Representation of Subgrid-Scale Orographic Effects in a General Circulation Model.  
Part I: Impact on the Dynamics of Simulated January Climate  

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ABSTRACT  

Effects of subgrid-scale orography are represented in most large-scale models of the atmosphere by means of parameterizing subgrid-scale orographic gravity wave drag and/or enhancing grid-scale orography, such as “envelope orography,” with the use of subgrid-scale orographic variance. A new gravity wave parameterization scheme and an envelope orography have been implemented in the UCLA general circulation model. The impact of gravity wave drag and envelope orography on simulations using the tropospheric–stratospheric 15-layer version of the model are briefly discussed and compared.  

The gravity wave parameterization scheme and the envelope orography have a qualitatively similar and beneficial impact on ensemble means of simulated January climate. The midlatitude westerlies are weakened at all levels and the polar atmosphere is warmed in the Northern Hemisphere. A combination of the two produces the best results. Sensitivity experiments with the parameterization scheme indicate the importance of the selective enhancement of low-level drag.  

Although the overall impact of gravity wave drag on the mean fields is similar when using the standard version of orography or the envelope orography, the magnitudes of gravity wave drag are systematically different in simulations using the two representations of orography in the midlatitude Northern Hemisphere. The modification in the magnitudes of simulated meridional eddy momentum fluxes by gravity wave drag with the standard orography is as in earlier studies. This is, however, not the case with the envelope orography. Whereas the impact of gravity wave drag and the envelope orography on the mean fields is similar, it is not necessarily true in terms of the individual components of simulated angular momentum budget.  

1. Introduction  

Recent general circulation models (GCMs) of the atmosphere as well as numerical weather prediction (NWP) models have shown tendencies to produce excessively strong midlatitude westerlies in the Northern Hemisphere during winters. It was earlier suggested that underrepresentation of the surface drag coefficient in these models was responsible for the systematic bias of the westerlies especially at the surface (e.g., Swinbank 1985). An increase of the drag coefficient, however, does not effectively increase the friction drag and as a result has relatively little effect on the strength of the midlatitude westerlies (Palmer et al. 1986; Miller et al. 1989). “Parameterization of subgrid-scale orographic gravity wave drag (GWD),” on the other hand, has been successful in increasing the surface drag (and imposing additional drag on the free atmosphere) and, therefore, in alleviating the systematic westerly bias in large-scale models (e.g., Boer et al. 1984; Palmer et al. 1986; McFarlane 1987; Rind et al. 1988). [See Gates (1992), Boer et al. (1992), and Kim and Arakawa (1995; hereafter referred to as K.A95) for intercomparison of the parameterization schemes.]  

Another approach to dealing with this problem is to increase the drag by using enhanced grid-scale orography, such as “envelope orography” (Wallace et al. 1983), “silhouette orography” (Mesinger 1985), and “significant heights orography” (Pfaendtner et al. 1985). [Mesinger and Collins (1986) give a review of this approach.] Enhancing grid-scale orography utilizing subgrid-scale orographic variations is considered roughly equivalent to filling subgrid-scale valleys, in which the flow is dynamically disconnected from the flows above. Envelope orography is an enhancement of model’s grid-scale orography with an increment proportional to the standard deviation of subgrid-scale orography. Envelope orography is shown to enhance the amplitudes of simulated planetary waves (e.g., Palmer and Mansfield 1986; Tibaldi 1986; Iwasaki and Sumi 1986). The dissipation of vertically propagating Rossby waves may cause the deceleration of zonal mean winds in the upper atmosphere (e.g., Schoeberl and Strobel 1984; Miller et al. 1989).  

Envelope orography and orographic GWD are usually considered as parameterizations of different physical  

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processes. The former incorporates the additional barrier or blocking effects due to subgrid-scale orography, while the latter formulates vertical momentum transport by internal gravity waves generated by flow over subgrid-scale orography. Both envelope orography and GWD parameterization are, however, constructed by using information on subgrid-scale orographic variations and tend to produce a similar impact on the models’ climate. Miller et al. (1989) argued that the impact of low-level gravity wave drag is similar to that of envelope orography. Some studies show that inclusion of a GWD parameterization generally produces better simulations than those with envelope orography only (e.g., Slingo and Pearson 1987; Miller and Palmer 1986; and Jarraud et al. 1988; Miller et al. 1989). Many studies report that a combination of these two is useful (e.g., Chouinard et al. 1986; Palmer et al. 1986; McFarlane et al. 1987; Stern et al. 1987; Miller et al. 1989; Iwasaki et al. 1989a) although the combination may introduce some redundancy.

To try to understand the relationship between enhanced orography and GWD, we show Fig. 1, which schematically describes the spectrum of vertical gravity wave propagation under typical midlatitude northern hemispheric winter conditions. Enhanced orography may be justifiable when gravity waves are external. External gravity waves decay in the vertical and thus do not propagate energy vertically, while forming a dynamically disconnected and/or wind-stagnant region above orography. This region acts as a barrier or elevated surface to incoming flow and is thus similar to the idea of implementing enhanced orography. Both these external gravity waves represented by enhanced

![Diagram showing the spectrum of gravity wave propagation under typical midlatitude northern hemispheric winter conditions.](image)

**Fig. 1.** Schematic illustration of the spectrum of gravity wave propagation under typical midlatitude northern hemispheric winter conditions for the horizontal scales of the waves governed by \( \varphi_z + (\varphi - \kappa)^2 = 0 \), where \( \varphi \approx N^2 |U|^2 \) is the Scorer parameter (Scorer 1949) and \( \kappa \) is the horizontal wavenumber (based on Iwasaki et al. 1989a). The effects of subgrid-scale irregularities can be parameterized in view of three drag mechanisms in large-scale models of the atmosphere.

![Map showing standard orography and deviations.](image)

**Fig. 2.** The elevations of the (a) standard orography, (b) envelope orography, and (c) standard deviation of subgrid-scale orography [km], for the 4° lat. x 5° long. version of the UCLA GCM (see appendix for details). Note that the Andes area was not enhanced for envelope orography.

orography and internal gravity waves represented by GWD are thus physical processes occurring in different regions of the wavenumber-height domain. Then, the effects of subgrid-scale irregularities can be parameterized basically in view of three mechanisms. The effect of turbulence near the surface is parameterized by a planetary boundary layer (PBL) parameterization, that of the external waves is parameterized by an enhanced grid-scale orography, and that of the internal waves is parameterized by a GWD parameterization.
This view implies that the physical processes associated with enhanced orography and GWD parameterization do not overlap in principle and thus provides a basis for a combined use of the two.

One of the main objectives of our research has been to verify and improve the parameterization of orographic gravity wave drag for large-scale models of the atmosphere. In our earlier study with a mesoscale gravity wave model (KA95), we showed that low-level breaking of large amplitude mountain waves mainly downstream of mountains is not uncommon and can lead to a significant enhancement of drag. We argued that a correct treatment of the effect of this low-level wave breaking is crucial in the parameterization of orographic GWD. We also pointed out that examining the overall improvement of large-scale fields is not necessarily the best way of evaluating GWD parameterization schemes. The reason is that mutual interactions of nonlinear processes in the simulated atmosphere hinder proper isolation and assessment of the improvement directly due to GWD itself (this will be further discussed later). This lead us to development of a GWD parameterization scheme using a mesoscale gravity wave model.

The purpose of this paper is to discuss the impact of our GWD parameterization scheme and an envelope orography in the UCLA GCM and investigate the effects of subgrid-scale orography on the dynamics of the simulated climate. We present ensemble means of January climate from simulations with and without the GWD parameterization scheme and envelope orography. Section 2 briefly describes the model and the design of the experiments. Section 3 provides a compact form of the GWD scheme. Section 4 presents results from the experiments with the UCLA GCM. Section 5 presents the results from some sensitivity experiments with the GWD scheme. Section 6 discusses the impact of GWD and envelope orography in terms of the monthly (zonal) means and meridional eddy flux fields. Finally, section 7 summarizes and discusses this work and concludes with further remarks.

2. The model and the design of the experiments

We use a 15-layer version of the UCLA GCM, with a horizontal resolution of 4° lat. × 5° long. and its top located at 1 mb, which thus includes the troposphere and the stratosphere. The vertical coordinate used is a modified σ-coordinate by Suarez et al. (1983). With this coordinate, the lowest layer of the model is the PBL. The model predicts surface pressure, PBL depth, horizontal wind, potential temperature, water vapor and ozone mixing ratios, and surface temperature and snow depth over land. The horizontal finite differencing for the momentum equation is on a staggered C-grid and based on a fourth-order version of the scheme by Arakawa and Lamb (1981) that conserves the potential enstrophy and energy when applied to the shallow-water equations. The thermodynamic energy and water vapor advection equations are also based on a fourth-order scheme. The vertical finite differencing on the Lorenz-type grid follows Arakawa and Lamb (1977) above 100 mb and Arakawa and Suarez (1983) between 100 mb and the PBL. This differencing conserves the global mass integrals of the potential temperature and the total energy under adiabatic, frictionless processes. For the integration in time, the leapfrog time-differencing scheme is used with the Matsuno scheme regularly inserted. PBL processes are parameterized using a mixed-layer approach after Suarez et al. (1983). Surface fluxes are calculated following the bulk formula proposed by Deardorff (1972). Parameterization of cumulus convection, including its interaction with the PBL, follows Arakawa and Schubert (1974), with a relaxed adjustment timescale for the cloud work function as described in Cheng and Arakawa (1994) and Ma et al. (1994). Long and shortwave radiation parameterization schemes are based on Harshvardhan et al. (1987, 1989) and Katayama (1972), respectively. The geographical distributions of sea surface temperature, planetary albedo, ground wetness, and ground type are prescribed from a 10-yr mean monthly climatology. Mechoso et al. (1985, 1986) presented simulations with an earlier version of the model (without GWD and with Katayama’s radiation parameterization for both the long and short waves).

As a preliminary test, the model was initialized with 1200 GMT 1 October 1982 data constructed from the National Meteorological Center (NMC, now known as the National Centers for Environmental Prediction) analysis and the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) data, and was integrated for 4 months with-
out GWD parameterization until January of the following year, giving the model time to reach an equilibrium state. We then applied the GWD parameterization scheme to the January mean simulated fields as reported by Kim and Arakawa (1994). This simple diagnostic method was convenient and effective in finalizing details of the scheme before it was fully implemented into the GCM. This was needed since the GWD scheme was developed under a 2D framework based on a 2D gravity wave model. The final results from this diagnostic test (not shown) were found to be qualitatively very similar to those from the actual model integrations that will be shown later. The magnitude of the diagnosed upper-level drag was smaller than that with the scheme based on Palmer et al. (1986), so that the ratio of upper to low-level drag is smaller with our scheme. The interpretation of this diagnostic experiment is, however, limited due to the inability of the method to include temporal variations of variables, especially those of the wind at low levels.

The model was then cold-started from 8 selected days in early October 1982 and integrated for 4 months with four combinations, with and without envelope orography and GWD. We focus on the January mean climatology, during which the atmospheric stability is relatively large and thus the effect of gravity wave drag is possibly the most important in the Northern Hemisphere. The "control experiment" is with the standard large-scale mean orography currently used in the UCLA GCM and without using the GWD parameterization scheme. The "GWD only experiment" is with the standard orography and the GWD scheme. The "envelope orography only experiment" is without GWD but with an enhanced orography obtained by adding to the grid-scale orog-
Fig. 5. Ensemble means of the simulated January mean zonal wind (m s$^{-1}$) obtained from (a) experiment SN (Standard Orography + No GWD), (b) experiment SG (Standard Orography + GWD), (c) experiment EN (Envelope Orography + No GWD), and (d) experiment EG (Envelope Orography + GWD), each consisting of eight simulations.

The standard deviation of subgrid-scale orography multiplied by $2^{1/2}$. The "combined experiment" is with both the envelope orography and the GWD schemes. The standard orography, envelope orography, and standard deviation of subgrid-scale orography are shown in Fig. 2. For a comparison, Fig. 3 shows a selected longitude–height cross section of the standard and envelope orography. The GWD scheme is described in the following section.

3. Gravity wave drag parameterization scheme

We describe here the scheme developed by KA95 with minor modifications and simplifications made for use in a 3D large-scale model. The drag at the reference level (denoted by a zero subscript), where the magnitude of the drag is first determined, and the drag above the reference level are expressed as

$$\tau_0 = E \frac{m}{\bar{d}} \frac{\rho_0 |U_0|^3}{N_0} G, \quad \tau = \frac{m}{\bar{d}} \rho N |U| h_a^3,$$

respectively, where $d$ is a distance representing the grid scale (fixed to 100 km in this study), $\rho$ is the density, $N$ is the Brunt–Väisälä frequency, $|U|$ is the horizontal wind speed, $h_a$ is the vertical displacement due to the wave, and the parameters $E$, $m$, and $G$ are the enhancement factor, the number of mountains and the flux function, respectively:

$$E = (OA + 2) \exp(0.8 Fr_0),$$

$$m = (1 + \sum L_x) \exp(OA + 1),$$

$$G = \frac{Fr_0^2}{Fr_0^2 + 0.5OC^{-1}}.$$

Note that this grid-scale orography, which is used to construct the envelope orography, is different from the (smoother) "standard orography."  

The Andes area is not enhanced to avoid noises due to very sharp slopes in the area.
Here, $\Sigma_x L_x$ is the fractional width covered by the subgrid-scale orography for the grid distance in the direction of the low-level wind, $F_{30} \left( = N_0 SD/|U_0| \right)$ is the (inverse) Froude number, $SD$ is the standard deviation of subgrid-scale orographic height, and OA and OC denote the orographic asymmetry and orographic convexity (see KA95 for details including the definitions), respectively.

Here, OA was designed for determining the drag enhancement associated with wave breaking at low levels, while OC was designed to incorporate the effects of multiple irregular barriers. The OC was designed to partially incorporate the effects of small-scale valleys, the effects that the use of envelope orography somehow tries to account for. It is thus possible that some effects of the GWD scheme are similar to those of envelope orography although the actual processes involved are different.3 KA95 argued that with the aid of these additional statistical measures of orography, the enhancement of low-level drag due to wavebreaking is more properly parameterized through selective enhancement of the drag. Three-dimensional effects of orography with respect to the impinging wind are taken into account mainly through OA, which depends on the low-level wind direction, and also through the height of the reference level, which depends on OA. The direction of the drag is thus determined depending on the height of the reference level as well as on the direction of the wind at the reference level. The details of the procedure to generate and use the orographic datasets are given in the appendix.

The vertical distribution of the drag is determined following Miller and Palmer (1986), which is based on the Eliassen–Palm theorem (Eliassen and Palm 1960) and Lindzen’s (1981) saturation hypothesis, except at low levels when $OA > 0$ (i.e., in the troposphere in downstream regions) for which $\tau_{2}/\tau_{30} = I_{2}/I_{30}$ is used with the ratio not allowed to exceed 1. Here, $i$ is the vertical level index and $I^2 \approx N^2/|U|^2$ is the Scorer parameter (Scorer 1949) obtained from the grid-scale variables.

4. Experiments with the UCLA GCM

a. Monthly (zonal) mean fields

Figure 4 shows observations of the zonal-mean zonal wind and temperature, the geopotential height at 10 mb, and the mean sea level pressure for January. The sea level pressure is from a direct European Centre for Medium-Range Weather Forecasts (ECMWF) analysis, but the wind and temperature are derived from the geopotential, which consists of the NMC operational analysis below 100-mb level and the Climate Analysis Center (CAC) NOAA (National Oceanic and Atmospheric Administration) analysis above it, using the gradient wind expression and the hydrostatic relation, respectively (Randel 1992).4 The following figures will show

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3 We believe, however, that the current horizontal resolution (4° lat x 5° long) is not sufficient to allow the scheme to deal with the full effects of small-scale valleys.

4 These figures are provided here only for rough comparisons. In particular, it is noted that the minimum temperatures over the equator and the north pole are higher than those of Boville and Randel (1986; see their Fig. 2).
the ensemble January means of eight 4-month simulations from the control runs with the standard orography (experiment SN, meaning Standard orography and No GWD), the GWD only experiments (experiment SG), the envelope orography only experiments (experiment EN), and the experiments with the envelope orography plus GWD (experiment EG).

We first compare the impact of envelope orography and GWD parameterization on the zonally averaged fields. A comparison of the simulated mean zonal wind fields (Fig. 5) shows that in the Northern Hemisphere the too strong jet of experiment SN has been significantly weakened at all levels in the other experiments. The reduction is larger for experiment EN than for experiment SG. Experiment EG produced the best result in that the stratospheric polar and tropospheric subtropical jets are well separated. There is little change in the Southern Hemisphere as expected from the fact that the effect of orography is smaller in the Southern Hemisphere due to relative scarcity of orography and to relatively small static stability in summer. The reduction of the mean zonal winds is more clearly seen in Fig. 6, which shows the differences from experiment SN. The introduction of GWD and the envelope orography decreases the westerlies mainly in middle and high latitudes of the Northern Hemisphere concurrently with the jet. The combination of the envelope orography and GWD further weakens and broadens the jet. The upper-level winds, however, become stronger in subtropical latitudes of the Northern Hemisphere due to the effect of the Coriolis torque induced by the secondary meridional circulation associated with the enhanced mountain drag and/or GWD as discussed by

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5 We note that some studies show that inclusion of a GWD parameterization in the model decreases the stratospheric jet while it increases the tropospheric jet in the Northern Hemisphere (e.g., Palmer et al. 1986; Boville 1991). In our simulations, however, the intensity of the tropospheric jet remains almost the same, although it becomes separated from the stratospheric jet (experiment EG).
Palmer et al. (1986). Figure 7 shows the horizontal wind interpolated to the 850-mb pressure surface, and Fig. 8 shows the differences of the zonal mean zonal winds at 10 mb and 850 mb. The weakening of the midlatitude westerlies is again the greatest in experiment EG at both levels.

A comparison of the monthly mean sea level pressure fields (Fig. 9) reveals that the envelope orography and GWD generally increased the pressure in the high-latitude Northern Hemisphere, filling the too deep Icelandic low, for example. This pressure increase results in reduced meridional pressure gradients and thus weaker surface westerlies in the midlatitude Northern Hemisphere, especially over the continents as seen in Fig. 8b. The pressure near the Iberian peninsula is rather too high in all simulations. Changes in the Southern Hemisphere are minor compared with the Northern Hemisphere. Figure 10 shows the corresponding zonally averaged sea level pressure. Clearly seen is the reduction of the meridional pressure gradient due to higher (lower) subpolar (subtropical) pressures in the Northern Hemisphere, which reduces midlatitude westerlies. The higher pressures in the high-latitude Northern Hemisphere and the lower pressure in the Southern Hemisphere are closer to the ECMWF observations than those of experiment SN.

Figure 11 shows the differences from experiment SN of the mean zonal temperature. In the Northern Hemisphere, the polar stratosphere is considerably warmed while the lower stratosphere is slightly cooled at low latitudes through adiabatic descent and ascent of air due to the secondary meridional circulation induced by the westerly drag (see Fig. 6), consistent with a flow in thermal wind balance. Figure 12 shows the differences in 850-mb temperature fields from experiment SN. In experiment EG, the temperature over the continents in higher latitudes of the Northern Hemisphere were significantly decreased. The temperatures rose, however, elsewhere over other major mountainous regions, except over Andes, which was not enhanced by the envelope orography. It is interesting that the difference over Eurasia is much bigger with the envelope orography than with GWD as consistently seen in the sea level pressure fields. The difference patterns match neither the orography itself nor its variance (see Fig. 2) and the field of EG-SG is very similar to the field of EN-SN. This suggests that the difference is due not mainly to the gravity wave drag but largely to the difference in the elevation of orography associated with the surface boundary. We investigated the impact of this temperature change on quantities, such as precipitation, cloud cover, various surface fluxes, humidity, heating rates, etc. From the ensemble averages, however, we found no systematic differences in any of these fields. The impact may be larger for higher resolution and/or northern summer.

Figure 13 shows the geopotential height at 10 mb. The introduction of the envelope orography and GWD improved the overall features by decreasing the meridional gradient of the geopotential and thus weakening the polar vortex consistently with the weakening of the mean zonal winds (Fig. 5). The values are closer to those observed over the pole while they are somewhat smaller than those observed near the equator. The best result is again found in experiment EG.

Moreover, in order to provide some evidence of the robustness of the difference among these experiments, a Student’s t-test was performed with respect to the monthly mean fields of the zonal-mean sea level pressure and zonal wind fields (Table 1). The significance values between the observations (ECMWF and NMC analysis) and experiment SN are $2 \times 10^{-6}$ and $6 \times 10^{-5}$ for the mean sea level pressure and zonal wind, respectively, whereas those values with experiment EG are 0.075 and 0.073, respectively. This shows that the envelope plus GWD experiments are overall statistically closer than the control to the observations.
b. Meridional eddy flux fields

We now compare the impact of the envelope orography and the GWD parameterization in view of zonally varying quantities, such as the meridional fluxes due to large-scale eddies. This provides further information regarding the response of the model to the changes in orographic representations. Figure 14 shows the ensemble means of the meridional eddy momentum fluxes calculated from each of the eight simulations, and Fig. 15 shows the corresponding flux calculated from the observed geopotential height data following Randel (1992). The simulated fluxes in all experiments, including experiment SN, generally agree well with observations. In the Southern Hemisphere, the simulated fluxes are also in good agreement with observations although experiment SN shows somewhat large values in the subpolar troposphere. In the Northern Hemisphere, the fluxes in the midlatitude troposphere are slightly stronger than those observed in all simulations. Relatively large differences exist between observations and all the simulations in the

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Fig. 9. As in Fig. 5 but for sea level pressure (mb).

Fig. 10. Zonally averaged sea level pressure (mb) for the experiments shown in Fig. 9 and that from ECMWF analysis (1980–87).

6 A similar overestimate of the fluxes was reported by Miller et al. (1989).
Northern Hemisphere high-latitude troposphere, where the equatorward fluxes are in general underestimated (especially in experiment SN). The combined use of the envelope orography and GWD somewhat improves the magnitude of the fluxes in this region. In the stratosphere, the maximum values in the Northern Hemisphere midlatitudes are similar to one another except in experiment SG, which shows significantly smaller values than the others.

Figure 16 shows profiles of the zonally and vertically averaged total meridional eddy momentum fluxes. In the upper atmosphere (from about 50 mb to 1 mb), the flux is larger in experiment EN and experiment EG than in experiment SN, and is nearly identical to that obtained from observations, whereas it is smaller in experiment SG. This is an interesting result in that the addition of GWD changes the flux in a different manner with the two different orographic representations, although the overall difference is rather small. The difference between experiment SG and experiment SN is, however, qualitatively consistent with some other numerical studies (e.g., Boer and Lazare 1988 with the model top at 50 mb; Boville 1991 at 0.025 mb) in that the poleward (equatorward) momentum transport in the Northern Hemisphere is smaller (greater) with the inclusion of a GWD parameterization in the model. In the lower atmosphere (from the surface to about 50 mb), the fluxes in the midlatitude Northern Hemisphere have decreased slightly although they remain larger than in observations. In high latitudes, the equatorward fluxes have increased although they are still smaller than in observations. This is in contrast to the studies cited above in which the improvement is mainly in the midlatitudes.

Figure 17 shows the zonally and vertically averaged meridional eddy fluxes of heat. In the upper atmosphere, the fluxes from experiment EN and experiment EG are greater than those from experiment SN. Although not large in magnitude, the fields of the eddy heat flux, which is proportional to the vertical component of the Eliassen–Palm (E–P) flux (Edmon et al. 1980), suggest that the vertically propagating Rossby waves are enhanced in experiment EN and experiment EG. The simulated fluxes in all experiments are, how-
ever, significantly underestimated possibly due to the coarse resolution of the model. In the lower atmosphere, on the other hand, the fluxes from all simulations are virtually the same.

In section 6, we will further discuss the impact of the envelope orography and GWD parameterization and argue that there is a systematic difference in the magnitude of drag with the two orographic representations.

5. Sensitivity to low-level drag

KA95 showed that the inclusion of low-level wave breaking is important in GWD parameterization since it can lead to a significant enhancement of low-level drag and its vertical divergence, supporting the notion proposed by several earlier modeling studies (see KA95 for references). The results from our parameterization are qualitatively similar to those of Miller et al. (1989) in that the low-level drag divergence due to wave breaking is substantial in the global average and the ratio of the upper to low-level drag is reduced. Our result is, however, obtained through selective enhancement of drag for parameterizing the possible effect of low-level wave breaking detected by the additional statistical measures of orography in the scheme, rather than through an overall enhancement of drag (see KA95 for details). In our scheme, the selective enhancement of low-level drag is twofold, through the enhancement factor ($E$) and the number of mountains ($m$) [see Eq. (1)]. The parameter $E$ is used only at the reference level, whereas $m$ is used at all levels. For example, as seen in Fig. 18, $E$ is large over the Andes area while $m$ is large over Antarctica. In this case, the drag is likely to be enhanced at the reference level by large $E$ over Andes and by large $m$ over Antarctica. Above the reference level, however, the drag over Antarctica is likely to be smaller since large $m$ gives smaller drag divergence as discussed in KA95.

To see the effect of the low-level drag enhancement on the simulations in view of the selectiveness or locality of drag and the ratio of upper to low-level drag, two sensitivity experiments were performed: The first one is with the reference-level drag coefficient ($Em/d$
Fig. 13. As in Fig. 5 but for geopotential height (m) at 10 mb.

=k_0) fixed to its global mean value and the other is through nearly complete elimination of vertical divergence of low-level drag achieved by removing its dependence on the Scorer parameter ratio (see section 3). When combined, these are roughly equivalent to testing the "original scheme" constructed by KA95 utilizing the essential features of existing schemes. Figure 19 shows the global averages of the deceleration due to GWD obtained from these experiments initialized on 1 October 1982. Figure 20 shows the corresponding zonally averaged sea level pressure. For a comparison, the result from the corresponding original experiment (experiment EG_1) is shown in Figs. 19 and 20 and that from observation is shown in Fig. 20. Although the magnitude of low-level drag looks not so different in terms of the global means (Fig. 19), the simulation with averaged coefficient produces stronger meridional pressure gradients in the midlatitude Northern Hemisphere (Fig. 20) and consequently overly strong surface westerlies. It is interesting to see that the experiment with practically no low-level wave breaking produces significantly larger deceleration at high levels (Fig. 19), which could contribute to deceleration of the surface winds through meridional circulation induced by GWD. Nevertheless, the surface westerlies are still too strong, as seen from the sea level pressure field...
Table 1. The \( t \) statistics and corresponding significance between the observations (ECMWF or NMC) and the simulations (SN or EG) with respect to the ensemble means of the sea level pressure and the zonal mean wind. The significance of the \( t \) statistics is in the interval [0.0, 1.0], where a small value indicates that the pair has significantly different means.

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(Fig. 20). These results suggest that both low-level drag and its selective enhancement are important in obtaining improved simulations at least for the resolutions currently used.

6. Impact of GWD and envelope orography

a. Magnitude of GWD with different orographic representations

In the previous sections, we showed that the use of the GWD scheme with the standard or envelope orography improves the January simulations. We now investigate whether there is any systematic difference or similarity in the magnitude of GWD with the two orographic representations. Figure 21 shows the zonal component of the acceleration of zonal wind for experiment EG due directly to GWD as calculated from the vertical divergence of GWD. The GWD scheme generates substantial drag in the midlatitude Northern Hemisphere. Low-level drag, which is due to wave breaking mainly in regions downstream of orography, is easterly in the midlatitude Northern Hemisphere, while it is westerly in the high latitudes. The drag in the high latitudes is significant in magnitude but confined to the lower atmosphere. Figures 22a and 22b show the GWD acceleration in the zonal direction for experiments SG and EG averaged over latitude. Systematic differences between the two experiments are mainly in the midlatitude Northern Hemisphere where mountains are prevalent. The deceleration is greater in experiment SG in the upper atmosphere, while it is greater in experiment EG in the lower atmosphere. This difference contributes to the overall change in the vertical profiles of the global averages over nonzero orographic variance points (Fig. 22c).\(^8\)

To ascertain whether the difference in the ratio of the upper to low-level drag between experiment SG and experiment EG is related to any difference in flow conditions, we investigated the geographical distribution of the Froude numbers averaged for the upper and lower atmospheres (not shown). We found that wave breaking occurred mainly at low levels where \( Fr \) is large. The values of \( Fr \) at low levels were, however, similar in the two experiments. What is more relevant than \( Fr \) to the magnitude of low-level wave breaking is in fact the vertical gradient of the Scorer parameter at the reference level. Indeed, the values of this gradient are \( 22 \times 10^{-3} \text{ m}^{-2} \) and \( 31 \times 10^{-3} \text{ m}^{-2} \) for experiments SG and EG, respectively. [This result is consistent with the discussion of KA95 that \( Fr \) cannot uniquely determine the vertical gradient of the Scorer parameter, which we believe serves as a measure of the drag enhancement due to low-level wave breaking.] Despite the difference in the ratio of the upper- to low-level drag divergence between experiments SG and EG, however, GWD has a similar overall impact on the (ensemble) monthly (zonal) mean fields. This is possibly because the horizontal resolution of the simulations performed in this study is rather low so that the difference is not visible when ensemble means are computed.

b. Partition among the drag mechanisms

In this study, the impact of the envelope orography and GWD on January simulations with the UCLA GCM is found clearly beneficial in view of improvements in the monthly zonal mean fields. It is not necessarily true, however, in terms of the net drag at the surface. Recent studies (e.g., Boer and Lazare 1988; Boville 1991) investigated effects of removing GWD in large-scale models. These simulations show that when the GWD routine is turned off the poleward eddy momentum flux increases, resulting in an increase in the total drag at the surface (friction drag + mountain drag + GWD) in midlatitudes. Boer and Lazare term this phenomenon a "paradox" because they anticipated a decrease in the total drag upon removal of GWD based on the conception that the absence of the

\(^1\) Here, we note that the upper-level drag produced by our scheme may be rather small whereas low-level drag is reasonably well estimated. If this is the case, the partition between upper and low-level drag may not be very realistic since the magnitude of the upper-level drag is very sensitive to that of the low-level drag.

\(^8\) At low levels away from the surface, a weak but noticeable acceleration of the winds is found with the standard orography (experiment SG). This was also found with the scheme based on Palmer et al. (1986) implemented by Dr. T. Ose in another version of the model.
drag from a GWD parameterization should lead to a decrease in the total drag. The inclusion of GWD parameterization in large-scale models was motivated by the notion that neglect of GWD may be a main cause of the excessively strong jetstream simulated by GCMs (Lilly 1972). Palmer et al. (1986) argued that addition of a GWD mechanism in a model lead to an increase in the total drag and eventually to the alleviation of the westerly bias. As shown by Boer and Lazare (1988) and Boville (1991), however, when GWD parameterization is removed the friction drag takes the part that was originally played by GWD and, as a result, the total drag may not decrease. What happens in the budget of the drag with addition or removal of GWD is mainly a change in the partition among the three (or possibly more) drag mechanisms. The notion that the total drag is underestimated without GWD should thus be amended.

In relation to the partition of the drag mechanisms, we further note that, as discussed by Palmer et al. (1986), the vertical momentum flux associated with orographically generated gravity waves is directly proportional to the Brunt–Väisälä frequency. In contrast, the friction drag coefficient is a decreasing function of the Brunt–Väisälä frequency near the surface. In winter when the PBL is generally very stable, the drag is very small over land and thus relatively insensitive to the degree of roughness of earth's surface. As discussed in section 1, therefore, an enhancement of the friction drag coefficient does not significantly change the magnitude of friction drag nor, consequently, the partition of the total drag.

As we have shown in Fig. 16, the poleward (equatorward) momentum flux in the upper atmosphere has been decreased (increased) by including GWD with standard orography. On the other hand, it almost remained the same in the GWD + envelope orography experiments. Thus, although the overall impact of the GWD scheme on the mean fields is similar in both experiments, the impact on the eddy fluxes is not necessarily so since the changes in the eddy fluxes involve complex wave-mean flow interactions. Therefore, an analysis of the eddy fluxes should be interpreted with caution and cannot be directly applied to discussing the performance of any GWD scheme. As large-scale models evolve into more detailed systems (in terms of phys-
7. Summary, discussion, and further remarks

A new GWD parameterization scheme developed by KA95 has been implemented and tested in a version of the UCLA GCM with resolutions of 4° lat. x 5° long., and 15 vertical layers with its top at 1 mb. The scheme is used with two different orographic height datasets, the standard orography and a newly created envelope orography. Incorporation of the envelope orography and the GWD parameterization scheme into the model improves (roughly equally with each and even further with both) the ensemble mean of January simulations through enhanced mountain drag and GWD. The midlatitude westerlies are reduced throughout the entire vertical domain, especially at upper levels. Correspondingly, the polar atmosphere is adiabatically warmed due to the induced mean meridional circulation. The sea level pressure in the Northern Hemisphere subpolar (subtropical) latitudes increases (decreases), thereby decreasing the meridional pressure gradient resulting in reduced midlatitude surface winds. Besides, it is interesting to note that the low-latitude easterlies in the tropical Pacific Ocean have been somewhat strengthened (Fig. 7). It remains to be seen whether this change would affect the simulation of interannual variability when the model is coupled to an oceanic GCM.

The meridional eddy fluxes obtained from our simulations with the standard orography are qualitatively consistent with those of some others (e.g., Boer and Lazare 1988; Boville 1991) in that the poleward momentum fluxes decrease with the inclusion of GWD although the differences are relatively small in our simulations. This is, however, not the case in the envelope orography simulations for which the fluxes do not decrease when GWD is included. It is our understanding that removal or inclusion of GWD changes the partition among the friction drag, mountain drag, and GWD, while the eddy fluxes reflect merely a final result of nonlinear interactions, that is, the fluxes are not directly related to changes in surface drag. Given that the ensemble mean fields are overall improved by using the GWD scheme with both the standard orography and the envelope orography, these results suggest that an analysis of the meridional eddy flux fields does not allow one to make any firm statements on the
Fig. 17. As in Fig. 16 but for meridional eddy heat flux (mK s\(^{-1}\)).

Fig. 18. Ensemble average for experiment EG of the enhancement factor (\(E\)) and the number of mountains (\(m\)) calculated by the GWD scheme. Contour intervals are 0.25 for both \(E\) and \(m\).

performance of a GWD scheme as also pointed out by the above studies.

A comparison of observations (Fig. 4a) with the simulations (Fig. 5) reveals that the jets are unusually strong in the control experiments (experiment SN) and are still not well separated nor correctly located in the envelope/GWD experiments. The overly strong jet of the control experiments could be associated with our standard orography, which may be excessively smoothed. If this is the case, the enhancement by the enveloping of orography may only compensate for the oversmoothed portion of orography as shown in the noncontrol simulations. As discussed above, however, our envelope orography is not uniformly proportional to the standard orography, since the grid-scale orography used to construct the envelope orography is not the standard orography. We may then have to regard the envelope orography and the standard orography as different versions of grid-scale orography. Generally speaking, it may even be possible that an envelope orography for one model, which is constructed on top of a very smooth grid-scale orography, is neither higher nor rougher than the smoothed grid-scale orography of another model. Given that the methods of calculating the grid-scale orography for large-scale models are not unique, it is not fair to discuss the impact of envelope orography in different models without going into the details of the preparation of the orography itself. Together with the differences in the amount of the enhancement (2\(^{1/2}\) in this study) among the models, this may explain the diversity in the impact of envelope orography in different models.

The difference between observations and experiment SN cannot entirely be attributable to deficiencies in representing the effects of subgrid-scale orography. For example, it is known that the mean state of the northern winter stratosphere is determined by a balance between dynamical and radiative processes. Some studies report that the magnitudes and positions of the jets or the magnitude of the surface winds can be improved by improving other physical processes, such as radiation and baroclinic eddy life cycles, and/or by increasing the resolutions without using a GWD scheme (e.g., Ramanathan et al. 1983; Mahlman and Umscheid 1994; Hamilton et al. 1995; Thorncroft et al. 1993; Klinker and Sardeshmukh 1996).
1992). Our effort to improve the representation of subgrid-scale orographic effects should thus be made together with those to improve other aspects of the model.

Investigation of the interaction among the GWD, planetary waves, and the zonal mean flow should also be useful for assessing the relative importance of the GWD and envelope orography. McLandress and McFarlane (1993) showed that the residual mean meridional circulation in the midlatitudes in the Northern Hemisphere winter stratosphere and mesosphere is maintained primarily by the combined action of GWD and the E-P flux divergence associated with climatologically forced stationary planetary waves. They demonstrated using a quasi-geostrophic quasi-linear model that zonally varying GWD enhances the planetary waves. Their results show that the deceleration of zonal mean winds due to both planetary waves and gravity waves are significant in similar locations in the midlatitude stratosphere. Iwasaki et al. (1989b) also compared the effects of GWD and planetary waves on wintertime medium-range forecasts. They found that planetary waves produce small deceleration due to the E-P flux convergence in the midlatitude stratosphere where the GWD deceleration is large. Although these studies did not discuss the planetary waves directly forced by enhanced orography as ours, their results can be compared with ours in view of the effects of GWD and planetary waves on the mean wind. Our results are similar to those of McLandress and McFarlane (1993) and in contrast to those of Iwasaki et al. (1989b) in that the location of the deceleration of the upper-level winds (Fig. 6) due to GWD (experiment SG) and that due to enhanced mountain drag by envelope orography (experiment EN) are similar. Further investigation is required to understand why the impact regions of GWD and the envelope orography almost coincide in our simulations.

The results of this study are from the ensemble means of eight January simulations and thus do not cover annual cycles. To obtain more robust results, long-term multiyear simulations are required. It also remains to be seen how the envelope orography and GWD parameterization perform in northern summer as some studies report degradation of summer simulations with envelope orography. In addition, we acknowledge the limitations due to the low resolution and, therefore, have developed a version of the UCLA GCM code suitable for massively parallel processors (MPPs) (Mecchoso et al. 1993; Wehner et al. 1995). Higher reso-

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**Fig. 19.** Deceleration of the zonal wind (m s\(^{-1}\) day\(^{-1}\)) due directly to GWD averaged over nonzero orographic variance points, as calculated from the vertical divergence of GWD, obtained from one of the envelope plus GWD experiments, and from additional experiments, one with the reference-level drag coefficient \(k_0\), globally averaged and the other without low-level drag divergence (these experiments were initialized on 1 October 1982). Note that the cancellation between the acceleration and deceleration of low-level winds, which reverse in direction with latitude, makes the globally averaged drag becomes even smaller in the lower atmosphere.

**Fig. 20.** As in Fig. 10 but for the experiments shown in Fig. 19 and for the ECMWF analysis (80–87).

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**Fig. 21.** Ensemble average for experiment EG of the zonal component of the acceleration of the zonal wind (m s\(^{-1}\) day\(^{-1}\)) due directly to GWD. The sigma-level index “0” or the height index “7” approximately corresponds to 100 mb, and sigma-level index “−1” corresponds to 1 mb, which is the top of the model.
Finally, it is worth noting that there are numerical modeling studies investigating the effects of orographic forcing on the large-scale temporal variability of the atmosphere—such as low-frequency variability, and anomalous synoptic-scale weather regimes—such as blocking phenomenon, which seem to be related to each other. These kinds of studies help evaluate model simulations with the modification or addition/deletion of physical processes in a more detailed manner. Rind et al. (1988) show that the variability of a large-scale model on both interannual and intraseasonal timescales results from interactions among the planetary waves, GWD, and the mean circulation. Mullen (1989) demonstrates that the use of enhanced orography leads to a more realistic simulation of blocking. Miller et al. (1989) show that a better positioning of storm tracks results from improvements in the transient wave structure associated with synoptic-scale systems after the inclusion of an envelope orography. Miller et al. (1989) argue further that the errors in simulating the time-mean jet may be indirectly related to inaccurate damping of storm track activity over land. The rather excessive momentum fluxes in the midlatitude troposphere in our simulations (see Fig. 16b) may then imply storm track activity that is too intense. More recently, Mullen (1994) shows that modest changes in orographic heights can cause significant changes in blocking and low-frequency variability. To fully discuss the variability of a large-scale model associated with changes in orographic representations, a large number of long simulations using observed surface conditions are required.

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Fig. 22. Zonally and vertically averaged deceleration of the zonal wind (m s$^{-1}$ day$^{-1}$) due directly to GWD for experiment SG and experiment EG, for the (a) upper (50 mb $\sim$ 1 mb) and (b) lower (surface $\sim$ 50 mb) atmosphere, and (c) its average over all nonzero orographic variance points.

It is of interest to perform higher horizontal resolution experiments since the GWD scheme was designed to parameterize the effects of subgrid-scale gravity waves in domains smaller than those corresponding to the current resolution of the model.
APPENDIX

Generation and Use of Orographic Data

The high-resolution 10° lat. × 10° long. (=1/6° × 1/6°) Navy orographic height dataset is first linearly interpolated to 0.1° lat. × 0.1° long., and then area-weighted averaging is applied to obtain heights at two lower resolutions: 0.5° lat. × 0.5° long. and 4° lat. × 5° long. The orographic variance (SD²) and orographic convexity (OC) for the resolution of the model (4° lat. × 5° long.) are calculated from the 0.1° lat. × 0.1° long. and 0.5° lat. × 0.5° long. data, respectively, by area-weighted averaging over each grid box. The orographic asymmetry (OA) is calculated with respect to the pre-set wind directions N, W, NW, and SW from the 0.5° lat. × 0.5° long. data by area-weighted averaging. The OA for S, E, SE, and NE are obtained from those of N, W, NW, and SW by changing the sign.

For the diagnostic experiment, the critical orographic height \( h_c = S D \times F_r / F_{r0} \) (Fr = 1), which determines the fractional width of subgrid-scale orography (\( L_s \)), is estimated from the SD by using the correlation found from mesoscale gravity wave simulations [Kim 1992; \( h_c = 1116.2 - 0.878 SD \) (correlation coefficient \( R = 0.81 \)]), whereas for the full experiments with the GCM \( h_c \) is calculated at each physics time step from a “high-resolution” mean orography calculated for the 0.5° lat. × 0.5° long. grid using the low-level flow conditions. After the direction of low-level wind is found, OA is taken from the precomputed dataset and is used to determine the height of the reference level: when OA is positive, the reference level is set to the lowest model layer (i.e., the PBL); when OA is nonpositive, it is set to the level above the PBL. This allows for low-level wave breaking only in the downstream regions and avoids an application of the parameterization scheme to the region of flow blocking. The gravity wave drag routine is called at grid points with a nonzero orographic variance in order to include the effects of subgrid-scale variance of orography at more points. There are more of these points (1599) than land/land-ice points (1109) since the orographic variance was computed from much higher-resolution data (0.1° × 0.1°).

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