The Recent Trend and Variance Increase of the Annular Mode

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ABSTRACT

This study examines whether both the trend and the increase in variance of the Northern Hemisphere winter annular mode during the past 30 years arise from atmospheric internal variability. To address this question, a synthetic time series is generated that has the same intraseasonal stochastic properties as the annular mode. By generating a distribution of linear trend values for the synthetic time series, and through a chi-square statistical analysis, it is shown that this trend and variance increase are well in excess of the level expected from internal variability of the atmosphere. This implies that both the trend and the variance increase of the annular mode are due either to coupling with the hydrosphere and/or cryosphere or to driving external to the climate system. This behavior contrasts that of the first 60 years of the twentieth century, for which it is shown that all of the interannual variability of the annular mode can be explained by atmospheric internal variability.

1. Introduction

During the past 30 yr, a trend has been observed in many atmospheric variables, particularly in the Northern Hemisphere (NH) during the winter season. This trend includes a warming of the surface temperature in mid- and high latitudes, a cooling in the high-latitude lower stratosphere, an increase in the strength of the westerlies in high latitudes, and a reduction in total column ozone [for a summary of these trends, including many additional references, see Thompson et al. (2000)]. These characteristics are consistent with the global warming scenario of many climate models. In a recent study, Thompson et al. (2000) placed this climate trend into a coherent, well-organized framework, by showing that the trend of many different climate variables is related to the trend in just one particular dominant mode of atmospheric variability, known as the NH annular mode (Thompson and Wallace 2000). The spatial structure of the NH annular mode[1] corresponds to the first empirical orthogonal function (EOF1) of the monthly averaged sea level pressure field. In fact, almost 50% of the observed trend in the above climate variables can be explained simply by the trend in the NH annular mode (Thompson et al. 2000). A similar trend over the same time interval has been observed for another important

and closely related mode of variability, the North Atlantic oscillation (NAO; Hurrell 1995, 1996; Hurrell and van Loon 1997).

A standard measure of the amplitude of the NH annular mode is the so-called Arctic oscillation (AO) index (Thompson and Wallace 1998). Northern Hemisphere winter[2] mean values of the AO index are illustrated in Fig. 1 for the years of 1899–1997.[3] This AO index data was kindly provided by D. Thompson of Colorado State University. As can be seen, a noticeable trend is apparent during the last 30 yr of the time series. In addition to this trend, another conspicuous feature during the past 30 yr is an increase in the variance[4] of the AO index. In fact, the ratio of the variance of the AO index for the 1967–97 time period to that for the 1899–1967 time period is found to be 2.02. As far as the author is aware, this change in the variance of the AO index has not yet been reported in the literature. A larger variance implies a greater frequency of NH winter seasons with a large-amplitude anomalous time-mean flow. Such a time-mean flow with a large amplitude may be more prone

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[1] As shown in Thompson and Wallace (2000), the annular mode is present in both hemispheres and during all months of the year.

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[2] We adopt the standard definition for NH winter as the months of December–February. It should be noted, however, that Thompson and Wallace (2000) find that the months of January–March are both the most active and those with the largest linear trend.

[3] This AO index was derived from the sea level pressure dataset developed by Trenberth and Paolino (1980). See that paper and the Web site online at http://www.cgd.ucar.edu/asphilli/DataCatalog/Data/trenpaol.html for detailed discussions about the various datasets used to construct the sea level pressure field and the issues of quality control, trends, and changes in data.

[4] Throughout this study, the term ''variance'' is reserved for time series of NH winter mean values, such as the AO index in Fig. 1.
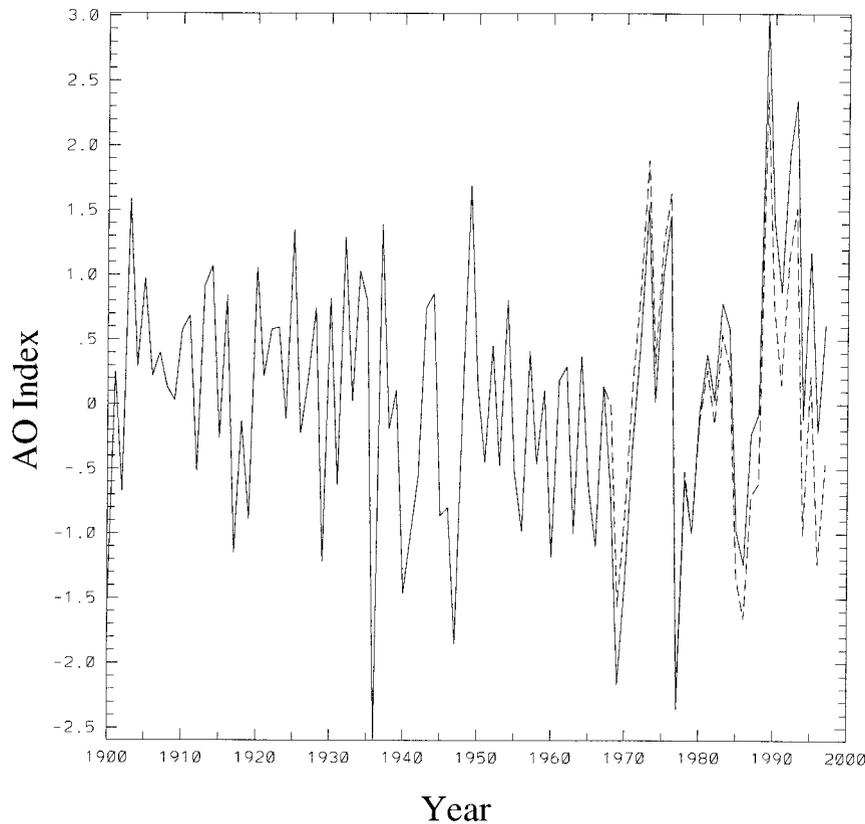
FIG. 1. The standardized AO index time series for the NH winter (solid line). The dashed line also corresponds to the standardized AO index, except that the linear trend for the years 1967–97 has been subtracted.

to development of extreme weather events (Houghton et al. 1996) due to instability.

Before further examination of the AO index trend and variance increase, it is first necessary to distinguish between various aspects of *internal variability* and *external forcing* of the climate system. In a manner similar to Tett et al. (1999) and Santer et al. (2000), I define internal variability to be variability that is confined to within the individual components of the climate system, that is, the atmosphere, hydrosphere, and cryosphere, as well as variability that arises from coupling between these components. On the other hand, anthropogenic influences, such as an increase in both greenhouse gases and sulfate aerosols, and changes in ozone are regarded as external forcing of the climate system.

An important question is whether both this trend in the AO index and the increase in its variance are within the range of variability for fluctuations internal to the climate system. If not, then it is likely that the AO index trend or variance increase is driven by forcing that is external to the climate system. With regard to the trend, this question was recently addressed with a Student's *t* test by Thompson et al. (2000). They showed that the *linear* component of this trend in the AO index is statistically significant above the 95% confidence level dur-

ing the NH winter. In another observational study, Stephenson et al. (2000) used a Kruskal–Wallis *H* statistic to examine whether decadal trends of the closely related NAO index exceed the 90% confidence levels against a white noise process. They find that four individual decades, including 1980–89, exhibit trends that are statistically significant. The same question has also been addressed by Gillett et al. (2000) within the context of a climate model. In that study, the statistical distribution of the linear trend values of the climate model's AO index was obtained from a "control" version of the climate model. The linear trend of the AO index was then calculated for an ensemble of climate model runs with the observed increase in greenhouse gases and sulfate aerosol, and the observed decrease in ozone. It was found that this model's linear trend of the AO index was not statistically significant above the 95% confidence level. However, Gillett et al. (2000) do find that the observed AO index trend is statistically significant in comparison with the trend variability in the control model. Other climate models that include greenhouse gas forcing have also shown a noticeable trend in the AO/NAO index (e.g., Fyfe et al. 1999; Paeth et al. 1999; Shindell et al. 1999).

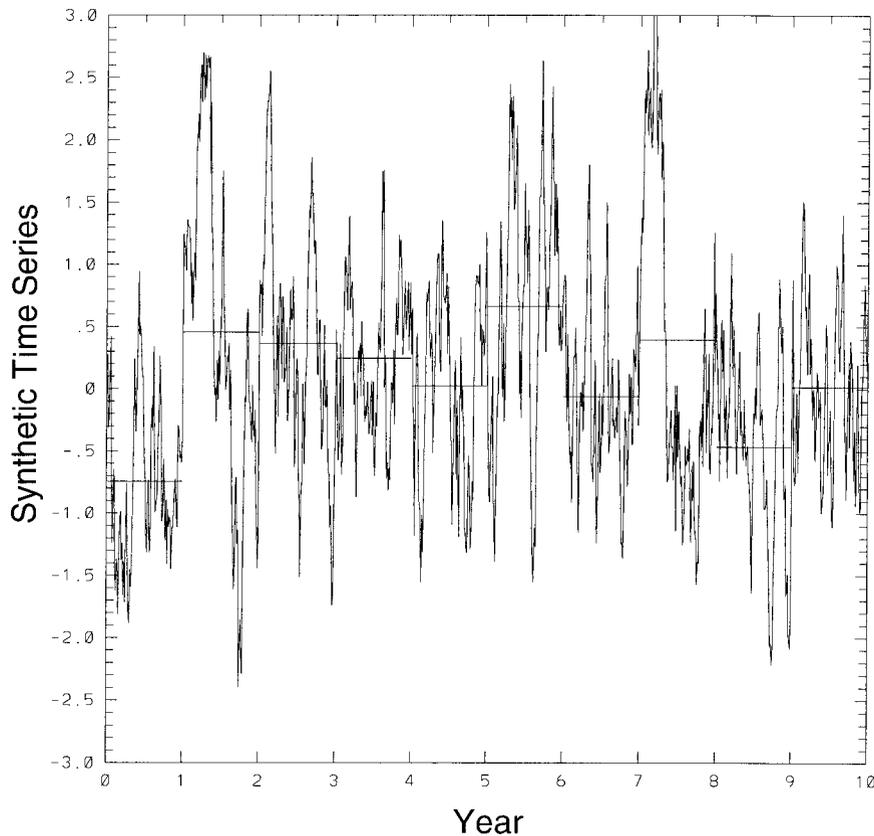While the above studies do test the statistical signif-

Fig. 2. A 900-day synthetic time series of a random variable with a decorrelation timescale of 10.6 days. The straight horizontal lines correspond to 90-day, winter-mean values.

icance of the AO index trend in the context of the full climate system, a more rigorous testing is extremely difficult because important coupling mechanisms and timescales are not yet well understood. On the other hand, the timescales of processes confined to the atmosphere, uncoupled to the hydrosphere and cryosphere, are well known and much better understood. This allows one to more rigorously address the question of whether the AO index trend and variance increase are within the range of variability expected for processes that are *internal to the atmosphere,* that is, atmospheric processes that are not coupled to the hydrosphere or cryosphere. This question is different from, and more limited than, the one discussed in the previous paragraph, which deals with the variability of the entire climate system. If the AO index trend and/or increase in variance are found to be within the range of variability for the atmosphere alone, then the AO index trend and variance increase must also be within the range of variability for the full climate system. On the other hand, if the observed trend or variance increase of the AO index is beyond that of the atmosphere's range of internal variability, then one can attribute the AO index trend and variance increase to be due to either coupling of the atmosphere with the hydrosphere or cryosphere, or due to external forcing.

I next discuss why evaluating the AO index trend and variance increase for the uncoupled atmosphere is much simpler than addressing the same question for the full climate system. In the absence of coupling to the hydrosphere or cryosphere, the seasonal cycle is expected to cause the atmosphere to lose all memory from one winter season to the next. As a result, there are no interannual processes that are internal to the atmosphere that drive interannual variability. Thus, all of the interannual variability of the AO index for the NH winter that is internal to the atmosphere must be driven by intraseasonal timescale processes.[5] This relationship between interannual variability and intraseasonal timescale processes is illustrated conceptually with the example in Fig. 2, which shows a 900-day time series of a random variable. This time series is specified to have a 10.6-day decorrelation timescale, the same value that is later found for the AO index. Also, this time series

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[5] As presented in Lorenz (1990), if the atmosphere is intransitive, i.e., more than one stable climate state exists within a given season, it is possible that the occurrence of the seasonal cycle may lead to interannual variability. This is because the initial conditions at the beginning of each season will be random, if the previous season was chaotic. While such behavior has been found in simple models, there is no evidence that it does occur in the real atmosphere (Lorenz 1990).

is restarted at a new random value every 90 days. I interpret each 90-day segment as corresponding to one "winter" season. Thus the horizontal lines in Fig. 2, which illustrate the mean value for each 90-day segment, correspond to "winter-mean" values. Because each winter season is specified to be uncorrelated with the previous winter season, there is no memory between consecutive seasons, and the interannual variance of this time series, that is, the variance of the winter-mean values, must arise from intraseasonal fluctuations. In this study, I examine the extent to which the picture in Fig. 2, that is, intraseasonal fluctuations accounting for interannual variability, applies to the AO index.

I will use the *intraseasonal* statistical properties of the AO index to examine whether the AO index trend and variance increase are beyond the range expected for atmospheric internal variability. As for other modes of large-scale ($>10^6$ m) atmospheric variability, such as the NAO and Pacific–North American teleconnection patterns (Feldstein 2000b), I will show that the annular mode is well described as a first-order Markov process with a decorrelation timescale on the order of 10 days. This indicates that on intraseasonal timescales the annular mode undergoes rapid stochastic fluctuations. In addition, by using the intraseasonal stochastic properties of the annular mode, I will be able to estimate the interannual *population* trend and variance characteristics of the annular mode in the absence of coupling to the hydrosphere, cryosphere, and external forcing on interannual timescales. (Implicit in this calculation is the assumption that the intraseasonal fluctuations of the annular mode are uncoupled to the hydrosphere, cryosphere, and external forcing. This assumption is based on the property that the timescales for the hydrosphere, cryosphere, and the external forcing are much greater than the approximate 10-day timescale of the annular mode.) I can then compare the observed trend and variance of the AO index time series for the NH winter with that of the population and evaluate their statistical significance.

The EOF and spectral analyses are presented in section 2, followed by the results in section 3, and the conclusions in section 4.

2. EOF and spectral analysis

I examine the statistical properties of the NH winter (December–February) annular mode for the years spanning 1958–97. As in most studies, for example, Thompson and Wallace (1998), I define the spatial structure of the annular mode to be the EOF1 of the NH winter, monthly averaged sea level pressure field. Data poleward of 20°N are used for calculating EOF1. The spatial structure for EOF1 is illustrated in Fig. 3. For this calculation, the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset was used. The pattern obtained is typical of that found in other studies of the
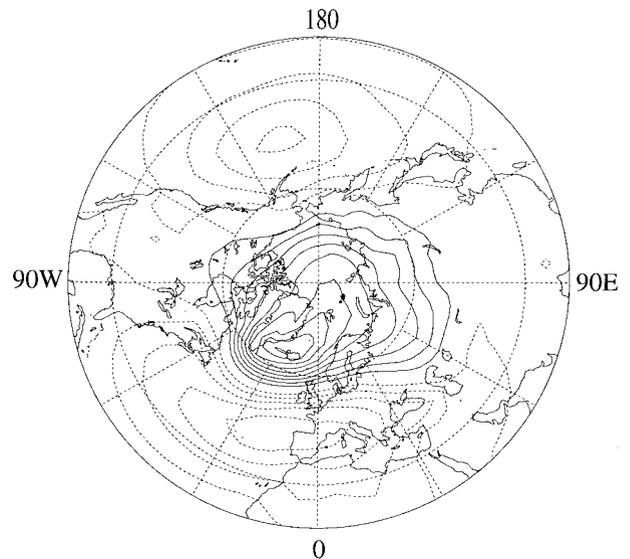

FIG. 3. EOF1 of the monthly averaged sea level pressure field for the 1958–97 boreal winter.

annular mode (e.g., Thompson and Wallace 1998; Thompson et al. 2000; Hartmann et al. 2000) for the latter half of the twentieth century, with one extremum encircling the North Pole and two other extrema of opposite sign located over the North Atlantic and North Pacific Oceans. However, because the method to be adopted in this study requires the use of data that has a sampling frequency much greater than one month, such as daily data, I need to define a daily annular mode time series. This daily annular mode time series is obtained by projecting the NH winter daily sea level pressure field onto the monthly averaged EOF1 spatial pattern shown in Fig. 3.

I next examine the intraseasonal power spectrum of the daily annular mode time series (Fig. 4). This power spectrum was obtained by calculating the average of the individual power spectra for each of the 39 winter seasons. Also illustrated in Fig. 4 are the red noise power spectrum and the corresponding 95% a priori and a posteriori confidence levels. [A detailed explanation about the concept of a posteriori confidence level can be found in Mitchell (1966) and Madden and Julian (1971).] The red noise spectrum is scaled by setting its variance equal to that of the daily annular mode time series. The shape of the red noise power spectrum was determined by performing a least squares fit on the quantity $\Sigma_i [f_r(\omega_i)^2 - f(\omega_i)^2]$, where $f(\omega_i)$ is the power spectrum of the daily annular mode time series in Fig. 4, $f_r(\omega_i)$ is the power spectral density function for a first-order Markov process (e.g., Chatfield 1989), and ω_i is a particular frequency. The function $f_r(\omega_i)$ has the form

$$f_r(\omega_i) = \frac{\sigma^2(1 - \alpha^2)}{\pi(1 - 2\alpha \cos\omega_i \alpha^2)}, \qquad (1)$$

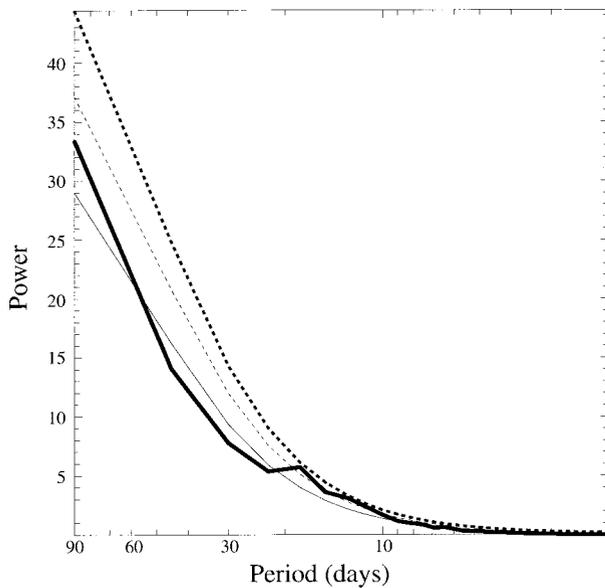where α is the lag 1-day autocorrelation, and σ^2 is the

FIG. 4. Intraseasonal power spectrum of the daily annular mode time series (thick curve). The red noise spectrum, and 95% a priori and a posteriori confidence levels are illustrated with the thin solid, thin dashed, and thick dashed curves, respectively. The units of the ordinate are arbitrary.
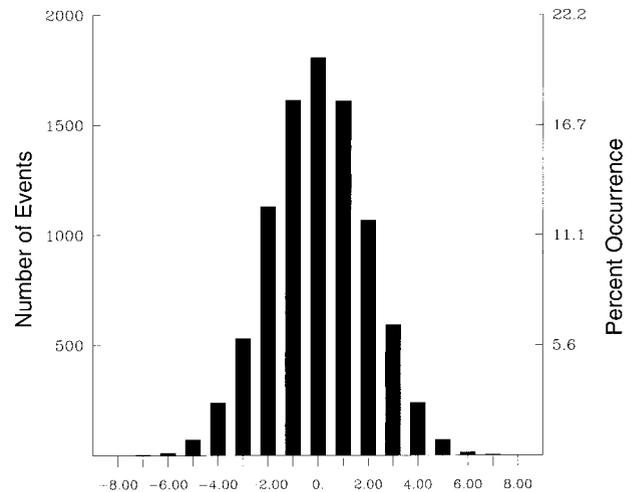

FIG. 5. Histogram illustrating the number of events and percent occurrence of the 30-yr trend values (multiplied by 100) for the synthetic time series.

variance of the AO index time series. For this least squares fit, the parameter α is varied until a minimum is obtained in $\Sigma_i [f_r(\omega_i)^2 - f(\omega_i)^2]$. For determining the confidence levels, 78 degrees of freedom are used for each spectral estimate, where it has been assumed that there are approximately two degrees of freedom for each seasonal periodogram value (Madden and Shea 1978). In addition, for each winter, the time series is tapered with a cosine bell that is applied to the initial and final 10% of the data. As can be seen from Fig. 4, the power spectrum for the daily annular mode time series is well described by a red noise, or first-order Markov, process. Given this property, I can estimate a decorrelation timescale T for the daily annular mode time series (first-order Markov processes decay by a factor of e in $T = -1/\ln\alpha$ days). It is found that the decorrelation timescale of the daily annular mode time series is 10.6 days.

I next examine the question of whether the first-order Markov process illustrated by the random time series in Fig. 2 and the power spectrum shown in Fig. 4 describes a substantial fraction of the interannual variability of the AO index. One approach may be to compare the red noise power spectrum shown in Fig. 4 extended to interannual timescales with the power spectrum of the interannual AO index in Fig. 1. However, because the latter time series consists of 3-month averages, once per year, it is likely that aliasing by many different timescales with periods less than 1 yr is a series problem. Instead, to address this question, the following procedure is adopted. I first generate a synthetic time series consisting of 270 000 90-day winter seasons. This

time series is specified to be a first-order Markov process that has the same variance and lag 1-day autocorrelation as the daily annular mode time series. In order to mimic the discontinuity from one winter season to the next, after each 90-day segment, the time series is restarted with a new random value. After this calculation is completed, a new time series is generated that consists of 270 000 winter-mean values. The extent to which the variability of this synthetic time series captures that of the AO index is evaluated by calculating the ratio of the variance of the AO index time series shown in Fig. 1 to that of the synthetic time series (recall that I defined variance to refer to that of winter-mean values). A ratio of 1.26 is found, indicating that the variance associated with the synthetic time series is a substantial fraction of that for the AO index (the results from statistical analyses that examine the relationship between the synthetic and AO index time series will be presented in more detail in the next section). Since the synthetic time series simulates the intraseasonal characteristics of the AO index, this result implies that a large fraction of the interannual variability of the AO index is indeed attributable to much shorter timescale intraseasonal processes.

3. Results

a. Trend

I first examine the statistical significance of the observed trend of the AO index. For this calculation, I use the same 270 000-yr first-order Markov, synthetic time series that was described in section 2. Since the observed trend of the AO index is conspicuous over a 30-yr period (1967–97), I then calculate the statistical distribution for 30-yr trend values in this synthetic time series. A histogram showing these trend values is illustrated in

Fig. 5. From Fig. 1, the observed trend over the 1967–97 period was found to be 0.057 yr^{-1} (note that the values on the abscissa in Fig. 5 are multiplied by 100), a value that is at the far tail of the distribution in Fig. 5. An examination of where the observed AO index trend falls within the histogram reveals that it is statistically significant above the 99% confidence level. I also examine the sensitivity of the histogram to the choice of α, or equivalently, the decorrelation timescale T. It is found that T must be increased to a value of 32.8 days, which is far above the observed 10.6-day decorrelation timescale, for the AO index trend value to drop to the 95% confidence level. [The variance on interannual timescales increases with the decorrelation timescale (von Storch and Zwiers 1999), which results in a greater range of trend values at larger T.] Thus, these results provide support that the observed AO index trend does arise either from coupling to the hydrosphere and/or cryosphere, and/or from driving external to the climate system.

b. Variance

The next question I address is whether the variance of the AO index during the 1967–97 time period is significantly different from that of the synthetic time series described in section 2. As discussed above, this synthetic time series captures the intraseasonal stochastic characteristics of the observed AO index time series. Also, as implied by the nonzero variance in Fig. 2, intraseasonal stochastic processes must contribute to the variance on interannual timescales, no matter how short is the decorrelation timescale. Such variance, which can also be interpreted as arising from statistical sampling fluctuations, is usually referred to as climate noise (e.g., Leith 1973; Madden 1976; Madden and Shea 1978; Nicholls 1983; Trenberth 1984, 1985; Dole 1986; Feldstein and Robinson 1994; Feldstein 2000a,b). This variance due to climate noise can also be understood as representing an estimate of the population variance of the AO index, in the absence of coupling to the hydrosphere and cryosphere, and driving external to the climate system.

The approach adopted involves the calculation of the statistic $\chi^2 = NS_a^2/S^2$, where N is the number of winter seasons, $N - 1$ is the number of degrees of freedom. The quantity S_a^2 is the variance of 90-day averages of the daily annular mode time series, for each winter season. The quantity S^2 is the variance of 90-day time-mean values of the same 270 000-yr synthetic time series used in sections 2 and 3a. I specify a null hypothesis that S_a^2 equals S^2. If it is found that the value of χ^2 exceeds the 95% confidence level, then the null hypothesis is rejected and it is assumed that some fraction of the variance of the annular mode is driven by coupling to the hydrosphere and/or cryosphere, and/or from driving external to the climate system. Otherwise, the

null hypothesis is accepted, and the variance is regarded as falling within the limits of climate noise.

I first examine the value of χ^2 for the period encompassing the years of 1967–97. A χ^2 value of 57.7 is obtained. Because this value exceeds the 99.5% confidence level of 52.3, I reject the null hypothesis and interpret the variance of the annular mode as resulting in part from coupling to the hydrosphere and/or cryosphere, and/or from driving external to the climate system. As for the trend analysis, the sensitivity of these results to the decorrelation timescale is also examined. It is found that the χ^2 value drops to the 95% confidence level for a decorrelation timescale of 15.8 days, which is still well above the observed decorrelation timescale.

I next investigate the climate noise properties of the annular mode for the years 1899–1967. Again, χ^2 statistics are used. To estimate S_a^2, I use the AO index time series shown in Fig. 1, and for S^2, I assign the same value as that used in the above χ^2 calculation for the 1967–97 period, that is, the variance of the synthetic time series described in sections 2 and 3a. Specifying this value for S^2 implies that I am assuming that the decorrelation timescale is the same both prior to and after 1967. Because this timescale most likely depends on physical processes such as surface friction, transient eddy forcing, and Rossby wave dispersion, and these processes would not be expected to undergo any long-term changes, it would be highly unlikely for the decorrelation timescale to change. The calculation of χ^2 for the 1899–1967 period yields a value of 65.6, which is close to that expected for the null hypotheses, i.e., $\chi^2 = 68.0$. These results allow me to accept the null hypothesis for the 1899–1967 time period and to interpret the interannual variability of the annular mode during that time period as resulting entirely from climate noise.

The above test for the statistical significance of the variance during the 1967–97 period includes the trend of the AO index. Because the trend must contribute to an enhancement of its variance (Fig. 1 shows that the removal of the linear trend results in a relatively small reduction in the variance), I perform the χ^2 analysis with the trend subtracted. This calculation yields a χ^2 value of 49.2, which is greater than the value for the 97.5% confidence level of 45.7. The sensitivity analysis shows that the decorrelation timescale at the 95% confidence level is 12.8 days, 2.2 days larger than the observed decorrelation timescale.

4. Conclusions

The results of this analysis suggest that both the linear trend and the increase in variance of the annular mode during the latter 30 yr of the twentieth century are well in excess of that to be expected if all of the interannual variability was due to atmospheric intraseasonal stochastic processes. This, in turn, implies that both the linear trend and the variance increase of the annular mode are due to either the coupling of the atmosphere

to the hydrosphere and/or cryosphere, and/or from driving external to the climate system. For the time period approximately corresponding to the first 60 yr of the twentieth century, the results suggest that the interannual variability of the annular mode could be entirely accounted for by internal fluctuations confined to the atmosphere. This suggests that beginning in the 1960s, the annular mode underwent marked changes as coupling to the hydrosphere and/or cryosphere and/or driving external to the climate system began to have an important influence. To the extent that the observed changes in the annular mode are related to changes in various other climate variables, such as temperature, wind, and ozone, as discussed in the introduction, it is possible that these climate variables have also undergone similar changes in their driving mechanisms on interannual timescales.

Last, because the NAO is well known to be closely related to the annular mode, it would not be surprising if the NAO index exhibited the same linear trend and variance characteristics as the AO index. To examine this question, I apply the same methodology that has been used for the AO index. A daily NAO index time series is obtained following the approach used in Feldstein (2000b), and the interannual characteristics are evaluated with the NAO index of Hurrell and van Loon (1997), which extends back to 1864. For the NAO, it is found that the 1967–97 linear trend does exceed the 99% confidence level, the variance for the 1864–1967 time is close to that for the null hypothesis, and the 1967–97 variance also exceeds the 99% confidence level. Thus, the NAO does indeed exhibit the same linear trend and variance characteristics as the annular mode.

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