Orography-Induced Gravity Wave Drag (GWDO) Parameterization in the WRF Model

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1. Introduction

Atmospheric gravity waves are sub-grid scale processes which cannot be fully resolved by global models, since the spatial scales of these waves are too small compared to the grid size generally used in the global models. Even though they are unresolved processes, they have important roles in the real atmosphere; one of the most important roles of the gravity waves is that they transport momentum from their sources to the regions where they are dissipated or absorbed during their propagations, and then produce synoptic scale body forces. These are known as the gravity wave drag (Kim et al., 2003).

There are many sources of the gravity waves, and it is found out that the orography is one of the most dominant sources of the waves; the gravity waves can be generated when air flows over surface obstacles such as an uneven topography. In many studies, it is demonstrated that the traditional problems in seasonal simulations-the westerly biases and the cold pole problem due to the westerly biases-are alleviated with the consideration of the orography-induced gravity wave drag.

The gravity wave drag induced by sub-grid scale orography (hereafter, GWDO) has been parameterized in many studies and tested with various global models. Alpert *et al*. (1988) developed a model for the upper level gravity wave drag and the enhanced drag at the lower level was suggested by Kim and Arakawa (1995). These two parameterizations already had been implemented in the National Centers for Environmental Prediction (NCEP) Global Spectral Model (GSM) and their impact was studied in Hong *et al.* (2008). Following the study, the GWDO parameterization considering low tropospheric enhancement (i.e, the parameterization suggested by Kim and Arakawa 1995) was implemented in the Weather Research and Forecasting (WRF) model and it became available from WRFV3.1 which was released in April 2009.

The objective of this study is evaluating the fundamental roles of the orography-induced gravity wave drag parameterization (GWDO) using the WRF model with global domain, and investigating its impact on short range and seasonal forecasts.

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2. An Overview of the GWDO parameterization

The GWDO parameterization implemented in the WRF model follows Kim and Arakawa (1995); the lower-tropospheric enhancement of gravity wave drag is considered.

When the air moves over irregular terrains, the stress occurs at the reference level (τ_0), and this stress vertically propagates as the form of gravity waves. During the propagation, the wave breaking occurs when the waves encounter unstable conditions, then they transport momentum from their sources to breaking regions; this momentum exchange is represented as the drag. In other word, only the residual stress (τ) continues to propagate after breaking, and then this vertical gradient of the stress makes the drag (cf. Fig. 1).

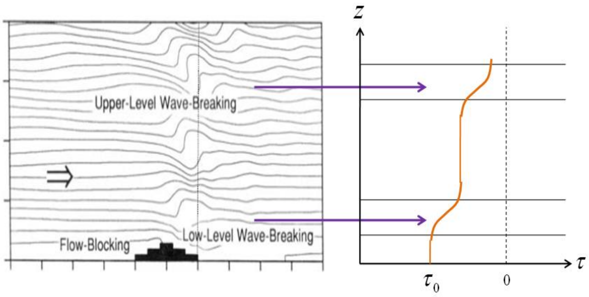


Fig. 1. A schematic diagram of the vertical momentum flux τ, for the GWDO parameterization in the WRF model. The left one is from Kim and Doyle (2004).

3. Experimental Setup

The model used in this study is the Advanced Research WRF (ARW) Version 3.1. The GWDO parameterization is evaluated over the global domain to investigate global responses to the gravity wave drag. The WRF model became available for the global domain from WRF Version 3.0.

The effect of the GWDO on short range forecasts is evaluated by a cyclone-genesis case. The seasonal experiments are also conducted to show the impact of the GWDO in removing the westerly bias and cold-pole problem as reported by previous studies. Sensitivity of the GWDO to radiation processes are investigated with the seasonal runs.

A set of the experiments with (GWD) and without (CTL) GWDO parameterization is conducted for both the short range and seasonal forecasts.

The physics package includes the Goddard shortwave radiation, the RRTMG longwave radiation, the WSM3 microphysics scheme, the Grell-Devenyi ensemble scheme for cumulus parameterization, the NOAH land-surface model, and the Yonsei University planetary boundary layer (YSUPBL) process.

a. Short range forecasts

The fundamental role of the orography-generated gravity wave drag (GWDO) is investigated by a strong lee side mountain cyclone-genesis case in February, 1995. The model integration time is 48 hours from 12UTC 13 to 12UTC 15 February 1995. Initial conditions are generated from the NCEP-Department of Energy (NCEP-DOE) Reanalysis Ⅱ (R2) data on 2.5°×2.5° grids. The horizontal resolution of 0.9375°×0.9375° is used in the model, which is comparable to the 100 km resolution at the equator. The number of vertical layer used here is 38 with the model top of 10 hPa. Intervals between the adjoining vertical levels are determined not to exceed 1 km or be comparable to 1 km.

b. Seasonal forecasts

The seasonal simulations are conducted for three boreal winters in December, January, and February (DJF) of 1996/97, 1997/98, 1999/2000 to evaluate the impact of the GWDO on the simulated climatology. For each winter, five ensemble runs are conducted with different initialization dates of 00UTC 1-5 November. Initial conditions are forced by the NCEP-Department of Energy (NCEP-DOE) Reanalysis Ⅱ (R2) data on 2.5°×2,5° global grids. The National Oceanic and Atmospheric Administration (NOAA) Optimal Interpolation Sea Surface Temperature (OISST) is used as the surface boundary condition every 24 hours. The resolution of 1.875°×1.875° is used, which is comparable to the 200 km resolution at the equator. The vertical resolution is the same with that of the short range forecasts.

Sensitivity experiments of the simulated climate and GWDO to shortwave radiation processes are also executed with three different shortwave schemes: the Goddard, RRTMG, and Dudhia schemes.

4. Results

a. Implementation – Short Range Forecast

The fundamental roles of the GWDO are studied from the short range forecasts. Figure 2 shows the standard deviation of the terrain height (σ) (figure 2a) and the reference level stress (figure 2b). It is apparent that the reference level stress is parameterized over the high terrain regions (e.g. over the Tibetan plateau, the Rockies, and the Antes) as expected.

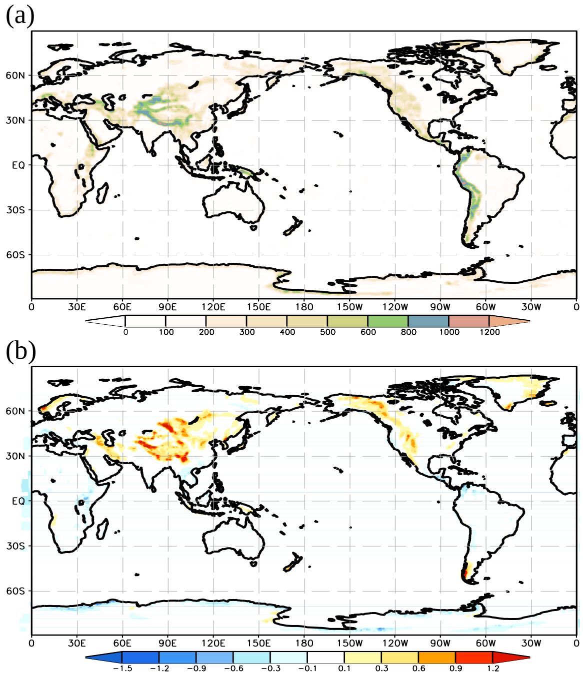


Fig. 2. (a) The variance of terrain height (σ) and (b) the reference level stress (τ_0) calculated from the GWDO parameterization.

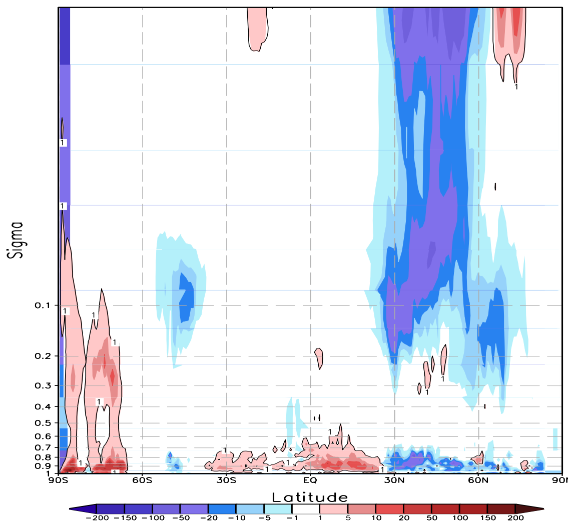


Fig. 3. The zonal mean zonal wind tendency (10^{-6} m s^{-2}) due to the GWDO averaged over the simulation period.

Figure 3 shows the 36-hr averaged zonal mean zonal wind tendency due to the GWDO, from the South Pole to the North Pole. The role of the GWDO (i.e., deceleration) is governing at upper regions of the reference level drag occurrence.

The GWDO has influence on the forecasting ability. With respect to the lee-side mountain cyclogenesis at 00UTC 15 February 1995, the cyclone is simulated at the further northeast regions with too strong intensity in the CTL experiment compared to the R2. The intensity and location of the cyclone is more realistically simulated when the

GWDO is considered (not shown here).

b. Impact of the GWDO - Seasonal Climate

In the performance of the global WRF, it is expected that the traditional cold pole problem associated with too strongly simulated westerlies (i.e., westerly biases) in the simulated climatology can be alleviated considering the gravity wave drag, as in the GSM results in the Hong et al. (2008).

Figure 4 compares simulated zonal mean zonal wind and temperature during three winters from the three CTL experiments-G_{sw}_CTL, R_{sw}_CTL, and D_{sw}_CTL-with the R2 data. It is clear that none of three experiments captures the separation of the stratospheric polar night from the tropospheric subtropical jet, regardless of the shortwave radiation processes. In association with this, all three experiments too underestimate temperature over the upper level of the North Pole, indicating the traditional cold-pole problem; the simulated minimum temperature is around 160 K and the R2 shows the minima about 200 K. The Dudhia scheme also does not reproduce the temperature inversion over the stratosphere, since the ozone effects are not included in the scheme (not shown here).

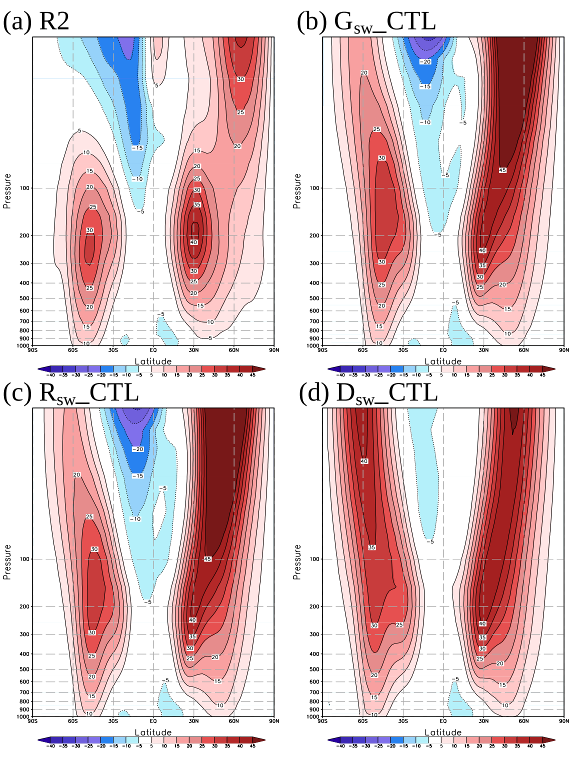
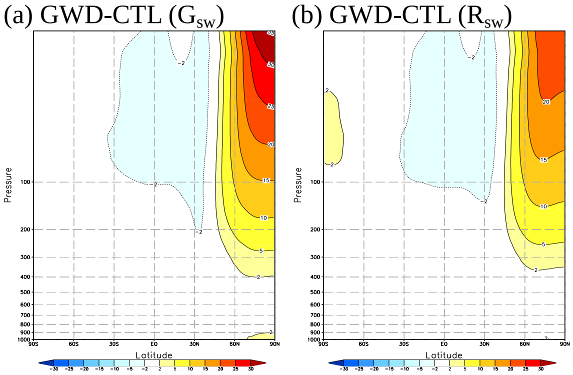


Fig. 4. The 3-year averaged zonal mean zonal wind during the DJF from the (a) R2 and three control simulations: (b) G_{sw}_CTL, (c) R_{sw}_CTL, and (d) D_{sw}_CTL.

From the all three GWD experiments-G_{sw}_GWD, R_{sw}_GWD, and D_{sw}_GWD-it is obvious that the gravity wave drag contributes in migrating the westerly biases and getting closer to the R2 in the Northern Hemisphere. The stratospheric polar night jet and tropospheric subtropical jet are separated in the G_{sw}_GWD and R_{sw}_GWD experiments which have ozone effects. In relation to this improvement, the traditional cold pole problem is also relaxed with increased temperature at the North Pole, regardless of the shortwave processes as seen in the Figure 5.



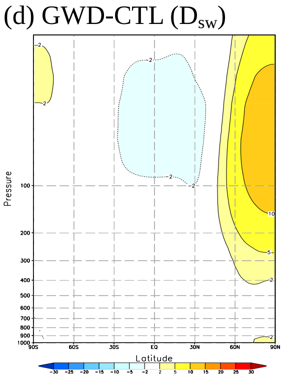


Fig. 5. The differences of the 3-year averaged temperature (GWD-CTL) from the (a) Gsw, (b) Rsw, and (c) Dsw experiment sets.

5. Concluding Remarks

The Orography-induced Gravity Wave Drag (GWDO) parameterization is implemented in the WRF model and evaluated using the WRF model with the global domain. The GWDO improves the predictability of the WRF model for the selected cyclogenesis case of the short range forecasts. The traditional problems in the simulated climate-westerly biases and cold pole problem-are alleviated by the GWDO. The sensitivity analysis of the simulated climate and GWDO to radiation processes shows that the ozone effects is needed to be included in the shortwave radiation processes for realistic seasonal (long-term) simulations over the global domain which covers the stratosphere.

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Acknowledgments

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