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CAN THE CCM3 GLOBAL CLIMATE MODEL ACCURATELY SIMULATE THE ARCTIC OSCILLATION?

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ABSTRACT   The Arctic Oscillation (AO) is the leading mode of mean sea level pressure from 20N poleward. This robust phenomenon is annular in nature and manifests itself on many different time scales ranging from multi-decadal to interannual. After filtering simulated sea-level pressure and surface temperature datasets, and an observed AO index, spectral analysis indicates that the first PCA of the pressure time series correlates with the AO index. The second PCA of surface temperature also correlates with the AO index at several frequencies. This study determines that the low frequency (defined as signals with 8-month periods or longer) AO signal can be accurately simulated in the CCM3 fields of sea level pressure and surface temperature.

INTRODUCTION   Thompson and Wallace (1998) defined the first EOF of the mean sea-level pressure (SLP) from 20°N poleward to be the Arctic Oscillation (AO). The AO is a well-defined naturally occurring mode of variability, which may be recovered using tropospheric data or a combination of tropospheric and stratospheric data (Baldwin and Dunkerton, 1999). The AO is robust (meaning it is insensitive to the details of the calculations performed on the data used to identify it (Baldwin and Dunkerton, 2001)) and is best summarized as having one center of action over the Arctic region, displaced toward Greenland, and an opposing ring at midlatitudes with prominent features over both the Atlantic and Pacific oceans (Ambaum et al., 2001; Baldwin and Dunkerton, 1999; Baldwin and Dunkerton, 2001; Deser, 2000). This annular AO is a result of internal dynamical feedbacks with the climate system, and as such can show a large response to rather modest external forcings (Hartman et al., 2000). Hartmann et al. (2000) and Thompson et al. (2000) suggest that since atmospheric climate models can simulate the observed structure, amplitude, and time series of the tropospheric AO by specifying the atmospheric composition and boundary conditions, the AO itself is free (meaning that it will occur in the absence of any external forcing). This also suggests that the AO is a

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real physical structure and not just a consequence of the EOF analysis used to define it.

The AO is hemispheric in nature (Thompson and Wallace, 1998) and transcends many different time scales (Hartmann et al., 2000; Ambaum et al. 2001). Wallace (2000) has shown that the AO is observable on intraseasonal and interannual time scales while Hurrell (1995) explains that quasistationary planetary waves in the atmosphere produce spatially coherent large patterns of anomalies in local surface variables on interannual and longer time scales. Thompson et al. (2000) suggest that the AO is prominent over a wide range of frequencies in all seasons because its zonal symmetry doesn't require local sources and sinks to counteract local tendencies induced by advection. The AO is evident throughout the year in the troposphere but its amplitude and meridional scales are somewhat larger during the cold season (Thompson and Wallace, 2000).

Not to be confused with the well-studied North Atlantic Oscillation (NAO), the annular character of the AO is more of a reflection of the dominance of its Arctic center of action than any coordinated behavior of the Atlantic and Pacific centers of action (Deser, 2000). The NAO, usually represented by sea level pressure anomalies of opposite sign between the Icelandic low and the tropical North Atlantic (Barnett, 1985), is a response to regional forcing over the North Atlantic. Because of its emphasis on atmosphere-ocean interaction, it is suggested that the AO is best studied on interannual time scales and longer. But because it transcends geographic and time scale classifications, it is useful in predicting climate and in studying polar, stratospheric, and atmospheric dynamics (Wallace, 2000). Some researchers, like Deser (2000) and Higgins et al. (2000), suggest that the AO encompasses the NAO. Deser (2000) asserts that the leading EOF includes the leading EOF of each of its subdomains. Because the AO is a hemispheric phenomenon and the NAO is primarily a North Atlantic phenomenon, this suggests that AO does indeed encompass the NAO. In fact, the AO is nearly indistinguishable from the NAO in the Atlantic sector (0.95 temporal correlation) in monthly data (Deser, 2000). Hurrell (1995) found a correlation between the first mode of SLP and a NAO index of 0.91. Ambaum et al. (2001) explains that the NAO and AO are highly correlated because of their overlap in the Atlantic sector. However, the NAO is worthy to be studied in its own right. It is the leading regional EOF of mean sea level pressure (Ambaum et al., 2001; Qian et al., 2000) in the Atlantic and the second mode of sea level pressure in a complex EOF (Barnett, 1985).

The AO signature is found not only in SLP, but in other tropospheric variables as well. Thompson et al. (2000) found an AO contribution in Northern Hemisphere wintertime trends in surface air temperature (SAT), precipitation, total column ozone, and tropopause height, all of which are well defined. For instance, Thompson and Wallace (2000) found that the leading mode of month-to-month variability in geopotential height is fundamentally zonally symmetric. Enfield and Mestas-Nunez (1999) suggested that the third mode of the detrended non-ENSO complex EOF in sea surface temperature (SST) anomaly is the AO. Likewise, Yasunaka and Hanawa (2002) found the second EOF of SST to have an elongated zonal signal in both the North Atlantic and North Pacific. This signature is very similar to the AO. Thompson and Wallace (1998) even found the AO signal in springtime SAT.

The AO is not confined to a zonal or meridional propagation, but can propagate vertically. Thompson and Wallace (1998) suggest that the AO is important because of the structural resemblance to the dominant mode of circulation variability in the lower stratosphere. Nikulin and Repinskaya (2001) found the second EOF of monthly winter total ozone anomalies in midlatitude Northern Hemisphere to be associated with the AO. Baldwin and Dunkerton (1999) found that the correlation between an AO index and zonal-mean temperature exceeds 0.9 at 150 hPa and 80°N, but stratospheric AO teleconnections only seem to exist in the active season (Thompson and Wallace, 2000). Hartmann et al. (2000) indicated that much theoretical and observational evidence exists to support the notion that the troposphere can drive stratospheric variability, but suggest that wave propagation, potential vorticity induction, and mass redistribution on the stratosphere can all drive the troposphere dynamically. Baldwin and Dunkerton (1999, 2001) also found a downward propagation through the tropopause of the AO signal in low-pass filtered (but not unfiltered) data. Baldwin and Dunkerton (1999) suggest that the large stratospheric anomalies are precursors to changes in tropospheric weather patterns. In fact, Baldwin and Dunkerton (2001) found AO surface pressure to lag middle stratospheric circulation by about sixty days.

The purpose of this study is to determine if the CCM3 global climate model can simulate the AO in the monthly mean SLP and surface temperature (TS) fields. An annual cycle version of the original CCM with no anomalous boundary conditions isolated the NAO signal (Barnett, 1985). The model used in this study was forced by a global SST dataset. In 1999, Robertson et al. reported that prescribing the SST variability over the North Atlantic in accordance with observations in a global climate model simulation substantially increases the interannual variability of the AO.

DATA AND METHODS The simulated data used in this analysis is from the CCM3 global climate model. The twenty-year period, 1970-1989, is considered in the study. The values of SLP and TS are used. The monthly mean values were reported on a 2.8° x 2.8° grid. Only data from 20° N poleward was used in the analysis. The data was converted to anomalies by subtracting the grid-averaged 20-year climatology from 1970-1989.

An EOF analysis was performed on the anomaly matrices and the leading three spatial eigenmodes were recorded. The leading mode of the sea-level pressure (1SLP) and the second leading mode of the surface temperature (2TS) was plotted to determine the stationary pattern of the AO. These patterns were described visually and compared to the description of the AO found in the literature to see if any preliminary conclusions could be found to attest to the model's successful simulation of the AO.

The principal components of the temporal eigenmodes were filtered twice using the low-pass Hanning Window. The monthly AO Index (created by projecting the daily 1000 hPa height anomalies poleward of 20°N onto the loading pattern of the AO) of the Climate Prediction Center was used and filtered using the same filtering process.

Squared-coherence values were calculated between the AO index and 1SLP. The 1SLP and AO are significantly correlated at a given frequency when the squared-coherence value at that frequency is greater than the 90% confidence level (0.25). The analysis was limited to phases ranging from approximately 8 months to 10 years. No conclusions were made about the squared-coherence between the AO and 1SLP (or between the AO and 2TS) on the multi-decadal time scale because my record length contains only one cycle of this signal. This method was repeated with the 2TS time series. Conclusions were drawn pertaining to the ability of the CCM3 to simulate the AO signal.

RESULTS The stationary EOF of (climatology removed) 1SLP and 2TS are plotted in Figure 1. In this study, 1SLP explains 36.35% of the variance in the dataset (Figure 1).

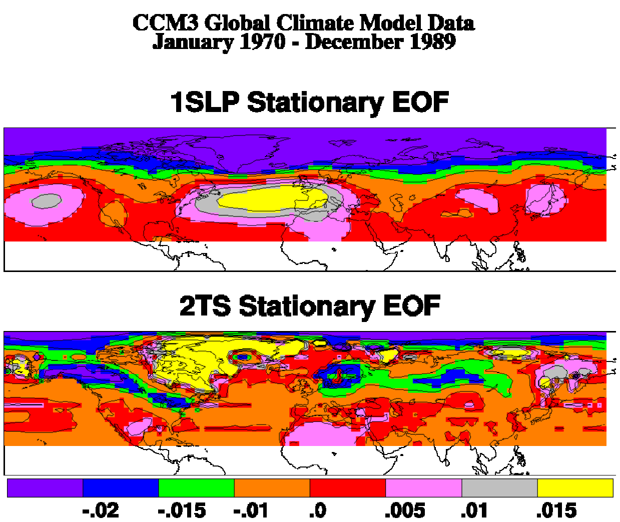

Figure 1 : Top – The stationary EOF of 1SLP explains 36.35% of variance. Bottom – The stationary EOF of 2TS explains 13.3% of variance.

This is much higher than the 22% of variance calculated by Thompson and Wallace (1998). However, the resulting pattern is quite zonal and symmetric in appearance. There are five distinct zonal bands in the plot with two distinct centers of action over the Pacific and Atlantic Ocean. The Atlantic center of action seems to be larger and more variable than the Pacific counterpart.

The Atlantic center of action is located in the North Atlantic Ocean and is the area between 30°N and 55°N, and 80°W and 40°E. This vast region encompasses both land and ocean and affects weather patterns. Drevillon et al. (2001) have shown using reanalysis data that a significant link exists between a summer North Atlantic SST anomaly and the following winter atmospheric circulation over Europe. The Pacific center of action exists only over ocean, and not much is known about the teleconnections between the Pacific center and atmospheric conditions elsewhere.

From analyzing 1SLP's stationary EOF, the CCM3 does not fully model the Arctic center of action. However, Greenland is well situated in the model's highest zonal band. There are two possible reasons for this discrepancy. This time series was taken while the AO was reversing polarity. According to the raw AO index, the decade of the seventies mainly had a positive index value, while the eighties had mostly a negative AO value. This change in polarity of the AO would cause the difference between Greenland's surface pressure and the pressure elsewhere in the zonal band to decrease. The model could have attempted to simulate the Arctic center of action but could not due to resolution issues. This is probable, because the contours of the zonal bands south of Greenland in Figure 1 (top) are closer together than everywhere else on the map.

Several features of this stationary EOF of 1SLP suggest that the CCM3 can model the AO signal. First, there is evidence of 5 distinct zonal bands, with a general trend of positive variability as one traverses meridionally. Secondly, the Atlantic and Pacific centers of action are well-modeled. However, other features suggest that the model does not accurately simulate the AO signal. First, the model suggests that the first mode explains 36% of variance, not 20-25%. And secondly, the model seems to incorrectly simulate the center of action that makes the AO different from the NAO, the Arctic center of action. Based on these competing criteria, the stationary EOF yields inconclusive information as to whether the CCM3 can model the AO.

2TS does not have a zonal appearance (Figure 1 - bottom). To begin, the model simulates the Arctic center of action in the surface temperature EOF. Greenland includes a core of negative variability surrounded by a vast region of positive variability. There are several zonal latitude bands north of Greenland. South of Greenland cannot be considered zonal except under the most liberal criterion.

However, the map is partially symmetric about the Arctic center of action. A variability band is evident from northwest United States to Maryland as well from Norway to China. South central United States has an area with positive variability surrounded by an area with no variability. This is seen as well in the Sahara Desert and surrounding area. There is only a faint suggestion of a Pacific core of action and no suggestion of an Atlantic center. This is in partial agreement with Ambaum et al. (2001) who found his temperature analysis to give patterns unrelated to the typical zonally symmetric AO signal. In addition, Thompson and Wallace (1998) explains that the zonally asymmetric SAT observed in association with AO may be secondary baroclinic features induced by land-sea contrasts. However, like Thompson and Wallace (2000), positive temperature anomalies are found in 2TS southward from the midlatitudes.

The model simulates an Arctic center with symmetry south of it and a zonal appearance to the north, while not modeling an Atlantic center and barely modeling a Pacific center. This stationary EOF yields inconclusive information as to whether the model is simulating the AO.

The EOF analysis of the CCM3 data is more successful in extracting the AO pattern from the SLP data than in the surface temperature data. Ambaum et al. (2001) suggests that this occurs if one field in the analysis is more orthogonal than the other.

To study the temporal coherence between the AO, SLP and TS fields, the squared coherence at each frequency was computed.

Those frequencies where peaks were located in a coherence vs. frequency plot were used in the analysis. According to the above criteria, Table 1 list the significant periods of both the AO-1SLP and AO-2TS studies with periods greater than or equal to eight months. Figure 2 shows the squared coherence of AO-1SLP and AO-2TS respectively (from left to right).

The AO-1SLP analysis had five peaks. These were at periods of 80 months, 34.3 months, 13.33 months, 10.91 months, and 8.57 months (signals A, B, C, D, and E respectively). Because there are significant periods bounding the annual cycle (signals C and D), some confusion arises as to whether the model can be used for annual AO studies. Even though there was no peak for the annual cycle in this analysis, the CCM3 can be used for annual studies because the monthly climatology was removed from the data prior to analyzing to try to isolate other significant frequencies. If left in, the annual cycle’s energy dwarfs all other frequencies.

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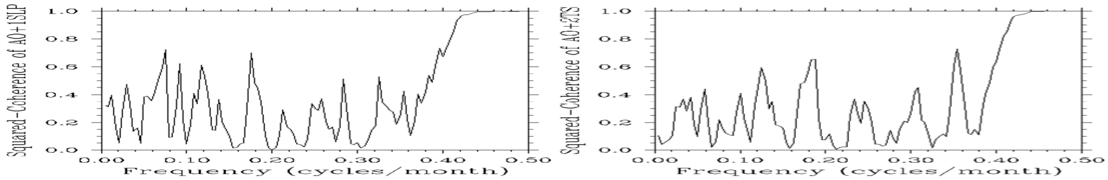

Figure 2 : Left - Squared Coherence of AO index and 1SLP at different frequencies. Right - Squared Coherence of AO index and 2TS at different frequencies.

Figures 3 shows the amplitude and phase of the AO-1SLP analysis. As expected, those frequencies with highest coherency had a peak in their amplitude. All of the signals have amplitudes significantly different from other “not as significant” signals in their frequency band except signal E. This is because signal E has a phase of 95.33 °. Consequently, its components are nearly out of phase.

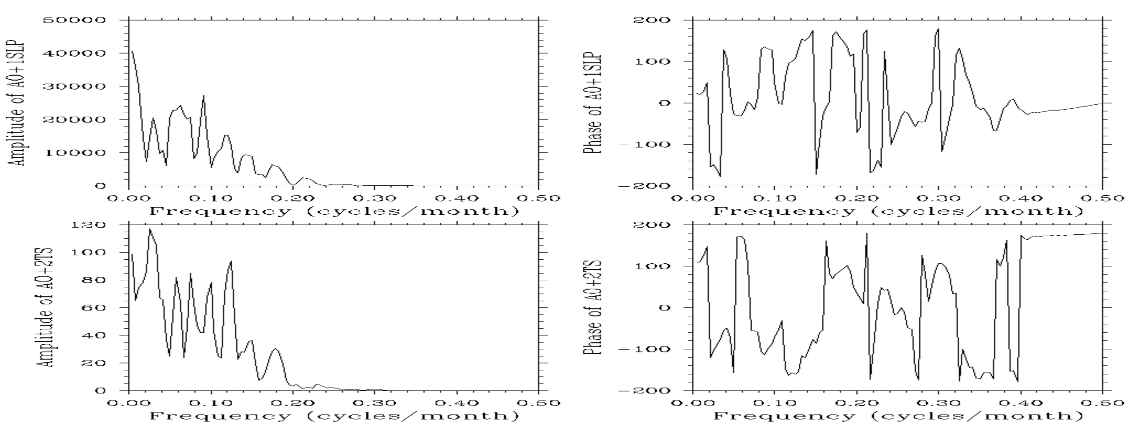

Figure 3 : Top Left – Amplitude of AO-1SLP signal. Top Right – Phase of AO-1SLP signal. Bottom Left – Amplitude of AO-2TS signal. Bottom Right – Phase of AO-2TS signal.

Signals A and C are in phase with the AO index leading the 1SLP. There is nearly no phase difference between these two at these frequencies. 1SLP leads the AO index by 161.81 ° in signal B whereas the index leads 1SLP by 131.30 ° in signal D. Signals A, C, and D have the greatest amplitudes, all of which have the AO index leading 1SLP. Signal B has the fourth highest amplitude (where 1SLP leads the index) and signal E (where they are out of phase with each other) has the smallest amplitude.

The CCM3 field of sea level pressure can, therefore, be used in AO studies with time scales ranging from interannual to intra-annual.

A similar analysis was performed for the AO-2TS study. Signals with periods of 30 months, 24 months, 17.1 months, 10 months, and 8 months (signals F, G, H, I, and J) were more coherent than other signals in their respective frequency band. Figure 3 also shows the amplitude and phases of the AO-2TS study. In all but signal H; the temperature leads the AO index. (Further research is needed to determine if this is because signal H is the only signal that is not a pure harmonic of the data used.) Signals F and I both have phases of 76.20 ° and 71.44 ° respectively. Signal G is much closer to being in phase at 49.43 ° as well as signal J with a 160.49° phase. The AO index and 2TS are in phase in H with the index leading the temperature.

Many frequencies in the temperature studies have amplitudes of comparable size. Out of the five used in this study, signal F had the biggest amplitudes. The temperature analysis is less sensitive to phase perturbations than the sea level pressure analysis but longer signals have slightly higher amplitude than shorter signals because of the high specific heat of the Northern Hemisphere oceans. More time is needed to show a forcing to some outside perturbation.

This study has found that the CCM3 can be used to study the AO signal on time scales ranging from interannual to intra-annual. However, surface temperature is best used for studies on interannual and shorter timescales, because spectral analysis of the surface temperature is more likely to be influenced by leakage from centennial signals, millennium signals, and even ice age signals.

Table 1 : Several frequencies with significant coherency of AO-1SLP and AO-2TS at the 90% confidence level (0.475).

Period (mos.)	AO - 1SLP	Period (mos.)	AO – 2TS
80	.630	30	.609
34.29	.688	24	.618
13.33	.850	17.1	.664
10.91	.789	10	.640
8.57	.782	8	.771

CONCLUSIONS The CCM3 model can indeed simulate the AO signal in the SLP and TS fields. CCM3 model data of SLP can be used to study the AO on interannual as well as intraannual timescales. However, one must remove the climatology from the dataset to do this, because most of the power of the SLP field is in the 0.833 cpm frequency band. The spatial graph of the stationary EOF of 1SLP is zonally symmetric with centers of action in the Atlantic and Pacific oceans. What was not evident was the existence of the signature Arctic center of action. However, the model does recognize an opposing center over Greenland. This is evident in the coherence between the model data and observational AO index on several different timescales. The lack of appearance of a closed-off center over the Arctic region must be due to a lack of resolution in the model and not a lack of relevant Physics.

2TS is zonally asymmetric below Greenland, but is still well correlated with the AO index on interannual and intraannual timescales. Even though the climatology was removed, the TS still had significant power in the 0.833 cpm frequency (not shown). This suggests that the climatology must be removed before studying the AO on timescales longer than the annual cycle.

Further research includes repeating this analysis to determine correlations between the AO and several other tropospheric and oceanic fields. Complex EOFs could then be analyzed to determine the propagating characteristic of these fields on interannual timescales.

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