Winter and Summer Rossby Wave Sources in the CMIP5 Models

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Abstract The Rossby wave source (RWS) in the upper troposphere plays an important role in the tropical-extratropical teleconnections. Using the daily outputs from the Phase 5 of the Coupled Model Intercomparison Project (CMIP5) models, the overall model performances in simulating the climatological Rossby wave sources in both winter and summer are evaluated. The ensemble mean of the CMIP5 models can simulate the large-scale geographical distributions of the RWS reasonably close to the observations, with the simulations of RWS in general better in the Southern Hemisphere. For the Northern Hemisphere, most models overestimate the subtropical RWS but underestimate the midlatitude RWS in both winter and summer. Many models even fail to simulate the seasonal source-sink shift of RWS in East Asia. Greatest intermodel differences are shown in East Asia, western North America in both seasons, and in the subtropical belt in winter hemisphere. Possible reasons for the model biases in RWS are further investigated. In the Southern Hemisphere, our analysis shows that model performance in simulating the local divergence, which might relate to the overly smoothed topography in Asia and western North America in the model, is most responsible for the biases of the RWS simulations. In the Southern Hemisphere, the bias in subtropical divergence pattern and tropical convection all contribute to the intermodel divergence of RWS simulation.

1. Introduction

Tropical heating associated with anomalous sea surface temperatures (SST) plays an important role in generating planetary-scale low-frequency disturbances in extratropical regions (Hoskins & Karoly, 1981; Lau, 1997; Trenberth et al., 1998). A simple theoretical explanation of this teleconnection is the “Gill-Hoskins picture” (Gill, 1980; Hoskins et al., 1977). In the tropics, the SST anomalies force anomalous convection and large-scale overturning Hadley circulation. The associated vertical motion and upper-tropospheric divergence (convergence) in the tropics (subtropics) result in anomalous vorticity. Such upper-level vorticity source, which is denoted as Rossby wave source (RWS) by Sardeshmukh and Hoskins (1988), always sets off Rossby wave trains that connect the tropical heating to extratropical atmospheric circulation in both hemispheres (Ambrizzi et al., 1995; Cook, 2001) and is suggested one of the main mechanisms responsible for the teleconnections (Qin & Robinson, 1993). For example, the Pacific-North American teleconnection pattern is suggested to be predominantly triggered by El Niño-Southern Oscillation (ENSO) (Horel & Wallace, 1981; Lin et al., 2005; Trenberth et al., 1998), and the Pacific-Japan pattern appears to be generated by strong convective activities over the Philippine Sea area associated with warmer SSTs there (Chen & Zhou, 2014; Gambo & Kudo, 1983; Wang et al., 2001). In the Southern Hemisphere (SH), the southern Australian rainfall is also influenced by both ENSO and Indian Ocean Dipole via atmospheric Rossby waves from the tropical Oceans (Cai et al., 2011). Those teleconnection patterns are the dominant atmospheric variability ranging from various time scales in both hemispheres and have strong impacts on the extratropical weather and climate. Furthermore, the tropical heating and the teleconnected extratropical circulation vary significantly in response to climate change (Held & Soden, 2006), which severely disrupt the global weather patterns and affect ecosystems and agriculture worldwide (Cai et al., 2015). Thus, examining the RWS and its components is worthwhile for not only understanding the mechanisms for the tropical-extratropical interactions but also improving the extratropical climate predictions and projections (Scaife et al., 2017).

Previous studies have pointed out that most of current climate models have great confidences in simulating the tropical SST (e.g., Kug et al., 2012) but still have significant deficiencies in simulating the extratropical conditions. A recent study by Qian et al. (2018) has found that the intermodel differences in simulating the RWS in the CMIP5 models are significant. This study aims to investigate the model performances in simulating the climatological RWS in both winter and summer using daily outputs from the Phase 5 of the CMIP5 models. The overall model performances in simulating the climatological RWS in both winter and summer are evaluated. The ensemble mean of the CMIP5 models can simulate the large-scale geographical distributions of the RWS reasonably close to the observations, with the simulations of RWS in general better in the Southern Hemisphere. For the Northern Hemisphere, most models overestimate the subtropical RWS but underestimate the midlatitude RWS in both winter and summer. Many models even fail to simulate the seasonal source-sink shift of RWS in East Asia. Greatest intermodel differences are shown in East Asia, western North America in both seasons, and in the subtropical belt in winter hemisphere. Possible reasons for the model biases in RWS are further investigated. In the Southern Hemisphere, our analysis shows that model performance in simulating the local divergence, which might relate to the overly smoothed topography in Asia and western North America in the model, is most responsible for the biases of the RWS simulations. In the Southern Hemisphere, the bias in subtropical divergence pattern and tropical convection all contribute to the intermodel divergence of RWS simulation.
circulation and the accompanied precipitation pattern (Boos & Hurley, 2012; Mehran et al., 2014). One cause of such unsatisfied model performance is the poor simulation skill of the tropic-extratropical teleconnections associated with the tropical SST. Weare (2013) and Lee et al. (2014), using monthly mean output data, evaluated the spatial patterns of the teleconnection in Phase 5 of the Coupled Model Intercomparison Project (CMIP5) models by accessing the teleconnection index and the leading empirical orthogonal function patterns. They showed that nearly all models can well reproduce the patterns of tropical atmospheric circulation associated with the tropical SST anomalies but the level of agreement with observation decreases evidently toward the extratropics. The reasons for such model biases remain unclear. This study aims to understand the model biases by assessing the simulation of the RWS in CMIP5 models. As the source of the teleconnection patterns, systematical assessment of the RWS simulation is necessary for improving the model ability in simulating both the tropical-extratropical connections and the extratropical climate variabilities.

Using the daily outputs of CMIP5 models, the present study evaluates the model simulations of the spatial pattern and the amplitude of climatological RWS. Though most models can capture the general spatial structure of RWS, strong model biases and model spread are found in East Asia and western North America in both seasons and in the subtropical belt in winter hemisphere. Some models even fail to simulate the source-sink shift of the RWS with seasons in those regions. Possible reasons for the model biases are further explored and discussed. The model performance in simulating the local divergence that likely relates to the overly smoothed topography is suggested most responsible for the biases of the RWS simulations. The structure of this paper is set as follows. Section 2 provides the introduction of the CMIP5 model output and diagnostic method for RWS. The model performance in simulating the RWS in winter and summer is examined in sections 3 and 4, respectively. Section 5 investigates the biases for different selected regions in multiple models, and section 6 investigates the possible causes for the model biases. Summary of the results and brief discussion are given in section 7.

2. Data and Analysis Methods

2.1. CMIP5 Model and Reanalysis Data

The model data used are outputs of 13 available global circulation model integrations performed for CMIP5, as listed in Table 1 (Taylor et al., 2012). For Rossby wave source, daily or higher-frequency data are needed due to the strong temporal variation of the involved terms (Simmonds & Lim, 2009); thus, we use the daily outputs of zonal wind $u$, meridional wind $v$ at 250 hPa of the historical simulations from 1979 to 2005 of each model experiment. To compare the model results with the observational statistics, the 27-year (1979–2005) European Center for Medium-Range Weather Forecasts reanalysis (ERA-Interim) 1.5° × 1.5° latitude-longitude gridded daily data at the same pressure level are also used (Dee et al., 2011).

In this study, each model's results have been constructed by interpolating to a common 1.5° × 1.5° grid comparable to the resolution of the ERA-Interim reanalysis data. The ensemble features in CMIP5 models are evaluated by comparing the multimodel ensemble mean and the observational reanalysis. The ensemble mean model bias is then defined as the difference between the multimodel ensemble mean and the reanalysis. The spread among model outputs is also estimated as in Gates et al. (1999), which refers to the standard deviation of outputs from the 13 CMIP5 models.

2.2. Diagnostic Framework

The RWS is derived from the barotropic vorticity equation in pressure coordinates as in Trenberth et al. (1998) and Holton and Hakim (2004):

$$\frac{\partial \zeta_a}{\partial t} + \mathbf{v} \cdot \Delta \zeta_a = -\zeta_a D - \mathbf{F},$$  \hspace{1cm} (1)

where $\zeta_a$ is the vertical component of absolute vorticity and $\mathbf{v}$ is the wind velocity. $D$ and $\mathbf{F}$ denote divergence and friction, respectively. The horizontal velocity field $\mathbf{v}$ can be further split into rotational $\mathbf{v}_r$ and divergent $\mathbf{v}_d$ components. By neglecting the terms involving the vertical velocity and friction, equation (1) can be rewritten as
\[ \frac{\partial \zeta_a}{\partial t} + \nabla \cdot \Delta \zeta_a = -\frac{\zeta_a D}{RWS} \]  

where the second term on the left-hand side is the advection of vorticity gradient by rotational wind, the term involving Rossby wave propagation. The two terms on the right-hand side are forcing terms and can be grouped into one term called RWS as in Sardeshmukh and Hoskins (1988).

Specifically, \(-\frac{\zeta_a D}{RWS}\) denotes the vortex stretching, representing the effects of upper-tropospheric divergence pattern on the vorticity change (Holton & Hakim, 2004; Vallis, 2006). For example, the regions of subtropical convergence associated with descending branch of local Hadley cell are always important source regions of upper-tropospheric Rossby waves. \(-\nabla \cdot \Delta \zeta_a\) denotes the advection of absolute vorticity gradient by the divergent flow. The regions with strong vorticity gradient (e.g., the regions of subtropical jet) are often preferable for the source/sink of Rossby waves as well. Therefore, equation (2) provides a diagnostic framework to quantify how the divergent flow, associated with the anomalous heating, leads to substantial forcing on the barotropic vorticity and acts as the RWS.

With the seasonal movement of tropical heating, RWS exhibits strong seasonality in both hemispheres (Lu & Kim, 2004; Shimizu & de Albuquerque Cavalcanti, 2011), inducing different teleconnection patterns in different seasons. Therefore, in this study, both the winter and summer climatologies of the RWS are assessed, with the seasonal means calculated from the daily value average. In the NH (SH), positive (negative) value indicates RWS, while negative (positive) value indicates Rossby wave sink.

### 3. Climatological RWS in Boreal Winter

The geographical distributions of December–February (DJF) RWS and its two components are examined in this section. Figures 1a and 1b show the global distributions of the RWS calculated from the ERA-Interim reanalysis and the ensemble mean of the CMIP5 models’ output. The main RWSs during winter in the Northern Hemisphere (NH) are located in East Asia, subtropical central and eastern Pacific, North America, subtropical North Atlantic, Mediterranean, and Arabian regions, as shown in Figure 1a. The ensemble mean of CMIP5 models in Figure 1b resembles the observed large-scale pattern. Figure 1c displays the standard deviation of simulated RWS between CMIP5 models. There is considerable scatter among the models’ results in subtropics, especially in East Asia, subtropical central Pacific, and western North America. The corresponding ensemble error of RWS relative to the observed mean is illustrated in Figure 1d as well. It is clear that the greatest discrepancy appears in East Asia and western North America.

In the SH, the subtropical RWS during DJF is much less intense, consistent with the relatively weaker tropical heating in the summer. The main wave sources, as shown in Figures 1a and 1b, are located over...
Intertropical South Pacific, South Atlantic (more intense), and South Indian Convergence Zones. The uncertainties and the ensemble error are also much smaller than the counterpart in the NH. The two components of RWS in DJF are also assessed in Figures 2 and 3, respectively. As shown in Figures 2a and 2b, the positions of peak vortex stretching are close to the locations of peak RWS in Figures 1a and 1b, with the amplitude of vortex stretching comparable to the total RWS as well. This suggests that the vortex stretching dominantly contributes to the total RWS in DJF. The ensemble standard deviation of vortex stretching (Figure 2c) shows that the principal intermodel disagreements occur in the subtropical regions, particularly in East Asia, central Pacific ocean, and western North America as well. Comparison between the model ensemble mean and observational reanalysis, as shown in Figure 2d, also displays that the model ensemble mean has greater deficiency in simulating the vortex stretching in East Asia and western North America.

Figure 1. The geographical distribution of December–February Rossby wave source (s$^{-2}$), (a) calculated from the ERA-Interim reanalysis and (b) the Phase 5 of the Coupled Model Intercomparison Project multimodel ensemble mean of year 1979–2005. (c) The intermodel standard deviation and (d) the ensemble error (multimodel ensemble mean minus observation). In panel (d), values above 95% confidence level using $t$ test are highlighted with gray dots.

Figure 2. As in Figure 1, but for the vortex stretching term in December–February.
America. The above results suggest that the model spread and model biases of the total RWS greatly attribute to the simulation of the vortex stretching.

The geographical distribution of DJF-averaged advection of vorticity by divergent flow is shown in Figure 3. The advection term mainly acts as a Rossby wave sink along the subtropical regions in the NH, which mildly compensates the strong RWS by vortex stretching. As shown in Figures 3a and 3b, the strongest sink appears in coastal East Asia. The other sink centers are located in Mediterranean, Arabian region, subtropical eastern Pacific Ocean, and Atlantic Ocean, and the model ensembles as a whole simulates a broadly realistic distribution of the advection term. The ensemble standard deviation of advection among CMIP5 models in Figure 3c shows that models have great disagreements along the narrow subtropical bands, with the greatest disagreements appearing at East Asia. Figure 3d displays the ensemble error of advection term relative to the observed mean. Strong model biases are observed over East Asian region as well.

Figure 3. As in Figure 1, but for the advection term of absolute vorticity by divergent flow in December–February.

Figure 4. The geographical distribution of June–August Rossby wave source (s$^{-2}$), (a) calculated from the ERA-Interim reanalysis and (b) the Phase 5 of the Coupled Model Intercomparison Project multimodel ensemble mean of year 1979–2005. (c) The intermodel standard deviation and (d) the ensemble error ( multimodel ensemble mean minus observation). In panel (d), values above 95% confidence level using t test are highlighted with gray dots.
To conclude, the DJF RWSs peak in the subtropics and are stronger in the NH. The vortex stretching dominantly contributes to the RWS, while the advection of vorticity gradient by divergent flow mainly acts as wave sink. CMIP5 models have large biases and disagreements along the subtropical regions, especially in East Asia and western North America. The biases and disagreements are dominantly contributed by vortex stretching.

4. Climatological RWS in Boreal Summer

The climatology of June–August (JJA)–averaged RWS is examined in Figure 4. The strong Northern Hemispheric RWSs in JJA are located over Mediterranean, Arabian, and Eastern Pacific close to North America, exhibiting evident seasonal difference compared to the situation in DJF. Specifically, East Asian region changes from vorticity source in DJF to vorticity sink in JJA, which is in agreement with earlier study by Lu and Kim (2004). In North Atlantic, the regions of RWS become much weaker and shrink to the eastern basin. The intermodel differences of JJA RWS are also investigated in Figure 4c. It is shown that the strong disagreements are found in the subtropical regions of Eurasia and North America.

Figures 5 and 6 further display the simulation of the two components of RWS in JJA. As shown in Figures 5a and 5b, the vortex stretching makes the dominant contribution to the total RWS in most regions of the NH. The ensemble standard deviation of vortex stretching (Figure 5c) shows that considerable scatters among models are located in Eurasia and North America as well. The advection term, as shown in Figures 6a and 6b, dominates the vorticity sink in East Asia, and the primary model uncertainties of the advection term are located along coastal East Asia (Figure 6c).

In the SH, the RWS shows similar spatial distribution to the DJF situation but with much stronger amplitude. As shown in Figures 4a 4b, the RWS peaks in the ITCZ located over South Indian, Pacific and Atlantic Ocean, and the regions in south of Australia. CMIP5 models have evident uncertainties in simulating the RWS over the subtropical areas as illustrated in Figures 4c and 4d. The vortex stretching in JJA acts as RWS along the subtropical South Indian Ocean, Australia, Eastern South Pacific, and South Atlantic Ocean, as shown in Figures 5a and 5b. The ensemble standard deviation of vortex stretching (Figure 5c) shows that models have greatest disagreement over these subtropical oceans as well. The advection of vorticity by divergent flow, as shown in Figures 6a and 6b, mainly acts as a vorticity sink and peaks in South Indian Ocean, central Australia, and western South Pacific Ocean. Considerable uncertainties are shown in these subtropical regions as well, as shown in Figures 6c and 6d.

In conclusion, the JJA RWS is relatively stronger in the Southern Hemispheric subtropics. The JJA RWS in NH exhibits evident seasonal variation. Subtropical regions such as East Asia vary from the source region of...
Rossby wave in DJF to the wave sink region in JJA. CMIP5 models have great biases and model spread in the SH subtropical bands and in East Asia, western North America. Many models cannot well simulate the source-sink shift in some Northern Hemispheric region such as East Asia. In the NH, the model performance in simulating the vortex stretching is the dominant contributor to the model biases, while in the SH the model biases and disagreements are determined by both vortex stretching and vorticity gradient advection by divergent flow.

5. Zonal Mean and Regional Biases in Multiple Models

5.1. Zonal Mean Features

We further investigate the biases of zonal mean and regional RWS simulations in each model. Figure 7 assesses the zonal mean features of RWSs in both seasons. In boreal winter, as shown in Figure 7a, the peaks of the RWSs are located at 30° N and 45° N in the NH and 40° S in the SH. Compared with the observation, the ensemble mean of model simulation overestimates the source in subtropics but underestimates the source in midlatitude region. Almost all models show their deficiency in simulating the extratropical peak of RWS. For example, in subtropics the GFDL-CM3 model doubles the wave source strength, while in extratropics the HadCM3 significantly underestimate the RWS strength. Almost all models and the model ensemble mean show biases in simulating the peak latitude of RWS in both hemispheres as well. Most models exhibit equatorward bias of the subtropical peak of RWS in both hemispheres, with the biases in the NH more evident. Figures 7b and 7c further display the zonal mean features of the vortex stretching and advection of vorticity by divergent flow, respectively. The biases of the RWS in strength and position stem from both of these two fields.

Similar analyses are also performed for JJA in Figures 7d–7f. The strongest RWS is located around 35° S associated with the seasonal variation of tropical convection. The subtropical source is mostly determined by the strong vortex stretching in the region. In the NH, the strong subtropical RWS source in DJF becomes wave sink in JJA; however, most models have deficiency in simulating this change, and greatest model spread is observed here. For example, BCC-CSM1.1, CNRM-CM5, and GFDL-CM3 all show a strong wave source feature in the subtropics. The model ensemble mean thus fails to represent such seasonal shift as well. Such evident model biases, as shown in Figures 7e and 7f, mostly come from the much stronger vortex stretching, which acts as a wave source in the model and overshoots the wave sink of vorticity advection by divergent flow.

5.2. Biases in East Asia and western North America during DJF

Since CMIP5 models exhibit strong disagreements in RWS simulation over East Asia and western North America especially during boreal winter, the detailed biases of each model in those two regions are
examined. The left column of Figure 8 plots the 100–140° E averaged distribution of DJF RWS and its two
components. As shown in Figure 8a, the peak of East Asian RWS is located at around 43° N, and the sink
peaks at 28° N. It is evident that the model ensemble mean underestimates both the source and sink by about
30% and exhibits a slightly equatorward bias. Such discrepancies of the intensity and central latitude of RWS
are mainly attributed to the vortex stretching as shown in Figure 8b. Advection of vorticity by divergent
flow plays a minor role.

The right column of Figure 8 displays the corresponding characteristics of RWS in western North America
sector (120–90° W). As shown in Figure 8d, the RWS center in western North American is located at
around 38° N in the reanalysis. The CMIP5 model ensemble mean positions the RWS center slightly

Figure 7. Zonal mean features of (a) Rossby wave source (s^2), (b) vortex stretching (s^2), and (c) advection of absolute
vorticity by divergent flow (s^2) during December–February (DJF). (d–f) As in (a)–(c), respectively, but for June–August
(JJA) average. The thin line denotes the features of each model, the bold solid red line is the multimodel ensemble
mean, and the bold solid black line is the observed value of each variable calculated from the ERA-Interim data set.
equatorward and tends to underestimate the peak of RWS. Both the vortex stretching and advection term contribute to such biases.

6. Possible Causes for the RWS Biases

The previous analyses have shown that most CMIP5 models exhibit strong biases in simulating the intensity and peaking latitude of the RWSs in East Asia, western North America, and SH subtropical belt in winter hemisphere. Based on the formation mechanisms of RWS as introduced in section 2, these biases may result from incorrect representation of the local thermodynamical process (i.e., vertical motion and resultant local

Figure 8. Zonal mean features of the December–February (a) Rossby wave source (s$^{-2}$), (b) vortex stretching (s$^{-2}$), and (c) advection term (s$^{-2}$) in the Asia sector (10–60° N, 100–140° E) for the ERA-Interim data set (black) and the Phase 5 of the Coupled Model Intercomparison Project ensemble mean (red). (d–f) As in (a)–(c) but for the western North America sector (10–60° N, 120–90° W). The shaded areas indicate ±1 standard deviation of intermodel spread.
divergence/convergence), the large-scale circulation (i.e., zonal wind), or the remote tropical convection (i.e., intertropical convergence zone, ITCZ, which is an important component of the upward branch of Hadley cell) thus can affect the subtropical divergence/convergence in the downward branch. We next strive to explore the relationship between the RWS biases and the biases in the above three processes.

6.1. Causes for the RWS Biases in East Asia and Western North America During DJF

We first examine the relation between the RWS bias and local thermodynamical process. The upper-level divergence is used to roughly represent the local thermodynamical process. Figure 9 shows the global distribution of the divergence in DJF and its bias in CMIP5 models. During DJF, the strongest tropical convection and the associated heating move to the SH. As shown in Figures 9a and 9b, the strongest divergence appears in intertropical Southern Indian, Pacific, Atlantic Ocean, and the adjacent continents. The strongest convergence is observed at around 10°–30° N, peaking at Arabian region, South Asia, central subtropical Pacific, and Atlantic. There are also two pronounced convergence centers over East Asia and western North America located in midlatitude. Standard deviation of divergence among CMIP5 models shown in Figure 9c illustrates that the regions with evident disagreements of RWS are also where the divergence/convergence amplitudes are strongest.

The relationship between RWS biases and local convergence biases is further quantified in Figure 10. The intensity bias of the RWS over East Asia shows evident linear relation to the intensity bias of local convergence. The latitude bias of RWS is strongly linked to the latitude bias of local convergence (Figures 10a and 10b) as well. Such strong linear relationships are also hold for North America region, as shown in Figures 10c and 10d. The results suggest that the RWS bias in East Asia and western North America are greatly attributed to the bias in local convergence. In East Asia and western North America, the local convergence is often related to the vertical motion that is modulated by the underlying topography. The above result implies that representation of the topography may contribute to the local convergence bias. As suggested by previous studies, coarse grid-scale GCMs are unable to resolve the complex topography thus have a biased representation of the regional vertical motion and resultant precipitation (Boos & Hurley, 2012; Cannon et al., 2017). CMIP5 climate models typically have horizontal grid resolutions between 0.9° and 3°. Such relatively coarse topography can produce unrealistic regional topographic forcing of weather and climate (Yorgun & Rood, 2014). Actually, as shown in Figure 1, the greatest discrepancy of RWS among CMIP5 models appears in East Asia and western North America with strong topography (e.g., Himalaya and Rocky Mountains). Models with finer horizontal resolution (e.g., CCSM4) have better performances in simulating...
the RWS. Thus, the overly smoothed topography in the models likely contribute to the RWS bias in East Asia and Western America.

The relation between the RWS bias and large-scale circulation bias is further examined in Figure 11. The background large-scale circulation is represented by the 250-hPa subtropical jet intensity and latitude. As shown in Figure 11, there is no evident linear relationship between the RWS bias and subtropical zonal wind bias for both intensity and central latitude. This is in agreement with the result in Scaife et al. (2017) that the model errors in teleconnection may not be due primarily to the errors in background winds in seasonal forecasts.

Finally, the relation of RWS bias with the remote tropical convection (e.g., ITCZ) is analyzed. The characteristic of the tropical convection is usually manifested by the ITCZ, which can be approximately represented by the upper-tropospheric divergence in tropics. Figure 12a plots the bias of the regional averaged RWS intensity over East Asia versus the bias of zonally averaged divergence intensity in tropics. There is no significantly linear relationship between the RWS intensity bias and tropical divergence intensity bias. The bias of the central latitude of the RWS in East Asia region versus the tropical divergence bias is plotted in Figure 12b. These two quantities correlate at $-0.68$, implying that the latitude-biased East Asian RWS may link to the latitude-biased tropical convection. The relation between RWS biases in western North America and tropical convection bias is further examined in Figures 12c and 12d. No significant linear relationships are found, suggesting that the biases in remote tropical convection play a minor role in the western North America RWS biases. The relations between regional RWS biases and tropical convection biases are also tested by examining

Figure 10. (a) Scatter plot of the intensity bias of East Asian Rossby wave source (RWS; 35–50° N, 100–140° E, unit: s$^{-2}$) versus the intensity bias of the divergence in the same area (unit: s$^{-1}$). (b) As in (a) but for the latitudinal bias (unit: degree). (c and d) As in (a) and (b) but for the western North America sector (35–50° N, 120–90° W).
the tropical precipitation, tropical SST, and the divergence in different tropical oceans (i.e., tropical Pacific Ocean, tropical Atlantic Ocean, and tropical Indian Ocean). All the results show that the biases of RWS in East Asia and western North America have no strong linear relation with tropical convection. The relations between regional RWS biases and tropical SST as well as precipitation are even weaker than that using tropical convergence/divergence to denote tropical convection (results thus not shown).

To conclude, model representation of the local divergence pattern is most responsible for the simulation of DJF RWS in East Asia and western North America where the topography is evident, implying that the overly smoothed topography may play an important role. In fact, the large-scale topography can affect the RWS in both thermodynamical and dynamical ways. The models’ relatively poor simulation skill in precipitation over the high mountain regions could induce significant diabatic heating bias aloft and thus result in evident bias in RWS. The topography can also affect the RWS dynamically by inducing the vortex stretching. Overly smoothed topography could result in RWS bias via such a dynamical way as well. Future studies are needed to further explore effects of the complex large-scale topography on the RWS and teleconnection patterns.

### 6.2. Causes for the Biases in SH Subtropical Belt During JJA

The causes for the JJA RWS biases in the subtropical belt are also briefly discussed. As shown in Figure 7d, the subtropical RWS bias in JJA is dominated by the intensity bias rather than the latitudinal bias; thus, only the causes for the RWS intensity biases in subtropics are identified. Similar to the above analyses, we explore the linkage between the RWS intensity bias and the biases in local thermodynamics, tropical convection, and large-scale background circulation. It is found that the subtropical intensity bias and the

Figure 11. (a) Scatter plot of the intensity bias of East Asian Rossby wave source (RWS; 35°–50° N, 100°–140° E, unit: s⁻²) versus the intensity bias of the regional averaged zonal wind (20°–35° N, 60° E–180°, unit: ms⁻¹). (b) As in (a) but for the latitudinal bias (unit: degree). (c) As in (a) but for the RWS bias of western North America (35°–50° N, 120°–90° W) versus the bias of the regional averaged zonal wind (20°–35° N, 120°–60° W, unit: ms⁻¹).

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The subtropical divergence intensity bias are significantly correlated at 0.85 as shown in Figure 13a, suggesting a dominant contribution of the subtropical divergence bias to the JJA RWS bias in subtropics. The correlation between the RWS intensity bias and the tropical divergence is 0.76 (Figure 13b), which suggests that the tropical convection makes contribution to the RWS bias as well. In contrast, the zonal wind bias has no apparent connection with the RWS bias, as shown in Figure 13c, suggesting the large-scale circulation plays a minor role in contributing to the RWS intensity bias.

**Figure 12.** (a) Scatter plot of the intensity bias of East Asian Rossby wave source (RWS; 35–50° N, 100–140° E, unit: s⁻²) versus the intensity bias of the regional averaged tropical divergence (10° S–10° N, unit: s⁻¹). (b) As in (a) but for the latitudinal bias (unit: degree). (c and d) As in (a) and (b) but for the western North America sector (35–50° N, 120–90° W).

subtropical divergence intensity bias are significantly correlated at 0.85 as shown in Figure 13a, suggesting a dominant contribution of the subtropical divergence bias to the JJA RWS bias in subtropics. The correlation between the RWS intensity bias and the tropical divergence is 0.76 (Figure 13b), which suggests that the tropical convection makes contribution to the RWS bias as well. In contrast, the zonal wind bias has no apparent connection with the RWS bias, as shown in Figure 13c, suggesting the large-scale circulation plays a minor role in contributing to the RWS intensity bias.

**Figure 13.** (a) Scatter plot of the intensity bias of the zonal mean June–August Rossby wave source (RWS; 25–45° S, unit: s⁻²) versus the intensity bias of the zonal mean divergence in the same region (unit: s⁻¹). (b) As in (a) but for the tropical convection (10° S–10° N, unit: s⁻¹) and (c) subtropical zonal wind (25–45° S, unit: ms⁻¹).
7. Summary and Discussion

The model performance in simulating the winter and summer RWS has been analyzed using the daily outputs of 13 different CMIP5 models. The main features of RWSs and the abilities of model simulations are summarized as follows.

- The observational RWSs are strongest in the subtropics in the winter hemisphere, due to the seasonal movement of tropical heating. Vortex stretching is the dominant source for generating the Rossby waves. Advection of vorticity by divergent flow acts as sink of Rossby waves, partly compensating the source effect of vortex stretching. In the NH, the main winter RWS regions are located over East Asia, subtropical Pacific and Atlantic Ocean, and North America. In summer, East Asia turns to wave sink because of the strong reduction of vortex stretching. In the SH, the main source regions lie in intertropical South Pacific, Atlantic, Indian convergence zones, and south of Australia, with much weaker seasonal variation.

- CMIP5 models can capture the basic geographical distribution of RWS, but most models overestimate the RWS intensity in the subtropics and underestimate the RWS in the midlatitude. Greatest disagreements among different models appear in East Asia and western North America in both seasons and in the subtropical belt in winter hemisphere. In East Asia, many models fail to simulate the source-sink shift of RWS in different seasons, due to the stronger-than-observational simulation of the vortex stretching in the model.

- Model representation of the local divergence pattern is found essential for the simulation of RWS. In the NH, the greatest biases of local divergence occur in East Asia and western North America where the topography is most evident, implying that the oversmoothed topographic effect likely plays a significant role. In the SH, biases of RWS simulation is strongly linked to the local divergence as well as the tropical convections. The background large-scale circulation such as the zonal wind is not the main cause of the biases of RWS simulation.

Reducing model biases in climatological RWS is fundamental for better simulating the tropical-extratropical interaction, which could also help advancing seasonal forecasting, climate prediction, and long-term climate projections. Based on our analysis, the extratropical RWS biases can be reduced by improving the simulation of local divergence/convergence pattern. Studies by Boos and Hurley (2012) and Cannon et al. (2017) suggest that relatively coarse grid-scale climate models are unable to resolve the complex topography, which can give rise to biased representation of the regional divergence/convergence pattern, vertical motion, and resultant precipitation. The analysis in this study further implies that optimizing the representation of the topography or enhancing the horizontal resolution might be helpful in improving the model simulation of RWS in extratropics. Actually, our analysis already shows that the CCSM4 model with finer horizontal resolution performs better in simulating the RWS. Our study also helps to understand the recent finding by de Souza Custodio et al. (2017), in which increasing the resolution in the climate model family results in a more realistic representation of spatial patterns of teleconnection. The improvement in simulating the teleconnection pattern may attribute to the better simulation of RWS. Through the RWS, the model performance in simulating the local divergence/convergence pattern may have a global impact with the teleconnection patterns.

In addition to the topography and horizontal resolution, parameterization schemes may also play a role in simulating the local divergence/convergence pattern. Previous studies (e.g., Han et al., 2016; Van Weverberg et al., 2012) have shown that parameterization schemes on convection, subgrid-scale cloud microphysical process of the convective clouds and resultant precipitation all can affect the convergence/divergence in models. Recent study by Sandu et al. (2019) suggests that parameterization schemes on topographic processes (e.g., turbulent form drag, low-level flow blocking, and mountain waves) may also impact on the atmospheric circulation. Optimizing the parameterization schemes could be helpful for further improving the RWS simulation.

In this study, the unsatisfied model performance in simulating the tropic-extratropical teleconnection is understood by assessing the model representation of RWSs. Besides the wave source, the teleconnection pattern also depends on the propagation of those Rossby waves. In extratropics, those waves triggered by tropical heating are always reinforced by nonlinear baroclinic eddy-mean flow feedbacks (Nie et al., 2014; Zhou et al., 2017) and atmospheric-ocean/land interactions (Fang & Yang, 2016; Xiao et al., 2016; Wang et al., 2019). A full understanding of the atmospheric response to tropical SST anomalies and the teleconnection pattern simulations must take into account the aggregate effects of the extratropical transient waves (Hoskins & Valdes, 1990) as well, which needs future investigations.
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