Simultaneous influence of the Southern Hemisphere annular mode on the atmospheric circulation of the Northern Hemisphere during the boreal winter

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This study has discovered a significant linear relationship between the Southern Hemisphere (SH) annular mode (SAM) and the mid-latitude Northern Hemisphere (NH) circulation in February using two reanalysis data sets. Significant positive height anomalies corresponding to the positive SAM appear over the mid-latitude region of the NH, and significant positive surface air temperature anomalies prevail over Western Europe and Northeast Asia. The realistic vorticity forcing associated with the SAM is applied in a dry linear baroclinic model, and the results demonstrate that the SAM in February can induce height anomalies with the same sign at 300 hPa over the mid-latitudes of the NH and that these anomalies have amplitudes as large as 22% of their counterparts in the SH. Further numerical experiments show that the positive height response over the mid-latitudes of the NH mainly comes from the influence of the realistic positive vorticity over the mid-latitudes of the SH and that the vorticity forcing over the southern Indian Ocean seems to be the most effective at exciting the NH circulation anomalies. The numerical experiments also demonstrate that the transient eddy feedback forcing contributes to the formation of mid-latitude NH circulation anomalies, especially over Northeast Asia. The maintenance of the negative vorticity anomalies over Europe is further diagnosed through vorticity budget analysis. In December, however, the significant vorticity anomalies associated with the SAM are not limited to the middle and high latitudes of the SH but also appear over the subtropics of the SH (approximately 30°S). The numerical experiments show that cancelling occurs between the responses to the subtropical vorticity forcing and the mid-latitude vorticity forcing, thereby accounting for the independence of the NH circulation from the December SAM variability.

KEYWORDS
cross-hemisphere influence, Southern Hemispheric annual mode, vorticity forcing

1 | INTRODUCTION

The Southern Hemisphere (SH) annular mode (SAM) is a hemisphere-scale anomalous atmospheric circulation pattern that is also known as the Antarctic oscillation (AAO). The positive SAM phase exhibits an annular feature in the horizontal direction that is characterized by a high-pressure belt across Chile and Argentina and low-pressure areas over the Weddell Sea and the Bellinghausen Sea (Gong and Wang, 1999; Wallace, 2000; Li and Wang, 2003). In the vertical direction, the SAM shows a barotropic structure throughout the troposphere (Gong and Wang, 1999;
Trenberth et al. (2005) investigated the interannual variability of the global atmospheric mass patterns and found that the dominant global monthly variability was associated with the SAM. Dynamically, the SAM is mainly an internal atmospheric model that is forced by high-frequency eddy forcing (Limpasuvan and Hartmann, 1999; Limpasuvan and Hartmann, 2000), while the El Niño Southern Oscillation (ENSO) can explain approximately 25% of the interannual variance in the boreal winter SAM (L'Heureux and Thompson, 2006). In the SH, the SAM is the most important mode of atmospheric circulation and has large influences on the local climate, including Antarctic sea ice (Yuan and Li, 2008), Antarctic surface temperature (Marshall and Bracegirdle, 2015) and rainfall over Australia, South Africa and South America (Silvestri and Vera, 2003; Hendon et al., 2007). Moreover, recent studies have shown that the SAM can also affect the frequencies of tropical cyclones (Choi et al., 2014a; 2014b) and blocking events (Mendes and Cavalcanti, 2014).

In fact, the SAM not only influences the SH climate but is also significantly correlated with particular anomalous circulation patterns in the Northern Hemisphere (NH) in every season. For example, the boreal spring SAM is significantly correlated with the summer rainfall over China (Nan and Li, 2003; Xue et al., 2003), South Africa (Sun et al., 2010) and North America (Sun, 2010). The August SAM is simultaneously and positively correlated with rainfall in North Korea (Choi et al., 2014a; 2014b). The boreal autumn SAM can lead to anomalous NH temperatures in boreal winter (Wu et al., 2009), and the boreal winter SAM has a significant negative relationship with winter precipitation (Wu et al., 2015) and the following spring precipitation (Zheng et al., 2015) over southern China.

Both the sea surface temperature (SST) anomalies and the cross-hemisphere circulation are emphasized when determining the mechanism of the impacts of the SAM on NH circulation. On the one hand, Wu et al. (2009) and Liu et al. (2015) noted that the signal of the boreal autumn SAM is first imprinted in the mid-latitude SST through the surface heat flux and meridional oceanic Ekman transport (Ciasto and Thompson, 2008; Liu et al., 2015). Due to the large thermal inertia, anomalous mid-latitude SSTs over the SH can persist into the boreal winter. The location of anomalous mid-latitude SSTs over the SH basically coincides with the location of the downward branch of the climatological mean Hadley circulation, and anomalous Hadley circulation is thus formed by the release or absorption of heat from the sea surface. Because the Hadley circulation is shared by the NH and SH, the NH circulation subsequently becomes abnormal. For the significant relationship between the boreal spring SAM and the West African summer rainfall, Sun et al. (2010) also emphasized the bridging role of SST anomalies. The boreal spring SST anomalies over the tropical South Atlantic induced by the SAM could lead to an anomalous meridional gradient in moist static energy, the West African summer monsoon and the consequent rainfall anomalies over West Africa. Therefore, the “memory” effect of SST could prolong the influence of the SAM. On the other hand, Fan and Wang (2004) and Wang and Fan (2006) emphasized the role of the meridional teleconnection in the zonal wind field in the simultaneous influence of the SAM on the NH circulation. Based on a statistical study, Xue et al. (2003) highlighted the roles of the Mascarene high and Australia high in bridging the boreal spring/summer SAM and the boreal summer rainfall over East Asia. Thus, these studies provide new insights for the seasonal forecast of NH circulation.

Numerical models are usually utilized to explore the cross-hemisphere influence of the boreal spring/winter SAM (Fan and Wang, 2007; Wu et al., 2009; Wu et al., 2015). In these studies, the bridging role of the SST anomalies over the middle and high latitudes of the SH are revealed in connection between the SAM and the NH circulation anomalies. However, in addition to the influence from the external SST anomalies, it remains unclear whether the boreal winter SAM can influence the NH directly through the internal dynamics of the atmosphere in the same manner as the boreal summer SAM (Xue et al., 2003). This issue is the main topic of the present study, and we explore it via two reanalysis data sets and a linearized baroclinic model (LBM).

The rest of the paper is organized as follows. We introduce the reanalysis data sets and the LBM in Section 2. The simultaneous relationship between the SAM and the NH circulation is presented in Section 3. In Section 4, the LBM is used to explore the key circulation of the SAM, which can influence the NH circulation. A summary and discussion are provided in Section 5.

2 DATA AND MODEL

2.1 Data

The present study uses two reanalysis data sets: the National Centers for Environmental Prediction (NCEP) and the Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) (Kanamitsu et al., 2002) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis (ERA-Interim) (Dee et al., 2011). The former has a horizontal resolution of $2.5° \times 2.5°$, and the latter has a horizontal resolution of $1.5° \times 1.5°$. The surface air temperature (SAT) from the NCEP reanalysis is on the global T62 Gaussian grid ($192 \times 94$). Because of data quality concerns prior to the incorporation of global satellite soundings, particularly in the SH, we restrict our analysis to the years following 1978 (January 1979–December 2017). The meteorological fields include SAT, wind velocity and geopotential height. Note that the geopotential field provided
by the ERA-Interim reanalysis data is converted to the geo-
potential height field by dividing the geopotential field by
the constant gravitational acceleration (9.8 m/s^2). The pre-
sent study shows only the results based on the NCEP data,
which are similar to those based on the ERA-Interim data
(Supporting Information Figure S1) but with much smoother
contours.

The SAM index is defined as the normalized time coeffi-
cient of the first empirical orthogonal function (EOF) of
monthly 700-hPa geopotential height anomalies poleward of
20°S (Thompson and Wallace, 2000). The SAM index is
downloaded from NOAA’s Climate Prediction Center (CPC)
(http://www.cpc.ncep.noaa.gov).

2.2 | Model

To illustrate the influence of the SAM, we turn to a
primitive-equation model linearized around the observed
monthly climatology for 1979–2017, as represented by the
NCEP reanalysis data. A detailed description of the LBM
can be found in Watanabe and Kimoto (2000). We use the
dry version with T21 horizontal resolution and 11 vertical
sigma levels. The model can be forced by prescribed vortic-
ity. Thus, calculating the steady response to the SAM-related
vorticity forcing is easy and can help answer the question of
whether the SAM could excite height anomalies over the
NH. A detailed description of the vorticity forcing related to
the SAM is shown in Section 4. The damping coefficient is
set at 2/day for the lowest sigma level (σ = 0.9) but at
30/day for the upper levels. The horizontal diffusion coeffi-
cient is equal to 8 × 10^{16} m^4/s, which corresponds to the
e-folding decay time of 1 day for the largest wave number.
With this dissipation and diffusion, a steady response is esti-
mated for approximately 30 days of integration. The output
of the integration at the sigma levels is interpolated onto the
pressure levels to ensure a convenient comparison with the
reanalysis data.

In fact, there is an evident interaction between the
migratory high-frequency eddy activity and the large-scale
low-frequency circulation anomalies, and the eddy feedback
forcing is crucial for the maintenance of the low-frequency
anomalies, especially over the middle and high latitudes. As
noted by Branstator (1995), transient eddy statistics can be
parameterized by a large number of linear integrations with
spatially random initial perturbations. Based on this method,
the present study utilizes a storm track model (STM) pro-
posed by Watanabe and Kimoto (2000) to produce transient
eddy statistics. Watanabe and Kimoto (2000) demonstrated
that the STM could adequately reproduce storm track activ-
ity. Eddy statistics, such as the eddy vorticity flux, are com-
puted using an ensemble of daily perturbation fields grown
out of random initial perturbations. These computations
require a large number of ensembles for statistical robust-
ness. To guarantee statistical robustness, 500 integrations are
performed separately with the same basic state and spatially
random initial perturbations. Since it is known that nonlinear
processes are involved in the decay stage of the transient
eddies, we stop the integration after 6 days, before reaching
a peak of eddy growth. Otherwise, some of normal modes
blow up beyond the timescale of baroclinic instability (less
than 10 days). The last 5 days of a 6-day integration are used
for the ensemble average.

3 | SIMULTANEOUS INFLUENCE OF SAM
ON NH CIRCULATION

To explore whether the SAM has a significant connection
with the NH circulation anomalies, the simultaneous linear
regression coefficients of geopotential height, relative vortic-
ity and SAT on the SAM index are calculated for every cal-
endar month. Consistent with previous studies (Gong and
Wang, 1999; Wallace, 2000; Li and Wang, 2003), the posi-
tive phase of the SAM is characterized by negative geopo-
tential height anomalies south of 60°S and positive
anomalies located in the zonal belt between 30°S and 60°S.
The positive phase is also characterized by a quasi-
barotropic structure in the vertical direction in the tropo-
sphere (not shown). The negative phase of the SAM also has
a quasi-barotropic structure but with an anomalous horizon-
tal pattern that is the opposite of that for the geopotential
height. Unless otherwise stated, the present study utilizes the
positive SAM phase as an example for discussion.

The most interesting phenomenon is that the significant
NH anomalies show evident monthly variations. The most
evident anomalies appear over the NH in February (the
fourth row of Figure 1). In February, positive height anom-
aliy appears over regions from southern North America to the
Black Sea and from Northeast Asia to the Northeast Pacific,
while negative height anomalies prevail over North America
and Iceland. Correspondingly, the SAT anomalies are posi-
tive over Europe and Northeast Asia (Figure 1l), which
might be associated with the anomalous warm advection
from the south. Because the abovementioned positive height
anomalies (Figure 1d) could replenish the climatological
mean troughs (not shown), that is, the Black Sea trough and
the East Asia trough, these anomalies tend to make the circu-
lation straighter in the west–east direction. This process can
weaken the northwest cold advection over the back of the
two troughs and produce anomalous warm advection from
the south over both Europe and Northeast Asia. The ampli-
tude of the positive height anomalies corresponding to one
standard deviation of the SAM over the mid-latitudes of the
NH is approximately 20 m, which is comparable to that of
the SH counterpart. In contrast to the situation in February,
there are almost no significant anomalies over the NH in
either December or January. Although there are significant
geopotential height anomalies over the Atlantic and Europe
in November (Figure 1a), the SAT anomalies over the NH
do not exceed the 95% significance test (Figure 1i). For the
other calendar months, there are marginally significant anomalies over the NH (not shown).

Another interesting phenomenon lies in the pattern of the relative vorticity (vorticity for brevity). Although the patterns of the height anomalies over the middle and high latitudes of the SH have a uniform zonal feature and bear close resemblance during different calendar months (the first column of Figure 1), the patterns of the vorticity show a different situation (the second column of Figure 1). Explicitly, the significant vorticity in February is mainly confined to the region south of 40°S with several isolated centres. The significant vorticity in December not only exhibits similar spatial patterns over the middle and high latitudes of the SH but also shows significant zonally elongated negative anomalies from the southern Atlantic to approximately 30°S in the southern Indian Ocean and significant zonally elongated positive anomalies to the west of Australia. The situation in January seems to be a transition from the December SAM to the February SAM. The reason for the co-appearance of the significant subtropical vorticity anomalies with the middle and high latitude vorticity anomalies is beyond the scope of the present study. For the sake of convenience, the significant circulation anomalies to the south of 20°S are referred to as the SAM-related circulation. The following discussion mainly focuses on a comparison of the SAM between December and February, in which the SAM-related circulation shows the sharpest contrast. The realistic vorticity anomalies in both December and February will be applied in the LBM to model the influence of the SAM.

One may expect that stronger SAM events can exert influence farther northward than weaker ones and, thus, the significant circulation anomalies over the NH in February (Figure 1) might be closely related to the larger variability in the SAM in February than in other winter months. Figure 2 shows the variance in the SAM during every calendar month during the period from 1979 to 2017. Clearly, the variance

FIGURE 1 Simultaneous regression coefficients of the geopotential height at 300 hPa (left column), the relative vorticity (middle column) and the surface air temperature (right column) at 2 m on the Southern Hemisphere annular mode index in different calendar months. From the upper to bottom rows are the regression coefficients in November, December, January and February, respectively. The contour intervals are 15 gpm for h300 in the left column and 2e-6/s for in the middle column. In the right column for T2 m, contours are drawn at every −2.5, −1.5, −0.5, 0.5, 1.5 and 2.5 °C. In all of the panels, the solid contours and the dashed contours denote positive and negative values, respectively. The zero lines are omitted. Shading denotes the statistically significant region at the 0.05 significance level [Colour figure can be viewed at wileyonlinelibrary.com]
In the SAM is much weaker in February than in December. In fact, the variance in the SAM in December is the second largest of the year. Therefore, the intensity of the SAM variance is not the main contributor to the appearance of significant NH circulation, which must be attributable to other factors that will be explored in Section 4.

In light of the evident increasing trend of the SAM index after 1979 (Zheng et al., 2015), the regression coefficients are re-calculated after the linear trend is removed. The results (not shown) show little difference except for the slight weakness of the significant circulation in February. In addition, the SAM indices obtained from the differences in the normalized monthly zonal-mean sea level pressure between the middle and high latitudes over the SH (Gong and Wang, 1999; Nan and Li, 2003) are also used to check the sensitivity of the anomalous circulation to the different SAM indices. The results do not change qualitatively (Figures S2 and S3), and this finding further supports the robustness of the result, as shown in Figure 1.

4 | LINEAR INFLUENCE OF THE SAM ON NH CIRCULATION

4.1 | SAM forcing experiment

Section 3 revealed that the SAM is significantly correlated with the circulation anomalies over the mid-latitudes of the NH in February (Figure 1d). However, the regression coefficient cannot elucidate the causality between the SAM and the NH circulation anomalies. In this section, the possible influence of the SAM is further diagnosed by an LBM. According to the realistic vorticity anomalies (Figure 1f,h), the different vorticity forcings (unit: per s/day or per s²) in December and February are applied in the LBM, which is shown in Figure 3a,c. Clearly, the vorticity forcings are not limited to the mid- and high-latitude regions, and the horizontal shape of every isolated forcing centre follows an elliptic function. The vertical profile at every location follows a gamma function with the centre level placed at $\sigma = 0.2025$. 

![FIGURE 2](image.png)

**FIGURE 2** Variance in the Southern Hemisphere annular mode index during every particular calendar month for the 1979–2017 period.

![FIGURE 3](image.png)

**FIGURE 3** The prescribed vorticity forcing at the level in (a) December and (b) the corresponding response of the geopotential height at 300 hPa at day 25. (c) and (d) are the same as (a) and (b), respectively, but in February. The contour interval is 4e-11/s² in both (a) and (c) and 10 gpm in both (b) and (d). The solid contours and the dashed contours denote the positive and negative values, respectively. The zero lines are omitted [Colour figure can be viewed at wileyonlinelibrary.com]
which is close to 250 hPa, where the centre level of the vorticity anomalies is located, as revealed in the NCEP reanalysis data (not shown). In December, the forcing is strong, and there are many more forcings at approximately 30°S.

Figure 3b,d show the steady response of the height anomalies at 300 hPa on day 25 of the integration. Evidently, both experiments show that the high-latitude region of the SH is covered by negative height anomalies, while the mid-latitude region is covered by positive anomalies, showing a typical SAM pattern. Although there is an evident height response over the middle and low latitudes of the SH, the response in December is mainly confined to the SH except for the weak negative height anomalies over northeastern North America. In sharp contrast, the height response spreads into the NH for the February forcing experiment. There are positive height anomalies with amplitudes of approximately 20 m over the mid-latitude regions of the NH, such as the northern Atlantic, the Mediterranean Sea and over the northern Pacific, which are similar to the results derived from the NCEP data (Figure 1d) but with the centre located slightly southward. If the centre amplitude of approximately 90 m for the positive height anomalies over southern Africa is taken as a reference, the positive height anomalies with a centre amplitude of 20 m over the mid-latitudes of the NH indicate that the SAM in February can induce height anomalies with the same sign over the mid-latitudes of the NH with amplitudes as large as 22% of their SH counterpart. There is no evident response anchoring over Northeast Asia, which is different from the pattern observed in the reanalysis data (Figure 1).

4.2 Transient eddy feedback forcing experiment

In general, there is a strong interaction between the low-frequency circulation and transient eddy over the middle and high latitudes. The former can modulate the activities of the latter. In turn, the latter can influence the former through its vorticity flux and heat flux (Lau and Holopainen, 1984). Since both the transient eddy vorticity flux and the heat flux are nonlinear terms, the feedback influences of the transient eddy are not included in the steady response (Figure 3d), which is obtained through the LBM. Because the steady response to the SAM-related vorticity forcing in February (Figure 3d) may modulate the storm tracks in the NH, it is necessary to evaluate the influence of the transient eddy feedback forcing modulated by the SAM-related circulation in February. By employing the method of Watanabe and Kimoto (2000), the response to the eddy feedback forcing is evaluated by successive use of the LBM and the STM. The climatological mean eddy statistics are first calculated by applying the climatological mean state in February to the STM. Second, the total eddy statistics modulated by the SAM-related circulation are obtained by applying the total basic field associated with the SAM in February to the STM. The total basic field is obtained by summing the climatological mean state and the response (anomalies) to the SAM forcing in February (Figure 3c). Third, the anomalies for the eddy statistics are thus achieved by subtracting the climatological mean eddy statistics from the total eddy statistics. Finally, the convergence of both the eddy vorticity flux and the eddy heat flux are calculated and then applied to the LBM to obtain the steady response.

Figure 4 shows the response to transient eddy feedback forcing. For the positive SAM, the response to transient eddy feedback forcing shows positive height anomalies over the mid-latitudes of the NH. Positive height anomalies with an amplitude of approximately 5 m prevail over both Western Europe and Northeast Asia, where significant SAT anomalies occur. However, transient eddy feedback forcing may play different roles over these two regions. In Western Europe, there is already a positive height response to the SAM forcing (Figure 3d). Thus, the height response to the eddy feedback forcing could amplify the response to the SAM vorticity forcing. In Northeast Asia, there is no evident height response to the SAM forcing (Figure 3d). Therefore, the formation of significant height anomalies over Northeast Asia in the reanalysis data sets (Figure 1d) might be closely associated with transient eddy feedback forcing.

Because the eddy feedback forcing is a nonlinear dynamical process, the response of the negative SAM is also shown in Figure 4b. Clearly, the response is almost identical to its positive SAM counterpart but with the opposite sign, showing a strong linear feature. Overall, the eddy activity over the NH is modulated by the response to SAM forcing, and the subsequent eddy feedback forcing contributes to the formation of height anomalies over the mid-latitudes of the NH.

**FIGURE 4** (a) 300 hPa height response to the eddy forcing due to convergence of eddy vorticity and heat fluxes associated with the positive phase of Southern Hemisphere annular mode (SAM) shown in Figure 3d. (b) Same as in (a) but for the negative phase of SAM. The contour interval is 5 m. The solid and dashed contours represent the positive and negative values, respectively. The zero lines are omitted [Colour figure can be viewed at wileyonlinelibrary.com]
4.3 Individual forcing experiment

Because the SAM is generally regarded as a mid- and high-latitude phenomenon, we also apply the vorticity forcing to the middle and high latitudes (Figure 5a,c). In other words, the subtropical parts of the SAM forcing shown in Figure 3 are discarded. Interestingly, the steady responses for the 2 months are remarkably similar to each other, especially for their centre locations. Consistent with the stronger forcing in December (Figure 5a), the corresponding response is stronger in December (Figure 5b) than in February (Figure 5d). The responses for both months can extend into the NH (Figure 5b,d), and these responses are very similar to those shown in Figure 3d but with stronger amplitudes. The climatological mean states in December and February are used in the December and February experiments, respectively. In fact, if the December mean state is used in the February experiment or the February mean state is used in the December experiment, the results are almost the same. Thus, it can be inferred that the steady response is insensitive to the small variations in the mean state for the different boreal winter months. Thus, whether the SAM can influence the NH circulation might be controlled by the distribution of the vorticity forcing.

As shown in Figure 3, despite being strong, the SAM forcing in December has only a small influence in the NH. To investigate this counter-intuitive phenomenon, the negative vorticity forcing at approximately 30°S is applied (Figure 6a), because this forcing is significant and distinct for the SAM in December (Figure 1f). In fact, the negative vorticity forcing have two centres, one over the southern Indian Ocean and the other to the south of Africa. The reason for combining the two vorticity forcing centres is that the steady response to the forcing over the southern Indian Ocean is comparable to that to the other forcing (not shown). For the sake of simplicity, the following experiments use only the February mean state because the response is not sensitive to the mean state, as discussed above. Clearly, the response pattern (Figure 6i) is almost identical to that shown in Figure 5b but with the opposite sign. Thus, the cancellation between the response to mid- and high-latitude vorticity forcing (Figure 5b) and the response to subtropical forcing (Figure 6i) could explain why there is a weak or absent signal over the NH, as revealed by the reanalysis data (Figure 1b) and the LBM (Figure 3b). In fact, evident positive or negative height responses over the mid-latitudes of the NH are observed if a stronger or weaker negative subtropical vorticity forcing, respectively, is applied at approximately 30°S in the LBM (not shown). This observation indicates that the relative amplitude of each isolated vorticity is also important in determining whether the SAM can influence the NH circulation. Overall, the distinct characteristics of the vorticity forcing over the SH in December mean that the SAM has only a small influence on the NH circulation.

To determine the key vorticity forcing that can effectively influence the NH circulation, every isolated vorticity forcing over the middle and high latitudes of the SH is applied in the LBM, and the corresponding steady responses are obtained, which are summarized in Figure 6. Bear in mind that the LBM used in the present study is a linear model; thus, the linear addition of the responses to some of the forcings is the total influence of those individual forcings. According to the observations (Figure 1h) and the February forcing in the LBM (Figure 3c), the isolated vorticity forcings over the middle and high latitudes are individually applied. The four positive vorticity forcings are placed in different locations at approximately 55°S (Figure 6b-e),
while the negative vorticity forcings are at approximately 70°S (Figure 6f-h). Interestingly, the steady responses for all four positive vorticity forcings (Figure 5m-p) consistently show positive height anomalies over the mid-latitudes of both the SH (30°–60°S) and NH (30°–60°N) and negative height anomalies over the tropics (30°S–30°N). This similarity in the responses should be determined by the climatological mean state, which is beyond the scope of the present study. The centre amplitudes of the four positive forcings over the mid-latitudes of the SH are comparable (Figure 3c or Figure 6b-e). Nevertheless, the respective steady responses show different amplitudes. The height anomalies over the middle and high latitudes of the NH (Figure 3d–d) seem to be most effectively excited by the vorticity forcing over the southern Indian Ocean (Figure 6l) and the least effectively excited by the forcing over southern Africa (Figure 6j). The underlying reason still needs further analysis.

On the other hand, the steady responses of the negative vorticity forcings over the high latitudes of the SH, except for the forcing at approximately 30°E, generally exhibit negative height anomalies southward of 30°S and over the mid-latitudes of the NH (30°–60°N) and positive height anomalies over the tropics (30°S–30°N). For the positive vorticity forcing over Western Australia (Figure 3a) and the negative forcing over southeastern Australia and southwestern Africa (Figure 3c), the corresponding responses over the NH are marginal (not shown).

Thus, the positive and negative vorticity forcings can lead to the opposite influence on the global circulation. The positive height response over the mid-latitudes of the NH (Figure 3d) mainly stems from the positive vorticity forcing over the mid-latitudes of the SH (Figure 3c), among which the vorticity forcing over the southern Indian Ocean seems to be the most effective forcing.
4.4 Vorticity budget diagnosis

Although the significant height/vorticity anomalies could lead to significant SAT anomalies over both Western Europe and Northeast Asia (Figure 11), the height/vorticity response to the SAM forcing is evident over only Europe (Figure 3d). As discussed in Section 4.2, the observational height anomalies over Northeast Asia (Figure 1d) might be mainly associated with the transient eddy feedback forcing rather than the direct influence of the SAM, which accounts for the disappearance of the height/vorticity response over Northeast Asia to the SAM-related forcing (Figure 3d). The maintenance of negative vorticity anomalies over Europe (Figure 3d) is analysed further based on the linearized vorticity equation at the pressure level:

\[
\frac{-u \frac{\partial \zeta}{\partial x} + u' \frac{\partial \zeta}{\partial x} - v \frac{\partial \zeta}{\partial y} + v' \frac{\partial \zeta}{\partial y} + v' \beta}{ZA} - (\zeta + f)D - \zeta D + \text{residuals} = 0
\]

In Equation 1, \( u \) and \( v \) are the zonal wind velocity and the meridional wind velocity, respectively. \( \zeta \) and \( D \) denote vorticity and divergence, respectively. The bar indicates the climatological mean state, and the prime denotes the steady response to vorticity forcing. \( \beta \) is the variation in the Coriolis parameter with latitude. The terms \( ZA \) and \( MA \) represent the zonal and meridional advections of vorticity, respectively. The term \( \text{DIV} \) represents the influence of the divergence. The residuals include vertical advection, tilting, nonlinear, damping and diffusion effects. A positive value of each term corresponds to an increasing tendency of cyclonic vorticity. Because both the \( \text{DIV} \) term and the residual term are much smaller than the \( MA \) or \( ZA \) term, only the \( MA \) and \( ZA \) terms are discussed.

Figure 7a shows the steady negative vorticity response (shading) over the Atlantic and Europe to the vorticity forcing (Figure 3c), which is overlaid by the wind velocity

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**FIGURE 6** (Continued) [Colour figure can be viewed at wileyonlinelibrary.com]
response (vectors). As a steady response to the SAM vorticity forcing, the southerlies appear over Western Europe (vectors in Figure 7a). Due to the northward gradient of the absolute vorticity over the NH, the southerlies can advect the absolute vorticity with a relatively low value northward (shadings in Figure 7d). In fact, \(-v' \beta\) accounts for the majority of the \(MA\) term (Figure 7b) over the Northeast Atlantic/Europe and Western Africa. Overall, there is a cancellation between the \(MA\) term (Figure 7b) and the \(ZA\) term (Figure 7d) for the steady response. Because the sign of the vorticity response (Figure 7a) over Western Europe is the same as that of the \(MA\) term, it is the \(MA\) term with the negative value that maintains the formation of the negative vorticity anomalies over Western Europe. Due to the prevalence of the climatological mean westerlies over the middle and high latitudes of the NH, the climatological mean zonal wind tends to advect the negative vorticity downstream (Figure 7e), contributing to the negative \(ZA\) term just east of Western Europe with the negative \(MA\) term (Figure 7c). Therefore, the negative vorticity responses over Western Europe and its eastern region are maintained by the \(MA\) and \(ZA\) terms, respectively.

5 | CONCLUSIONS AND DISCUSSION

Based on two reanalysis data sets, the present study reveals that the SAM is significantly and linearly correlated with the NH circulation in February. In particular, for the positive SAM, significant positive height anomalies/negative
vorticity anomalies appear over the mid-latitude region of the NH, and significant positive SAT anomalies prevail over Western Europe and Northeast Asia. This simultaneous linear relationship is further diagnosed through a dry LBM with T21 resolution and 11 vertical levels. Based on the realistic vorticity forcing associated with the SAM, the model results show that the SAM in February can induce height anomalies at 300 hPa over the NH with amplitudes as large as 22% of the SAM amplitude. The transient eddy feedback forcing also contributes to the formation of mid-latitude NH circulation anomalies, especially over Northeast Asia.

In light of the significant correlation between the ENSO and the SAM (L’Heureux and Thompson, 2006), we re-evaluate the relationship between the SAM and the NH circulation after removing the linear ENSO signals. The ENSO signals were obtained by regressing every meteorological variable onto the averaged SST anomalies over the Nino3.4 region. The ENSO-free component was obtained by subtracting the ENSO signals from the meteorological variables. The purified observational regression results (Figure 8) do not show a qualitative difference; for example, Figure 8 shows that weakened height anomalies occur over only the northern Pacific, thereby demonstrating the robustness of the close relationship between the SAM in February and the mid-latitude NH circulation. Keep in mind that the cross-hemisphere influence of the SAM may be relayed by tropical circulation. However, the observational tropical circulation shows significant positive anomalies (Figure 8), which are different from the negative steady height response to the SAM vorticity forcing (Figure 3d or d). Currently, we do not fully understand the circulation discrepancy over the tropics between the model results and the observational reanalysis data. There may be other processes through which the SAM can significantly influence the mid-latitude NH circulation. In the future, an ocean–atmosphere coupled model should be used to discuss the contributions from moist processes and/or nonlinear processes over the tropics. Moreover, we do not know the reason why the SAM exhibits a different horizontal distribution for different calendar months (second column of Figure 1), and this issue deserves further study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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