1998) is an attempt at a compromise that retains the flavour of Walker’s original label, while making more explicit the annular mode’s unique relation to the planetary geometry. One can envision that conferences organized under the rubric of the NAM, the NAO, and the AO would attract quite different mixes of attendees, and have quite different programs. By the same token, it can be argued that the title of a primer, a tutorial, a request for proposals, or a section of an assessment of recent climatic trends relating to this phenomenon could influence the overall impression that readers take away from it. Over the course of time, I believe that these differing impressions will make a noticeable difference in the way NAO / annular mode-related scientific research is justified, organized, conducted, and perceived by the public. It’s an important issue because this phenomenon rivals ENSO in terms of its significance for understanding global climate variability and trends.

4. Achieving a consensus

In the interests of clarity, I believe it is incumbent upon the research community to come to grips with the differing definitions and interpretations of the NAO / annular mode phenomenon, and to make a choice between them based, not simply on the basis of historical precedent or programmatic expediency, but upon objective scientific evidence.

Observational or model budget diagnostics cannot, in and of themselves, tell us which of the two paradigms is closer to the truth. Planetary-wave features in the Atlantic sector appear to be capable of forcing fluctuations in the zonally symmetric flow that resemble the observed (DeWeaver and Nigam 1999a) and, conversely, interactions between the zonally symmetric component of this pattern and the zonal gradients of the background climatology appear to be capable of accounting for much of the embedded stationary-wave pattern (Ting et al. 1996; DeWeaver and Nigam 1999b). Evidence based on EOF analysis for different domains is also subject to ambiguity. For example, Deser (1999) has shown that the leading PC’s of the SLP fields for the full Northern Hemisphere poleward of 20°N and just the Atlantic half of the hemisphere are very similar, whereas the leading PC for the Pacific half is entirely different. This result could be interpreted as indicating that the full hemispheric annular mode derives its character from the NAO signature in the Atlantic sector. However, it could equally well be interpreted as indicating that the SLP variability in the Atlantic sector is dominated by the annular mode, while other dynamical modes such as ENSO the PNA pattern are competing for the spotlight in the Pacific sector. Hence it is necessary to look to other kinds of evidence.

The apparent ubiquity of annular modes in general circulation model simulations of earth-like atmospheres, including those without land sea contrasts suggests a strategy for determining the fundamental cause of the pattern. The following set of experiments could be performed with one (or more) model(s): (a) a run with prescribed zonally symmetric boundary conditions; (b) several runs with prescribed boundary conditions as in (a) but with an anomalously warm lower boundary extending into high latitudes within a sector roughly the width of the Atlantic, the strength of the anomaly increasing from one experiment to the next; and (c) a run with realistic lower boundary conditions with prescribed climatological-mean wintertime SST.

If the leading EOF's of SLP recovered from these experiments proved to be a family of patterns with a common zonally symmetic component and an embedded planetary wave structure whose amplitude increases roughly in proportion to the degree of zonal asymmetry in the prescribed boundary conditions, it would support the notion that this pattern should be regarded as the expression of the annular mode. If, on the other hand, zonally asymmetric boundary conditions proved to be essential for obtaining a strong leading EOF, or if the warmth or the poleward extent of the warm sector strongly influenced the amplitude or meridional structure of the zonally symmetric component of the leading EOF, it would support the NAO paradigm.

One could envision another set of experiments with various treatments of the North Atlantic Ocean: prescribed climatological-mean SST, mixed layers of various depths, and more complete treatments of the ocean dynamics. If the inclusion of a more active ocean results in a more realistic simulation of the observed structure of the mode in question, it would argue that the pattern in question is indeed a sectoral NAO. On the other hand, if the treatment of the ocean dynamics affects the amplitude of the mode but not the structure, it would argue that the atmosphere-ocean interaction should be interpreted as a feedback upon an independently existing annular mode.

As an alternative to performing numerical experiments, one might consider criteria relating to how the NAO / annular mode phenomenon affects regional climate. If its impacts prove to be largely attributable to (1) anomalous temperature advection involving the strong thermal contrasts between the North Atlantic and the upstream and downstream continents, (2) changes in the latitude or intensity of the North Atlantic storm track and its downstream extension into Europe, (3) anomalies in the stationary wave configuration induced by diabatic heating and/or storm track dynamics over the North Atlantic, or (4) changes in the frequency of blocking in the North Atlantic sector, it would argue in favour of the NAO paradigm. On the other hand, if the impacts can be shown to be more pervasive and extensive than can be accounted for by processes operating in or remotely forced from the Atlantic sector, it would argue in favour of the annular mode paradigm. For example, Namias (1950) envisioned that the 'low index' (weaker subpolar westerlies) polarity of the zonal index, with its more extensive and less tightly confined pool of cold air at the surface, would exhibit a higher frequency of cold air outbreaks throughout the hemisphere. One might also expect high latitude blocking to be more pervasive during the low index polarity, not only within the Atlantic sector, but over Alaska and Russia as well. A hemisphere-wide survey is currently underway to determine whether the expressions of the NAO /annular mode include phenomena such as these.

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References

Baldwin, M. P., X. Cheng and T. J. Dunkerton 1994 Observed correlations between winter-mean tropospheric and stratospheric circulation anomalies. *Geophys. Res. Lett.*, **21**, 1141-1144

Baldwin, M. P., and T. J. Dunkerton 1999 Propagation of the Arctic Oscillation from the stratosphere to the troposphere. *J. Geophys. Res.*, in press

Barnston, A. and R.E. Livezey 1987 Classification, seasonality and persistenmce of low-frequency circulation patterns. *Mon. Wea. Rev.*, **115**, 1083-1126

Barsugli, J.J. and D.S. Battisti 1998 The basic effects of atmosphere-ocean thermal coupling on midlatitude variability. *J. Atmos. Sci.* , **55**, 477-93

Basnett, T. A., and D. E. Parker 1997 Development of the global mean sea level pressure data set GMSLP2. *Clim. Res. Tech. Note CRTN79,* Hadley Centre, U.K. Met. Off., 53 pp.

Bjerknes, J. 1964 Atlantic air-sea interaction. *Adv. in Geophys.*, **10**, 1-82

Bretherton, C. S. and D. S. Battisti 1999 An interpretation of the results from atmospheric general circulation models forced by the time history of the observed sea surface temperature distribution. *Geophys. Res. Lett.,* submitted

Deser, C. 1999 A note on the annularity of the annular mode. *Geophys. Res. Lett.,* submitted

DeWeaver, E. and S. Nigam 1999a Zonal-eddy coupling and the dynamics of the North Atlantic Oscillation. *J. Clim.*, submitted

DeWeaver, E. and S. Nigam 1999b Do stationary-waves drive the zonal-mean jet anomalies of the northern winter? *J. Clim.*, submitted

Dickson, R.R., J. Meincke, S. -A. Malmberg, and A.J. Lee 1988 The 'Great Salinity Anomaly' on the northern Atlantic 1968-82. *Prog. Oceanogr.*, **38**, 241-295

Feldstein, S. B., and S. Lee 1998 Is the atmospheric zonal index driven by an eddy feedback? *J. Atmos. Sci.,* **55**, 3077-3086

Fyfe, J. C., G. J. Boer, and G. M. Flato 1999 The Arctic and Antarctic Oscillations and their projected changes under global warming. *Geophys. Res. Lett.,* in press

Gates, W. L. 1950 A statistical analysis of northern hemisphere sea-level pressure patterns accompanying high and low polar pressure deficit. S. B. thesis, Mass. Inst. Tech., unpublished

Gong, D., and S. Wang 1999 Definition of Antarctic Oscillation index. *Geophys. Res. Lett.,* **26**, 459-462

Graf, H. -F., J. Perlwitz, I. Kirchner, and I. Schult 1995 Recent northern winter climate trends, ozone changes and increased greenhouse forcing. *Contr. Atm. Phys.,* **68**, 233-248

Hartley, D. E., J. T. Villarin, R. X. Black, and C. A. Davis 1998 A new perspective on the dynamical link between the stratosphere and troposphere. *Nature,* **391**, 471-474

Hartmann, D. L., and F. Lo 1998 Wave-driven zonal flow vacillation in the Southern Hemisphere. *J. Atmos. Sci.,* **55**, 1303-1315

Hurrell, J. W. 1995 Decadal trends in the North Atlantic Oscillation region temperatures and precipitation. *Science,* **269**, 676-679

Hurrell, J. W. 1996 Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperature. *Geophys. Res. Lett,* **23**, 665-668

Hurrell, J.W. and H. van Loon 1994 A modulation of the atmospheric annual cycle in the Southern Hemisphere. *Tellus,* **46A**, 325-338

Hurrell, J.W. and H. van Loon 1997 Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change,* **36**, 301-326

Jones, P. D. 1994 Hemispheric surface air temperature variations: A reanalysis and an update to 1993. *J. Climate,* **7**, 1794-1802

Kalnay, E. et al. 1996 The NCEP / NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77**, 437-471

Karoly, D. J. 1990   The role of transient eddies in low- frequency zonal variations of the Southern Hemisphere circulation. *Tellus,* **42A**, 41-50

Kelly, P.M., P.D. Jones, C.B. Sear, B.S.G. Cherry, and R.K. Tavakol   1982   Variations in surface air temperatures, Pt. 2: Arctic Regions, 1881-1980. *Mon. Wea. Rev.,* **110**, 71-83

Kerr, R. A. 1999   A new force in high-latitude climate. *Science,* **284**, 241-242

Kidson, J. W. 1988*a*   Indices of the Southern Hemisphere zonal wind. *J. Clim.,* **1**, 183-194

Kidson, J. W. 1988*b*   Interannual variations in the Southern Hemisphere circulation. J. Climate, **1**, 1177-1198

Kidson, J. W., and M. R. Sinclair   1995 The influence of persistent anomalies on Southern Hemisphere storm tracks. *J. Climate,* **8**, 1938-1950

Kidson, J. W., and I. G. Watterson   1999   The structure and predictability of the "High-Latitude Mode" in the CSIRO9 general circulation model. *J. Atmos. Sci.*, in press

Kitoh, A., H. Koide, K. Kodera, S. Yukimoto and A. Noda   1996 Interannual variability in the stratospheric-tropospheric circulation in a coupled ocean-atmosphere GCM. *Geophys. Res. Lett.,* **23**, 543-546

Kodera, K., M. Chiba, H. Koide, A. Kitoh, and Y. Nikaidou 1996   Interannual variability of the winter stratosphere and troposphere in the Northern Hemisphere. *J. Met. Soc. Japan,* **74**, 365-382

Kodera, K. and H. Koide   1997   Spatial and seasonal characteristics of recent climate trends in the Northern Hemisphere troposphere and stratosphere. J. *Geophys. Res.,* **102**, 19433-19447

Kodera K. and K. Yamakazi 1994 A possible influence of recent stratospheric coolings on the troposphere in the Northern Hemisphere winter. *Geophys. Res. Lett.,* **21**, 809-812

Kushnir, Y. and J.M. Wallace 1987 Low frequency variability in the Northern Hemisphere winter: Geographical distribution, structure and time dependence. *J. Atmos. Sci.,* **46**, 3122-3142

Kutzbach, J. E. 1970 Large-scale features of monthly mean Northern Hemisphere anomaly maps of sea- level pressure. *Mon. Wea. Rev.,* **98**, 708-716

Lee, S. 1997 Maintenance of multiple jets in a baroclinic flow. *J. Atmos. Sci.,* **54**, 1726-1738

Limpasuvan, V. and D. L. Hartmann 1999 Eddies and the annular modes of climate variability. *Geophys. Res. Lett.,* in press

Lorenz, E.N. 1950 Seasonal and irregular variations of the Northern Hemisphere sea-level pressure profile. *J. Meteorol.,* **8**, 52-59

McPhee, M. G., T. P. Stanton, J. H. Morison, and D. G. Martinson 1998 Freshening of the upper ocean in the Arctic: Is perennial sea ice disappearing? *Geophys. Res. Lett.,* **25**, 1729-1932

Namias, J. 1950 The index cycle and its role in the general circulation. *J. Meteorol.,* **7**, 130-139

Perlwitz, J., and H. -F. Graf 1995 The statistical connection between tropospheric and stratospheric circulation of the Northern Hemisphere in winter. *J. Climate,* **8**, 2281-2295

Randel, W. J., and F. Wu 1999 Cooling of the Arctic and Antarctic polar stratospheres due to ozone depletion. *J. Clim.,* **12**, 1467-1479

Robinson, W. A. 1991 The dynamics of the zonal index in a simple model of the atmosphere. *Tellus,* **43A**, 295-305

Robinson, W.A. 1996 Does eddy feedback sustain variability in the zonal index? *J. Atmos. Sci.,* **53**, 3556-3569

Rodwell, M. J., D. P. Rowell, and C. K. Folland 1999 Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature,* **398**, 320-323

Rogers, J. C. 1984 Association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Mon. Wea. Rev.,* **112**, 1999-2015

Rossby C.-G. 1939 Relations between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semipermanent centers of action. *J. Mar. Res.,* **3**, 38-55

Rothrock, D.A., Y. Yu and G.A. Maykut 1999 Thinning of the Arctic sea-ice cover. *Geophys. Res. Lett.,* submitted

Shindell, D. T., R. L. Miller, G. Schmidt, and L. Pandolfo 1999 Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature,* **399**, 452-455

Simmons, A.J., J.M. Wallace and G. Branstator 1983 Barotropic wave propagation and instability, and atmospheric teleconnection patterns. *J. Atmos. Sci.,* **40**, 1363-1392

Shiotani, M. 1990 Low-frequency variations of the zonal mean state of the Southern Hemisphere troposphere. *J. Met. Soc. Japan,* **68**, 461-471

Szeredi, I., and D. J. Karoly 1987 Horizontal structure of monthly fluctuations of the Southern Hemisphere troposphere from station data. *Australian Met. Mag.*, **35**, 119-129

Thompson, D.W.J., and J.M. Wallace 1998 The Arcti c Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.,* **25**, 1297-1300

Thompson, D.W.J., and J.M. Wallace 1999 Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Clim.,* in press

Thompson, D.W.J., and J.M. Wallace and G. Hegerl 1999 Annular modes in the extratropical circulation. Part II: Trends. *J. Clim.,* in press

Ting, M., M. P. Hoerling, T. Xu, A. Kumar 1996 Northern Hemisphere teleconnection patterns during extreme phases of the zonal-mean circulation. *J. Clim.,* **9**, 2614-2633

Trenberth, K. E., and D. A. Paolino 1981 Characteristic patterns of variability of sea level pressure in the Northern Hemisphere. *Mon. Wea. Rev.,* **109**, 1169-1189

van Loon, H. and J. Rogers 1978 The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. *Mon. Wea. Rev.,* **106**, 296-310

Volodin, E.M. and V. Ya. Galin 1999 Interpretation of winter warming over the Northern Hemisphere continents in 1977-1994. *J. Clim.,* in press

von Storch, J. 1999 The reddest atmospheric modes and the forcings of the spectra of these modes. *J. Atmos, Sci.,* **56**, 1614–1626

Walker, G.T. and E.W. Bliss 1932 World Weather V, *Memoirs of the R. M. S.,* **4**, 53-83

Walsh, J. E., W. L. Chapman and T. L. Shy 1996 Recent decrease of sea level pressure in the central Arctic. *J. Climate,* **9**, 480-486

Wallace, J.M. and D.S. Gutzler 1981 Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109**, 784-812

Williams, G. P. 1979 Planetary circulations, Pt. 3, Terrestrial quasi-geostrophic regime. *J. Atmos. Sci.,* **36**, 1409-1435

World Climate Research Programme 1998 *CLIVAR Initial Implementation Plan.* WCRP No. 103; WMO/TD No. 869, 314pp

Yoden, S., M. Shiotani, and I. Hirota 1987 Multiple planetary flow regimes in the Southern Hemisphere. *J. Met. Soc. Japan*, **65**, 571-586

Yu, J.-Y., and D. L. Hartmann 1993 Zonal flow vacillation and eddy forcing in a simple GCM of the atmosphere. *J. Atmos. Sci.,* **50**, 3244-3259

Table 1 Specifics of the December-February North Atlantic Oscillation (NAO) index as presented in Walker and Bliss (1932). The first column shows the weights the time series were assigned in the index and the second column shows the temporal correlations between the station time series and the NAO index. *p* denotes sea-level pressure and *T* denotes surface air temperature.

	weight	*correlation*
Vienna *p*	1.0	0.76
Stornoway *T*	1.0	0.84
Bodö *T*	1.0	0.86
Stykkisholm *p*	–1.0	–0.80
Ivigtut *p*	–1.0	–0.84
Bermuda *p*	0.7	0.66
1/2 (Hatteras *T* + Washington *T)*	0.7	0.72
Godthaab *T*	–0.7	–0.70

Table 2 Correlation matrices between various indices of the NAO / annular mode phenomenon based on seasonal-mean December - March data for the period of record 1950-94. WB refers to the Walker and Bliss index, whose weights are listed in Table 1; P–I is the difference between Portugal and Iceland standardised SLP; N–G is the difference between Norway and Greenland surface air temperature; PC1 is the leading principal component of the monthly December - February SLP field poleward of 20°N; U 55 is zonally averaged zonal wind in the 50-60°N latitude belt and *p*45 is the polar pressure deficit; i.e, the zonally averaged SLP on 45°N minus SLP averaged over the polar cap region poleward of 45°N. SLP is based on United Kingdom Meteorological Office (UKMO) data (Basnett and Parker 1997) and surface air temperature on University of East Anglia data (Jones 1994).

	WB	P–I	N–G	PC1	U55	*p*45
WB	---	.74	.59	.86	.79	.83
P–I		---	.37	.83	.87	.83
N–G			---	.37	.32	.35
PC1				---	.95	.97
U55					---	.98
*p*45						---

Table 3 As in Table 2, but the station-based indices WG, P–I and N–G are replaced by optimal indices derived from the hemispheric SLP field, in which the weight assigned to each gridpoint is linearly proportional to the correlation coefficient between SLP at that gridpoint and the station-based index.

	WB	P–I	N–G	PC1	U55	*p*45
WB	---	.97	.98	.99	.94	.97
P–I		---	.92	.97	.94	.94
N–G			---	.98	.92	.96
PC1				---	.95	.97
U55					---	.98
*p*45						---

Fig. 1 Correlation maps for DJF seasonal-mean sea-level pressure based on the North Atlantic Oscillation (NAO) of Walker and Bliss (1932). Top panel: a reproduction of Chart 2 from their paper: contour interval 0.6. Bottom panel: the same analysis for 1950-94 based on gridded United Kingdom Meteorological Office SLP (Basnett and Parker 1997). See text for further details. Contour interval 0.3; negative contours are dashed; the zero contour is bold.

Fig. 2   Correlation maps for the indices listed in Table 2 based on (*a*,*b*,*c*) seasonal-mean and (*d*,*e*,*f*) monthly December - March UKMO SLP data (Basnett et al. 1997) for the period of record 1950-94. Contour interval 0.15; negative contours are dashed; the zero contour is bold.

Fig. 3 Correlation maps for the two leading principal components of monthly global sea-level pressure anomalies based on data for all calendar months based on the NCEP/NCAR Reanalyses (1949-94) (Kalnay et al. 1996)   To minimize the possible impact of spurious trends, the data were subjected to a 5-year highpass filter, and the first and last 2.5 years of the record discarded. Contour interval 0.3; negative contours are dashed; the zer contour is bold.

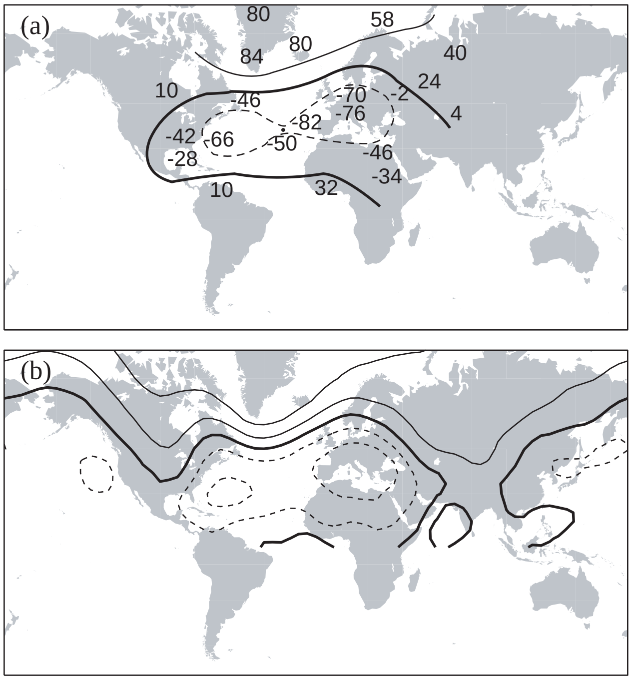

Figure 1.

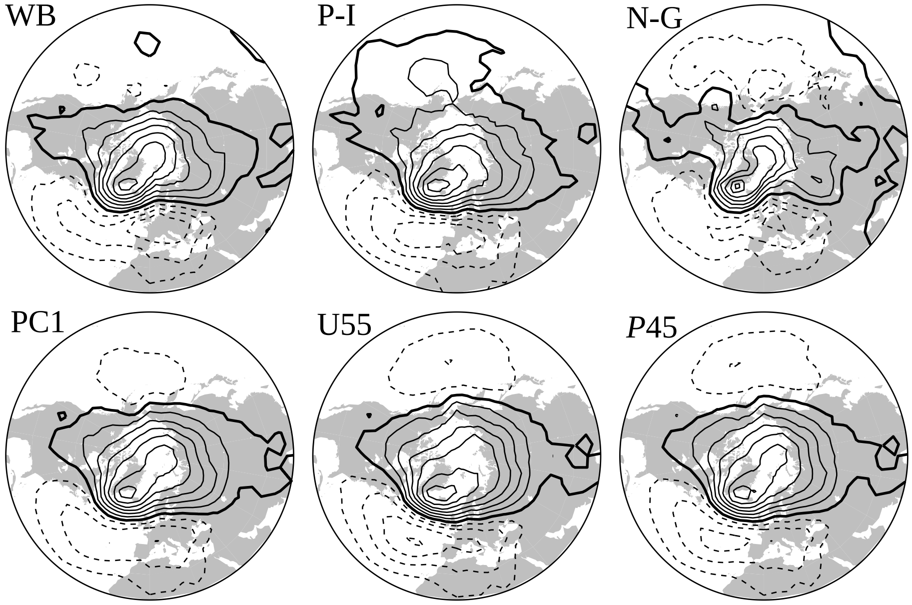

Figure 2

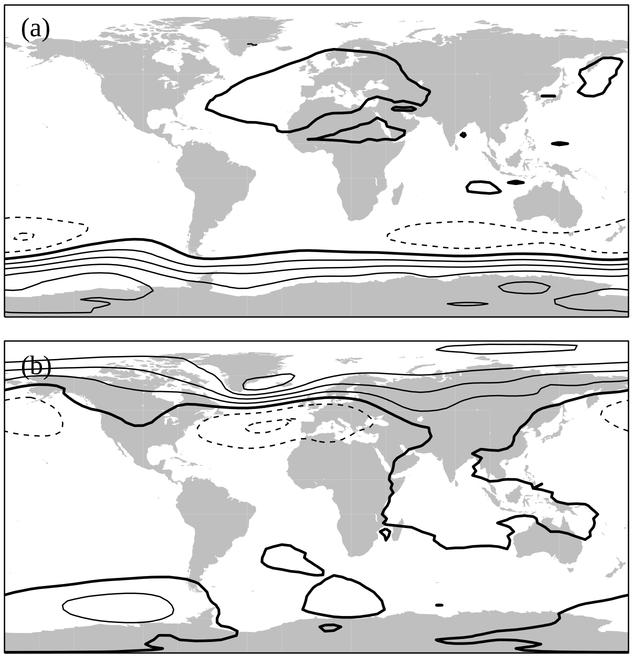

Figure 3