Relative Importance of the Austral Summer and Autumn SAM in Modulating Southern Hemisphere Extratropical Autumn SST*

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ABSTRACT

Sea surface temperature (SST) variability in the extratropical Southern Hemisphere is mainly determined by physical processes at the air–sea interface associated with the Southern Hemisphere annular mode (SAM). Both the austral summer [December–February (DJF)] and autumn [March–May (MAM)] SAM can imprint their signals on southern extratropical MAM SST. Here three approaches are employed to determine the relative importance of the DJF and MAM SAM in modulating southern extratropical MAM SST: a simple lead–lag correlation without SST decomposition, a decomposition method based on linear regression, and a new approach named the persistent signal decomposition (PSD). The results show that the DJF SAM plays a more important role than the MAM SAM in driving MAM large-scale southern extratropical SST anomalies, implying that MAM SST anomalies caused by the preceding DJF SAM would not be largely perturbed by the MAM SAM, and thus the DJF SAM can be regarded as an effective predictor for the following season's climate. The PSD also provides an estimation of the contribution of atmospheric persistence and SST persistence toward cross-seasonal influence of the DJF SAM on MAM southern extratropical SST. The results show that this cross-seasonal influence is mainly caused by the SST persistence. The detection of the relative importance of the preceding and contemporaneous atmospheric signal in driving SSTA contributes to the understanding of air–sea interactions and helps to obtain better SST-based statistical predictions. The PSD has the potential to be employed in the North Atlantic and other extratropical oceans.

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1. Introduction

Sea surface temperature (SST) provides an important source of predictability in climate systems due to its signal persistence, which is usually greater than that of the atmospheric circulation because of the large heat capacity of the ocean (e.g., Frankignoul and Hasselmann 1977; Namias et al. 1988; Wang et al. 2000; Watanabe and Kimoto 2000; Deser et al. 2003; Pan 2005, 2007; Deser

et al. 2010; Ding and Li 2011, 2012; Ciasto et al. 2011; Tokinaga et al. 2012). Therefore, SST is an important “linking bridge” for cross-seasonal connections and an important predictor in climate predictions.

In particular, the SST persistence is a foundation for the cross-seasonal influence of the December–February (DJF) Southern Hemisphere annular mode (SAM) on southern China March–May (MAM) precipitation (Zheng and Li 2012). The SAM is the dominant mode of atmospheric circulation in the southern extratropics (Gong and Wang 1999; Thompson and Wallace 2000; Thompson et al. 2000; Li and Wang 2003). A seasonal prediction model for southern China MAM precipitation has been developed based on the DJF SAM and employed successfully in statistical prediction (Li et al. 2013a). The corresponding mechanism may be summarized as follows. The DJF SAM alters southern extratropical SST through both dynamical and thermodynamic processes (Watterson 2000; Cai and Watterson 2002; Lefebvre et al. 2004; Sen Gupta and England 2006; Wu et al. 2009a; Thompson et al. 2011; Zheng and Li 2012), and leads to a dipolelike SST anomaly (SSTA) pattern south of 30°S. For brevity, this SAM-induced SSTA pattern is referred to as the Southern Hemisphere ocean dipole (SOD). The SAM-induced SOD persists to MAM due to SST persistence, influences the vertical motion over southern China through its modulation on zonal-mean meridional circulation via wave–mean flow interactions and corresponds to changes in the position of northwestern Pacific subtropical high, and thus leads to MAM precipitation anomalies over southern China (Zheng and Li 2012).

In short, the DJF SAM imprints its signal on MAM SST and provides a source of predictability for southern China MAM precipitation. However, as will be shown in section 3b, the MAM SAM may also influence MAM SST and lead to a similar SSTA pattern in the southern extratropics (see also Ciasto and Thompson 2008). Therefore, the MAM SST field in the southern extratropics contains both anomalies caused by the DJF and MAM SAM. The problem then is to estimate the relative importance of the DJF and MAM SAM in modulating the MAM SST. If the DJF SAM plays a dominant role in influencing MAM SST, the DJF SAM and associated SSTA can be regarded as effective predictors for the following season’s climate. However, if the MAM SAM makes a larger contribution, the MAM SSTA caused by the DJF SAM may be modulated to a great extent by the MAM SAM, and thus the preceding season signals for seasonal prediction would be perturbed. Therefore, the aim of this study is to detect the relative contributions of the DJF and MAM SAM in driving MAM SSTA in the Southern Hemisphere extratropics.

One may imagine that the relative contributions of the DJF and MAM SAM–MAM SST could be found by directly calculating the correlation coefficients of MAM SST with the DJF and MAM SAM, respectively. Undoubtedly, this method is effective and concise in the absence of strong SST persistence, and is convenient for understanding the elementary features of the correlation between the SAM and SST. If we take the SST persistence into account and need to compare the role of the DJF and MAM SAM in regulating MAM SST, a comparison between this “direct” correlation of MAM SST with the DJF and MAM SAM may be not accurate enough. Although the direct correlation between the DJF SAM and MAM SST still reflects the “pure” linkage between them in view of their temporal leading relationship, the direct correlation between the MAM SAM and MAM SST may not reflect their real linkage, since the contemporaneous correlation is not equal to causality and the total MAM SST contains a persistent component caused by the DJF SAM (more details in sections 5a and 5b).

Combining statistics with physical process allows getting closer to causality. A more accurate understanding of the relative importance of the DJF and MAM SAM on MAM SST is facilitated by first figuring out the physical process through which the cross-seasonal influence of the DJF SAM on MAM SST occurs, and then by decomposing total MAM SST into persistent and non-persistent components. One way to conduct SST decomposition has been used in studies exploring the influence of the North Atlantic Oscillation (NAO) on Northern Hemisphere extratropical SST. For example, Wu et al. (2009b) estimated June–August (JJA) SSTA generated by the MAM and JJA NAO, and found that the MAM NAO is more important than the JJA NAO in driving triple-like JJA SSTA in the North Atlantic. In their work, they make a simple decomposition of JJA SST using unary linear regression, in which the dependent variable is JJA SST and the independent variable is MAM SST. Therefore, JJA SST is decomposed to a persistent component derived from MAM SST and a nonpersistent component independent of MAM SST (see Pan 2005; also see sections 4d and 5b in the current manuscript).

However, the above SST decomposition method did not consider the role of air–sea interaction in the cross-seasonal influence and cannot distinguish the persistent SST component related with one specific atmospheric factor (e.g., NAO or SAM) from the total persistent component. Therefore, we need to reconsider the physical process through which the cross-seasonal influence occurs under the framework of air–sea interactions, and to develop a new SST decomposition process for

distinguishing the persistent SST component related with a special atmospheric factor, here the SAM.

The aim of this work is to explore the relative importance of the DJF and MAM SAM in influencing southern extratropical MAM SST and develop a new process for accurately understanding their relative contribution. Taking into consideration that the zonal symmetric component is dominated in the SAM signal, the focus of the present study is the large-scale zonal-mean southern extratropical SSTA. The remainder of this paper is organized as follows. In [section 2](#), we introduce the data and basic statistical method. The direct correlation of the DJF and MAM SAM with contemporaneous SST and the cross-seasonal influence of the DJF SAM on MAM SST are analyzed in [section 3](#). In [section 4](#), we introduce three approaches used to detect the relative importance of the DJF and MAM SAM in influencing MAM SST, including a new SST decomposition approach named the persistent signal decomposition (PSD). In [section 5](#), three approaches are employed to quantify the relative importance of the DJF and MAM SAM in modulating MAM SST. Finally, a discussion and the conclusions are presented in [section 6](#).

2. Data and basic statistical methods

a. Data

This study focuses on the austral summer (DJF) and the following austral autumn (MAM) seasons, and the analysis period is from 1978/79 to 2011/12. In most cases, the variables were converted to seasonal means prior to analysis. We use atmospheric circulation data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis 1, with a resolution of $2.5^\circ \times 2.5^\circ$. The main variables employed are horizontal wind velocity, vertical velocity, geopotential height, and sea level pressure. The SST dataset is the Hadley Centre Sea Ice and SST dataset (HadISST), with a resolution of $1.0^\circ \times 1.0^\circ$.

We quantify the effect of the SAM by using the SAM index (SAMI) defined by [Nan and Li \(2003\)](#), which is the difference in normalized monthly zonally averaged sea level pressure between 40° and 70°S . This definition is widely used in research on the SAM and its climatic impact ([Nan et al. 2009](#); [Wu et al. 2009a](#); [Feng et al. 2010](#), [2013](#); [Li and Li 2012](#)).

The SAM-associated dipolelike SSTA pattern south of 30°S , referred to as the SOD, is expressed in terms of an index defined as the difference in normalized SST between 40° and 60°S . We choose these two latitudes because the zonal-mean SSTs are strongest anticorrelated here. The positive (negative) phase of the SOD denotes warmer

(cooler) SST in the southern middle latitudes and cooler (warmer) SST at high latitudes. In most areas north of 65°S , the sea ice melts completely in the seasons of interest (December–May). Therefore, in the definition of the SOD index (SODI), it is reasonable to choose 40° and 60°S and generally ignore the influence of sea ice.

The SAM, El Niño–Southern Oscillation (ENSO), and Southern Hemisphere extratropical SST are closely correlated in the austral warm seasons (e.g., [Karoly 1989](#); [Seager et al. 2003](#); [Zhou and Yu 2004](#); [Ciasto and Thompson 2008](#); [Simpkins et al. 2014](#); [Ciasto et al. 2015](#)). To explore the linkage among the SAM, ENSO, and southern extratropical SST, the Niño-3.4 index is used to represent the ENSO variability. The Niño-3.4 index is defined as the regionally averaged SST over 5°S – 5°N , 170° – 120°W .

b. Basic statistical methods

The linear regression analysis is the basis for the PSD. Standardized linear regression is adopted to explore linkage between the independent variables and the dependent variable. For two variables (x_1 and x_2), the standardized binary regression equation is expressed as

$$\hat{y} = b_1 x_1 + b_2 x_2, \quad (1)$$

where $\hat{y}$ is the fitting of the dependent variable y ; b_1 and b_2 are the standardized partial regression coefficients.

Note that we use standardized variables (x_1 , x_2 , y) to build the regression equation to remove the units of the predictors and the predictand. The standardized regression coefficients b_1 and b_2 are interpreted as change in the predictand, in standard deviations, per standard deviation change in the predictors, and thus can be used to determine the relative importance of the independent variables to the dependent variable y . The b_1 and b_2 in Eq. (1) can be estimated by least squares method and are calculated as follows:

$$b_1 = \frac{r_{yx_1} - r_{yx_2} r_{x_1 x_2}}{(1 - r_{x_1 x_2}^2)} \quad \text{and} \quad (2)$$

$$b_2 = \frac{r_{yx_2} - r_{yx_1} r_{x_1 x_2}}{(1 - r_{x_1 x_2}^2)}, \quad (3)$$

where r means correlation coefficient (e.g., r_{yx_1} indicates the correlation coefficient between y and x_1).

For Eq. (1), the regression variance s_y^2 by the regression equation can be calculated as

$$s_y^2 = b_1 r_{x_1 y} + b_2 r_{x_2 y}. \quad (4)$$

The explained variance by x_1 and x_2 in the total variance ($s_y^2 = 1$) can be calculated as

$$C_{x_1} = \frac{b_1 r_{x_1 y}}{s_y^2} \times 100\% = b_1 r_{x_1 y} \times 100\%, \quad (5)$$

$$C_{x_2} = \frac{b_2 r_{x_2 y}}{s_y^2} \times 100\% = b_2 r_{x_1 y} \times 100\%, \quad (6)$$

where the abbreviated notation C means contribution (explained variance).

Partial correlation is also adopted to estimate the pure connection between the predictor and the predictand after removing effect of other predictors. For two variables x_1 and y , the partial correlation after removing the effect of x_2 is calculated by the following formula:

$$r_{x_1 y, x_2} = \frac{r_{yx_1} - r_{yx_2} r_{x_1 x_2}}{\sqrt{(1 - r_{yx_2}^2)(1 - r_{x_1 x_2}^2)}}. \quad (7)$$

Similarly, the partial correlation between x_2 and y after removing the effect of x_1 can be expressed as

$$r_{x_2 y, x_1} = \frac{r_{yx_2} - r_{yx_1} r_{x_1 x_2}}{\sqrt{(1 - r_{yx_1}^2)(1 - r_{x_1 x_2}^2)}}. \quad (8)$$

A comparison between Eqs. (2) and (7) illustrates that partial regression coefficients and partial correlation coefficients are closely linked. The numerators in Eqs. (2) and (7) are the same, and both formulas measure the unique effect of x_1 on y ; the numerators in Eqs. (3) and (8) are the same, and both formulas measure the unique effect of x_2 on y .

The significance test of partial correlation coefficient (partial regression coefficient) is based on Student's t distribution:

$$t = \frac{r_{x_1 y, x_2}}{\sqrt{\frac{1 - r_{x_1 y, x_2}^2}{n - 3}}}, \quad (9)$$

where t follows Student's t distribution with degrees of freedom $n - 3$, and n is the size of the sample.

For variables characterized with strong autocorrelation, the effective degree of freedom (denoted by n^*) based on Davis (1976) and Chen (1982) is calculated as follows:

$$n^* = \frac{n}{T}, \quad (10)$$

$$T = \sum_{\tau=1}^{\tau=\text{lag}} R_{xx}(\tau) \times R_{yy}(\tau), \quad (11)$$

$$R_{xx}(\tau) = \frac{1}{n - \tau} \sum_{t=1}^{n-\tau} x_t^* \times x_{t+\tau}^*, \quad (12)$$

$$R_{yy}(\tau) = \frac{1}{n - \tau} \sum_{t=1}^{n-\tau} y_t^* \times y_{t+\tau}^*, \quad (13)$$

where the lag in Eq. (11) is usually taken as one-half of n , and the asterisks indicate standardized variables.

3. Connections between the SAM and SST

Before analyzing the relative importance of the DJF and MAM SAM on MAM southern extratropical SST, we review some basic features of the DJF and MAM SAM and their direct correlation with southern extratropical SST.

a. Basic features of the DJF and MAM SAM

The basic feature of the SAM is a foundation for us to understand its correlation with local SST. Figure 1a shows composite differences in the DJF zonal-mean zonal wind (contours) and meridional circulation (streamlines) between high and low SAM years. The high and low SAM years were selected based on the fluctuations of the SAMI beyond one standard deviation. A comparison with climatological DJF zonal-mean circulation (Fig. 1b) illustrates that the Ferrel cell is stronger and shows a slight shift toward the Antarctic in the positive phase of the SAM. Meanwhile, zonal wind through the whole troposphere in the high latitudes increase and that in the middle latitudes decrease, implying a poleward shift of the middle latitude westerly in the positive SAM phase (see also Gong and Wang 1999; Watterson 2000; Limpasuvan and Hartmann 1999; Thompson and Wallace 2000; Li and Wang 2003). Note that the zonal wind anomalies associated with the SAM in the high latitudes are stronger than that in the middle latitudes.

Similar analyses for the MAM are shown in Figs. 1c and 1d. The characteristics of circulation anomalies during the positive SAM phase in MAM are generally in accordance with those in DJF, which are featured by increased zonal wind in the high latitudes and decreased zonal wind in the middle latitudes. Similarly, the wind anomalies in the high latitudes are stronger than that in the middle latitudes.

b. Correlation between the SAM and contemporaneous SST

Changes in surface wind may alter local SST. Correlation coefficients between the SAM and contemporaneous zonal-mean SST in DJF and MAM are shown in Fig. 2a as the dotted and the dashed lines, respectively.

The common feature of the correlations in DJF and MAM is that there is positive correlation in the middle latitudes (48°–30°S) but negative correlation in the high latitudes (70°–52°S), indicating that positive (negative) phases of the SAM tend to cause cooler (warmer) SST in the high latitudes, but warmer (cooler) SST in the middle latitudes. Another common feature is that the

FIG. 1. (a) Composite difference in DJF zonal-mean zonal wind (m s^{-1} , contours) and meridional circulation (streamlines) between high and low DJF SAM years. The high and low SAM years were selected based on the fluctuations of the SAMI beyond one standard deviation. The gray shadings indicate the 95% significance level for zonal-mean meridional wind. The thick red lines in (a) [and (c)] indicate significance at the 95% confidence level for zonal-mean zonal wind. The black shadings show the zonal-mean surface pressure. (b) As in (a), but for the climatology. (c),(d) As in (a),(b), but for MAM season.

correlations in high latitudes are stronger than that in the middle latitudes. This similarity between the correlation patterns in DJF and MAM is reasonable because the zonal wind anomalies caused by the DJF and MAM SAM show a degree of consistency (Figs. 1a and 1c). One difference between these correlation patterns in DJF and MAM as shown in Fig. 2a is that the correlation in MAM is weaker than that in DJF. Another difference is that the negative-correlated region in MAM is narrower than that in DJF.

As noted before, this SAM-related dipolelike SSTA pattern in the southern extratropics is referred to as the SOD. The SODI is used to reflect the temporal variability of the SOD variability (details in section 2a). The correlation matrix between the SAMI and the SODI is shown in Table 1. It is found that the correlations between the SAMI and the contemporaneous SODI are 0.71 and 0.48 in DJF and MAM, respectively. Both of them are significant at the 95% confidence level, whereas the correlation in MAM is weaker than that in

DJF, which is in accordance with what has been shown in Fig. 2a.

Besides, the correlation maps of the SAM and SST on the horizontal plane in DJF and MAM are shown in Figs. 3a and 3c, respectively. In spite of the zonal asymmetry, the dipolelike SSTA pattern is also evident in DJF (Fig. 3a) but with a weaker strength in MAM (Fig. 3c). Note that there is zonal asymmetry of the correlation coefficients between the SAM and SST (see also Sen Gupta and England 2006). There are many interesting ideas that help us understand the deviations from zonal symmetry of the climate, but this is beyond the scope of the present study. We mainly concentrate on zonal-mean variability.

c. Removing the ENSO signal

The SAM and ENSO are closely correlated in the austral warm seasons (e.g., Karoly 1989; Seager et al. 2003; Zhou and Yu 2004; Ciasto et al. 2015). It can be seen in Table 1 that the correlation between the SAMI

FIG. 2. (a) Correlation coefficients between the SAM and southern extratropical zonal-mean SST. The dotted line indicates correlation between the DJF SAM and DJF SST, the solid line between the DJF SAM and MAM SAM, and dashed line between the MAM SAM and MAM SST. The crosses on the lines represent significance at the 95% confidence level. The gray areas indicate significance is at <80% confidence level for the correlation between the DJF SAM and MAM SST. (b) As in (a), but after removing the ENSO signals. For DJF SST, we remove the DJF ENSO signal and for MAM SST, both the DJF and MAM ENSO signals.

and ENSO is -0.41 in DJF, which is stronger than that in MAM (-0.31), further confirming the relationship between the SAM and ENSO as revealed by previous studies (Zhou and Yu 2004; Gong et al. 2010; Ding et al. 2011, 2012). In addition, there is also a close linkage between ENSO and Southern Hemisphere extratropical

SST. It can be seen in Table 1 that the correlation between ENSO and the SOD is -0.66 (-0.55) in DJF (MAM), which is consistent with previous studies (e.g., Ciasto and Thompson 2008; Ciasto et al. 2015). Therefore, it is necessary to verify that the correlation between the SAM and contemporaneous southern extratropical SST is not only a reflection of their connection with ENSO.

First, partial correlations were conducted to detect the connection between the SAMI and the SODI after removing the ENSO signal. The partial correlations between the SAMI and contemporaneous SODI in DJF and MAM after removing ENSO are 0.64 and 0.39 (Table 1), respectively. Compared with the raw correlation before removing the ENSO signal (0.71 and 0.48), the strengths of correlations weaken but are still significant at the 95% confidence level, implying the robustness of the linkage between the SAM and the SOD in DJF and MAM. Besides, the partial correlations between ENSO and the SOD also weaken from -0.66 to -0.58 in DJF and from -0.55 to -0.48 in MAM after removing the SAM signal. The above analyses illustrate that the correlations among the SOD, the SAM, and ENSO influence each other because of the linkage between the SAM and ENSO. The correlation between the SAM and contemporaneous SOD is still robust without the ENSO variability, implying their relationship is not only a reflection of ENSO influences.

In addition, similar correlation analyses as in Fig. 2a but after removing the ENSO signal are shown in Fig. 2b. For DJF SST, we remove the DJF ENSO signal. For MAM SST, we remove both the DJF and MAM ENSO signals. By a comparison between Figs. 2a and 2b, it is found that the correlations between the SAM and contemporaneous SST in DJF and MAM weaken after removing the ENSO signal. The decrease of correlation is stronger in the middle latitudes than that in the high latitudes, indicating that the perturbation of ENSO on the SAM-related SSTA is stronger in the middle latitudes than that in the high latitudes. Because the linkage between the SAM and the ENSO is stronger in DJF than that in MAM (Table 1),

TABLE 1. Correlation coefficient matrix between DJF SAMI, MAM SAMI, DJF SODI, MAM SODI, DJF ENSO, and MAM ENSO for the period 1978/79–2011/12. The italics indicate that the value is not significant at the 95% confidence level. The numbers in parentheses indicate partial correlation coefficients. For the SAM cases, partial correlation means removing the ENSO signal and for the ENSO cases, the SAM signal.

	DJF SAMI	MAM SAMI	DJF SODI	MAM SODI	DJF ENSO	MAM ENSO
DJF SAMI	1	0.39 (0.33)	0.71 (0.64)	0.61 (0.51)	-0.41	-0.43
MAM SAMI		1	0.21	0.48 (0.39)	-0.24	-0.31
DJF SODI			1	0.87 (0.80)	-0.66 (-0.58)	-0.59
MAM SODI				1	-0.58 (-0.45)	-0.55 (-0.48)
DJF ENSO					1	0.87
MAM ENSO						1

FIG. 3. (a) Correlation coefficients between the DJF SAM and DJF SST. (b) As in (a), but for the DJF SAM and MAM SST. (c) As in (a), but for the MAM SAM and MAM SST. The thick contour lines denote the 95% confidence level. (d)–(f) As in (a)–(c), but for the partial correlation after removing the ENSO signals. For DJF SST, we remove the DJF ENSO signal and for MAM SST, both the DJF and MAM ENSO signals.

the weakening of the correlation after removing the ENSO signal in Fig. 2b is more evident in DJF than that in MAM, both in the middle and high latitudes. However, in spite of the weakened strength, the dipolelike correlation patterns in DJF and MAM are still significant, indicating again that the correlation between the SAM and the contemporaneous SOD is not only a reflection of their relationship with ENSO.

Furthermore, we recalculate the correlation coefficients in Figs. 3a and 3c after removing the ENSO signal, and the results are showed in Figs. 3d and 3f. Compared with the zonal-mean component in Fig. 2, the changes in the zonal asymmetric component after removing ENSO signal (Fig. 3) are larger than that in the zonal-mean component (Fig. 2). This is possibly due to the fact that the zonal symmetric component is dominated in the SAM signal, while the influence of ENSO on SST is featured by stronger zonal asymmetry. Although removing the ENSO signal reduces the correlation between the SAM and

southern extratropical SST, the large-scale correlation patterns in Figs. 3d and 3f are generally consistent with that in Figs. 3a and 3c. The spatial correlations between Figs. 3a and 3d, 3c and 3f reach 0.8 and are significant at the 95% confidence level, indicating once more the robustness of correlation between the SAM and southern extratropical SST. There are many interesting ideas that help us understand the zonal asymmetry of the SSTA, but this is beyond the focus of the present study, which is the zonal-mean component of SSTA.

In short, although there are linkages between the SAM, ENSO, and the SOD, the connections between the SAM and the contemporaneous SOD in DJF and MAM still show robustness after removing the ENSO variability.

d. Cross-seasonal influence of the DJF SAM on MAM SST

As shown in Table 1, the cross-seasonal correlation between the DJF SAMI and MAM SODI is 0.61, which

TABLE 2. List of the primary abbreviations and their meanings in this study. Type reflects the part/method where the abbreviation appears. In particular, 1 indicates the general representation of the air–sea system; 2, the direct lead–lag correlation; 3, the SST decomposition based on the unary regression; and 4, the PSD.

Abbreviations	Type	Meanings
A	1	The large-scale atmospheric signal, which plays a dominant role in controlling large-scale SSTA pattern (S).
S	1	The large-scale SSTA pattern.
$t - 1, t$	1	Two adjacent seasons on the timeline.
$A(t)$	1	$A(t)$ can be separated to $A_P(t)$ and $A_H(t)$ under the framework of the PSD.
$S(t - 1)$	1	$S(t - 1)$ can be separated to $S_A(t - 1)$ and $S_R(t - 1)$ under the framework of the PSD.
a_P, C_P	2	The regression coefficient (a_P) of MAM SST on the DJF SAM and the corresponding explained variance (C_P). See Eqs. (25) and (27).
a_{HP}, C_{HP}	2	The regression coefficient (a_{HP}) of MAM SST on the MAM SAM and the corresponding explained variance (C_{HP}). See Eqs. (26) and (28).
$S_P(t)$	3	The persistent component in $S(t)$ derived from the SST decomposition based on the unary regression analysis. See Eq. (29).
$A_P(t), a_{AP}, C_{AP}$	4	$A_P(t)$ is the component associated with $A(t - 1)$; a_{AP} and C_{AP} are the partial regression coefficient and the explained variance corresponding to $A_P(t)$ in Eq. (18). See Eqs. (14), (18), and (23).
$A_H(t), a_{AH}, C_{AH}$	4	$A_H(t)$ is independent of $A(t - 1)$ and $A_P(t)$; a_{AH} and C_{AH} are the partial regression coefficient and the explained variance corresponding to $A_H(t)$ in Eq. (18). See Eqs. (15), (18), and (23).
$S_A(t - 1), a_{SP_A}, C_{SP_A}$	4	$S_A(t - 1)$ is the component caused by $A(t - 1)$; a_{SP_A} and C_{SP_A} are the partial regression coefficient and the explained variance corresponding to $S_A(t - 1)$ in Eq. (18). See Eqs. (16), (18), and (23).
$S_R(t - 1), a_{SP_R}, C_{SP_R}$	4	$S_R(t - 1)$ is independent of $A(t - 1)$ and $S_A(t - 1)$; a_{SP_R} and C_{SP_R} are the partial regression coefficient and the explained variance corresponding to $S_R(t - 1)$ in Eq. (18). See Eqs. (17), (18), and (23).
C_{AH_R}	4	The residual explained variance which cannot be explained by Eq. (18). Its calculation can be found in Eq. (24).

is significant at the 95% confidence level. The partial correlation after removing the ENSO signal is 0.51, which is still significant, verifying that the DJF SAM can imprint its signal on MAM SOD.

In addition, the cross-seasonal correlation between the DJF SAM and MAM zonal-mean SST is shown in Fig. 2a as the solid line. It can be seen that the DJF SAM is correlated with SST in the following MAM, and the dipolelike SOD pattern is evident. The similar cross-seasonal correlation between the DJF SAM and MAM zonal-mean SST after removing the ENSO signal is shown in Fig. 2b as the solid line. Although the strength of the correlation is weaker after removing the ENSO signal, the dipolelike SSTA is still clear, implying that the DJF SAM may imprint their signals on MAM SST without the effect of ENSO. Furthermore, Figs. 3b and 3e also illustrate the cross-seasonal linkage between the DJF SAM and MAM SST on the horizontal panel.

Above all, the MAM SAM is associated with MAM SOD; nevertheless, the DJF SAM may also regulate MAM SOD. Therefore, MAM SST field in the southern extratropics contains anomalies both from the DJF SAM and the MAM SAM. We next explore the relative importance of the DJF and MAM SAM in modulating MAM southern extratropical SSTA.

4. Methods to detect the relative importance of the DJF and MAM SAM in influencing MAM SST

The three approaches used to detect the relative importance of the DJF and MAM SAM in influencing MAM SST are introduced in this section, including the PSD (sections 4a and 4b), the direct lead–lag correlation (section 4c), and SST decomposition based on the unary regression method (section 4d). The results from these approaches are shown in section 5. The primary abbreviations and their meanings are listed in Table 2 for easy checking.

a. The framework of the PSD

The PSD is based upon a conceptual framework of simplified extratropical air–sea interactions on seasonal scale, shown schematically in Fig. 4, in which one large-scale atmospheric signal (A ; e.g., SAM) plays a dominant role in controlling large-scale SSTA pattern (S ; e.g., SOD). The downward arrows indicate the influence of A on S , and the upward dashed arrows denote the feedback of S on A . The $t - 1$ and t indicate two adjacent seasons on the timeline. Here, these two seasons are the DJF and the following MAM. The horizontal arrows represent the persistence of A and S . The persistence of SST is well established, as aforementioned in section 1.

FIG. 4. Schematic of the persistent signal decomposition (PSD). Here A and S represent the dominant atmospheric signal (e.g., SAM) and the corresponding SSTA pattern (e.g., SOD), respectively. The $t-1$ and t indicate two consecutive seasons on the timeline. The horizontal arrows represent the persistence of A and S . The downward arrows indicate the influence of A on S and the upward dashed arrows denote feedback of S on A . The symbols $[A(t-1), A(t), S(t-1), \text{ and } S(t)]$ in the small blue shaded boxes represent raw signals before decomposition. The meanings of the abbreviations $[A_P(t), A_H(t), S_A(t-1), S_R(t-1), a_{AP}, a_{AH}, a_{SP_A}, a_{SP_R}, C_{AP}, C_{AH}, C_{SP_A}, \text{ and } C_{SP_R}]$ and the formula are in section 4.

The persistence of the SAM is also taken into consideration because its autocorrelation is significant. The autocorrelation between the DJF SAM and MAM SAM is shown in Table 1, which is 0.39 and is significant at the 95% confidence level. Although the persistence of the SAM on a daily scale is only several days (Ciasto and Thompson 2008), its intraseasonal autocorrelation is relatively strong. Many low-frequency modes have statistically significant persistence at interseasonal scale as revealed by previous studies (e.g., Barnston and Livezey 1987). The mechanism of the interseasonal persistence of the SAM is, however, beyond the scope of this study.

In Fig. 4, the $A(t)$ can be separated to two independent parts. The first part $A_P(t)$ is associated with $A(t-1)$ due to signal persistence, and the subscript P means persistence;

the second part $A_H(t)$ is independent of $A(t-1)$ and $A_P(t)$, and the subscript H represents homochronous or contemporaneous. Based on standardized regression equation, $A_P(t)$ and $A_H(t)$ are expressed as

$$A_P(t) = b_1 A(t-1) \quad \text{and} \quad (14)$$

$$A_H(t) = A(t) - A_P(t), \quad (15)$$

where b_1 is the regression coefficient between $A(t)$ and $A(t-1)$.

The $S(t-1)$ can be also separated into two independent parts, $S_A(t-1)$ caused by $A(t-1)$, and the residual part, $S_R(t-1)$, which is independent of $A(t-1)$ and $S_A(t-1)$. The subscript A in $S_A(t-1)$ represents

component associated with the atmospheric signal $A(t-1)$, and the subscript R in $S_R(t-1)$ means the residual part which is not associated with $A(t-1)$. Similarly, based on standardized regression equation, $S_A(t-1)$ and $S_R(t-1)$ are expressed as

$$S_A(t-1) = c_1 A(t-1) \quad \text{and} \quad (16)$$

$$S_R(t-1) = S(t-1) - S_A(t-1), \quad (17)$$

where c_1 is the regression coefficient between $A(t-1)$ and $S(t-1)$.

It is evident in Fig. 4 that the cross-seasonal influence of $A(t-1)$ on $S(t)$ occurs in two ways. One is through the persistence of the atmospheric variable $A(t-1)$, which imprints its signal on $S(t)$ through $A_P(t)$. The second is through the persistence of SST $S(t-1)$, which imprints its signal on $S(t)$ through $S_A(t-1)$. Both the persistence of SST and the atmospheric signal are taken into consideration for the cross-seasonal influence of $A(t-1)$ on $S(t)$.

Based on the above analyses, $S(t)$ can be expressed by a quaternion standardized regression equation:

$$\hat{S}(t) = a_{AH}A_H(t) + a_{AP}A_P(t) + a_{SP_A}S_A(t-1) + a_{SP_R}S_R(t-1), \quad (18)$$

where $\hat{S}(t)$ is the fitting of $S(t)$ by the linear regression; and a_{AH} , a_{AP} , a_{SP_A} , and a_{SP_R} are the standardized partial regression coefficients.

b. The calculation of the PSD

To quantify the contribution of different terms on the right-hand side of Eq. (18) to $S(t)$, one way is to calculate the regression coefficient (a_{AH} , a_{AP} , a_{SP_A} , and a_{SP_R}) and their corresponding explained variances. However, calculating the regression coefficients in multiple regression equation requires a matrix solution and is relatively complex. To simplify the calculation procedure for the regression coefficient (a_{AH} , a_{AP} , a_{SP_A} , and a_{SP_R}) and their corresponding explained variances, we first simplify the quaternion regression equation in Eq. (18). It is easy to know from Eqs. (14) and (15) that $A_H(t)$ and $A_P(t)$ are independent of each other. Similarly, $S_A(t-1)$ and $S_R(t-1)$ are independent according to Eqs. (16) and (17). Besides, it can be inferred that $A_H(t)$ and $S_A(t-1)$ are independent, and $A_P(t)$ and $S_R(t-1)$ are also independent. Therefore, to conveniently calculate the regression coefficients, we can simplify the quaternion regression equation in Eq. (18) to two binary linear standardized regressions:

$$\tilde{S}(t) = a_{AP}A_P(t) + a_{SP_A}S_A(t-1) \quad \text{and} \quad (19)$$

$$\hat{S}(t) = a_{AH}A_H(t) + a_{SP_R}S_R(t-1), \quad (20)$$

where $\tilde{S}(t)$ and $\hat{S}(t)$ are the fittings of $S(t)$ by Eqs. (19) and (20), respectively. Although the fittings of $S(t)$ by Eqs. (19)–(20) are different from that by Eq. (18), the standardized regression coefficients (a_{AH} , a_{AP} , a_{SP_A} , a_{SP_R}) by the least squares method from Eqs. (18)–(20) are the same. For brevity, we use $\tilde{S}(t)$ to represent the fitting of $S(t)$ in the following analysis. Note that the $\tilde{S}(t)$ by different regression equations may be different. Furthermore, given that the variables in Eq. (19), $A_P(t)$ and $S_A(t-1)$, are highly correlated with each other, it is impossible to calculate a_{AP} and a_{SP_A} because the denominators in Eqs. (2) and (3) are almost equal to zero. We further make a transformation of Eq. (19) to two equations to calculate a_{AP} and a_{SP_A} separately:

$$\tilde{S}(t) = a_{AP}A_P(t) + a'S(t-1) \quad \text{and} \quad (21)$$

$$\tilde{S}(t) = a'A(t) + a_{SP_A}S_A(t-1). \quad (22)$$

Therefore, we can calculate a_{AH} , a_{AP} , a_{SP_A} , and a_{SP_R} based on the simplified binary regression equations in Eqs. (20)–(22) rather than based on the quaternion regression equation in Eq. (18). The solutions to standardized binary regression coefficients can be found from Eqs. (2) and (3), and the corresponding explained variances are shown in Eqs. (5) and (6).

The explained variances of a_{AH} , a_{AP} , a_{SP_A} , and a_{SP_R} are referred to as C_{AH} , C_{AP} , C_{SP_A} , and C_{SP_R} . The total explained variance of $S(t)$ is separated to the following parts:

$$\text{Var}[S(t)] = C_{AH} + C_{AP} + C_{SP_A} + C_{SP_R} + C_{AH_R}, \quad (23)$$

where Var means variance, and C_{AH_R} represents the residual explained variance that cannot be explained by Eq. (18), which indicates the contribution from other contemporaneous influencing factor of $S(t)$ rather than $A(t)$. The subscript R means the residual part that is not associated with the atmospheric factor A . The C_{AH_R} is calculated as follows:

$$C_{AH_R} = \text{Var}[S(t)] - C_{AH} - C_{AP} - C_{SP_A} - C_{SP_R}. \quad (24)$$

The other terms on the right side of Eq. (24) have the following meanings:

- 1) C_{AH} represents the component that is induced by the homochronous influence of $A_H(t)$ on $S(t)$ without any contribution from the persistent component.
- 2) C_{AP} and C_{SP_A} are associated with the persistence of $A(t-1)$ and $S(t-1)$, respectively, and reflect the two ways in which the cross-seasonal influence of $A(t-1)$ on $S(t)$ can occur. The sum of these two

terms describes the total cross-seasonal influence of $A(t-1)$ on $S(t)$.

- 3) C_{SP_R} is the component caused by persistence of SSTA that is not associated with $A(t-1)$.

Detecting the relative importance of the DJF and MAM SAM in modulating MAM SST, which is the focus of our work, can be regarded as a comparison between contribution of C_{AH} and the sum of C_{AP} and C_{SP_A} to total MAM SST.

c. Lead-lag correlation

The direct correlations of MAM SST with the DJF and MAM SAM are equal to the regression coefficients in the following standardized unary regression equations:

$$\tilde{S}(t) = a_P A(t-1) \quad \text{and} \quad (25)$$

$$\tilde{S}(t) = a_{HP} A(t), \quad (26)$$

where a_P and a_{HP} are the standardized regression coefficients, and other symbols have the same meanings as in previous sections. The subscript P indicates persistence, and the subscript HP means component including both homochronous and persistent signals. The explained variances corresponding to a_P and a_{HP} are expressed as follows:

$$C_P = a_P^2 \quad \text{and} \quad (27)$$

$$C_{HP} = a_{HP}^2. \quad (28)$$

As aforementioned before, a_P (C_P) is used to reflect the linkage between $A(t-1)$ and $S(t)$ in the direct lead-lag correlation. Compared with the PSD, it is found that the C_P can be treated as a combination of C_{AP} and C_{SP_A} , indicating that the cross-seasonal connection between $A(t-1)$ and $S(t)$, C_P , is a combination of the atmospheric persistence (C_{AP}) and SST persistence (C_{SP_A}). Hence, the ways to quantify the cross-seasonal influence of $A(t-1)$ on $S(t)$ are consistent in the direct lead-lag correlation (C_P) and in the PSD (the sum of C_{AP} and C_{SP_A}); only the PSD can distinguish the persistence caused by the atmosphere (C_{AP}) and that by the SST (C_{SP_A}). However, one of the significant difference between the PSD and the direct lead-lag correlation is the way to quantify the homochronous influence of $A(t)$ on $S(t)$. In particular, the direct lead-lag correlation uses a_{HP} (C_{HP}) to reflect this homochronous influence, while the PSD uses a_{AH} (C_{AH}). The a_{AH} (C_{AH}) in the PSD only contains the homochronous component by conducting SST decomposition, while the a_{HP} (C_{HP}) contains a persistent component caused by the $A(t-1)$. Therefore, a_{AH} (C_{AH}) from the PSD is more accurate in reflecting the homochronous linkage between $A(t)$ and

$S(t)$. It will be shown in section 5c that a_{AH} (C_{AH}) is indeed different from a_{HP} (C_{HP}).

d. SST decomposition based on unary regression

The unary regression method is employed to decompose the MAM SST to a persistent component related to DJF SST and a nonpersistence component. The persistent component of the $S(t)$, referred to as $S_P(t)$, can be calculated according to the following formula:

$$S_P(t) = q_1 S(t-1), \quad (29)$$

where q_1 is the regression coefficient between $S(t)$ and $S(t-1)$. Dividing both sides of Eq. (29) by $S(t-1)$ and multiply by 100%, we get

$$\frac{S_P(t)}{S(t-1)} \times 100\% = q_1 \times 100\% = \text{pr}_1, \quad (30)$$

where pr_1 indicates the percentage of the $S(t-1)$ that can persist to the following time t in the total $S(t-1)$. In addition, we can calculate the percentage of persistent component $S_P(t)$ in the $S(t)$:

$$\frac{S_P(t)}{S(t)} \times 100\% = \text{pr}_2, \quad (31)$$

where this percentage is referred to as pr_2 .

The difference between the above unary regression and the PSD is the way to conduct SST decomposition. The unary regression cannot distinguish the persistent SST component related with one specific atmospheric factor from the total persistent component, while it will be shown in section 5c that the PSD could separate the SAM-related SST persistence from the total SST persistence.

5. Results

a. Lead-lag correlation

The lead-lag correlation coefficients of the MAM SODI with sea level pressure are shown in Fig. 5. The correlated sea level pressure field shows a positive SAM phase from a lead of -4 months through 0 month (Figs. 5a–d). The SAM patterns of the correlation coefficients reach a maximum at a -3 -month lead (i.e., sea level pressure leads by 3 months; Fig. 5b), and then continuously decrease from a -2 -month lead (Fig. 5c) to a 0-month lead (Fig. 5e). It indicates that SAM-like atmospheric anomalies in DJF could produce a dipolelike SSTA pattern in MAM. However, the correlation between the MAM SOD and MAM sea level pressure shows a weaker SAM-like pattern (Figs. 5d–f). The

FIG. 5. Lead-lag correlation between the MAM SODI and sea level pressure for values of the lag between (top left) -4 and (bottom right) $+4$ months. The lag values decrease by one month in each case and the sea level pressure in (a) leads the SODI by 4 months and in (i) lags by 4 months.

similar analyses after removing the ENSO signal not change much (not shown).

b. SST decomposition based on unary regression

To explore the percentage of the $S(t - 1)$ that can persist to the following time t in the total $S(t - 1)$, the pr_1 is shown in Fig. 6a as the black solid line. It is found that more than 50% of the total DJF SSTA persists into the following MAM over most of the southern extratropics. In particular, the percentage can reach about 60% in the bands between 50° – 20° S and 70° – 65° S. These results imply the strong persistence of the DJF extratropical SSTA. The results of pr_2 are shown in Fig. 6b as the

black solid line. The persistent component derived from the DJF SST accounts for more than 50% in the total variability of southern extratropical MAM SSTA. In particular, the pr_2 is relatively larger in the bands 70° – 60° S and 40° – 25° S. Combined with Fig. 6a, it is found that a large part of DJF SSTA can persist to the MAM (Fig. 6a), and these persistent component indeed take a large part in total MAM SSTA (Fig. 6b).

Given that Ciasto and Thompson (2008) revealed that ENSO contributes to the persistence of SAM-related southern extratropical SSTA, similar analyses for pr_1 and pr_2 after removing the ENSO signals are shown in Figs. 6a and 6b as the red dotted–dashed lines. For DJF

SST, we remove the DJF ENSO signal. For MAM SST, we remove both the DJF and MAM ENSO signals. It can be seen that after removing the ENSO signal, the pr_1 did not change much. In most regions, the changes are less than 5%. The weakening of pr_2 is about 10%. This illustrates that ENSO indeed contributes to the DJF SST persistence after removing the ENSO signal. Although there is a weakening of persistence, the pr_2 is still evident only decreasing about 10%. In most latitudes, the pr_2 is still larger than 50% after removing the ENSO signal.

According to Eq. (29), we can isolate the persistent component $S_p(t)$ from the total MAM SST. The correlation between the persistent component in MAM SST and the MAM SAM is shown in Fig. 6c as the black dotted–dashed line. Meanwhile, the correlation of total MAM SST with the MAM SAM is also shown in Fig. 6c as the black dashed line, which is same as the black dashed line in Fig. 2a (a_{HP}). It can be seen that the persistent component contributes to the direct correlation between the MAM SAM and total MAM SST (a_{HP}). In the region between 70° and 51°S and between 43° and 20°S, the sign of these two correlations are the same implying the positive contribution of the persistent component. However, in the region between 51° and 43°S, the sign of these two correlations are opposite implying the negative contribution of the persistent component.

The reason for the negative contribution may be related to the fact that the signs of the correlation patterns between the SAM and SST in DJF and MAM are opposite in the regions where the negative contribution occurs (Fig. 2a). Regardless of whether the contribution is positive or negative, it is known from Fig. 6c that the persistent component indeed contributes to the direct correlation between the MAM SAM and total MAM SST (a_{HP}), and thus this direct correlation (a_{HP}) may not reflect the real linkage between the MAM SAM and MAM SST, because the total MAM SST contains a persistent component caused by the DJF SAM [$S_p(t)$ as shown in Eq. (29)]. By a comparison between Fig. 6b and 6c, it is found that the contribution of the persistent component in Fig. 6c is larger in the regions where the pr_2 is stronger as shown in Fig. 6b (70°–60°S and 40°–25°S).

The red lines in Fig. 6c are similar to the black lines but after removing the ENSO signals. As previous studies have pointed out, ENSO contributes to the persistence of SAM-related southern extratropical SST (Ciaffaglia and Thompson 2008). Removing the ENSO signal indeed impairs the contribution of the persistent component in the direct correlation between the MAM SAM and MAM SST. Generally, in regions with stronger decrease in the correlation between the MAM SAM

FIG. 6. (a) Percentage of persistent component in total DJF SST (pr_1). (b) Percentage of persistent component in total MAM SST (pr_2). (c) Correlation coefficients of the MAM SAM with MAM total SST (dashed) and the MAM persistent component SST (dotted–dashed). The black (red) lines in (a), (b) are the raw (after removing the ENSO signals) results. For DJF SST, we remove the DJF ENSO signal and for MAM SST, both the DJF and MAM ENSO signals. The plus symbols in (c) represent the 95% confidence level. The gray areas in (c) indicate that the significance is at the <80% confidence level for the correlation between the DJF SAM and MAM SST.

and MAM persistent SST, the decrease in the correlation between the MAM SAM and MAM total SST is also stronger, indicating the importance of the persistent component in total MAM SST.

Through the above method in Eqs. (29)–(31), we can quantize the strength of the persistence by decomposing total MAM SST into the persistent component derived from DJF SST and the nonpersistent component independent of DJF SST. The results show that the persistent component indeed contributes to the direct correlation between the MAM SAM and MAM total SST (a_{HP}), implying that this direct correlation (a_{HP}) may not reflect the real linkage between the MAM SAM and MAM SST. However, the above method does not consider air–sea interaction and cannot distinguish the persistence of SST that is induced by a specific

atmospheric factor (e.g., SAM). Therefore, the PSD is developed for distinguishing the persistent SST component related to a special atmospheric factor, here the SAM.

c. Persistent signal decomposition

The results based on the PSD are shown in Fig. 7. Under the framework of the PSD, a_{AH} [Eq. (18)] is used to reflect a more “accurate” homochronous linkage between the MAM SAM and MAM SST rather than the direct regression a_{HP} [Eq. (26)]. As noted in section 4, a_{AH} only contains the homochronous component, whereas a_{HP} contains both homochronous and persistent signals. To intuitively explore the difference between a_{AH} and a_{HP} , they are shown together in Fig. 7a as the yellow solid and the black dashed line. It is clearly evident that a_{AH} is indeed different from a_{HP} . There is $|a_{HP}| > |a_{AH}|$ in most regions, indicating that the persistent component makes a positive contribution to the direct correlation between the MAM SAM and MAM SST (a_{HP}). However, there is $|a_{HP}| < |a_{AH}|$ in regions between 50° and 43°S, indicating the negative contribution of the persistent component. The above results about the sign of the contribution of the persistent SST are consistent with Fig. 6c (details in section 5b).

The a_P [Eq. (25)] reflects the influence of the DJF SAM on MAM SST, and it is also shown in Fig. 7a as black solid line. Detecting the relative importance of the DJF and MAM SAM in modulating MAM SST, which is the focus of our work, can be regarded as a comparison between a_P (C_P) and a_{AH} (C_{AH}). It can be seen that there is $|a_P| > |a_{AH}|$ at most latitudes, indicating that the influence of DJF SAM on southern extratropical MAM SST is stronger than that of the MAM SAM. To more clearly show this relative contribution, we investigate the corresponding explained variances, C_P and C_{AH} , which are shown in Fig. 7c. Similarly, there is $|C_P| > |C_{AH}|$ at most latitudes, revealing that the influence of the DJF SAM on MAM SST is greater than that of the MAM SAM. This is especially the case in the high latitudes. The DJF SAM plays a more important role in driving MAM dipolelike SSTA in the southern extratropics.

To further explore the role of atmosphere persistence and SST persistence in the cross-seasonal influence, the a_{SP_A} and a_{AP} are shown in Fig. 7b as the green and blue lines. It is found in Fig. 7b that there is $|a_{SP_A}| > |a_{AP}|$ at most latitudes, implying that the cross-seasonal influence of the DJF SAM on MAM SST is mainly caused by the SST persistence (a_{SP_A}), with a smaller contribution from the persistence of SAM (a_{AP}). The a_{AP} is very weak at most latitudes, indicating that there is almost no evident relationship between DJF SAM and MAM SSTs

FIG. 7. The results from the PSD: (a) a_P , a_{AH} , and a_{HP} ; (b) a_P , a_{SP_A} , and a_{AP} ; and (c) C_P , C_{AH} , C_{SP_R} , and C_{AH_R} . The plus symbols represent the 95% confidence level. The gray areas indicate that the significance is at the <80% confidence level for the correlation between the DJF SAM and MAM SST.

if the SST persistence is removed. Thus, the ocean memory effect should be regarded as the crucial factor responsible for the cross-seasonal influence of the DJF SAM on MAM SST.

Furthermore, the C_{SP_R} and C_{AH_R} are shown in Fig. 7c as the gray solid line and the gray dotted line. As we mentioned before, the subscript R in C_{SP_R} and C_{AH_R} means the residual parts, which are generally not associated with the atmospheric factor A (here the SAM). Specifically, the C_{SP_R} is the component caused by persistence of SSTA, which is not associated with $A(t-1)$, and the C_{AH_R} represents the contribution from other contemporaneous influencing factors rather than

FIG. 8. Explained variances of the DJF SAM-related SSTA [$S_A(t-1)$; black line] and the residual component independent of the DJF SAM [$S_R(t-1)$; gray line] in total DJF SST [$S(t-1)$]. The plus symbols represent the 95% confidence level. The gray area indicates that the significance is at the $<80\%$ confidence level for the correlation between the $S_A(t-1)$ and $S(t-1)$.

$A(t)$. It can be seen in Fig. 7c that the C_{SP_R} is very strong in most regions in the southern extratropics, which is even stronger than the SAM-related terms C_P and C_{AH} at most latitudes. In view of the high consistency between C_{SP_R} and a_{SP_R} (see Fig. S1 in the supplementary material), it is reliable that a_{SP_R} is also stronger than a_P and a_{AH} . The reason behind this is that the SAM is not the only factor that could influence southern extratropical SST, and the residual factors that could modulate southern extratropical SST cover a considerably wide range (e.g., oceanic eddies; Screen et al. 2009). For convenience, we treat the influence of the residual factors as a whole and show the explained variances of these residual factors [taken as $S_R(t-1)$] and that of the DJF SAM-related SSTA [taken as $S_A(t-1)$] in total DJF SST [taken as $S(t-1)$] in Fig. 8. It can be seen that DJF SAM-related SSTA account for about 40% in the total variance of the DJF SST at around 40° and 60°S. In the regions at around 50°S, the explained variance by the DJF SAM-related SSTA is nearly zero. The $S_R(t-1)$ includes the contributions from all other factors that could influence southern extratropical SST except for the SAM. The explained variance from $S_R(t-1)$ is greater than that from the SAM-related $S_A(t-1)$. Therefore, it is reasonable that the C_{SP_R} is stronger than the contribution from the SAM-related terms C_P and C_{AH} .

Finally, Fig. 9 is similar to Fig. 7, but only after removing the ENSO signal. Comparing Figs. 7a and 9a and Figs. 7b and 9b, it is found that removing the ENSO signal almost has no effect on a_{AH} and a_{AP} . As reveal by Ciasto and Thompson (2008), ENSO contributes to the persistence of the SAM-related southern extratropical SST. In the PSD, the a_{SP_A} is a reflection of the role of SST persistence. It can be seen from Fig. 9b that removing the ENSO signal indeed impairs the a_{SP_A} . The decrease of a_{SP_A} is stronger in the middle latitudes than that in the high latitudes, indicating that the perturbation of ENSO on the persistence of SAM-related SSTA is stronger

FIG. 9. As in Fig. 7, but after removing the ENSO signals. For DJF SST, we remove the DJF ENSO signal and for MAM SST, both the DJF and MAM ENSO signals.

in the middle latitudes than that in the high latitudes. Although ENSO contributes to the persistence of the SAM-related SSTA, it is evident from Fig. 9c that there is still $|C_P| > |C_{AH}|$ at most latitudes, especially in the high latitudes. These results illustrate again that the influence of the DJF SAM on MAM SOD is greater than that of the MAM SAM.

6. Conclusions and discussion

In this work, we propose a new calculating process under the framework of extratropical air–sea interactions for exploring the relative importance of the DJF and MAM SAM in influencing the MAM southern

extratropical SST. It is found that the DJF SAM plays a more important role than the MAM SAM in modulating the large-scale dipolelike MAM SSTA in the southern extratropics, implying that the DJF SAM and associated SSTA can be regarded as effective predictors for the following season's climate because the MAM SSTA caused by the DJF SAM would not be largely perturbed.

Note that this conclusion concentrates on the large-scale zonal-mean southern extratropical SSTA. As previously mentioned, there is zonal asymmetry of the correlation coefficients between the SAM and SST, and the MAM SAM may be dominant in influencing spring SST in some specific locations. In addition, the seasonal dependence of the persistence of large-scale SSTA is well established, and is usually linked with the depth of the ocean mixed layer (Screen et al. 2009; Ciasco et al. 2011). Considering the seasonal variation in SST persistence, although the preceding SAM is more important than the contemporaneous SAM in influencing MAM SST, the relative importance of the preceding and contemporaneous SAM in modulating SST in other seasons should be investigated further.

Compared with traditional SST decomposition, the new calculating process proposed here, the PSD, takes the extratropical air–sea interactions into account and provides a more detailed decomposition of total SST. On the one hand, the PSD can detect the SST persistence associated with one specific atmospheric factor. The PSD detects persistent SST that is closely related to the dominant atmospheric signal (C_{SP_A}), instead of treating C_{SP_A} and C_{SP_R} together. In fact, it is found that C_{SP_R} (a_{SP_R}) is a very large term, which reflects the strong persistence of SSTA that is not related to the SAM. This is because other factors apart from the SAM could also modulate southern extratropical SST. The C_{SP_R} (a_{SP_R}) reflects a combination of the SSTA persistence caused by all these residual factors, which cover a considerably wide range (e.g., oceanic eddies; Screen et al. 2009). On the other hand, the PSD distinguishes the persistence of the dominant atmospheric signal (C_{AP}) from that of SST (C_{SP_A}). Our results show that the cross-seasonal influence of the DJF SAM on spring SST is mainly caused by the persistence of SST (C_{SP_A}). The persistence of the SAM (C_{AP}) plays a limited role.

The detection of the relative importance of the preceding and contemporaneous atmospheric signal in driving SSTA has more general applicability. It can contribute to our understanding of air–sea interactions and help to obtain better SST-based statistical predictions, because the persistent component originating in the preceding season has the potential to be used as a predictor. Detecting persistent and nonpersistent SSTA originating in different

seasons is a general question in the “ocean–atmosphere coupled bridge” (Zheng and Li 2012; Li et al. 2013a; Zheng et al. 2013), in which the ocean memorizes the signal of the large-scale atmospheric circulation as SSTA, which persists to the following season, alters the atmospheric circulation, and finally influences local and remote climate. Detecting persistent and nonpersistent SSTA originating in different seasons is also a general question in the “seasonal footprinting mechanism” (Vimont et al. 2001, 2003; Alexander et al. 2010), which can be summarized as follows. During the winter season, intrinsic atmospheric variability (North Pacific Oscillation) imparts an SST footprint onto the ocean. This SST footprint persists into the late spring and summer seasons, which in turn, forces a pattern of atmospheric circulation anomalies (e.g., zonal wind stress anomalies along the equator) and finally produces an ENSO-like pattern of variability. In the ocean–atmosphere coupled bridge and seasonal footprinting mechanism, the persistence of SST provides an important source of predictability, and thus it is necessary to explore the relative importance of the atmospheric signal in different seasons in influencing the SSTA.

Except for the influence of DJF SAM on southern China MAM precipitation, other cross-seasonal teleconnection that are based on the ocean–atmosphere coupled bridge can be found in the influence of the MAM NAO on East Asian summer monsoon (Wu et al. 2009b) and in the connection between the June–August (JJA) NAO and September–November (SON) precipitation over central China (Xu et al. 2013). The North Atlantic SST has important implications for statistical seasonal prediction in many regions of the world (Rodwell et al. 1999; Pan 2007; Wu et al. 2009b, 2012; Li et al. 2013b; Zuo et al. 2013). To obtain better statistical predictions based on the North Atlantic SST, it is helpful to conduct signal decomposition to explicitly detect the origination of the SSTA. The PSD has the potential to be employed in the North Atlantic and other extratropical oceans.

There are also some limitations to the PSD. Note that the PSD only considers two consecutive seasons when carrying out SST decomposition (Fig. 4). Actually, $S(t)$ may also contain SSTA associated with $A(t - 2)$. When carrying out the decomposition for $S(t)$ in the present study, given that influence of the SON SAM on MAM SOD is relatively weak (not shown), we did not single out the role of the SON SAM, and its influence is actually included in C_{SP_R} . In addition, the schematic of PSD in Fig. 1 is a simplification of the complex extratropical air–sea interaction system with persistent features. The PSD only considers the one-way influence of the atmospheric signal on SST. This assumption is regarded as relatively reliable in the extratropics for the

large-scale SST anomaly pattern, but is not appropriate in the tropics where the ocean has strong feedback effects on the atmospheric circulation. Some recent meaningful researches have paid attention to the feedback of SSTA pattern on the atmospheric mode in the extratropics (Sen Gupta and England 2007). Although this feedback is generally weaker than the influence of the atmospheric mode on SST in the extratropics, the feedback of SAM-related SSTA on SAM contributes to the persistence of the SAM (Sen Gupta and England 2007). Further analyses are needed to enrich the framework of the PSD and take into account the feedback of the SSTA on the atmospheric signal.

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