IMPACT OF VARIOUS REPRESENTATION OF OROGRAPHY ON A GCM WINTER CLIMATE

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Summary: series of winter simulations with the LMD-GCM where the model ground is flat and where the mountains are represented by applying forces to the flow are presented. They show that drag forces (i.e., locally opposite to the local wind) improve the zonal wind but can degrade the steady planetary wave while lift forces (i.e., locally perpendicular to the zonal wind) scarcely affect the zonal wind and drive a realistic steady planetary wave. The drag force is formulated following the realistic Subgrid Scale Orographic (SSO) scheme, developed recently at ECMWF. The lift force essentially enhances vortex stretching over large-scale mountains. In the context of SSO parametrization, these results suggest that the recent SSO schemes which are validated against data, and which decelerate significantly the low level flow can be beneficial to GCMs, if they do not break the overall balance between the mountain drag and lift forces that exists in the real atmosphere.

1. INTRODUCTION

In General Circulation Models (GCM), it seems natural to try to correct part of the model errors on the large-scale steady and quasi-steady features by improving the representation of the forces exerted on the flow by the mountains. For instance, the parametrization of mountain gravity waves alleviates systematic errors in GCM simulations of the tropospheric westerlies (Palmer et al., 1986; Miller et al. ,1989). More recently, Lott and Miller (1997) (hereafter LM97) have proposed a Subgrid Scale Orographic (SSO) drag scheme which represent gravity waves and which also gives a particular attention to the drag of the flow at levels that intersect the subgrid-scale orography (hereafter referenced as the "blocked flow" part of the scheme). This last part of the scheme, account for nonlinear processes which were not represented well in the previous schemes. This scheme is also validated against the PYREX data (Bougeault et al., 1993) in all the situations for which the incident wind perpendicular to the ridge is strong.

Nevertheless, if one wishes to correct errors on the non-zonal part of the large-scale flow, schemes that essentially drag the large-scale flow are not necessarily helpful. Indeed, in the quasi-geostrophic models, often used with success in diagnosing the forcing of planetary waves (Charney and Eliassen, 1949; Held, 1983), the mountains induce vortex stretching, a process driven by a force whose horizontal component is perpendicular to the incident flow to the lower order in the mountain height (Smith, 1979).

These different studies suggest that all components of the mountain induced forces are important and the purpose of the paper is to emphasize this point, on the basis of GCM simulations. In Section 2, the parametrized forces are presented and a brief discussion is also given of their impact on the large-scale flow, in the quasi-geostrophic context. In Section 3, GCM tests are made. To adress the importance of each mountain force components, series of 5-winter integrations are presented where the orography in the model is suppressed (the lower boundary is set everywhere to the sea level). In these set of experiments, the mountains are entirely parametrized either by large low-level drag or by large low-level lift applied directly in all gridpoint region at the model levels located below the maximum height of the orography, Z_{max}.

2. THE DIFFERENT MOUNTAIN FORCES REPRESENTATION

In many circumstances in meteorology the force exerted by an obstacle on the flow is oriented in a direction that is different from that of the incident wind. The drag is the component of the force **F** which decelerates the fluid because it is opposite to the wind and works against it,

$$\mathbf{u}\mathbf{F} < 0 \,.$$

In nature, the low level wake behind three-dimensional mesoscale high obstacles can be understood as the result of the drag the obstacle exerts on the flow at the levels which do not pass over the orography. It is the process parametrized in the "blocked-flow" part of the LM97 scheme.

The lift is the component of the force **F** which modifies the direction of the flow but does not decelerate it locally, and does not work against it. A good example of lift in geophysical fluid dynamics occurs in quasi-geostrophic flows over low ridges, during the process of vortex compression. As often assumed in GCM, this force is correctly represented when the model lower boundary is the mean orography, the lift being essentially related to the mountain volume. Nevertheless, some models use enhanced orography (envelope) essentially because the planetary wave response to orographic forcing is too small. This suggests that in some models, it is the mountain lift rather than the mountain drag which is not correctly represented.

2.1 Orographic drag

The orographic drag used in the present study is derived from the one presented in LM97. The SSO over one gridpoint region (GPR) is represented by five parameters, μ, γ, σ, θ, and Z_{max} which stand for the standard deviation, the anisotropy, the slope, the orientation, and the maximum elevation of the orography respectively. These five parameters are evaluated over a GPR from the US Navy ($10' \times 10'$) dataset. For each layer below the maximum mountain height Z_{max} a force per unit volume is applied:

$$\mathbf{D_b}(z) = -\rho C_d \max\left(2 - \frac{1}{r}, 0\right) \frac{\sigma}{2\mu} \left(\frac{Z_{max} - z}{Z_{max}}\right) (B\cos^2\psi + C sin^2\psi) \frac{\mathbf{u}|\mathbf{u}|}{2} \; . \quad (1)$$

In Eq. (1) the angle between the incident flow and the normal ridge direction is ψ, the aspect ratio of the obstacle as seen by the incident flow is r, and the constant $B(\gamma)$ and $C(\gamma)$ are as in LM97. The parameter C_d tunes the blocked flow drag amplitude. In the experiments presented $C_d = 1$, in agreement with the literature on flow dynamics around bluff body. Compared to LM97, one sees that all the levels below the orography maximum height are decelerated and that the gravity waves part of the scheme is not activated.

2.2 Orographic lift

In the model itself, the lift representation consists of applying a force per unit volume **L** that is perpendicular to the wind at each levels below the mountain maximum height Z_{max}

$$\mathbf{L} = -\rho C_l f \left(\frac{Z_{max} - Z}{Z_{max}} \right) \mathbf{k} \times \mathbf{u} . \tag{2}$$

In Eq. (2), f is the Coriolis frequency, and $C_l = 1$. When the incident wind is uniform in the vertical, Eq. (2) integrated from the model ground Z_o to the mountain peak Z_{max} gives a stress,

$$\mathcal{L} = -\rho C_l f \left(\frac{Z_{max}}{2} \right) \mathbf{k} \times \mathbf{u} . \tag{3}$$

which is similar to the lift stress exerted by an obstacle of mean height $\bar{h}$ on a quasi-geostrophic flow (Smith, 1979),

$$\mathcal{S} = -\rho f \bar{h} \mathbf{k} \times \mathbf{u}, \tag{4}$$

provided that the maximum mountain elevation is twice the mountain mean.

2.3 Impact in a shallow water quasi geostrophic flow

To adress some issues about the response of the large-scale flow to momentum forcings close to those presented before, we consider a shallow water flow of depth H, which is distorted by the force **F**, or/and by an explicit mountain h. For this fluid the equations of motion writtes:

$$\begin{cases} d_t u - f v + \frac{1}{\rho}\partial_x p = \frac{1}{\rho} F_x \\ d_t v + f u + \frac{1}{\rho}\partial_y p = \frac{1}{\rho} F_y \\ d_t H + H \nabla \mathbf{u} = 0 \end{cases} \tag{5}$$

and we assume an incident flow $U(y)$ driven by a sloping free interface of elevation $\nu = \nu_0$ above a reference flow depth H_0,

$$H(y) = H_0 + \nu_0(y) = H_0 - \int_0^y \frac{f}{g} U(s) ds. \tag{6}$$

Under the action of the force **F** and/or of the mountain h, the fluid response can be described by the potential vorticity equation,

$$\frac{d}{dt} \frac{\xi + f}{H_0 + \nu - h} = \frac{\nabla \times \mathbf{F}}{\rho (H_0 + \nu - h)} . \tag{7}$$

For large scale and small amplitude forcings, F and h, the quasi geostrophic version of the potential vorticity equation can be adopted,

$$\frac{d}{dt}\left(\Delta\Psi - \frac{f_0^2}{gH_0}\Psi + f + f_0\frac{h}{H_0}\right) = \frac{1}{\rho}\nabla \times \mathbf{F} \tag{8}$$

where Ψ is the streamfunction. Now, if a flow force that is everywhere perpendicular to the wind, $\mathbf{F} = -\rho e(x, y, \mathbf{u})\mathbf{k} \times \mathbf{u}$ is introduced, it can be included in the potential vorticity equation, leading to,

$$\frac{d}{dt}\left(\Delta\Psi - \frac{f_0^2}{gH_0}\Psi + f + f_0\frac{h}{H_0} + e(x, y, \mathbf{u})\right) = 0 \tag{9}$$

One sees that in the QG limit, it is equivalent to specify a lower bound h or a lift forcing, providing that $e = f_0 h/H_0$, an expression that is very close from the lift force (2) averaged vertically over the fluid depth H_0. In the quasi geostrophic limit, it is important to note that the lift representation used is exactly equivalent to the orography representation used in the many quasi geostrophic studies of the influence of mountains on the large scale flow. By integration over y, z of the meridional momentum equation in (5) it is also straightforward to verify that when $e = f_0 h/H_0$, the overall force exerted on the fluid is, to the lowest order in the forcing amplitude, opposite to the mountain lift force that exists on an obstacle h in a large-scale flow (Smith, 1979). Similarly, the zonal integration of the horizontal momentum equation in (5), shows that the lift force can induce a non-zero zonal contribution to the zonal mean flow. This is consistent with the fact that large scale topographic Rossby waves can drag the large scale flow. Compared to the averaged lift, if the non-zonal part of the flow is only driven by orography, this force is of second order into the mountain elevation.

In this context one can also determine qualitatively the impact of a drag force like (1) on the large-scale flow. For simplicity we only retain here that the drag force is opposite to the wind,

$$\mathbf{F} = -\rho e(x, y, \mathbf{u})\mathbf{u}. \tag{10}$$

This force modifies the potential vorticity because it induces a potential vorticity flux that is perpendicular to the flow,

$$\frac{d}{dt}\left(\Delta\Psi - \frac{f_0^2}{gH_0}\Psi + f + f_0\frac{h}{H_0} +\right) = \nabla\left(e(x, y, \mathbf{u})\mathbf{k} \times \mathbf{u}\right). \tag{11}$$

Accordingly, a drag induces a potential vorticity dipole, downstream of the area where it is applied. When the forcing is related to the parametrisation of SSO, this produces a wake downstream of the mountains which is the results of the retardation of the large scale flow by all the individual mesoscale peaks behind which mesoscale wakes are known to occur (Miranda and James, 1992; Schär and Durran, 1996). There is some evidences that those large-scale wakes exist (Lott, 1995), and that they can be reproduced by low-level drag parametrizations (LM97).

Within a same approach it is easy to verify that the lift representation induces potential vorticity fluxes which are always along the streamlines. In the steady case, it means that the potential vorticity anomalies induced by the lift, remain located over the area where the lift force is applied, and never extend downstream of it: when a fluid parcel looses potential vorticity locally, because the vorticity flux diverges, it is advected toward a region where the same vorticity flux converges and where it gains back all the potential vorticity it has lost. This property is already apparent in Eq.(9), the lift being included into the advective part of the potential vorticity equation.

3. IMPACT ON WINTER CLIMATIC RUNS

The model used in this study is the LMD GCM (Sadourny and Laval, 1984), rewritten recently. Gridpoints are regularly distributed in the longitude-latitude coordinates with resolution $3.75^0 \times 2.5^0$ and it has 19 vertical sigma-levels unevenly spaced to provide more resolution near the ground and in the lower stratosphere. The horizontal resolution has been adopted to ensure that the synoptic weather systems are resolved well enough to transport the correct amount of angular momentum between the tropics and the extratropics (Palmer et al., 1986), while keeping the numerical cost of the simulations low. To perform simulations that can be compared to the observed climate, and to ensure that the results presented are significant, the model is integrated over long periods and forced with observed SST and sea-ice distribution. The experiments presented consist of 3 different sets of 5 winters runs (January 85 - December

90) with no explicit mountains ($Z_0 = 0$), but with three different mountain force parametrizations (no force, lift only, drag only).

Experiments without model resolved orography ($Z_0 = 0$) and with parametrized forces are performed to verify that the mountains affect the model climate and to determine which forces are important to simulate properly the large scale flow. In the first experiment there is no parametrized force, in the second a large drag is applied to the flow as described in the subsection (2.1). In the third experiment, a large lift force is applied as described in subsection (2.2). The resulting zonal mean flows are shown on the Fig. (1) and compared to the NMC analysis. Fig. (1)b shows that in the absence of any mountain representation, the model has westerlies in the northern hemisphere which are too strong at all levels. At each altitudes below $200HPa$ the zonal wind maximum in the model is $5ms^{-1}$ too large when compared to the climatology (Fig. (1)a). Above the tropopause, the jet does not close, and reaches values in the stratosphere that are more then $30ms^{-1}$ larger than the climatology. When the low-level drag is introduced (Fig. (1)c), the errors on both the low-level winds and the jet maximum are significantly reduced. However, the low-level drag does not reduce the errors in the upper levels (above $100HPa$), which is natural since there are no gravity waves parametrized. To a certain extent, the large low-level lift Fig. (1)d also has a beneficial impact on the zonal mean, but it is less pronounced than for the drag. In this case, the impact follows that the time-mean flow is not as zonal as it is without any mountain forcing, as will be discussed next. It also follows that the zonal component of the low level lift parametrisation (2) can have a non-zero zonal mean. In this case, it drags the zonal flow which is consistent with the fact that there exists a mountain drag associated with large scale Rossby waves (Charney and De Vore, 1979), in the quasi geostrophic context.

The Fig. (2). shows the planetary waves in these three set of experiments. Fig. (2)b shows that without orography, the steady planetary wave in the model is very weak compared to the climatology (Fig. (2)a). This means that in the model used the land-sea contrast and the associated non-zonal thermal forcings

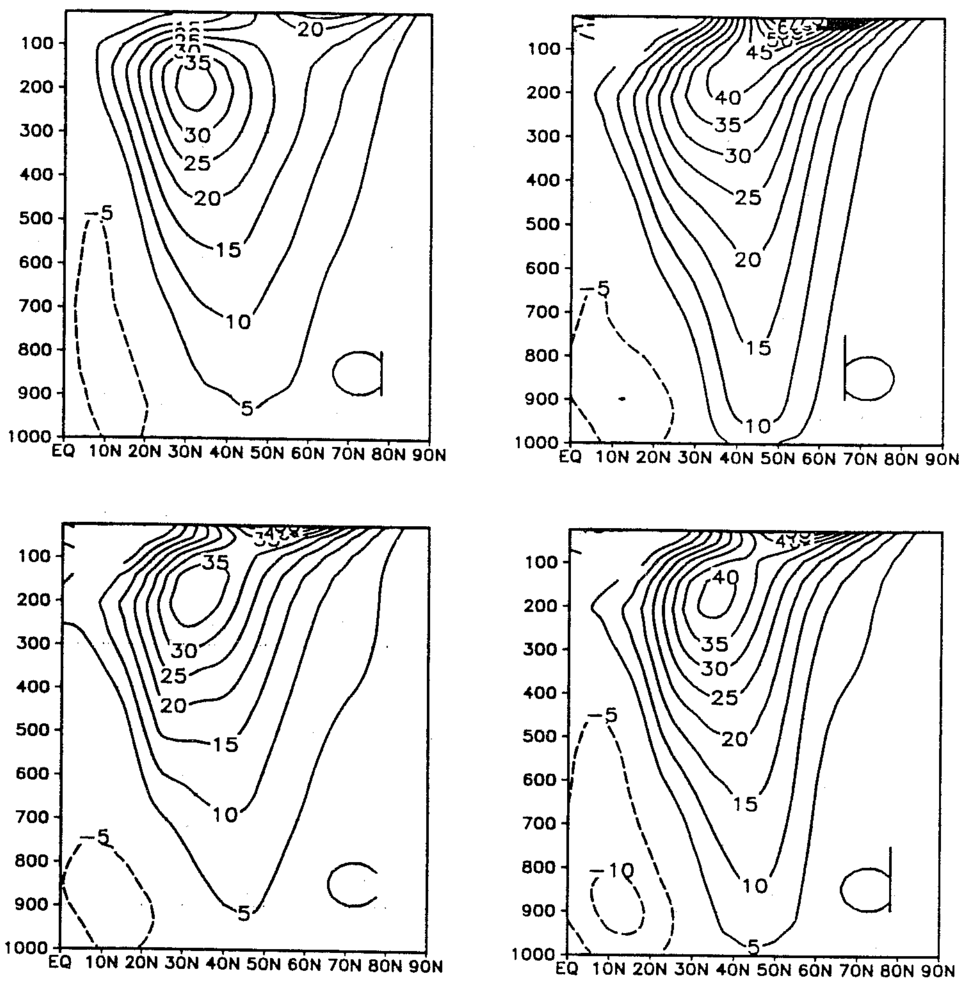

Fig.1 Zonal mean wind averaged over the winter months (DJF) of the period 85-90. LMD run with no explicit orography. (a) NMC analysis; (b) LMD no drag, no lift; (c) LMD low drag only; (d) LMD low lift only. Zero line not shown, negative values are dashed.

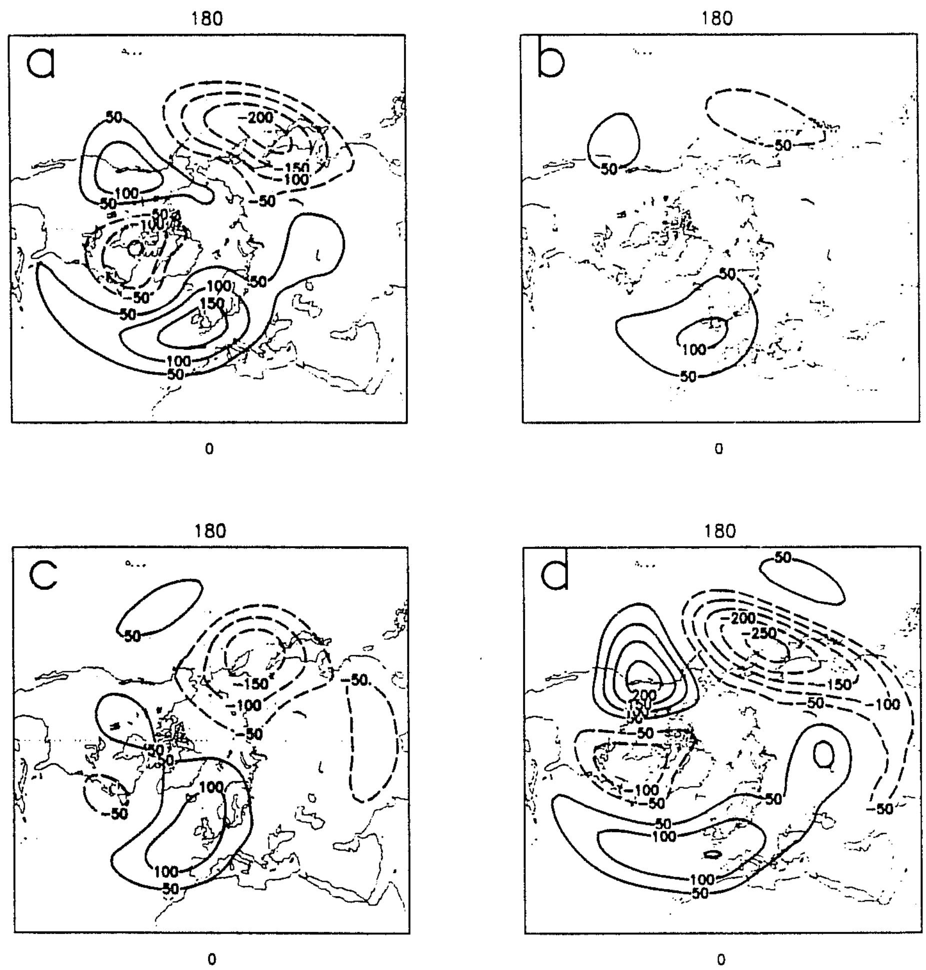

Fig.2 Anomaly to the zonal mean of the geopotential height at $500HPa$ averaged over the winter months (DJF) of the period 85-90. LMD run with no explicit orography. (a) NMC analysis; (b) LMD no drag, no lift; (c) LMD low drag only; (d) LMD low lift only. Zero line not shown, negative values are dashed.

do not contribute significantly to the steady planetary wave. With large low-level drag (Fig. (2)c), the model response shows a more pronounced planetary wave response, with dominant wavenumber 1, which does not look like the climatology over the continents. With large low-level lift, on the other hand, (Fig. (2)d), the steady planetary wave has dominant zonal wavenumber 2-3 as in the observed climatology. In this case, the model is closer to the climatology over the continents than over the oceans, because the model with the lift forces simulates the ridges over the rockies and the Himalayan plateau correctly.

4. DISCUSSION

On the basis of three well-known results, i.e. that the cross flow force over mountain is sometimes very large (Lott, 1995), that it is associated with anticyclonic circulation over (Smith, 1979) and around mountains, and that theoretical models of the steady planetary waves essentially consider orographic vortex stretching (Held, 1983), it has been verified that in a GCM, the reactive force to the lift exerted by the atmosphere on mountains has to be represented correctly. Indeed, numerical experiments where mountains are suppressed only recover a realistic steady planetary wave if large sideways forces are applied above the major mountain massives. To simulate the steady planetary wave in the same context, it appears that a mountain drag scheme is not much help. The same experiments show that the low level blocked part of the LM97 mountain drag schemes improves significantly the zonal mean flow at low levels, while the lift forces does not affect it as much. At first sight these results concerning mountain lift forces are not much more then a conceptual curiosity. Indeed, to try to keep the discussion as simple as possible, the sideways force representation adopted here has been taken to be linear in both the large scale flow and the mountain volume. In this case if one assumes that the lift force is that given by Smith(1979), it only depends on the mountain volume, so that a GCM with a mean orography should represent correctly the large scale mountains. Nevertheless, as pointed by Wallace et al. (1983), models with mean orography sometimes understate the impact of the large scale massives, because mesoscale flow blocking inside the valleys, causes areas of complex terrain to act on the large scale flow as if they have a larger height than that prescribed by the actual mean. In this context, and when the model lower boundary is the mean orography, a mountain representation scheme that enhances lift over large-scale mountains can have impacts comparable to that of an envelope orography.

Nevertheless, the intention of the calculations presented in this paper was rather to suggest that the direction of the forces exerted by the orography on the atmosphere should be represented properly in GCMs. Indeed, there are many examples in the literature for which the lateral forces due to mountains are important. For instance, for the mesoscale mountain waes themselves, Shutts (1995) and Broad (1996) have shown that when the wind turns with height, gravity waves encounter critical levels at nearly all altitudes and exert a drag that is perpendicular to the local flow. In these configurations, the most recent drag schemes are still not very helpful, although they begin to represent directional effects, related to the anisotropy of the mountain ridges (Phillips, 1985). In view of these processes, and others which are not listed here, it is believed that the GCM tests presented in this paper, show that if there is a need to improve the representation of orographic forcing in a GCM (by changing the lower boundary definition or/and by some parametrization scheme) one has to consider with care this directional issue.

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