# Influence of Gravity Waves on the Atmospheric Climate

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1)Dynamical impact of mountains on atmospheric flows

2)Representation of mountains in General Circulation Models

3)Non-orographic gravity waves sources

4)Impact of gravity waves on the middle atmosphere dynamics

# Influence of Gravity Waves on the Atmospheric Climate

2) Representation of mountains in General Circulation Models

   a) Formulation of a Subgrid Scale Orography Parameterization

   b) Validation and testing in a Numerical Weather Prediction model

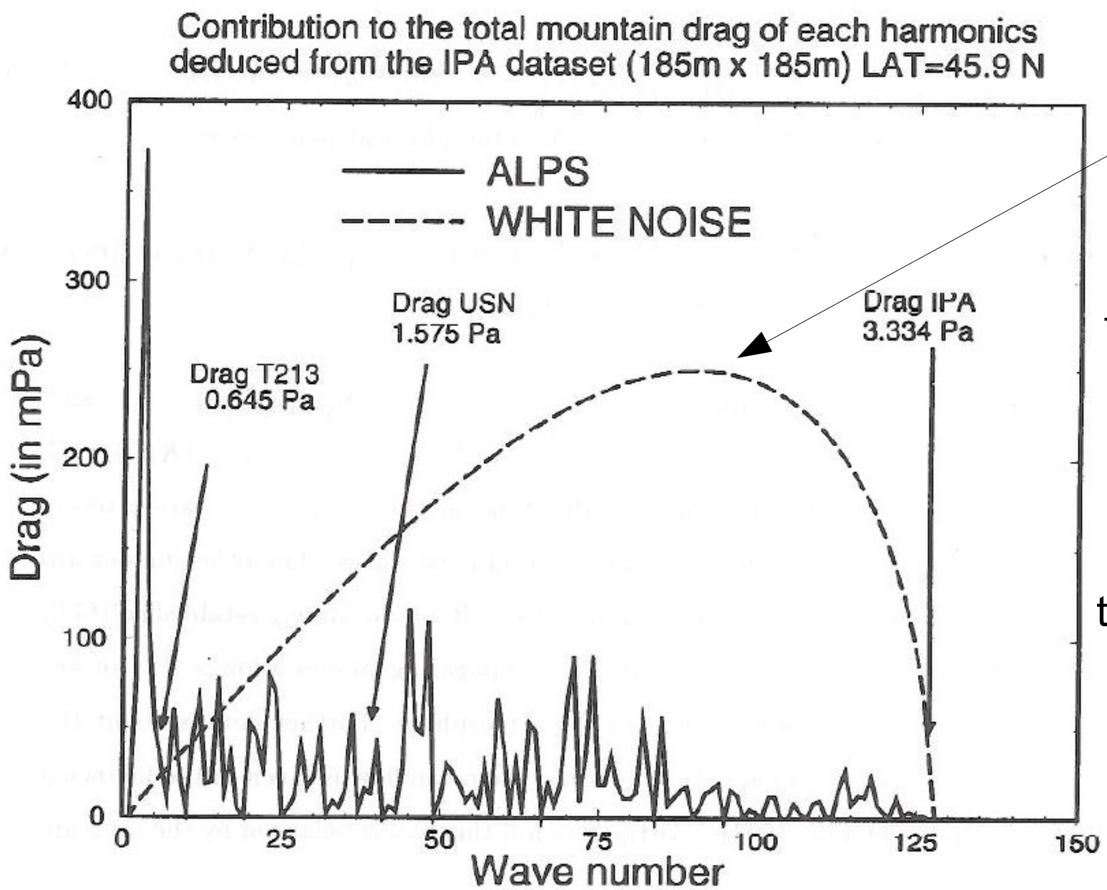
   c) Impact in a General Circulation Model

# 2)Representation of mountains in General Circulation Models
# a)Formulation of a SSO parameterization

Only the gravity waves contribute to the drag in the linear case, and that apparently a lot of drag was missing in resonnably high resolution GCM. So, let us start by this!

$$Dr = \frac{1}{2X} \int_{-X}^{X} p \frac{dh}{dx}$$

$$Dr = \frac{1}{2} \sum_{K=K_f}^{K_N} \rho(0) \sqrt{\left|(N^2 - k^2 U^2)(k^2 U^2 - f^2)\right|} h_K^2$$




$$\sqrt{\left|(N^2 - k^2 U^2)(k^2 U^2 - f^2)\right|}$$

A drag due to the Alps of 1Pa corresponds to a zonal mean tendency of around 1 m/s/day (a barotropic zonal flow of 10m/s is stopped In 10 days). This is large !

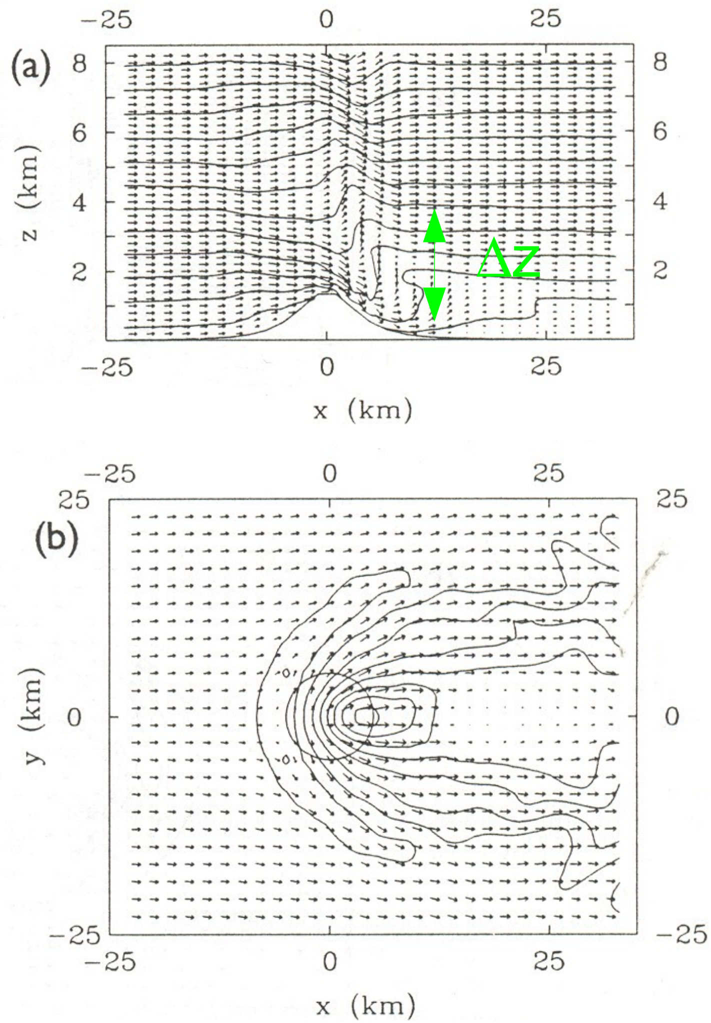
The difference between the T213 drag and the High Res datasets drag tells that there is a large need to parameterized Subgrid Scales Orographies!

# 2)Representation of mountains in General Circulation Models
# a)Formulation of a SSO parameterization

But soon after, we have realized that nonlinear effect occur very near aloft the obstacle (e.g. Flow « lateral splitting » and/or Low level wave breaking)

Single obstacle simulation with $h$~1km, $U=10$m/s, N=0.01s$^{-1}$ : $H_{ND=1}$ !

(Miranda and James 1992)




Note:

Quasi vertical isentropes at low level downstream: Wave breaking occurs over a finite depth Δz.

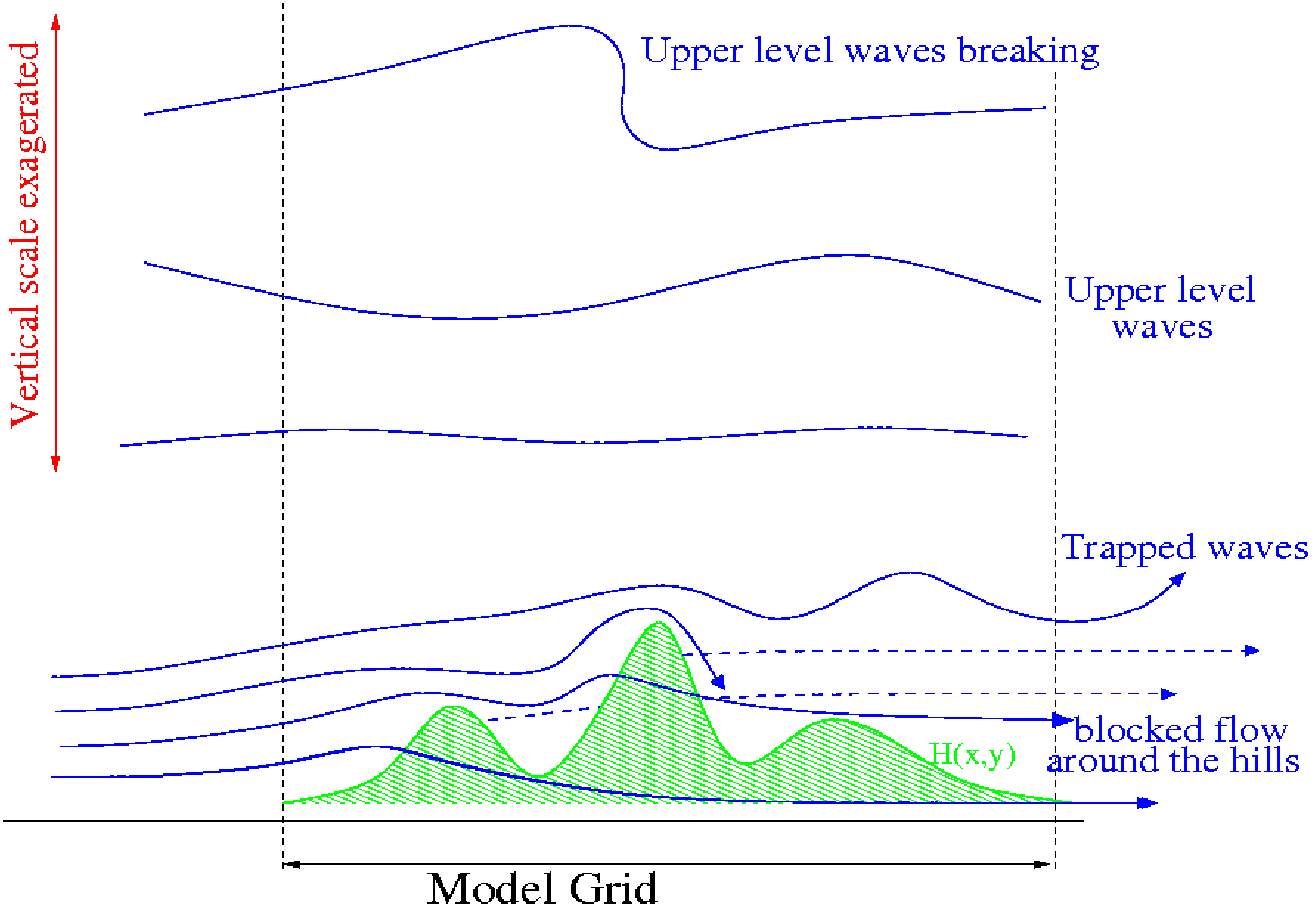
The strong Foehn at the surface downstream

Residual GWs propagating aloft

Apparent slow down near the surface downstream, and over a long distance

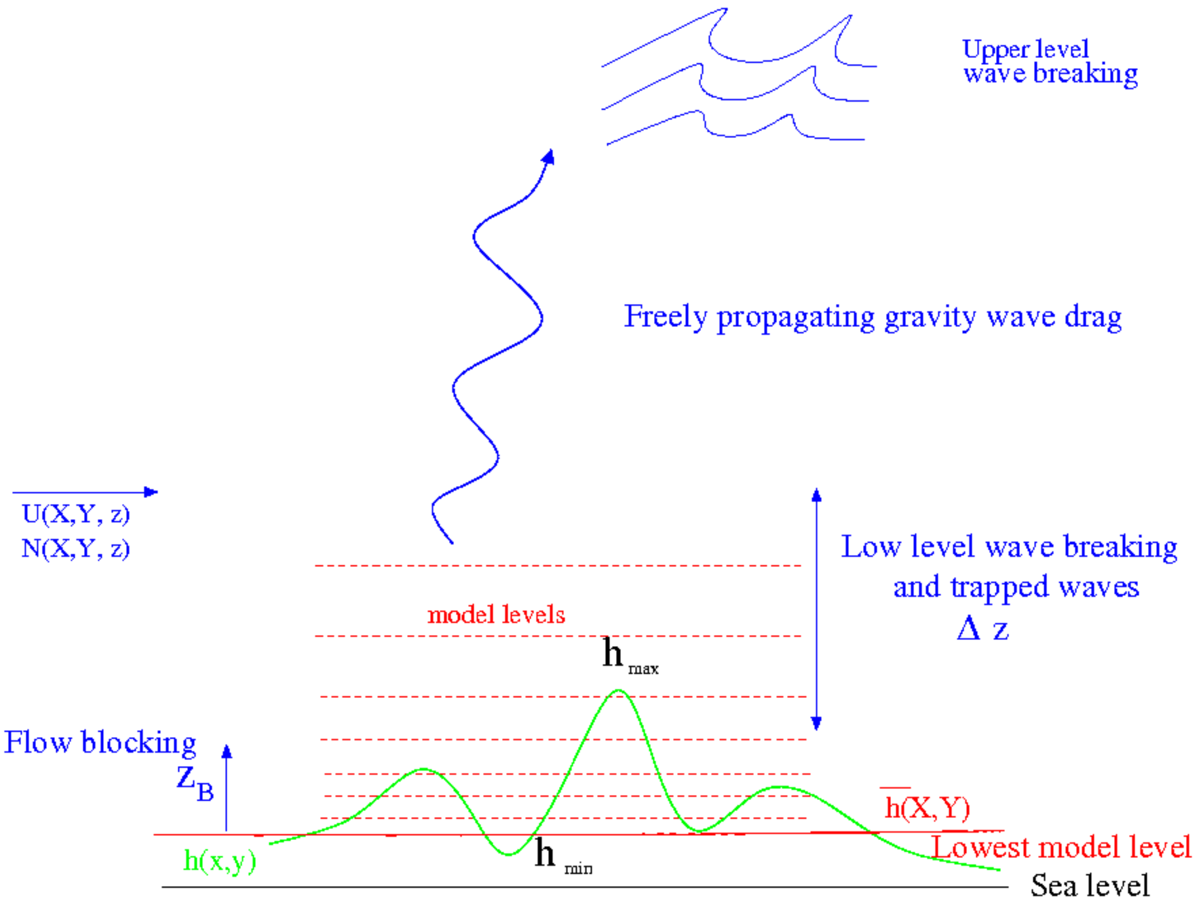
# 2)Representation of mountains in General Circulation Models
# a)Formulation of a SSO parameterization

These, plus trapped lee-waves, plus the fact that they are many obstacles mean that we have to treat a problem like this one:



# 2)Representation of mountains in General Circulation Models
# a)Formulation of a SSO parameterization

Or, if we put model level on this picture, we have to represent a situation like:

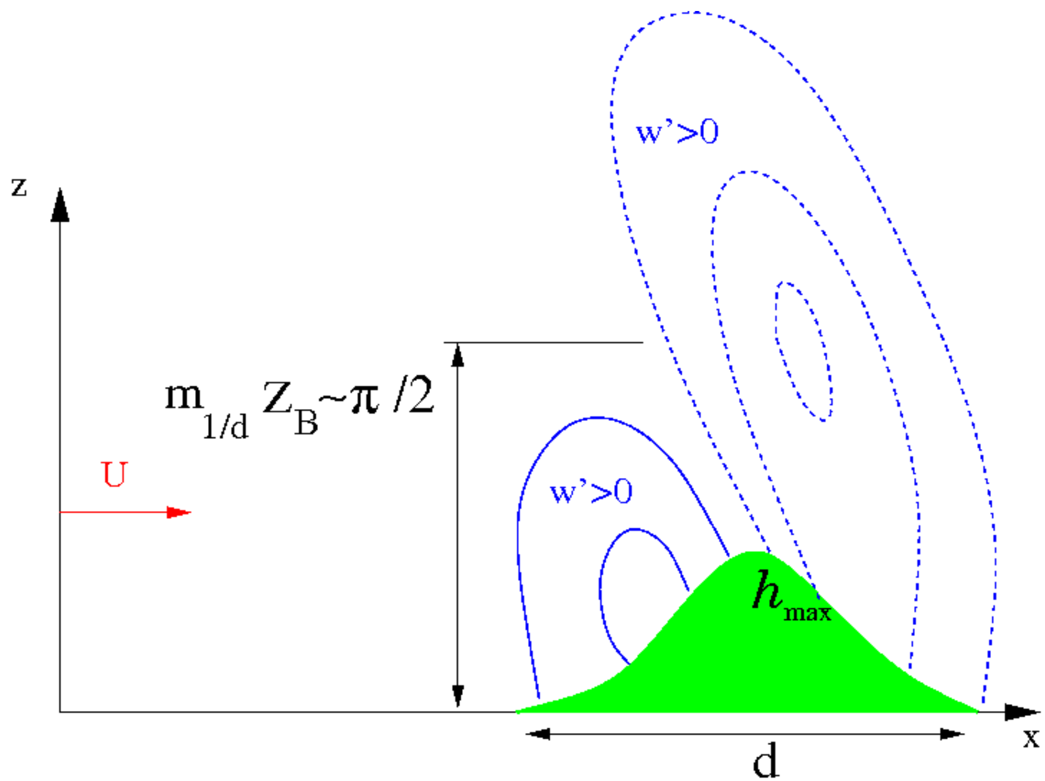


# 2)Representation of mountains in General Circulation Models
# a)Formulation of a SSO parameterization

First task, define the amount of flow that is going to be blocked at low level

Heuristic definition of a « Blocking Height »

$Z_B$




$$Ro^{-1} = \frac{f\,d}{U} \qquad Fr^{-1} = \frac{N\,d}{U}$$

$Z_B$ can be written:

$$Z_B \sim \frac{\pi}{2\,m_{1/d}} = \frac{\pi}{2}\,\frac{U}{N}$$

# 2)Representation of mountains in General Circulation Models
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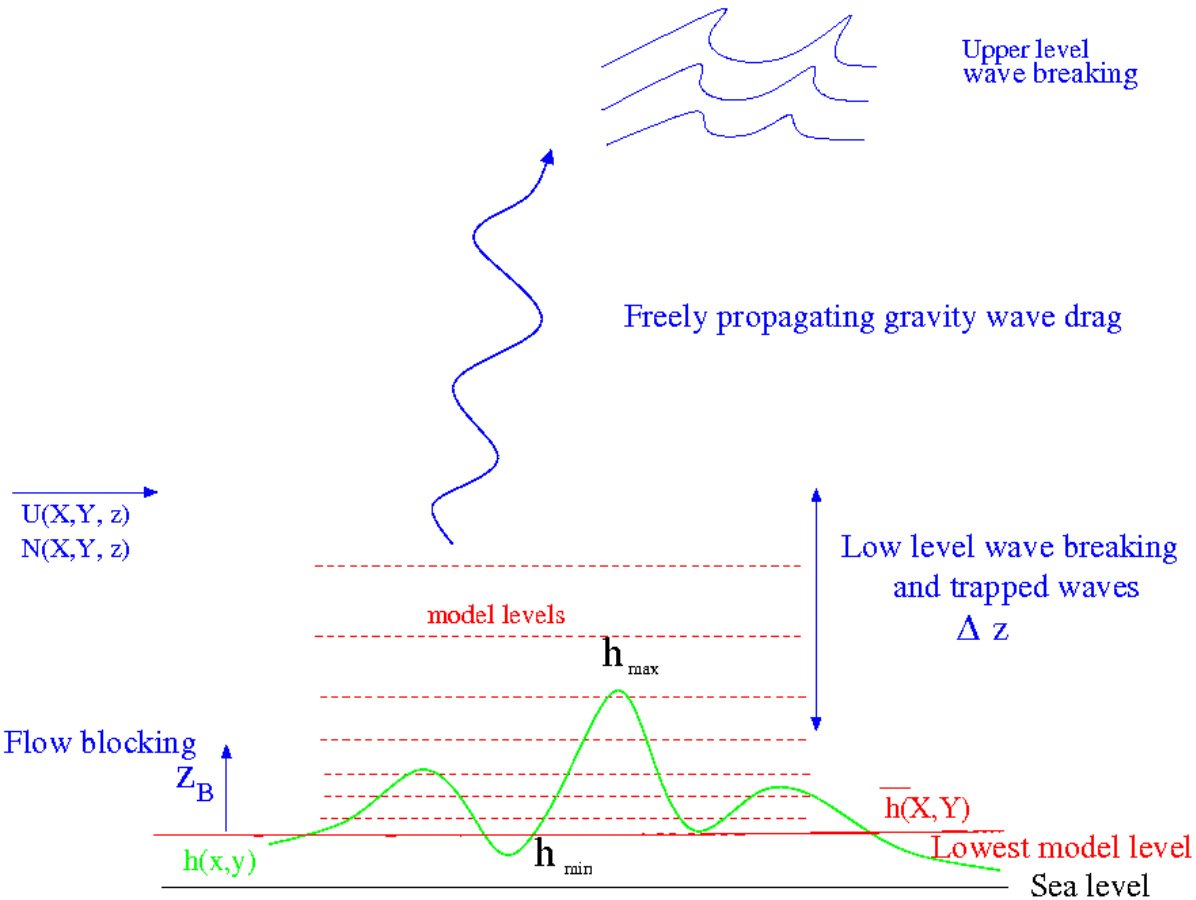
But N and U vary with altitude, so we have to extent this concept and look at the change
In wave phase in a WKB sense



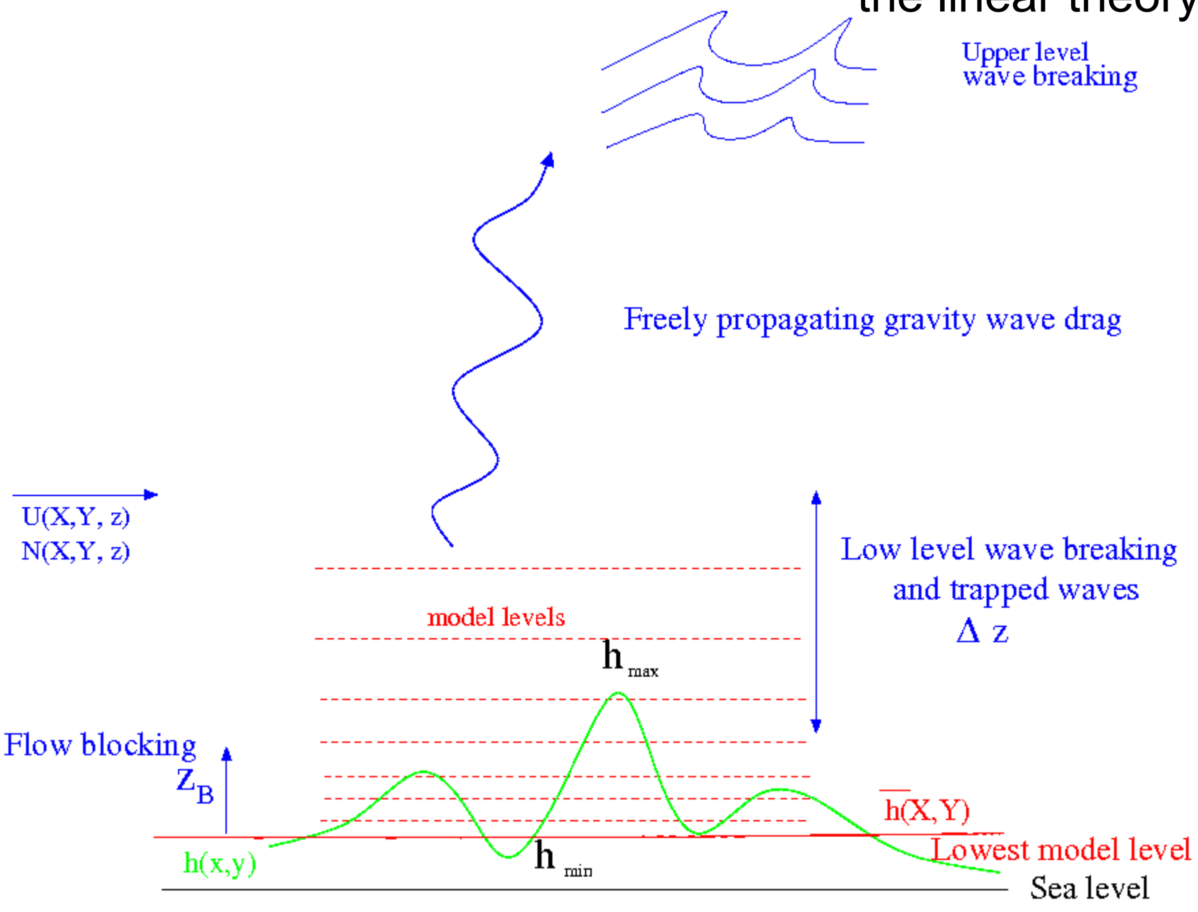

Flow blocking ($H_{NC}$)

$$\int_{Z_B}^{h_{max}} \frac{N}{U} dz < H_{NC}$$

All quantities in red are non-dimensional parameters of order 1

# 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterization

The levels above $Z_B$ ondulates and produce gravity waves, so they induce a gravity wave stress and break somewhere in altitude. The breaking can also be predicted by the linear theory




Breaking based on a total Richardson number criteria (***Ric***):

Gravity wave stress ($\boldsymbol{C_g}$)

$$\bar{F}^z = \rho C_g N U (H_{SSO} - Z_B)^2$$

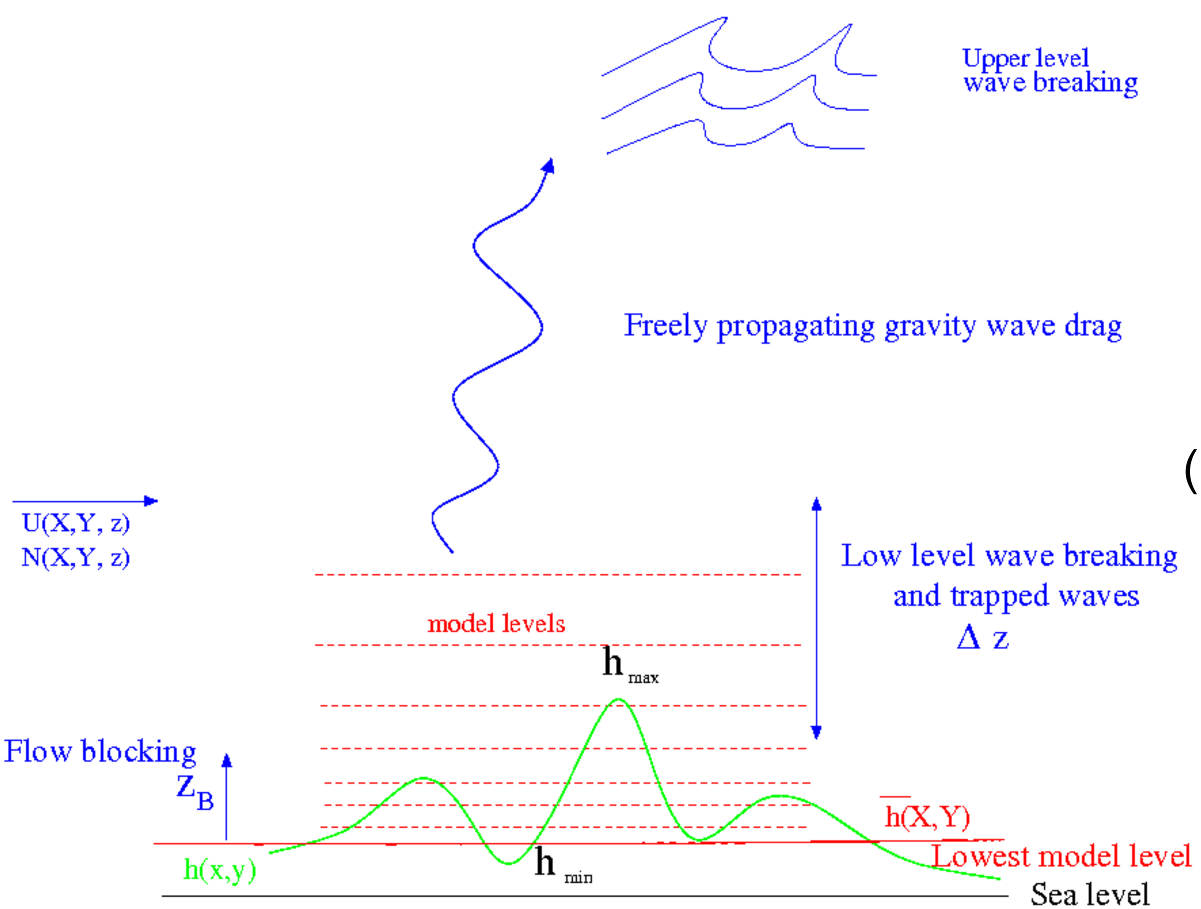
Flow blocking ($\boldsymbol{H_{NC}}$)

$$\int_{Z_B}^{h_{max}} \frac{N}{U} dz < H_{NC}$$

All quantities in red are non-dimensional parameters of order 1

# 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterization

But breaking can occur at low level!




Breaking based on a total Richardson number criteria (***Ric***):

Gravity wave stress (***$C_g$***)

$$\bar{F}^z = \rho C_g N U (H_{SSO} - Z_B)^2$$

If breaking is diagnosed at low level (between $Z_B$ and $Z_B+\Delta Z$), a fraction of the drag is distributed over $\Delta Z$:

$$\int_{Z_B}^{Z_B+\Delta Z} \frac{N}{U} dz < \frac{\pi}{2}$$

Flow blocking (***$H_{NC}$***)

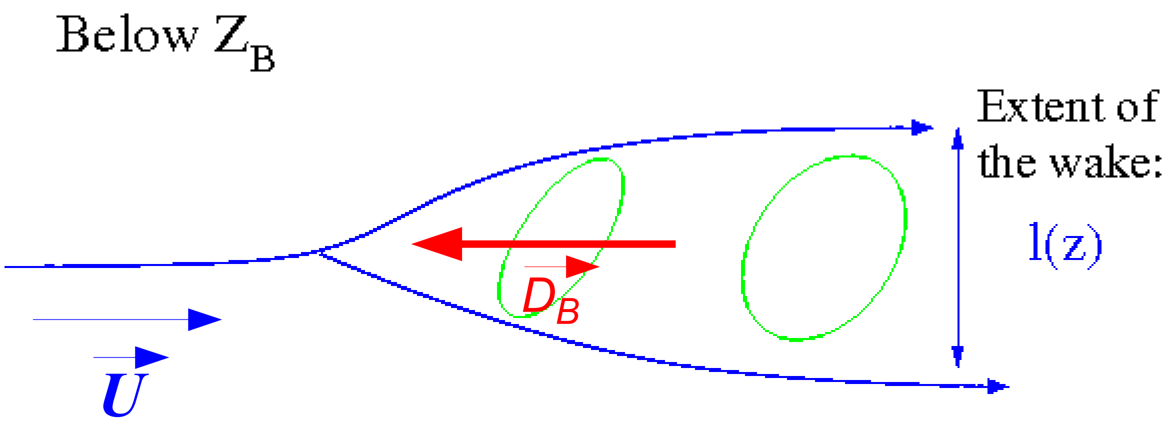
$$\int_{Z_B}^{h_{max}} \frac{N}{U} dz < H_{NC}$$

## 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterization

This scheme relies on few non-dimensional parameters, all of Order 1, and which are tunable to a certain extent

A arbitrary fraction of the drag (around 50%) is also deposited in the low troposphere to represent trapped lee waves.

Blocked flow drag is applied below $Z_B$ (***Cd***) :




Bluff body drag applied at each model layer that intersects the Subgrid Scale Orography (SSO):

$$\vec{D}_B = -\rho\, l(z)\, C_d \frac{\vec{U}\,\|\vec{U}\|}{2}$$

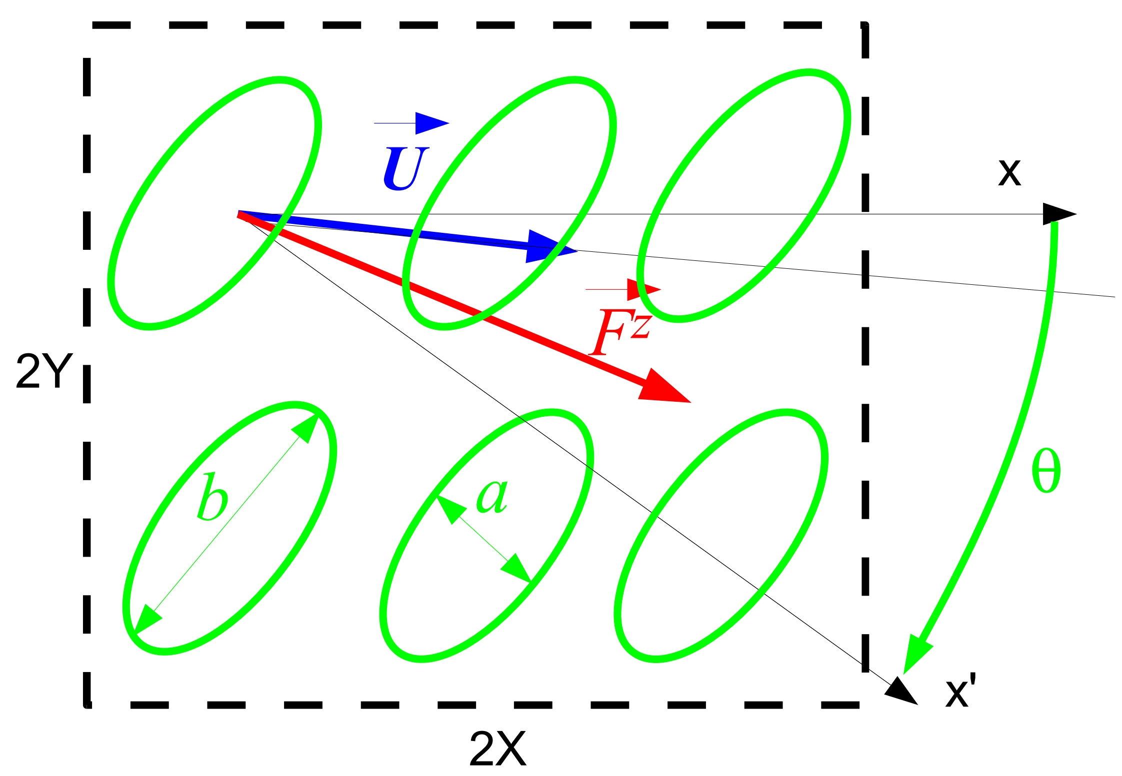
# 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterisation

The scheme also takes into account the anisotropy of mountains, with the direction of the drags in between the direction of the flow and the minor axis of the mountains.
We include this anisotropic effect by modelling the SSO as ensemble of elliptical mountains uniformely distributed over the model grid

For anisotropic mountains, the wave drag direction at the surface is in between the direction of the flow and the direction of max descent of the mountain

For one elliptic mountain formulae are in Phillips (1984)

$$h = \frac{h_{max}}{1 + \frac{x'^2}{a^2} + \frac{y'^2}{b^2}}$$



# 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterization

We have to express the formulae in Phillips (1985) by evaluating $h_{max}$, $a$, $b$, the angle $\theta$, the number of ridges in the gridbox $N_{ridges}$~$ab/(XY)$....

They are related to statistics of the SSO elevation evaluated from a high resolution orography database that gives:
the variance $\mu$, the slope $\sigma$, the angle $\theta$, and the anistropy $\gamma$.

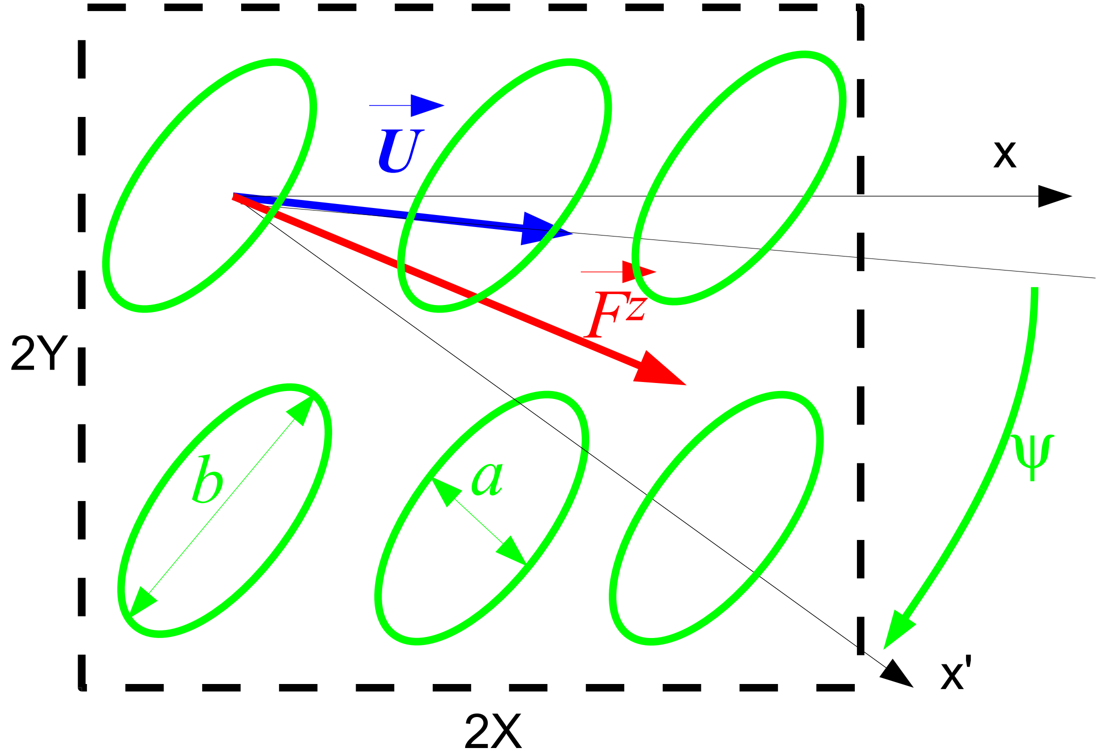
For one mountain: $h=\dfrac{2\mu^3}{\mu^2+\sigma^2 x'^2+\gamma^{-2}\sigma^2 y'^2}$

For $N_{ridges}$ the drag vector becomes:

$$\bar{F}^z_{x'}=\rho\, U\, N\, \mu\, \sigma\, C_g\left(B\cos^2\psi+C\sin^2\psi\right)$$
$$\bar{F}^z_{y'}=\rho\, U\, N\, \mu\, \sigma\, C_g\left(B-C\right)\cos\psi\sin\psi$$

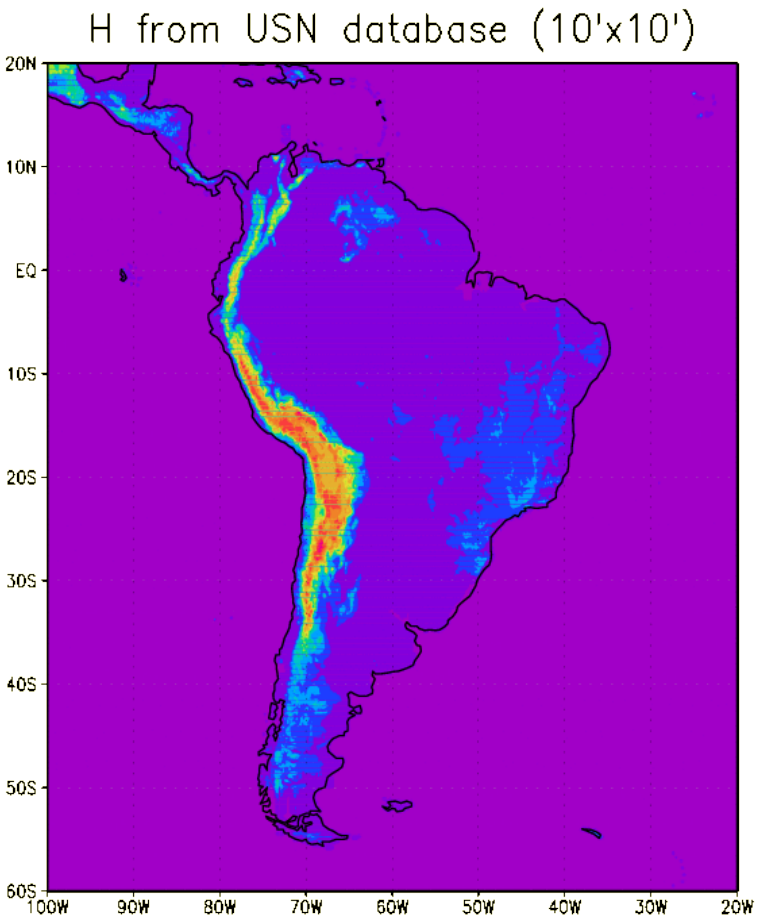
From Phillips (1985):

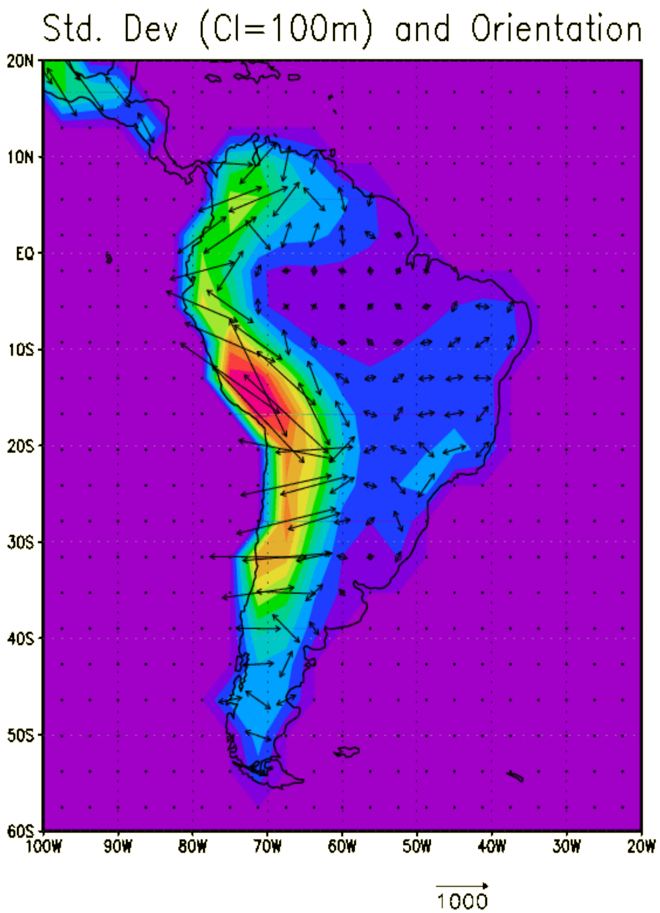
$$B=1-0.18\,\gamma-0.04\,\gamma^2,\; C=0.48\,\gamma+0.3\,\gamma^2$$



# 2)Representation of mountains in General Circulation Models
## a)Formulation of a SSO parameterization

All the subgrid parameters, $H_{min}$, $H_{max}$, $\mu$, $\sigma$, $\theta$, and $\gamma$ are build from statistics of measured mountain elevations




GCM with 2.5°x2.5° grid

# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

There are 2D and 3D theoretical simulations for uniform flows over mountains

2D, Stein (1992)

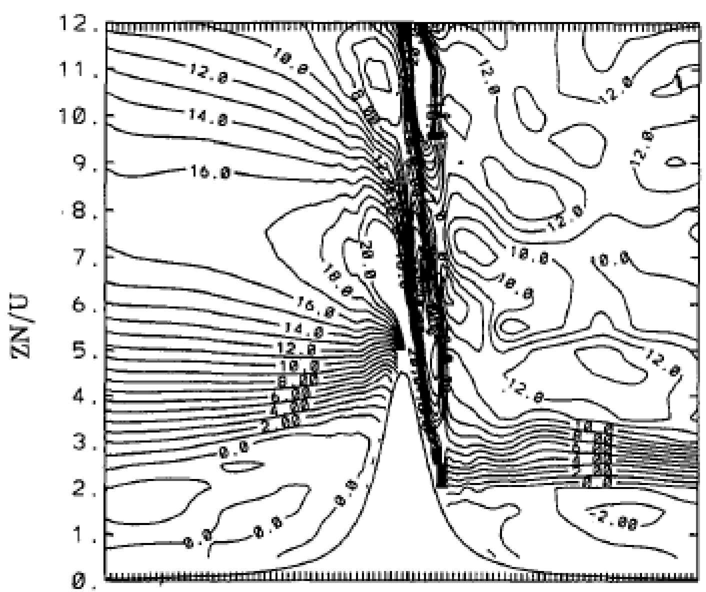
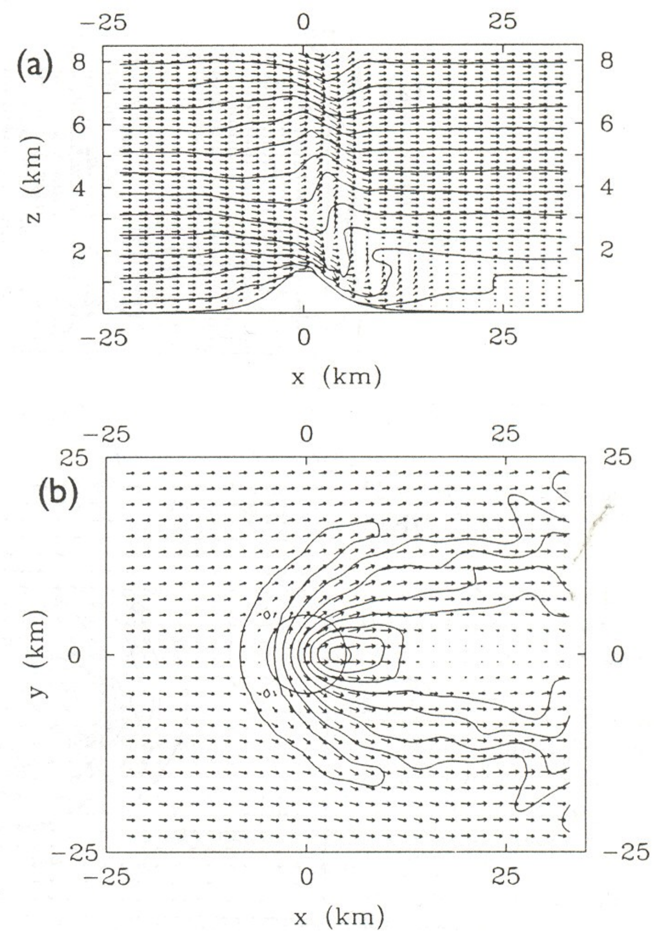



FIG. 9. Horizontal wind at $t_*$ = 20 for $F$ = 4.5, $S$ = 0.01.

3D, Miranda and James (1992)



# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

There are 2D and 3D theoretical simulations for uniform flows over mountains,
The scheme can be used to predict the drag in those simulations
(Lott and Miller 1997).

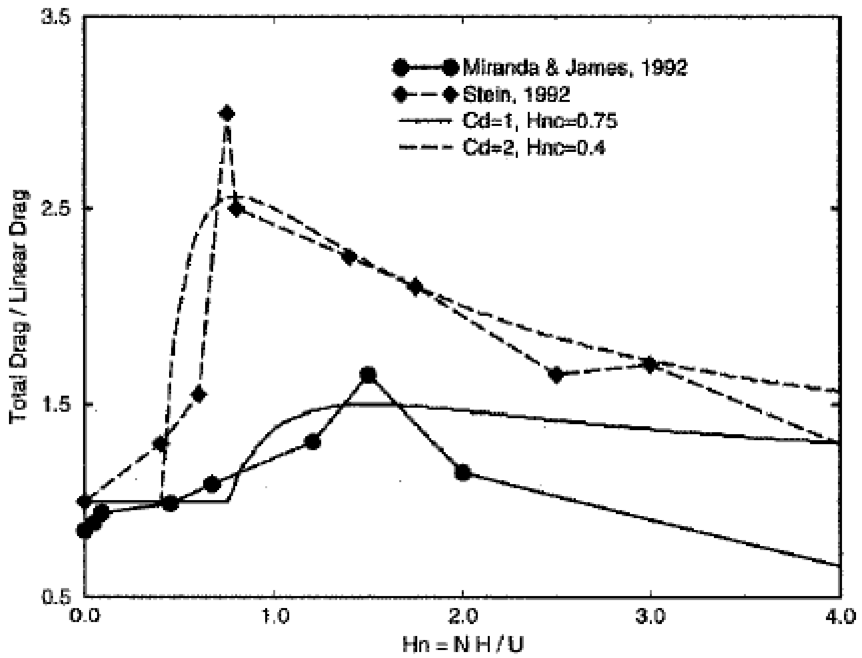



Figure 2. Ratio between the total mountain drag and the linear gravity-wave drag as a function of $H_n$. The continuous line and the dotted line correspond to the drag ratio predicted by the conceptual model upon which the new subgrid-scale orographic drug scheme is based. The dotted line with diamond symbols corresponds to values found in 2-D nonlinear simulations (Stein 1992). The continuous line with circle symbols correspond to values found in 3-D nonlinear simulations (Miranda and James 1992).

The low level blocked flow drag has an amplitude comparable to the gravity wave drag. The sum of the 2 can mimics the high-drag states found when

$$\frac{h_{max} N}{U} = H_{ND} > 1$$

# 2)Representation of mountains in General Circulation Models b)Validation and testing in a NWP model

There are field experiments, where the surface drag was measured by arrays of micro-barographs, and in some occasion, the wave momentum fluxes by Airplanes.

For the Pyrénées and the ECMWF forecast model, we have used the Pyrex data (Bougeault et al. 1992)

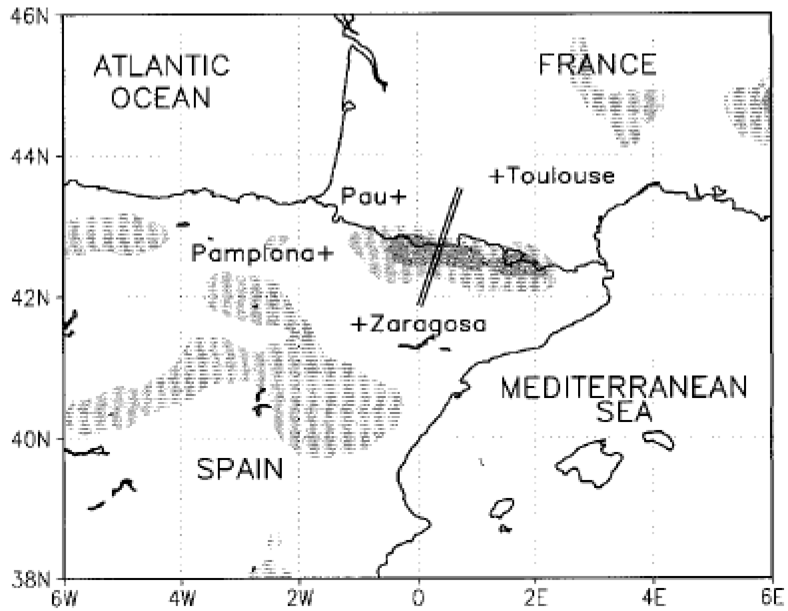



FIG. 1. Smoothed terrain elevation and PYREX data used. Here, + denotes the location of the high-resolution soundings. The two thick lines indicate the airplane paths during the IOP 3. The light- and dark-shaded areas denote terrain elevation above 1000 m and 1500 m, respectively.

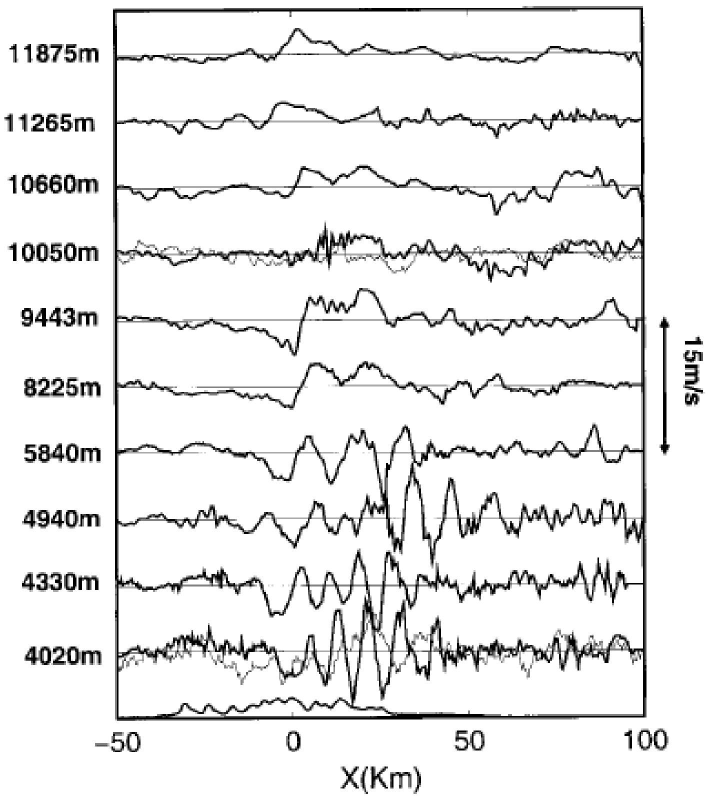



FIG. 2. Observed vertical velocities from different aircraft legs, from 15 Oct 1990 around 0600 UTC. Thick lower curve represents the Pyrénées; the thin curve at the $Z = 4$ km and $Z = 10$ km are red-noise surrogates with characteristics adapted to the measured vertical velocity at that level.

# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

There are field experiments, where the surface drag was measured by arrays of micro-barographs, and in some occasion, the wave momentum fluxes by Airplanes.

At a truncature T106, typical of the GCMs used today in the Earth System Models, The SSO drag scheme makes up the total drag due to the Pyrénées (the resolution is too coarse to see this mountain explicitely).
The model does a good job, if we add to the mountain drag the boundary layer drag, which is also enhanced over mountaneaous areas

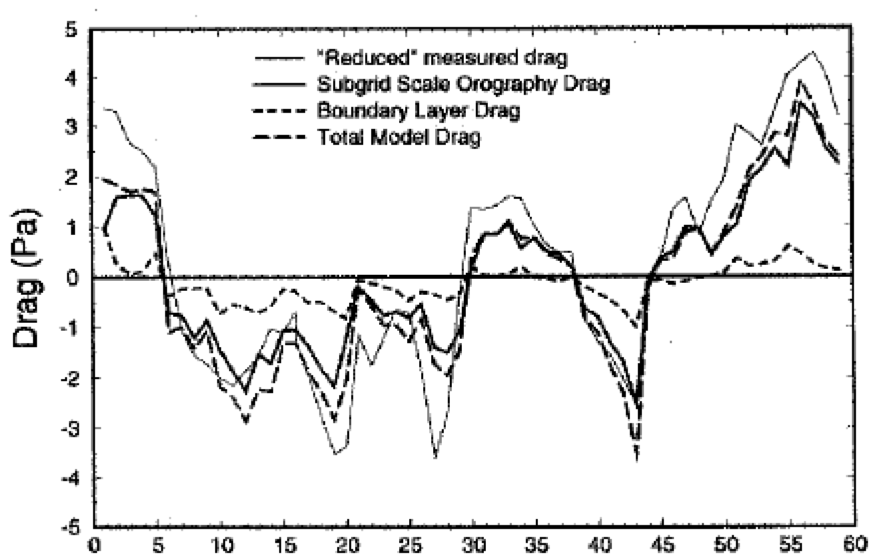
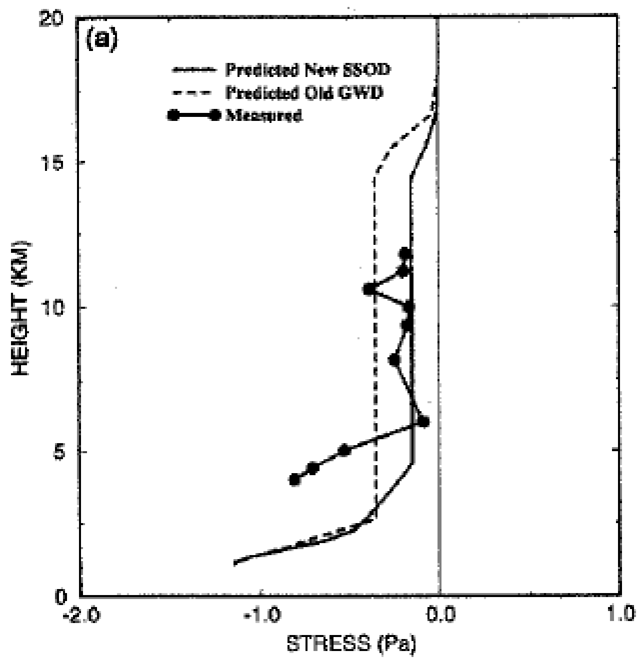



Figure 8. T106 forecasts: ECMWF model with mean orography and the new subgrid-scale orographic drag scheme. Parametrized mountain drags during PYREX. The comparison is limited to the 60 PIO cases defined in the text.

# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

The scheme also produce a profil of wave momentum flux aloft the mountain that Matches somehow the measured one.
Note that the momentum fluxes are almost an order of magnitude lower than the surface drag, which witness that a lot occurs at low level, and that it was sounded to consider this low level effect explicitely into the scheme



# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

Analogy between low level breaking waves and Hydraulic jumps in shallow water flow (Schar and Smith 1992), case where the mountain pierces the free surface.

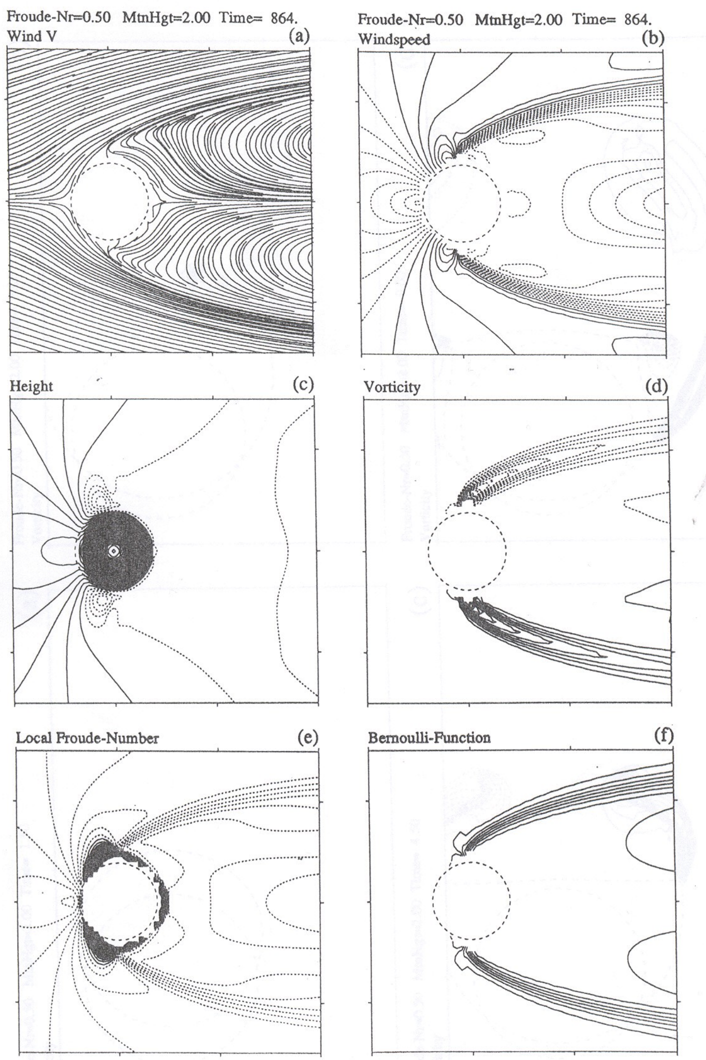
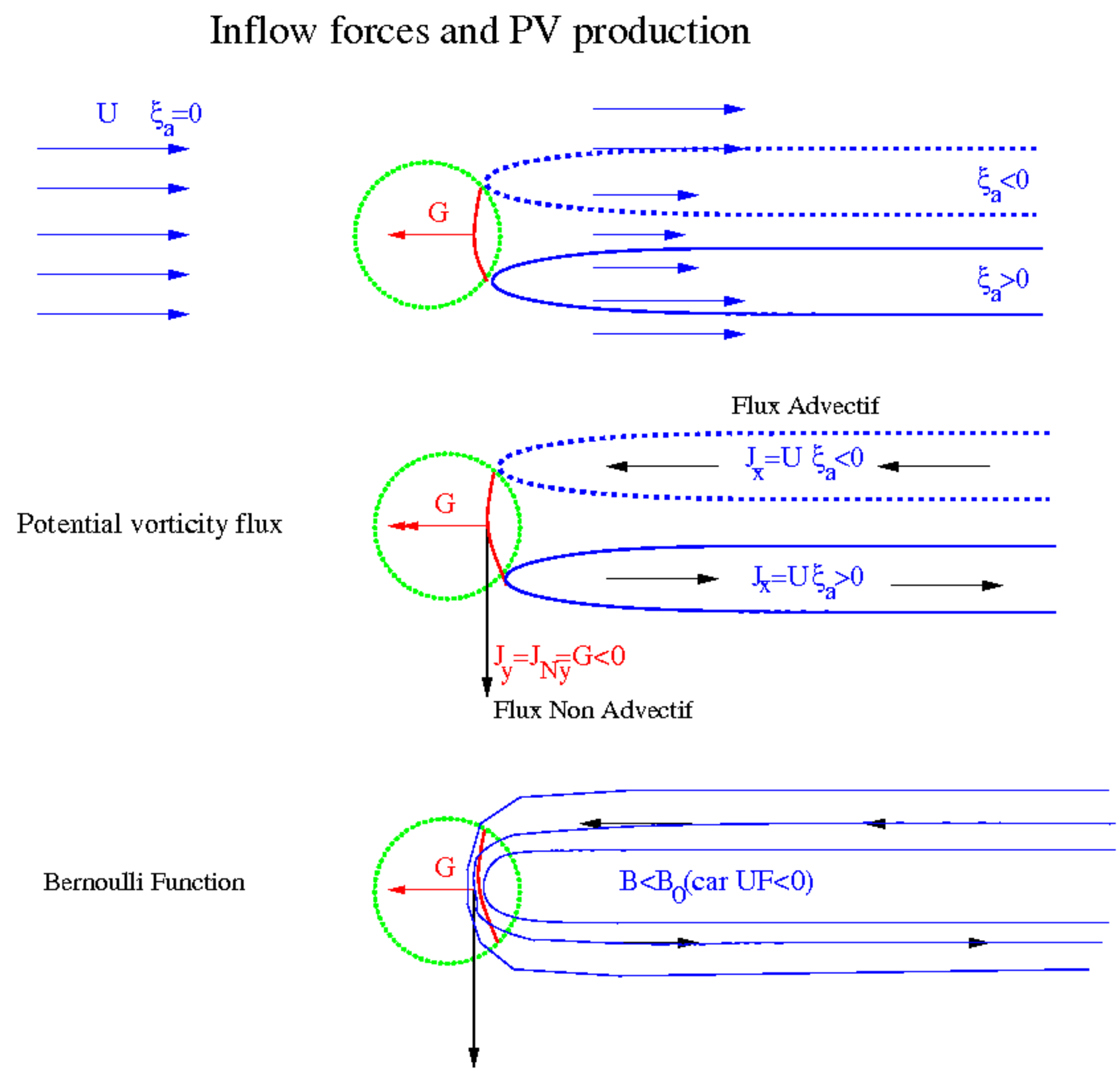



FIG. 7. As in Fig. 6 but for $Fr_\infty = 0.5$ and $M = 2$ (regime III). Here the mountain pierces the fluid surface (blank areas). Panel (c) shows the topography in pierced regions of the flow.



# 2)Representation of mountains in General Circulation Models
# b)Validation and testing in a NWP model

The effect of the low level drag is to produce a low level wake, quite in agreement with the higher resolutions forecast and analysis used during the campain

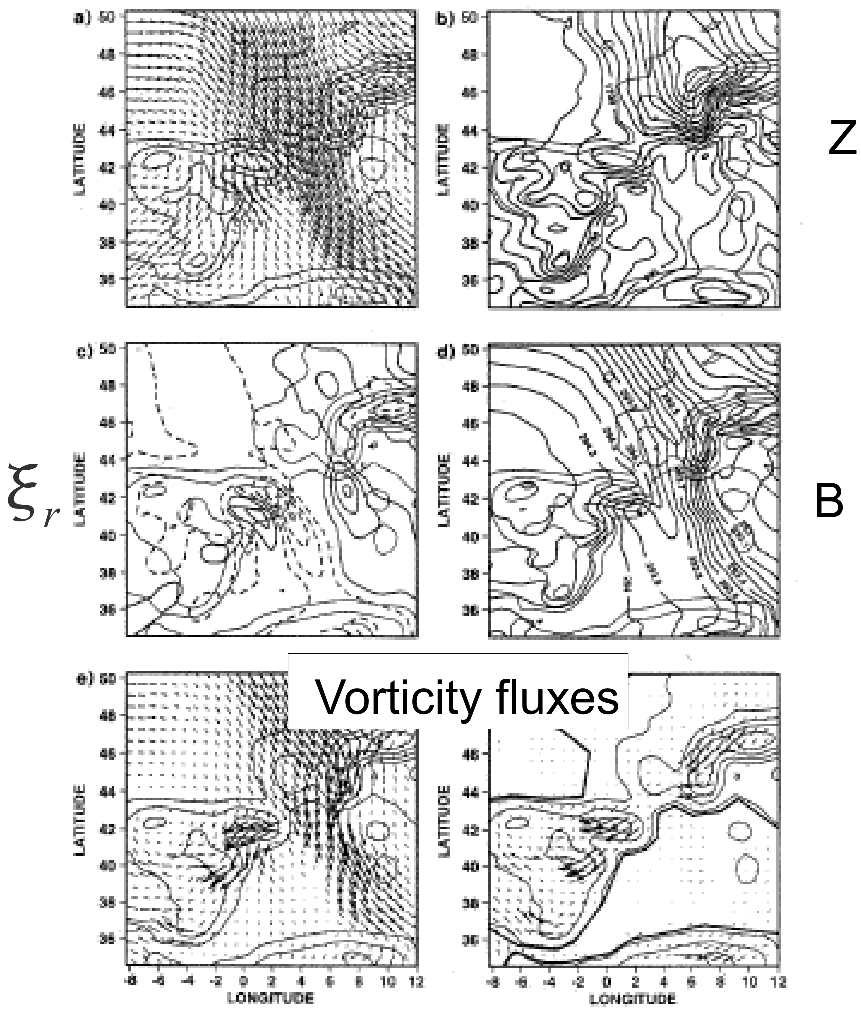



Figure 10. T213 forecast: ECMWF model with mean orography and the new subgrid-scale orographic drag scheme, 15 November 1990 at 6 UTC. Orography (interval: 400 m) and flow diagnostics on the isentropic surface $\theta = 293$ K. (a) wind; (b) height of isentropic surface, interval: 200 m; (c) isentropic relative vorticity, interval: $0.5 \times 10^{-4}\ s^{-1}$; (d) Bernoulli function, interval: $100\ J\ kg^{-1}$; (e) total potential vorticity flux; (f) potential vorticity fluxes due to the parametrized frictional forces and diabatic heating. Coastlines are shown on Fig. 10(f).

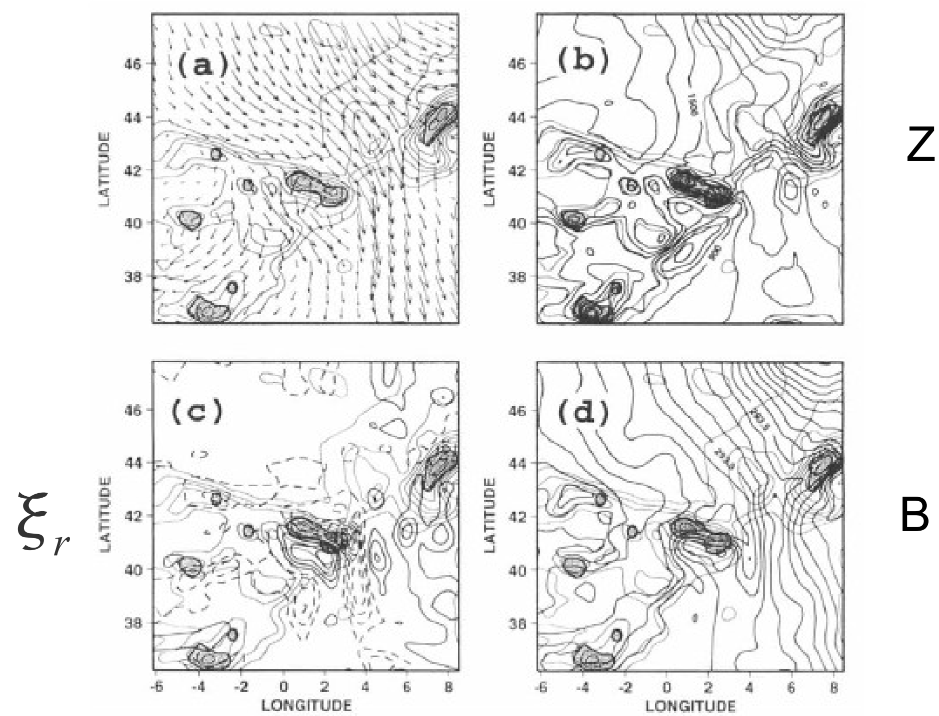



Figure 13. Peridot analysis, 06 UTC 15 November 1990. Orography (contour interval = 400 m) and flow diagnostics on the isentropic surface $\theta = 293$ K. In the shaded area the isentrope goes below the lowest model level. (a) Wind, (b) elevation (contour interval = 200 m), (c) isentropic relative vorticity (contour interval = $0.5 \times 10^{-4} s^{-1}$, with negative values dashed), and (d) Bernoulli function (contour interval = $100\ J\ kg^{-1}$).

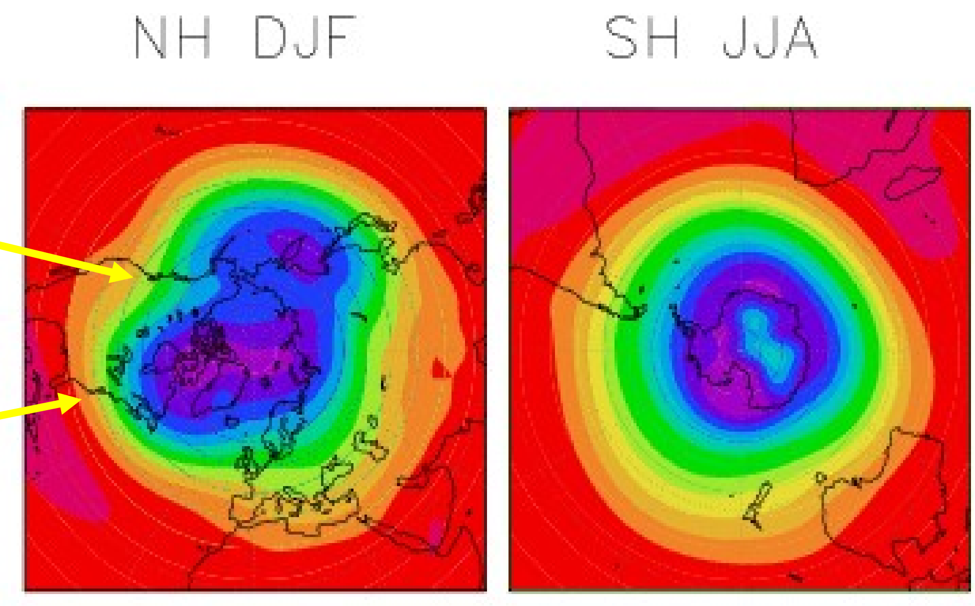
Those diagnostics are on an isentropic surface that intersects the mountain in the real world

# 2)Representation of mountains in General Circulation Models
## c)Impact in a GCM

Although the Lott and Miller (1997) SSO drag scheme improve the performances of the ECMWF forecasts (e.g.few days simulations), it does not improve the structure of the steady planetary waves in climate simulations (decennal and centennial simulations).

Ridges ($\xi<0$)

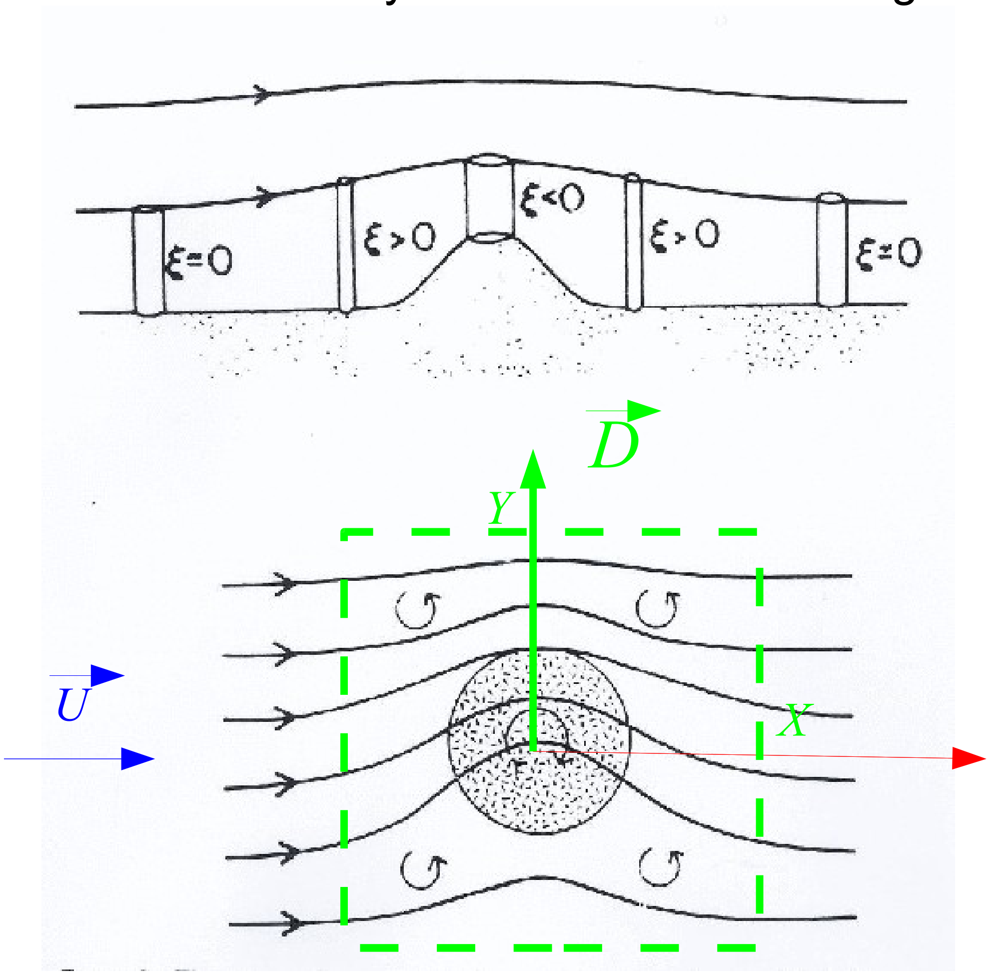
Troughs ($\xi>0$)




**NCEP reanalysis, géopotentiel à 700hPa, average over winter months**

# 2)Representation of mountains in General Circulation Models
# c)Impact in a GCM

To fix this problem remember that the forcing of the planetary waves by mountains is essentially due to vortex stretching ! A process that is associated to a large lift force.




During vortex stretching in the midlatitudes
The mountain felt the backgound pressure meridional gradient in geostrophic equilibrium with the background wind :

$$P = P_s - f\,U\,y$$

$$\vec{D}_r = \frac{1}{4XY} \int_{-Y}^{Y} \int_{-X}^{X} + p\,\vec{\nabla}\,h\,dx\,dy$$

In the linear case:

$$\vec{D}_r = \rho\,f\,U\,\overline{h}\,\vec{y}$$

# 2)Representation of mountains in General Circulation Models
# c)Impact in a GCM

A reason for which the models that use mean orographies at the lower boundary may underestimate the lift force, because they neglect that the air in valleys can be quite isolated from the large scale circulation.

$H(x)$

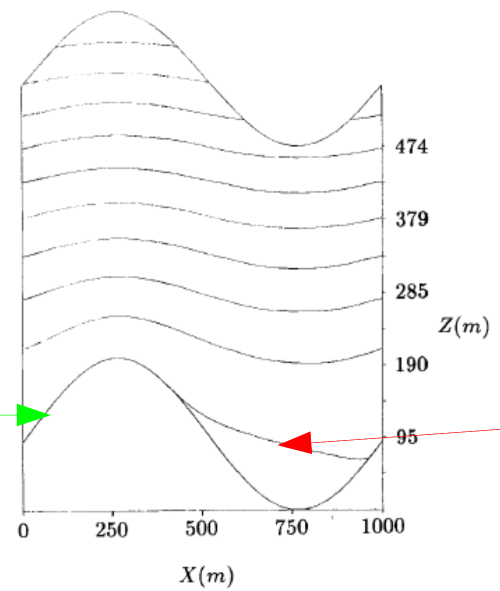



Figure 1. The model-derived streamlines for flow over the two-dimensional hill with $h = 200$ m ($\lambda = 1000$ m and $Z_0 = 0.1$ m). The vertical axis is linear in height above the upstream surface. The horizontal axis shows distance from the point on the upstream slope at which the hill height is half of its maximum value. A separation streamline is clearly visible.

Streamlines from a 2D Neutral Simulations
From Wood and Mason (QJ 1993)

$S=0.2,\ Fr^{-1}=0$

Note the separation streamline

Weak ventilation: small drag

# 2)Representation of mountains in General Circulation Models
## c)Impact in a GCM

A solution can be to higher up the mountains elevation by a fraction of its variance,
This the concept of envelop orography (Wallace et al. 1983)

An other is to keep a mean orography and to apply the missing forces directly in the models levels that intersect the mountain peaks (Lott 1999).

Lift parameter of order 1 ($C_l$)

$$\vec{D}_l = -\rho C_l f \left( \frac{h_{max} - z}{h_{max} - h_{mean}} \right) \vec{k} X \vec{U}$$

When integrated from $h_{mean}$ to $h_{max}$ this the lateral Lift if $C_l$ =2

# 2)Representation of mountains in General Circulation Models
# c)Impact in a GCM

Illustration of those concepts by parametrizing all the mountains by forces in
A GCM (explicit lower model level stays at sea level!). All maps are
for geopotential anomalies (e.g. after substraction of zonal mean values)

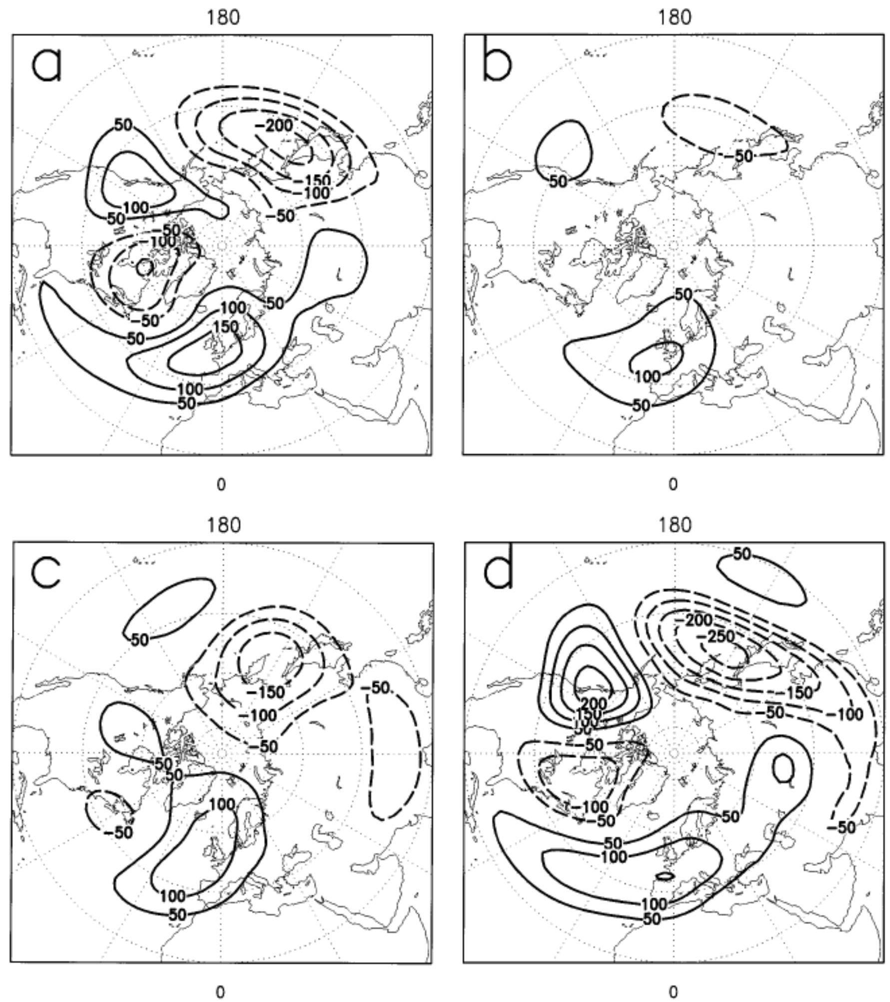
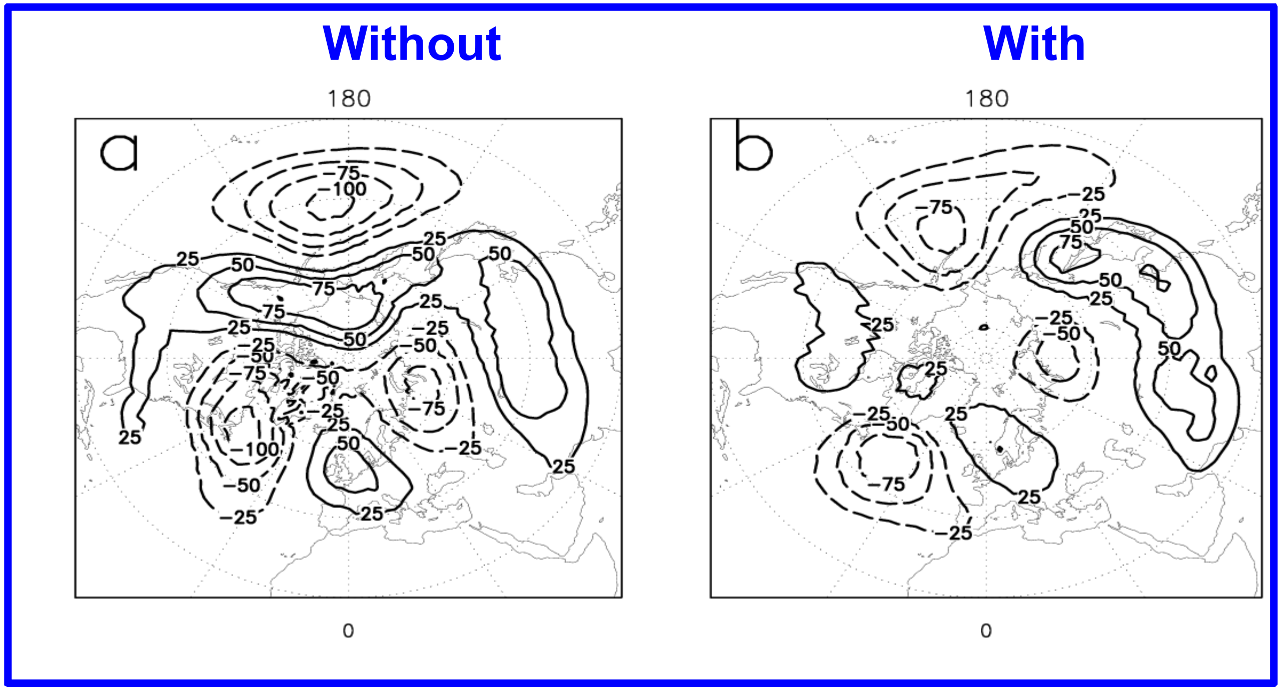



FIG. 3. Anomaly to the zonal mean of the geopotential height at 500 hPa averaged over the winter months (DJF) of the period 1985–90. LMD run with no explicit orography. (a) NMC analysis; (b) LMD no drag, no lift; (c) LMD low drag only; (d) LMD low lift only. Zero line not shown; negative values are dashed.

# 2)Representation of mountains in General Circulation Models
## c)Impact in a GCM

Simulation with mean explicit orography without and with the subgrid scale orographic drag scheme including enhanced lift

Error maps between the Geopotential height at 700hPa,
NCEP reanalysis minus LMDz
Winter months out of a 10years long simulation

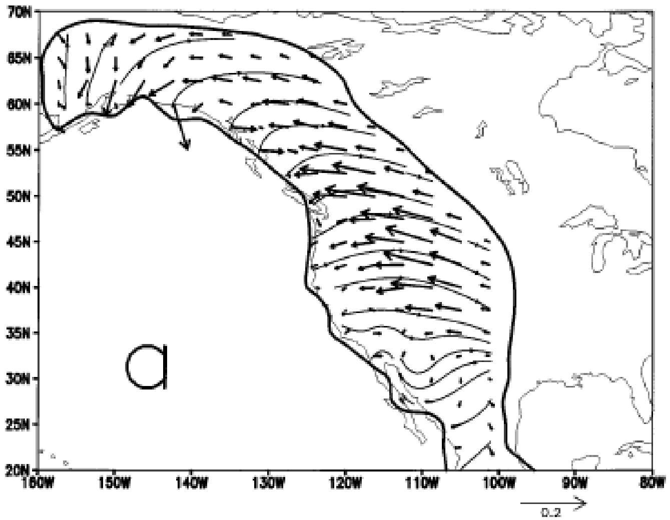


# 2)Representation of mountains in General Circulation Models
# c)Impact in a GCM

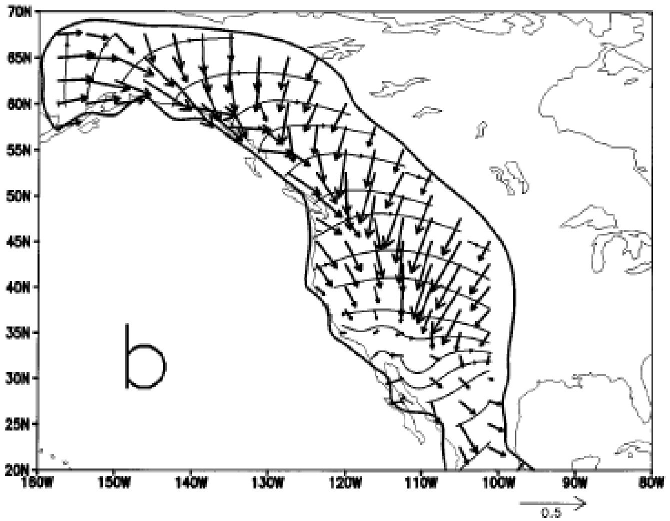
Simulation with mean explicit orography with the subgrid scale orographic drag and enhanced

Drag force **<u>onto</u>** the flow over the Rockies

The lift force is the major cause for the improvement of the planetary wave!




«SSO Drag »



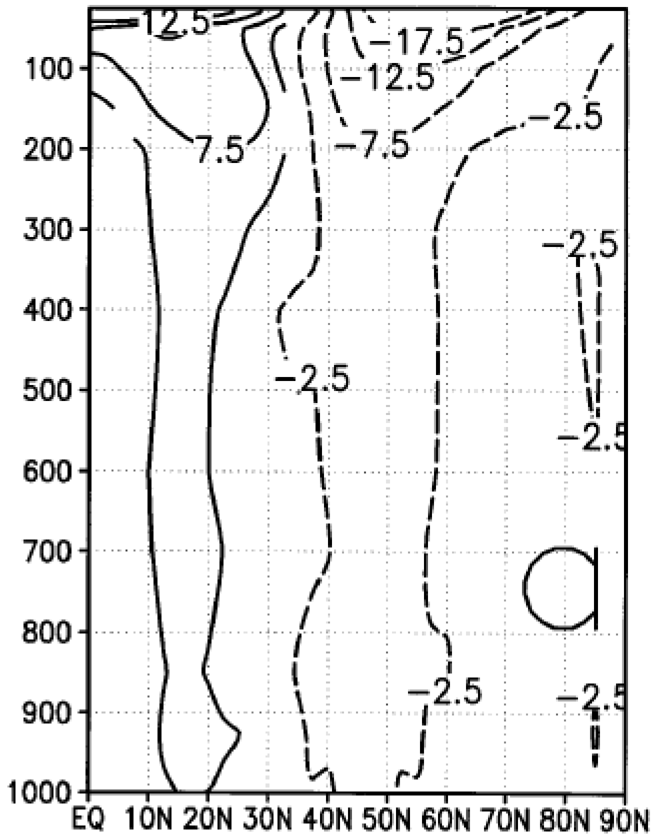

«SSO Lift»

# 2)Representation of mountains in General Circulation Models
# c)Impact in a GCM

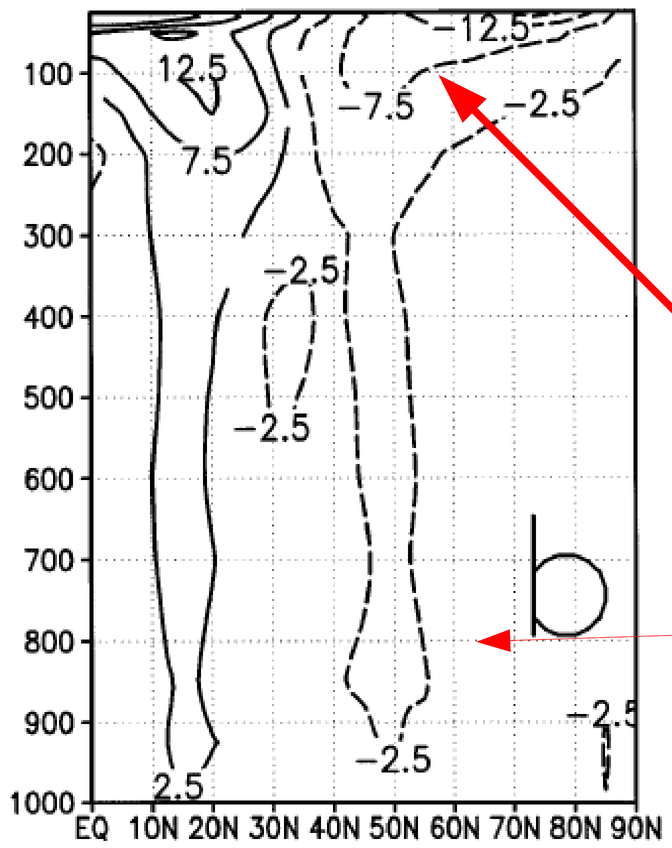
Simulation with mean explicit orography without and with the subgrid scale orographic drag scheme including enhanced lift

Errors and on the zonal mean zonal wind (Analyse-model)

**Without**




**With**




Now it is more the SSO drag that does the job:

With the upper level gravity waves helping close the jet at the Tropopause

The low level drag reducing the jet amplitude in the Low and Mid troposphere