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Arctic Oscillation and Antarctic Oscillation in Internal Atmospheric Variability with an Ensemble AGCM Simulation

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ABSTRACT

In this study, we investigated the features of Arctic Oscillation (AO) and Antarctic Oscillation (AAO), that is, the annular modes in the extratropics, in the internal atmospheric variability attained through an ensemble of integrations by an atmospheric general circulation model (AGCM) forced with the global observed SSTs. We focused on the interannual variability of AO/AAO, which is dominated by internal atmospheric variability. In comparison with previous observed results, the AO/AAO in internal atmospheric variability bear some similar characteristics, but exhibit a much clearer spatial structure: significant correlation between the North Pacific and North Atlantic centers of action, much stronger and more significant associated precipitation anomalies, and the meridional displacement of upper-tropospheric westerly jet streams in the Northern/Southern Hemisphere.

In addition, we examined the relationship between the North Atlantic Oscillation (NAO)/AO and East Asian winter monsoon (EAWM). It has been shown that in the internal atmospheric variability, the EAWM variation is significantly related to the NAO through upper-tropospheric atmospheric teleconnection patterns.

Key words: internal atmospheric variability, North Atlantic Oscillation, Arctic Oscillation, Antarctic Oscillation, extratropical climate anomalies, East Asian winter monsoon

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1. Introduction

The annular mode perspective, illustrated by the Arctic Oscillation (AO) and Antarctic Oscillation (AAO), provides a different view of low-frequency atmospheric variability from the classic region-to-region teleconnections to the hemispheric scale zonally symmetric patterns (Thompson and Wallace, 2000; Li and Wang, 2003). Discussion on the AO has been stimulated due to its crucial associations with the linear trend of temperature in the observed atmosphere (Thompson et al., 2000), and its impacts on regional climate (Thompson and Wallace, 2001). In particular, there was evidence that the AO/AAO are associated with East Asian summer climate (Gong et al., 2003; Ho et al., 2005; Ju et al., 2005; Wang and Fan, 2005) and winter monsoon (Wu and Wang, 2002a; Jeong and Ho, 2005; Gong and Drange, 2005). The variability in the AO would change in global warming simulations, and the observed AO trend in recent decades might be attributed to the increase in atmospheric greenhouse gas concentrations (Fyfe et al., 1999; Shindell et al., 1999; Yukimoto and Kodera, 2005).

The annular mode has been questioned by the regional perspective that views the annular mode as a statistical artifact of local occurring dynamics of the North Atlantic Oscillation (NAO). Deser (2000) found that the Arctic center of action of the AO is significantly correlated with both the Atlantic and Pacific centers, but no direct correlation was observed be-

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tween the Atlantic and Pacific centers. Ambaum et al. (2001) and Dommenget and Latif (2002) found that annular structures appear as mathematical construct in the outputs of idealized statistical models in which variability in the Pacific and Atlantic sectors was constrained to be linearly independent. Wallace and Thompson (2002) counteracted this argument and suggested that the absence of significant correlation between the Atlantic and Pacific centers comes from a contamination by the second empirical orthogonal function (EOF) pattern, which is associated with the El Niño-Southern Oscillation (ENSO). After removing the second EOF pattern by linear regression from sea level pressure (SLP) data, Wallace and Thompson (2002) noted a significant correlation between the Atlantic and Pacific oscillations.

The NAO has a rich blend of frequencies, those with both high (intraseasonal to interannual) and low frequency (decadal to multi-decadal or trend) variabilities (Hurrell, 1995). The former is believed to be dominated by atmospheric internal variability (Lee and Feldstein, 1996; Watterson, 2000), while the mechanism responsible for the latter is not clear, although ocean-atmosphere interactions (Grätzner et al., 1998; Rodwell et al., 1999) and global warming (Kuzmina, 2005) are possible candidates. The vacillations in the zonal flow reminiscent of the annular modes are clearly evident in models with the absence of ocean-atmosphere coupling (e.g., Lee and Feldstein, 1996). Thus, at least for the high-frequency variability of the AO/NAO, the internal atmospheric variability is dominant and needs to be specially examined.

The ocean-atmosphere interaction may make the AO ambiguous. As an indirect support of this hypothesis, Wallace and Thompson (2002) obtained a more coherent structure of the AO after the second EOF pattern, which is associated with the ENSO, is removed from the data. The ENSO, the strongest ocean-atmosphere coupling phenomenon on the interannual timescale, is associated with the various temperature and precipitation anomalies that are pronounced in the tropics but frequently extend into the extratropics. The ENSO is likely to be associated with the SLP anomalies in the North Atlantic region that are projected in the NAO (Huang et al., 1998; Dong et al., 2000; Pozo et al., 2001). The effects of ocean-atmosphere interaction on the NAO on the interannual timescale, whether statistically significant or not, veil the nature of the internal atmospheric variability.

Although the effects of AO on regional climate have been extensively investigated, the relationship between the EAWM and the AO and the physical mechanism behind the relationship remains unclear. Gong et al. (2001) first showed a connection between the AO and EAWM, suggesting that the AO influences the EAWM through its impacts on the Siberian High. Wu and Wang (2002b), however, argued that the AO and Siberian High are relatively independent of each other in influencing the EAWM, although the relationship between the EAWM and AO is marginally significant. Indeed, the relationship between the EAWM and AO is subtle in observations, and is no longer found to be significant after the linear trend is removed (Gong et al., 2001).

There has been no statistically significant relationship identified between the EAWM and NAO, although the latter is highly correlated with the AO. It is expected to some extent, however, since the AO illustrates a hemispheric scale zonally symmetric teleconnection pattern and thus might correlate with more phenomena in the extratropical Northern Hemisphere. Jhun and Lee (2004) suggested that the relationship between the EAWM and AO/NAO is dominant on the interdecadal timescale but not on the interannual timescale. On the other hand, Watanabe (2004) found that when the NAO accompanies the Mediterranean convergence anomaly, the anomalies associated with the NAO extend toward East Asia via quasi-stationary Rossby waves trapped on the Asian jet waveguide, and are similar to the spatial structure of the AO. This is in contrast to the understanding that the NAO is relatively confined to the Atlantic and Europe without the anomalous Mediterranean convergence. Furthermore, there is evidence for the climate linkage between East Asia and North America. Yang et al. (2002) found that a stronger East Asian upper-tropospheric westerly jet (EAJ) corresponds to strengthened EAWM and warmer (colder) condition in the western (eastern) Unites States.

The questions remain: what are the features of the AO/AAO in internal atmospheric variability? Do these features differ from those in observations, which involve the ocean-atmosphere interaction and anthropogenic climate change? These questions are essential for providing a better understanding of the physical mechanisms responsible for the climatic variability in the AO/AAO and in attaining a better prediction of the anthropogenic impacts. In this study, we address these questions by investigating the internal atmospheric variability through an ensemble of integrations by a model forced with the global observed SSTs. In addition, we investigate the relationship between the NAO/AO and EAWM in the internal atmospheric variability.

Some previous studies have investigated the AO/AAO using Atmospheric General Circulation Models (AGCMs), but they emphasized the predictability of the AO/AAO, and thus focused on the ensemble-mean variability. Although there were a few studies using AGCMs forced with climatological SSTs (Watterson, 2000), these did not discuss the spatial structure of AO/AAO and AO/AAO-associated climate anomalies for internal variability in great detail. In addition, in this study, we focused on the interannual variability of the AO/AAO, and its associations with climate, although the internal atmospheric dynamics are generally more essential for the subseasonal variability than for the interannual variability.

The experimental design and the approaches toward analysis are described in section 2. We analyze the features of internal AO and AAO in section 3 and section 4, respectively. The relationship between the NAO/AO and EAWM is presented in section 5. Section 6 is devoted to a summary.

2. Experimental design and analysis approaches

The Met Office Hadley Centre atmospheric general circulation model, known as HadAM3, was used in this study. The model uses a 2.5° latitude by 3.75° longitude grid and 19 model levels. There are 7 levels above 200 hPa, and the top level is at 4.6 hPa. It includes the new land surface scheme developed by Cox et al. (1999). This new land surface scheme includes a representation of the freezing and melting of soil moisture leading to better simulations of surface temperatures, and a new formulation of evaporation which includes the dependence of stomatal resistance to temperature, vapour pressure deficit and CO_2. A detailed description of the model formulation and its performance is documented in Pope et al. (2000).

Experiments were conducted over the period from 1 December 1985 to 28 February 2001 with global observed SSTs and sea ice extent, as described by Reynolds et al. (2002). We analyzed the data from December 1986 to February 2001. In order to separate internal atmospheric variability from externally forced variability, an ensemble of ten integrations was performed with slightly different initial states. The initial conditions were taken from 10 consecutive days of a spin-up integration. In this study, the simulated interannual variability was separated into an external component and an internal component, similar to the approach of Rowell et al. (1995). That is, the internal atmospheric variability is defined as the deviations from the ensemble mean. The sample size of the internal variability is 150. The only assumptions required are that the internal atmospheric variability is the same for each year, and that the effect of altering the initial atmospheric conditions has a purely random impact on the simulated seasonal mean anomalies. For the details of the calculation method, refer to Rowell et al. (1995).

The analysis of the internal atmospheric variability in this study parallels previous observational analyses to the largest extent to facilitate comparison with previous results. Thus, the analysis method used in this study includes EOF, correlation, and regression analyses.

3. Arctic Oscillation in internal atmospheric variability

Figure 1a shows the spatial structure of the leading EOF pattern for the DJF (December–January–February) mean SLP in the internal atmospheric variability. This pattern is widely used to represent the AO pattern and it is remarkably similar to the spatial structure of the leading EOF pattern in observations. The leading pattern for the internal atmospheric variability is well separated from the second pattern, indicated by the great difference in their explained variances (37.3% and 9.8%, respectively). In observations, the first and second EOF patterns of SLP account for about 25% and 14% of the variance, respectively (e.g., Ambaum et al., 2001). The leading pattern for the internal atmospheric variability accounts for a larger percentage of the variance than those found in observations, indicating that the AO is likely to be blurred by the coupling between atmosphere and various other components.

The AO, the "annular perspective", has been questioned by the fact that there is no significant association between the North Pacific and North Atlantic. Deser (2000) found that the correlation between the Pacific and Atlantic centers of action is not significant. We performed a correlation analysis similar to that of Deser (2000), that is, investigating correlations among the regional DJF-mean time series formed by averaging the area-weighted SLP anomalies within the outer (non-zero) contours in Fig. 1a for the appropriate sectors. We found that all of the correlation coefficients exceed the 99% confidence level: r(Arctic, Atlantic)=−0.65, r(Arctic, Pacific)=−0.35, and r(Atlantic, Pacific)=0.24.

The linkage between the North Pacific and North Atlantic centers can be confirmed by the point correlations (Fig. 1b). Although the correlation pattern clearly shows a local feature (or the NAO feature), the North Pacific and North Atlantic centers are significantly correlated. In observations, however, these centers are not significantly correlated (Fig. 1 of Wallace and Thompson, 2002; and Fig. 2 of Ambaum et al., 2001).

After removing the EOF-2 pattern from SLP data

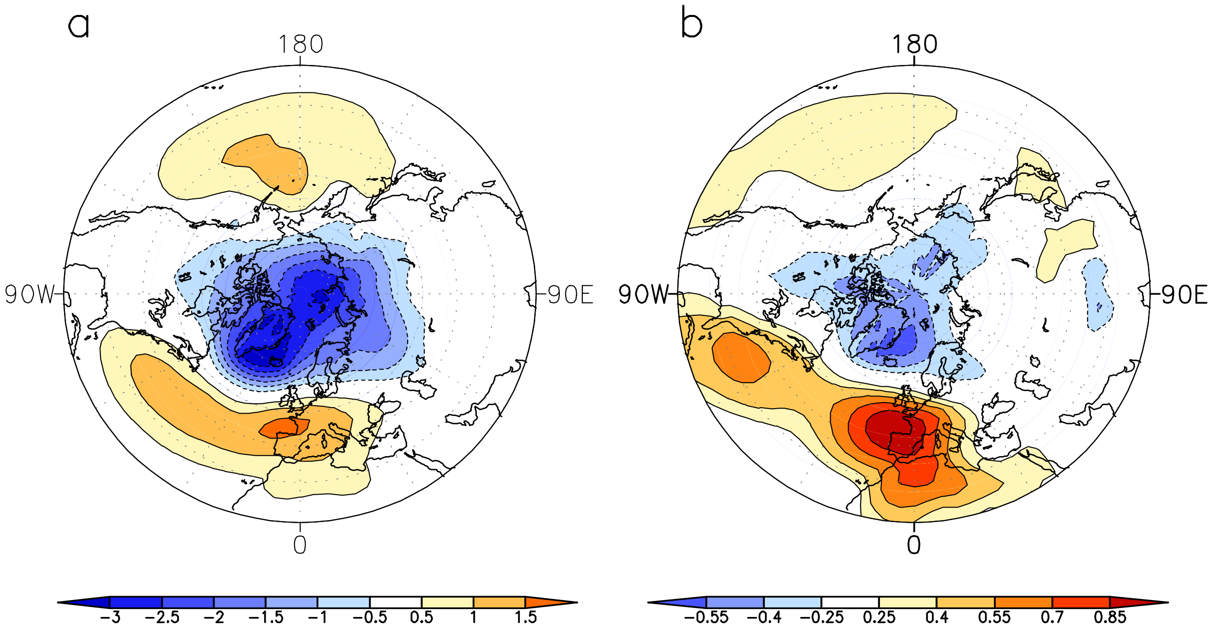

Fig. 1. (a) The spatial pattern of the leading EOF for DJF-mean SLP in internal atmospheric variability. The analysis domain is poleward of 20°N. The pattern displayed is the regression map of DJF-mean SLP onto the standardized leading EOF time series. Unit: hPa. (b) One-point correlation map for the base point (45°N, 7.5°W). This point is the North Atlantic center shown in Fig. 1a.

by linear regression, Wallace and Thompson (2002) noted a significant correlation between the Atlantic and Pacific. However, we obtained a significant correlation without any changes of data in internal variability. The present analysis shows that significant correlation coefficients exist between the regional mean time series of the original data in the internal atmospheric variability, indicating a more coherent spatial structure of the AO in the internal atmospheric variability.

Figure 2 shows the 200-hPa zonal wind (top panel), surface air temperature (middle panel), and precipitation (bottom panel) regressed onto the standardized principal component (PC) of EOF-1, which is used to represent the AO index. The positive AO index corresponds to a poleward displacement of the upper-tropospheric westerly jet stream in the whole Northern Hemisphere, except the eastern North Atlantic and North Africa, and such a displacement is prominent in the North Pacific and western North Atlantic. The zones around 60°N and 30°N are characterized by westerly and easterly anomalies, respectively. These features of 200-hPa zonal wind anomalies are generally consistent with previous observational results, but show a clear poleward displacement of upper tropospheric westerly jet streams. In observations, the positive anomalies of AO/NAO correspond to a weakened Pacific jet and strengthened Atlantic jet (Ambaum et al., 2001).

The positive polarity of the AO is marked by the anomalously high temperatures over high latitudes of Eurasia, with two centers over Europe and Siberia (Fig. 2b). It is also associated with the anomalously high temperatures over eastern North America. Anomalously low temperatures appear over extreme eastern Russia, Alaska, extreme eastern Canada, Greenland, North Africa, and the Middle East. The spatial structure and amplitude of temperature anomalies are consistent with previous observational results (e.g., Thompson and Wallace, 2000).

The AO pattern is clearly related to the rainfall anomalies in the North Pacific and North Atlantic (Fig. 2c). In these oceans, the positive polarity of the AO corresponds to the anomalously light rainfall in the middle latitudes at about 35°N and anomalously heavy rainfall in the low and high latitudes. The precipitation anomalies in the Pacific tend to be stronger in its eastern extent, and are slightly weaker than those in the Atlantic. These precipitation anomalies are basically oriented in the zonal direction, but with a slight southwest-northeast tilt.

The clear precipitation signature of the AO in the internal atmospheric variability does not appear in observations. In comparison with the anomalous surface air temperatures associated with the NAO/AO, the anomalous precipitations have been less documented, possibly due to the short period of observed precipitation data over the oceans available and due to much weaker signals in precipitations over most of the lands.

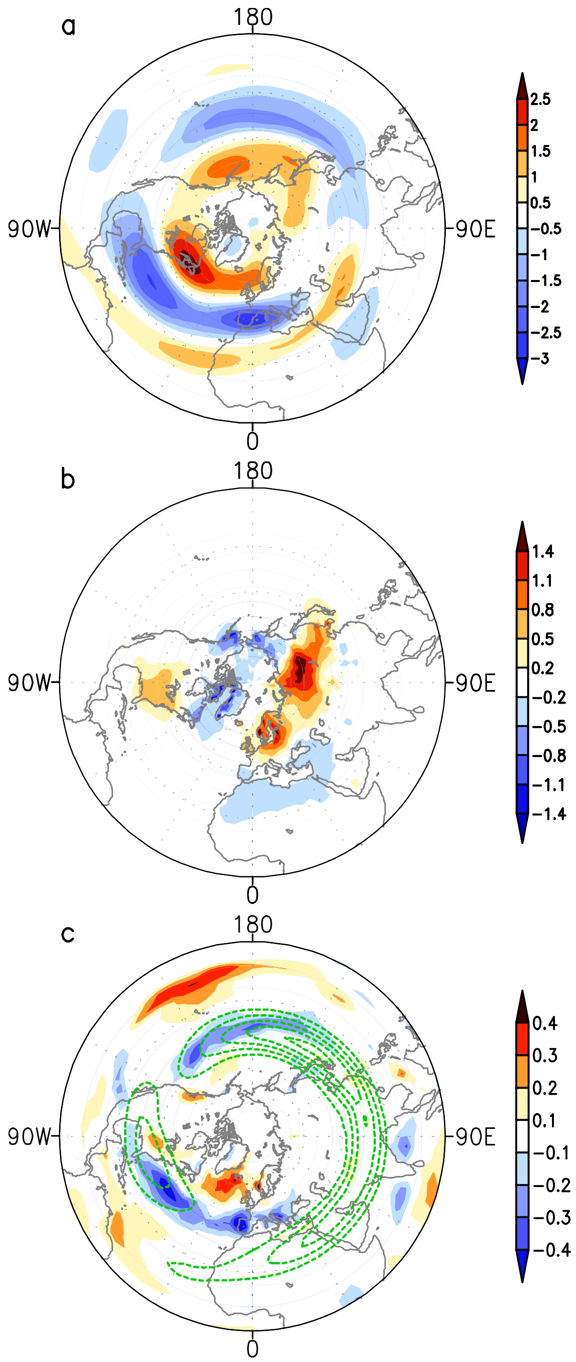

Fig. 2. (a) The 200-hPa zonal wind, (b) surface air temperature, and (c) precipitation regressed onto the standardized internal leading PC of Fig. 1a. Units are m s^{-1} for zonal wind, K for surface air temperature, and mm d^{-1} for precipitation. All shading values exceed the 95% confidence level based on the F-test, except those for precipitation in the South China Sea. Bold, green, dashed lines show the position and intensity of westerly jet streams, indicated by the contour lines of 30, 40, 50, 60, and 70 m s^{-1} of the DJF-mean 200-hPa zonal wind in model climatology.

In observations, the AO/NAO was found to be associated with the weak precipitation decrease in some regions in the North Pacific and the precipitation increase in the "conduit" of Norwegian-Greenland Seas and Scandinavia (Dickson et al., 2000). There are great differences between the present result and that of Dickson et al. (2000) in the North Pacific and continents, although there is some resemblance in the North Atlantic sector. In addition, the stratosphere annular mode, which is closely related to the AO, is associated with the meridional displacement of the storm track over the eastern Pacific, as well as over the Atlantic sector (Baldwin and Dunkerton, 2001).

There is a longer and more reliable precipitation dataset at stations in lands. The land precipitation anomalies associated with the AO in internal atmospheric variability, that is, anomalously dry conditions over southern Europe and the Mediterranean and wetter conditions over eastern Canada and Scandinavia (Fig. 2c) are consistent with some previous observational results based on the station data (Hurrell and van Loon, 1997; Osborn et al., 1999). The present result shows a clear connection between the land and the ocean in the Atlantic sector, which has never been identified in observations, previously.

4. Antarctic Oscillation in internal atmospheric variability

Figure 3a shows the leading EOF mode of DJF mean SLP of the internal atmospheric variability poleward of 20°S. We consider the mode as the internal AAO, and the PC as the AAO index. The internal AAO explains most of total variance (70.5%), much more than the second leading mode (only 4.8%). The variance explained is much more than the leading mode in observations (at the scope of 20%–40%). Its spatial structure, i.e., negative values in the Antarctic and positive values in the outer ring, resembles that of observations (Gong and Wang, 1999).

In the Southern Hemisphere, the point correlation patterns for internal atmospheric variability are also remarkably different with those for observations. A clear annular mode appears in the correlation pattern by using the maximum center in the outer ring as base point (Fig. 3b). We have calculated the point correlation patterns by using other centers in the outer ring as base point, and found similar annular modes (not shown). The outer ring of the AAO is more clearly reflected in point correlation maps in internal atmospheric variability than in observations (Fig. 2 of Wallace and Thompson, 2002).

The AAO is also associated significantly with the climate anomalies in the Southern Hemisphere. The

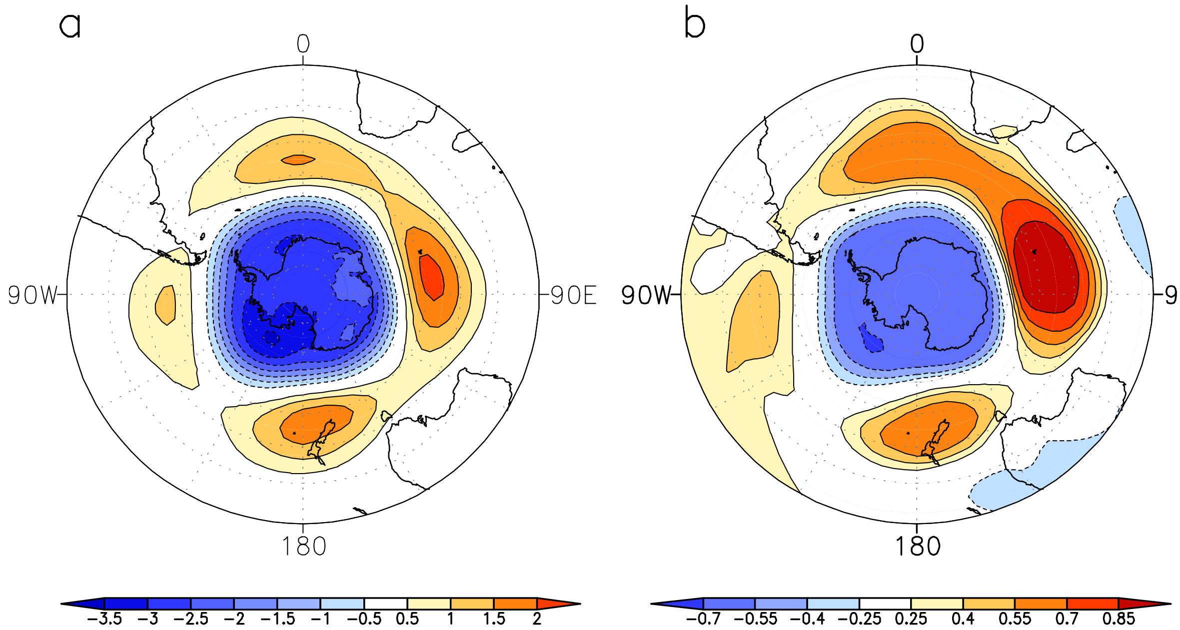

Fig. 3. (a) Same as Fig. 1a, but for the extratropical Southern Hemisphere. (b) One-point correlation map for the base point (50°S, 78.75°E). This point is the maximum center in the outer ring shown in Fig. 3a.

positive phase of the AAO corresponds to the westerly anomalies at the zonal band of 50°–70°S, and easterly anomalies north of it (Fig. 4a). This indicates a poleward displacement of the westerly jet stream in the Southern Hemisphere. The surface air temperatures are decreased over the Antarctic and lands of three Southern Hemisphere continents approximately along 30°S at the positive phase of the AAO (Fig. 4b).

The positive phase of the AAO corresponds to the negative precipitation anomalies at the zonal band of 40°–50°S and positive anomalies at the band of 50°–70°S (Fig. 4c). Along 30°S, the precipitations tend to be heavier, but only over several separate regions, not along the entire zonal band. These precipitation anomalies that are associated with the AAO are partially consistent with previous observational results (Jones and Widmann, 2003), although the quality of the Antarctic analysis in the NCEP-NCAR reanalysis has been questioned (Marshall, 2002; Hines et al., 2000). Jones and Widmann (2003) calculated the correlations between the AAO index and precipitation in observations, and found that the correlation coefficients are generally positive over Australia and the southern part of Africa, and are negative in the southern part of America.

These zonally-oriented precipitation anomalies associated with the AAO in the internal atmospheric variability result from the poleward displacement of the westerly jet stream and resultant poleward shifted storm track (Trenberth, 1991). Trenberth (1991) analyzed the observational data from 1979 to 1989, and found that the storm-track activity in the Southern Hemisphere is persistent through the year in both location (near 50°S) and intensity, and is strongly related to the major tropospheric polar jet stream.

The present result is also consistent with previous GCM simulated results (Watterson, 2000). Among the simulations with four different types of ocean in Watterson (2000), those with the climatological SSTs are most similar to the internal variability in the present study. In the simulations forced with the climatological SSTs, the zonal vacillation is associated with zonal mean precipitation anomalies, centered respectively at 30°S, 43°S, and 60°S. The results of Watterson (2000) are quite similar to the present result. This similarity implies that the present result may not strongly depend on models. However, the statistical significance of local, rather than zonal mean, correlations is low possibly due to the small number of samples (only 30 samples) in Watterson (2000).

5. Relationship between the NAO/AO and EAWM

The upper-tropospheric meridional wind can depict zonally oriented teleconnections quite well (e.g., Lu et al., 2002; Watanabe, 2004). Other variables, such as height, stream function, and vorticity, are closely related to the zonal winds and tend to show zonally elongated anomalous patterns. Thus, these va-

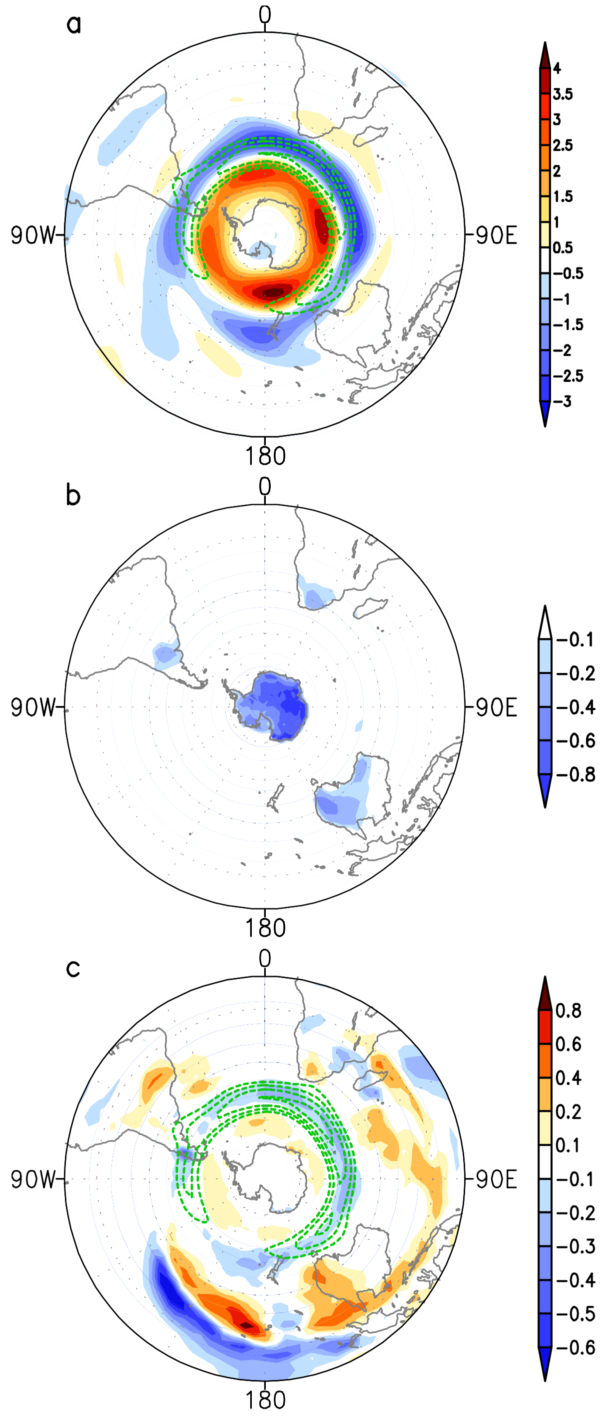

Fig. 4. Same as Fig. 2, but for the anomalies regressed onto the standardized internal leading PC of Fig. 3a. The westerly jet streams are indicated by the contour lines of 30, 33, 36, and 39 m s^{-1}.

riables tend to exhibit the AO pattern, which is an annular mode dominating in the Northern Hemisphere extratropics. In this section, we emphasize the relationship between the EAWM and NAO, and attempt to diminish the possible role of the AO on this relationship by using upper-tropospheric meridional wind. We start with an observational analysis, followed by an analysis on internal variability.

Figure 5 shows the 200-hPa meridional wind regressed onto the standardized EAWM index and NAO index, respectively, in observations. In this study we define the EAWM index simply as averaged 850-hPa northerly anomalies over the region (25°–45°N, 115°–145°E). There are a few previous studies defining the EAWM index by a variable in the lower troposphere as well. Yang et al. (2002) defined the EAWM index by the anomalous 850-hPa meridional wind averaged over (20°–40°N, 100°–140°E). Wang and Jiang (2004) gave a similar definition, but used the intensity of the horizontal wind averaged over a slightly different region (25°–50°N, 115°–145°E). Our definition is similar to theirs, but there are some slight differences. First, we use the meridional wind, same as Yang et al. (2002), since the temperature anomalies in East Asia are mainly caused through the anomalous advection of temperature by the meridional wind anomaly. In addition, the average region for our definition is similar to that in Wang and Jiang (2004), in agreement with the region of the strongest climatological northerly, but is eastward shifted in comparison with that in Yang et al. (2002). The NAO index is defined as the principal component of the leading EOF pattern for the DJF-mean SLP. The domain of the EOF analysis is poleward of 20°N and between 60°W and 30°E, following Wallace and Thompson (2002). The observational data used here are the NCEP-NCAR reanalysis data for 25 winters from 1979/80 to 2003/04.

An anomalous EAWM is associated with significant meridional wind anomalies in the Northern Hemisphere (Fig. 5a). There appears to be teleconnection patterns from the eastern Pacific to the North Atlantic and to East Asia through the southern edge of the Eurasian continent. The significant meridional wind anomalies associated with the NAO anomaly are mainly confined in the North Atlantic-Euro sector (Fig. 5b). However, there are meridional wind anomalies at the southern Eurasian continent, which is consistent with Watanabe (2004), though they are very

Table 1. Correlation coefficients between the indices in the internal atmospheric variability. The EAJ index is defined by the DJF-mean 200-hPa zonal wind anomalies averaged over the region (30°–35°N. 130°–160°E), following Yang et al. (2002).

	NAO	AO
EAWM	−0.221	−0.285
EAJ	−0.329	−0.374

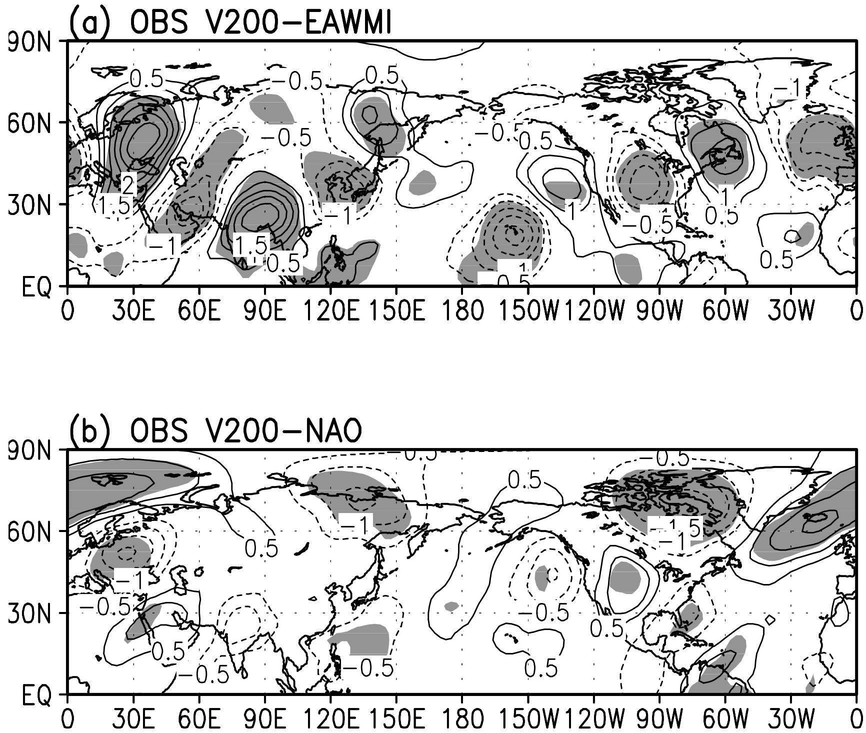

Fig. 5. 200-hPa meridional wind regressed onto the (a) standardized EAWM index and (b) NAO index in observations.

weak in East Asia.

In the internal atmospheric variability, both the EAWM and NAO are associated with broad regions of significant meridional wind anomalies (Fig. 6). The teleconnection patterns associated with the EAWM in the internal variability (Fig. 6a) differ significantly from those in observations (Fig. 5a). In the internal variability, the teleconnection pattern over the Eurasian continent, except East Asia, essentially disappears, but the meridional wind anomalies become much greater and more significant in the North Pacific. Thus, these anomalies indicate a teleconnection pattern from East Asia to the North Atlantic through the North Pacific and America. In the NAO region, the meridional wind anomalies associated with the EAWM tend to show opposite signs with those associated with the NAO (Fig. 6b).

On the other hand, the anomalies associated with the NAO in the internal atmospheric variability (Fig. 6b) are similar to those in observations (Fig. 5b) in spatial distribution, but the former show a much higher significance level than the latter. The significant anomalies appear in the whole Eurasian continent. There appears to be a zonally oriented teleconnection pattern from the North Atlantic eastward to northeastern Asia, besides the teleconnection pattern at the southern Eurasian continent mentioned by Watanabe (2004). Associated with the positive phases of NAO, there is a southerly anomaly in East Asia and the western North Pacific, indicating a weaker EAWM. In the internal variability, the NAO does not correspond to notable meridional wind anomalies in the North Pacific.

Interestingly, in the internal atmospheric variability, both the EAWM and NAO do not correspond to significant meridional wind anomalies in the upstream regions, which are the Eurasian continent for the EAWM and the North Pacific for the NAO. Absence of a teleconnection pattern at the upstream regions implies that this interaction between the EAWM and NAO is weak. On the other hand, the downstream teleconnection patterns suggest that the EAWM anomalies affect the climate in North America and the Atlantic, and the NAO anomalies affect the climate in East Asia. This relationship between the EAWM and NAO can be confirmed by the correlation coefficients shown in Table 1. The relationship between the EAWM index and NAO index is statistically significant at the 95% level, although each can only explain a small fractional variance of the other. Besides, the correlation coefficient between the indices of EAWM and AO, or correlation coefficient between the indices of EAJ and NAO/AO, is greater. The EAJ is an integrated component of the EAWM in the upper

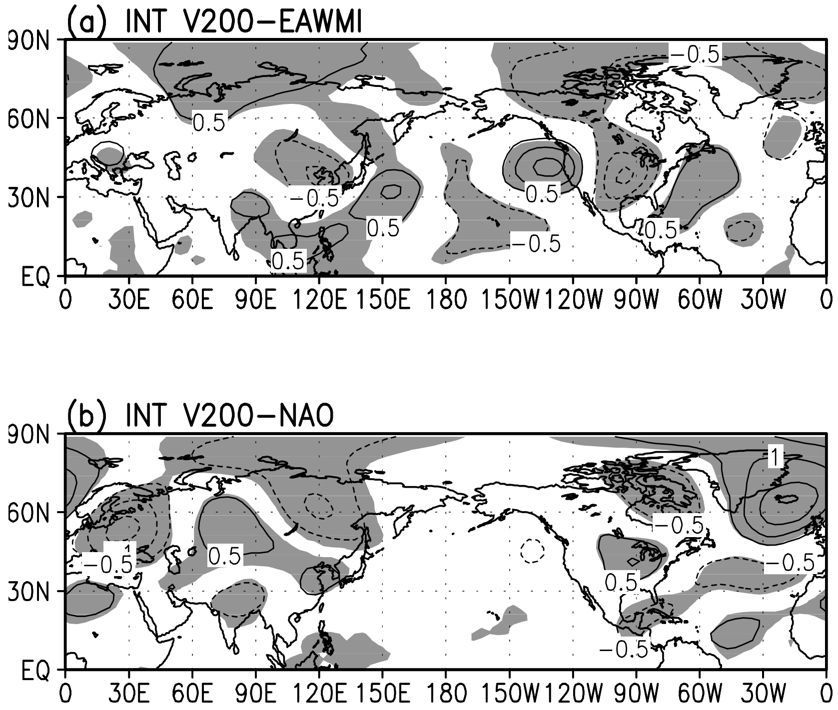

Fig. 6. Same as Fig. 5, but in the internal atmospheric variability.

troposphere.

6. Conclusions and discussion

The AO and the AAO in the internal atmospheric variability has been investigated in this study using ensemble integrations by an AGCM forced with the global observed SSTs. The AO/AAO bears some similar characteristics to that found in observations. For instance, in internal atmospheric variability, the AO/AAO is associated with a spatial structure of SLP that is very similar to that found in observations. In addition, the internal AO-associated surface air temperature anomalies are consistent with previous observational results. These similarities confirm that the AO and AAO are dominated by the internal atmospheric variability.

However, the AO/AAO in internal atmospheric variability exhibits a much clearer spatial structure, in comparison with observations. First, the North Pacific and North Atlantic centers of action are significantly linked to each other in the internal variability, which has not been identified in observations. Second, the internal AO/AAO is associated with much stronger and more significant precipitation anomalies over the oceans. In the North Pacific and Atlantic, a positive polarity of the AO corresponds to less precipitation in the middle latitudes (about 35°N) and more precipitation in the low and high latitudes. Similarly, a positive polarity of the AAO corresponds to less precipitation in the middle latitudes (40°–50°S) and more precipitation in the low and high latitudes of the Southern Hemisphere. Third, the internal AO/AAO is associated with the meridional displacement of upper-tropospheric westerly jet streams in the whole Northern/Southern Hemisphere.

The impacts of the annular modes on the global climate may be more important than those currently estimated from the observational results, in which the remarkable and oceanic-scale precipitation signature of AO/AAO may be dramatically underestimated due to poor and short-period observations and other various climatic signals. The AO/AAO is associated with the significant changes in the surface air flows and precipitation in the extratropical oceans, which may affect the temperatures, salinity and circulation of the oceans. It is not unlikely that these changes in the extratropical oceans eventually affect the tropical ocean conditions, on the decadal or longer timescales.

The present results suggest that separating the internal atmospheric variability through AGCMs' simulations might be an excellent approach to investigate the physical mechanisms of the AO/AAO, which are hard to be obtained by observations and by other simpler or more sophisticated numerical experiments. Such mechanisms are a basis for better understanding of the impacts of global warming on the regional climate in the extratropics.

We also examined the linkage of NAO/AO with the East Asian winter monsoon (EAWM). In the internal atmospheric variability, the EAWM is significantly related to the NAO/AO. A stronger EAWM corresponds to the negative polarity of NAO/AO. The teleconnection patterns suggest that the EAWM effects the climate in North America and the Atlantic, and the NAO affects the climate in East Asia. Thus, the EAWM and NAO interact. However, this interaction is weak, suggested from the analyses of the correlation and teleconnection patterns.

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