Cross-Seasonal Influence of the SAM on Southern Hemisphere Extratropical SST and its Relationship with Meridional Circulation in CMIP5 models

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ABSTRACT: Using outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, the influence of the December–February (DJF) Southern Hemisphere Annular Mode (SAM) on March–May (MAM) zonal-mean meridional circulation found in reanalysis data is assessed. Considering that the DJF Southern Hemisphere extratropical SST pattern associated with the SAM (SESST hereafter) acts as an important ‘bridge’ in the cross-seasonal influence of the DJF SAM on MAM meridional circulation, model performance in simulating the influence of the DJF SAM on SESST and in capturing the connection between SESST and MAM meridional circulation are investigated. Most of the models are equipped to capture the influence of the DJF SAM on SESST. However, the model-simulated influence is stronger than the observations, which is partially attributed to an overestimation of the association between the SAM and surface zonal wind by these models. The simulated cross-seasonal influence of the DJF SAM on MAM meridional circulation tends to be closer to the observations in models with high performance in depicting the influence of MAM SESST on MAM meridional circulation than in models with relatively low performance.

KEY WORDS Southern Hemisphere Annular Mode (SAM); Southern Hemisphere extratropical SST; meridional circulation; CMIP5 models

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1. Introduction

The Southern Hemisphere (SH) Annular Mode (SAM) dominates large-scale atmospheric circulation in the SH extratropics (Gong and Wang, 1999; Thompson and Wallace, 2000; Li and Wang, 2003). The SAM is characterized by a see-saw oscillation in sea level pressure (SLP) between middle and high SH latitudes. The positive phase of the SAM corresponds to negative and positive SLP anomalies over the Antarctic and middle latitudes, respectively. The SAM features evident zonal symmetry, but zonal asymmetry also exists, particularly in the South Pacific due to the Amundsen Sea Low (Fogt et al., 2012). The SAM variability is accompanied by a meridional shift of the polar jet (Feldstein and Lee, 1998; Hartmann and Lo, 1998; Kidson and Watterson 1999, Thompson and Wallace, 2000; Lorenz and Hartmann, 2001). Specifically, the polar jet shifts towards the Antarctic during positive SAM phases, and towards the tropics during negative phases. Previous studies have reported that the SAM is an internal atmospheric mode that is maintained by the feedbacks between eddy activity and zonal mean flow (e.g., Feldstein and Lee, 1998; Lorenz and Hartmann, 2001; Luo et al., 2007; Zhang et al., 2012), and that air-sea interactions may contribute to SAM variability (Watterson, 2000; Sen Gupta and England, 2007).

Although the SAM itself is confined to the SH extratropics, its climate influence extends to the tropics and even to the Northern Hemisphere (NH) subtropics. For example, Thompson and Lorenz (2004) demonstrated that the SAM signal leads tropospheric zonal-mean zonal wind anomalies over the tropics and the NH subtropics by about two weeks. They reported that a positive SAM phase is usually followed by anomalous westerlies in the upper tropical troposphere, and the coupling between the SAM and zonal wind in the upper tropical troposphere is mainly due to wave forcings originating in the SH extratropics associated with the SAM. In addition, the SAM was found to influence variability in the East Asian summer monsoon (e.g., Nan and Li, 2003; Wang and Fan, 2005; Fan and Wang, 2006; Nan et al., 2009), East Asian winter monsoon (Wu et al., 2009, 2015; Liu et al., 2015), South China spring precipitation (Zheng and Li, 2012), precipitation in North America (Song et al., 2009), the West...
been found that shifts in zonally averaged circulation anomalies caused by the SAM act as an essential factor in the above-mentioned cross-hemispheric influences, either by directly transmitting the SAM signal from the SH to the NH (i.e., oceanic bridge; e.g., Nan et al., 2009) or by triggering atmospheric teleconnections that propagate through different latitudes (i.e., atmospheric bridge; e.g., Wu et al., 2009, Zheng et al., 2015a).

Reanalysis data indicate that the preceding austral summer (December–February, DJF) SAM plays a role in modulating austral autumn (March–May, MAM) zonal-mean meridional circulation, as also verified by atmospheric general circulation model (AGCM) simulations (Zheng et al., 2015a). The underlying mechanism for the cross-seasonal influence of DJF SAM on MAM meridional circulation is associated with the “ocean–atmosphere coupled bridge” in which the SH extratropical ocean stores the signal of the DJF SAM as a SST anomaly pattern, which persists to MAM and then alters the meridional circulation. A physical mechanism based on a momentum budget has been proposed to explain the influence of the MAM SST anomalies on MAM SH extratropical meridional circulation. SH extratropical SST anomalies associated with the DJF SAM results in increased baroclinicity south of 50°S, and thus leads to anomalous vertical eddy heat flux convergence, which is compensated by the anomalous eddy momentum flux convergence in the upper troposphere. In contrast, decreased baroclinicity exists north of 50°S resulting from SH extratropical SST anomalies related to the DJF SAM, and thus leads to anomalous vertical eddy heat flux divergence, which is compensated by the anomalous eddy momentum flux divergence in the upper troposphere.

Anomalous eddy momentum flux convergence/divergence leads to a southerly anomaly south of 50°S, a northerly anomaly between 50°S and 30°S, descent at about 45°S, and ascent at about 30°S. Finally, anomalous clockwise and counterclockwise meridional cells develop in the high and middle latitudes, respectively, in the SH extratropics. The anomalous middle-latitude eddies associated with SH extratropical SST may further lead to changes in tropical and NH subtropical meridional circulation in view of the role of eddies in influencing the Hadley cell (Held and Phillips 1990; Kim and Lee, 2001a, 2001b; Trenberth and Stepaniak, 2003). The influence of the MAM SH extratropical SST on MAM meridional circulation from the SH extratropics to the NH subtropics has been further verified by numerical simulations (Zheng et al., 2015a) using the Community Atmosphere Model version 5 (CAM5) developed by the National Center for Atmospheric Research (NCAR). The corresponding physical processes of the cross-seasonal influence of the DJF SAM on MAM meridional circulation are briefly summarized in Section 3 as a reference for assessing model performance.

Understanding the variability of zonally averaged meridional circulation is a topic of great interest. It has been found that shifts in zonally averaged circulation could be attributed to external forcing such as Antarctic stratospheric ozone (e.g. Kang et al., 2011; Polvani et al., 2011; Thompson et al., 2011) and global warming (e.g., Lu et al., 2007), and to internal forcings such as tropical (e.g., Seager et al., 2005) and extratropical thermal forcings (e.g., Chiang and Bitz, 2005; Broccoli et al., 2006; Kang et al., 2008, 2009). Zheng et al. (2015a) and Liu et al. (2015) showed that the SAM may also modulate meridional circulation, based on reanalysis datasets and AGCM simulations. However, less is known about whether advanced coupled models are capable of simulating this relationship. Therefore, the main scope of this work is to further verify the cross-seasonal influence of the DJF SAM on MAM meridional circulation, using outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5).

The remainder of this paper is organized as follows. In Section 2, the data, models, and methodology used in this study are briefly described. In Section 3, the primary aspects of the cross-seasonal influence of the DJF SAM on MAM meridional circulation, as obtained from reanalysis datasets, are briefly described. Given that the SH extratropical SST plays an important role in transmitting DJF SAM signals to the following MAM and acts as an important basis for the cross-seasonal influence of the DJF SAM on MAM meridional circulation, model performance in reproducing the influence of the DJF SAM on SH extratropical SST is assessed in Section 4, and the model-simulated influence of SH extratropical SST on MAM meridional circulation is investigated in Section 5. On the basis of Sections 4 and 5, the simulated cross-seasonal influence of the DJF SAM on MAM meridional circulation is presented in Section 6. Finally, a discussion and conclusions are presented in Section 7.

2. Data, models and methodology

2.1. Reanalysis data

The monthly atmospheric circulation reanalysis dataset employed in this study is the National Centers for Environmental Prediction (NCEP)/NCAR reanalysis, with a horizontal resolution of 2.5°×2.5°. Variables used include surface air pressure, surface zonal wind (SZW) at 10 m above ground level, SLP, and zonal and meridional wind at 17 pressure levels. ERA40 reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a horizontal resolution of 2.5°×2.5° is also used to cross-validate results from NCEP/NCAR reanalysis. Unless otherwise stated, atmospheric reanalysis in this study denotes the NCEP/NCAR reanalysis. The monthly SST data are from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) V3b, with a horizontal resolution of 2.0°×2.0°. The terms ‘observations’ or ‘observed’ in this study indicate results from the reanalysis datasets.

2.2. CMIP5 coupled models

From a large set of model simulations in CMIP5, monthly outputs of historical experiments from 32 coupled models...
are employed. Model-simulated atmospheric variables used in this work include surface air pressure, SZW, SLP, and zonal and meridional wind at pressure levels. The oceanic variable used is SST.

The horizontal resolutions of both the atmospheric and oceanic variables are different among the various CMIP5 models. To enable a clear comparison among results from these models and facilitate the calculation of a multi-model mean (MMM), model outputs and reanalysis datasets are first interpolated to the same horizontal resolution (1.0° × 1.0°) prior to statistical analysis.

2.3. Methodology

We follow the definition of the SAM index reported by Nan and Li (2003), which is the difference in normalized monthly zonal averaged SLP between 40°S and 70°S (http://ijp.gCESS.cn/dct/page/65609). Moreover, to examine the reliability of the reanalysis-based SAM index before the satellite era, the station-based SAM index of Marshall (2003) (SAM-M03 hereafter) is employed; this can be obtained from https://climatedataguide.ucar.edu/climate-data/marshall-southern-annular-mode-sam-index-station-based. The SAM-M03 is based on observational records of SLP from six stations at roughly 65°S and six stations at roughly 40°S, and extends back to 1957. As shown in Figure 1a, the station-based SAM-M03 and the reanalysis-based SAM indices are highly consistent, with a correlation coefficient of 0.92.

We focus on the seasons of DJF and MAM. Unless otherwise stated, all indices and meteorological elements were converted to seasonal means prior to statistical analysis. Considering the ending year of historical experiments from CMIP5 is 2005 and the SAM-M03 index is available starting in 1957, therefore the period of analysis is 1957/58–2004/05.

The Niño 3.4 index, which is defined as the regional averaged SST in the range 5°S–5°N, 170°–120°W, is adopted to represent the El Niño–Southern Oscillation (ENSO) variability (http://www.cpc.ncep.noaa.gov/data/indices/stsoiindices). The zonal-mean meridional stream function (MSF) is calculated as the vertically integrated, zonally averaged meridional mass transport:

$$\psi = \frac{2\pi a \cos \varphi}{g} \int_{p_1}^{p_2} [v] dp,$$

where $a$ represents the radius of the Earth, $p_1$ is surface pressure, $v$ is meridional wind, $\phi$ is latitude, $g$ is gravitational acceleration, and $[\cdot]$ indicates the zonal average. A zonal-mean perspective is adopted in this study.

The primary statistical methods used are regression and correlation analyses. Correlation analysis is abbreviated as R in the following figures. When performing regression analysis, the index (e.g., SAM index) regressed upon was first standardized. The resultant regression coefficients therefore represent circulation anomalies corresponding to one standard deviation of the index. Student’s two-tailed t-test is employed to assess the statistical significance of the correlation and regression coefficients. Partial correlation/regression analysis is employed to detect the relationship between two variables after excluding the effect of the third variable. Partial correlation/regression analysis is abbreviated as PR in the following figures. Completely removing variations related to a specific variable from the climate records is challenging due to ambiguities arising from nonlinear influences. Although partial correlation/regression analysis is one of the most common approaches used to identify the relationship between two variables after removing the effect of the third one, it only excludes linear components and may not completely exclude the signal of the third variable in the presence of nonlinear effects.

A field significance test (Livezey and Chen 1983) based on 1000 Monte Carlo simulations is conducted to evaluate the significance of partial regression fields. Details of the field significance test can be found in Livezey and Chen (1983). In brief, the index (e.g., the SAM index) used to conduct the regression analysis is replaced with a random time series sampled from a Gaussian distribution $N(0, 1)$. Regressions of climatic variable on this random time series are then obtained at every grid point and tested for significance using the Student’s $t$ test. The percentage of significant area is then calculated. This experiment is completed 1000 times with different random inputs, and the frequency distributions of the percentages of significant area are then obtained and further used to evaluate the field significance of the corresponding regression pattern.

Singular value decomposition (SVD) analysis can determine the coupled modes of orthogonal singular vectors, as well as expansion coefficient correlations from the covariance matrix of two geophysical fields. Here, SVD analysis was used to reveal coupled spatial patterns between DJF SLP over the SH extratropics and DJF SST over the tropics.

A significant linear trend exists in the SAM index, which is attributed mainly to external forcings such as ozone depletion over Antarctica or increasing greenhouse gases (e.g., Gillett and Thompson, 2003; Marshall et al., 2004; Fogt et al., 2009; Thompson et al., 2011; Simpkins and Karpechko, 2012; Zheng et al., 2013; Jones et al., 2016). Since the linear trend in the SAM index is beyond the range of natural variability, a detrended SAM index was employed in this work. Likewise, all other climatic variables used in this study (e.g., SST, atmospheric circulation) were detrended by a least squares method prior to statistical analyses.

3. Observed cross-seasonal influence of the DJF SAM on MAM MSF

3.1. Distinguishing the effects of the DJF SAM and DJF ENSO

Previous studies have reported that the ENSO and the SAM are negatively correlated during DJF (Zhou and Yu, 2004; Fogt and Bromwich, 2006; L’Heureux and Thompson, 2006; Ciation et al., 2015). A physical explanation for the
Figure 1. (a) Standardized expansion coefficients (EC) of DJF SLP (orange line) and DJF SST (green line) for the first dominant coupled mode of the SVD analysis. Also shown are standardized time series of the DJF SAM index (red line), inverted DJF Niño 3.4 index (blue line), and DJF SAM-M03 index (black solid line). Correlations between the above indices are labeled in the panel, and an asterisk indicates significance at the 95% confidence level. (b) Heterogeneous correlation pattern for the first dominant coupled mode of DJF SLP south of 20°S (contours) and DJF tropical SST between 30°S and 30°N (shading) in the SVD analysis. (c) Correlations between the SAM index and Niño 3.4 index during DJF, as derived from individual models, the MMM, and the observations. The dotted black lines indicate significance at the 90% and 95% confidence levels.

shaping role of the ENSO on the SAM is that tropical SST anomalies related to La Niña lead to weakening of the subtropical jet, thereby shifting the critical latitudes at which extratropical waves break (e.g., L’Heureux and Thompson, 2006; Lu et al., 2008; Gong et al., 2010; Lim et al., 2016a), which tends to drive positive SAM events.

Figure 1(a) and (b) show results from SVD analysis performed on DJF SLP south of 20°S and DJF SST fields between 30°S and 30°N to reveal their coupled spatial pattern. The associated expansion coefficients (EC) of DJF SLP and DJF SST exhibit strong covariability (Figure 1a), yielding a correlation coefficient of 0.75. The variability of DJF SAM is in strong agreement with the EC of the first coupled mode of DJF SLP, with a correlation coefficient of 0.86. The distribution of DJF SLP in the first coupled mode from the SVD analysis corresponds to the typical positive SAM polarity (Figure 1b). The first coupled mode of MAM SST appears as a negative correlation in the central and eastern tropical Pacific, with the strongest correlation in the Niño 3.4 region (Figure 1b). The DJF Niño 3.4 index is consistent with the EC of the first coupled mode of DJF SST, with a correlation coefficient of 0.95. These results from SVD analysis show the connection between SAM and ENSO during DJF, yielding a correlation of −0.29 (Figure 1a). Figure 1c shows the correlation between SAM and ENSO during DJF in CMIP5 models. Compared with the observed correlation, most models underestimate the correlation or even simulate an opposite positive correlation. The MMM of the correlation coefficient (−0.17) is weaker than that obtained from the observations, implying the MMM of the correlation coefficient is substantially weaker than that obtained.
from the observation, which is consistent with the finding of Lim et al. (2016b).

In view of the covariability between the ENSO and the SAM during DJF, to avoid ENSO effects when exploring influence of the DJF SAM, partial regression/correlation is performed after removing the DJF ENSO effects in the following analysis for both observations and simulations. This is done despite the fact that the covariability of SAM and ENSO in most CMIP5 models is insignificant and weaker than the observations.

Figure 2a shows the partial regression of MAM MSF on the DJF SAM after removing the DJF ENSO effects. An anomalous descent and ascent exist at about 45°S and 30°S, respectively. In the tropics, an anomalous descent and ascent occur at about 10°S and 10°N, respectively. Figure 2b shows the partial regression of MAM MSF on the DJF ENSO after removing the DJF SAM effects. An obvious counterclockwise circulation exists in the range 45°S – 30°S. An obvious difference between the SAM-related and ENSO-related MSF anomalies emerges in the tropics. The strongest tropical MSF anomalies associated with the DJF ENSO occur in the NH tropics between the equator and 10°N, while the strongest MSF anomalies related to the DJF SAM exist in the SH tropics between 10°S and the equator. Figure 2a and b suggest that the cross-seasonal influence of the DJF SAM on MAM MSF differs from the influence of DJF ENSO, and that the influence of the DJF SAM is independent of DJF ENSO.

To conduct the field significance test, the SAM/ENSO index used to regress MAM MSF as in Figure 2a and b is replaced with a random time series sampled from a Gaussian distribution $N(0, 1)$. Regressions of MAM MSF on this random time series are then obtained at each grid point and tested for significance using Student’s two-tailed $t$-test. The percentage of the area that is significant at the 90% confidence level is then calculated. This experiment is conducted 1000 times with different random inputs, and the frequency distributions of the percentages of significant area are shown in Figure 2c and d. In Figure 2a and b, the percentage of the area that is significant at the 90% confidence level of Student’s two-tailed $t$-test is 32.7% and 32.6%, respectively. As shown in Figure 2c and d, about 10% of the Monte Carlo simulations have greater than 31.0% of area significant. The hypothesis that the regression patterns in Figure 2a and b are a chance occurrence can therefore be rejected at the 90% confidence level. The results of the field significance test verify the linkage between the DJF SAM and MAM MSF.

A similar partial regression analysis is conducted using ERA40 reanalysis. The SAM indices derived from NCEP/NCAR and ERA40 reanalysis are consistent with each other (Figure 2e), yielding a correlation coefficient of 0.96. Temporal variability in the two indices shows agreement with SAM-M03, and the SAM index from NCEP/NCAR reanalysis has an even higher correlation (0.92) than the SAM index from ERA40 (0.85). Regressions of MAM MSF on the DJF SAM and ENSO (Figure 2f and g) are basically in agreement with the results from NCEP/NCAR, thereby validating the linkage between DJF SAM/ENSO and MAM MSF.

In short, Figure 2 suggests that the cross-seasonal influence of the DJF SAM on MAM MSF differs from the influence of DJF ENSO, which is consistent with the previous study (Zheng et al., 2015a). In the following analysis, partial regression or correlation is used to linearly remove ENSO effects when exploring influence of the DJF SAM.

3.2. Role of SH extratropical SST anomalies

SAM variability is accompanied by a meridional shift of westerlies in the SH extratropics. SZW anomalies caused by the SAM alter local SST through both dynamic and thermodynamic processes, such as Ekman currents and surface turbulent heat flux. Specifically, when the SAM is in a positive phase, strengthened westerlies occur at high latitudes, and thus SST is cooler because of increased loss of heat by turbulent heat flux and cooler Ekman heat transport. The mechanism by which the SAM influencing SH extratropical SST has been well illustrated in previous studies (e.g., Watterson, 2000; Cai and Watterson, 2002; Lefebvre et al., 2004; Sen Gupta and England, 2006; Ciasto and Thompson, 2008; Wu 2008; Wu et al., 2009; Thompson et al., 2011; Hu et al., 2016), providing a solid basis for understanding the cross-seasonal influence of the DJF SAM on MAM MSF.

Figure 3a shows the lead–lag partial correlation between the DJF SAM and monthly zonal-mean SST from the preceding October to the following September after removing the DJF ENSO. The DJF SAM is negatively correlated with SST at high latitudes but positively correlated at middle latitudes during DJF, in agreement with previous studies (e.g., Watterson, 2000; Cai and Watterson, 2002; Lefebvre et al., 2004; Sen Gupta and England, 2006; Ciasto and Thompson, 2008; Wu et al., 2009; Thompson et al., 2011). The partial correlation between the DJF SAM and the seasonally averaged zonal-mean SST during DJF after removing DJF ENSO is shown in Figure 3b. The structure with positive and negative correlations at middle and high latitudes is clearly evident and consistent with Figure 3a. The strongest positive correlation at middle latitudes is 0.48 at 38.6°S, and the strongest negative correlation at high latitudes is −0.71 at 57.7°S. The extratropical SST anomaly pattern associated with the SAM is referred to as SE SST hereafter. A positive SE SST phase is characterized by warmer and colder SST anomalies at middle and high latitudes, respectively, and vice versa for the negative phase.

A SE SST index is defined by projecting anomalous SST onto the partial regression patterns similar to Figure 3b. The standardized DJF SE SST index is shown in Figure 3c, together with the standardized DJF SAM and inverted DJF Niño 3.4 indices. The partial correlation coefficient
Figure 2. (a) Partial regression of MAM MSF (shading, $10^9$ kg s$^{-1}$) on the DJF SAM after removing the DJF ENSO effects. Climatological MSF are shown as contours with intervals of $30 \times 10^9$ kg s$^{-1}$. The green and red hatching represents significance at the 90% and 95% confidence levels, respectively. The numbers above the top-right corners of the panels represent the percentage of the total area that is significant at the 90% confidence level. (b) As in (a), but for partial regression on the DJF ENSO (inverted Niño 3.4 index) after removing the DJF SAM effects. (c, d) Frequency distributions of the percentage of area significant at the 90% confidence level for the regressed MAM MSF on 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 the corresponding bar. (e) Standardized SAM indices derived from NCEP/NCAR (blue) and ERA40 (red), and the standardized SAM-M03 (black). Correlations between the above indices are shown in the panel, and an asterisk indicates significance at the 95% confidence level. (f) Partial regression of MAM meridional circulation (vectors) on the DJF SAM, derived from ERA40, after removing the DJF ENSO. The units for vertical and horizontal velocity are $10^{-2}$ Pa s$^{-1}$ and m s$^{-1}$, respectively. Shading represents significance at the 90% confidence level. (g) As in (f), but for partial regression on the DJF ENSO (inverted Niño 3.4 index) after removing the DJF SAM.
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Figure 3. (a) Lead–lag partial correlation between the DJF SAM and monthly zonal-mean SST from the preceding October to the follow September after removing the DJF ENSO derived from reanalysis datasets. The contour interval is 0.2, and shading represents significance at the 95% confidence level. (b) Partial correlation between seasonally averaged zonal-mean DJF (red), and MAM (black) SST and the DJF SAM after removing the DJF ENSO. The crosses mark the latitudes with the strongest positive or negative correlations south of 30°S. (c) Standardized time series of SAM indices in DJF (solid black) and MAM (dashed black), SESST indices in DJF (solid blue) and MAM (dashed blue), and DJF ENSO (inverted Niño 3.4 index, solid red). Partial correlations between the above indices are shown in the panel, and an asterisk indicates significance at the 95% confidence level. (d) As in Figure 2a, but for partial regression on MAM SESST after removing the DJF ENSO. (e) As in Figure 2a, but for partial regression on the DJF SAM after removing both the DJF ENSO and MAM SESST.

As a result of the large heat capacity of the ocean (e.g., Ciaseto and Thompson, 2008), the DJF SESST caused by the DJF SAM persists to the following MAM (Figure 3a). Figure 3b shows the partial correlation between the DJF SAM and seasonally averaged zonal-mean SST during MAM after removing the DJF ENSO, yielding strongest positive and negative correlation coefficients of 0.37 and −0.66 at about 40.6°S and 60.7°S, respectively. The standardized MAM SESST index is shown in Figure 3c. The partial correlation coefficient between MAM SESST and DJF SESST after removing DJF ENSO is 0.81 (Figure 3c), verifying the strong persistence of SH extratropical SST anomalies associated with the DJF SAM. The MAM SAM also imprints its signal on SH extratropical MAM SST and resulting in a similar SST anomaly pattern to that observed for the DJF SAM, while the DJF SAM plays a more important role than the MAM SAM in modulating the MAM SESST (Zheng et al., 2015b). As shown in Figure 3c, the partial correlation coefficient between DJF SAM and MAM SESST after linearly removing the DJF ENSO (0.62) is stronger than that between MAM
SAM and MAM SESST (0.22). Similar situation exists in the model simulations. In all the 32 CMIP5 models employed in this study, the linkage between the DJF SAM and MAM SESST is stronger than that between the MAM SAM and MAM SESST (not shown).

The focus of the present study is the zonal-mean component, because the partial correlation coefficients between the DJF SAM and DJF, MAM zonal-mean SESST after removing DJF ENSO (0.72 and 0.62) are stronger than those between the DJF SAM and SST in most specific regions of the southern extratropics. Based on the regressed non-zonal-mean (the raw two-dimensional) SST maps on the DJF SAM (not shown), a SESST-nonzm index is defined by projecting the anomalous SST onto the regression maps. The correlation coefficients between SESST and SESST-nonzm indices are 0.94 and 0.62 in DJF and MAM, respectively, and the MMM of the above correlations from the CMIP5 models are 0.76 and 0.93, suggesting that the zonal-mean SESST index reflects a large part of the characteristics of SAM-related SST anomalies in the SH extratropics. In addition to the zonally symmetric component, SAM-related SST anomalies are characterized by zonal asymmetry (e.g., Watterson, 2000; Cai and Watterson, 2002; Lefebvre et al., 2004; Sen Gupta and England, 2006; Ciasto and Thompson, 2008; Wang, 2010). The effect of the zonal asymmetrical component is not explored in the present study but cannot be ruled out in reality.

Figure 4. As in Figure 3a, but for results derived from individual models, the MMM, and the difference between the MMM and the observations. The contour interval is 0.2, although when the absolute value is greater than 0.8 the interval is 0.1. The thick dashed-dotted lines represent the specific latitudes where the observed correlation coefficients during DJF in Figure 3b reach the maximum. Shading for individual models represents significance at the 95% confidence level, and shading in the last panel indicates values greater than 0.2. Shading in the second last panel represents the MMM is significant; i.e., at least 25 of 32 models have the same sign as the MMM. The character above the top-right corners of the panel is used to represent the corresponding model. [Colour figure can be viewed at wileyonlinelibrary.com].

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The MAM SESST was found to affect MAM MSF. Figure 3d shows the partial regression of MAM MSF on MAM SESST after removing the DJF ENSO. Based on the field significance test, the hypothesis that the regression pattern in Figures 3d is a chance occurrence can be rejected at the 90% confidence level. The MSF anomalies associated with MAM SESST resemble MSF anomalies related to the DJF SAM, implying a role for SESST in the cross-seasonal influence of DJF SAM on MAM MSF. Figure 3e shows the partial regression of MAM MSF on the DJF SAM after removing both the DJF ENSO and MAM SESST. Compared with Figure 2a, significant MSF anomalies almost disappear after removing MAM SESST, and the regression pattern as a whole is insignificant according to the field significance test, suggesting an important role for MAM SESST in the cross-seasonal influence of DJF SAM on MAM MSF. Besides, one may wonder that whether the cross-seasonal influence of the DJF SAM on MAM MSF is a manifestation of the role of the MAM SAM. Considering that the MAM SESST (a key process linking the DJF SAM and MAM MSF) is mainly caused by the DJF SAM rather than the MAM SAM, and that MAM MSF anomalies related to the MAM SAM (not shown) differ from those related to the DJF SAM and MAM SESST, it is reasonable to believe the cross-seasonal influence of the DJF SAM on MAM MSF not depends on the MAM SAM.

4. Model performance in simulating the influence of the DJF SAM on SESST

4.1. Lead—lag correlation between the DJF SAM and SST

Figure 4 shows the similar analyses as in Figure 3a, but for historical experiments from the 32 CMIP5 models. Most models capture the structure of the linkage between the DJF SAM and zonal-mean SST in the SH extratropics during both DJF and MAM, which is also evident in the MMM. To quantify the consistency between the modeled and observed lead—lag partial correlation patterns, a Taylor diagram (Taylor, 2001) is shown in Figure 5a. The pattern correlation coefficients between the modeled and observed partial lead—lag correlations with a value less than 0.7 occur in INMCM4 and NorESM1-ME. In the other 30 models, the pattern correlation coefficients exceed 0.7, indicating that most models perform well in simulating the lead—lag correlation pattern between the DJF SAM and SH zonal-mean SST. However, model-simulated correlations in the middle latitudes are stronger than those in the observations, which is evident in the difference between the MMM and the observations (last panel in Figure 4). In fact, most models exaggerate the association between the DJF SAM and zonal-mean SST in the SH middle latitudes. The strongest correlations in middle latitudes from the observations are about 0.4. However, in most models the strongest correlations in the middle latitudes exceed 0.6. For example, the positive correlations in the SH extratropics in IPSL-CM5A-MR exceed 0.8. This characteristic is also evident in the ratio of the standard deviation between modeled and observed lead—lag partial correlation patterns in the Taylor diagram, in which 29 models exaggerate the amplitude of the lead—lag partial correlation pattern, and the other two models (INMCM4 and NorESM1-ME) underestimate the amplitude.

Figure 5b shows a scatterplot of the partial correlations between the DJF SAM and MAM SESST after removing the DJF ENSO, against those between the DJF SAM and DJF SESST. The MMM of partial correlations between the DJF SAM and DJF SESST is 0.80, which is stronger than the observed value of 0.72; the MMM of partial correlations between the DJF SAM and MAM SESST is 0.77, which is also stronger than the observed value of 0.62. The exaggeration of the relationship between the DJF SAM and SESST by most models agrees with results in Figures 4 and 5a. In addition, it is clear in Figure 5b that models with a stronger simulated correlation between the DJF SAM and DJF SESST tend to simulate a stronger correlation between the DJF SAM and MAM SESST. This is because the cross-seasonal linkage between DJF SAM and MAM SESST is due mainly to the persistence of DJF SST anomalies caused by the DJF SAM. Figure 5c shows the partial correlations between DJF SESST and MAM SESST after removing the DJF ENSO. The MMM (0.80) is close to the observed value of 0.81, indicating that the persistence between the DJF SESST and MAM SESST is well reflected in most models.

The meridional location of the SH extratropical SST anomaly pattern related to the DJF SAM in Figures 3a and 4 is referred to as the location of the SAM—SESST relationship hereafter. As shown in Figure 4, the location of the SAM—SESST relationship varies among the CMIP5 models. For example, the dipole patterns in IPSL-CM5A-LR and MIROC-ESM-CHEM show a clear equatorward shift compared with those from the observations. Therefore, to acquire a comprehensive understanding of model performance in reproducing the influence of the DJF SAM on SESST, it is necessary to detect the model-simulated location of the SAM—SESST relationship, in addition to exploring the strength of this relationship.

In the correlation patterns in Figures 3a and 4, there are two extremums within the SH extratropics corresponding to one positive and one negative correlation in the middle and high latitudes, respectively. The extremums of the correlation coefficient are referred to as $R_{\text{max}}$. The latitude at which $R_{\text{max}}$ occurs is referred to as $\lambda_{\text{max}}$, which is used to represent the location of the SAM—SESST relationship. Both the $\lambda_{\text{max}}$ corresponding to the strongest positive correlation at middle latitudes and that corresponding to the strongest negative correlation at high latitudes during DJF and MAM are shown in Figure 6 as scatterplots against the value of the strongest correlation ($R_{\text{max}}$). The ranges of $\lambda_{\text{max}}$ among the 32 models are about 9° and 18° for the middle and high latitudes, respectively. These relatively large meridional ranges indicate uncertainty in simulating the location of the dipole correlation pattern between the DJF SAM and SST, which is especially true
Figure 5. (a) Taylor diagram of the lead–lag partial correlation patterns between the DJF SAM and monthly zonal-mean SST after removing DJF ENSO as shown in Figures 3a and 4. The pattern correlation coefficients and the ratio of the standard deviation between modeled and observed lead–lag partial correlation patterns are shown by the cosine of the azimuth angle and the radial distance, respectively. The term ‘REF’ on the horizontal axis indicates the reference point. The RMS difference between the individual model and the observations is proportional to the distance from the ‘REF’ point. (b) Scatterplot of partial correlations between the DJF SAM and MAM SESST after removing the DJF ENSO (ordinate), against partial correlations between the DJF SAM and DJF SESST after removing the DJF ENSO (abscissa). (c) Partial correlations between DJF SESST and MAM SESST after removing the DJF ENSO. The dotted black lines indicate significance at the 90% and 95% confidence levels. [Colour figure can be viewed at wileyonlinelibrary.com].

for SST in the MAM season. Nevertheless, the location of the SAM-SESST relationship in the MMM is quite similar to that from the observations. For example, as shown in Figure 6c, the MMM of $\lambda_{\text{max}}$ at high latitudes during DJF is $55.7^\circ$S, which is close to the observed value of $57.7^\circ$S. In addition, as shown in Figure 6b, the MMM of $\lambda_{\text{max}}$ at middle latitudes during MAM is $40.3^\circ$S, which is close to the observed value of $40.6^\circ$S.

4.2 Understanding model performance

To better understand model performance in simulating the influence of the DJF SAM on SESST, as shown in the last
CROSS-SEASONAL INFLUENCE OF THE SAM IN CMIP5 MODELS

Figure 6. Scatterplots of $\lambda_{\text{max}}$ at (a, b) middle and (c, d) high latitudes during (a, c) DJF and (b, d) MAM, against the corresponding $R_{\text{max}}$, as derived from individual models, the MMM, and the observations. [Colour figure can be viewed at wileyonlinelibrary.com].

section, the model-simulated connection between the DJF SAM and zonal-mean SZW is investigated in this section. This connection is explored because the influence of the DJF SAM on SESST occurs mainly via SZW anomalies caused by the DJF SAM.

Figure 7 shows the lead–lag partial correlations between the DJF SAM and monthly zonal-mean SZW from the preceding October to the following September after removing the DJF ENSO derived from reanalysis datasets. Given that the persistence of the atmospheric signal does not typically exceed one season, the correlation between the DJF SAM and SZW is mainly confined to DJF. The DJF SAM is positively correlated with SZW at high latitudes, but negatively at middle latitudes. The out-of-phase relationship between the middle and high latitudes exists due to the behavior of the SAM, which features a shift of zonal-mean zonal wind. During positive SAM phases, the upper level polar jet shifts toward Antarctica, and the SZW at high latitudes tends to increase while that at middle latitudes tends to decrease. During negative SAM phases, the displacement of the upper-level polar jet is equatorward, and the SZW at middle and high latitudes is enhanced and reduced, respectively. The partial regression of seasonal-mean zonal-averaged SZW on the DJF SAM after removing the DJF ENSO is consistent with monthly mean results. The strongest negative and positive correlation coefficients occur at about 33.6°S and 55.6°S, respectively, where the absolute value of the correlation exceeds 0.8.

To explore model performance in reproducing the lead–lag correlation between the SAM and SZW, Figure 7 also shows analyses similar to those performed with the reanalysis datasets, but for CMIP5 model results. All of the models exhibit negative and positive correlations at middle and high latitudes, respectively, implying that the models are equipped to simulate the poleward shift of westerlies corresponding to a positive SAM phase. One notable feature in Figure 7 is the strength of the correlation between the SAM and SZW at middle latitudes, which in most CMIP5 models is stronger than that from the observations. In the MMM, the models exaggerate the magnitude of the connection between the DJF SAM and DJF SZW at SH middle latitudes, suggesting that most models magnify the circulation variability associated with the SAM, which is in agreement with previous studies (Zheng et al., 2013). This exaggeration may be related to the fact that the variance in SZW attributed to the zonal-mean component is overestimated in the SH extratropics in CMIP5 simulations compared with the observations (not shown).

In view of the close linkage between SZW and SST in the SH extratropics, the exaggerated association between the DJF SAM and SZW by the CMIP5 models may contribute
Figure 7. The top two panels are as in Figure 3a and b, but for SZW. Others panels are as in Figure 4, but for SZW. [Colour figure can be viewed at wileyonlinelibrary.com].

to an overestimated linkage between the DJF SAM and SESST. Table 1 lists the correlation coefficients between the model-simulated strength of the SAM–SESST relationship and the model-simulated strength of the SAM–SZW relationship. The strength is represented by the extremums of the correlation coefficients ($R_{\text{max}}$) between the DJF SAM and SZW/SST within the SH extratropics. There are two extremums in the correlation pattern, one positive and one negative. A strong positive correlation exists between $R_{\text{max}}$ (DJF SST, DJF SAM) and $R_{\text{max}}$ (DJF SZW, DJF SAM) for both the middle (0.61) and high (0.65) latitudes (Table 1). This significant positive correlation
CROSS-SEASONAL INFLUENCE OF THE SAM IN CMIP5 MODELS

Table 1. Correlation matrix among model-simulated $R_{\text{max}}$ (DJF SZW, DJF SAM), $R_{\text{max}}$ (DJF SST, DJF SAM), and $R_{\text{max}}$ (MAM SST, DJF SAM). $R_{\text{max}}$ denotes the extremums of correlation coefficients between the DJF SAM and SZW/SST within the range of the SH extratropics. Results for the two extremums, one positive and one negative, in the middle and high latitudes are shown.

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<th>Middle Lat.</th>
<th>High Lat.</th>
<th></th>
<th>Middle Lat.</th>
<th>High Lat.</th>
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<tbody>
<tr>
<td>$R_{\text{max}}$ (DJF SZW, DJF SAM)</td>
<td>0.61</td>
<td>0.65</td>
<td>$R_{\text{max}}$ (MAM SST, DJF SAM)</td>
<td>0.60</td>
<td>0.77</td>
</tr>
<tr>
<td>$R_{\text{max}}$ (DJF SST, DJF SAM)</td>
<td>1</td>
<td>1</td>
<td></td>
<td>0.73</td>
<td>0.69</td>
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Figure 8. As in Figure 6a and c, but for SZW. [Colour figure can be viewed at wileyonlinelibrary.com].

suggests that models with a stronger correlation between DJF SZW and DJF SAM tend to simulate a stronger connection between DJF SST and the DJF SAM. The correlation coefficients between $R_{\text{max}}$ (MAM SST, DJF SAM) and $R_{\text{max}}$ (DJF SST, DJF SAM) are 0.73 and 0.69 for middle and high latitudes, respectively, implying that models which overestimate the DJF SST anomalies related to the DJF SAM tend to overestimate MAM SST anomalies related to the DJF SAM. This is because the linkage between DJF SAM and MAM SST depends mainly on the persistence of DJF SST anomalies caused by the DJF SAM. Accordingly, a significant positive correlation also exists between $R_{\text{max}}$ (MAM SST, DJF SAM) and $R_{\text{max}}$ (DJF SZW, DJF SAM), with correlation coefficients of 0.60 and 0.77 for middle and high latitudes, respectively. This suggests that models with a stronger linkage between the DJF SAM and DJF SZW usually reproduce a stronger linkage between the DJF SAM and MAM SST. Thus, the results presented in Table 1 support that the exaggerated SAM-SESST relationship in the CMIP5 models can be partially attributed to an overestimated SAM–SZW relationship.

The meridional location of the SZW anomaly pattern in the SH extratropics related to the DJF SAM is referred to as the location of the SAM–SZW relationship hereinafter. The location of the SAM–SZW relationship is quantified...
5. Model performance in simulating the influence of SESST on MAM MSF

Partial regressions of MAM MSF on MAM SESST after removing the DJF ENSO derived from individual CMIP5 model simulations are shown in Figure 9. As shown in Figure 9, the partial regression patterns simulated by several models are close to the observations (e.g., CanESM2), while in several other models the regression patterns exhibit obvious differences from the observations (e.g., GISS-E2-H-CC). Model uncertainty in simulating the partial regression patterns is larger in the tropics than in the SH extratropics. In particular, the clockwise and counterclockwise circulation anomalies in the SH extratropics (south of 30°S) are captured by most models, while obvious differences in the simulated MSF anomalies in the tropics exist among the models.

To quantify the consistency between the modeled (Figure 9) and the observed (Figure 3d) partial regression patterns of MAM MSF on MAM SESST, a Taylor diagram is shown in Figure 10a. A comparison between Figures 10a and 5a suggests that models differ more in their ability to simulate the linkage between MAM SESST and MAM MSF (Figure 10a) than they do in capturing the connection between the DJF SAM and SH extratropical SST (Figure 5a). Using root-mean-square (RMS) differences between the simulations and the observations, shown as the distance between the model point and the “REF” point in the Taylor diagram, the 32 models are divided into three groups: the top five models (~15%) labeled Group I, the last five models (~15%) labeled Group III, and the mid-range 22 models (~70%) labeled Group II. The models in Group I are BCC-CSM1–1, CMCC-CM, CNRM-CM5, GISS-E2-H, and MPI-ESM-P, and those in Group III are CMCC-CMS, FGOALS-s2, GISS-E2-H-CC, GISS-E2-R, and IPSL-CM5A-LR.

Averaged partial regressions for the three groups are shown in Figures 10b–10d. The anomalous MSF cells extending from the SH high latitudes to the tropics, associated with MAM SESST, are well simulated by Groups I and II (Figure 10b and c). The anomalous MSF cells in Group II are weaker than those in Group I. In contrast, the simulated connection between MAM SESST and MAM MSF in Group III differ significantly from the observations (Figure 10d). In particular, the simulated pattern of anomalous MSF cells in the SH extratropics is wider than that in the observations, and in the tropics the cells have the opposite sign of those from the observations.

Figure 10e shows the MMM of partial regressions of MAM MSF on MAM SESST after removing the DJF

by $\lambda_{max}$, which is the latitude at which $R_{max}$ occurs. As shown in Figure 8, the $\lambda_{max}$ in the MMM is similar to the observations. The MMM of $\lambda_{max}$ at middle latitudes is 34.9°S, which is similar to the observed value of 33.6°S (Figure 8a); the MMM of $\lambda_{max}$ at high latitudes is 55.2°S (Figure 8b), which is again similar to the observed value of 55.6°S. Nevertheless, models differ in reproducing $\lambda_{max}$, with a range of about 10° and 8° for middle and high latitudes, respectively.

Because the model-simulated strengths of the SAM–SESST and SAM–SZW relationships are positively correlated (Table 1), one may infer that this linkage also applies to the model-simulated locations of the SAM–SESST and SAM–SZW relationships. As shown in Table 2, the correlations between $\lambda_{max}$ (DJF SST, DJF SAM) and $\lambda_{max}$ (DJF SZW, DJF SAM) for middle and high latitudes are 0.47 and 0.56, respectively. This indicates that when model-simulated negative correlations between DJF SZW and DJF SAM show a poleward shift, the model-simulated correlations between DJF SST and DJF SAM also tend to shift poleward. The correlations between $\lambda_{max}$ (MAM SST, DJF SAM) and $\lambda_{max}$ (DJF SST, DJF SAM) for middle and high latitudes are 0.81 and 0.30, respectively. These significant correlations indicate that the model-simulated location of the MAM SST anomalies related to the DJF SAM is dependent in part on the model-simulated location of the DJF SST anomalies related to the DJF SAM, especially for the middle latitudes. The correlation coefficients between $\lambda_{max}$ (MAM SST, DJF SAM) and $\lambda_{max}$ (DJF SZW, DJF SAM) are 0.50 and 0.20 for middle and high latitudes, respectively. The results shown in Table 2 suggest that an accurate location of the SAM–SESST relationship basically ensures an accurate simulation of the location of the SAM–SESST relationship. The weaker correlation coefficient between $\lambda_{max}$ (MAM SST, DJF SAM) and $\lambda_{max}$ (DJF SZW, DJF SAM) at high latitudes (0.20) is related to the weaker correlation coefficient between $\lambda_{max}$ (MAM SST, DJF SAM) and $\lambda_{max}$ (DJF SST, DJF SAM) at high latitudes (0.30).

In short, most of the CMIP5 models employed in this study are equipped to capture the influence of the DJF SAM on SESST, despite the fact that for most models the simulated influence is stronger than that from the observations. Although the models differ in their ability to simulate the location of the SAM–SESST relationship, due in part to model uncertainty in depicting the location of the SAM–SZW relationship, the meridional location of the SAM–SESST correlation in the MMM is similar to that from the observations.

<table>
<thead>
<tr>
<th>$\lambda_{max}$ (DJF SZW, DJF SAM)</th>
<th>$\lambda_{max}$ (DJF SST, DJF SAM)</th>
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<tr>
<td>Middle Lat.</td>
<td>High Lat.</td>
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<tr>
<td>0.47</td>
<td>0.56</td>
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<tr>
<td>$\lambda_{max}$ (MAM SST, DJF SAM)</td>
<td>$\lambda_{max}$ (MAM SST, DJF SAM)</td>
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<td>Middle Lat.</td>
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<td>0.50</td>
<td>0.20</td>
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CROSS-SEASONAL INFLUENCE OF THE SAM IN CMIP5 MODELS

Figure 9. Partial regression of MAM MSF (shading, 10^9 kg s^{-1}) on MAM SESST after removing the DJF ENSO derived from individual models. Climatological MSF shown as contours with an interval of 30 × 10^9 kg s^{-1}. The green hatching and stippling denote significance at the 90% and 95% confidence levels, respectively.

ENSO, as derived from all 32 models employed in this study. As a whole, the distribution of anomalous clockwise and counterclockwise cells between 70°S and 20°N is captured in the MMM. Significance is defined when at least 25 of 32 models have the same sign as the MMM, indicating consistency among the models. Model simulations have larger uncertainties in the tropics than in the SH extratropics. As a result, the significance in the tropics (10°S – 10°N) is weaker than that in the SH extratropics (Figure 10e). The difference between the MMM and the observed partial regression patterns is shown in Figure 10f. Circulation anomalies in the SH extratropics in the MMM are slightly stronger than in the observations, while those in the tropics are weaker.

6. Simulated cross-seasonal influence of the DJF SAM on MAM MSF

Figure 11 shows partial regressions of MAM MSF on the DJF SAM after removing the DJF ENSO derived from individual CMIP5 models. The consistency between the simulated and the observed partial regression patterns of MAM MSF on the DJF SAM is quantified using a Taylor diagram (Figure 12a). The 32 models are divided into
Figure 10. (a) Taylor diagram of the partial regression patterns of MAM MSF on MAM SESST as shown in Figures 3d and 9. Averaged partial regression of MAM MSF (shading, $10^9 \text{ kg s}^{-1}$) on MAM SESST among models in (b) Group I, (c) Group II, (d) Group III, (e) the MMM, and (f) the difference between the MMM and the observations. The models in Groups I, II, and III selected according to the Taylor diagram in (a) are listed in Section 5. Climatological MSF are shown as contours with an interval of $30 \times 10^9 \text{ kg s}^{-1}$. The stippling in (b)-(e) indicates the averaged value is significant, which is defined as when at least (b) 3 of 5, (c) 18 of 22, (d) 3 of 5, or (e) 25 of 32 models have the same sign as the average value.

Three groups according to RMS differences between the simulations and the observations, as shown in the Taylor diagram (Figure 12a). Group I consists of the top five models (BCC-CSM1–1, CMCC-CM, GFDL-CM3, GFDL-ESM2G, and MPI-ESM-MR), Group III comprises the last five models (BNU-ESM, CMCC-CMS, FGOALS-s2, GISS-E2-R, and NorESM1-M), and the remaining 22 models are assigned to Group II.

Averaged partial regressions in the three groups are shown in Figures 12b–12d. Models in Groups I and II generally capture the cross-seasonal influence of the DJF SAM on MAM MSF (Figure 12b and c). The strength of
the anomalous MSF cells in Group II is not reproduced as well as those in Group I. However, the cross-seasonal influence of the DJF SAM on MAM MSF is not well captured in Group III (Figure 12d). As in the case of MAM SESST (Figure 10d), the pattern of anomalous MSF cells in the SH extratropics simulated by Group III is wider than in the observations, and in the tropics the cells have the opposite signs of those from the observations (Figure 12d).

The MMM of the simulated cross-seasonal influence of the DJF SAM and MAM MSF from all the models is shown in Figure 12e, and the difference between the MMM and the observations is shown in Figure 12f. The distribution of anomalous clockwise and counterclockwise cells is generally captured in the MMM (Figure 12e), despite the fact that circulation anomalies in the SH extratropics in the MMM are close to the observations while those in the tropics and NH subtropics are weaker than in the observations (Figure 12f).

Both the influence of the DJF SAM on MAM SESST (Section 4) and the modulating role of the MAM SESST on MAM MSF (Section 5) contribute to the cross-seasonal influence of the DJF SAM on MAM circulation. Model ability in simulating the cross-seasonal influence of the DJF SAM on MAM MSF may be affected by ability to simulate the connection between the DJF SAM and MAM SESST (Section 4) and by ability to simulate the linkage between MAM SESST and MAM MSF (Section 5). We next explore the relative contributions of the model-simulated connection between the DJF SAM and MAM SESST and the model-simulated linkage between MAM SESST and MAM MSF to the ability to simulate the cross-seasonal influence of the DJF SAM.
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Figure 12. As in Figure 10, but for the DJF SAM. The models in Groups I, II, and III selected according to the Taylor diagram in (a) are listed in Section 6.

on MAM MSF. Model performance is quantified by the pattern correlation coefficient and the ratio of the standard deviation between modeled and observed patterns, shown as the cosine of the azimuth angle and the radial distance in the Taylor diagrams (Figures 5a, 10a, and 12a).

Model performance in simulating the linkage between the DJF SAM and MAM MSF, represented by the pattern correlation, is shown as the abscissa in Figure 13a and b, and is plotted against model performance in simulating the linkage between MAM SESST and MAM MSF (ordinate in Figure 13a), and against model performance in simulating the linkage between the DJF SAM and SESST (ordinate in Figure 13b). The correlation coefficient between the ordinate and abscissa in Figure 13a

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is 0.71, implying that model ability in simulating the cross-seasonal influence of the DJF SAM on MAM MSF is closely linked to model performance in capturing the linkage between MAM SESST and MAM MSF. Compared with the ordinate of Figure 13a, the variation of pattern correlations between modeled and observed lead-lag correlation between the DJF SAM and MAM SESST, as shown in the ordinate of Figure 13b, is relatively small. The correlation coefficient between the ordinate and abscissa in Figure 13b is 0.31, suggesting that model ability in simulating the cross-seasonal influence of the DJF SAM on MAM MSF is weakly linked to model performance in capturing the linkage between the DJF SAM and MAM SESST.

Figure 13c and d show similar analyses to Figure 13a and b, but using the ratio of the standard deviations as a criterion for measuring model performance. In agreement with results based on pattern correlation, Figure 13c and d suggest that model ability in simulating the cross-seasonal influence of the DJF SAM on MAM MSF depends mainly on model performance in simulating the connection between MAM SESST on MAM MSF. Model performance in simulating the linkage between the DJF SAM and SESST plays a secondary role.

7. Conclusion and discussion

Understanding variability in meridional circulation is of great interest, because it basically determines the spatial and temporal characteristics of large-scale precipitation. A comprehensive understanding of variability in meridional circulation requires investigations of various influencing factors. Recent results showed that the DJF SAM is a potential influencing factor of the MAM meridional circulation, which was found based on reanalysis datasets and was verified through AGCM simulation (Zheng et al., 2015a).

Using outputs of historical experiments from 32 CMIP5 coupled models, this work assesses model performance in simulating the cross-seasonal influence of the DJF SAM on MAM meridional stream function (MSF). The “ocean–atmosphere coupled bridge” is the underlying mechanism for the cross-seasonal influence, in which the SH extratropical ocean stores the signal of the DJF SAM, referred to as the SESST, which persists to MAM and then alters MAM MSF. Therefore, in order to understand model ability in reflecting the cross-seasonal influence, model performance in simulating the influence of the DJF SAM on MAM SESST and in simulating the influence of MAM SESST on MAM MSF are both assessed.

Results show that most models are equipped to capture the influence of the DJF SAM on DJF and MAM SESST. However, the model-simulated influence is stronger than that from the observations, which is partially attributed to an overestimation of the association between the SAM and SZW by these models. The meridional location of the SAM–SESST correlation in the MMM is close to that from the observations. Nevertheless, models differ in their ability to simulate this location, which is affected by model performance in reproducing the location of SZW anomalies related to the DJF SAM.
In regards to simulating the association between MAM SESST and MAM MSF, models performance in the SH extratropics is better than that in the tropics. The clockwise and counterclockwise circulation anomalies in the SH extratropics, related to MAM SESST, are captured by most models, while the simulated MSF anomalies in the tropics show obvious differences among the models. As a whole, the distribution of anomalous clockwise and counterclockwise cells between 70°S and 20°N is captured in the MMM, despite the weaker consistency among models in the tropics than in the SH extratropics.

Model ability in simulating the connection between the DJF SAM and MAM SESST is better than in simulating the linkage between MAM SESST and MAM MSF. Accordingly, model performance in reproducing the cross-seasonal influence of the DJF SAM on MAM MSF limited by model performance in simulating the relationship between MAM SESST and MAM MSF. The simulated cross-seasonal influence of the DJF SAM on MAM MSF in models with high performance in simulating the linkage between MAM SESST and MAM MSF tends to be closer to the observations than in models with relatively low performance. Model performance in simulating the linkage between the DJF SAM and MAM SESST plays a secondary role in determining model performance in depicting the cross-seasonal influence of the DJF SAM on MAM MSF.

Finally, physical mechanism for explaining the influence of MAM SESST on MAM extratropical meridional circulation was proposed based on extratropical momentum budget. More work is needed to gain a deeper understanding of the influence of MAM SESST on MAM tropical meridional circulation (i.e., Hadley circulation). In addition, the DJF SAM exhibits a significant positive linear trend in the past half century. In view of the cross-seasonal influence of the DJF SAM on MAM meridional circulation, further work is needed to explore the role of the DJF SAM in contributing to the changes in MAM meridional circulation.

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References


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