Revised: 31 March 2020

# Impacts of wind profile shear and curvature on the parameterized orographic gravity wave stress in the Weather Research and Forecasting model

Xin Xu<sup>1</sup> | Miguel A. C. Teixeira<sup>2</sup> | Ming Xue<sup>1,3</sup> | Yixiong Lu<sup>4</sup> | Jianping Tang<sup>1</sup>

<sup>1</sup>Key Laboratory of Mesoscale Severe Weather, Ministry of Education, and School of Atmospheric Sciences, Nanjing University, Nanjing, P. R. China

<sup>2</sup>Department of Meteorology, University of Reading, Reading, UK

<sup>3</sup>Center for Analysis and Prediction of Storms, and School of Meteorology, University of Oklahoma, Norman, Oklahoma

<sup>4</sup>Beijing Climate Center, China Meteorological Administration, Beijing, P. R. China

### Correspondence

X. Xu, School of Atmospheric Sciences, Nanjing University, No. 163, Xianlin Avenue, Nanjing, Jiangsu, 210023, P. R. China. Email: xinxu@nju.edu.cn

### **Funding information**

National Natural Science Foundation of China, Grant/Award Numbers: 41505046, 41750965, 41875068, 91837207

## Abstract

The parameterization of orographic gravity wave drag (OGWD) in the Weather Research and Forecasting model is extended by including the second-order Wentzel-Kramers-Brillouin (WKB) corrections to the surface wave momentum flux (SWMF) caused by wind profile shear (WSHR) and curvature (WCUR) effects. Simulations of the atmospheric circulation are performed to study the behaviour and impact of the WKB corrections. In January, the SWMF is weakened in the Northern Hemisphere (NH) midlatitudes by the WSHR term, while the WCUR acts to enhance the SWMF over Antarctica. In July, the WSHR corrections are similar to those in January, whereas the WCUR term produces corrections of opposite sign in the high latitudes of each hemisphere. The latter is attributed to the increase of near-surface winds in the cold season which reverses the low-level wind profile curvature. The seasonal reversal of the WCUR term contradicts previous findings obtained from offline evaluation using reanalysis datasets. This may be due to the different OGWD parameterization schemes used, or it may suggest a sensitivity to the height at which the wind profile effects are evaluated. Changes in the SWMF can affect the vertical distribution of parameterized OGWD. In January, the OGWD in the NH midlatitudes is decreased in the lower troposphere but increased in the upper troposphere. This is because a reduced SWMF inhibits wave breaking in the lower troposphere. Therefore, more wave momentum flux (WMF) is transported to the upper troposphere which enhances wave breaking there. The increased upper-tropospheric wave breaking in turn decreases the WMF propagating into the stratosphere where the OGWD is reduced. In July, the reduction of SWMF over Antarctica is more notable than in the NH midlatitudes in January. Consequently, the OGWD is weakened in the upper troposphere over Antarctica.

### **KEYWORDS**

gravity waves, orography, parameterization, wind profile effects, WKB approximation

RMet?

# **1** | INTRODUCTION

It has been widely recognized that the momentum transport by orographic gravity waves (OGWs) greatly affects the general circulation, especially in the middle atmosphere (e.g., Alexander *et al.*, 2010). In general circulation models, the transport and deposition of momentum by OGWs are treated via the parameterization of OGW drag (OGWD; Kim *et al.*, 2003) due to the small horizontal scales of OGWs as compared to the model grid spacing, that is, the OGWs are of subgrid scale. Parameterizations of OGWD have been developed since the 1980s, and necessary improvements continue to take place. Essentially, an OGWD parameterization scheme (a) calculates the wave momentum flux (WMF) at the surface (i.e., wave generation), and (b) handles the vertical propagation and dissipation of OGWs defining the WMF profile.

The surface WMF (hereafter SWMF) plays a key role in the parameterization of OGWD because it governs the total subgrid-scale orographic (SGSO) forcing in the model. In the first OGWD parameterizations, the SWMF was calculated using the analytical solution of linear gravity waves forced by sinusoidal orography (e.g., Palmer et al., 1986; McFarlane, 1987). Since then, many efforts have been made to improve the accuracy of the SWMF formulation. According to high-resolution numerical simulations, the SWMF of nonlinear gravity waves forced by large-amplitude mountains could be much larger than predicted by linear gravity wave theory, in situations that are known as "high-drag states" (Miranda and James, 1992). This nonlinear enhancement was accounted for in the parameterization scheme developed by Kim and Arakawa (1995; hereafter KA95), which was validated against mesoscale numerical simulations. Following Phillips (1984), Lott and Miller (1997; hereafter LM97) adopted the analytical solution of gravity waves generated by three-dimensional (3D) orography with an elliptical horizontal cross-section in their parameterization scheme, rather than using the simple two-dimensional (2D) sinusoidal terrain of earlier studies. KA95 had also considered the effect of the shape of isolated orography (i.e., orographic asymmetry and convexity), but only in a 2D framework. Kim and Doyle (2005; hereafter KD05) extended the KA95 scheme to 3D conditions by incorporating the effect of orographic anisotropy.

The analytical solution of OGWs employed in LM97 and other parameterization schemes was derived under the assumption of constant flow over topography (e.g., Smith, 1980; Phillips, 1984). Using linear gravity wave theory, Grubišić and Smolarkiewicz (1997) and Xu *et al.* (2012, 2017a) derived analytical formulae for the SWMF for linearly sheared airflow over circular bell-shaped mountains. Their results revealed that, in the presence of vertical wind shear, the SWMF was weaker than in the constant-flow case. Based on a second-order Wentzel-Kramers-Brillouin (WKB) approximation, Teixeira et al. (2004) developed an analytic model which accounted for the effects of both wind profile shear and curvature on the SWMF. In the case of hydrostatic flow over an isolated axisymmetric mountain, the SWMF was shown to decrease as the mean-flow Richardson number (Ri) decreased for a linearly sheared wind profile (in agreement with the precise results mentioned above); however, the SWMF was instead shown to be amplified above its zero-shear value as Ri decreased for a wind profile rotating with height at a constant wind speed. This analytic model was also extended to cases of gravity waves forced by 2D ridges and 3D elliptical mountains (Teixeira and Miranda, 2004, 2006).

Miranda et al. (2009; hereafter M09) first assessed the impacts of wind profile shear and curvature on the global atmospheric torque by applying their analytical model to the ERA-40 reanalysis data and performing an offline evaluation. The overall effect was to reduce the global westerly OGWD torque. However, significant drag enhancement of up to 50% occurred over Antarctica and East Africa, suggesting dominance of the wind profile curvature over the shear effect (which tends to reduce the drag) in those regions. Recently, Turner et al. (2019; hereafter T19) further examined the sensitivity of SWMF to the wind profile shear and curvature over Antarctica using the same method. The effects were evaluated at two different levels: at the top of the planetary boundary layer and at a height of the order of the standard deviation of the SGSO elevation, for both isotropic and anisotropic orography. The results showed that the effects were qualitatively robust to changes in the height at which they were evaluated. Drag enhancement was found over Antarctica, especially in the austral winter. This confirmed the important and dominant role of wind profile curvature (relative to linear shear) over Antarctica as found by M09.

Although OGWD parameterization has long been adopted in numerical weather prediction and climate models, the effects of wind profile shear and curvature on the SWMF have not been considered in any operational OGWD scheme. In a recent study by Xu *et al.* (2019; hereafter X19), the OGWD parameterization scheme in the Weather Research and Forecasting (WRF) model was extended by including the directional absorption (or selective critical-level filtering; e.g., Shutts, 1995; Xu *et al.*, 2018) of OGWs associated with directional wind shear. X19 considered the propagation and dissipation of OGWs within the atmosphere but not their generation. This study aims to further extend the OGWD scheme by considering the impacts of wind profile shear and curvature on the SWMF. The main purpose is to study the features of wind profile effects (i.e., changes to the SWMF induced by wind profile shear and curvature), focusing on the different impacts on the SWMF magnitude (enhancement or reduction) they might have. The wind fields used in the *offline* studies of M09 and T19 were from reanalysis datasets and were thus affected by the OGWD scheme adopted in the model. In this regard, wind profile effects need to be re-examined in a more consistent framework by performing simulations with an OGWD parameterization scheme that itself includes these effects. Moreover, the changes in the SWMF can also affect the vertical distribution of OGWD, an aspect which has not been examined before.

The rest of this article is organized as follows. Section 2 first introduces and extends the OGWD scheme in the WRF model and then describes the set-up of the numerical simulations. The impacts of wind profile shear and curvature on the SWMF and the vertical distribution of OGWD are analysed in section 3. The article is summarized in section 4, along with further discussion.

# 2 | METHODOLOGY

# 2.1 | OGWD parameterization scheme in WRF

The OGWD scheme in the WRF model was developed by KD05, accounting for various aspects of the SGSO, for example, orographic asymmetry (OA), orographic convexity (OC) and effective orographic length  $(L_x)$ . Note that  $L_x$  is defined along the direction of low-level mean wind  $\mathbf{V}_L$  (see below). For gravity waves forced by the SGSO, the WMF at the reference level (i.e., the level at which the OGWs are generated) is the SWMF. In the WRF model, the reference level is set to the maximum of either  $2\sigma_h$ above the model surface or the planetary boundary layer (PBL) height (Hong *et al.*, 2008), with  $\sigma_h$  being the standard deviation of the SGSO height. This definition has a certain degree of arbitrariness, but may be used for a number of purposes, including defining the height at which the wind profile effects that are the focus of the present study are estimated (see below). The underlying assumption is that the pressure contribution from these inviscid effects is transmitted with little change across the PBL. The SWMF is given by

$$\tau_{\rm ref} = \rho_0 E \frac{m}{\lambda_{\rm eff}} G \frac{|\mathbf{V}_L|^3}{N},\tag{1}$$

$$E = (OA + 2)^{C_E \frac{Fr_0}{Fr_c}}, m = (1 + L_x)^{OA+1},$$
  

$$G = \frac{Fr_0^2}{Fr_0^2 + C_G OC^{-1}}, Fr_0 = \frac{2\sigma_h N}{|\mathbf{V}_L|} OD.$$
(2)

Here, the factor *E* accounts for the effect of drag enhancement by low-level wave breaking and/or lee wave trapping, while factor *G* provides a smooth transition between blocking and non-blocking flows determined using a critical Froude number of  $Fr_c = 1$ . The two constants  $C_E = 0.8$  and  $C_G = 0.5$  are obtained empirically from the mesoscale numerical simulations of KA95. *m* denotes the number of SGSO elements within the model grid cell and  $\lambda_{\text{eff}}$  is the effective grid length.  $\rho_0$ ,  $\mathbf{V}_L$  and *N* are the low-level air density, wind velocity and Brunt–Väisälä frequency averaged between the surface and  $2\sigma_h$  above the surface.  $OD = \frac{L_x}{L_x}$  is the orographic direction quantifying the SGSO anisotropy, with  $L_x^{\perp}$  being the effective orography length normal to  $L_x$  (i.e., normal to the low-level wind).

In the model, the reference-level WMF is propagated upward level by level. At each model level, flow instability is checked in accordance with the wave saturation hypothesis (Lindzen, 1981). In the event of wave saturation, OGWs will break and exert a body force on the mean flow through the deposition of wave momentum, that is,

$$\frac{d\mathbf{V}(\mathbf{z})}{dt} = \frac{1}{\rho(z)} \frac{\partial \tau(z)}{\partial z},\tag{3}$$

where  $\mathbf{V}(z)$  and  $\tau(z)$  are the mean flow velocity and WMF vectors at height *z*, respectively. Note that the direction of  $\tau(z)$  is parallel to the mean flow at the low level (i.e.,  $\mathbf{V}_L$ ). The remaining WMF continues to propagate upward until OGWs are completely absorbed by the mean flow or reach the model top.

# 2.2 Revision of the KD05 scheme

Using a second-order WKB approximation, Teixeira and Miranda (2006; hereafter TM06) derived analytical expressions for the corrections to the SWMF ( $D_x$ ,  $D_y$ ) due to wind profile shear and curvature (their eqs. 31 and 32):

$$\frac{D_x}{D_{0x}} = 1 - \frac{1}{8} \left\{ \alpha \left( \frac{U_0'^2}{N^2} + 2\frac{U_0 U_0''}{N^2} \right) + (1 - \alpha) \\
\times \left( \frac{V_0'^2}{N^2} + 2\frac{V_0}{U_0} \frac{U_0' V_0'}{N^2} + 2\frac{V_0}{U_0} \frac{U_0'' V_0}{N^2} + 4\frac{V_0'' V_0}{N^2} \right) \right\},$$
(4)

$$\begin{aligned} \frac{D_y}{D_{0y}} &= 1 - \frac{1}{8} \left\{ \beta \left( \frac{V_0'^2}{N^2} + 2 \frac{V_0 V_0''}{N^2} \right) + (1 - \beta) \right. \\ & \left. \times \left( \frac{U_0'^2}{N^2} + 2 \frac{U_0}{V_0} \frac{U_0' V_0'}{N^2} + 2 \frac{U_0}{V_0} \frac{V_0'' U_0}{N^2} + 4 \frac{U_0'' U_0}{N^2} \right) \right\}, \end{aligned}$$
(5)

where  $(D_{0x}, D_{0y})$  is the SWMF calculated assuming a constant flow and  $(U_0, V_0)$  is the horizontal wind at the surface, with  $(U'_0, V'_0)$  and  $(U''_0, V''_0)$  the wind profile shear and curvature, respectively. By "surface" here we mean the level at which the shear and curvature in the wind profile most affect the SWMF. It is not a priori obvious what this height should be, but it is reasonable to suppose that it should not be too high above the ground (otherwise its contribution to the surface pressure would be negligible), nor should it be so low as to be inside the PBL, because the theory used to derive Equations 4-5 is inviscid (and pressure fluctuations are known to be transmitted with relatively small modifications across thin boundary layers). The coefficients  $\alpha$  and  $\beta$  depend on the mountain anisotropy. In the case of an elliptical bell-shaped mountain, that is,

$$h(x,y) = \frac{h_m}{[1 + (x/a)^2 + (y/b)^2]^{3/2}},$$
(6)

with *a* and *b* the mountain half-widths along its main axes and  $h_m$  the mountain amplitude,  $\alpha$  and  $\beta$  take the following form (eqs. 33 and 34 in TM06):

$$\alpha(\gamma) = \frac{I_1(\gamma)}{B(\gamma)} = 1 - \frac{I_2(\gamma)}{B(\gamma)} = \frac{1}{1 - \gamma^2} \left\{ 1 - \frac{C(\gamma)}{B(\gamma)} \right\}, \quad (7)$$

$$\beta(\gamma) = \frac{\gamma I_1(1/\gamma)}{C(\gamma)} = 1 - \frac{\gamma I_2\left(\frac{1}{\gamma}\right)}{C(\gamma)} = \frac{\gamma^2}{1 - \gamma^2} \left\{ \frac{B(\gamma)}{C(\gamma)} - 1 \right\},\tag{8}$$

where  $\gamma = a/b$  is the horizontal aspect ratio of the elliptical mountain and

$$B(\gamma) = \int_0^{\pi/2} \frac{\cos^2\theta}{(\cos^2\theta + \gamma^2 \sin^2\theta)^{1/2}} d\theta, C(\gamma)$$
$$= \gamma^2 \int_0^{\pi/2} \frac{\sin^2\theta}{(\cos^2\theta + \gamma^2 \sin^2\theta)^{1/2}} d\theta, \qquad (9)$$

$$I_{1}(\gamma) = \int_{0}^{\pi/2} \frac{\cos^{4}\theta}{(\cos^{2}\theta + \gamma^{2}\sin^{2}\theta)^{1/2}} d\theta, I_{2}(\gamma)$$
$$= \gamma^{2} \int_{0}^{\pi/2} \frac{\cos^{2}\theta \sin^{2}\theta}{(\cos^{2}\theta + \gamma^{2}\sin^{2}\theta)^{1/2}} d\theta, \qquad (10)$$

which are eqs. 21–22 and 27–28 in TM06. It can be easily verified that  $\alpha(\gamma) = \beta(1/\gamma)$  and  $\alpha = \beta = 3/4$  for an axisymmetric mountain (i.e.,  $\gamma = 1$ ). Figure 1 shows the variation of  $\alpha(\gamma)$  with the terrain anisotropy, which approaches unity at  $\gamma = 1/10$  and decreases to about 0.36 at  $\gamma = 10$ .

As noted above, in the KD05 scheme the effective orography lengths (namely,  $L_x$  and  $L_x^{\perp}$ ) of the assumed SGSO are defined in directions along and perpendicular to the



**FIGURE 1** Variation of  $\alpha$  with  $\gamma$  from 1/10 to 10. Note that the horizontal scale is only linear for  $\gamma > 1$ 

low-level mean wind, respectively (see Figure 7 in KD05 and Figure 1 in X19). For lack of more complete information about the orography, the best choice consistent with this assumption in the framework of TM06 is to take  $L_x$  and  $L_x^{\perp}$  as the mountain widths along the main axes of the elliptic orography, as if the low-level wind were aligned with one of those axes. In this simple case, to account for the effects of wind profile shear and curvature, the reference-level WMF for the KD05 scheme is simplified to

$$\widetilde{\tau}_{\rm ref} = \tau_{\rm ref} \left[ 1 - \frac{\alpha}{8} \left( \frac{U_L^{\prime 2}}{N^2} + 2 \frac{U_L U_L^{\prime \prime}}{N^2} \right) \right]$$
$$= \tau_{\rm ref} \left[ 1 - \frac{\alpha}{8} \left( \frac{1}{Ri} + 2 \frac{U_L U_L^{\prime \prime}}{N^2} \right) \right], \qquad (11)$$

where  $U_L = U_L(z)$  is the wind component in the direction of the low-level mean wind  $\mathbf{V}_L$ . In deriving the above equation, the wind component orthogonal to the low-level mean wind and its vertical derivatives are omitted. This is consistent with the unidirectional wind assumption adopted for the SWMF in the KD05 scheme. This assumption is also adopted in a number of other OGWD parameterization schemes, for example, the LM97 scheme (although in this scheme the flow may be oblique to the main axes of the orography). The first term inside the parentheses on the right-hand side of Equation 11 represents the second-order WKB correction due to wind profile shear (hereafter the WSHR term). It is always negative and inversely proportional to Ri. The second term accounts for the effect of wind profile curvature (hereafter the WCUR term). Unlike the WSHR term, there is no a priori indication for the sign of the WCUR term.

For the implementation of the revised OGWD scheme in the WRF model, the first and second derivatives of  $U_L(z)$ at the reference level are calculated using centred finite differences at three consecutive model levels, that is, the reference level and the levels below and above it. As shown in Teixeira et al. (2004) and TM06, the second-order WKB corrections are formally valid for Ri as low as 0.5, while it is known that dynamic/static instabilities can occur when Ri falls below 0.25. Hence the WKB corrections are only applied at grid points where Ri is greater than 0.5. Furthermore, since the wind profile effects (as formulated here) change the magnitude of the SWMF rather than its direction, the WKB corrections are limited to be higher than -1 relative to the original SWMF value, so that the SWMF does not change sign. If this occurred, the WKB correction would be of questionable validity anyway, since due to its asymptotic nature it is supposed to be smaller than the SWMF value it corrects.

#### 2.3 Numerical simulations

As in X19, numerical simulations are performed using the global version of the WRF model (GWRF), which is an extension of the mesoscale version of WRF and a variant of planetWRF (Richardson et al., 2007). The model uses a latitude-longitude grid, with a Fourier spectral filter applied in the polar regions to prevent numerical instability near the Poles. To study wind profile effects, two sets of free-running numerical simulations are conducted using the KD05 scheme (the "OLD" experiment) and the revised scheme (the "NEW" experiment), respectively. In each set there are 20 one-month simulations, with 10 in January and 10 in July of 2009-2018. Note that to focus exclusively on the effects of the modified SWMF, the modifications made by X19 to the propagation of OGWs due to directional wind shear are not included herein.

The horizontal resolution of the GWRF model is set to  $1^{\circ} \times 1^{\circ}$ , with 41 levels in the vertical. The model top is located at 10 hPa, because the model's initial conditions are derived from the  $1^{\circ} \times 1^{\circ}$  Global Forecast System (GFS) analyses, which are limited to 10 hPa in the vertical. A sponge layer is employed in the uppermost 5 km of the model to damp waves reflected from the top of the domain. A number of parameterization schemes are used for model physics, for example, the WRF single-moment 3-class microphysical scheme (Hong et al., 2004), the RRTMG long-wave and short-wave radiation schemes (Iacono et al., 2008), the Yonsei University (YSU) PBL scheme (Hong et al., 2006), the MM5 similarity scheme for





FIGURE 2 Top: Zonal-mean surface wave momentum flux (WMF) in January (blue) and July (red) in experiment OLD. Bottom: Zonal-mean standard deviation of the subgrid-scale orographic (SGSO) height

the surface layer (Beljaars, 1994), the new Tiedtke scheme for cumulus convection (Zhang et al., 2011) and the Noah land surface model (Tewari et al., 2004).

#### 3 1 RESULTS

0.18

0.15

0.12 s<sup>-2</sup>) 0.09

#### General features of simulated WKB 3.1 corrections

The zonal-mean SWMF in experiment OLD is shown in Figure 2. In January, the largest SWMF occurs in the midlatitudes of the Northern Hemisphere (NH), where the SGSO is most remarkable. Two other peaks of SWMF also appear in the high latitudes of the NH due to the local SGSO maxima existing there. In the Southern Hemisphere (SH), the SWMF is much weaker except in the polar region, where the SGSO is comparable to that in the midlatitudes of the NH. In July, the SWMF decreases markedly in the NH mid- and high latitudes but increases dramatically over Antarctica. The differences between the SWMF in January and July are mainly due to the fact that the horizontal wind is weaker in summer than in winter for each hemisphere. According to Equation 1, the SWMF is increased as the horizontal wind speed increases.

In experiment NEW, the zonal-mean SWMF is similar to that in OLD because the zonal-mean corrections due to the wind profile shear and curvature are relatively small. Figure 3 displays the zonal-mean WKB correction terms to the SWMF (i.e., terms in the square brackets in Equation 11) in experiment NEW. In January (Figure 3a), the WKB corrections due to wind profile shear (i.e., WSHR) are negative, with notable corrections found over Antarctica and between about 30°S and 60°N. By contrast, the wind profile curvature (WCUR) generally



**FIGURE 3** Zonal-mean relative Wentzel-Kramers-Brillouin (WKB) drag corrections (in %) in (a) January and (b) July in experiment NEW. Blue and red lines are the wind profile shear (WSHR) and curvature (WCUR) terms, respectively, with the black line denoting the sum of the two (i.e., total WKB correction)

induces positive corrections except in the high latitudes of the NH. Overall, the WSHR term is dominated by the WCUR in the SH (especially over Antarctica), giving rise to an enhancement of the SWMF there. This is consistent with the results of M09 and T19. In the NH, however, the SWMF is predominantly reduced owing to the more negative WSHR term.

Although the zonal-mean WKB corrections only account for about 1% of the SWMF, they show large spatial variability. In localized regions the corrections can reach values as high as about 30%, that is to say, they are of the same order of magnitude as those of M09. Figure 4a shows the spatial distribution of the total WKB corrections in January, with the WSHR and WCUR terms presented in Figure 4c,e, respectively. Negative WKB corrections mainly occur in western North America, southwestern Greenland, and in a vast region extending from southern Europe to East Asia (Figure 4a). Conversely, the total WKB corrections are positive in eastern South America, southern Africa, northwestern Australia and in parts of Antarctica. Regarding the WSHR term (Figure 4c), notable corrections are found between 45°S and 45°N, especially in East Asia, western North America, southern South America, and southern and eastern Africa. The WCUR term is positive almost everywhere, with salient corrections found in southern Africa, eastern South America and Antarctica (Figure 4e). However, there are still negative corrections due to the WCUR term over the Tibetan Plateau (TP), southwestern Greenland and parts of the northern Rocky Mountains. As a consequence, these regions are characterized by important negative total WKB corrections (Figure 4a).

In July, the zonal-mean WKB corrections differ markedly from those in January (Figure 3b). In the high latitudes of the NH, although the WSHR term becomes more negative than in January, the positive WCUR term increases more notably there, leading to a net enhancement of SWMF. In the high latitudes of the SH, the WCUR term changes to negative, which adds to the salient reduction of SWMF by the WSHR term. Moreover, the WCUR term is found to increase notably in the NH subtropical region. The two terms are hardly changed at other latitudes, however.

The spatial distributions of the total WKB correction, the WSHR term and the WCUR term in July are shown, respectively, in Figure 4b,d,f. Compared to January, the total WKB corrections change to negative (positive) in Antarctica (Greenland), which is mainly attributed to the seasonal reversal of the WCUR term (see below). The WSHR term (Figure 4d) is strengthened, that is, it becomes more negative over northern North America and Eurasia. Meanwhile, the WCUR term increases over northern Eurasia and in the lower latitudes of the NH (e.g., western India, Figure 4f). In particular, the WCUR term changes from negative (positive) to positive (negative) in Greenland (Antarctica), giving rise to the seasonal reversal of the total WKB correction there. Similarly, over the TP, the WCUR term changes from largely negative in January to slightly positive in July. As a consequence, the total WKB corrections are significantly reduced in July (Figure 4b). This seasonal reversal of the WCUR drag correction (and consequently of the total drag correction) is at odds with the findings of M09 and T19, so it warrants a more detailed analysis.

# 3.2 | Seasonal variation of the WCUR

In January and July, the WCUR term at high latitudes (i.e., Antarctica and Greenland) and over the TP has different signs. According to Equation 11, the WCUR term is positive when the sign of the wind profile curvature is opposite to that of the low-level mean flow. Figure 5a,b shows



**FIGURE 4** Geographic distribution of the fraction (in %) of the total WKB correction to the surface WMF (SWMF) in (a) January and (b) July, in regions where the standard deviation of the SGSO height is greater than 50 m. (c, d) and (e, f) are the same as (a, b) but for the WSHR and WCUR terms, respectively. The boxes in (e) and (f) denote the regions from which the wind profiles in Figure 6 were extracted

the horizontal wind at the first model level above the ground in the SH polar region. In July (i.e., the austral winter), the near-surface winds over Antarctica are notably increased compared to those in January (i.e., the austral summer), especially in the mountainous regions. These strong near-surface winds, known as katabatic winds, are one of the most common meteorological features over Antarctica (Parish and Bromwich, 1991). As shown below, the enhanced near-surface winds may not only lead to an increase in the SWMF (Figure 2) but may in fact contribute to a decrease in the SWMF, depending on the sign of the wind profile curvature at the reference-level height.

Figure 6a illustrates the vertical profile of the horizontal wind averaged over eastern Antarctica (see Figure 4e,f). Note that before taking the area average, the horizontal wind profile is projected onto the direction of the low-level mean wind at each model grid. Given the high wind speed near the surface, the vertical shear is notably increased (i.e., more negative) below the reference level, producing a positive vertical curvature at the reference level. Therefore, the WCUR term becomes negative in July. This can also help to explain the seasonal reversal of the WCUR term in Greenland, where the near-surface winds are increased in January (Figure 5c,d). High winds occurring in winter over Greenland have been widely reported (e.g., Moore and Renfrew, 2005; Oltmanns *et al.*, 2014). Note that the even stronger wind shear and curvature that exist below the reference level in Figure 5 do not affect the SWMF



**FIGURE 5** Horizontal wind velocity (vectors) and wind speed (shading) (in  $m \cdot s^{-1}$ ) at the first model level in the polar regions in (a, c) January and (b, d) July in the NEW experiment

because in the OGWD scheme the airflow is assumed to be blocked below the reference level, with the OGWs only generated above that level.

The seasonal reversal of the WCUR term over the TP, on the other hand, is caused by the variation of the subtropical jet in the upper troposphere. Figure 6b is akin to Figure 6a, but presents the wind profile averaged over the TP. In January, there is a westerly jet located in the upper troposphere near 250 hPa, which produces a stronger vertical shear above the reference level than below it. As a result, the wind profile curvature is positive at the reference level, giving rise to negative WCUR. This

westerly jet is actually part of the subtropical jet existing in the NH mid- to low latitudes in winter (Figure 7a). In July (Figure 7c), the TP (indicated by the box) is on the northern flank of a large-scale anticyclone associated with the South Asian High (SAH) in the upper troposphere and lower stratosphere. The weakening of the upper-level jet reverses the wind profile curvature at the reference level, giving rise to the slightly positive WCUR term found in July (Figure 4f).

The enhancement of the WCUR term in the low latitudes of the NH in July is briefly analysed next. Taking western India as an example, a low-level jet is formed at



**FIGURE 6** Profiles of the horizontal wind averaged over (a) eastern Antarctica, (b) the Tibetan Plateau and (c) western India in experiment NEW. Solid lines with filled circles indicate wind profiles in January, while dashed lines with empty circles denote wind profiles in July. The horizontal solid and dashed lines represent the reference levels of the orographic gravity wave drag (OGWD) parameterization in January and July, respectively

the level of about 900 hPa in July, which increases the wind profile curvature at the reference level (Figure 6c). This low-level jet is associated with the southwesterly monsoonal flow originating from the SH (Figure 7d). In January (Figure 7b), the monsoonal flows are much weaker than those in July and blow from the interior of the Asian continent. Nonetheless, the WCUR term over western India is not reversed between the two seasons, which is in contrast to what happens in the polar regions and over the TP.

While this reversal of the sign of the WCUR may be understood as an artefact of the level where the wind profile corrections to the drag are evaluated, its mere existence is important because it contradicts the idea, advocated by M09 and T19, that the sign of the drag corrections is robust with respect to the choice of this level. In M09 and T19, the WCUR term was shown to be overwhelmingly positive over Antarctica, with no seasonal reversal as found in the present study. This difference might be attributed to the following reasons. First, in M09 and T19, the wind profile effects were evaluated offline using reanalysis datasets (ERA-40 and ERA-Interim), the vertical resolutions of which may have been too coarse to capture the seasonal reversal of the wind profile curvature accurately. Second, the levels at which the WKB corrections were estimated in M09 and T19 differ from those adopted herein. It is

not immediately obvious which choice is the best one, but the present results suggest a sensitivity to these levels (see Figure 6), which is important enough to reverse the sign of the total correction to the SWMF. Third, the WKB corrections depend on the terrain anisotropy (see the coefficients  $\alpha$  and  $\beta$  in Equations 4, 5 and 11). In M09 and T19, this anisotropy was calculated following the LM97 scheme, which differs from the KD05 scheme employed herein. Lastly (and relatedly), M09 and T19 used the fully 3D version of the WKB corrections, while the reduced 2D version given by Equation 11 was used here.

# 3.3 | Influence on the vertical distribution of OGWD

Changes in the WMF at the surface can affect the height at which OGWs break and hence the vertical distribution of OGWD. Figure 8 presents the zonal-mean zonal OGWD for both the OLD and NEW experiments as well as their differences. In January, the most prominent OGWD is located above the NH subtropical jet (Figure 8a,c), which is consistent with previous studies (e.g., Xu *et al.*, 2017b; X19). Westward OGWD is also found in the lower troposphere between about 30 and 50°N, although it is weaker than at upper levels. In the SH, however, there is little



**FIGURE 7** Horizontal wind velocity (vectors) and wind speed (shading) (in  $m \cdot s^{-1}$ ) in (a, b) January and (c, d) July at 200 hPa (a, c) and 900 hPa (b, d) in experiment NEW. The boxes in the left (right) panels denote the regions from which the wind profiles in Figure 6b (Figure 6c) were extracted

OGWD at high altitudes (not shown). This is because the SWMF is very weak in the mid- and low latitudes of the SH in this season (Figure 2). In the high latitudes, although there is noticeable SWMF over Antarctica, OGWs are prone to break in the lower troposphere rather than at upper levels. This is owing to the reversal of the zonal wind at about 600 hPa, with easterlies below and westerlies above this level (not shown). This horizontal wind reversal forms a critical level for vertically propagating OGWs. The difference between the OGWD in the OLD and NEW experiments (NEW minus OLD) is shown in Figure 8e. Compared to that in OLD, the OGWD in the NEW experiment is reduced in the lower troposphere and stratosphere but is enhanced in the upper troposphere of NH midlatitudes.

In July (Figure 8b,d) the OGWD is notably enhanced in the lower and upper troposphere over Antarctica, which is consistent with the increase of the SWMF occurring there (Figure 2). Compared to the OLD experiment, the NEW experiment shows weaker OGWD between about 300 and 100 hPa in the upper troposphere over Antarctica (Figure 8f). In contrast, the differences between the OGWD for the two experiments are very small in the NH. In fact, the OGWD in the midlatitudes of the NH is greatly reduced in July, almost vanishing (not shown). This can be partly ascribed to a weakening of the SWMF, which corresponds to about 40% of that existing in January around 45°N (Figure 2). Given the even greater seasonal variation of the OGWD in the midlatitudes of the NH, the weaker vertical wind shear above the NH subtropical jet core in July compared to that in January may also contribute to a reduction of the OGWD.

Differences between the OGWD in the OLD and NEW experiments, which are attributable to the WKB corrections caused by wind profile shear and curvature, may be interpreted in the following way. As shown in Figure 3a, the zonal-mean SWMF is reduced in the midlatitudes of the NH in January. Figure 9a displays the vertical profile of the normalized WMF averaged between 30 and 50°N in January. The normalization is made using the SWMF in experiment OLD. In experiment NEW, the SWMF is weakened by about 2% compared to its value in OLD, which indicates OGWs of smaller amplitude. Therefore, gravity wave breaking is inhibited in the lower troposphere, leading to smaller OGWD there (Figure 8e). Owing to the suppression of low-level wave breaking, OGWs can transport more WMF to the upper troposphere, as evidenced by the larger WMF between about 700 and 150 hPa in the NEW experiment. The increased amount of WMF originating from below favours wave breaking in the upper troposphere, where more WMF is deposited into the mean flow, thus producing a stronger OGWD there



**FIGURE 8** Vertical distribution of the zonal-mean OGWD (shading;  $m \cdot s^{-1} day^{-1}$ ) in the Northern Hemisphere in January in experiment (a) OLD and (c) NEW, with their difference (NEW minus OLD, exaggerated by a factor of five for clarity) given in (e). (b, d, f) are similar to (a, c, e) but for the Southern Hemisphere in July. Contour lines are the corresponding zonal-mean zonal winds (in  $m \cdot s^{-1}$ , plotted at intervals of 5  $m \cdot s^{-1}$ ). Statistical significance at the 90% level using the Student's *t* test is indicated by green dots in (e) and (f)

(Figure 8e). Higher up, the stratospheric OGWD weakens (Figure 8e) due to the fewer number of OGWs that are left, and can propagate into the stratosphere (see in Figure 9a the smaller WMF above 100 hPa in NEW). This type of change to the OGWD is qualitatively similar to that predicted in X19; however, in that study it was caused by the directional absorption of OGWs, which is a completely different physical process. Moreover, changes in the mean flow caused by changes in the propagation and breaking of resolved waves (e.g., Rossby waves) may also contribute to



**FIGURE 9** (a) Profiles of the normalized WMF in experiment OLD (solid lines) and NEW (dashed lines) between 30 and 50°N in January. The normalization is made with respect to the reference-level WMF in OLD. (b) Similar to (a) but between 80 and 90°S in July

the changes in stratospheric OGWD in midlatitudes (e.g., Cohen *et al.*, 2013; Sigmond and Shepherd, 2014; Sandu *et al.*, 2016). However, the interaction between the resolved and parameterized waves, as well as between the resolved waves and the mean flow, is beyond the scope of this work.

Figure 9b illustrates the vertical profile of the normalized WMF averaged between 80 and 90°S in July. In the austral winter, the wind profile shear and curvature tend to more markedly reduce the SWMF in Antarctica (Figure 3b) than in the NH midlatitudes in the boreal winter (Figure 3a). As shown in Figure 9b, the SWMF in the NEW experiment is about 5% weaker than that in the OLD. Because of this large reduction, the NEW experiment produces a smaller WMF than the OLD at all levels, which differs from what occurs in the NH midlatitudes in January (Figure 9a). As a result, the OGWD in the upper troposphere over Antarctica is weakened rather than increased (Figure 8f).

# 4 | CONCLUSION AND DISCUSSIONS

Using the analytic formulae derived by TM06, based on a second-order WKB approximation, the KD05 OGWD parameterization scheme in the WRF model was revised by considering the effects of wind profile shear and curvature in the evaluation of the SWMF. Then the wind profile effects on the SWMF, and hence the vertical distribution of OGWD, were investigated via two sets of numerical experiments conducted using the GWRF model, namely, (a) experiment OLD using the original KD05 scheme, and (b) experiment NEW using the revised scheme. The reference-level height used in the KD05 scheme was adopted to estimate the corrections to the drag due to wind profile shear and curvature, as this is both consistent with the assumptions of the scheme and logical for corrections that were derived for inviscid conditions. For the OGWD scheme in the WRF model, the reference level appears to be the most reasonable choice because OGWs are assumed to be generated at this level.

In January, the WSHR term causes notable negative corrections to the SWMF over Antarctica and between about 30°S and 60°N, while the WCUR term acts to enhance the SWMF everywhere except in the high latitudes of the NH. The net effect of wind profile shear and curvature is to increase (decrease) the SWMF in the SH (NH). In July, the behaviour of the WSHR term is quite similar to that in January, although this term is increased in the high latitudes of the NH. On the contrary, the behaviour of the WCUR term differs markedly from that in January, with the most remarkable differences taking place in the high latitudes of the SH (i.e., Antarctica). The WCUR term becomes negative in July, giving rise to a pronounced reduction of the SWMF there. The sign of the WCUR term is also reversed in the high latitudes of the NH (e.g., Greenland). The seasonal reversal of the WCUR term at high latitudes is due to the enhancement of near-surface winds in the winter season of each hemisphere. This enhancement increases the low-level vertical shear, leading to a reversal of the sign of the wind profile curvature. The ability of the wind profile curvature to, in practice (i.e., for real meteorological data), produce negative corrections to the SWMF over Antarctica is a new finding which contradicts the results of M09 and T19. This result of course relies on the type of drag parameterization used (which is different here from that adopted in the offline calculations of M09 and T19), on the simplifications assumed for the drag correction terms and on the level used to evaluate these terms. This suggests that the behaviour of these drag corrections is not as robust to the choice of level as previously thought.

Changes in the SWMF are able to influence the vertical distribution of the OGWD. In January, the OGWD is found to be more significant in the midlatitudes of the NH, at low levels below about 700 hPa, and in the upper troposphere and lower stratosphere. When wind profile effects are considered, the OGWD is increased in the upper troposphere but decreased in the lower troposphere and lower stratosphere. In July, the most notable OGWD is found in the lower and upper troposphere over Antarctica, with little OGWD in the NH. Under the influence of wind profile shear and curvature, the OGWD in the upper troposphere over Antarctica is reduced, which is different from what occurs in the NH midlatitudes in January. This is because the SWMF over Antarctica is more markedly affected by negative wind profile effects than in the NH midlatitudes.

To sum up, this study examines for the first time the behaviour of the second-order WKB corrections to the SWMF due to wind profile effects derived by TM06, as well as their impacts on the vertical distribution of parameterized OGWD, in online simulations of a numerical model which provide some useful insights into those effects. While the impact of these effects on the SWMF magnitude is relatively modest, their effect on the OGWD exerted in the overlying atmospheric column can be surprisingly strong at localized levels. This is because the magnitude of the SWMF determines the lowest level at which OGW breaking occurs, which in turn controls the depletion of the WMF that remains available to propagate to higher levels. Hence even a slight change in the SWMF can substantially modify the heights at which wave breaking takes place (and consequently flow deceleration is exerted).

To maintain compatibility with the unidirectional wind assumption employed in the KD05 scheme, the present study had to adopt a reduced 2D version of the WKB corrections, which accounts for the fact that wind profile shear and curvature are in the direction of the low-level mean wind only. Extending these corrections to their fully 3D version would enable better capture of the wind profile effects on the SWMF. Moreover, sensitivities to the model vertical resolution and to the height where the SWMF and wind profile effects are evaluated were not addressed herein. Finally, this study only examined the impact of wind profile effects on the SWMF and on the WMF profiles. How these effects will influence the resolved atmospheric circulation is still unclear. This will be investigated using more comprehensive climate model simulations with the model top extended to higher levels (e.g., in the mesosphere) rather than at 10 hPa (as in the present study), given that the impacts of OGWs are stronger in the middle atmosphere than in the troposphere. The effect of directional absorption of OGWs, addressed separately in X19, will also be studied.

# ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers for their comments. This study is mainly supported by the National Science Foundation of China (grants 91837207, 41875068, 41505046 and 41750965) and Fundamental Research Funds for the Central Universities (0207-14380046). X.X. is also supported by the Beijing Climate Center (QHMS2019006).

## ORCID

*Xin Xu* https://orcid.org/0000-0002-4495-3677 *Miguel A. C. Teixeira* https://orcid.org/0000-0003-1205-

3233

*Ming Xue* https://orcid.org/0000-0003-1976-3238 *Yixiong Lu* https://orcid.org/0000-0001-9823-9367 *Jianping Tang* https://orcid.org/0000-0002-1098-2656

### REFERENCES

- Alexander, M.J., Geller, M., McLandress, C., Polavarapu, S., Preusse, P., Sassi, F., Sato, K., Eckermann, S., Ern, M., Hertzog, A., Kawatani, Y., Pulido, M., Shaw, T.A., Sigmond, M., Vincent, R. and Watanabe, S. (2010) Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models. *Quarterly Journal of the Royal Meteorological Society*, 136, 1103–1124. https://doi.org/10.1002/qj.637.
- Beljaars, A.C.M. (1994) The parameterization of surface fluxes in large-scale models under free convection. *Quarterly Journal of the Royal Meteorological Society*, 121, 255–270. https://doi.org/10. 1002/qj.49712152203.
- Cohen, N.Y., Edwin, P.G. and Oliver, B. (2013) Compensation between resolved and unresolved wave driving in the stratosphere: implications for downward control. *Journal of the Atmospheric Sciences*, 70, 3780–3798. https://doi.org/10.1175/JAS-D-12-0346.1.
- Grubišić, V. and Smolarkiewicz, P.K. (1997) The effect of critical levels on 3D orographic flows: linear regime. *Journal of the Atmospheric Sciences*, 54, 1943–1960. https://doi.org/10.1175/ 1520-0469(1997)054<1943:TEOCLO>2.0.CO;2.
- Hong, S.-Y., Choi, J., Chang, E.-C., Park, H. and Kim, Y.-J. (2008) Lower-tropospheric enhancement of gravity wave drag in a global spectral atmospheric forecast model. *Weather and Forecasting*, 23, 523–531. https://doi.org/10.1175/2007WAF2007030.1.
- Hong, S.-Y., Dudhia, J. and Chen, S. (2004) A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly Weather Review*, 132, 103–120. https:// doi.org/10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2.
- Hong, S.-Y., Noh, Y. and Dudhia, J. (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review*, 134, 2318–2341. https://doi.org/ 10.1175/MWR3199.1.
- Iacono, M.J., Delamere, J.S., Mlawer, E.J., Shephard, M.W., Clough, S.A. and Collins, W.D. (2008) Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. *Journal of Geophysical Research: Atmospheres*, 113, D13103. https://doi.org/10.1029/2008JD009944.

Kim, Y.-J. and Arakawa, A. (1995) Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. *Journal of the Atmospheric Sciences*, 52, 1875–1902. https://doi.org/10.1175/1520-0469(1995)052<1875:IOOGWP> 2.0.CO;2.

Kim, Y.-J. and Doyle, J.D. (2005) Extension of an orographic-drag parameterization scheme to incorporate orographic anisotropy and flow blocking. *Quarterly Journal of the Royal Meteorological Society*, 131, 1893–1921. https://doi.org/10.1256/qj.04.160.

Kim, Y.-J., Eckermann, S.D. and Chun, H.Y. (2003) An overview of the past, present and future of gravity-wave drag parametrization for numerical climate and weather prediction models. *Atmosphere – Ocean*, 41, 65–98. https://doi.org/10.3137/ao.410105.

Lindzen, R.S. (1981) Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Geophysical Research: Atmospheres*, 86, 9707–9714. https://doi.org/10.1029/JC086iC10p09707.

Lott, F. and Miller, M. (1997) A new sub-grid orographic drag parameterization: its formulation and testing. *Quarterly Journal of the Royal Meteorological Society*, 123, 101–127. https://doi.org/10. 1002/qj.49712353704.

McFarlane, N.A. (1987) The effect of orographically excited gravity wave drag on the general circulation of the lower stratosphere and troposphere. *Journal of the Atmospheric Sciences*, 44, 1775–1800. https://doi.org/10.1175/1520-0469(1987)044<1775:teooeg> 2.0.co;2.

Miranda, P.M.A. and James, I.N. (1992) Non-linear threedimensional effects on the wave drag: splitting flow and breaking waves. *Quarterly Journal of the Royal Meteorological Society*, 118, 1057–1081. https://doi.org/10.1002/qj.49711850803.

Miranda, P.M.A., Martins, J.P.A. and Teixeira, M.A.C. (2009) Assessing wind profile effects on the global atmospheric torque. *Quarterly Journal of the Royal Meteorological Society*, 135, 807–814. https://doi.org/10.1002/qj.393.

Moore, G.W.K. and Renfrew, I.A. (2005) Tip jets and barrier winds: a QuikSCAT climatology of high wind speed events around Greenland. *Journal of Climate*, 18, 3713–3725. https://doi.org/10.1175/JCLI3455.1.

Oltmanns, M., Straneo, F., Moore, G.W.K. and Mernild, S.H. (2014) Strong downslope wind events in Ammassalik, southeast Greenland. *Journal of Climate*, 27, 977–993. https://doi.org/10.1175/ JCLI-D-13-00067.1.

Palmer, T.N., Shutts, G.J. and Swinbank, R. (1986) Alleviation of systematic westerly bias in general circulation and numerical weather prediction models through an orographic gravity wave drag parameterization. *Quarterly Journal of the Royal Meteorological Society*, 112, 1001–1039. https://doi.org/10.1002/ qj.49711247406.

Parish, T.R. and Bromwich, D.H. (1991) Continental-scale simulation of the Antarctic katabatic wind regime. *Journal of Climate*, 4, 135–146. https://doi.org/10.1175/1520-0442(1991)004<0135:CSSOTA>2.0.CO;2.

Phillips, D.S. (1984) Analytical surface pressure and drag for linear hydrostatic flow over three-dimensional elliptical mountains. *Journal of the Atmospheric Sciences*, 41, 1073–1084. https://doi. org/10.1175/1520-0469(1984)041,1073:ASPADF.2.0.CO;2.

Richardson, M.I., Toigo, A.D. and Newman, C.E. (2007) PlanetWRF: a general purpose, local to global numerical model for planetary atmosphere and climate dynamics. *Journal of Geophysical Research: Atmospheres*, 112, E09001. https://doi.org/10.1029/ 2006JE002825. Sandu, I., Bechtold, P., Beljaars, A., Bozzo, A., Pithan, F., Shepherd, T.G. and Zadra, A. (2016) Impacts of parameterized orographic drag on the Northern Hemisphere winter circulation. *Journal of Advances in Modeling Earth Systems*, 8, 196–211. https://doi.org/ 10.1002/2015MS000564.

Shutts, G. (1995) Gravity-wave drag parameterization over complex terrain: the effect of critical-level absorption in directional wind-shear. *Quarterly Journal of the Royal Meteorological Society*, 121, 1005–1021. https://doi.org/10.1002/qj.49712152504.

Sigmond, M. and Shepherd, T.G. (2014) Compensation between resolved wave driving and parameterized orographic gravity wave driving of the Brewer–Dobson circulation and its response to climate change. *Journal of Climate*, 27, 5601–5610. https://doi.org/ 10.1175/JCLI-D-13-00644.1.

Smith, R.B. (1980) Linear theory of stratified flow past an isolated mountain. *Tellus*, 32, 348–364. https://doi.org/10.1111/j.2153-3490.1980.tb00962.x.

Teixeira, M.A.C. and Miranda, P.M.A. (2004) The effect of wind shear and curvature on the gravity wave drag produced by a ridge. *Journal of the Atmospheric Sciences*, 61, 2638–2643. https://doi.org/10. 1175/JAS3282.1.

Teixeira, M.A.C. and Miranda, P.M.A. (2006) A linear model of gravity wave drag for hydrostatic sheared flow over elliptical mountains. *Quarterly Journal of the Royal Meteorological Society*, 132, 2439–2458. https://doi.org/10.1256/qj.05.220.

Teixeira, M.A.C., Miranda, P.M.A. and Valente, M.A. (2004) An analytical model of mountain wave drag for wind profiles with shear and curvature. *Journal of the Atmospheric Sciences*, 61, 1040–1054. https://doi.org/10.1175/1520-0469(2004)061< 1040:AAMOMW>2.0.CO;2.

Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M.A., Mitchell, K., Ek, M., Gayno, G., Wegiel, J. and Cuenca, R.H. (2004) Implementation and verification of the unified NOAH land surface model in the WRF model. 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction, pp. 11–15.

Turner, H.V., Teixeira, M.A.C., Methven, J. and Vosper, S.B. (2019) Sensitivity of the surface orographic gravity wave drag to vertical wind shear over Antarctica. *Quarterly Journal of the Royal Meteorological Society*, 145, 164–178. https://doi.org/10.1002/qj. 3416.

Xu, X., Shu, S. and Wang, Y. (2017a) Another look on the structure of mountain waves: a spectral perspective. *Atmospheric Research*, 191, 156–163. https://doi.org/10.1016/j.atmosres.2017. 03.015.

Xu, X., Tang, Y., Wang, Y. and Xue, M. (2018) Directional absorption of mountain waves and its influence on the wave momentum transport in the Northern Hemisphere. *Journal of Geophysical Research: Atmospheres*, 123, 2640–2654. https://doi.org/10.1002/ 2017JD027968.

Xu, X., Wang, Y. and Xue, M. (2012) Momentum flux and flux divergence of gravity waves in directional shear flows over three-dimensional mountains. *Journal of the Atmospheric Sciences*, 69, 3733–3744. https://doi.org/10.1175/JAS-D-12-044.1.

Xu, X., Wang, Y., Xue, M. and Zhu, K. (2017b) Impacts of horizontal propagation of orographic gravity waves on the wave drag in the stratosphere and lower mesosphere. *Journal of Geophysical Research: Atmospheres*, 122, 11301–11312. https://doi.org/10. 1002/2017jd027528.

- Xu, X., Xue, M., Teixeira, M.A.C., Tang, J. and Wang, Y. (2019) Parameterization of directional absorption of orographic gravity waves and its impact on atmospheric general circulation simulated by the Weather Research and Forecasting model. *Journal of the Atmospheric Sciences*, 76, 3435–3453. https://doi.org/10.1175/ JAS-D-18-0365.1.
- Zhang, C., Wang, Y. and Hamilton, K. (2011) Improved representation of boundary layer clouds over the southeast Pacific in ARW-WRF using a modified Tiedtke cumulus parameterization scheme. *Monthly Weather Review*, 139, 3489–3513. https://doi. org/10.1175/MWR-D-10-05091.1.

**How to cite this article:** Xu X, Teixeira MAC, Xue M, Lu Y, Tang J. Impacts of wind profile shear and curvature on the parameterized orographic gravity wave stress in the Weather Research and Forecasting model. *Q J R Meteorol Soc*. 2020;146:3086–3100. https://doi.org/10.1002/qj. 3828