Revisiting Mountains and Stationary Waves: the Importance of the Zonal Mean Response

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Key Points:

• Orography significantly alters tropospheric and stratospheric Northern Hemisphere winter zonal mean climate, impacting the stationary waves
• The dominant effect of orography is to amplify the pattern of wintertime stationary waves forced by land-sea contrast
• When orography is flattened stationary wave amplitudes are reduced to as little as 1/3 of the present day values

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Abstract

We revisit the impact of global orography on wintertime climate using a state-of-the-art climate model, with sophisticated parameterization of the impacts of sub-gridscale orography (the Whole Atmosphere Community Climate Model, WACCM). The main impact of orography is to amplify the stationary waves produced by land-sea thermal contrasts, as evidenced by the strong spatial resemblance between the stationary wave pattern in a no-mountain (NM) simulation with that induced by orography. Orography amplifies extratropical NM stationary waves at all levels, with an amplification factor of $a \sim 1.6$ in the mid-latitudes, increasing to $a > 1.9$ in the high-latitude stratosphere. Orography also decelerates the zonal mean zonal wind poleward of 40°N throughout the troposphere and stratosphere. The effect of the weakening of the zonal winds on stationary waves is twofold: it amplifies the thermal forcing and it amplifies the planetary-wave response to a prescribed thermal forcing.

1 Introduction

Earth’s atmospheric stationary waves are seen in the planetary scale wave-like structure in climatological sea level pressure or geopotential height. In the Northern Hemisphere the dominant features of the wintertime stationary waves are so prominent that they have been given names: the Aleutian low, the Icelandic low, and the Siberian high. The forcing of stationary waves is provided by planetary features that are, unsurprisingly, largely stationary: orography (Charney & Eliassen, 1949; Bolin, 1950), and zonal asymmetries in atmospheric heating, typically from land-sea contrasts (e.g. Smagorinsky, 1953; Manabe & Terpstra, 1974; Hoskins & Karoly, 1981; Valdes & Hoskins, 1991).

From the 1980s to 2010 numerous studies examined the relative contributions of ‘orographic’ and ‘thermal’ forcing to the observed stationary waves. This research, collectively using linear and non-linear stationary wave models, as well as full general circulation models (GCMs), has shown that orography produces anywhere between 30% and 66% of the observed stationary wave amplitude, with recent estimates towards the lower end of this range (Held, 1983; Chen & Trenberth, 1988a, 1988b; Nigam et al., 1988; Valdes & Hoskins, 1989; Ting et al., 2001; Held et al., 2002; Chang, 2009). The authors’ impression is that the value of 30% from the review of Held et al. (2002) is often taken as the best estimate of the role of mountains, even if it were not intended as such. The large range of results can be at least partially understood from differences in the background flow into which the orography was placed, including differences in low-level winds (e.g. Valdes & Hoskins, 1989; Held & Ting, 1990; Ringler & Cook, 1995; Held et al., 2002), as well as model differences in atmospheric dissipation strength and imposed drag (Valdes & Hoskins, 1989).

Much less attention has been paid to the impact of orography on the axisymmetric flow. As Held et al. (2002) noted, the tropospheric zonal mean zonal wind structure is broadly similar between the Northern and Southern hemispheres (NH and SH), suggesting that the orography of the NH has relatively little impact in the troposphere, consistent with earlier modelling results (Manabe & Terpstra, 1974). Conversely, a strong asymmetry exists between the wintertime zonal mean stratospheric jets in each hemisphere, caused by large differences in wave activity generated by land-sea contrasts and orography (Waugh & Polvani, 2010; White et al., 2018). Early modelling results suggest that orography reduces the speed of the NH winter stratosphere jet by approximately 15% (Manabe & Terpstra, 1974), although large biases in that model existed. In a modern GCM, White et al. (2018) found that the presence of the ‘Mongolian mountains’ of Asia alone reduces zonal mean stratospheric wind speeds in winter by up to 40%.

In addition to acting as a large-scale obstruction to the flow, orography impacts the climate through subgrid-scale orographic drag, through the forcing of orographic gravity waves, as well as the blocking of flow (e.g. McFarlane, 1987; Shaw et al., 2009; Sig-
inclined gravity wave parameterization of orographic effects substantially increases zonal mean sea level pressure in the high latitude NH (shown in the appendix of Broccoli & Manabe, 1992), and will thus impact the low-level zonal mean zonal wind ($U$). Parameterizing the effects of orographic drag reduces tropospheric $U$ (Sandu et al., 2016) and alters stationary waves (van Niekerk et al., 2017; Sandu et al., 2019). The representation of such impacts within GCMs has improved in recent years, through both increased resolution, and improved parameterizations (Garcia et al., 2007; Richter et al., 2010; Garcia et al., 2016), although limitations and biases still exist (Sandu et al., 2019). The time therefore seems ripe to re-evaluate the role that orography plays in the wintertime climate using a state-of-the-art climate model.

Using NCAR’s Whole Atmosphere Community Climate Model (WACCM), we quantify the total role of orography on the observed stationary waves, including both local and remote changes in diabatic heating, as well as changes in SSTs due to air-sea heat fluxes. We present evidence for a substantial impact of orography on the zonal mean climate in both the troposphere and stratosphere, and highlight the remarkable similarity between the stationary wave patterns from ‘land-sea forcing’ and from ‘orographic’ forcing, offering a new perspective on how orography influences the stationary waves. We propose that the most important impact of orography on stationary wave amplitude is to amplify the ‘land-sea’ stationary waves, in addition to forcing a stationary wave pattern of its own, as in the traditional view.

2 Models and Experiments

We use the WACCM4, an atmospheric dynamical model with 66 vertical levels, including a well-resolved stratosphere (Marsh et al., 2013). In addition to high resolution in the upper atmosphere, the WACCM has improved parameterizations of vertically propagating gravity waves and surface stress from unresolved topography (termed turbulent mountain stress, TMS), relative to the lower-top CAM model (Garcia et al., 2007; Richter et al., 2010; Marsh et al., 2013). A horizontal resolution of 1.9°x 2.5°is used.

Mountains are known to affect the ocean circulation (Kitoh, 2002; Sinha et al., 2012) through impacts on wind stress and freshwater fluxes (Warren, 1983; Emile-Geay, 2003). Here we focus on the dynamical atmospheric response to global mountain ranges and do not consider dynamical ocean changes. Orographic forcing can also influence SSTs through air-sea heat fluxes (Okajima & Xie, 2007; Chang, 2009). This influence may affect the impact of orography on diabatic heating, in the past considered to be small (Held, 1983).

Since the WACCM is not currently coupled to a slab ocean, we allow atmospheric changes to affect SSTs by using simulated changes in monthly climatological SSTs from a slab-ocean model coupled to the CAM model with and without orography. The NH extratropical SSTs for each experiment, as well as the CTL-NM difference, are shown in supplemental Fig. S1.

To investigate the role of orography in shaping the stationary waves, two WACCM simulations are performed, each 30 years in length (following a one year spin-up period). The ‘CTL’ simulation has present-day topography, and the ‘NM’ (No-Mountain) simulation has all topography flattened to 50m above sea level. In addition to the topographic height, we reduce the variables associated with subgrid-scale variability in orography, ‘SGH’ and ‘SGH30’, to approximate values associated with regions of low orography in the CTL simulation (30 and 10 m respectively).

The WACCM model reproduces tropospheric and stratospheric circulations well, albeit with a cold pole bias (Marsh et al., 2013). Throughout this paper we further evaluate the WACCM by comparing it with the ERA-interim re-analysis data (Dee et al., 2011).
3 Results

The stationary wave pattern can be seen in the eddy geopotential height, $Z' = Z - \overline{Z}$, where the overbar denotes the zonal mean. Fig. 1 shows $Z'$ at 60°N for ERA-I, the CTL and NM simulations, and the CTL-NM difference. The CTL simulation reproduces the observed pattern from ERA-interim re-analysis data well (compare Figs. 1a and b). The climate in the CTL and NM simulations, and thus the climate response to orography (CTL-NM), is broadly similar to that found in earlier studies (e.g. Nigam et al., 1986; Held, 1983; Held et al., 2002). The orographic response (CTL-NM) and NM pattern are generally of similar magnitude.

To provide a quantitative metric for comparing the relative contributions of orography and land-sea contrast, we calculate the ‘stationary wave strength’, defined as the longitudinal standard deviation ($\sigma$) in $Z$. The ‘orographic contribution’ is calculated as $(\sigma(Z_{\text{CTL}}) - \sigma(Z_{\text{NM}}))/\sigma(Z_{\text{CTL}})$. There is substantial variation in the orographic contribution with latitude and height (see supplemental Fig. S2a), with a maximum value of $\sim 85\%$ in the high latitude stratosphere, and a latitude-weighted value in the NH mid-latitudes (30-70°N) of approximately 45% throughout the troposphere and stratosphere.

In idealized simulations, the stationary response to a single mountain has a zonal wavenumber of around 4-6 (Hoskins & Karoly, 1981; Valdes & Hoskins, 1991; Cook & Held, 1992; Held et al., 2002; White et al., 2017). In contrast to these idealized studies, the CTL-NM response has a wavenumber, phase, and vertical structure remarkably similar to that in the NM simulation (compare Figs. 1c and d), with a pattern of approximately wavenumber 2 in the troposphere, and wavenumber 1 in the stratosphere. That is, the first order effect of the mountains is to amplify the mid-latitude stationary wave pattern that is already present as a consequence of the land-sea contrast.

This amplification of the land-sea stationary wave pattern (NM) in the CTL simulation can also be seen in maps of $Z'$ (Fig. 2). A comparison of $Z'$ between ERA-I and our CTL simulation shows that the WACCM simulates the observed spatial pattern of stationary waves well at both 300 and 1000 mb (c.f. Fig. 2a with 2b and Fig. 2d and 2c; colours show the eddy component, whilst black contours show the full fields). The NM eddy fields (Figs. 2c and f) exhibit a spatial structure similar to that of the CTL fields, but with muted amplitude; the first order effect of orography is to greatly amplify this pattern.

We calculate the Pearson correlation coefficient between the CTL-NM and NM fields, with masking for points that are below the surface in the CTL simulation. At 1000, 300, and 30 mb respectively, the latitude-weighted correlation coefficients for the mid-latitudes are 0.33, 0.60, and 0.81, thus confirming that a large component of the CTL-NM response is to amplify the background stationary wave pattern present in the NM simulation, particularly above the lower troposphere. To provide a quantitative metric for the strength of this amplification by orography we define an ‘amplification factor’, $a$, as the slope of the linear regression between the CTL and NM fields; we can thus write $Z'_{\text{CTL}} = aZ'_{\text{NM}} + Z'_M$, where $Z'_M$ is the orography-induced change in eddy geopotential height that does not project onto the NM pattern. The latitude-weighted mean amplification factor $a \sim 1.6$ throughout the troposphere and stratosphere. Vertical cross-sections of both the correlation coefficient and amplification factor are shown in supplemental Figs. S2b and c.

4 Zonal mean response to orography

In addition to the stationary wave response, orography substantially shapes the wintertime zonal mean zonal wind climatology. Figure 3 shows a pole-to-pole meridional cross-section of $\bar{U}$ (colours), and $\bar{Z}$ (black contours) for winter in each hemisphere, i.e. DJF in the NH and JJA in the SH. Fields are masked between 10°S and 10°N to emphasise the discontinuity at the equator. The WACCM reproduces the general structure of the
Figure 1. Eddy geopotential height, $Z'$, at 60°N: a. ERA-I, b. CTL, c. NM, and d. CTL - NM.
Figure 2. DJF $Z$, full fields (black contours; zero contour bold) and zonal anomalies ($Z'_0$; colours), at 1000 mb (left), and 300 mb (right). Top row: ERA-I; centre: CTL, and bottom row: NM. Prominent highs and lows in the full fields are denoted with H and L respectively. At 300 mb the contour interval for the full fields for CTL and NM is 200 m, whilst at 1000 mb the contour interval is 20 m.
wintertime geopotential and zonal jets in both hemispheres well, including the difference in strength of the NH and SH stratospheric jets (c.f. Figs 3a and b). The NM fields (Fig. 3c) show much greater symmetry between the NH and SH, as expected. At 10 mb the NH wintertime stratospheric jet in the NM simulation is only ~ 10% weaker than its SH counterpart: orography thus plays a dominant role in the hemispheric differences in the stratospheric winter jet (see also White et al., 2018).

Fig. 3d shows the CTL-NM differences in the zonal mean fields. The orographic impact on the NH stratospheric jet is substantial: at 10 mb the jet reaches 82 m/s in the NM simulation, in contrast to 39 m/s in the CTL (c.f. figures 3b and c). Consistent with previous understanding (e.g. Held et al., 2002), changes in the sub-tropical jet are small. There is, however, a significant orographically-induced weakening of tropospheric U north of 50°N, extending all the way down to the surface. Whilst the absolute magnitude of the near-surface changes is small relative to the stratospheric changes (~ 3m/s at 925 mb between 50-80°N), it has a profound effect on the character of the low-level flow.

To explore the mechanisms behind the weakening of U in CTL relative to NM, Fig. 4 shows the Eliassen-Palm (EP) wave activity flux and its divergence (Eliassen & Palm, 1961; Andrews & McIntyre, 1976; Edmon et al., 1980). Arrows are scaled (see caption), and thus should not be used to estimate divergence. The EP fluxes are calculated based on climatological wintertime data, that is, they show the propagation of stationary wave activity, and the impacts of the stationary waves on the zonal mean flow. Positive divergence of the EP fluxes signifies a strengthening of the zonal mean flow by the waves (Andrews & McIntyre, 1976; Edmon et al., 1980).

The CTL simulation reproduces the ERA-I spatial pattern of stationary wave EP fluxes, and their divergence, relatively well (c.f. Figs. 4a and b), although the magnitude of EP flux divergence in the mid-latitude troposphere is underestimated; we thus avoid making quantitative conclusions based on this analysis. The EP flux arrows show a reduction in the propagation of wave activity strength away from the surface in the NM simulation relative to the CTL (c.f. Figs 4b and c). Stationary wave activity is still present in the troposphere in the NM simulation: the land-sea forcing is sufficient to produce substantial tropospheric wave activity at lower latitudes; however the strong EP flux divergence north of 40°N is absent in the NM simulation. There is also a stark absence of wave activity (and thus divergence) reaching into the stratosphere in the NM simulation. Calculation of EP fluxes on daily data confirms that stationary waves dominate the stratospheric CTL-NM response, consistent with a relatively small propagation of transient waves into the stratosphere (Li et al., 2011).

5 Discussion

The impact of global orography on the wintertime wind climatology is examined with the WACCM, a state-of-the-art climate model, revisiting the seminal work of the 1980s and 1990s. The influence of orography on the NH mid-latitude stationary waves is generally comparable to land-sea thermal contrasts, with orography dominating in some parts of the troposphere and stratosphere. This is consistent with previous work, but suggests a larger role for orography than the most recent estimates (Held et al., 2002; Ting et al., 2001; Chang, 2009). We highlight the remarkable similarity between the NM stationary wave pattern and the CTL-NM response, concluding that the first-order role of orography is to amplify the stationary wave pattern that would be present by virtue of the land-sea contrast alone. The amplification factor, a measure of how much orography amplifies the NM stationary wave pattern, is approximately 1.6 for the troposphere, and 1.8 for the stratosphere.
Figure 3. Wintertime (DJF for NH, JJA for SH) $\overline{U}$ (colours), and $\overline{Z}$ (black contours, contour interval 200 m for a-c and 100 m for d; negative values dashed and 0 contour bold), for a. ERA-I, b. CTL, c. NM, and d. CTL - NM. Wintertime fields are shown for both hemispheres; values are masked between 10°S to 10°N.
Figure 4. Wintertime (JJA for SH, DJF for NH) stationary wave Eliassen-Palm flux (arrows, m/s$^2$) and flux divergence (colours, m/s/day) for a. ERAI, b. CTL and c. NM. The EP flux follows the scaling of (Edmon et al., 1980) for log-pressure coordinates, and divides by the square root of 1000/pressure to aid visualization (Taguchi & Hartmann, 2006). Wintertime fields are shown for both hemispheres; values are masked between 10°S to 10°N.
In addition to the amplification of the stationary waves, orography has a strong impact on the zonal mean flow poleward of 40°N. Without orography, the NH wintertime polar night jet is much stronger than in observations and the WACCM CTL simulation, and is comparable to the strength of the SH wintertime stratospheric jet. The strong sensitivity of the NH stratospheric winter jet to the inclusion of mountains is consistent with the concept of a positive feedback in stratospheric zonal wind: faster stratospheric flow limits the waves that can propagate into the stratosphere to smaller wavenumbers (Charney & Drazin, 1961); this reduces the Eliassen-Palm flux convergence in the stratosphere, further enhancing the zonal wind. Our results suggest that, in the absence of orography, very little stationary wave activity is able to propagate into the stratosphere. The impact of orography on zonal winds extends all the way down to the surface poleward of ~50°N.

This profound impact of orography on the zonal mean flow can be connected to the orographic amplification of the land-sea stationary wave that we have highlighted. For low-level extratropical heating, the amplitude of the stationary wave response to a given diabatic heating profile is inversely proportional to the low-level mean zonal wind (Held & Ting, 1990). The linear model of Held and Ting (1990) shows a stationary wave amplitude response to low-level wind changes of the same order of magnitude that we see in our simulations: an amplification of ~1.6 for a reduction in $U$ from, for example, ~6 m/s (NM) to 2 m/s (M).

In addition to the reduction in stationary wave amplitude for a fixed diabatic heating, deceleration of the zonal mean flow allows stronger zonal temperature gradients (from land-sea contrast) to be maintained; in the limit of infinite zonal flow, no zonal temperature gradients could be maintained. Thus a reduced zonal flow can enhance the diabatic heating pattern from land-sea contrast, leading to an amplification of the ‘thermal’ stationary wave pattern. Supplemental Fig S1 shows that the diabatic heating patterns are indeed enhanced in the CTL simulation relative to NM.

The positive feedback of stratospheric zonal wind speed, discussed above, may provide an additional mechanism by which orography amplifies the existing stationary wave in the stratosphere: in the presence of orography, enhanced stationary wave EP flux convergence in the stratosphere weakens the stratospheric jet; this in turn enhances the probability of waves generated by land-sea contrast being able to propagate into the stratosphere. This mechanism differs somewhat from that discussed by White et al. (2018), who removed individual mountain regions; this difference suggests non-linear interactions between different orographic regions. The amplification of the NM stationary wave pattern by the orography may also be affected by the location of the main orographic features of the NH. Both the North American Rockies and the dominant orography in Asia are located approximately 30° longitude upstream of the eastern edge of a continent; the mechanical forcing of the orography results in northerly flow and cold advection downstream of the mountain range, which is thus, rather coincidentally, located such that it enhances the existing land-sea temperature contrast (e.g. Brayshaw et al., 2009).

The impact of orography is reduced when SSTs are held fixed to the observed climatology in both the CTL and NM simulations (shown in Supplemental Fig. S3). The degree of correlation between the CTL-NM and NM patterns, and the orographic amplification factor, are also reduced (although still present). This lower boundary condition may thus be part of the reason that this amplification effect has remained largely unnoticed up until now. In retrospect, this ‘constructive interference’ can be seen to some degree in earlier studies, even when SSTs were fixed to observed values in both the CTL and NM simulations. Held (1983), Held et al. (2002) and Chang (2009) mention a constructive interference between the thermal forcing and the orography forcing between 120E and 60W, but did not explore this further.
This work offers a new perspective of how orography shapes Earth’s stationary waves: orography provides a substantial amplification of the background, land-sea generated, stationary wave pattern, through the impact of orography on the zonal mean flow, as well as forcing an additional stationary wave pattern.

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References


Garcia, R. R., Smith, A. K., Kinnison, D. E., Câmara, Á. d. l., & Murphy, D. J. (2016). Modification of the gravity wave parameterization in the whole at-
mosphere community climate model: Motivation and results.  

In R. P. P. B J Hoskins (Ed.), *Large-Scale dynamical processes in the atmosphere* (pp. 127–167).  
Academic Press.


Manabe, S., & Terpstra, T. B. (1974). The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments.  


*J. Atmos. Sci.*, 45(9), 1433–1452.


*J. Atmos. Sci.*, 52(14), 2548–2560.

*J Adv Model Earth Syst.*, 8(1), 196–211.

*npj Climate and Atmospheric Science*, 2(1), 10.

*J. Clim.*, 22(10), 2726–2742.

*J. Clim.*, 23(6),


Supporting Information for Revisiting Mountains and Stationary Waves: the Importance of the Zonal Mean Response

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1. Figures S1 to S3

Introduction This supporting information provides additional figures to supplement the main text.
Figure S1. Supplemental Fig. S1. DJF fields for ERA-I (top row), CTL (2nd row), NM (3rd row) and CTL-NM difference (bottom row). Left: sea surface temperature; centre: mass-weighted average diabatic heating between 1000-850 mb; right: mass-weighted average diabatic heating between 850-500 mb. Note the change in colour scale for the CTL-NM plots.
Figure S2. Supplemental Fig. S2. Cross-section of DJF metrics of orographic impact on stationary waves. a. orographic contribution to stationary wave strength \( ((\sigma(Z_{CTL}) - \sigma(Z_{NM}))/\sigma(Z_{CTL})) \); b. Pearson correlation coefficient between CTL-NM and NM fields; c. orographic amplification factor (the slope of the linear regression between the CTL and NM fields).
Figure S3. Supplemental Fig. S3. As Fig. S2, but for simulations where SSTs are fixed to observed values in both CTL and NM experiments.