Cross-Seasonal Influence of the December–February Southern Hemisphere Annular Mode on March–May Meridional Circulation and Precipitation

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ABSTRACT

New evidence suggests that interannual variability in zonal-mean meridional circulation and precipitation can be partially attributed to the Southern Hemisphere annular mode (SAM), the dominant mode of climate variability in the Southern Hemisphere (SH) extratropics. A cross-seasonal correlation exists between the December–February (DJF) SAM and March–May (MAM) zonal-mean meridional circulation and precipitation. This correlation is not confined to the SH: it also extends to the Northern Hemisphere (NH) subtropics. When the preceding DJF SAM is positive, counterclockwise, and clockwise meridional cells, accompanied by less and more precipitation, occur alternately between the SH middle latitudes and NH subtropics in MAM. In particular, less precipitation occurs in the SH middle latitudes, the SH tropics, and the NH subtropics, but more precipitation occurs in the SH subtropics and the NH tropics. A framework is built to explain the cross-seasonal impact of SAM-related SST anomalies. Evidence indicates that the DJF SAM tends to lead to dipolelike SST anomalies in the SH extratropics, which are referred to in this study as the SH ocean dipole (SOD). The DJF SOD can persist until the following MAM when it begins to modulate MAM meridional circulation and large-scale precipitation. Atmospheric general circulation model simulations further verify that MAM meridional circulation between the SH middle latitudes and the northern subtropics responds to the MAM SOD.

1. Introduction

The Southern Hemisphere annular mode (SAM), also known as the Antarctic Oscillation (AAO), high-latitude mode, and zonal wind vacillation, is the
dominant mode of atmospheric circulation in the Southern Hemisphere (SH) extratropics (Hartmann and Lo 1998; Gong and Wang 1999; Kidson and Wattersson 1999; Thompson and Wallace 2000; Thompson et al. 2000; Wattersson 2000; Lorenz and Hartmann 2001). The SAM is characterized by a north–south fluctuation in the position of the middle latitude atmospheric westerly jet (Kidson and Wattersson 1999), and a seesaw of atmospheric mass between the middle and high southern latitudes (Thompson and Wallace 2000; Li and Wang 2003). During positive SAM phases the westerly jet tends to shift toward Antarctica, while in negative phases it tends to move equatorward. The shift in the jet is driven by eddy–zonal flow interactions (Lorenz and Hartmann 2001; Zhang et al. 2012) and is also regulated by its interaction with the ocean (Wattersson 2000, 2001; Sen Gupta and England 2007).

The lower-tropospheric zonal wind also shifts between the middle and high latitudes during different phases of the SAM, which may further alter local sea surface temperature (SST) through both dynamic and thermodynamic processes, leading to a dipolelike SST anomaly (SSTA) pattern in the SH middle and high latitudes. Both observations and model simulations have shown that the positive (negative) phase of the SAM tends to cause cooler (warmer) SST in high latitudes, but warmer (cooler) SST in the middle latitudes (Wattersson 2000, 2001; Cai and Wattersson 2002; Lefebvre et al. 2004; Sen Gupta and England 2006; Wu et al. 2009; Thompson et al. 2011; Zheng and Li 2012).

As a result of the large heat capacity of the ocean, these SAM-related SSTAs generally persist longer than the SAM itself (e.g., Ciasto and Thompson 2008). Analyses of seasonal mean data show that persistent SAM-related SSTAs retain the SAM signal and carry it forward to the following season, thus providing a source of predictability. Several hints relating to this kind of predictability can be found in the literature. For example, Wu et al. (2009) used observations and model simulations to demonstrate that the East Asian winter [December–February (DJF)] monsoon responds to the preceding September–November SAM, and Zheng and Li (2012) found that the DJF SAM modulates spring [March–May (MAM)] precipitation in southern China.

Previous studies have focused on the influence of the SAM on NH regional climate, including the climate of East Asia (e.g., Nan and Li 2003; Wang and Fan 2005; Fan and Wang 2006; Nan et al. 2009), North America (Song et al. 2009), and West Africa (Sun et al. 2010). Little research has been devoted to detecting large-scale linkages between the SAM and NH climate. However, in view of the large spatial response of MAM meridional circulation to the DJF SAM (Zheng and Li 2012), and the fact that the distribution of zonal-mean precipitation is largely determined by the location of the ascending branch of meridional circulation, a broad climate response to the DJF SAM is expected.

Understanding broadscale changes in meridional circulation and precipitation is of considerable interest. It is known that shifts in the zonal-mean atmospheric circulation and large-scale precipitation may be induced by global warming (e.g., J. Lu et al. 2007), Antarctic stratospheric ozone loss (e.g., Perlwitz 2011; Kang et al. 2011; Polvani et al. 2011; Thompson et al. 2011), tropical and extratropical thermal forcing (e.g., Kang et al. 2008; Chiang and Friedman 2012; Sun et al. 2013), and El Niño–Southern Oscillation (ENSO) (e.g., Seager et al. 2005). However, a comprehensive understanding of the variability of meridional circulation and precipitation requires investigations of various influencing factors, including the SAM. Although studies have explored the relationship between the SAM and SH zonal-mean precipitation (e.g., Wattersson 2001; R. Y. Lu et al. 2007; Hendon et al. 2014), the relationships in these studies are mainly contemporaneous. The cross-seasonal influence of the SAM on zonal-mean precipitation, especially precipitation in the NH, has not been well documented. Accordingly, the aim of the present study is to provide an understanding of the possible impacts of the DJF SAM on MAM zonal-mean meridional circulation and precipitation.

Theoretically, the cross-seasonal influence of the DJF SAM on MAM meridional circulation and precipitation may act in three possible ways. In the first mechanism, the DJF SAM imprints its signal on DJF SSTAs, which persist to MAM and modulate meridional circulation and precipitation. The second cross-seasonal influence is the lagged response of MAM circulation and precipitation to DJF SAM-related SST. That is, even without the persistence of SSTAs, MAM meridional circulation and precipitation may still respond to preceding DJF SSTAs. The third effect is the transfer of the DJF SAM signal to the MAM SAM. This transfer may directly influence meridional circulation or act on MAM SST, which then regulates MAM meridional circulation and precipitation.

The present study investigates the underlying processes that explain the cross-seasonal influence from the perspective of the persistence of SAM-related SSTAs. An atmospheric general circulation model (AGCM) simulation is also performed to briefly investigate the lagged response of MAM circulation to DJF SAM-related SSTAs. The direct transfer of the DJF SAM signal to the MAM SAM is not addressed in depth. In the first two mechanisms described above, SAM-related SSTAs serve as an important “bridge” for
cross-seasonal influences. Therefore, this study is particularly relevant to understanding climate adjustments to extratropical SSTAs (thermal forcing).

There has been considerable interest in the climate response to SAM-related SSTAs. Watterson (2001), for example, used multicentury runs from both an AGCM–slab ocean model and an AGCM–full ocean general circulation model to show that SAM-related SSTAs have a significant effect on tropospheric zonal winds. Sen Gupta and England (2007) imposed SAM-like SSTAs onto atmosphere-only and fully coupled climate models and found that the direct thermal response affects lower-tropospheric temperature and surface meridional winds. Using AGCM simulations, Wu et al. (2009) found that the SAM-related SSTAs in the SH middle latitudes can induce meridional circulation responses in the Northern Hemisphere (NH) subtropics.

An increasing number of studies have also explored extratropical–tropical interactions and interhemispheric interactions caused by extratropical thermal forcing. Chiang and Bitz (2005) and Broccoli et al. (2006), for example, found that perturbations of extratropical thermal forcing in an AGCM–slab ocean model alter tropical circulation such that the position of the inter-tropical convergence zone (ITCZ) shifts toward the warmed hemisphere. Using another idealized AGCM–slab ocean model, Kang et al. (2008, 2009) reported that both the ITCZ and tropical precipitation shift toward the warmed hemisphere. In phase 3 of the Coupled Model Intercomparison Project (CMIP3), Frierson and Hwang (2012) also identified causes of ITCZ shifts and demonstrated that similar processes occur in slab ocean simulations of global warming. Ceppi et al. (2013) addressed the influence of a thermal forcing confined to the northern middle latitudes on global zonal-mean circulation using an AGCM–slab ocean model, and showed that changes in interhemispheric thermal gradients caused by extratropical forcing lead to a shift in the SH eddy-driven jet toward the warmed NH. Their findings are consistent with an earlier study by Lee et al. (2011), in which anomalous cooling in the North Atlantic was found to trigger changes in the strength of the SH eddy-driven jet. Other evidence for the influence of the extratropics on the tropics and beyond can also be found in the literature (Liu et al. 2002; Liu and Yang 2003; Yang and Liu 2005; Zhang et al. 2005; Wu et al. 2007; Chiang et al. 2008; Wu et al. 2009; Swann et al. 2012; Hwang and Frierson 2013).

These pioneering studies on the influence of extratropical SSTAs (thermal forcing) on large-scale circulation and precipitation provide a solid foundation for further investigations of the response of MAM meridional circulation and precipitation to the SAM through the SAM-related SSTAs. The remainder of the paper is organized as follows. Section 2 provides an overview of the data, methodology, dynamical processes, and the AGCM model used in this work. In section 3, we analyze the association between the DJF SAM and MAM atmospheric circulation. The focus is on zonal-mean meridional circulation because it is directly connected with zonal-mean precipitation. The mechanisms involved in this cross-seasonal association are discussed in section 4. The impact of the DJF SAM on MAM precipitation is explored in section 5, and a discussion and conclusions are presented in section 6.

2. Data, model, and methodology

a. Data

Atmospheric circulation data are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. The SST dataset is the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST), version 3b. We use monthly mean precipitation values from 1979 to 2012 from two global precipitation datasets with a horizontal resolution of 2.5° × 2.5°: the Global Precipitation Climatology Project (GPCP), version 2.2, and the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP). Two higher-resolution (0.5° × 0.5°) gridded land-only precipitation datasets, the NOAA Precipitation Reconstruction over Land (PREC/L) and the University of Delaware precipitation archive (Delaware), version 3.01, are also employed to further validate the results. These latter datasets cover the period from 1951 to 2012.

This study focuses on DJF and the following MAM. Unless otherwise stated, all meteorological variables were converted to seasonal means prior to analysis. The analysis period is 1950/51–2011/12, except for the results based on CMAP and GPCP precipitation, which start from 1979. Considering the accuracy of the SH extratropical circulation data before the satellite era, similar analyses were also conducted based on the satellite-only period of 1979/80–2011/12. The results obtained using these two periods are consistent, and the results based on the longer 1950/51–2011/12 period are shown to reduce statistical uncertainty.

b. Methodology

The variability of the SAM is quantified two widely used indices (Kidson and Watterson 1999; Watterson 2000, 2001, 2007; Wu et al. 2006a,b; Feng et al. 2010; Li and Li 2012; Zheng et al. 2013, 2015). The first SAM index (SAMI), reported by Nan and Li (2003), is defined
as the difference in normalized zonal-mean sea level pressure between 40° and 70°S. The second SAMI, developed by Kidson (1988), is defined as the difference in zonal-mean wind anomalies at 500 hPa between 57.5° and 37.5°S.

The standardized time series of the two SAMIs are highly correlated, with a correlation coefficient of 0.946 (0.914 for the detrended series) (Fig. 1). Since relationships between meteorological variables and these two indices are generally consistent, results are only presented for the pressure-based SAMI (Nan and Li 2003). Significant linear trends exist in the SAMI (Fig. 1a) and related meteorological variables (Gillett and Thompson 2003; Fogt et al. 2009). To remove the influence of these trends, all variables were detrended using the least squares method.

The Niño-3.4 index is used to represent the ENSO variability and is defined as the regionally averaged SST (5°S–5°N, 170°–120°W). The position of the eddy-driven jet is defined as the latitude of the maximum westerly at 850 hPa.

The primary statistical tools used in the study are regression and correlation analysis. Partial correlation is also performed to detect the “pure” relationship between two variables after removing the effect of the third variable. All indices were standardized before regression analysis. The resultant regression coefficients, therefore, represent circulation anomalies corresponding to one standard deviation of the index and can be used to determine the magnitude of circulation anomalies associated with the index. The ratio between regression coefficients and the standard deviation of circulation is equal to the corresponding correlation coefficient in this case.

The Student’s t test is employed to assess the statistical significance of correlation and regression coefficients, and the differences between results of the sensitivity experiment and those of the control run. Given the strong correlation between meteorological variables across space, a field significance test (Livezey and Chen 1983; Feldstein 2002; Feldstein and Franzke 2006; Li et al. 2012; Scheff and Frierson 2012; Yoo et al. 2012) based on 1000 Monte Carlo simulations is conducted to evaluate the regression (correlation) patterns. Details of the field significance test can be found in Livezey and Chen (1983).

c. Dynamic processes

The zonal-mean zonal momentum and thermodynamic energy equations for the middle latitudes β plane (Holton 2004) can be expressed as follows:

$$\frac{\partial [u]}{\partial t} - f v = -\frac{\partial [u u^* v^*]}{\partial y}$$

and

(1)
The AGCM used in this study is the Community Atmosphere Model (CAM), version 5 (CAM5) developed by NCAR. The horizontal resolution is T42 spectral truncation (approximately 2.8° longitude × 2.8° latitude), with 26 hybrid vertical levels. A complete description of this model version is provided in Neale et al. (2012).

### 3. Linkage between the DJF SAM and MAM meridional circulation

Figure 2a shows the regression of MAM mass streamfunction on the DJF SAM. The regression pattern shows an anomalous counterclockwise circulation between 45° and 30°S, with a weaker anomalous clockwise circulation...
Based on the relationship between mass streamfunction and vertical velocity, anomalous ascent (descent) is inferred at around 30°S (45°S). Correlation coefficients between the DJF SAM and both MAM vertically averaged lower-tropospheric vertical velocity (1000–500 hPa) and wind divergence (not shown) clearly illustrate anomalous ascent (descent) and convergence (divergence) in MAM in the lower troposphere at around 30°S (45°S).

**Figure 2a** also shows that linkages between MAM meridional circulation and the DJF SAM are not confined to the SH extratropics, but also extend to the tropics and NH subtropics. When the DJF SAM is positive, counterclockwise circulation occurs in the tropics (10°S–10°N) alongside anomalous descent and horizontal wind divergence in the lower troposphere at around 10°S. Anomalous ascent and convergence occur in the lower troposphere at around 10°N. Furthermore,
there is an anomalous clockwise circulation in the NH subtropics (10°–30°N), corresponding to anomalous descent and divergence in the lower troposphere at around 30°N (not shown).

The regression of MAM zonal-mean zonal wind onto the DJF SAM is shown in Fig. 2b. The strongest values lie between the upper troposphere and stratosphere. Specifically, the DJF SAM is positively correlated with MAM zonal wind between 70° and 50°S, but negatively correlated between 50° and 30°S. The long-term (1951–2012) average position of the eddy-driven jet is shown in Fig. 2b at around 50°S (thick black line). This jet is known to shift slightly toward the Antarctic (tropics) when the preceding DJF SAM is positive (negative). Figure 2b also shows easterly anomalies in the NH extratropics between 15° and 30°S. The strongest values lie between the upper troposphere and stratosphere. The spatial correlations (significant at the 99% confidence level) between Figs. 2b and 2d and Figs. 2a and 2c are 0.94 and 0.90, respectively. In addition, the significance of primary circulation anomalies (e.g., anomalous counterclockwise circulation between 45° and 30°S, and easterly anomalies in the NH extratropics between 15° and 30°N) persist, indicating the relationship between the DJF SAM and MAM zonal-mean circulation is not solely related to the influence of the ENSO.

4. Mechanisms by which the DJF SAM influences MAM meridional circulation

a. SAM-related SOD

The role of southern extratropical SSTAs is investigated to understand the cross-seasonal influence of the DJF SAM on MAM meridional circulation. The lead–lag correlations between the DJF SAM and DJF zonal-mean SST are shown in Fig. 3a (blue dotted line). Negative and positive correlations occur at high (70°–47°S) and middle (44°–30°S) southern latitudes, respectively, with 47°–44°S being the transition area between these correlation patterns. These results indicate that in DJF cooler SST occurs at high latitudes and warmer SST occurs at middle latitudes during the positive phase of the DJF SAM, which is consistent with results from previous studies (Watterson 2000, 2007; Cai and Watterson 2002; Lefebvre et al. 2004; Sen Gupta and England 2006; Wu et al. 2009; Thompson et al. 2011; Zheng and Li 2012). As indicated in these studies, the correlation pattern can be partially attributed to increased (decreased) sea surface wind at high (middle) latitudes during the positive phase of the SAM, which increases (decreases) evaporation and latent heat release from high (middle) latitudes of the ocean, thus resulting in cooler (warmer) SST. Dynamic ocean processes, such as Ekman currents and the perturbation of ocean temperature below the ocean surface, also modify SST (Watterson 2000, 2001).

The orange dotted line in Fig. 3a shows the correlation between the DJF SAM and MAM SST. The significant correlation between the DJF SAM and SH extratropical SST also extends to the following MAM. This persistence of SAM-related SSTAs serves as a bridge for the cross-seasonal influence of the DJF SAM. The corresponding regression coefficients in Fig. 3a show the magnitude of SAM-related SSTAs, which are about 0.05–0.1 K in regions with the most significant regressions. The standard deviations of zonal-mean SST (dashed lines in Fig. 3a) show that the standard deviations of southern extratropical (70°–30°S) SST in DJF and MAM range from about 0.1 to 0.2 K. A comparison of the solid and dashed lines in Fig. 3a shows the magnitude of DJF SAM-related SSTAs. Maps showing the correlations between the DJF SAM and both the DJF and MAM SST are shown in Figs. 3c and 3d. There is a clear zonal asymmetry in the correlation maps (see also Sen Gupta and England 2006), but a full description of the reasons for the asymmetry is beyond the scope of the present study.

For brevity, the dipolelike SSTAs pattern south of 30°S is referred to as the SOD. A positive (negative) phase of the SAM tends to result in a positive (negative) phase of the SOD, which results in cooler (warmer) SST in southern high latitudes but warmer (cooler) SST in southern middle latitudes (Fig. 3b). The temporal variability of the SOD is measured by an index (the SODI), defined as the difference between normalized SST at 40° and 60°S. We choose these two latitudes because zonal-mean SST is most strongly anticorrelated in these regions (not shown). In most places north of 65°S, sea ice melts completely in the seasons considered (December–May). Therefore, it is reasonable to choose 40° and 60°S for the definition of the SODI and to disregard the
influence of sea ice. The magnitude of the SOD-related SSTAs is also about 0.1–0.2 K (Fig. 3b).

In view of the relationship between the SAM and ENSO, there may also be a linkage between ENSO and southern extratropical SSTAs. Correlation coefficients between the SAMI, SODI, and ENSO are listed in Table 2 to distinguish SAM-related SSTAs from those related to ENSO. The correlation coefficient between the DJF SAMI and DJF SODI is 0.60, again indicating a linkage between the SAM and SOD. The correlation coefficient between the DJF SODI and MAM SODI is 0.84, indicating significant persistence of this SAM-related SSTAs into MAM. The correlation coefficient between the DJF SAMI and MAM SODI is 0.49, further verifying that the DJF SAM can imprint its signal on MAM SOD. On the other hand, the correlation coefficients between the SAM and ENSO are −0.28 and −0.29 in DJF and MAM, respectively, confirming that they have a weak negative relationship as described previously (Zhou and Yu 2004; L’Heureux and
Thompson 2006; Gong et al. 2010; Cai et al. 2011; Ding et al. 2011, 2012). The correlation coefficient between DJF ENSO and DJF SOD is $\sim 0.48$, and that between DJF ENSO and MAM SOD is $\sim 0.43$, both of which are weaker than the correlation coefficients with the DJF SAM (0.60 and 0.49, respectively).

Partial correlation is performed to further illustrate the relationships between the DJF SAM and the DJF SOD (MAM SOD) after removing the ENSO signal. The correlation coefficients for these relationships are 0.55 (0.44). Although the strengths of the correlations are weaker than raw correlations containing the ENSO signal (0.60 and 0.49, respectively), relationships are still significant at the 99% confidence level. In contrast, if we remove the SAM signal and then calculate the partial correlation between ENSO and the SOD, the correlations are also weakened. Therefore, although relationships exist among the SAM, ENSO, and the SOD, the linkages between the SAM and SOD are significant and remain evident after removing ENSO variability.

**b. Linkage between the MAM SOD and MAM meridional circulation**

Figure 4 is as in Fig. 2 but for the MAM SOD. The primary features of the regression pattern are generally in agreement with those in Fig. 2 (e.g., an anomalous counterclockwise circulation between 45° and 30°S, and easterly anomalies in the NH extratropics between 15° and 30°N). The spatial correlation coefficients for Figs. 4a–d and 2a–d are 0.89, 0.85, 0.84, and 0.85, respectively, all significant at the 99% confidence level. Given that the DJF SAM imprints its signal on the MAM SOD, the similarity between Figs. 2 and 4 verifies the potential role of the SOD in the cross-seasonal linkage between the DJF SAM and MAM meridional circulation.

To further test the linkage between tropical and NH subtropical MAM circulation and the MAM SOD, field significance tests (Livezey and Chen 1983) based on 1000 Monte Carlo simulations are employed to evaluate regression patterns in the tropics and NH subtropics (1000–100 hPa, 15°S–30°N). The results (Fig. A1 in the appendix) verify the significance of the linkage between the MAM SOD and MAM meridional circulation in the tropics and NH subtropics at the 95% confidence level. Similar field significance tests for the DJF regression pattern were conducted. Results show that regression patterns in the tropics and the NH subtropics in Fig. 2a–d are also significant at the 90% confidence level (Fig. A1).

Zonal-mean tropical SST (25°S–10°N) is also linked to the DJF SAM and MAM SOD (Figs. 3a and 3b). Although the correlation of tropical SST with the DJF SAM (Fig. 3a) and MAM SOD (Fig. 3b) is weaker than that for extratropical SST, in view of the importance of tropical SST in triggering perturbations in meridional circulation, we repeat the analyses in Figs. 4a and 4b. This analysis is conducted after defining a tropical SST index (TSTI) based on regionally averaged SST over 25°S–10°N, and then removing the TSTI signal from both the SOD and MAM circulation elements. The results shown in Fig. 5 illustrate that the primary features of the regression patterns are generally consistent with those in Figs. 4a and 4b. The spatial correlation between the corresponding panels in Figs. 4 and 5 are significant at the 99% confidence level. In particular, subtropical (25°–15°S) SST and the DJF SAM are correlated (Figs. 3a and 3b). The area of significant correlation in the subtropical region is larger if the SAMI defined by Kidson (1988) is used. More information about the SAM-related subtropical SSTs and its atmospheric feedbacks can be found in Watterson (2000, 2001). In the present study, we mainly focus on the SOD pattern in the southern middle and high latitudes (south of 30°S).

In summary, although tropical SST variability may contribute to the relationship between the SOD and MAM meridional circulation due to its linkage with the SOD, the relationship between the SOD and MAM

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<th>DJF SAM</th>
<th>MAM SAM</th>
<th>DJF SOD</th>
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<th>DJF ENSO</th>
<th>MAM ENSO</th>
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<tr>
<td>DJF SAM</td>
<td>1</td>
<td>0.32</td>
<td>0.60 (0.55)</td>
<td>0.49 (0.44)</td>
<td>−0.28</td>
<td>−0.34</td>
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<tr>
<td>MAM SAM</td>
<td>1</td>
<td>0.10</td>
<td></td>
<td></td>
<td>−0.24</td>
<td>−0.29</td>
</tr>
<tr>
<td>DJF SOD</td>
<td>1</td>
<td>0.84</td>
<td></td>
<td></td>
<td>−0.48 (−0.40)</td>
<td>−0.42</td>
</tr>
<tr>
<td>MAM SOD</td>
<td>1</td>
<td></td>
<td>−0.43 (−0.35)</td>
<td></td>
<td>−0.46</td>
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<tr>
<td>DJF ENSO</td>
<td>1</td>
<td>0.77</td>
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<tr>
<td>MAM ENSO</td>
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meridional circulation does not change appreciably after removing tropical SST variability.

c. Mechanisms for MAM meridional circulation responses to the MAM SOD

The extratropical SST meridional gradient is important for regulating meridional circulation and zonal wind (e.g., Marshall and Connolley 2006; Frierson et al. 2007; Chen et al. 2010). The filled line in Fig. 6c shows the correlation between the SH extratropical SST meridional gradient and the MAM SOD. The SST gradient is enhanced between 57°S and 37°S but reduced south of 57°S. These SST gradient anomalies have the potential to modify atmospheric baroclinicity. The regression of the MAM potential temperature meridional gradient on the MAM SOD is shown in Fig. 6a. The potential temperature gradient is enhanced south of 50°S but reduced north of 50°S, indicating that baroclinicity increases (decreases) south (north) of 50°S. Although the anomalous atmospheric gradient peak (Fig. 6a) might not coincide exactly with that of the anomalous SST gradient (Fig. 6c), the direction of the SST gradient shift is consistent with the shift of atmospheric potential temperature.

Changes in baroclinicity may excite wave adjustment. When the MAM SOD is in a positive (negative) phase,
the poleward transport of the eddy heat flux is generally enhanced (reduced) between 50° and 30°S (not shown). Based on Eq. (4), convergence of the eddy heat flux corresponds to ascent, whereas divergence corresponds to descent. This relationship is first tested in the context of the long-term seasonal mean. The contours in Fig. 7a show seasonal mean values of the MAM eddy heat flux convergence over the period 1951–2012. There is eddy heat flux divergence at middle latitudes (40°–20°S and 20°–40°N), which is in accordance with climatological descent. This further illustrates that the relationship between vertical velocity and convergence/divergence of the eddy heat flux, as expressed in Eq. (4), applies to seasonal mean flow outside the tropics. The shading in Fig. 7a shows the regression of MAM eddy heat flux convergence on the MAM SODI. There is anomalous divergence and convergence of the eddy heat flux in the lower troposphere at around 50°–35°S and 35°–25°S, respectively, which explains the anomalous descent and ascent in the lower troposphere at around 45° and 30°S, respectively (Fig. 4). There is also anomalous eddy heat flux convergence in the lower troposphere at around 65°–60°S, which corresponds to anomalous ascent in the lower troposphere. However, the ascent south of 60°S is relatively “noisy.”

There is a close linkage between eddy heat and momentum fluxes in the upper troposphere, which can be partially attributed to the tendency toward
nonacceleration in the upper troposphere; that is, the tendency for convergence/divergence of the horizontal Eliassen–Palm (EP) flux and divergence/convergence of the vertical EP flux to cancel each other out (Lu et al. 2010). Since the MAM eddy heat flux is correlated with the MAM SOD (Fig. 7a), the eddy momentum flux may also be perturbed by the MAM SOD.

The regression of eddy momentum flux convergence and detrended MAM SOD is shown in Fig. 7b. As described by Eq. (3), convergence (divergence) of the eddy momentum flux corresponds to southerly (northerly) wind in the SH but northerly (southerly) wind in the NH. This result is further tested in the context of the long-term seasonal mean. Figure 7b shows contours of the MAM eddy momentum flux convergence seasonal mean values over the period 1951–2011. There is convergence in the upper troposphere in the middle latitudes (60°S–30°S and 30°–60°N), which is in accordance with the climatological southerly and northerly wind in the SH and NH middle latitudes. This further illustrates that the relationship expressed in Eq. (3) applies to seasonal mean flow outside the tropics. The shading in Fig. 7b shows the regression of MAM eddy momentum flux convergence on the MAM SOD. There is anomalous eddy momentum flux convergence south of 50°S and divergence between 50° and 30°S, explaining southerly
wind anomalies in the upper troposphere south of 50°S and northerly wind anomalies in the upper troposphere between 50° and 30°S (Fig. 4).

A schematic diagram summarizing the local atmospheric responses to the MAM SOD is shown in Fig. 8. The SOD leads to changes in the meridional gradient of potential temperature, which is a measure of baroclinicity. The baroclinicity increases (decreases) south (north) of 50°S, leading to increases in vertical eddy heat flux convergence (divergence) south (north) of 50°S. This is compensated for by the anomalous eddy momentum flux convergence (divergence) in the upper
Anomalous eddy heat and momentum flux convergence/divergence lead to a southerly anomaly south of 50°S, a northerly anomaly between 50° and 30°S, descent at around 45°S, and ascent at around 30°S. Finally, anomalous clockwise and counterclockwise meridional circulation develops in extratropical regions of the SH. Based on the principle of the Coriolis force, the anomalous southerly south of 50°S corresponds to stronger westerly flow, and the anomalous northerly between 30° and 50°S corresponds to weaker westerly flow. Hence, a positive phase of the SOD is generally associated with a strengthening and slight southward shift of the SH eddy-driven jet. Further analyses show that transient eddies play a dominant role in the total anomalous eddy heat and momentum flux convergence/divergence. In contrast, stationary eddies play a limited role, especially in the SH (not shown).

Figures 6b and 7c,d show the results of similar regression analyses to those presented in Figs. 6a and 7a,b, but for the DJF SAMI. These regression patterns for the DJF SAMI south of 30°N are generally in agreement with those for the MAM SODI, but differences exist north of 30°N. These differences illustrate that random variability may be introduced into regression patterns north of 30°N. Therefore, as mentioned previously, we mainly focus on circulation anomalies south of 30°N.

In the NH subtropics, the anomalous easterly in the upper troposphere between 10° and 30°N is also explained by anomalous eddy heat and momentum flux convergence/divergence. As shown in the following section, tropical circulation indeed responds to SH extratropical SSTAs in the numerical simulations. The studies cited in section 1 suggest that the regulation of tropical circulation by extratropical thermal forcing is possible. Although tropical meridional circulation (i.e., the Hadley cell) is a direct thermal cell forced primarily by diabatic terms, the eddy flux also contributes to its formation (Kim and Lee 2001; Lee and Kim 2003; Caballero 2008; Kang and Polvani 2011; Ceppi and Hartmann 2013). More theoretical analyses are required to further understand the corresponding dynamic processes associated with the influence of the MAM SOD on tropical circulation.

d. Numerical experiments using CAM5

To further elucidate cause-and-effect relationships between the MAM SOD and MAM meridional circulation, we examine the behavior of zonal-mean meridional circulation in different AGCM simulations using CAM5.

The responses of the MAM mass streamfunction to the positive-SOD-like SSTAs are quantified by differences between POS and CTL (Fig. 9a). A significant change is observed in MAM mass streamfunction between the SH high latitudes and NH subtropics. As seen in observational data, local atmospheric responses to positive-SOD-like SSTAs consist of two opposite meridional circulations: a clockwise cell...
south of 45°S and a counterclockwise cell between 45° and 30°S. Both are significant at the 90% confidence level. In the NH subtropics there is a clockwise cell between 10° and 30°N, significant at the 90% confidence level, and this is generally consistent with observations.

The responses of tropical circulation to positive-SOD-like SSTAs (Fig. 9a) consist of counterclockwise and clockwise circulation between 30°S and 10°N. Counterclockwise circulation in the AGCM simulation is stronger and wider than that in observations. The magnitude of the NH response in the AGCM simulations is weaker than in observations. The primary features of the atmospheric response to the positive-SOD-like SSTAs are consistent with observations, and thus verify the linkage between the MAM SOD and MAM mass streamfunction. However, the differences between the simulation and observations suggest that random variability exists in the regression patterns, and that an AGCM simulation without air–sea interactions might misrepresent the real climate.

Similarly, atmospheric responses to the negative-SOD-like SSTAs are quantified by the difference between NEG and CTL (Fig. 9b). Atmospheric responses are generally opposite to those from POS, except that the significance of the NH subtropical response is weaker than in the POS run. However, the differences in the NH subtropical mass streamfunction between the NEG and POS simulations (Fig. 9c) are significant at the 90% confidence level.

To further test the remote response of MAM NH subtropical circulation to MAM SH extratropical SST, and to explore the relative role of mid- and high-latitude SSTAs, the results from the POS-Mid and POS-High runs are shown in Figs. 9d and 9e. Both mid- and high-latitude SSTAs play a role in triggering the response of the meridional streamfunction. However, there is non-linearity in total atmospheric responses to the SOD-like SSTAs, which are not a simple linear combination of the responses to the mid- and high-latitude SSTAs.

The above four experiments (POS, NEG, POS-Mid, and POS-High) quantify the contemporaneous response of MAM circulation to the MAM SOD. In contrast, SSTAs in the NEG-DJF run are confined to DJF (Fig. 9f). The lagged response of the MAM streamfunction to the DJF SOD is clear, but more work is
needed to gain an in-depth understanding of the mechanisms that drive these responses.

Since only SOD-like SST perturbations in the SH extratropics are imposed in SST sensitivity experiments, the circulation response in these AGCM simulations may primarily reflect meridional circulation anomalies associated with SOD-like SSTAs. It is important to note that imposed SSTAs in the SST sensitivity experiments are larger than the observed SSTAs magnitude. Therefore, leaving aside the consideration of possible non-linearity in the above processes, circulation anomalies in Fig. 9 may reflect a more realistic atmospheric response to the SOD if they are scaled down by a factor of 5–10.

5. Impact of the DJF SAM on MAM precipitation via the SOD

The responses of MAM meridional circulation to the DJF SAM and MAM SOD suggest that the DJF SAM influences large-scale precipitation via the MAM SOD. Correlations between MAM precipitation and the MAM SOD (DJF SAM) are used to further test these relationships (Figs. 10 and 11). We first focus on zonal-mean total precipitation over land and ocean. As shown in Figs. 10c,f, correlations are negative over the southern middle latitudes (50°–37°S), the tropics (12°–2°S), and the northern middle latitudes (22°–38°N), but are positive in the southern subtropics (35°–25°S) and the NH subtropics (5°–18°N). Correlations in most of the above regions are significant, which is consistent with the significant correlation between vertical velocity and the SOD. One exception is the region between 35° and 25°S, where the correlation is weak and not significant at the 90% confidence level, possibly reflecting the weak correlation between zonal-mean precipitation and lower-tropospheric vertical velocity in this region (not shown). Similar analyses for the DJF SAM are shown in Figs. 11e,f. Except for the region between 35° and 25°S, the negative correlation in the tropics (12°–2°S) and the positive correlation in the NH subtropics (5°–18°N) are consistent with those in Figs. 10e and 10f. Although the negative correlation in the northern middle latitudes (22°–38°N) is more noisy than in Figs. 10e,f, it will be shown later that the negative correlation between land precipitation and the DJF SAM (Figs. 11g,h) is still significant.

We use two high-resolution land precipitation datasets to further verify the relationship between the DJF SAM, MAM SOD, and MAM zonal-mean precipitation (Figs. 10g,h and 11g,h). In the NH, the results for precipitation over land are similar to those for total precipitation. There is less precipitation in the northern middle latitudes (22°–38°N) but more precipitation in the NH subtropics (5°–18°N). In the SH, because the land area is much smaller than the total area, there are some differences between precipitation over land and total precipitation.

Maps of the correlation between MAM precipitation and the DJF SAM, and between MAM precipitation and the MAM SOD, are shown in Figs. 10a–d and 11a–d, respectively. MAM precipitation in the tropical and NH middle latitudes is indeed correlated with the MAM SOD and DJF SAM. Results from the field significance test (Fig. A2) illustrate that the correlation patterns between the MAM SOD (DJF SAM) and MAM precipitation in the region between 15°S and 30°N are significant at the 99% (95%) confidence level, for both the GPCP and CMAP datasets. Note that the correlation maps in Figs. 10 and 11 have a zonally asymmetric component, but a comprehensive investigation of this complex asymmetry is beyond the scope of the present study.

6. Discussion and conclusions

This study offers new insights into the variability of meridional circulation and precipitation from the perspective of the SAM, the dominant mode of atmospheric circulation in the SH extratropics. The results show that the DJF SAM modulates the MAM mass streamfunction and precipitation on a large scale. A framework is constructed to explain this cross-seasonal modulation (Fig. 12). First, in the positive (negative) phase of the DJF SAM, SST decreases (increases) at southern high latitudes and increases (decreases) at southern middle latitudes. This SSTAs pattern is referred to as the SOD. The DJF SOD can persist to the following MAM and affect MAM meridional circulation, thus serving as an important “bridge” in the association between the DJF SAM and MAM circulation and precipitation. Second, possible mechanisms for explaining MAM meridional circulation responses to the MAM SOD are proposed. MAM precipitation adjusts to the SAM-related SOD via wave–mean flow interactions due to changes in eddy momentum and heat flux. Bands of decreased and increased precipitation alternate from the southern middle-to-high latitudes to the northern subtropics. When the SOD is in a positive phase, there is less precipitation in the SH middle latitudes (50°–37°S), the SH tropics (12°–2°S), and the NH subtropics (22°–38°N), but more precipitation in the SH subtropics (35°–25°S) and NH tropics (5°–18°N).

This process is an example of the “ocean–atmosphere coupled bridge” (Nan et al. 2009; Wu et al. 2009; Zheng and Li 2012; Li et al. 2013), in which the ocean retains a memory of large-scale atmospheric circulation signals,
which persist to the following season, alter atmospheric circulation, and finally influence local and remote climate. This ocean–atmosphere coupled bridge may provide a source of predictability. However, the persistence of SH extratropical SST is seasonally dependent and is sensitive to the time scale employed. For example, analyses of monthly mean data from numerical simulations show that the persistence and predictability

![Diagram](image-url)

**FIG. 10.** Correlation between the detrended MAM SOD and detrended MAM precipitation from (a),(e) CMAP; (b),(f) GPCP; (c),(g) Delaware; and (d),(h) PRECL. The panels on the right are as for those on the left but for zonal-mean precipitation. Dashed lines represent the 90% confidence level, and the dark and light stippling indicate latitudes with positive and negative correlations, respectively. Note that the latitudes are selected based on an overall consideration of the results in Figs. 2, 4, 5, 6, 7, 10, and 11, and thus there may be some “noise” in one specific stripe in one specific panel. Results at high latitudes are not shown. The number in the top-right corner of (a) and (b) is the percentage of area significant at the 90% confidence level in the tropics and NH subtropics (15°S–30°N).
of SAM-related SSTAs are generally limited (Watterson 2000, 2001), whereas analyses of weekly mean data from observations reveal that the $e$-folding time scale of SAM-related SSTAs exceeds 4 months (Ciasto and Thompson 2008). Our focus in the present study is on seasonal mean data, and on this time scale the persistence of the DJF SAM-related SSTAs is significant and can be used to predict MAM climate (Nan et al. 2009; Wu et al. 2009; Zheng and Li 2012). The cross-seasonal influence and prediction capabilities of the SAM and SOD in other seasons require further investigation.

This study provides new evidence for the influence of the extratropics on the tropics and beyond. Although the SAM itself is mainly confined to the SH middle and high latitudes, its influence on zonal-mean circulation

![Fig. 11. As in Fig. 10, but for the detrended DJF SAM.](image-url)
may reach the tropics and even the NH. Baldwin (2001) noted that variations in sea level pressure in the tropics are associated with the SAM, and Thompson and Lorenz (2004) showed that the association between circulation variations and the SAM extends as far as the NH subtropics. However, these studies focused on daily time scales, whereas the present study extends our understanding of the cross-hemispheric influence of the SAM to the seasonal scale.

More work is needed to gain a deeper understanding of the cross-seasonal influence of the DJF SAM on MAM meridional circulation and precipitation. In the present study, SOD-like SSTAs are prescribed in AGCM simulations, but in observational data the SAM causes the SOD. Prescribing DJF SAM wind in a coupled model, and then exploring the coupled response, would be helpful to further verify the role of the SAM. In addition, exploring the responses of the eddy heat and momentum flux in model simulations may help further verify the mechanisms proposed in this study. Higher-resolution models may also provide further evidence for the response of precipitation to the SOD. The dynamic mechanisms explored in the present study mainly concentrate on the middle latitudes, and the response of tropical meridional circulation needs further investigation. Finally, although we show that the linkage between the DJF SAM and MAM meridional circulation is not dominated by random variability, the limited sample size means that some random variability may still be incorporated into the statistical relationship (DelSole and Shukla 2009). Observational datasets or model simulations over longer periods may advance our understanding of the cross-seasonal influence of the SAM.

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APPENDIX

Field Significance Test

As shown in Fig. 4a, the percentage of area significant at the 90% confidence level (1000–100 hPa, 15°S–30°N) is 58.37%. The field significance test is based on 1000 Monte Carlo simulations in the tropics and the NH subtropics (1000–100 hPa, 15°S–30°N) (Fig. 4a). In the field significance test, the MAM SODI is replaced with a random time series sampled from a Gaussian
Regressions of mass streamfunction and zonal wind on this random time series are then obtained at every grid point and tested for significance at the 90% confidence level using the Student’s t test. The percentage of area significant at the 90% confidence level is then calculated for the tropics and the NH subtropics (1000–100 hPa, 15°S–30°N). This experiment is completed 1000 times with different random inputs, and the frequency distributions of the percentages of significant area are presented in Fig. A1. At least 10% of Monte Carlo simulations have greater than 23.10% of area significant at the 90% confidence level. The hypothesis that the regression pattern in Fig. 4a is a chance occurrence can, therefore, be rejected at the 90% confidence level. That is, the regression pattern in Fig. 4a is significant at the 90% confidence level. In fact, as seen in Fig. A1a, the confidence level of the regression in Fig. 4a is as high as 99%. Similar analyses are performed for the data in Figs. 4b–d, and the percentage of significant area at the 90% confidence level is 55.02%, 50.72%, and 44.02%, respectively. The results of the 1000 Monte Carlo simulations are shown in Figs. A1b–d. Regression patterns (1000–100 hPa, 15°S–30°N) in Figs. 4b–d are significant at the ≥95% confidence level.

Similar field significance tests are also conducted for the regression pattern in Fig. 2. The percentages of significant area at the 90% confidence level (1000–100 hPa, 15°S–30°N) for Figs. 2a–d are 24.40%, 39.23%, 22.49%, and 24.00%, respectively. Based on the 1000 Monte Carlo simulations in Fig. A1, field significance levels for the regression patterns in the tropics and NH subtropics in Figs. 2a–d are about 90%, 95%, 90%, and 90%, respectively.

The field significance test is also performed to test the significance of results presented in Figs. 10a,b and 11a,b. For Figs. 10a and 11a, the percentage of significant area at the 90% confidence level between 15°S and 30°N is 43.83% and 39.74% for CMAP and GPCP, respectively. For Figs. 11a and 11b the percentage of significant area is 27.35% and 25.39%, respectively. The results of the 1000 Monte Carlo simulations are shown in Fig. A2. The correlation patterns between the
MAM SOD (DJF SAM) and MAM precipitation in the region between 15°S and 30°N are significant at the 99% (95%) confidence level for both the GPCP and CMAP datasets.

REFERENCES


Fig. 2. Frequency distributions of the percentage of area significant at the 90% confidence level (15°S–30°N) for the correlation between detrended MAM precipitation from (a) CMAP and (b) GPCP and Gaussian noise in 1000 Monte Carlo simulations. The abscissa is the percentage of significant area; the left and right ordinates are the frequency and percentage in all 1000 simulations, respectively. The numbers above the bars indicate the percentage for corresponding bars. The results for correlation with the detrended DJF SAM (Fig. 9) and detrended MAM SOD (Fig. 10) are also shown.


