The influence of orographic Rossby and gravity waves on rainfall

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Orography is known to influence winter precipitation in Asia and the Indo-Pacific Ocean by mechanically forcing winds, but the dynamics involved in the precipitation response are incompletely understood. This study investigates how two types of orographically forced oscillatory motions alter time-mean winds and precipitation. The quasi-geostrophic omega equation is used together with previous ideas of “downward control” to develop a simple theory for the spatial distribution and amplitude of the vertical motion response to orographically forced stationary Rossby waves and gravity wave drag in a precipitating atmosphere. This theory is then used to understand the response of the boreal winter atmosphere to realistic Asian orography in a global numerical model that includes representations of moist processes and unresolved gravity wave drag. The effects of the orographically forced stationary Rossby wave and the gravity wave drag are isolated by incremental addition of wave sources in this model. The peak precipitation response to the forced Rossby wave is about a factor of three larger than that of the response to the gravity wave drag, but the wave drag response has a distinct spatial structure that dominates in some regions. Both the Rossby wave and the gravity wave drag perturb precipitation in regions distant from orography, producing shifts in the equatorial intertropical convergence zone, an increase in precipitation over South Asia, and drying in much of Northern Asia.

Key Words: Rossby waves; gravity waves; orography; rainfall; omega equation; Tibetan Plateau; moisture

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1. Introduction

The mountains and plateaus of Asia, which form the largest expanse of elevated terrain on Earth, are known to exert a great influence on precipitation during boreal summer and on the jet stream during winter. During summer, elevated terrain heats the troposphere and inhibits the horizontal mixing of dry and moist air, creating local and planetary-scale perturbations of rainfall (see reviews by Yanai and Wu 2006; Boos 2015). In winter, a wide spectrum of oscillatory motions are excited when the jet stream impinges on Asian orography; standing Rossby waves stretch around Earth’s circumference (Held et al. 2002) and smaller-scale gravity waves propagate vertically to break in the upper atmosphere, accelerating the mean zonal flow there (e.g., Teixeira 2014; Bühler 2014). Yet despite much previous study of orographically forced Rossby and gravity waves, little attention has been given to the precipitation perturbations that accompany these oscillatory motions.

It may at first seem logical that most work on orographically excited waves has focused primarily on horizontal flow (e.g., Nigam et al. 1988; Cook and Held 1992) or on vertical velocities local to mountain slopes (e.g., Trenberth and Chen 1988; Rodwell and Hoskins 2001), because humidities are low and precipitation is thus small over most continental interiors during boreal winter (e.g., Fig. 1a), when the mean flow that impinges on orography is strong. However, precipitation rates are high over the ocean surrounding Asia and there is a high degree of zonal asymmetry in precipitation in the Asian region during winter. Parts of continental Asia (e.g., eastern China) and much of the Indian and West Pacific Oceans receive more than half their annual rainfall during winter (Fig. 1b). Does orography exert a non-local influence on the spatial distribution of winter precipitation over and around Asia?

Orographically forced Rossby waves can be understood using potential vorticity conservation: when air flows over elevated terrain, the height of the air column changes so that planetary and relative vorticity must change in order to conserve potential vorticity. For westerly flows, this results in a succession of large-scale vortices to the east of the terrain (e.g., Holton and Hakim 2012, chapter 4). After some time, this wave train circumnavigates the planet and achieves a stationary pattern. In the presence of a temperature gradient, such as that which exists between Earth’s equator and its poles, these vortices will be accompanied by vertical motions according to the diagnostic \( \omega \) equation (e.g., Holton and Hakim 2012, chapter 6). In a moist environment, one also needs to account for condensation and precipitation; if precipitation can be thought to simply reduce the effective
static stability in ascending regions, moisture might then amplify vertical motions in the wave.

Elements of this picture of moist, quasi-geostrophic ascent in orographically forced stationary Rossby waves have been invoked in previous studies, though often without clear reference to the wave dynamics. Manabe and Terpstra (1974) showed that orography increased the zonal variability of precipitation in a 45-day time-average of one general circulation model (GCM). In particular, orography decreased precipitation over South Asia but increased precipitation over the West Pacific during their boreal winter simulation (their Fig. 9.1). Broccoli and Manabe (1992) found that, during boreal winter in a GCM, large-scale subsidence and infrequent storm development occurred upstream of the troughs of orographically induced stationary waves, contributing to dryness in the continental interiors of North America and Asia. Wills and Schneider (2016) showed that an idealized midlatitude mountain in a GCM with otherwise zonally symmetric boundary conditions produced a Rossby wave train that perturbed time-mean atmospheric moisture convergence (i.e., precipitation minus evaporation, P-E) from the midlatitudes all the way to the equator. They explained how most of this hydrological response could be explained as the precipitation needed to balance the vertical flux of moisture by time-mean ascent in the stationary wave. Yet none of these studies drew a direct connection between vortices in stationary Rossby waves and the quasi-geostrophic ascent expected to occur downstream of cyclonic parts of these waves; making such a connection is one of the goals of this paper.

Another goal of this paper is to examine the precipitation response to orographically forced Rossby and gravity waves in a unified framework. Orographic gravity waves (GW) propagate vertically across stratification surfaces and transfer angular momentum from their source to higher levels where they break, typically decelerating the flow (e.g., Bühler 2014). Because of their typically small horizontal scales (about 1-10 km), GCMs cannot resolve their influence and must parameterize their effects on the resolved flow (e.g., Alexander et al. 2010). Most studies of orographic gravity wave drag (OGWD) have focused on the zonal mean (e.g., Palmer et al. 1986; McFarlane 1987; Stephenson 1994). Yet Broccoli and Manabe (1992) showed that parameterized OGWD in their GCM enhanced the dryness of central Eurasia and contributed to other changes in annual mean precipitation. Recently, Shaw and Boos (2012) and Boos and Shaw (2013) used idealized analytical and numerical solutions to better understand how an upper-tropospheric westward torque, such as that produced by OGWD, can produce regional perturbations to precipitation. Shaw and Boos (2012) showed that the vertical motion response to an upper-level, subtropical westward torque confined to a band of longitudes generally consists of ascent on the equatorward side of the torque and subsidence on the poleward side. Boos and Shaw (2013) showed that these vertical motions were generally amplified in a precipitating atmosphere and that subtropical, upper-level torques could induce non-local perturbations in near-equatorial precipitation.

Although we are interested in the precipitation induced by orographic waves in general, we focus on the effects of Asian orography because it provides the largest source of OGWD and stationary Rossby waves on Earth (Held et al. 2002; Cohen and Boos 2016). We examine boreal winter conditions because the flow over Asian orography is stronger during that season and thus excites greater wave activity. We will show that orographic Rossby waves influence precipitation over both Asia and the surrounding ocean, and that OGWD also contributes significantly and distinctly to the organization of precipitation. To be clear, the effects of Asian orography on precipitation and winds during boreal summer involve an entirely separate set of mechanisms outside the scope of this paper; mountains and plateaus act as a heat source to drive local precipitation (Wu et al. 2012), and they also strengthen the interhemispheric South Asian monsoon by insulating its thermal maximum from the drying effects of extratropical air (e.g., Ma et al. 2014; Boos 2015).

This paper is structured as follows: the next section details the comprehensive atmospheric model used in this study. In section 3 we summarize the implications of the quasi-geostrophic \( \omega \) equation for the stationary Rossby wave response to an idealized orographic forcing, with an emphasis on the effects of moisture. A theoretical framework is constructed to estimate the moist response to orographically induced Rossby and gravity waves. Section 4 compares these estimates with results from the comprehensive atmospheric model that includes parameterized gravity waves and that accounts for moist processes. We focus on precipitation changes caused by the forced waves. We conclude and summarize our findings in section 5.

2. Methods

We use the atmospheric and land components of the Community Earth System Model (CESM) version 1.0.4. CESM is a comprehensive global climate model sponsored by the National Science Foundation and the U.S. Department of Energy. We
integrate the model with prescribed sea surface temperature, land ice, and sea ice, all with cyclic climatology but with no interannual variability. The horizontal resolution is about $1^\circ \times 1^\circ$ in the horizontal, with 42 vertical levels extending into the upper stratosphere. Here we present analyses of the last 40 years of 41-year long integrations. The OGWD parameterization used in the model is based on McFarlane (1987).

We use three integrations to investigate the effect of waves forced by flow over Asian orography. In the first, we remove (flatten) the Tibetan Plateau and other orography within the region $60^\circ-135^\circ$E, $22^\circ-55^\circ$N, and eliminate any tendencies produced by the OGWD parameterization in the same region. We refer to this integration as “FLAT”. In the second integration, we maintain all orography but keep the OGWD parameterization turned off in the aforementioned region (we call this integration “TOPO”). In the third integration, which is effectively a control, we maintain both the large-scale topography and the OGWD parameterization (denoted by “TOPO+GW”). We isolate the effects of large-scale orographic Rossby waves and small-scale orographic gravity waves by subtracting FLAT from TOPO and by subtracting TOPO from TOPO+GW, respectively. We do not perform an integration with only OGWD (but without grid-scale orography) because that seems unphysical; our integrations can be viewed as representing the incremental effects of raising orography while suppressing its effect on the subgrid-scale gravity wave field, then turning on the gravity wave drag. We present averages for boreal winter (December to February), when the orographically induced waves are strongest.

3. Theory

3.1. The moist $\omega$ equation

Consider the quasi-geostrophic (QG), hydrostatic, Boussinesq equations of motion on a $\beta$-plane with fixed stratification (e.g., Holton and Hakim 2012, chapter 6),

\begin{align}
\nabla \cdot \mathbf{u} &= 0, \\
\nabla ^2 \phi &= F, \\
\nabla ^2 \pi &= 0.
\end{align}

(1)

(2)

(3)

The first two equations are the zonal and meridional momentum equations where $(u, v)$ are velocities in the zonal and meridional, $(x, y)$, directions. An overbar denotes a geostrophic quantity and $\nabla = \partial _x + \tau _0 / \tau _y$ is the material derivative following the geostrophic flow. The Coriolis frequency is linearly expanded about latitude $\phi_0$ as $f = f_0 + \beta y$, where $f_0 = 2\Omega \sin \phi_0$, Earth’s rotation frequency $\Omega = 2\pi / 86400$, $\beta = 2\Omega \cos \phi_0 / \tau _0$, and $\tau _0$ is Earth’s radius. $F$ represents an external mechanical forcing, here assumed to be that produced by OGWD. Equation (3) is the moist thermodynamic equation where $b$ is the buoyancy, $w$ is the ageostrophic vertical velocity, and $N^2 = (1 - \epsilon)N_2$ is a reduced stratification that approximately accounts for the effects of precipitating convection. The dry stratification, $N_2$, is reduced to account for the fact that adiabatic cooling is offset by latent heat release in ascending regions, consistent with convective quasi-equilibrium theories for tropical dynamics (Emanuel et al. 1994). The precipitation efficiency $\epsilon$ is zero for a dry atmosphere but approaches one for a saturated atmosphere. Boos and Shaw (2013) showed that this approximation provides a good description of the precipitation response to OGWD in an idealized GCM. For simplicity, we assume that $N^2$ and $\epsilon$ are fixed. Finally, equation (4) is the mass continuity equation, where $z$ denotes the vertical coordinate and subscripts denote partial derivatives.

To obtain a moist $\omega$ equation, we add $-f_0 \partial_y \phi$ of equation (2) to $\partial_x$, of equation (3), then add $f_0 \partial_x \phi$ of equation (1) to $\partial_y$ of equation (3). This eliminate the $\nabla ^2 \pi$ terms in (1)-(3) through use of thermal wind balance, $f_0 \pi_z = b_y$ and $f_0 \pi_x = -b_x$. Additional manipulation using the geostrophic continuity relation $\pi_x + \pi_y = 0$ and definition of the vector $\mathbf{Q} = (Q_1, Q_2) = (\pi_x b_y, \pi_y b_x + \pi_y b_y)$ yields a set of two equations,

\begin{align}
N^2 w_x - f_0^2 u_x &= f_0 b_y \pi_z - 2Q_1, \\
N^2 w_y - f_0^2 v_z &= f_0 b_y \pi_z - 2Q_2 + f_0 F z.
\end{align}

(5)

(6)

By combining $\partial_x$ of equation (5) with $\partial_y$ of (6) and using (4), we obtain a moist $\omega$ equation,

\begin{align}
N^2 \nabla ^2 w + f_0^2 w_{zz} &= -2 \nabla \cdot \mathbf{Q} + f_0 \pi_z + f_0 F w_z. \quad (7)
\end{align}

This moist $\omega$ equation is essentially the same as the classic dry $\omega$ equation but with the dry stratification replaced by a reduced, moist stratification, and the acceleration due to OGWD included.

3.2. Ascent in stationary Rossby waves

On a $\beta$ plane, flow over orography induces Rossby waves due to conservation of potential vorticity (e.g., Holton and Hakim 2012, Chapter 4). With no momentum forcing ($F = 0$), the vertical velocity can then be diagnosed solely from the divergence of $\mathbf{Q}$ and the $\beta$-term that is nonzero in the presence of longitudinal temperature gradients (since $\pi_x \propto b_y$).

To simplify analysis we assume that meridional variations in temperature are much larger than zonal variations, i.e., $b \approx b(y)$, with $b_y$ negative and constant and our region of interest lying in the Northern Hemisphere. Then $\mathbf{Q} \approx (\pi_x b_y, \pi_y b_y) = -b_y(\pi_x, \pi_y)$, and the right-hand side of (8) is well-approximated by $2|b_y| \nabla ^2 \pi$. We further assume that eastward flow over the large-scale orography induces a zonally elongated wave train of positive and negative vorticity gyres, so that along a latitude circle through the center of this wave train the zonal derivatives of $\pi$ dominate $\mathbf{Q}$. In this idealized, zonally elongated wave train, the moist $\omega$ equation (8), simplifies to

\begin{align}
N^2 \nabla ^2 w &= -2|b_y| \pi_{xx}. \quad (9)
\end{align}

For example, across a cyclone $\pi_x > 0$ while across an anticyclone $\pi_x < 0$. Thus, east of a cyclone $\pi_{xx} < 0$ and ascent is expected, while to the west $\pi_{xx} > 0$ and descent is expected. The locations of these vertical motions in the orographic Rossby wave train are illustrated in Fig. 2.

To estimate the amplitude of vertical motion in the Rossby wave, we assume a plane wave solution by writing $\mathbf{Q} = (\pi, w) = (\tilde{\pi}, \tilde{w}) \exp(ikx)$, where $k$ is a zonal wave number, and for simplicity we assume that the amplitudes $(\tilde{\pi}, \tilde{w})$ are constants. Then

\begin{align}
-N^2 k^2 \tilde{w} &= -2|b_y|k^2 \tilde{v}, \quad (10)
\end{align}
and hence
\[ w = \frac{2b_0|\overline{v}|}{N^2} \exp(ikx). \]  

This confirms that ascent is expected in regions of poleward motion. Furthermore, \( w \) is amplified as \( \epsilon \) becomes larger; diabatic heating reduces the effective stratification as a larger fraction of the water condensing in updrafts precipitates without reevaporation. We estimate a rough scale for the basic state buoyancy gradient of \( b_y \sim 1.5 \times 10^{-7} \text{ m s}^{-2} \) by using thermal wind balance at 30°N with a 20 m s\(^{-1}\) change in zonal wind speed over 10 km of altitude. We also use scales of \( \overline{v} \sim 1 \text{ m s}^{-1} \), \( N^2 \sim 10^{-4} \text{ s}^{-2} \), and \( \epsilon = 0 \) for a dry atmosphere and \( \epsilon = 0.9 \) for a moist atmosphere. This yields
\[ |w|_{\text{dry}}^{\text{GW}} \sim 0.3 \text{ cm s}^{-1}, \quad |w|_{\text{moist}}^{\text{GW}} \sim 3 \text{ cm s}^{-1}. \]  

3.3. Ascent forced by orographic gravity wave drag

In a stratified atmosphere, flow over orography also induces gravity waves (e.g., Sutherland 2010). These waves can propagate vertically to high altitudes and their associated momentum flux can significantly alter the momentum budget of the atmosphere (e.g., Andrews et al. 1987). In the above equations, we used \( F \) to represent the acceleration of the large-scale flow by the net effects of gravity wave breaking at smaller scales (these smaller scales would be unresolved in a typical GCM).

We first consider the case in which horizontal temperature gradients are weak near the orography (i.e., \( b_x \approx b_y \approx 0 \)). It follows that equation (8) reduces to
\[ N^2 \partial^2_w w \approx f_0 F_{yz}. \]  

A subtropical, upper-tropospheric westward force is known to produce ascent on the equatorial side of the forcing and subsidence on the poleward side in what is known as the “downward control” response (Haynes et al. 1991). Shaw and Boos (2012) showed that the ascent and subsidence become strongly localized in longitude when the momentum forcing is localized in longitude, in both dry and moist models (Boos and Shaw 2013). For such a horizontally confined wave drag with a vertical structure similar to that of a first-baroclinic mode (as in Boos and Shaw 2013), we can use (13) to show that the vertical velocity induced by \( F \) scales as
\[ w \sim -\frac{f_0 AL}{4\pi^2 H N^2}, \]  

where \( A \) is the retrograde wave drag amplitude, \( L \) the horizontal scale of the drag, and \( H \) the vertical scale. A rough estimate of the vertical velocity amplitude can be achieved by using these approximate scales for a wave drag at 30°N: \( A \sim -30 \text{ m s}^{-1} \text{ day}^{-1}, L \sim 10^6 \text{ km}, H \sim 10 \text{ km}, \) and \( N^2 \sim 10^{-4} \text{ s}^{-2} \). The amplitude of \(-30 \text{ m s}^{-1} \text{ day}^{-1}\) is meant to represent the peak upper-level strength of the drag localized over Asian orography, and is consistent with typical estimates of the zonal mean OGWD being about an order of magnitude smaller (e.g., Palmer et al. 1986; McFarlane 1987; Shaw and Boos 2012). Again using \( \epsilon = 0 \) for a dry atmosphere and \( \epsilon = 0.9 \) for a moist atmosphere yields the vertical velocity scales
\[ |w|_{\text{dry}}^{\text{GW}} \sim 0.1 \text{ cm s}^{-1}, \quad |w|_{\text{moist}}^{\text{GW}} \sim 1 \text{ cm s}^{-1}. \]  

In the presence of a basic state temperature gradient (\( b_y \neq 0 \)), one also needs to account for the effect of the wave drag on the divergence of \( Q \). By taking the curl of the horizontal momentum equations (1) and (2), it becomes clear that a localized, single-signed torque will force a meridional dipole in relative vorticity, i.e. \( \nabla_t (\pi_x - \pi_y) + \ldots = -F_y \). This vortex dipole will be advected by the mean zonal flow (which is nonzero because \( b_y \neq 0 \)); more importantly, in the presence of a horizontal temperature gradient, it will also be accompanied by vertical motions described by the \( \omega \) equation. Similar to the case of stationary Rossby waves, one would expect to see ascent downstream of cyclonic parts of the flow. The exact location of these regions of ascent and subsidence will depend on the wavelength of the stationary Rossby wave excited by the torque and on how that Rossby wave is refracted by the mean flow. OGWD can thus be viewed as directly forcing vertical motions through a localized downward control mechanism, and indirectly producing vertical motions through the QG descent and subsidence that occur in Rossby waves excited by the wave drag.

Figure 2 illustrates the locations of the expected vertical motions due to the OGWD. The meridional dipole of ascent and subsidence that is centered on the orographic forcing is the localized downward control response that has been well-examined in previous studies. The alternating regions of ascent and subsidence downstream (east) of the orography are more speculative, and their magnitude and location will depend greatly on the interaction of the forced vorticity dipole with the basic state flow. These might interfere, constructively or destructively, with the vertical motions that accompany the stationary Rossby wave discussed in the previous subsection.

In the next section we use the theoretical ideas developed here to better understand the flow perturbations caused by the Tibetan Plateau during boreal winter, as represented by a comprehensive model that includes parameterizations of both OGWD and moist processes.

4. Results

Without the Asian orographic forcing, the climatological mean surface wind would largely flow from southwest to northeast during boreal winter over Central and Northern Asia, as evidenced by results from our FLAT integration (Fig. 3, arrows). The extratropical temperature field has a prominent meridional gradient in this model (\( T_y < 0, T_x \approx 0 \)), consistent with assumptions about the basic state made in the previous section on ascent in orographically forced Rossby waves.

We isolated the effect of large-scale orographic Rossby waves by subtracting the FLAT integration from the TOPO integration.
and examining differences that are significant at the 5% level. Flow over Asian orography generates a stationary Rossby wave train with a cyclonic gyre immediately to the east of the orography and an anticyclonic gyre to the northwest, as evidenced by the anomalous 300 hPa geopotential height, which is the streamfunction for the geostrophic wind at that level (Fig. 4a). As expected from the diagnostic $\omega$ equation, there is ascent to the east of the cyclone and descent to the west. Unsurprisingly, the precipitation anomaly is positively correlated with the vertical velocity anomaly, with stronger precipitation anomalies at lower latitudes where moisture is more abundant (Fig. 4c). The Rossby wave train bends southward to the east of the orography and an anticyclonic gyre to the northwest, as evidenced by the anomalous vertical motion produced by the OGWD parameterization (Fig. 4b) shows large deceleration (i.e., deposition of westward momentum) over Tibet at 100hPa (arrows).

In section 3, this acceleration was denoted by $F$ and was argued to produce ascent to the south and descent to the north of the upper-level westward forcing. That idealized, theoretical result is generally consistent with the anomalous vertical motion produced by the OGWD parameterization (Fig. 4b shows the statistically significant difference between TOPO+GW and TOPO). The anomalous vertical motion is accompanied by anomalous precipitation, with larger rainfall anomalies occurring closer to the equator (Fig. 4d). The peak anomalies produced by the OGWD have magnitudes roughly one-third of those produced by the orographic Rossby wave, but can dominate in select regions. The OGWD enhances precipitation over much of South Asia and in a zonally elongated band in the northern Bay of Bengal and West Pacific. Anomalous descent and suppressed precipitation occur northwest, rather than directly north of the forcing; Boos and Shaw (2013) also found that anomalous descent did not occur directly poleward of the forcing in idealized models, but could be offset in either zonal direction depending on model details and the basic state. There is also a zonally elongated band of anomalous subsidence and suppressed rainfall over the equator, which together with the band of anomalous precipitating ascent near 10°N indicates a northward shift of the ITCZ. While enhanced ascent in the basic state ITCZ is expected since the ITCZ lies on the equatorial side of the torque and the ascent response will be amplified in humid, precipitating regions due to the reduced moist static stability there, the anomalous subsidence that accompanies the ITCZ shift is less straightforward to explain. Nevertheless, Boos and Shaw (2013) found a clear poleward shift in the equatorial ITCZ in response to a subtropical westward momentum forcing, and attributed this shift to a reduction in equatorial eddy momentum flux convergence induced by the forcing.

The wave drag also induces a series of cyclones and anticyclones — a Rossby wave train — that alters vertical motion and rainfall in the presence of the wintertime meridional temperature gradient. Immediately east of the momentum forcing there is a small anticyclone (centered at 120°E, 30°N) with subsidence to its east, and east of that there is a cyclone with ascent to its east (Fig. 4b). The phasing of the vertical motion and horizontal wind anomalies is as described in our preceding theory section.

The location of the geopotential anomalies west of the OGWD forcing deserve some explanation. At 100 hPa, where the OGWD...
Figure 4. The large-scale effects of orographically forced Rossby waves and orographic gravity wave drag on geopotential height, vertical motion, and precipitation. Panels (a) and (c) show the isolated effect of the stationary Rossby wave directly forced by orography, obtained by subtracting the FLAT from TOPO integration. Panels (b) and (d) show the isolated effect of orographic gravity wave drag obtained by subtracting the TOPO from TOPO+GW integration. Panels (a) and (b) show the change in geopotential height at 300 hPa (black contours, in m) and 500 hPa vertical velocity (shading, in cm s$^{-1}$). Panels (c) and (d) show the change in 300 hPa geopotential height (black contours) and precipitation (shading, in mm day$^{-1}$). The gravity wave drag is denoted by arrows in panels (b) and (d). Solid contours show positive values and dashed negative. The contour interval in (a) and (c) is 20 m while in (b) and (d) it is 5 m. All panels show only statistically significant differences (at the 5% confidence level) computed using a bootstrap method with 200 iterations.

5. Summary and Discussion

Although much of continental Asia is very dry in boreal winter, some parts of Asia and large parts of the Indo-West Pacific ocean receive the majority of their annual precipitation during that season. Earlier studies have shown that orography influences Asian precipitation during boreal winter, producing strong zonal asymmetries (e.g., Manabe and Terpstra 1974; Broccoli and Manabe 1992; Wills and Schneider 2015, 2016). However, the dynamics responsible for the precipitation response to Rossby and gravity waves forced by realistic orography have not been previously examined in a unified framework and have remained incompletely understood.

Starting with what is essentially a summary and extension of prior theories, we showed that both orographically forced stationary Rossby and gravity waves are expected to exert significant and distinct influences on the large-scale structures of vertical motion and precipitation. Then we used these theoretical concepts to understand the detailed response to Asian orography during boreal winter, as simulated by a comprehensive numerical model.

Similar to Manabe and Terpstra (1974, their Fig. 9.1), we find that the stationary Rossby wave that is directly forced by Asian orography enhances precipitation over the West Pacific near Japan but reduces precipitation over much of northern and central Asia. Unlike previous studies of the stationary Rossby wave response to orography, we show clearly that the vertical velocity and rainfall patterns follow nicely from the diagnostic $\omega$ equation applied to the Rossby wave train. The precipitation perturbations are non-local and appear to be weighted by the basic state moisture content, with precipitation increasing over parts of South Asia and just north of the equator in the West Pacific and East Indian Oceans (Fig. 4c). Our arguments implicitly assume that time-mean vertical velocity anomalies determine the precipitation response to first order, with the contribution of transients being comparatively small. The general correspondence between vertical motion and precipitation anomalies in our
integrations qualitatively supports this, though there are certainly regions where precipitation changes do not exactly follow time-mean vertical velocity changes (e.g., over central Asia near 60°N in Fig. 4a, c). Broccoli and Manabe (1992) suggested that precipitation might be suppressed upstream of troughs in orographically induced stationary waves because of both time mean subsidence and the suppression of storm development, but Wills and Schneider (2016) found that most anomalies in vertically integrated moisture flux convergence created by a midlatitude mountain in an idealized GCM were associated with time-mean ascent.

Orographically induced gravity wave drag influences the precipitation field significantly during boreal winter, as the wave drag over Tibet is large during that season [Fig. 4b, d and Cohen and Boos (2016)]. The peak precipitation anomalies caused by the wave drag have amplitudes that are only one-third as large as those produced by the direct Rossby wave response to the orography, but the response to the wave drag can dominate in particular regions. The precipitation response to the OGWD is distinct and can be understood in terms of a zonally confined downward control response to the westward forcing, combined with the QG vertical motions that occur in the Rossby-wave train excited by the gravity wave drag. The localized downward control mechanism suppresses precipitation over northwest Asia, enhances it over most of South Asia, and produces a poleward shift of the ITCTZ over the near-equatorial Indo-West Pacific ocean (Fig. 4d). Many of these features of the precipitation response were predicted by Boos and Shaw (2013), but it was not obvious that results from their idealized models, which had zonally symmetric boundary conditions and an entirely oceanic lower boundary, would be relevant in more realistic models; furthermore, the forcing used by Shaw and Boos (2012) and Boos and Shaw (2013) was an imposed westward acceleration rather than a drag on the upper-level flow.

While the direct Rossby wave response to the continental-scale orographic forcing may be well-resolved and thus well-simulated by GCMs, the gravity wave drag is entirely parameterized in our model and may contain large errors. Indeed, Cohen and Boos (2016) found large differences in the magnitude and vertical structure of the climatological mean gravity wave drag over Asia parameterized by two different atmospheric reanalyses; the error in GCMs may be even larger because their grid-scale winds are not constrained by observations. Thus, the magnitude of the OGWD forcing in our GCM and the associated precipitation response may be greatly overestimated or underestimated. Although it is in some ways artificial to partition the precipitation response to orography into that produced by a directly forced Rossby wave and that produced by gravity wave drag, this partitioning may be useful until parameterizations of OGWD are better constrained.

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