Interhemispheric Influence of the Northern Summer Monsoons on Southern Subtropical Anticyclones

SANG-KI LEE

Cooperative Institute for Marine and Atmospheric Studies, University of Miami, and NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

CARLOS R. MECHOSO

Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, California

CHUNZAI WANG

NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida

J. DAVID NEELIN

Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, California

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ABSTRACT

The southern subtropical anticyclones are notably stronger in austral winter than summer, particularly over the Atlantic and Indian Ocean basins. This is in contrast with the Northern Hemisphere (NH), in which subtropical anticyclones are more intense in summer according to the ''monsoon heating'' paradigm. To better understand the winter intensification of southern subtropical anticyclones, the present study explores the interhemispheric response to monsoon heating in the NH during austral winter. A specially designed suite of numerical model experiments is performed in which summer monsoons in the NH are artificially weakened. These experiments are performed with both an atmospheric general circulation model and a simple two-layer model. The highlight of the findings presented here is that during the boreal summer enhanced tropical convection activity in the NH plays important roles in either maintaining or strengthening the southern subtropical anticyclones. Enhanced NH convection largely associated with the major summer monsoons produces subsidence over the equatorial oceans and the tropical Southern Hemisphere via interhemispheric meridional overturning circulations and increases the sea level pressure locally. In addition, suppressed convection over some regions of climatological subsidence produces stationary barotropic Rossby waves that propagate far beyond the tropics. These stationary barotropic Rossby waves and those forced directly by the summer heating in the NH are spatially phased to strengthen the southern subtropical anticyclones over all three oceans. The interhemispheric response to the NH summer monsoons is most dramatic in the South Pacific, where the subtropical anticyclone nearly disappears in the austral winter without the influence of the NH.

1. Introduction

In our current understanding, the principal driver of subtropical anticyclones (also known as subtropical highs) varies with season. This principal driver is heating associated with monsoons over adjacent continents during the summer season, and orographic effects on trade easterlies and midlatitude westerlies during the winter season. Rodwell and Hoskins (2001, hereafter RH01) argued that monsoon heating generates a Kelvin wave response over the ocean to the east, forming the equatorward portion of the subtropical anticyclone with a poleward low-level jet to satisfy Sverdrup balance. The heating also generates a Rossby wave response that produces adiabatic descent over regions to the west (Rodwell and Hoskins 1996). An equatorward low-level

Corresponding author address: Dr. Sang-Ki Lee, CIMAS, University of Miami, 4600 Rickenbacker Cswy., Miami, FL 33149.
E-mail: sang-ki.lee@noaa.gov

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jet forms to satisfy Sverdrup balance closing off the subtropical anticyclone on its eastern flank. Additional effects, such as intense near-surface sensible heating over continents and air–sea interactions involving cold sea surface temperatures (SSTs) and low-level clouds in the eastern part of the oceans, also contribute to drive subtropical anticyclones in the summer season (e.g., Seager et al. 2003; Liu et al. 2004; Miyasaka and Nakamura 2005). In the winter season, monsoon heating is absent and subtropical anticyclones weaken. Consistent with this line of reasoning, subtropical anticyclones in the Northern Hemisphere (NH) are stronger and better defined in the boreal summer than in winter [see Fig. 1, obtained with data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis]. See Ting (1994), Chen et al. (2001), and Chen (2003) for further discussions on the stationary wave response to summer monsoon heating in the NH.

Subtropical anticyclones in the Southern Hemisphere (SH) behave in a qualitatively different manner: They are notably stronger in the austral winter than in summer over the Atlantic and Indian Oceans (see Fig. 1). This could be due to a combination of monsoons being less important generators of zonal asymmetries in the mostly ocean-covered SH, and of topographic effects becoming stronger in winter as the flow intensifies. The former is plausible because the summertime subtropical anticyclones are significantly stronger in the NH than in the SH (Miyasaka and Nakamura 2010). However, an argument based on the seasonality of the SH is questionable because the SH has weaker seasonal variability. Furthermore, although the Andes Cordillera is high and has strong slopes, the topography over southern Africa and Australia is relatively low and has a weaker blocking effect on the mean westerly flow (Richter and Mechoso 2004, 2006).

Some revision of the RH01 conceptual model is, therefore, needed to address the seasonality of southern subtropical anticyclones. Recent studies with numerical models have provided some guidance for such a revision. Wang et al. (2010) used an atmospheric general circulation model (AGCM) to demonstrate that convection over the Western Hemisphere warm pool (WHWP) during the boreal summer (i.e., austral winter) can produce adiabatic subsidence over the southeastern tropical Pacific and, thus, contribute to maintaining the equatorward portion of the South Pacific subtropical anticyclone and the equatorward low-level jet along the South American coast. In addition, Wang et al. (2010) showed, by performing experiments with the simple two-level atmospheric model developed by Lee et al. (2009), that the interhemispheric connection between the WHWP and

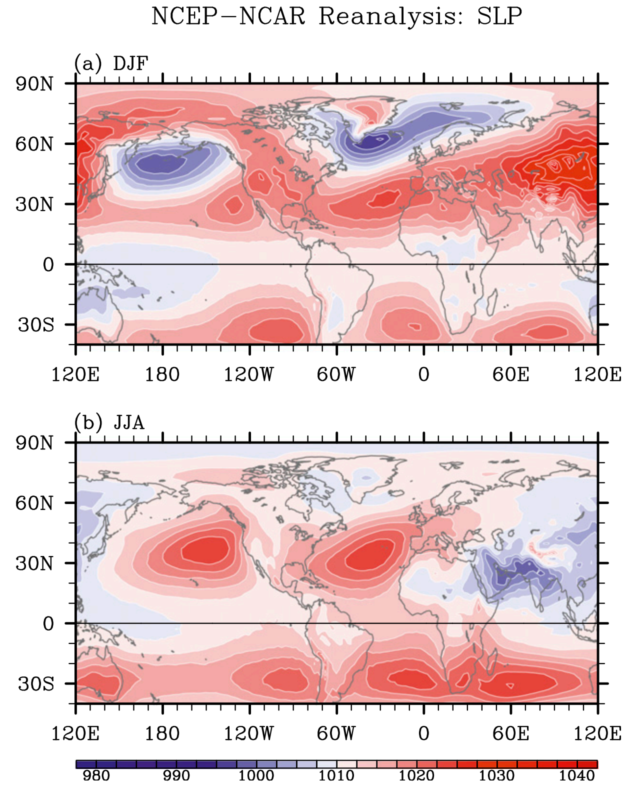

FIG. 1. Mean SLP (hPa) for (a) December–February (DJF) and (b) June–August (JJA) during 1971–2000 from the NCEP–NCAR reanalysis.

the South Pacific subtropical anticyclone depends critically on the configuration of the mean zonal winds in the SH. Richter et al. (2008) demonstrated a similar interhemispheric connection between the African–Indian summer monsoon and the South Atlantic subtropical anticyclone when comparing simulations by two versions of the University of California, Los Angeles (UCLA), AGCM that reproduce climate features with significantly different levels of success.

On the basis of the studies by Wang et al. (2010) and Richter et al. (2008), one could advance the following conjecture. Interhemispheric teleconnections associated with the major summer monsoons and deep tropical convection over warm SSTs in the NH contribute to the wintertime strengthening of the southern subtropical anticyclones. The present study examines this conjecture. Our goals are to explore to what extent southern subtropical anticyclones during austral winter are affected by major monsoons and deep tropical convection in the NH and to gain insight into the underlying mechanisms at work for the teleconnections. To achieve these goals, we perform and analyze a suite of specially designed AGCM simulations complemented by additional experiments using a simple atmosphere model.

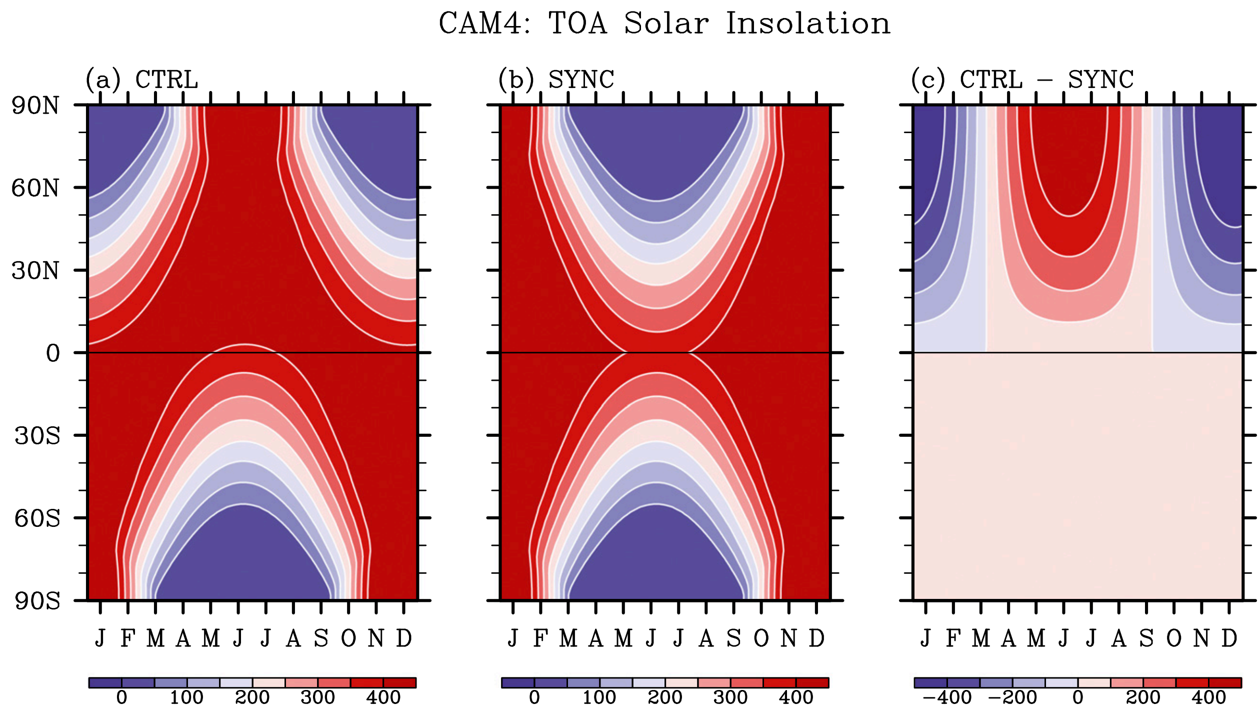

FIG. 2. Daily solar insolation at the TOA in (a) CTRL, (b) SYNC, and (c) CTRL − SYNC (W m^{-2}).

In evaluating the SH subtropical anticyclone response to NH convection, we focus primarily on sea level pressure (SLP). SLP will have contributions arising from both baroclinic and barotropic dynamics, and can be made precise in models that carry out a vertical mode decomposition (e.g., Lee et al. 2009; Neelin and Zeng 2000). In these cases, the first baroclinic mode has high surface pressure and cool tropospheric temperatures in regions of upper-level convergence and adiabatic subsidence, and low surface pressure and warm tropospheric temperatures in regions of diabatic heating. The baroclinic Rossby wave response to monsoon heating is at the core of the RH01 conceptual model, but can in turn excite barotropic Rossby waves via several interaction mechanisms: vertical wind shear and surface stress acting on the baroclinic mode, and vertical advection of baroclinic mode vorticity (e.g., Lee et al. 2009; Ji et al. 2013). The barotropic mode contribution to subtropical SLP can thus have significantly different teleconnection characteristics than the direct baroclinic mode contribution.

In section 2, we present our research strategy, give a brief description of the AGCM we use, and list the AGCM simulations we performed. Next, using the AGCM results, we describe the SLP response in the SH over each ocean basin to major summer monsoons in the NH. In sections 4 and 5, we analyze the AGCM simulations. We then posit that major summer monsoons in the NH force interhemispheric meridional overturning circulation, and diabatic cooling over certain sinking regions forces stationary barotropic Rossby waves in the extratropical SH to enhance southern subtropical anticyclones. In section 6, this hypothesis is supported by specially designed experiments with the simple two-level model of Lee et al. (2009). Section 7 provides a summary and discussion.

2. Strategy, model, and experiments

Our strategy in this study is based on performing AGCM runs in which a control simulation (CTRL) is compared to an idealized experiment with artificially weakened summer monsoons in the NH (SYNC). This weakening in SYNC is achieved by shifting both the insolation at the top of the atmosphere (TOA) and the SSTs and sea ice cover in the NH by one-half the seasonal cycle (6 months), that is, by synchronizing the seasonal cycles in the model's external and boundary conditions across hemispheres (see Fig. 2). In SYNC, therefore, there is a global warm season in DJF and a global cold season in JJA, which, in the calendar year, correspond to those in the SH.

We use the NCAR Community Atmospheric Model, version 4 (CAM4). CAM4 is a global atmosphere–land model with prescribed SSTs and sea ice cover (Neale et al. 2013). The finite-volume dynamic core has a horizontal resolution of 2.5° (zonal) × 1.9° (meridional) and

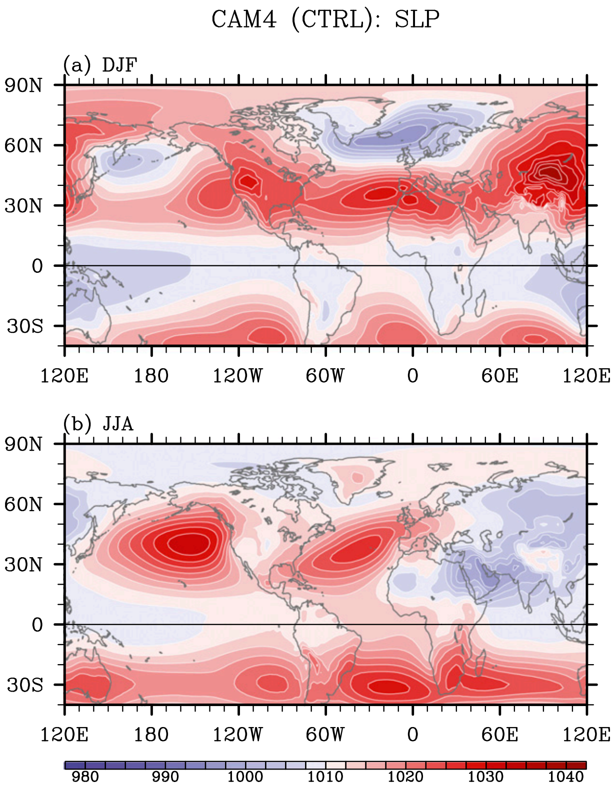

FIG. 3. Mean SLP for (a) DJF and (b) JJA from CTRL (hPa).

26 hybrid sigma-pressure layers. AGCM runs are 20 yr long, of which the first 5 yr are discarded to minimize any possible transient spinup effects. The time mean of the remaining 15 yr is analyzed in the following sections.

3. Results

Figure 3 shows the mean SLP obtained in CTRL for DJF and JJA. The simulated subtropical anticyclones are realistic, but are generally stronger than in the NCEP–NCAR reanalysis (see Fig. 1). The simulation captures two important features of subtropical anticyclones: 1) those in the NH are better defined in the boreal summer than in boreal winter and 2) those in the SH remain quite strong and well defined in the austral winter. In view of these results, it is reasonable to conclude that CAM4 is an appropriate tool for the present study.

Figure 4 shows time–latitude plots of monthly mean, zonally averaged SLP over the South Pacific, South Atlantic, and South Indian Oceans from the NCEP–NCAR reanalysis, CTRL, and SYNC. The zonal average is carried out from the eastern to the western boundaries of the respective ocean basins.

Starting with the South Pacific, the maximum SLPs in both the NCEP–NCAR reanalysis and CTRL occur during the austral spring (August–November; Figs. 4a,d). In SYNC, however, when the interhemispheric effect is removed (Fig. 4g), the maximum SLPs occur in DJF and the minimum in JJA. This latter feature of the seasonal cycle is consistent with the monsoon heating mechanism of RH01. This suggests that the NH heating is a key contributor to the strength of the subtropical anticyclone over the South Pacific during the austral winter.

For the South Atlantic and South Indian Oceans, the maximum SLPs in both the NCEP–NCAR reanalysis and CTRL occur around July–August (Figs. 4b,c,e,f). In SYNC (Figs. 4h,i), the maximum SLP occurs a little earlier with a much weaker magnitude than in CTRL (Figs. 4e,f). This suggests again that the NH heating plays a major role in the strengthened subtropical anticyclones over the South Atlantic and South Indian Oceans during the austral winter. It is interesting to note that the maximum SLP still does not occur in the austral summer, suggesting that the subtropical anticyclones over the South Atlantic and South Indian Oceans could be still strengthened during the austral winter without the NH heating. A potential mechanism that may explain this seasonal cycle in SYNC is discussed in section 7.

In summary, the AGCM experiments indicate that the interhemispheric response to NH heating plays a crucial role in either maintaining or strengthening the southern subtropical anticyclones in austral winter. The interhemispheric response is very strong over all three oceans, but is more dramatic in the South Pacific, where the subtropical anticyclone nearly disappears in austral winter without the influence from the NH. In the following sections, we explore the physical processes that determine the interhemispheric response to heating in the NH and its impact on southern subtropical anticyclones.

4. Interhemispheric meridional overturning circulation

In CTRL, the mean Hadley circulation during JJA (Fig. 5a) shows rising motion in the tropical NH and sinking motion in the tropical SH. In SYNC, with external and boundary forcings in the NH corresponding to DJF, this configuration changes drastically (Fig. 5b). Instead, there is a pair of ''Hadley cells'' with rising motion near the thermal equator at around 5°N and sinking motion in the latitude band between 15° and 30° of each hemisphere. The difference in the Hadley circulations between CTRL and SYNC (Fig. 5c) is the net meridional overturning circulation forced by NH heating during the warm season of that hemisphere. The net interhemispheric meridional overturning circulation shown in Fig. 5c is, in general, consistent with the suggestion of an association between the seasonal

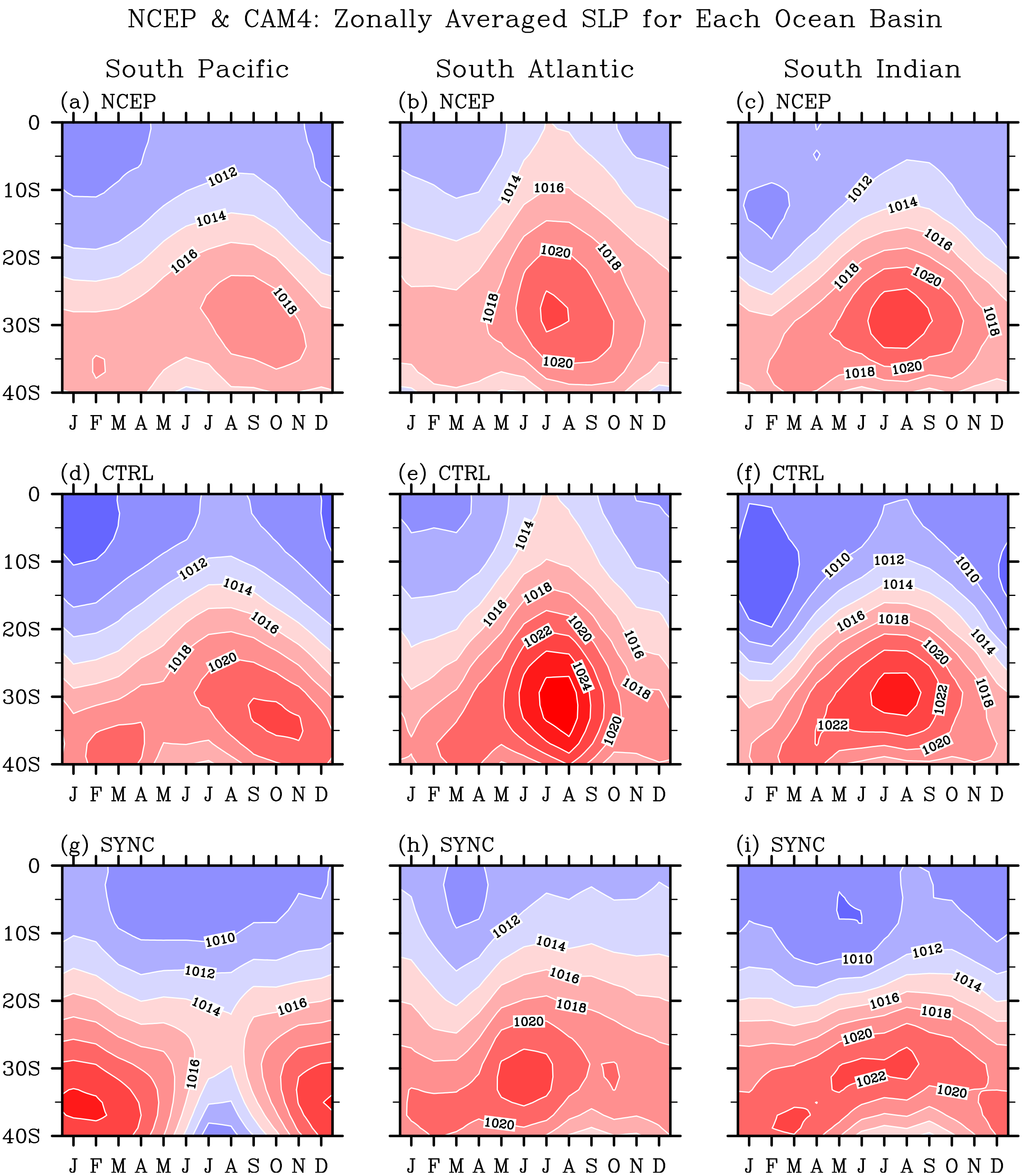

FIG. 4. Seasonal cycle of SLP (hPa) averaged zonally for the (a),(d),(g) South Pacific, (b),(e),(h) South Atlantic, and (c),(f),(i) South Indian Oceans from (top) the NCEP–NCAR reanalysis, (middle) CTRL, and (bottom) SYNC.

cycle of the Hadley cell and the monsoons put forward by Dima and Wallace (2003).

Associated with the net interhemispheric meridional overturning circulation (Fig. 5c) is the upper-level convergence field over the tropical SH. At the convergence centers, subsiding air tends to yield local SLP increases (e.g., Rodwell and Hoskins 1996). It is important to point out, however, that the extent of the sinking

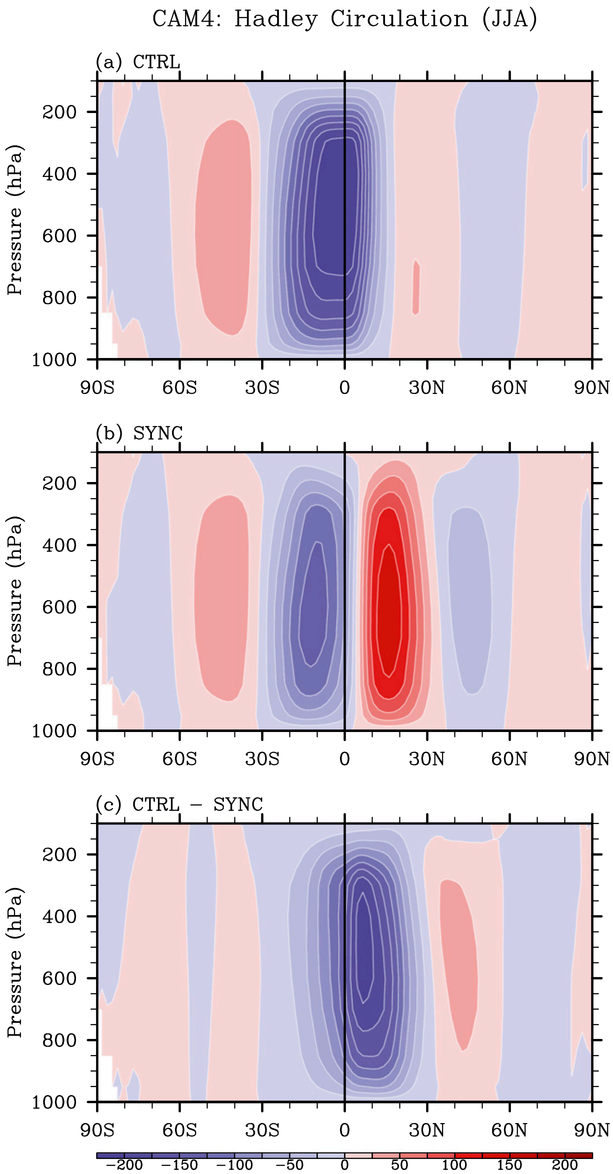

FIG. 5. Mean meridional overturning circulation (mass streamfunction; 10^9 Kg s^{-1}) obtained from (a) CTRL, (b) SYNC, and (c) CTRL − SYNC. Circulation is clockwise (anticlockwise) around positive (negative) streamfunction.

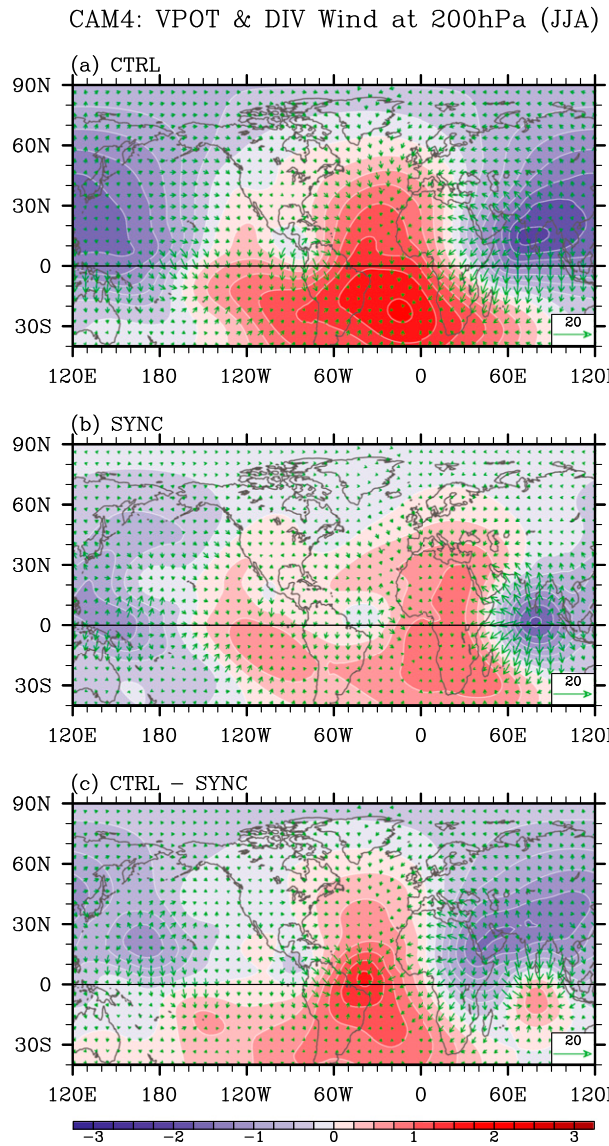

FIG. 6. Mean velocity potential (10^7 m^2 s^{-1}) and divergent wind vector (m s^{-1}) at 200 hPa from (a) CTRL, (b) SYNC, and (c) CTRL − SYNC.

branch of the net interhemispheric meridional overturning circulation is limited to the deep tropics equatorward of around 20°S (Fig. 5c). Therefore, the strengthening of the southern subtropical anticyclones south of around 20°S cannot be simply explained as the direct result of the net interhemispheric meridional overturning circulation forced from the NH.

Figure 6 shows the mean velocity potential and divergent winds during JJA at 200 hPa for CTRL, SYNC, and CTRL − SYNC. In CTRL, divergent winds (rising motions) occur over India and East Asia, in association with the local summer monsoon, the northwestern tropical Pacific, and the WHWP, whereas convergent winds (sinking motions) occur over the southeastern tropical Pacific and much of the Atlantic, especially the tropical South Atlantic (Fig. 6a). When the interhemispheric effect is removed (i.e., SYNC), the centers of rising motion in the NH are shifted toward the equator over the western equatorial Atlantic Ocean and the equatorial Indian Ocean (Fig. 6b). Therefore, the net result of the interhemispheric response to the heating in the NH is to produce subsidence over the western equatorial Atlantic Ocean and the equatorial Indian Ocean (Fig. 6c).

In addition, a broad region of subsidence exists in CTRL − SYNC over the south-central tropical Pacific, the southeastern tropical Pacific, and the tropical South Atlantic. It appears that the subsidence in the south-central tropical Pacific is linked mainly to the summer expansion of the western Pacific warm pool in the region of the northwestern tropical Pacific. The subsidence in the southeastern tropical Pacific appears to be linked to the WHWP, consistent with Wang et al. (2010), whereas the subsidence over the tropical South Atlantic appears to be linked to the Indian and West African summer monsoons, as suggested by Richter et al. (2008), and also to the WHWP. These effects occur essentially as baroclinic mode teleconnections, which have no trouble crossing the equator, but tend to remain trapped within the equatorial waveguide (Gill 1980). In the next two sections, we turn to potential barotropic contributions.

5. Propagation of stationary Rossby waves to the subtropics

As shown in Fig. 7a, the interhemispheric effect on SLP is not limited to the tropical SH where the sinking branch of the net interhemispheric meridional overturning circulation directly increases the local SLP. Over the regions of subsidence in the equatorial oceans and the tropical SH, slowly sinking air is heated by adiabatic compression and thus limits the vertical development of convection. Therefore, the sinking regions in the south-central Pacific Ocean, the western equatorial Atlantic Ocean, and the equatorial Indian Ocean are characterized by a suppressed moist convective heating rate at 500 hPa (Fig. 8) and a reduced convective precipitation rate (not shown). Potentially, the diabatic cooling (i.e., reduced diabatic heating relative to SYNC) over these regions can produce stationary barotropic Rossby waves far beyond the tropics (e.g., Hoskins and Karoly 1981; Horel and Wallace 1981; Branstator 1983; Sardeshmukh and Hoskins 1988; Ting and Held 1990; Lee et al. 2009). Consistent with this hypothesis, the spatial pattern of SLPs in response to the interhemispheric teleconnections closely resembles the streamfunction response at 500 hPa, which is a widely used proxy for identifying stationary barotropic Rossby waves (Fig. 7b). Note that the streamfunction sign is reversed (i.e., circulation is anticlockwise around positive streamfunction) for a better visual comparison with the SLP (Fig. 7a). It is important to point out that, due to cold SSTs and low-level clouds, conditions are not suitable for deep convection in the southeastern tropical Pacific or the southeastern tropical Atlantic. Therefore, the subsidence in these regions directly increases SLPs locally, but cannot induce diabatic cooling

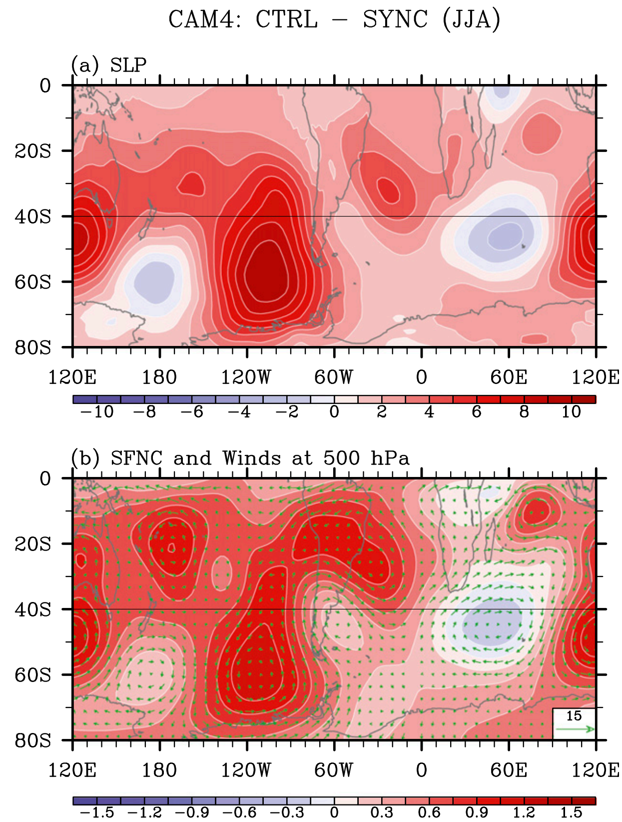

FIG. 7. (a) Mean SLP (hPa) and (b) streamfunction (10^7 m^2 s^{-1}) and wind vectors (m s^{-1}) at 500 hPa from CTRL − SYNC. The zonal line at 40°S roughly marks the southern end of southern subtropical anticyclones in JJA. The streamfunction sign is reversed in such a way that the circulation is anticlockwise around positive streamfunction.

(Fig. 8) or force stationary barotropic Rossby waves to the extratropical SH.

6. Simple model experiments

We next qualitatively examine the interpretation we have given to the differences between CTRL and SYNC, particularly to the forcing of stationary barotropic Rossby waves shown in Fig. 7b by diabatic cooling (i.e., reduced diabatic heating relative to SYNC) in the equatorial oceans and the tropical SH. For such an examination, we select the simple atmospheric model of Lee et al. (2009). This is a two-level, minimal complexity model of both the local and remote stationary responses of the atmosphere to tropical heating anomalies. The model equations are linearized about background wind fields, and recast as baroclinic and barotropic components with thermal advection in the tropics neglected. See Lee et al. (2009) and Wang et al. (2010) for more details about this model.

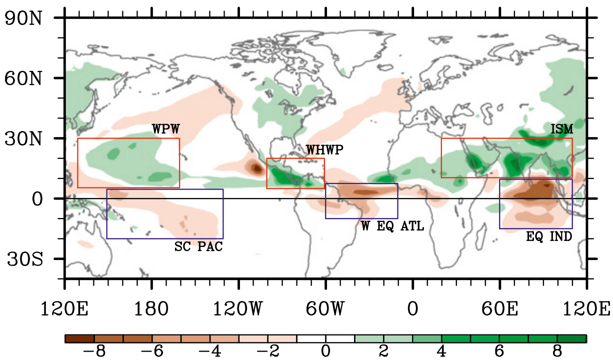

FIG. 8. Mean moist convective heating rate (K day^{-1}) at 500 hPa for JJA from CTRL − SYNC. The three regions of diabatic heating in the NH, namely the northwestern Pacific Ocean affected by summer expansion of the western Pacific warm pool, the WHWP, and the Indian summer monsoon region are indicated by red borderlines. The three regions of diabatic cooling in the equatorial oceans and the tropical SH, namely the south-central Pacific, the western equatorial Atlantic, and the equatorial Indian Ocean, are shown with blue borderlines.

The band of easterlies in the tropics makes it difficult for stationary Rossby waves to propagate across the equator (e.g., Branstator 1983). This is particularly true if the stationary barotropic Rossby waves are forced in the tropical NH during the boreal summer when the zonal background barotropic flow is mainly westward equatorward of around 20°N (Peixoto and Oort 1992). In the simple model experiments of Wang et al. (2010), however, diabatic heating in the tropical NH directly influences the SH without invoking the associated diabatic cooling. In Wang et al. (2010), the baroclinic response to diabatic heating in the tropical NH comprises two centers of low SLP anomalies, one in the northwest and the other in the southwest of the forcing region, consistent with the simple Gill model (Matsuno 1966; Gill 1980). As further investigated by Ji et al. (2013), the low SLP anomaly to the southwest of the forcing region in the tropical NH can be positioned in the tropical SH with a weaker amplitude compared to its counterpart in the NH. Also according to Ji et al. (2013), the Gill-type baroclinic circulations in the tropical SH may in turn interact with the background flows in this hemisphere to produce stationary barotropic Rossby waves.

Additionally, Watterson and Schneider (1987) suggested that a meridional background wind associated with Hadley circulation could enable wave propagation across the equator even under an easterly background wind. Dima et al. (2005) analyzed the NCEP–NCAR reanalysis data to find some supporting evidence. Kraucunas and Hartmann (2007) and Liu and Wang (2013) further demonstrated this mechanism using a nonlinear shallow-water model and a linearized simple two-level model, respectively.

An important implication drawn from the above-mentioned studies is that summertime diabatic heating in the tropical NH can directly force stationary barotropic Rossby waves in the extratropical SH, without invoking the associated diabatic cooling in the equatorial oceans and the tropical SH and, thus, can directly affect the southern subtropical anticyclones. Therefore, it is important to address how effectively the diabatic heating in the tropical NH can directly induce stationary barotropic Rossby waves in the extratropical SH.

To address these issues and also to further explore how the heating in the tropical NH and the cooling in the equatorial oceans and the tropical SH, considered separately in six major forcing regions (see Fig. 8), affect the southern subtropical anticyclones, we performed seven experiments using the two-level model. In the first experiment, the moist convective heating rate at 500 hPa for JJA obtained from CTRL − SYNC (Fig. 8) is prescribed. The other six experiments are identical to the first, except that the thermal forcing is prescribed only over selected regions (see Fig. 8). In the second, third, and fourth experiments, the moist convective heating rate is prescribed only in the south-central Pacific (20°S–5°N, 150°E–130°W), the western equatorial Atlantic (10°S–7.5°N, 60°–10°W), and the equatorial Indian Ocean (20°S–10°N, 60°–110°E), respectively. In the fourth, fifth, and sixth experiments, the moist convective heating rate is prescribed only in the northwestern Pacific Ocean affected by summer expansion of the western Pacific warm pool (5°–30°N, 130°E–160°W), the WHWP (5°–20°N, 100°–60°W), and the Indian summer monsoon region (10°–30°N, 20°–110°E), respectively. See Fig. 8 for the regions of forcing and the heating rates prescribed for these experiments.

For all seven experiments, the background fields are the zonally averaged climatological streamfunction and velocity potential for JJA in the upper and lower troposphere derived from CTRL. The simple two-level model assumes that barotropic divergence is zero (Lee et al. 2009). Thus, the model is prescribed with only the baroclinic background velocity potential, which is directly related to the Hadley cell in CTRL (Fig. 5a), and with both the barotropic and baroclinic background streamfunctions. The zonally averaged barotropic and baroclinic background zonal winds and the zonally averaged baroclinic meridional winds (computed from the streamfunction and velocity potential fields) derived from SYNC and CTRL are shown in Fig. 9 along with those derived from the NCEP–NCAR reanalysis. Because the simple model mainly solves a set of linearized equations, nonlinear effects are not considered in our experiments.

Figure 10 shows the barotropic streamfunction response to the thermal forcing shown in Fig. 8. The streamfunction

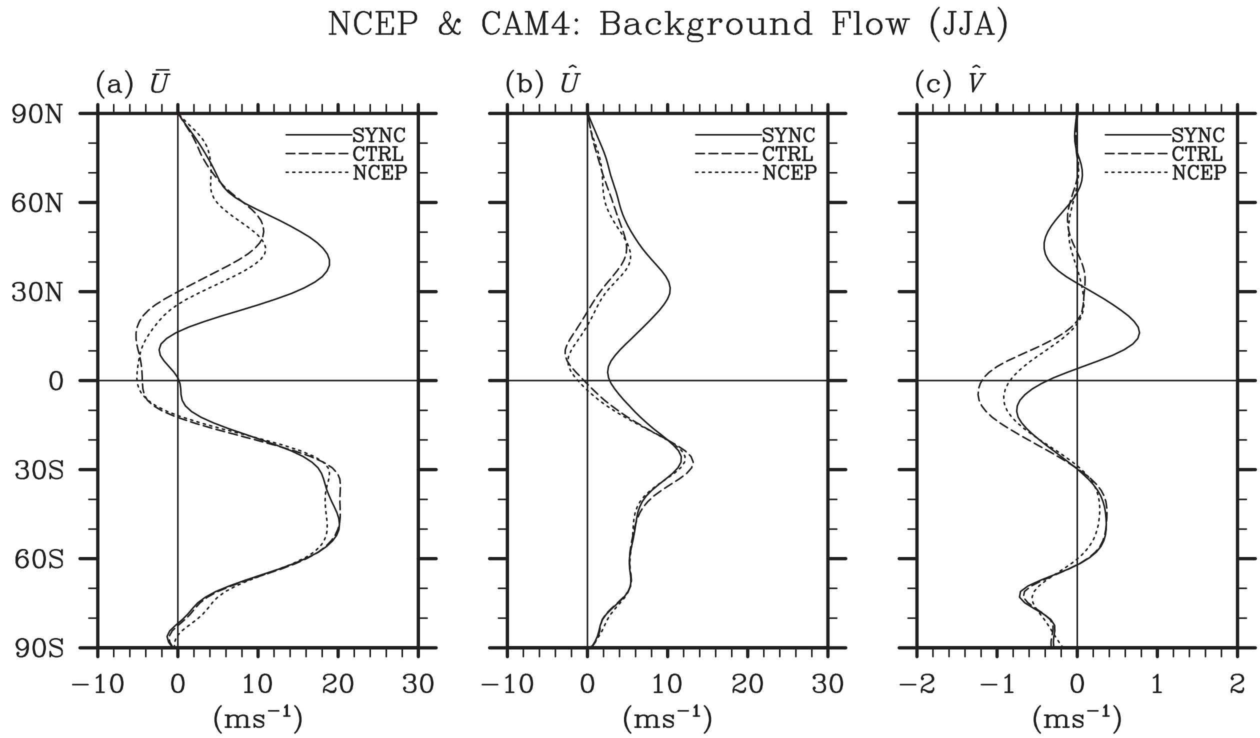

FIG. 9. Zonally averaged climatological (a) barotropic zonal, (b) baroclinic zonal, and (c) baroclinic meridional winds in JJA obtained from SYNC (solid lines), CTRL (long-dashed lines), and the NCEP–NCAR reanalysis (short-dashed line). The barotropic zonal winds are obtained by vertically averaging the zonal winds in the troposphere (from 100 to 1000 hPa). To compute the baroclinic zonal winds, the zonal winds are vertically averaged separately for the upper (from 100 to 500 hPa) and lower (from 500 to 1000 hPa) troposphere and the latter is subtracted from the former and then divided by 2. The same methodology is used to compute the baroclinic meridional winds.

sign is again reversed (i.e., circulation is anticlockwise around positive streamfunction) for a better visual comparison with the SLP in the AGCM experiments (Fig. 7a). The simple two-level model is an oversimplification of the real atmosphere and is unable to reproduce the exact shape or propagation pathway of the stationary Rossby waves simulated by CAM4 (Fig. 7b). Nevertheless, a comparison between Figs. 7b and 10 reveals several important common features. In particular, the anticyclones are roughly in place to enhance the southern subtropical anticyclones in all three oceans.

Figures 11a–c show the barotropic streamfunction response to diabatic cooling in the south-central Pacific Ocean, the western equatorial Atlantic Ocean, and the equatorial Indian Ocean, respectively. It is clear that the stationary barotropic Rossby waves originating from the south-central Pacific greatly strengthen the South Pacific subtropical anticyclone. Similarly, the stationary barotropic Rossby waves originating from the western equatorial Atlantic Ocean propagate to the extratropical South Atlantic and strengthen the South Atlantic subtropical anticyclone. It appears that diabatic cooling in the equatorial Indian Ocean and the associated stationary waves contribute to the strength of the South Indian subtropical anticyclone particularly to the south and west of Australia.

Figures 12a–c show the barotropic streamfunction response to diabatic heating in the northwestern Pacific Ocean, the WHWP, and the Indian summer monsoon region, respectively. Unlike those forced in the south-central Pacific Ocean, the stationary barotropic Rossby waves forced in the northwestern Pacific Ocean hardly

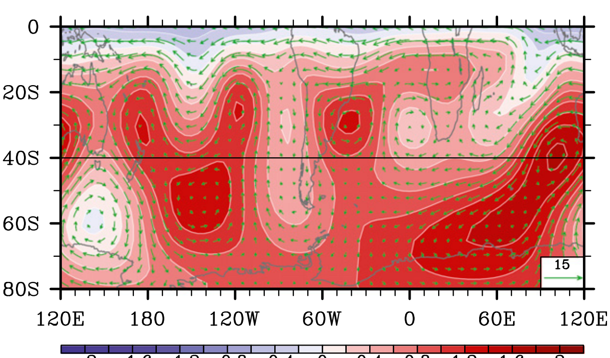

FIG. 10. Barotropic streamfunction (10^7 m^2 s^{-1}) and wind vector (m s^{-1}) responses in the simple model experiments to the moist convective heating and cooling derived from CTRL − SYNC.

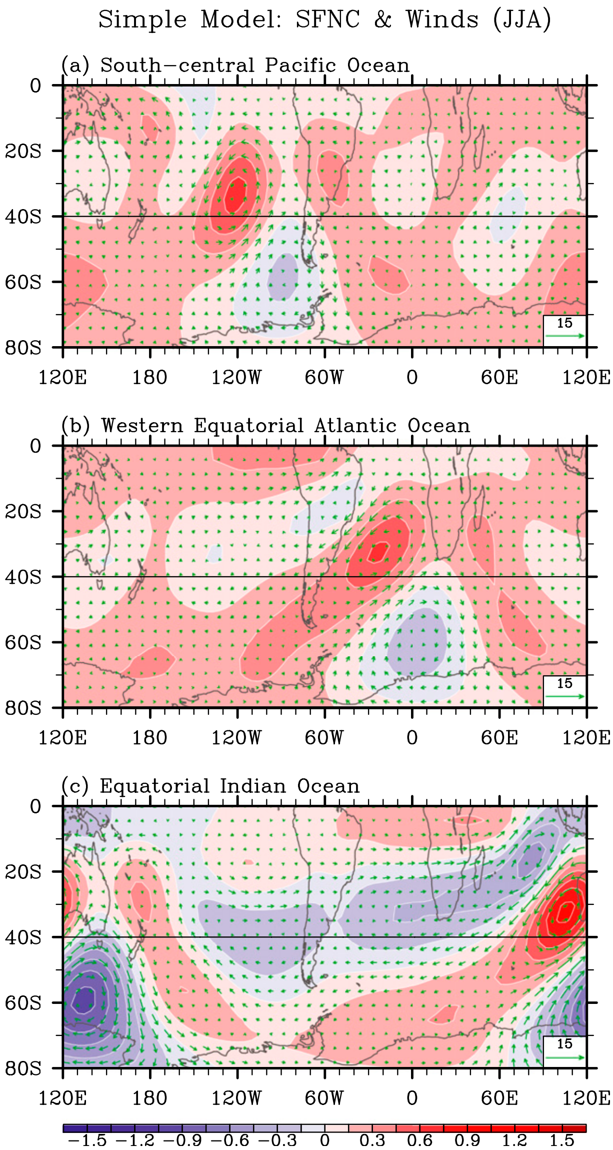

FIG. 11. Barotropic streamfunction ($10^7\ m^2\ s^{-1}$) and wind vector ($m\ s^{-1}$) responses in the simple model experiments to diabatic cooling in the (a) central South Pacific, (b) western equatorial Atlantic, and (c) the equatorial Indian Oceans.

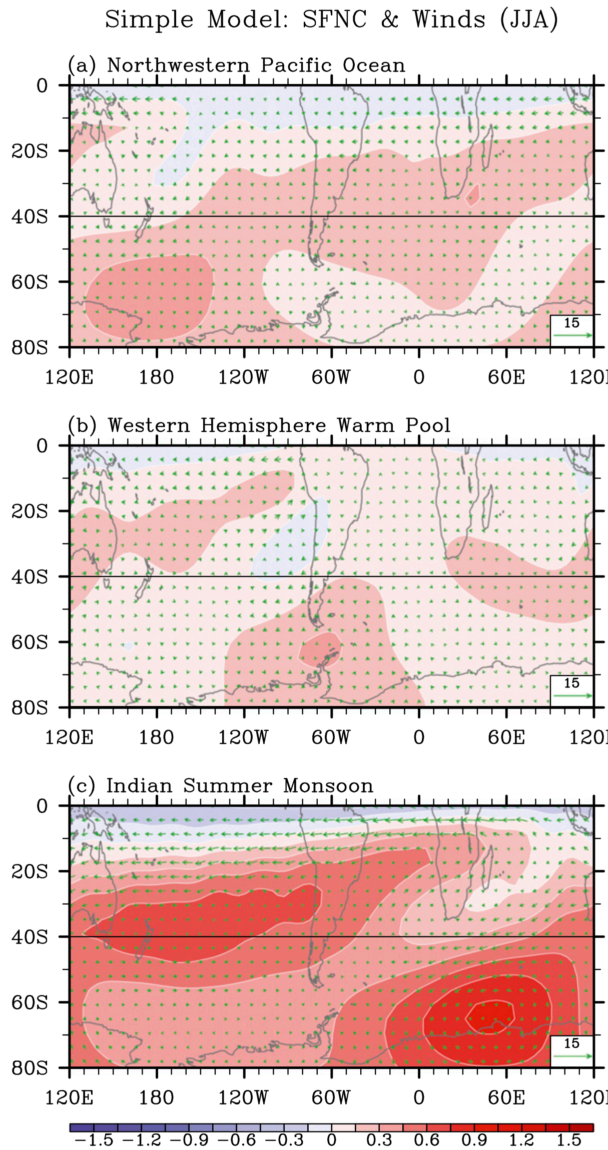

FIG. 12. Barotropic streamfunction ($10^7\ m^2\ s^{-1}$) and wind vector ($m\ s^{-1}$) responses in the simple model experiments to diabatic heating in the (a) northwestern Pacific Ocean, (b) the WHWP, and (c) the Indian summer monsoon region.

influence the southern subtropical anticyclones. The stationary waves directly forced in the WHWP only weakly influence the South Pacific subtropical anticyclone.

However, it is interesting to note that the stationary waves directly forced in the Indian summer monsoon region have large influences on the South Pacific and South Atlantic subtropical anticyclones. This experiment is repeated without the baroclinic background meridional winds to find that the baroclinic background meridional winds across the equator (i.e., interhemispheric overturning circulation) play an important role in enhancing the propagation of the Indian summer monsoon–forced stationary waves to the SH, in line with the explanation offered by Watterson and Schneider (1987).

In summary, the simple model experiments support our hypothesis that, in response to the heating in the tropical NH, diabatic cooling occurs in the equatorial oceans and the tropical SH, which in turn forces the stationary barotropic Rossby waves shown in Fig. 7b and, thus, strengthens the southern subtropical anticyclones. The simple model experiments suggest that diabatic heating in the Indian summer monsoon region can also enhance the South Pacific and South Atlantic subtropical anticyclones without invoking the cooling in the equatorial oceans and the tropical SH.

In interpreting these barotropic Rossby wave trains, it should be recalled that they are excited in the simple model by the prescribed diabatic heating or cooling (see Lee et al. 2009). The diabatic cooling is itself a teleconnected response to heating in the tropical NH and is primarily a reduction in deep convective heating that could potentially occur in certain locations over the equatorial oceans and the tropical SH if the tropical NH heating were absent. It is also important to recall that the simple two-level model does not include moist processes. Therefore, unless prescribed, the simple model cannot simulate diabatic processes such as radiative cooling or convective heating. See an intermediate complexity model study by Ji et al. (2013) for further discussion on interhemispheric teleconnections in response to a localized heat source in the tropical NH via the baroclinic mode affecting moist processes and thus convective heating in the tropical SH.

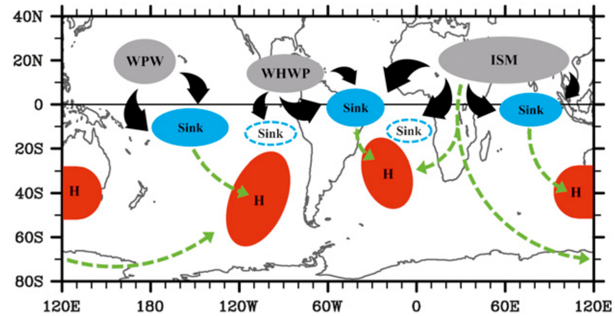

FIG. 13. Sketch of the physical processes linking the major summer monsoons in the NH and the southern subtropical anticyclones. The three regions of rising motion, the three regions of sinking motion, and the regions of southern subtropical anticyclones affected are colored gray, sky blue, and red. The sinking regions in the southeastern tropical Pacific and the southeastern tropical Atlantic are indicated by dashed sky blue borderlines. Thick black arrows represent divergent winds in the upper level, while light green arrows represent the ray paths of the stationary barotropic Rossby waves forced by diabatic cooling over the three regions of sinking motion and by diabatic heating in the Indian summer monsoon region.

7. Summary and discussion

The present study examines the conjecture that major summer monsoons in the NH contribute to the wintertime strengthening of the southern subtropical anticyclones through interhemispheric teleconnections. To explore this conjecture, we perform a specially designed suite of AGCM experiments in which summer monsoons in the NH are artificially weakened. To elucidate the underlying mechanisms at work for the teleconnections, we also perform several experiments using the simple numerical two-level model of Lee et al. (2009).

The results obtained in the AGCM and simple model experiments suggest that the interhemispheric response to heating in the NH does play a crucial role in either maintaining or strengthening southern subtropical anticyclones in the austral winter. Although the interhemispheric response is very strong over all three oceans, it is more dramatic in the South Pacific because the subtropical anticyclone over this ocean nearly disappears in the austral winter without the influence from the NH.

The sketch in Fig. 13 encapsulates results from several parts in the text. During the boreal summer, the interhemispheric meridional overturning circulation is fueled from three hot spots in the tropical NH. These spots are located over the Indian–East Asian summer monsoon region, the northwestern tropical Pacific region affected by summer expansion of the western Pacific warm pool, and the WHWP (see Fig. 6). The associated subsidence and SLP increases occur over the western equatorial Atlantic Ocean, the equatorial Indian Ocean, the south-central tropical Pacific Ocean, the southeastern tropical Pacific Ocean, and the South Atlantic Ocean. Because conditions are suitable for deep convection in the western equatorial Atlantic Ocean, the equatorial Indian Ocean, and the south-central tropical Pacific Ocean due to warm SSTs therein, the subsidence over these three regions suppresses convection (see Fig. 8). The diabatic cooling (i.e., reduced diabatic heating relative to SYNC) in these regions produces stationary barotropic Rossby waves that propagate far beyond the tropical SH. These stationary Rossby waves and those forced directly by summer heating in the tropical NH are spatially phased to strengthen the southern subtropical anticyclones over all three oceans.

It is argued that the stationary barotropic Rossby waves forced directly by heating in the tropical NH have a generally weaker influence on the southern subtropical anticyclones than those forced by cooling in the equatorial oceans and the tropical SH. However, the simple two-level model used to arrive at that conclusion excludes nonlinear effects. Therefore, further analyses are needed to clarify this point. A potentially promising method is to prescribe localized heating profiles in a fully nonlinear AGCM (e.g., Jang and Strauss 2012).

The subtropical anticyclones over the South Atlantic and South Indian Oceans could be still strengthened during the austral winter without the NH convective heating (Figs. 4h,i). It appears that in the absence of the NH heating the equatorial oceans, especially the equatorial Indian Ocean, could drive rising motions aloft to force subsidence motions over the broad regions of

South Atlantic and southwestern Indian Ocean (see Fig. 6b) and, thus, increase SLPs therein.

The results of this study leave open some important scientific questions, which deserve future investigation. For instance, in our AGCM experiments the model SSTs in the SH are not allowed to respond to (or to the lack of) the interhemispheric teleconnections. Therefore, it remains to be determined if and how our conclusions are modified if thermal and dynamic interactions with the surface ocean mixed layer are activated. An important and related point is that the trade winds over the SH are closely linked to the southern subtropical anticyclones. An enhanced southern subtropical anticyclone during the boreal summer could potentially increase the trade winds in the SH and, thus, affect surface ocean dynamics and SSTs in the tropical SH. To explore potential air–sea interactions involving the interhemispheric teleconnections, the next step is to perform experiments of the CTRL and SYNC types with CAM4 coupled to a slab-ocean mixed layer model over the SH.

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