Seasonal Variations of Subtropical Precipitation Associated with the Southern Annular Mode

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ABSTRACT

Seasonal variations of subtropical precipitation anomalies associated with the southern annular mode (SAM) are explored for the period 1979–2011. In all seasons, high-polarity SAM, which refers to a poleward-shifted eddy-driven westerly jet, results in increased precipitation in high latitudes and decreased precipitation in midlatitudes as a result of the concomitant poleward shift of the midlatitude storm track. In addition, during spring–autumn, high SAM also results in increased rainfall in the subtropics. This subtropical precipitation anomaly is absent during winter. This seasonal variation of the response of subtropical precipitation to the SAM is shown to be consistent with the seasonal variation of the eddy-induced divergent meridional circulation in the subtropics (strong in summer and weak in winter). The lack of an induced divergent meridional circulation in the subtropics during winter is attributed to the presence of the wintertime subtropical jet, which causes a broad latitudinal span of eddy momentum flux divergence due primarily to higher phase speed eddies breaking poleward of the subtropical jet and lower speed eddies not breaking until they reach the equatorward flank of the subtropical jet. During the other seasons, when the subtropical jet is less distinctive, the critical line for both high and low speed eddies is on the equatorward flank of the single jet and so breaking in the subtropics occurs over a narrow range of latitudes. The implications of these findings for the seasonality of future subtropical climate change, in which a shift to high SAM in all seasons is expected to be promoted, are discussed.

1. Introduction

This study addresses the seasonality of the interaction of the eddy-driven westerly jet in the Southern Hemisphere with subtropical precipitation. We concentrate on variability of the jet associated with the southern annular mode (SAM), which is the leading mode of circulation variability in the extratropics of the Southern Hemisphere at time scales beyond 1 week (e.g., Thompson and Wallace 2000). In its high-polarity phase, the midlatitude westerlies are shifted poleward and surface pressure is anomalously low over the polar cap and high in the midlatitudes. The associated meridional shift in the midlatitude storm tracks (e.g., Karoly 1990; Brahmananda Rao et al. 2003) is accompanied by changes in precipitation, air temperature, sea surface temperature, and ocean surface currents throughout the extratropics of the Southern Hemisphere (e.g., Hall and Visbeck 2002; Gillett et al. 2006; Sen Gupta and England 2007). Although the SAM is fundamentally an extratropical phenomenon, its impacts extend well into the subtropics, where the Hadley circulation (e.g., Thompson and Lorenz 2004; Kang and Polvani 2011), precipitation, and surface temperatures (e.g., Gillett et al. 2006; Sen Gupta and England 2007; Hendon et al. 2007; Meneghini et al. 2007; Karpechko et al. 2009; Kang et al. 2011) are affected.

The magnitude of the regional impacts of SAM on subtropical surface climate is comparable to other well-known modes of climate variability such as El Niño–Southern Oscillation (ENSO; e.g., Hendon et al. 2013) and the Madden–Julian oscillation (MJO; e.g., Risbey et al. 2009). Furthermore, the SAM is now appreciated to be a source of predictability at intraseasonal (Hudson et al. 2011; Marshall et al. 2012) and seasonal (e.g., Hendon et al. 2013; Lim et al. 2013) time scales. Recent climate change in the Southern Hemisphere has also been attributed to a forced upward trend in the SAM as a result primarily of ozone depletion in austral summer (e.g., Gillett and Thompson 2003; Arblaster and Meehl

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Continued increasing greenhouse gases are projected to result in a robust upward trend of the SAM in all seasons (Yin 2005; Lu et al. 2008; Fyfe et al. 2012). Hence, elucidating and understanding how the SAM affects subtropical climate and, in particular, subtropical precipitation is fundamental to improved predictions on time scales from intraseasonal to climate change.

Although many impacts of variations of the SAM on subtropical climate have been elucidated, some key questions remain about the mechanism and especially the seasonality. For instance, high-polarity SAM is associated with increased precipitation across subtropical Australia during austral spring and summer but with reduced precipitation across the southernmost portions of the continent during winter (e.g., Hendon et al. 2007). An explanation for this seasonality was offered by Hendon et al. (2007): subtropical easterly anomalies attributable to high SAM during winter act to decrease precipitation by deflecting poleward and weakening the midlatitude storm track that is the source of wintertime precipitation across the south of the country. In contrast, during summer the anomalous easterlies result in onshore transport of moist air from the warm Coral Sea, thereby acting to increase precipitation along and inland of much of the eastern (subtropical) seaboard. However, Karpechko et al. (2009) point out that this explanation cannot account for the widespread extension of the anomalous precipitation well inland from the east coast. Furthermore, Kang et al. (2011) show that high SAM during summer results in increased precipitation throughout the SH subtropics, which suggests the increased precipitation in the Australian subtropics associated with high SAM during summer is probably related to the hemispheric-wide (i.e., zonally symmetric) changes in the meridional overturning circulation rather than just local effects along the Australian coast, but the precise mechanism needs to be clarified.

Variations in the latitude of the poleward edge of the sinking branch of the Hadley cell are also found to be more strongly related to the latitude (Kang and Polvani 2011) and speed (Ceppi and Hartmann 2013) of the extratropical westerly jet in summer than in winter. An explanation for this seasonality has been proposed by Ceppi and Hartmann (2013) that builds on Chen and Held’s (2007) hypothesis to account for the recent poleward shift of the Southern Hemisphere extratropical westerlies. In brief, increases in the speed of the midlatitude westerly jet, caused by either external forcing or internal variability, result in faster eddies that then break at higher subtropical latitudes as they propagate equatorward from their source region in the extratropics, thereby shifting poleward the momentum flux divergence and hence shifting the westerly jet poleward. The induced meridional circulation that acts to balance these anomalous momentum fluxes then results in a poleward shift of the edge of the sinking branch of the Hadley circulation. Ceppi and Hartmann (2013) argue that the wintertime-mean westerly jet has a sharper latitudinal gradient on its equatorward flank than in summer, so that, for the same increase in speed of the midlatitude eddies, less of a poleward shift of the critical line (where the eddy phase speed matches the background zonal flow) occurs in winter compared to summer, resulting in less of a poleward shift of the momentum flux divergence and therefore less of a shift of the westerly jet and Hadley circulation.

To explain the response in subtropical precipitation to the SAM, it is necessary to account for the meridional divergence of the eddy-induced mean meridional flow (i.e., the anomalous vertical motion) in addition to any meridional displacement of the edge of the Hadley cell (cf. Ceppi and Hartmann 2013). The purpose of this paper is thus to establish the seasonality of the response of subtropical precipitation to the SAM by connecting this to the seasonality of the induced divergent meridional circulation so as to offer a dynamical explanation. The outcomes of this work will provide new insight into the seasonality of intraseasonal–interannual predictability of subtropical climate as well as providing an improved understanding of the seasonality of impacts of future climate change in the subtropics.

The observational datasets and analysis techniques are described in section 2. Composite behavior of zonal-mean precipitation and circulation associated with SAM variations are developed seasonally using regression in section 3. The zonal-mean zonal momentum budget for the SAM and its implications for the seasonality of the induced divergent meridional circulation in the subtropics are developed section 4. Conclusions are provided in section 5.

2. Data and methods

a. Datasets

The primary observational data used in this study are the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011). We use 6-hourly analyses of $u$, $v$, and $\omega$ (pressure vertical velocity) on 28 pressure levels from the surface to 10 hPa, which are available on a 1.5° grid. Monthly means are formed and anomalies, when required, are created by subtracting the monthly climatology for 1979–2011. Transient eddy momentum fluxes are formed using the 6-hourly analyses by first removing the
TABLE 1. Seasonal correlation coefficients $r$ between SAMI and the Niño-3.4 index and linear trends expressed as the total change in monthly standardized units for the period January 1979 through December 2011.

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$ (SAMI–Niño-3.4)</td>
<td>−0.51*</td>
<td>−0.07</td>
<td>−0.36*</td>
<td>−0.32</td>
</tr>
<tr>
<td>Trend SAMI</td>
<td>0.39*</td>
<td>0.25</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Trend Niño-3.4</td>
<td>−0.11</td>
<td>−0.11</td>
<td>0.01</td>
<td>−0.06</td>
</tr>
</tbody>
</table>

*Value significant at the 95% confidence level.

monthly mean from each field. The covariance is then formed and averaged for each month. Precipitation is taken from the Global Precipitation Climatology Project, version 2 analyses (GPCP; Adler et al. 2003). GPCP is a merged analysis that incorporates surface rain gauge observations and satellite precipitation estimates based on microwave and infrared data. High-latitude (poleward of ~50°S) precipitation in the GPCP analyses, especially in winter, is thought to be less reliable (e.g., Adler et al. 2012) and so we include a comparison to the precipitation product provided by ERA-Interim.

b. SAM indices and regression

The SAM is defined using monthly index values provided by the U.S. National Weather Service Climate Prediction Center (CPC; http://www.cpc.ncep.noaa.gov/products/precip/CWLink/daily_aio_index/aio/monthly.aio.index.b79.current.ascii). We have also developed our results using other indices of the SAM (e.g., Marshall 2003) and the results are qualitatively similar. The CPC SAM index (SAMI) is constructed by projecting monthly 700-hPa height anomalies onto the leading empirical orthogonal function (EOF) of monthly-mean 700-hPa height poleward of 20°S. The height data are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). The EOF analysis was conducted on the base period of 1979–2000.

SAMI negatively covaries with ENSO (Table 1), with the strongest relationship in austral summer when La Niña conditions promote high SAM by directly forcing tropical precipitation that acts to shift poleward the equatorward flank of the subtropical jet, thereby acting to shift poleward the critical latitude of equatorward propagating eddies (e.g., Seager et al. 2003; Lu et al. 2008; Lim et al. 2013). To focus on internal variations of the SAM and to avoid confounding effects of ENSO, we remove the influence of ENSO from the SAMI by subtracting the linear regression onto the Niño-3.4 SST index that is formed using extended reconstructed SST, version 3b (ERSST.v3b; Smith et al. 2008), which is available online (http://www.cpc.ncep.noaa.gov/data/indices/).

All analyses are based on the 33-yr period of 1979–2011. Because the SAMI exhibits a pronounced upward summertime trend for this period (Table 1), we also linearly remove the trend from the SAMI in order to emphasize anomalies associated with internal variations of the SAM. Hence, for the rest of the analysis, SAMI refers to the detrended and ENSO-removed index unless otherwise noted.

Our key analysis technique is to regress monthly anomalies of precipitation, winds, and momentum fluxes onto the monthly standardized time series of the SAM. The resulting regression coefficients then have units that are reflective of a one standard deviation anomaly of the SAMI. To elucidate the seasonality of the anomalies associated with the SAM, we form the regressions separately using monthly data in the four standard seasons [December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON)]. Statistical significance of the regressions is assessed using a $t$ test assuming 33 × 3 degrees of freedom (3 months for each of 33 yr).

c. Zonal-mean zonal momentum budget

To provide insight into the dynamical forcing of subtropical precipitation by the SAM, we use the zonal-mean zonal momentum budget to estimate the zonal-mean meridional circulation (and its divergence) that is in balance with the SAM-induced anomalous momentum fluxes. Kang et al. (2011) used a similar approach to dynamically link externally forced trends in the SAM (i.e., ozone depletion) with trends in subtropical precipitation. We create a covariant momentum budget for SAM variations following the approach of DeWeaver and Nigam (2000) by regressing the monthly zonal momentum budget terms onto the monthly time series of SAMI. We use overbars to represent monthly means, asterisks for departures from the zonal mean, and primes to indicate departures from the monthly mean (recalling that the transient momentum fluxes are computed using 6-hourly data). Signifying the SAM covariant anomaly using subscript $c$ and the climatological monthly average over all years using subscript $a$ and assuming the anomalous relative vorticity is small compared to the mean-state absolute vorticity, the SAM covariant momentum budget in spherical coordinates can be expressed as

$$-(f + \zeta_c)\bar{\eta}_a = -\frac{\partial u}{\partial p}_a \frac{\partial}{\partial \phi} + \frac{1}{\alpha \cos^2 \phi} \frac{\partial}{\partial \phi} \left[ \cos^2 \phi \left( u \bar{\omega} \right)_a \right] - \left( u \bar{\omega} \right)_a \left[ (u \bar{\omega})_a + (u^2 \omega^2)_a \right].$$

(1)
where $u$, $v$, and $\omega$ are the zonal wind, meridional wind, and the vertical pressure velocity, respectively; $\phi$ is latitude; $p$ is pressure; $a_e$ is the radius of Earth; $f$ is the Coriolis parameter; and $\zeta = -\partial \phi / \partial a \partial \phi$ is the climatological zonal-mean relative vorticity. We have neglected in Eq. (1) any residual attributable to momentum dissipation, monthly-mean tendencies, and observational and computational errors.

We can develop the anomalous meridional wind $\mathbf{v}$ associated with the SAM using two different approaches. The direct method is to regress $\mathbf{v}$ directly on to SAMI to obtain $\bar{v}_a$. The second is to solve Eq. (1) for $\mathbf{v}$ in order to obtain an estimate of the meridional wind that is induced by anomalous fluxes of momentum associated with the SAM, which we refer to as $\bar{v}_{\text{eddy}}$.

We will show in section 4, consistent with Hartmann and Lo (1998), that the dominant term on the rhs of Eq. (1) for SAM variations in the upper troposphere is the meridional flux convergence of zonal momentum by the submonthly transients,

$$\frac{1}{a_e \cos^2 \phi} \frac{\partial}{\partial \phi} \cos^2 \phi (u'v')_a,$$

which is largely balanced by the anomalous meridional advection of mean-state vorticity [lhs of Eq. (1)]. However, to better close the momentum budget for the SAM, we will also show in section 4 that there is a nonnegligible contribution in the extratropics from the meridional flux convergence by anomalous stationary eddies

$$\frac{1}{a_e \cos^2 \phi} \frac{\partial}{\partial \phi} \cos^2 \phi (u'v')_a$$

and that the vertical flux convergence of westerly momentum by submonthly transients

$$\frac{\partial}{\partial p} (u'w')_a$$

is also nonnegligible in the subtropics during winter. Thus, to very good approximation we simplify Eq. (1) in order to estimate $\bar{v}_{\text{eddy}}$ for the SAM from the observed momentums fluxes as

$$\bar{v}_{\text{eddy}} = \left[ \frac{1}{f + \zeta} \left[ \frac{1}{a_e \cos^2 \phi} \frac{\partial}{\partial \phi} \cos^2 \phi (u'v')_a + (u^\alpha v^\alpha)_a \right] + \frac{\partial}{\partial p} (u'w')_a \right].$$

We refer to $\bar{v}_{\text{eddy}}$ as the eddy-induced vertical velocity. We compare this to the direct regression of vertical velocity from the reanalyses onto SAMI in order to confirm that our approximations are valid.

The zonal-mean vertical velocity depends on the latitudinal gradient of zonal-mean meridional wind; thus, from Eqs. (2) and (3), $\bar{v}_{\text{eddy}}$ depends on the latitudinal gradient of the SAM-induced momentum flux divergence. Previous work has emphasized the important implication of the zeroes in the latitudinal profile of the momentum flux divergence for understanding variations in the extent of the Hadley cell (i.e., the zeroes in the meridional circulation coincide with the zeroes in the momentum flux divergence; Ceppi and Hartmann 2013). Here we emphasize that it is the meridional gradient of anomalous momentum flux divergence that is key to understanding the induced vertical motion that is more directly relevant to the low-latitude precipitation anomalies.

To relate the latitudinal profile of the momentum flux convergence/divergence to eddy propagation and absorption at critical latitudes (where the phase speed of the eddies equals the zonal wind speed and the eddies break and act to decelerate the zonal flow), we compute the space–time power spectrum of the convergence of eddy momentum flux and display as a function of latitude and phase speed following Randel and Held (1991). We compute the space–time power spectrum by Fourier transforming 6-hourly $u$ and $v$ at each latitude for each season (90 days in summer and 92 days in winter). We then form the space–time momentum flux cospectra (real part of the complex cross power spectrum) at each latitude, compute the meridional convergence, and smooth in frequency with 8 passes of a 1–2–1 smoother. The resulting wavenumber–frequency cospectra (momentum flux convergence) are rebinne into 1 m s$^{-1}$ phase speed bins, retaining zonal wavenumbers 1–15. The climatological cospectrum is formed by averaging these cospectra over all 33 yr. The SAM anomaly of the momentum flux convergence cospectrum is formed by regression of the smoothed cospectrum anomalies each year onto the SAMI.

3. Seasonality of SAM-induced subtropical precipitation and circulation anomalies

The regression coefficients of zonal-mean precipitation from GPCP onto the standardized monthly SAMI time series are shown in Fig. 1 for each season. In this and all
The high phase of SAM is associated with increased precipitation centered just south of 60°S, decreased rainfall centered at about 45°S, and increased precipitation in the deep subtropics from about 20° to 35°S (but not evident in winter). In all seasons, the precipitation anomalies in the middle–high latitudes represent a poleward shift of the climatological storm track (dashed curves in Fig. 1 display the climatological precipitation profile). This poleward shift of precipitation in the storm track during high SAM (moistening at high latitudes and drying in midlatitudes) is consistent with previous observational and model studies of the impact of the SAM on extratropical precipitation (e.g., Gillett et al. 2006; Sen Gupta and England 2007).

The positive precipitation anomaly for high SAM at high latitudes as depicted in GPCP (Fig. 1) is much less distinctive in winter than in the other three seasons, which we think is largely because of the unreliability of the GPCP precipitation analyses at higher southern latitudes, especially during winter (e.g., Adler et al. 2012). As an independent check, we also display in Fig. 1 the regression using the monthly precipitation product from ERA-Interim. The precipitation analyses from ERA-Interim are a model product but are consistent with the resolved dynamics and moisture fields that are constrained by observations in the assimilation cycle.

The middle–high-latitude precipitation dipole associated with SAM is generally better defined in all seasons based on ERA-Interim precipitation analyses as compared to that from GPCP, and the wintertime anomaly in high latitudes is particularly more prominent. We conclude then that the distinctive dipole anomaly in middle–high-latitude precipitation, which we interpret to represent a poleward shift of the midlatitude storm track, is a robust feature of SAM variability that occurs in all seasons.

The additional positive precipitation anomaly in the subtropics during the high phase of the SAM, is highly seasonally dependent, being most pronounced in spring and summer and largely absent in winter (Fig. 1). A similar seasonality is depicted when using ERA-Interim precipitation. We note that the profile of precipitation anomaly during summer in Fig. 1 is similar to that described by Kang et al. (2011), although they did not explicitly remove ENSO from their regression. We have repeated our analysis without removing the influences of ENSO from SAMI and obtain a nearly identical result shown in Fig. 1, except that during summer the precipitation anomalies for high SAM are strongly negative over the equator (because of the association of high SAM with La Niña during summer; Table 1) and the positive anomaly in the subtropics is slightly stronger. Nonetheless, we conclude that a shift to high SAM induces increased precipitation in the subtropics during summer (and spring and autumn) independently of any promotion by ENSO.
We next explore these precipitation anomalies in relation to the circulation anomalies associated with the SAM. We focus on the differences of behavior between the winter and summer seasons, which are the seasons with the most contrasting behavior of precipitation anomaly in the subtropics. We note that the SAM behavior in circulation in the transition spring and autumn seasons (not shown) is generally consistent with behavior during summer. In Fig. 2, we display the regression coefficients for the monthly anomalies of zonal-mean zonal wind, momentum flux convergence, and meridional circulation for high SAM during winter (left panels) and summer (right panels). For reference, we also include the climatological zonal-mean zonal wind for each season, which emphasizes the distinctive occurrence of the subtropical jet in winter while only a single jet structure is apparent in summer.

Despite the strong seasonality of the mean-state zonal wind, high-polarity SAM in both seasons is characterized by an equivalent barotropic meridional shift of the middle–high-latitude westerly (eddy driven) jet (Fig. 2, top). In both seasons, the SAM anomaly in zonal wind has a dipole structure centered on the midlatitude eddy-driven jet (e.g., Thompson and Wallace 2000). Despite the relative lack of seasonality of the SAM signal in the middle–high latitudes (e.g., Hartmann and Lo 1998), a clear seasonality in the subtropics is evident, with the equatorward extension of the easterly anomalies being greater in winter than in summer.

The meridional dipole in zonal wind anomaly in middle–high latitudes coincides with a similar dipole of transient eddy momentum flux convergence/divergence in the middle–upper troposphere (Fig. 2, bottom), which elucidates the primary mechanism for promotion of the SAM (i.e., the westerly anomalies coincide with momentum flux convergence and the easterly anomalies coincide with momentum flux divergence: Hartmann and Lo 1998). The mean meridional circulation anomalies indicate that anomalous equatorward flow in the upper troposphere develops to balance the anomalous westerly acceleration resulting from momentum flux convergence, and poleward flow develops to balance the anomalous easterly acceleration resulting from momentum flux divergence. By mass continuity, anomalous upward motion occurs poleward of the region of anomalous momentum flux convergence (poleward of 60°S) and downward motion occurs between the momentum flux convergence and divergence along about 45°S. Near the surface, return poleward flow occurs in association with the westerly anomaly and equatorward flow occurs in association with the easterly anomaly, which indicates the anomalous near-surface zonal flow is sustained by a Coriolis torque acting against surface friction. We also see in summer an additional deep meridional cell in the subtropics with a region of upward motion between about 25° and 35°S, which is largely absent in winter. Comparing to the precipitation anomalies in the subtropics (Fig. 1), we see good agreement between increased precipitation and anomalous upward motion in the subtropics in summer and note that the absence of a subtropical precipitation anomaly in winter is consistent with the lack of a subtropical vertical velocity anomaly.

In summary, SAM-induced precipitation anomalies in the subtropics exhibit a distinct seasonality that is consistent with the seasonality in the concomitant divergent meridional circulation in the subtropics. This distinctive seasonality in the vertical velocity is highlighted in Fig. 3a, which shows the SAM anomalies of vertical velocity at mid troposphere (600 hPa) for summer and winter. The subtropical zone of interest is highlighted in gray. For reference, we also include the climatological vertical velocity, which also exhibits a strong seasonality whereby the peak mean subsidence in the subtropics in winter is equatorward and much stronger than in summer. It is clear that the SAM anomalies of vertical velocity in the subtropics in winter are much weaker than in summer, which together with the much stronger mean subtropical subsidence in winter means that there will be much weaker SAM-induced precipitation in the subtropics in winter compared to summer.

The primary role of the anomalous mean meridional circulation for driving the subtropical precipitation changes is emphasized in Fig. 3b, which shows the regression of the zonal-mean monthly root-mean-square (rms) transient vertical velocity onto the SAMI. The transient vertical velocity is defined as the 6-hourly deviations from the monthly mean and its rms (averaged over 1 month) is taken to be representative of rainfall variability associated with synoptic-scale weather systems. We see in Fig. 3b that the magnitude of the anomalous rms transient vertical velocity is comparable to the zonal-mean vertical velocity in the extratropics and its latitudinal profile in the extratropics better matches the anomalous precipitation profile (Fig. 1), consistent with the notion that the precipitation variations attributable to the SAM in the extratropics are driven largely by the associated shifts in the storm track. However, in the subtropics, the anomalous zonal-mean vertical velocity is much larger than the anomalous rms transient vertical velocity, suggestive that it is the direct changes in zonal-mean vertical velocity that are more relevant to the precipitation changes there. The focus of the remainder of this paper is to understand this seasonality in the response of the subtropical divergent meridional circulation to the SAM.
4. Eddy-induced divergent meridional circulation

a. Inferences from zonal momentum budget

Prior to using Eqs. (2) and (3) to infer the eddy-induced meridional overturning circulation anomalies, we first look at the individual terms on the rhs of the anomalous zonal momentum budget in Eq. (1) for the regression onto the SAMI (Fig. 4) in order to confirm our approximation to develop Eq. (2). In both summer and winter, the meridional convergence of westerly momentum by the transient eddies, which exhibits a dipole structure in the middle–high latitudes that supports the poleward shift of the westerlies (Fig. 2), is dominant, as expected (cf. Hartmann and Lo 1998). However, as discussed in section 2, we also see that a modest contribution is made by the meridional convergence attributable...
to anomalous stationary eddies, which typically opposes the transient contribution in the extratropics. The vertical flux convergence by transient eddies also makes a small contribution in the midlatitudes. The remaining terms in Eq. (1) are negligible, so Eq. (2) is seen to be a very good approximation of Eq. (1).

Importantly, the anomalous easterly forcing in the subtropics during high SAM arising from eddy momentum flux divergence (primarily attributable to transient eddies) is seen to extend deep into low latitudes in winter (Fig. 4a) but more abruptly decays to zero at about 30°S in summer (Fig. 4b). This contrasting behavior is also seen in the momentum flux divergence anomalies in Fig. 2, which emphasizes that in winter the anomalous momentum flux divergence has broad meridional profile with two peaks on either side of the subtropical jet while in summer the profile is narrower with a single peak on the equatorward flank of the single jet. The explanation for this different latitudinal profile of momentum flux divergence and the implication for the induced vertical motion in the subtropics are explored below.

In Fig. 5a, we display the vertical-mean (100–600 hPa) eddy-induced meridional flow $\mathbf{v}_{\text{eddy}}$ for high SAM as derived using Eq. (2) and compare to vertical-mean $\mathbf{v}_{\text{a}}$ from the direct regression of $\mathbf{v}$ from the reanalyses onto SAMI. The correspondence between the eddy-induced anomaly and the actual anomaly is excellent in both summer and winter seasons, confirming the utility of Eq. (2). The key feature of the anomalous negative (poleward) flow in the middle and low latitudes during summer that acts to oppose the eddy-induced easterly acceleration (Fig. 4b) is that it abruptly goes to zero at about 30°S. In winter, however, this anomalous poleward flow extends all the way to the equator, reflecting a similar slow drop off of the anomalous momentum flux divergence (easterly acceleration) into the tropics, as seen in Figs. 2 and 4a.

The impact of these vastly different latitudinal profiles of meridional flow for the induced vertical motion is demonstrated in Fig. 5b, which shows the eddy-induced vertical velocity at the midtroposphere $v_{\text{eddy}}$ (600) derived using Eq. (3) and also from the direct regression of vertical velocity from the reanalyses onto SAMI (which is a repeat of that shown in Fig. 3). Again, the agreement of $v_{\text{eddy}}$ with $v_{\text{a}}$ is seen to be excellent. The rapid meridional decay of the momentum flux divergence into the subtropics during summer results in a strongly divergent meridional flow in the subtropics and hence strong upward motion there, whereas the slow meridional decay of the momentum flux divergence into low latitudes during winter results in little induced vertical velocity in the subtropics.

Although the slow decay of the meridional divergence of transient eddy momentum flux from the midlatitudes into the subtropics (or equivalently the double-peaked momentum flux divergence on either side of the subtropical jet) appears to be the primary cause of the weak SAM rainfall signal in the subtropics during winter, the mean-state vorticity associated with the subtropical jet may also contribute. This possibility is motivated by examination of the mean-state absolute vorticity profiles in the upper troposphere for summer and winter (not shown but can be inferred from the climatological-mean zonal-mean wind in Fig. 2). In summer, the absolute vorticity has weaker magnitude than $f$ everywhere equatorward of about 50°S, because the relative vorticity on the equatorward side of the single midlatitude westerly jet is everywhere anticyclonic. In winter, however, the presence of a distinctive subtropical jet contributes
to cyclonic vorticity on its poleward flank, acting to make the absolute vorticity more cyclonic than $f$ in the latitudinal range $30^\circ$–$45^\circ$S. The very strong drop off of the subtropical jet on its equatorward flank is associated with strong anticyclonic relative vorticity, so the mean absolute vorticity is markedly more anticyclonic than $f$ equatorward of $30^\circ$S.

From Eq. (2), we can infer that, for a given profile of meridional momentum flux divergence that extends into the subtropics, inclusion of the mean-state relative vorticity resulting from the subtropical jet would result in stronger compensating poleward flow developing on the equatorward flank of the subtropical jet, where the mean-state absolute vorticity has weaker magnitude than $f$, and weaker poleward flow developing on the poleward flank of the subtropical jet, where the mean-state absolute vorticity has greater magnitude than $f$. Hence, the mean-state relative vorticity resulting from the subtropical jet contributes to the convergence of the SAM-induced upper-tropospheric meridional flow, centered on about the latitude of the subtropical jet. This is confirmed in Figs. 5c and 5d, which show the eddy-induced meridional wind and vertical velocity computed with and without inclusion of the mean-state relative vorticity in the absolute vorticity. In summer, the effect of the mean-state relative vorticity is negligible, whereas during winter the induced vertical motion in the subtropics would be slightly more divergent/ upward if the subtropical jet were not present. Hence, the mean-state relative vorticity resulting from the subtropical jet in winter does act to damp the eddy-induced upward motion in the subtropics attributable to the SAM, but this impact appears to be modest.

The most dominant cause of the weaker SAM-induced vertical velocity in the subtropics apparently is the double-peaked momentum flux divergence on either side of the subtropical jet in winter, which thus results in weaker latitudinal gradient of eddy momentum flux divergence in the subtropics compared to summer. We now will explain this meridionally broader, double-peaked momentum flux divergence during winter from the perspective of the impact of the subtropical jet on eddy propagation and wave breaking.

b. Impact of subtropical jet on eddy propagation and breaking

The eddies responsible for transporting momentum are well explained to behave like Rossby waves that are primarily propagating horizontally in the middle–upper troposphere (e.g., Hartmann 2007). The eddies flux westerly momentum in the opposite direction of their group velocity and tend to converge westerly momentum into their source region and diverge momentum into regions where they break and dissipate. They tend to propagate toward large values of the meridional gradient of mean-state absolute vorticity $\beta^*$ and break at their critical latitude where their phase speed approaches $u$ and their group velocity tends to zero (e.g., Hoskins and Karoly 1981). The $\beta^*$ typically increases toward the equator where $u$ goes to zero, so there is a strong tendency for eddies to propagate equatorward from their middle–high-latitude source region, where they eventually encounter their critical line at low latitudes (e.g., Karoly and Hoskins 1982).

Insight into the meridional profile of anomalous momentum flux convergence/divergence attributable to the SAM is provided by decomposing the momentum flux convergence in the upper troposphere (300 hPa) as a function of latitude and eddy phase speed for winter (Fig. 6a) and summer (Fig. 6b). The climatological zonal

![Figure 4](https://example.com/figure4.png)

**FIG. 4.** Terms in the SAM covariant momentum budget [rhs of Eq. (1)]. Terms have been vertically integrated (100–600 hPa). The sum of all terms on the rhs of Eq. (1) is shown as dark gray dashed curve, and the three-term approximation used in Eq. (2) is the purple dashed curve for (a) winter (JJA) and (b) summer (DJF). Units are meters per second per day.
wind (dashed purple curves) and the zonal wind that includes the positive SAM anomaly (solid green curves) are also shown. The SAM anomalies of eddy momentum flux convergence/divergence (contours in Fig. 6) represent an intensification and poleward shift of the climatological pattern of convergence/divergence in both winter and summer (shading in Fig. 6). The climatological eddy momentum flux convergence spectrum in both seasons shows familiar convergence in mid and high latitudes (indicative of the eddy source region) and divergence along the critical line in the subtropics where the eddy phase speed approaches the background zonal wind and the eddies break (e.g., Chen and Held 2007). Because the mean zonal wind decreases toward the equator, the peak eddy momentum flux divergence in low latitudes shifts to slower phase speed with decreasing latitude.

Although the climatological eddy source (i.e., momentum flux convergence shaded red in Fig. 6) during winter is much broader than in summer, suggesting that the middle–high-latitude westerlies act as the source of higher phase speed eddies while the westerlies on the poleward side of the subtropical jet appear to be a source of lower phase speed eddies (e.g., Trenberth 1986; Lee and Kim 2003), the anomalous eddy source associated with SAM (i.e., the anomalous momentum flux convergence contoured in Fig. 6) during both winter and summer is associated primarily with a poleward shift of the middle–high-latitude source region. There is also an indication of a shift of the momentum flux convergence to higher phase speed eddies, which Chen and Held (2007) argue accounts for the poleward shift of the zonal wind for SAM (higher phase speed eddies break at higher latitudes, thereby shifting the momentum flux and hence the midlatitude jet poleward). However, the key feature to emphasize here is that the anomalous momentum flux divergence in the midlatitudes–subtropics during winter (Fig. 6a) clearly shows a preference for breaking to occur on the equatorward flank of the midlatitude jet (anomalous momentum flux divergence peaked at about 40°S) primarily because of higher phase...
speed eddies but breaking extends onto the equatorward flank of the subtropical jet (anomalous momentum flux divergence peaked at about 20°S) because of lower phase speed eddies. In contrast, during summer, the anomalous eddy momentum flux divergence for eddies of all phase speed aligns along the equatorward flank of the single jet but is shifted poleward of its climatological profile.

The latitudinal span of anomalous momentum flux divergence attributable to the SAM thus extends from about 45° to 15°S in winter. In contrast, during summer the region of anomalous momentum flux divergence occurs over a narrower range of latitudes (45°–25°S). Hence, the latitudinal gradient of momentum flux divergence in the subtropics attributable to the SAM is weaker in winter than in summer, so a weaker divergent meridional circulation in the subtropics will be induced. Therefore, the upward motion and precipitation response in the subtropics is weaker in winter than in summer.

Breaking of eddies on the flanks of both the eddy-driven and subtropical jet during winter has previously been reported in both idealized model studies and observations by Barnes and Hartmann (2012). They show that breaking between the jets is intensified when the westerly jet and the subtropical jet are distinct and well separated (i.e., like high SAM during winter) but that some breaking still occurs on the equatorward flank of the subtropical jet. We emphasize here that it is primarily higher phase speed eddies that break on the equatorward flank of the midlatitude jet where these eddies apparently first encounter their critical line, while lower phase speed eddies do not break until they encounter their critical line on the equatorward flank of the subtropical jet.

Close inspection of Fig. 6a suggests peak anomalous eddy breaking on the equatorward flank of the midlatitude jet occurs well before the eddies have encountered their critical line (e.g., peak momentum flux divergence for eddies with phase speed of ~15 m s⁻¹ at ~40°S occurs some 25° poleward of where the mean zonal wind is 15 m s⁻¹ on the equatorward flank of the subtropical jet). A poleward displacement of peak divergence (eddy breaking) from the critical latitude was previously noted by Randel and Held (1991), who suggest that the interaction of the eddies with their critical line is nonlinear and that the distance the wave breaks away from the critical line is proportional to the eddy amplitude. However, this apparent breaking well poleward of the critical latitudes might possibly be an artefact of forming the zonal mean across two distinctive regions where one has a strong subtropical jet but with weak midlatitude jet (i.e., the Indo-Pacific sector from about 90°E to 90°W) and the other has a strong midlatitude jet but weak subtropical jet (the east Pacific–Atlantic sector from about 90°W to 90°E; referred to here as the Atlantic sector). For instance, it is possible that most of the breaking (momentum flux divergence) of low phase speed eddies on the equatorward side of the subtropical jet might be occurring in the Indo-Pacific sector where the subtropical jet is most prominent. Most of the breaking of higher phase speed eddies on the
equatorward flank of the midlatitude jet might be occurring in the Atlantic sector, where the midlatitude jet is more prominent. However, as we will show below, this is not the case, with a broad profile of momentum flux divergence in the subtropics occurring in both sectors.

We demonstrate this by recomputing the latitude–height regressions of transient eddy momentum flux convergence onto SAMI in the two sectors during winter (Fig. 7). In the Atlantic sector, where the mean subtropical jet is weaker, the anomalous extratropical momentum flux convergence/divergence dipole straddles the location of the eddy-driven jet, indicative that the SAM in this sector is typified by a north–south shift of the eddy-driven jet. In contrast, in the Indo-Pacific sector, where the subtropical jet is pronounced although an eddy-driven jet is still apparent but at higher latitude than in the Atlantic sector, the anomalous momentum flux convergence more closely aligns with the eddy-driven jet, so the SAM in this sector is better described as a pulse rather than a shift. These sectoral differences in the characteristics of the SAM are consistent with Codron (2007), who used slightly different sectoral averages. They are also consistent with Eichelberger and Hartmann (2007), who show that the SAM is characterized as a pulse when the subtropical jet is strong and as a shift when the subtropical jet is weak.

However, the focus here is on the profile of momentum flux divergence in lower latitudes. We see that in the Atlantic sector (Fig. 7a) there is distinctive breaking (divergence) on the anticyclonic (equatorward) side of both the midlatitude jet and the subtropical jet (even though the subtropical is relatively weak), supportive of our notion that higher phase speed eddies break on the critical line set by the midlatitude jet and lower phase speed eddies break on the critical line set by the subtropical jet. In the Indo-Pacific sector, the profile of momentum flux divergence (breaking) is more difficult to interpret, with maximum divergence occurring on the cyclonic (poleward) side of the more prominent subtropical jet but still with a broad extension of divergence onto the anticyclonic (equatorward) side of the subtropical jet. This location of maximum momentum flux divergence on the cyclonic (poleward) flank of the subtropical jet might be indicative of refractive effects resulting from the strong cyclonic vorticity on the poleward flank of the subtropical jet which would act to prevent equatorward propagation of eddies emanating from the midlatitudes (e.g., Thorncroft et al. 1993; Eichelberger and Hartmann 2007) and would also help account for the pulsing rather than shifting nature of the SAM in this sector. However, the key point here is that breaking (momentum flux divergence) appears to be spread into lower latitudes because of the presence of the subtropical jet in both sectors so as to result in weak induced divergent motion in the subtropics, although the details of eddy breaking and interaction with the mean flow in the presence of a distinctive subtropical jet needs further investigation.

5. Conclusions

SAM is primarily characterized as a north–south fluctuation of the midlatitude, eddy-driven, westerly jet with concomitant latitudinal shifts in the midlatitude...
storm track. High–middle-latitude precipitation varies in concert with these north–south shifts of the storm track, so that in the high phase of the SAM, when the jet is shifted poleward, precipitation increases on the poleward flank of the midlatitude storm track and decreases on its equatorward flank. However, SAM also affects lower-latitude circulation and precipitation. In particular, during spring–autumn high SAM results in increased precipitation in the subtropics. This subtropical precipitation anomaly is absent during winter. We have shown that the subtropical precipitation variations associated with the SAM are consistent with the eddy-induced divergent meridional circulation in the subtropics that is driven by the SAM. The absence of the subtropical precipitation anomaly in winter stems from the absence of a concomitant induced divergent meridional circulation.

We attribute this lack of impact in the subtropics during winter to the presence of the distinctive subtropical jet, which acts to cause higher phase speed eddies that originate in the higher-latitude westerlies during positive excursions of the SAM to break between the midlatitude and subtropical jets, while lower speed eddies propagate equatorward deep into the subtropics, where they break on their critical line on the equatorward flank of the subtropical jet. In summer, high and low phase speed eddies break in a narrower range of latitudes on the equatorward flank of the single midlatitude westerly jet, resulting in a more rapid meridional decay of momentum flux divergence into the subtropics. Thus, the latitudinal gradient of anomalous momentum flux divergence in the subtropics associated with the SAM is much weaker in winter than in summer, so the eddy-induced anomalous divergent meridional circulation (and therefore upward motion) in the subtropics is weaker in winter than in summer.

This explanation for the seasonality of the eddy-induced divergent circulation in the subtropics in response to the SAM builds on the mechanism proposed by Ceppi and Hartmann (2013) to account for the seasonality in the sensitivity of position of the poleward edge of the Hadley circulation to SAM variations. They argue that, because the wintertime-mean westerly jet has a sharper latitudinal gradient on its equatorward side than in summer, the same increase in speed of the midlatitude eddies associated with the SAM leads to less of a poleward shift of the low-latitude critical line, ultimately resulting in less of a poleward shift of the edge of the Hadley circulation in winter compared to summer. Their argument does not take into account the impact of the wintertime subtropical jet on the latitudinal distribution of breaking of the eddies that originate in the midlatitude westerly jet and that it is this latitudinal profile of breaking that accounts for the induced divergent meridional circulation in the subtropics which accounts for the subtropical precipitation response to the SAM.

The lack of a subtropical precipitation anomaly during winter means that the net impact of high SAM during winter can be characterized as a poleward expansion of the subtropical dry zone (e.g., Schef and Frierson 2012). In contrast, during summer (and spring and autumn) the net impact of high SAM in the subtropics is better characterized as a poleward shift of the subtropical dry zone: the wet-equatorward edge and the dry-poleward edge of the subtropical dry zone move poleward in unison (e.g., Kang et al. 2011).

This seasonality of impact of the SAM on subtropical precipitation has important implications for predicting current and future climate. For instance, Hendon et al. (2013) show that the state of the SAM plays a leading role in determining the warm season (spring–summer) rainfall anomaly in subtropical eastern Australia during La Niña events. The occurrence of high SAM would add to the La Niña–induced wet anomaly and low SAM would detract. Thus, limited predictability of the SAM on seasonal time scale (e.g., Lim et al. 2013) places a strong constraint on predictability of subtropical rainfall, even during highly predictable La Niña events. High SAM has also been promoted by ozone depletion (e.g., Arblaster and Meehl 2006; Gillett et al. 2013). Hence, a primary impact of the recent upward trend in the SAM has been an upward trend in summertime subtropical precipitation (Kang et al. 2011), which can be viewed as a poleward shift of the subtropical dry zone. However, a robust finding of projected future climate in response to increased greenhouse gases is a promotion of high SAM in all seasons (e.g., Yin 2005; Gillett et al. 2013). The emergence of this upward trend of the SAM in winter would then result in an expanded subtropical dry zone in winter (e.g., Schef and Frierson 2012), which would have severe consequences for instance on water resources in subtropical Australia and South America, where there is a strong dependence on wintertime rainfall.

Finally, we have emphasized a key role of the Southern Hemisphere wintertime subtropical jet for determining the impact of SAM variability on subtropical precipitation. Although the impact of variations of the subtropical jet on the SAM attributable to direct forcing by ENSO has been previously considered (e.g., Seager et al. 2003; L’Heureux and Thompson 2006; Lim et al. 2013), future changes in the Southern Hemisphere subtropical jet—for instance, as driven by a reduced outflow from a weakened Asian summer monsoon in response to anthropogenic aerosols (e.g., Turner and
Annimalai 2012)—may profoundly change how SAM interacts with the subtropical precipitation and circulation. A fruitful focus of future research would appear to be an improved understanding of how the wintertime subtropical jet may change and vary in a future climate.

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