# Dynamical impact of mountains on atmospheric flows

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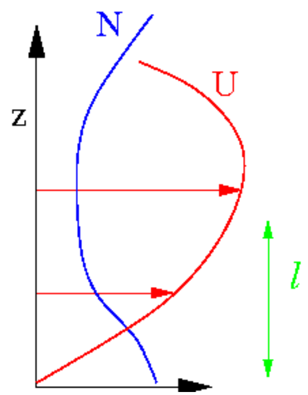
**a)Heuristic linear analysis**
**b)Mesoscale dynamics**
**c)Mesoscale dynamics impact on the planetary scale**
**d)Synoptic and planetary scales dynamics**
**e)Improving the synoptic and planetary scales**
**f)Planetary scales dynamics**
**g)Sumary of issues**

Sorry, this will be the theoretical view of a large-scale modeller!

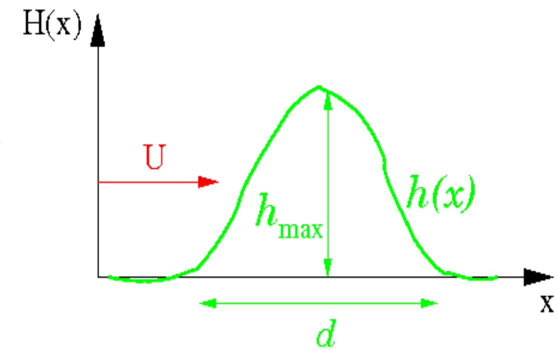
# Dynamical impact of mountains on atmospheric flows
# a) Heuristic linear analysis

## Dimensional analysis:

Background flow parameters
$N$, $U$, $l$, (and $f$ )




Mountain dimensions
$d$ and $h$




## Param. controlling the linear dynamics:

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

and low level « trapped waves »: $L=\frac{N\,l}{U}$

## Param. controlling the non-linear dynamics:

$$S=\frac{h_{max}}{d} \qquad H_{ND}=\frac{N\,h_{max}}{U}$$

Boundary layer dynamics | Mesoscale dynamics (incl. Gravity waves) | Synoptic scale and planetary scale dynamics

Trapped waves

« Vortex Stretching »

**Drag on~ Earth**

$\rho\, C_d\, U^2 h_{max}$ | $\rho\, C_g\, N\, U\, h^2_{max}$ | $\rho\, C_l\, f\, U\, h_{max}\, d$ (almost perpendicular to $U$) | *Rossby wave drag*

$Fr^{-1}=1$ $\qquad$ $Ro^{-1}=1$ $\qquad$ $d$

# Dynamical impact of mountains on atmospheric flows
# b) mesoscale dynamics ($f<kU<N$)

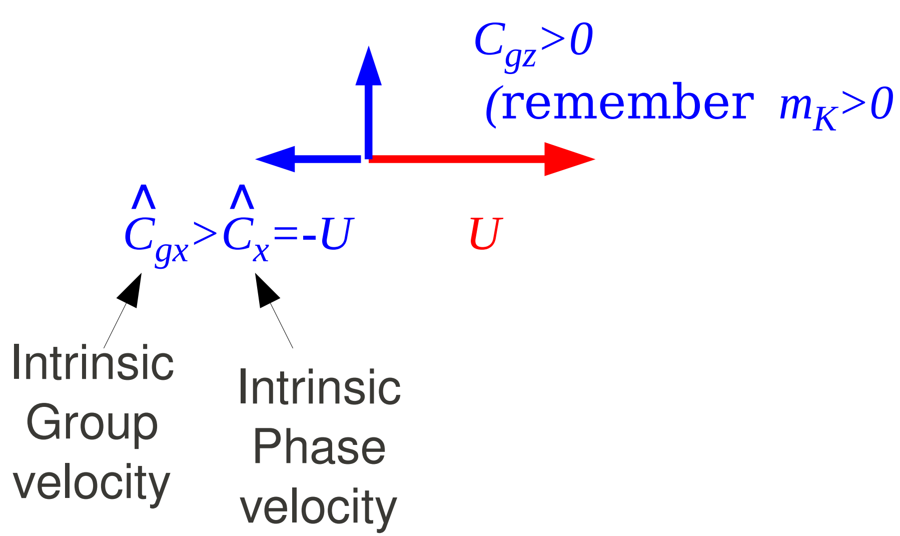
The 2D linear analysis of Queney (1947), mountain drag: $Dr = \frac{1}{2X}\int_{-X}^{X} p \frac{dh}{dx}$

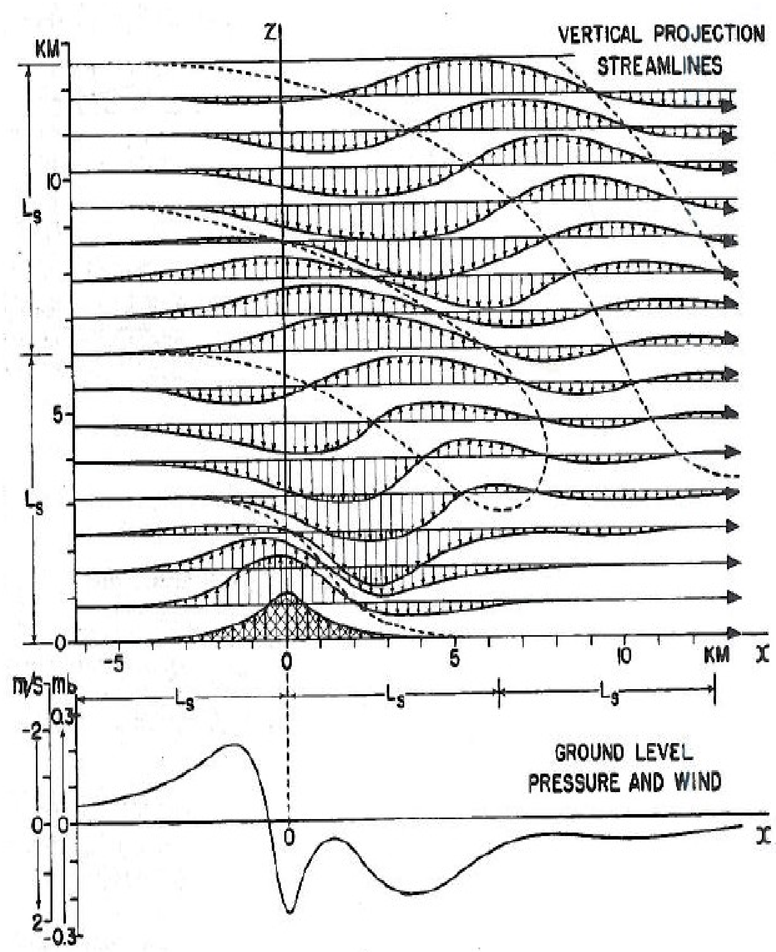
$U=10 m/s$, $N=0.01\ s^{-1}$, $f=10^{-4}\ s^{-1}$

$$h(x) = \frac{h_{max}}{1+\frac{x}{d}^{2}}$$

Case (b):

$d=1$km, non-hydrostatic, non-rotating



# Dynamical impact of mountains on atmospheric flows
# b) mesoscale dynamics ($f<kU<N$)

## **Linear dynamics and trapped lee-waves** (U(z) and N(z) varies)

2D-Boussinesq linear non-rotating theory

$$\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}+\left(\frac{N^2}{U^2}-\frac{U_{zz}}{U}\right)w=0$$

Non Hydrostatic

$S(z)$
Scorer parameter

Fourier decomp: $w(x,z)=\int_{-\infty}^{\infty}\hat{w}(k,z)e^{ikx}dk$

$$\frac{\partial^2 \hat{w}}{\partial z^2}+\left(\frac{N^2}{U^2}-\frac{U_{zz}}{U}-k^2\right)\hat{w}=0$$

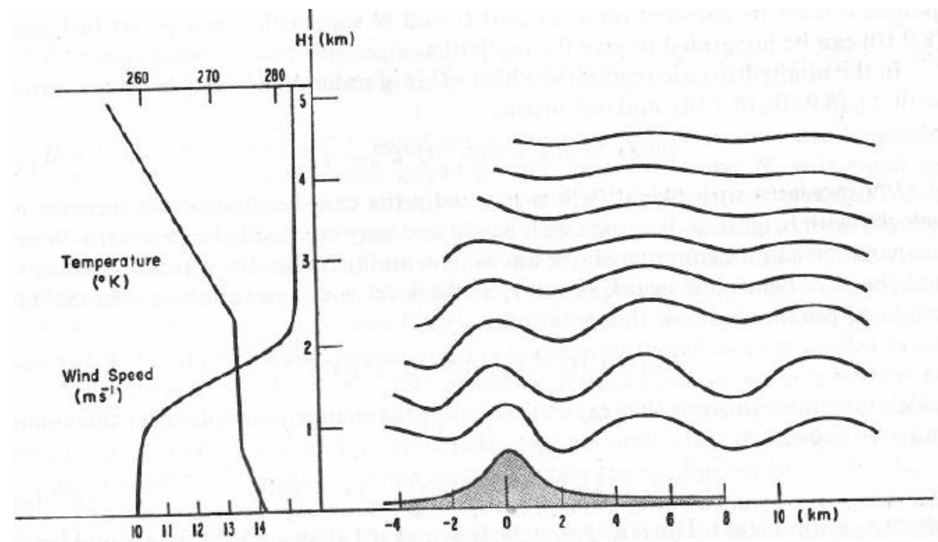
WKB theory: $m_k^2(z)=S(z)-k^2$

Turning heigh: $S(z_c)-k^2=0$

WKB theory predicts $\lim_{z\to z_c} m_k(z)\to 0$

Total or partial reflection around $z_c$

Free modes such that w(k,z=0)=0 can be resonantly excited leeding to trapped lee waves




*Scorer (1949) + Gossard and Hooke (1975)*

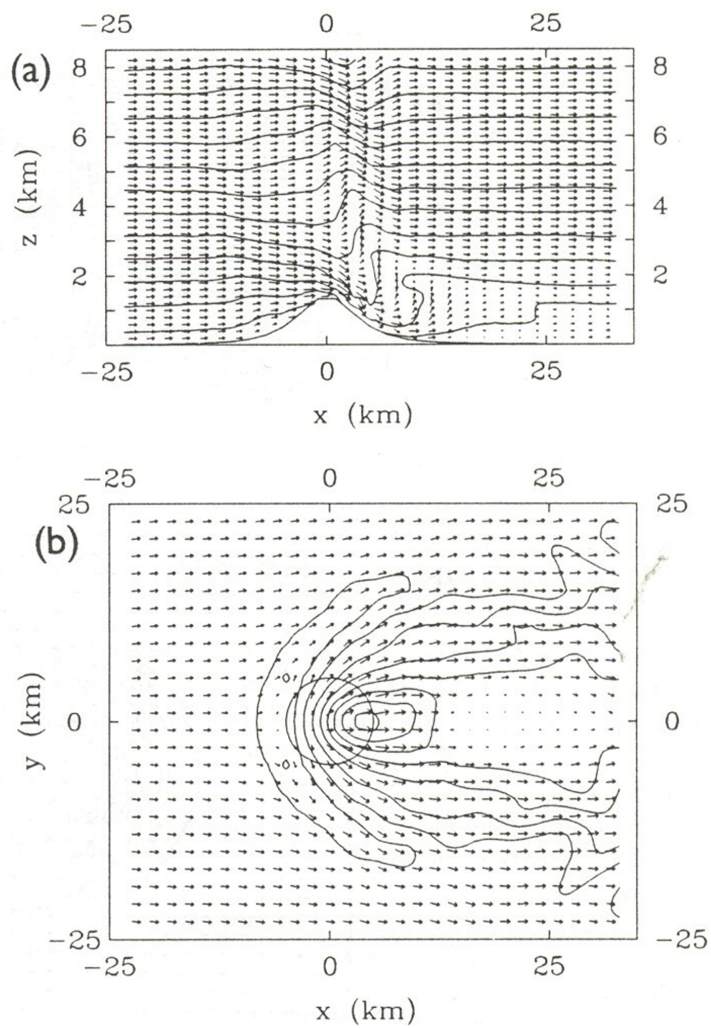
**Issues : Interaction between trapped waves and the PBL**

# Dynamical impact of mountains on atmospheric flows
# b) mesoscale dynamics ($f<kU<N$)

**Nonlinear dynamics for Stratified or « slow » Flows :** $Fr^{-1}=\frac{N\,d}{U}\gg 1$

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.

The strong Foehn at the surface downstream

Residual GWs propagating aloft

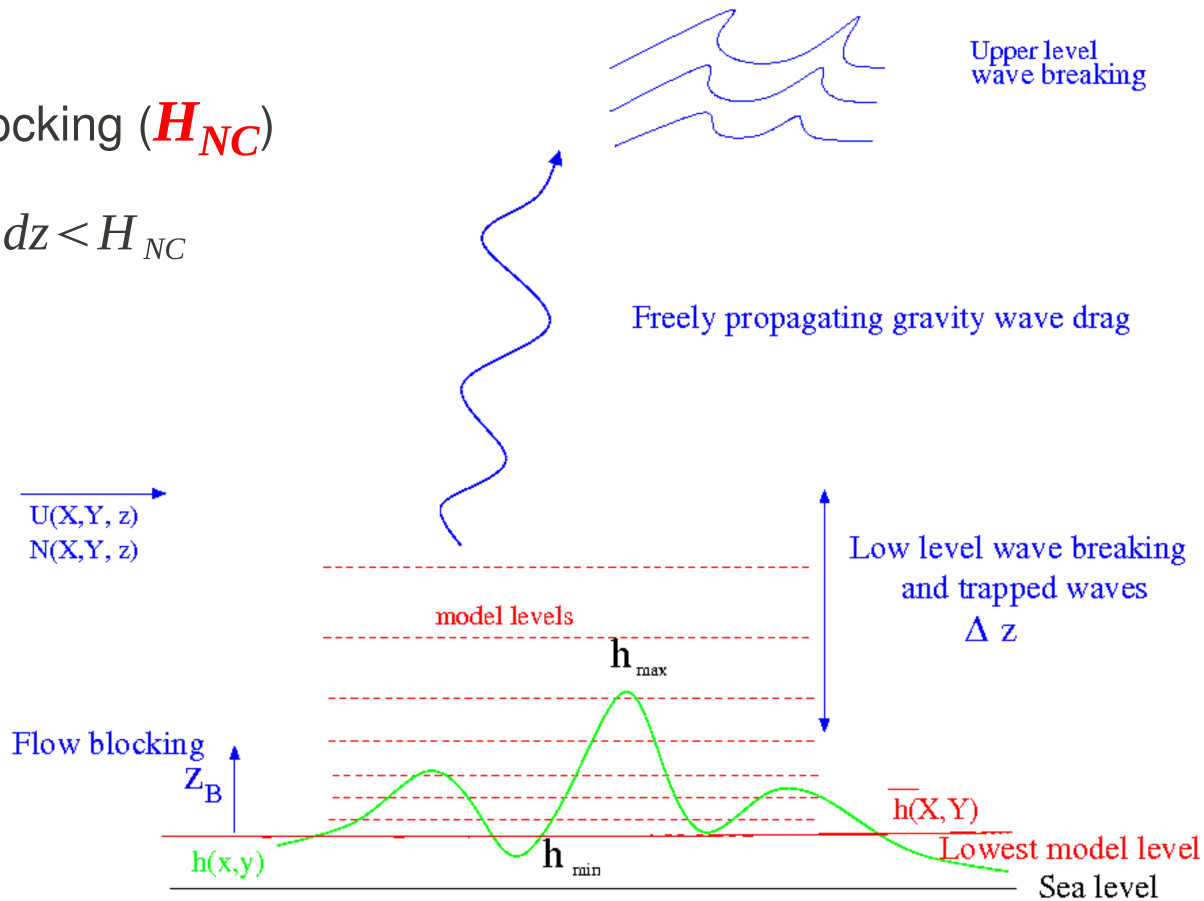
Apparent slow down near the surface downstream,
And over a long distance

# Dynamical impact of mountains on atmospheric flows
# c) Mesoscale dynamics impact on the planetary scale

## Subgrid-Scale Orography (SSO) parameterization

Flow blocking ($H_{NC}$)

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



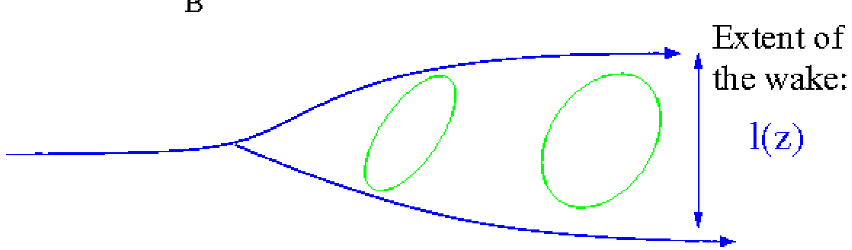

Breacking based on a total Richardson number criteria (**Ric**):

Gravity wave stress ($C_g$)

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

Breaking at low level and Trapped waves are also represented

Below $Z_B$




Bluff body drag (**Cd**) applied at each model layer that intersects the SSO:

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

# Dynamical impact of mountains on atmospheric flows
# c) Mesoscale dynamics impact on the planetary scale

## Subgrid-Scale Orography (SSO) parameterization

Issues about the formulation itself :

Trapped lee waves are paremetrized in an ad-hoc way (the theory beneath the Parameterization is essentially hydrostatic)

Concerning mountaion waves prediction, the reality is much more stochastic than We could expect from such a steady forcing

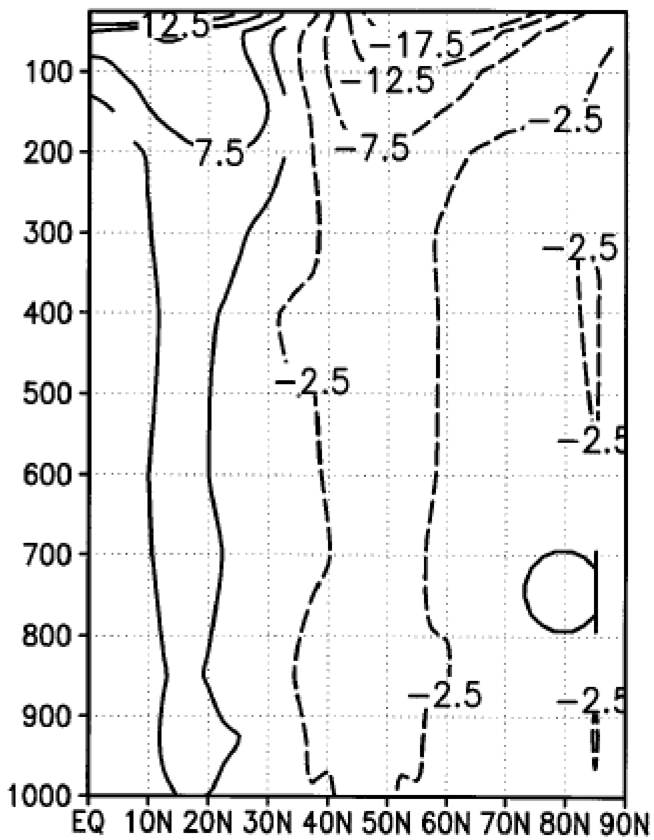
Directional effects have to be re-examined thoroughly

All these can be handled via parameterisations using large ensembles of Monochromatic mountain waves produced stochastically (for a good part of their amplitude)

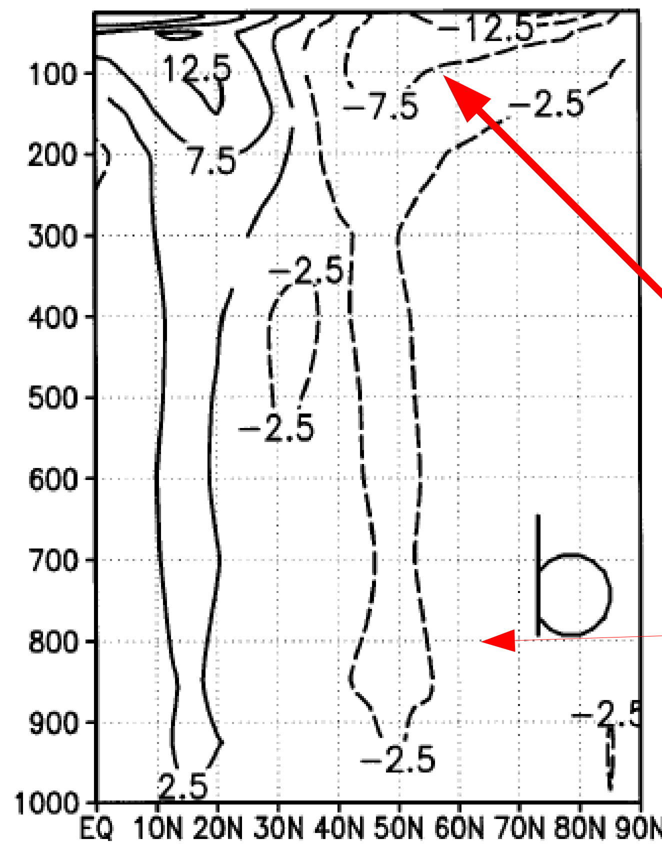
# Dynamical impact of mountains on atmospheric flows
# c) Mesoscale dynamics impact on the planetary scale

Impact in a GCM's troposphere
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

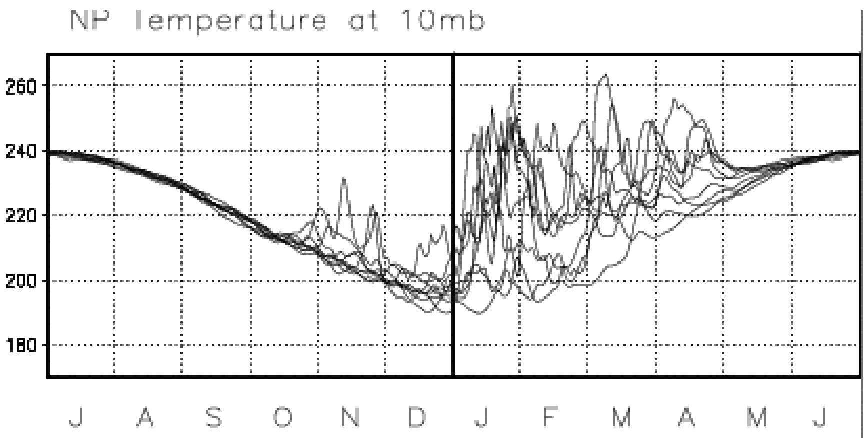
The low level
drag reducing the jet
amplitude in the
Low and Mid troposphere

# Dynamical impact of mountains on atmospheric flows
# c) Mesoscale dynamics impact on the planetary scale

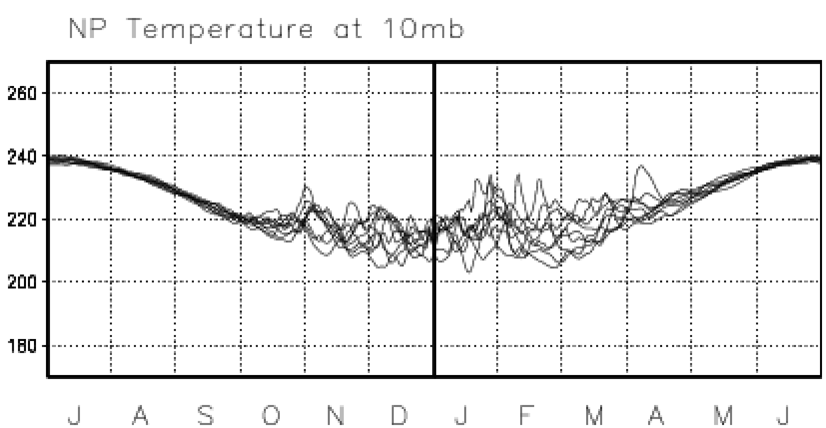
Impact in a GCM's stratosphere

**NH stratospheric warming**

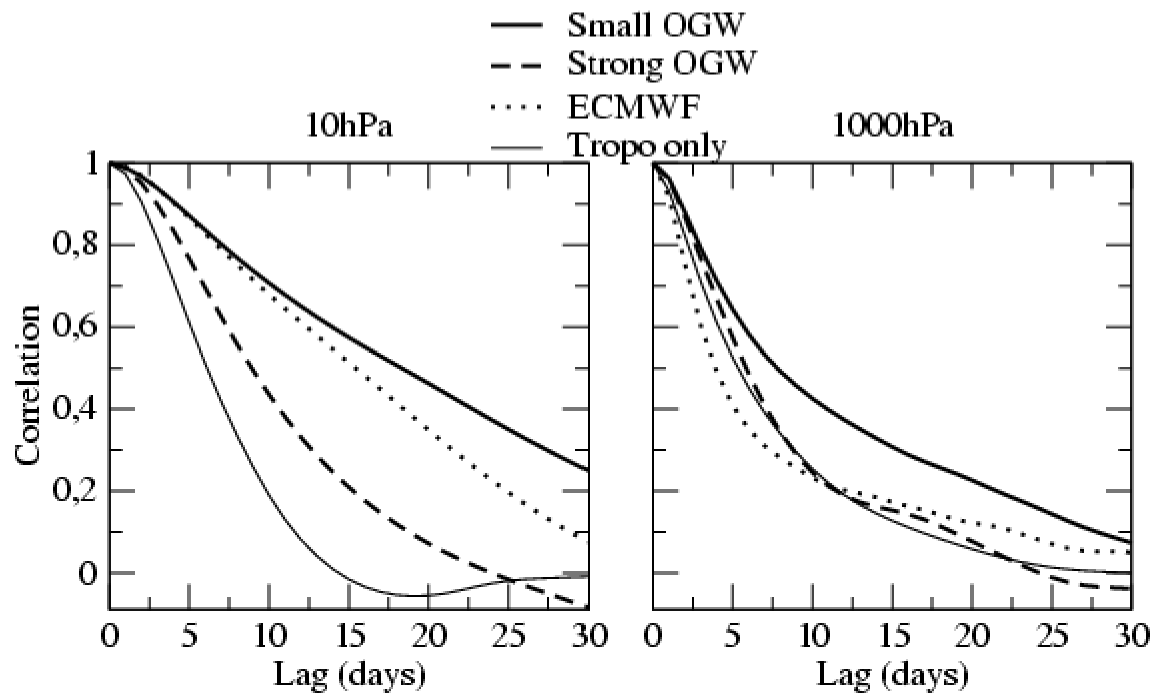
Weak OGWs




Strong OGWs



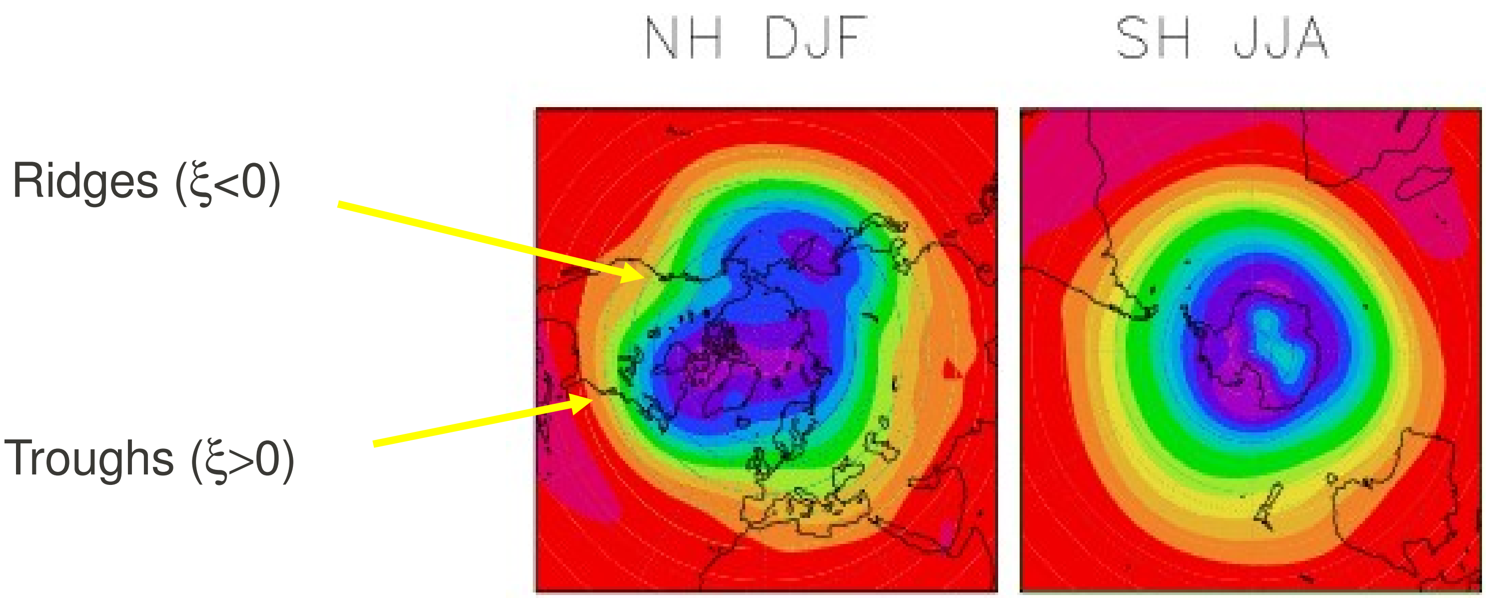

**Arctic Oscillation persistence**




Issues : Effects of GWs in a changing climate.
Southern hemisphere: case of the Andes and of the montaneous Islands lost in the southern hemisphere oceans.

# Dynamical impact of mountains on atmospheric flows
# c) Mesoscale dynamics impact on the planetary scale

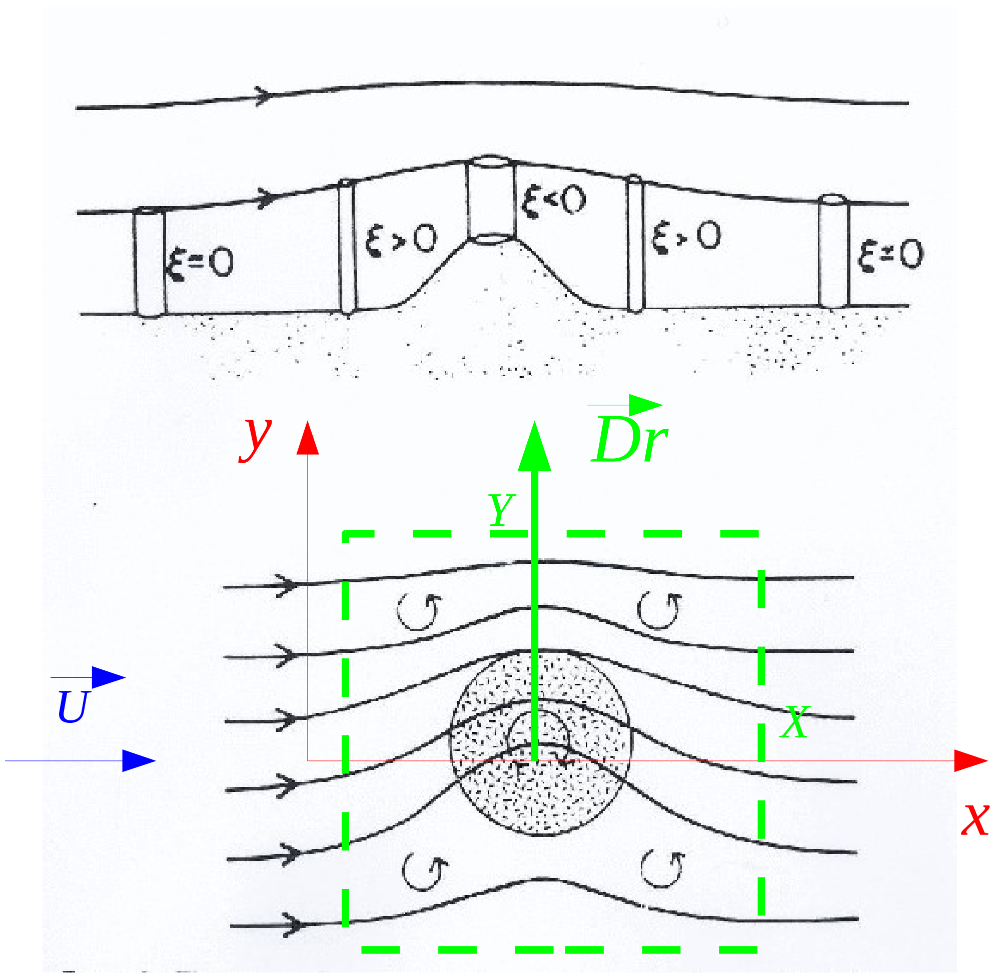
Although the Lott and Miller (1997) SSO drag scheme improve the performances of the ECMWF forecasts (e.g.few days simulations) And the LMDz GCM zonal mean state, it does not improve the structure of the steady planetary waves in the troposphere in climate simulations.




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

# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

Basic mechanism is vortex stretching (linear theory):




The force exerted on the mountain is almost perpendicular to the low level incident wind (like a lift force!).

It follows that the mountain felt the backgound pressure meridional gradient in geostrophic equilibrium with the background wind :

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

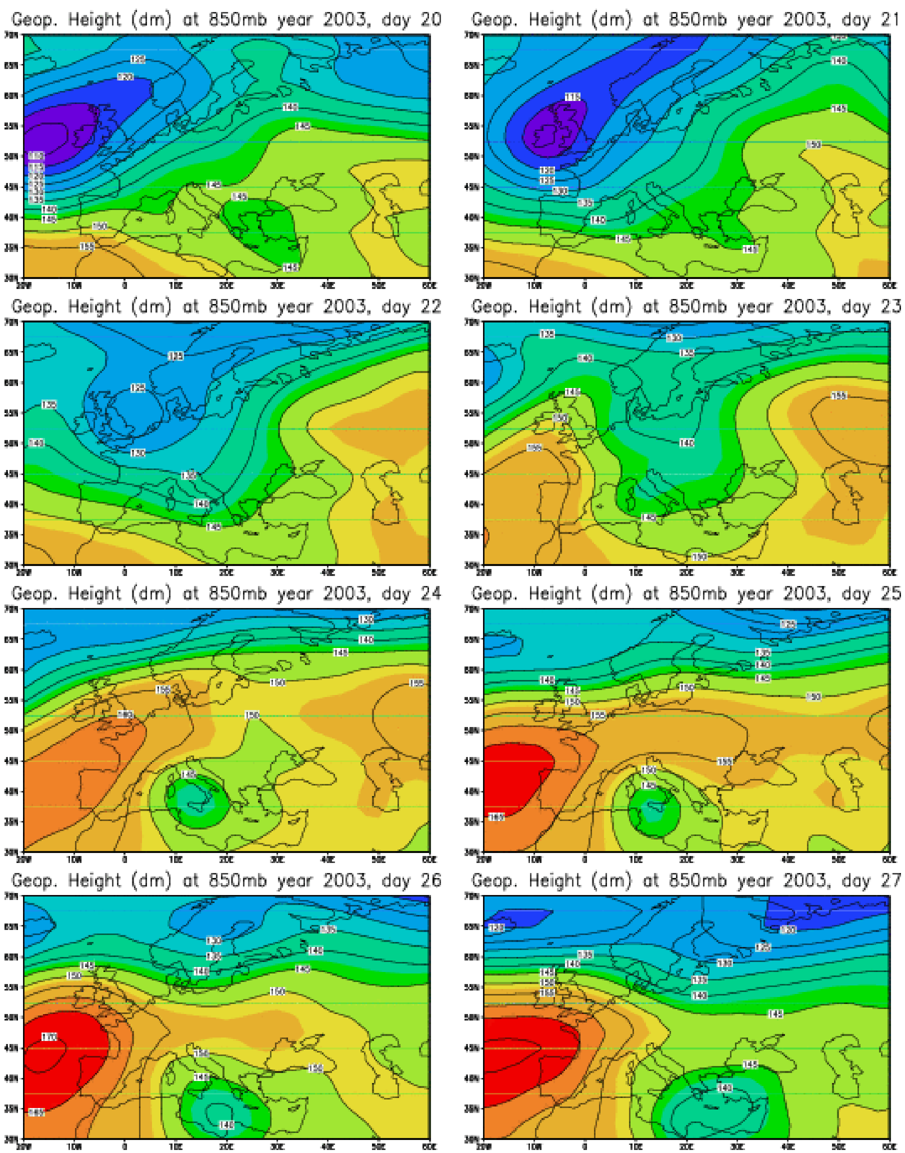
$$\vec{D}r = \frac{1}{4XY} \int_{-Y}^{Y} \int_{-X}^{X} + p \vec{\nabla} h \, dx \, dy$$

In the linear case:

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

# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

### A case of lee-cyclogenesis (NCEP Data)



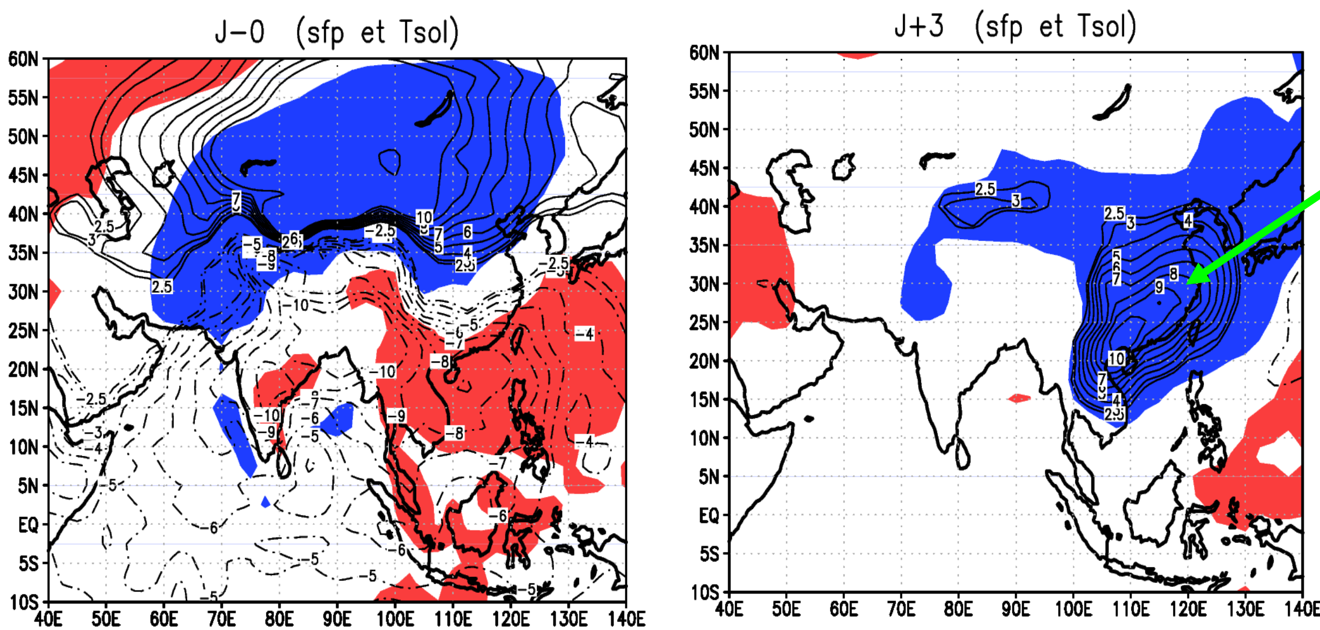

This basic mechanism is in part operand during the triggering of mountain lee Cyclogenesis.

The lift force therefore needs to be well represented in models

# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

## Relation with Eastern Asia Cold Surges

**Composites of surface maps keyed to -$D_y$** (NCEP Data, 40 cases out of 28 years)




Almost the structure of the cold surges.

Patterns affecting cold surge onset and monsoon precipitations (not shown, but very significant over the South-China sea)

*SFP anomaly (contours, Student index),significant surfacetem perature anomalies (blue=cold, red=warm)*
*Mailler and Lott (2009, 2010)*

**The peaks of -$D_Y$ are due high pressures and low temperatures over the Tibet to the North of the Himalayas**

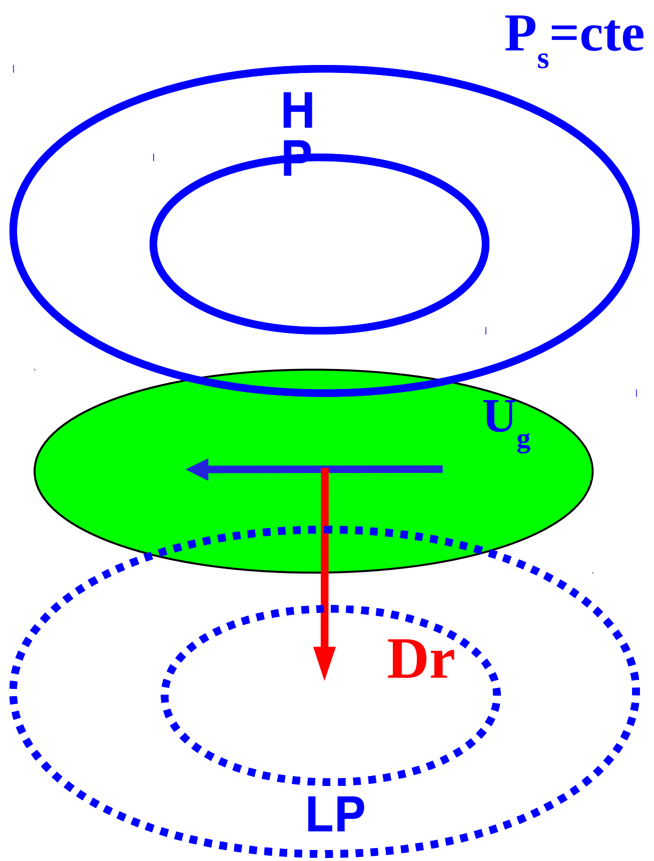
**These structures are few days systematic precusors of the *Cold Surges*, the cold surges ptoducing high negative values in $D_X$**

# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

**Basic Mechanism** :

How can a lateral force supplement the orographic forcing ?

View supported by A theoretical model




$U_g$: Geostrophic wind
**Dr**: Drag
**Mountain** is in green
$P_s$: Surface pressure

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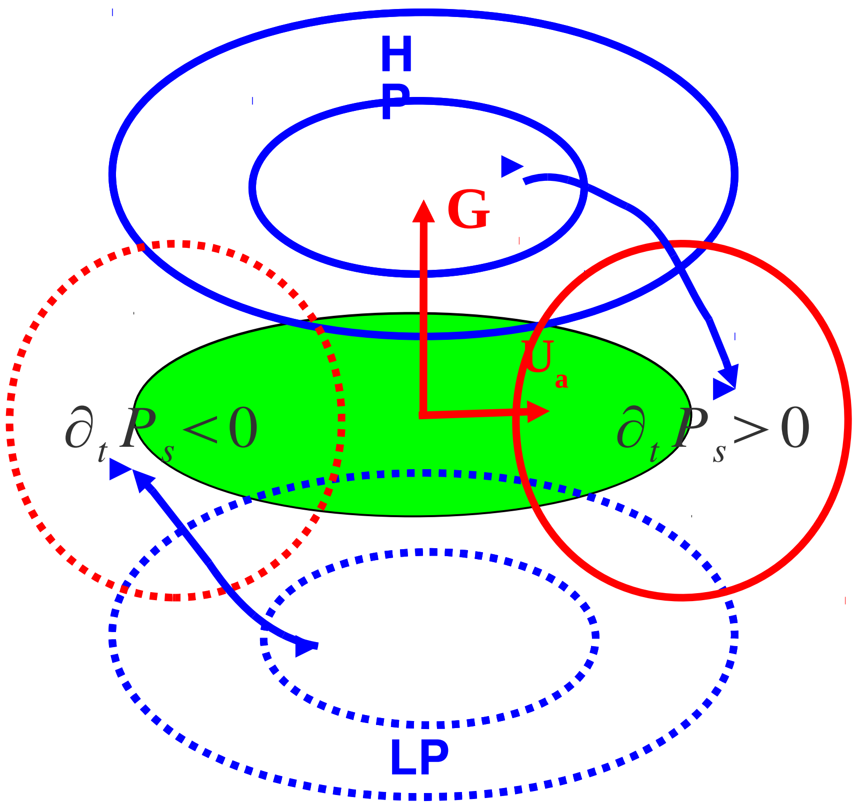


$$f\, u_a = G_y$$

**G=-Dr: the force on the atmosphere is opposite to the drag**

**U$_a$** ageostrophic wind:

Equilibrate **G** via Coriolis

Transport mass from left to the right here

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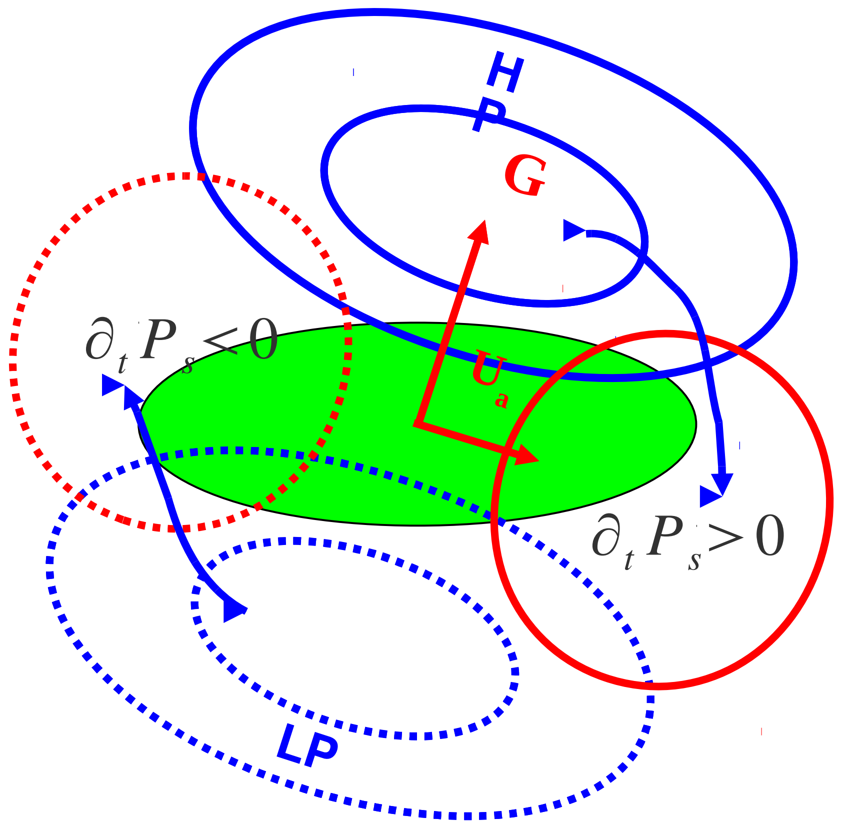


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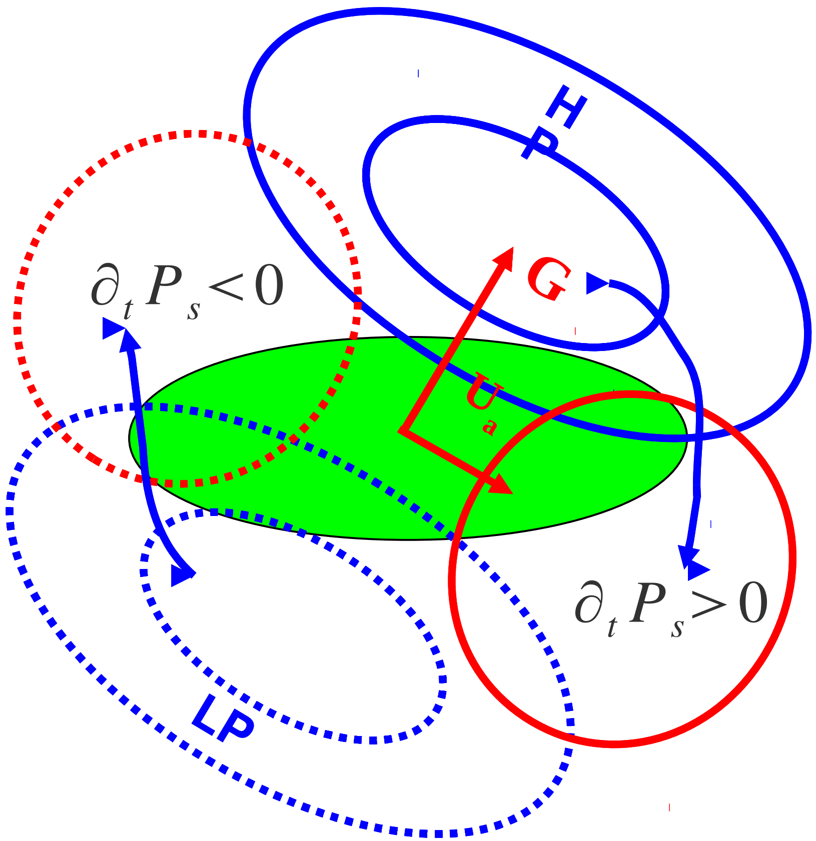


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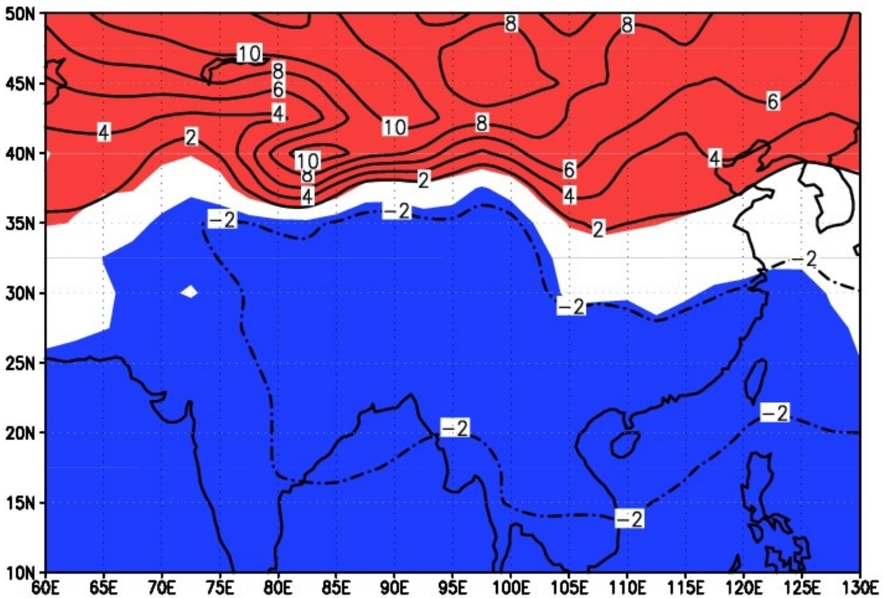
Equilibrate **G** via Coriolis
Transport mass from left to the right here

# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

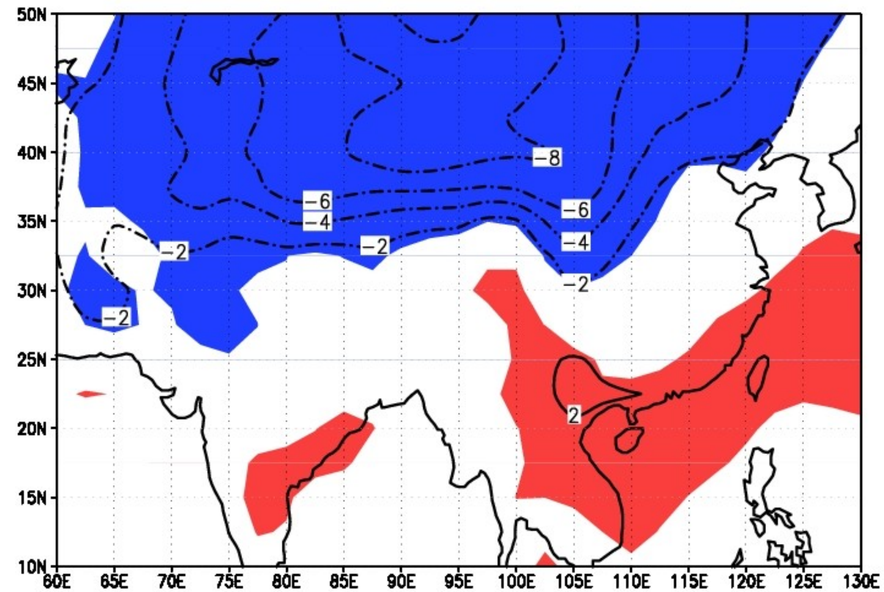
## Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Himalayas

Surface Pressure




Day 0

Surface Temperature



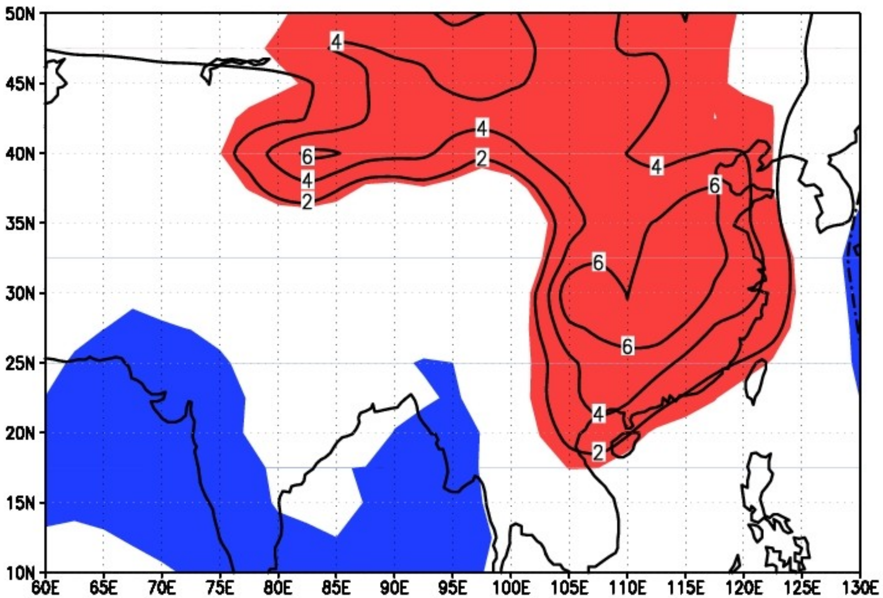

Situation corresponding to negative peaks of $D_{TPy}$:

- High pressure and low temperature over Siberia, corresponding to a strengthening of the Siberian High
- Low pressure in the subtropics

# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

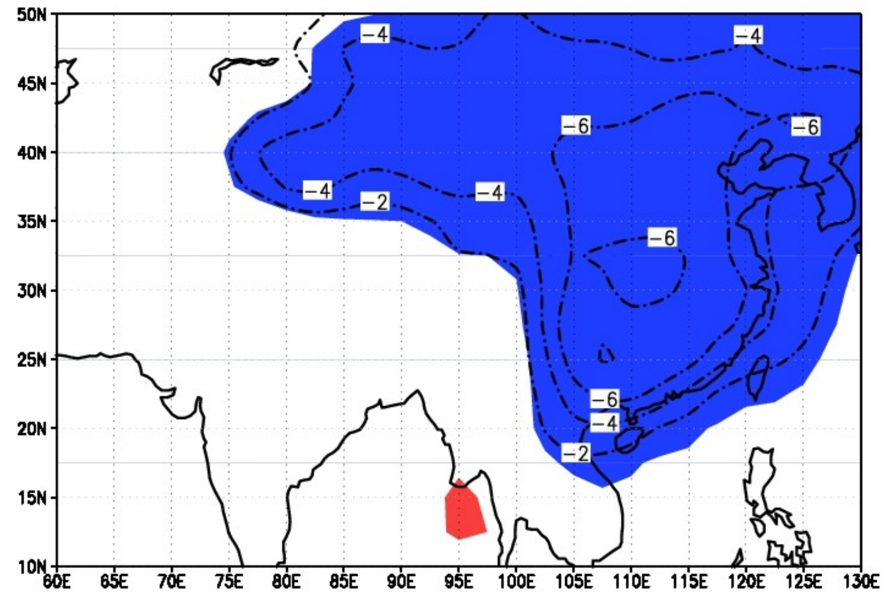
## Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Himalayas

Surface Pressure




Day 2

Surface Temperature



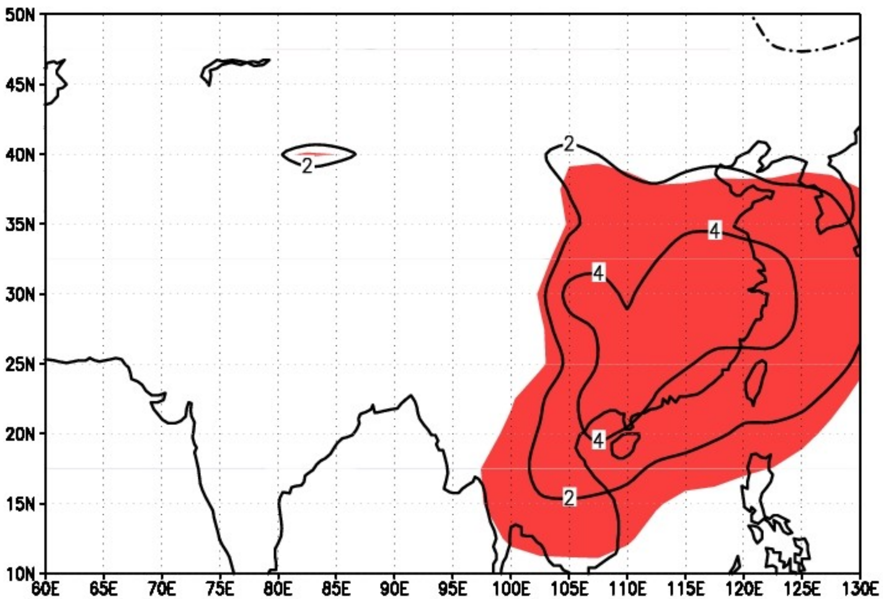

Situation 2 days after :

- Significant high pressure and low temperature in eastern China
- Extends to the subtropics
- Typical of east-asian cold surge

# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

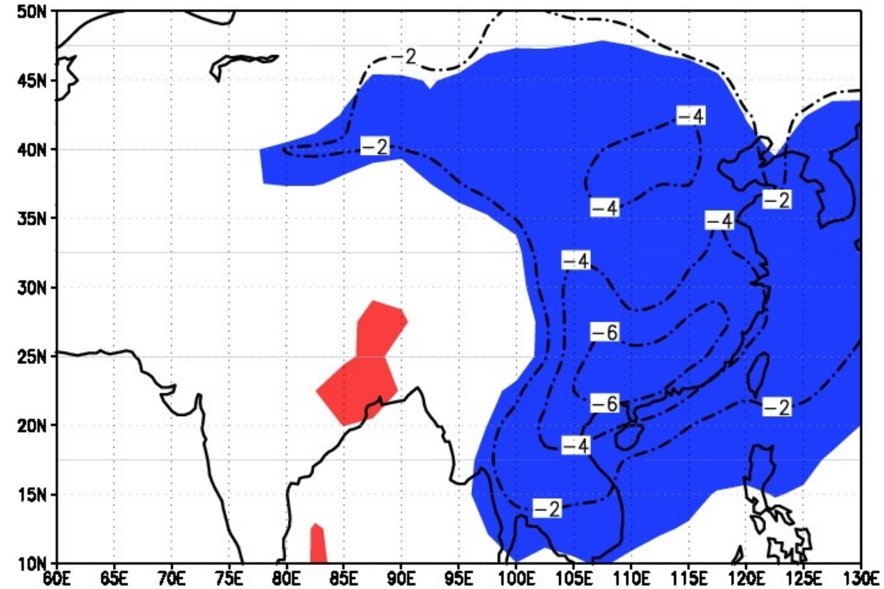
**Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Himalayas**

Surface Pressure




Day 4

Surface Temperature



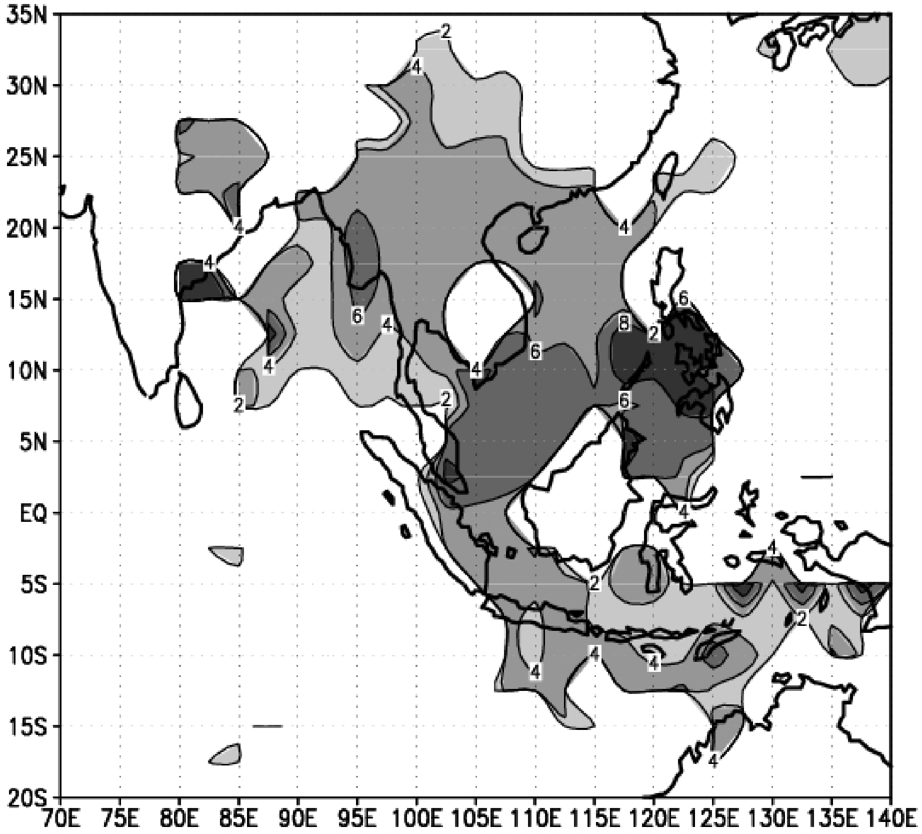

Situation 4 days after :

•Cold surge is mature and strongly affects tropical regions

• Anomalies of surface temperature and surface pressure reach 4 hPa and 6K respectively

# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

## Impact on precipitations over Southern East Asia




*Zones over which the OLR composite keyed on the intraseasonal $T_1$ has a significant minimum between D+2 and D+10 (all shaded zones), and lag at which this maximum is reached*

Issues : Precipitations near mountain ranges
In Models.
Impact of mountain representation
on precipitations in Models

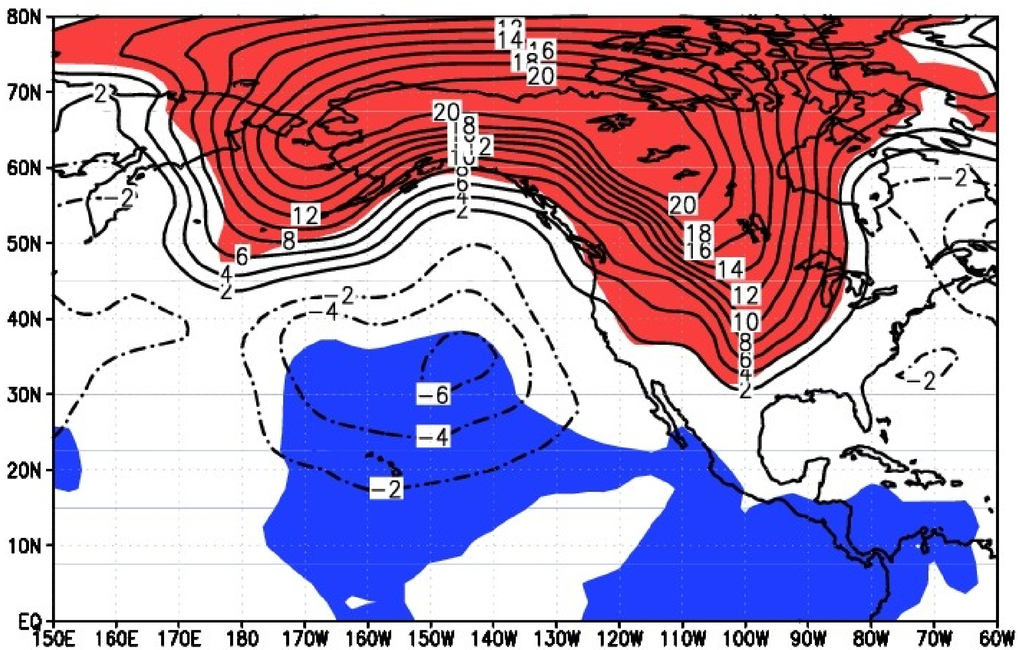
# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

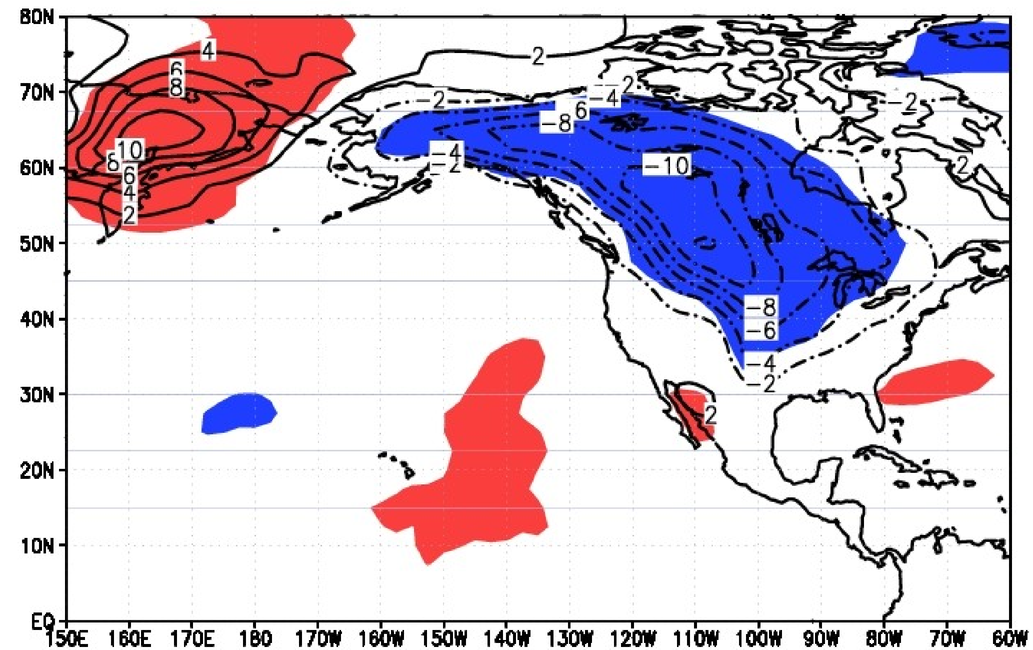
**Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Rockies**

Surface Pressure

Surface Temperature

D0

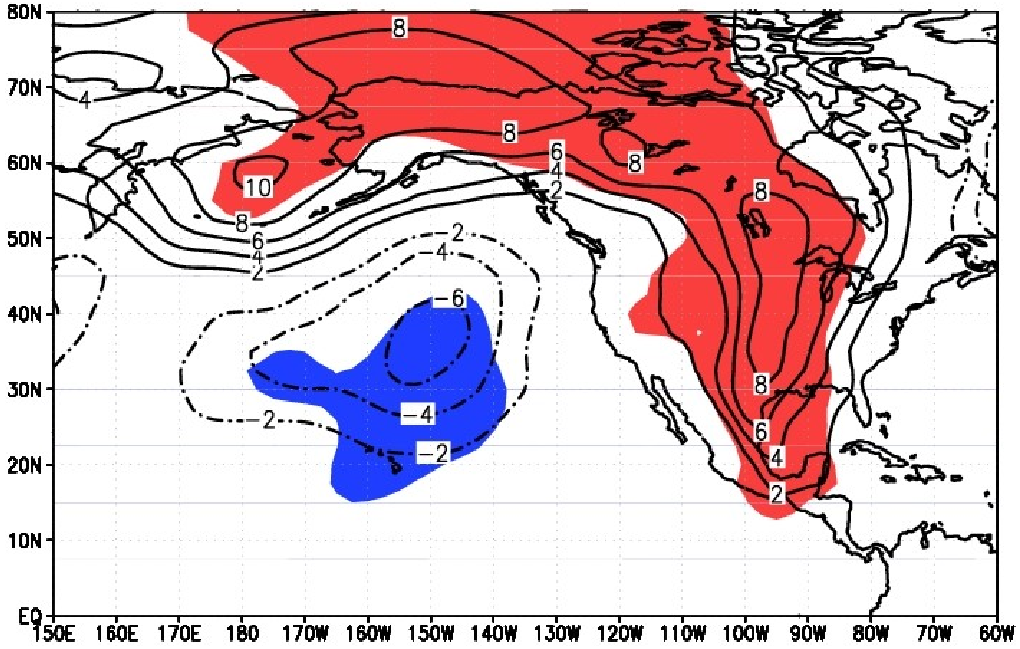


# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

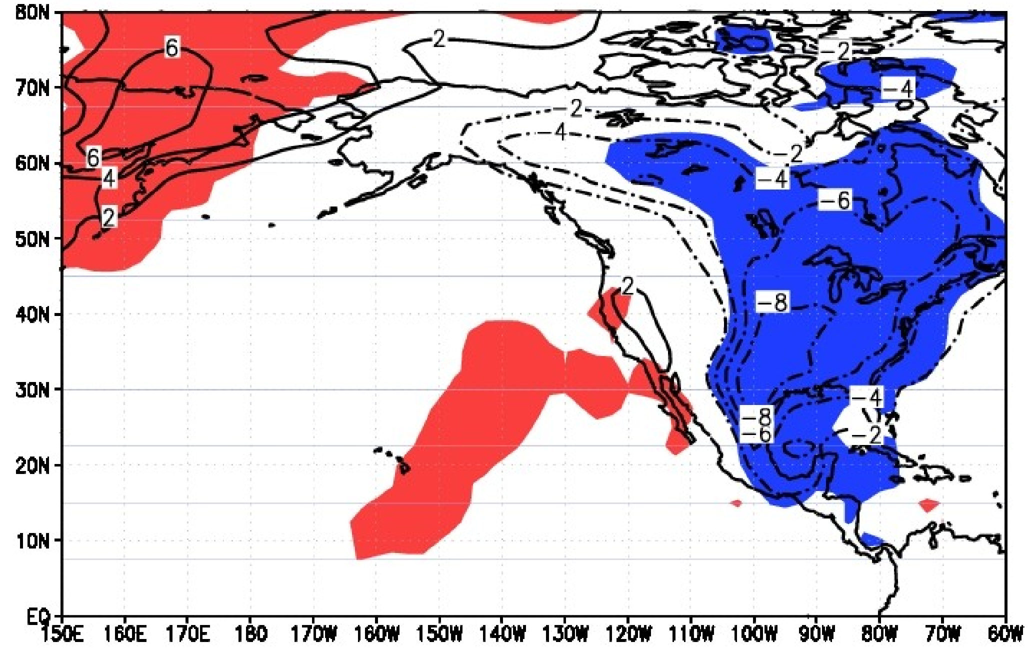
**Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Rockies**

Surface Pressure




D+2

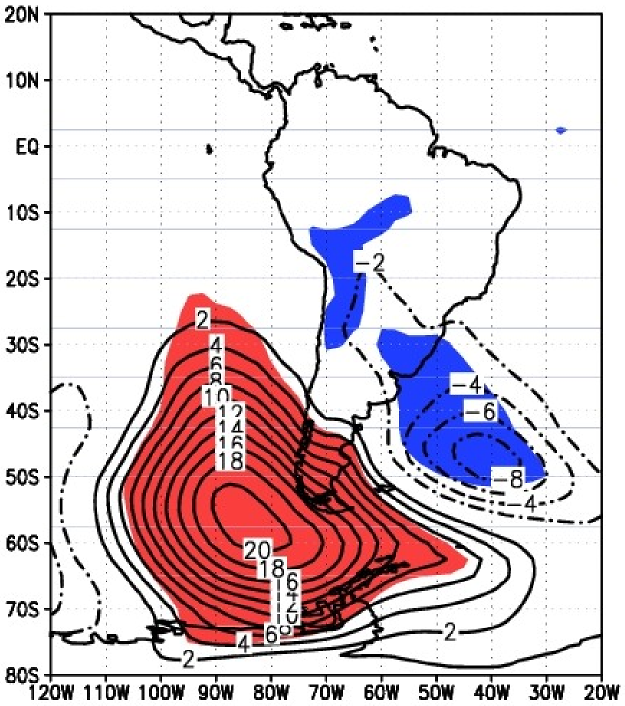
Surface Temperature



# Dynamical impact of mountains on atmospheric flows
# d) Synoptic and planetary scales dynamics

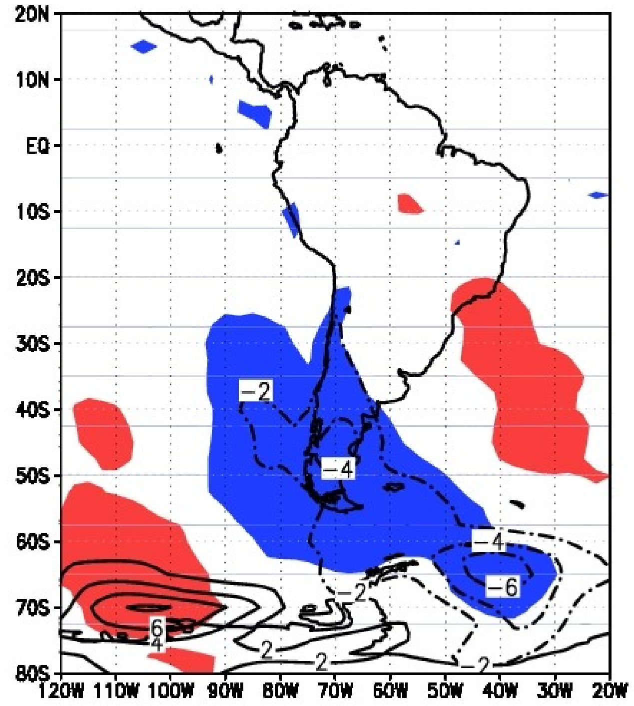
**Composite of anomalies keyed to the anomalous equatorward pressure force felt by the Andes**

Surface Pressure



D-2

Surface Temperature



# Dynamical impact of mountains on atmospheric flows
## d) Synoptic and planetary scales dynamics

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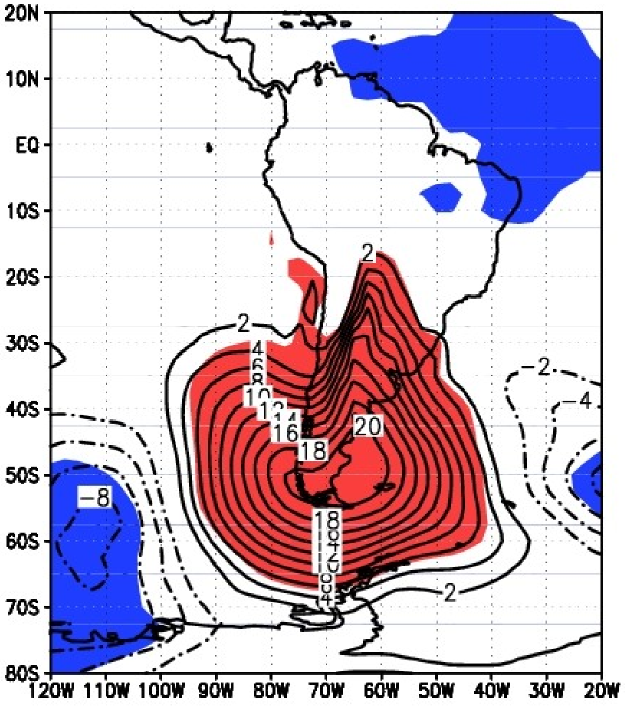
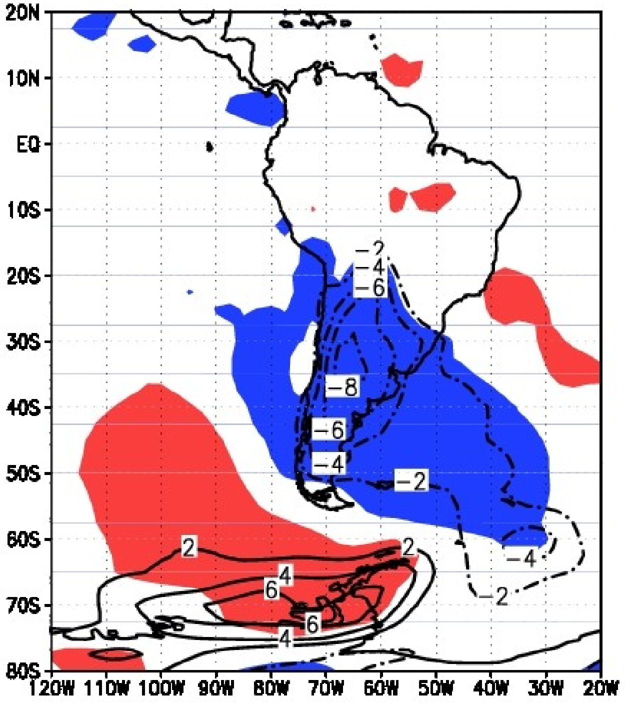
Surface Pressure




D0

Surface Temperature



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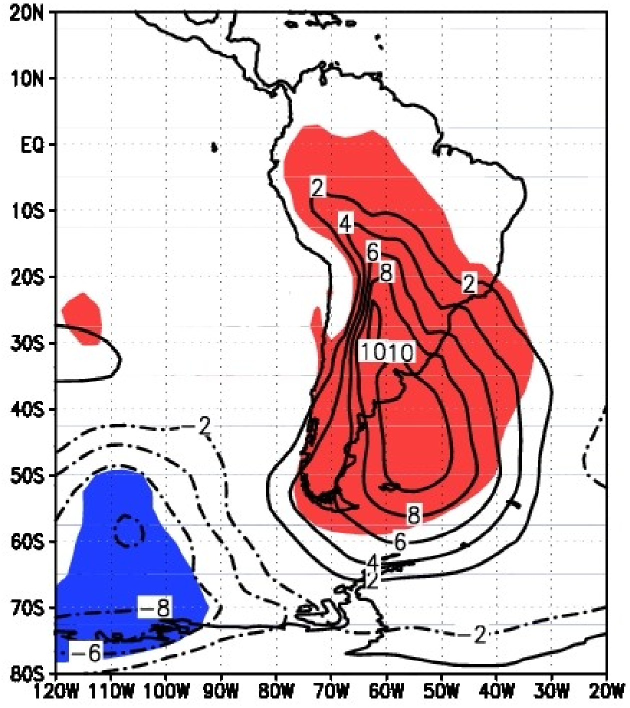
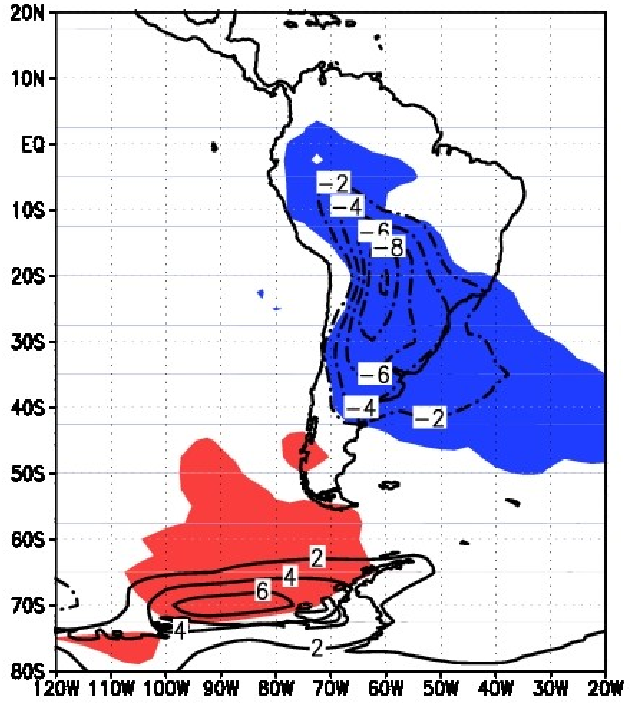



D+2

Surface Temperature



# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

**An argument to enhance vortex stretching over the large scale mountains**

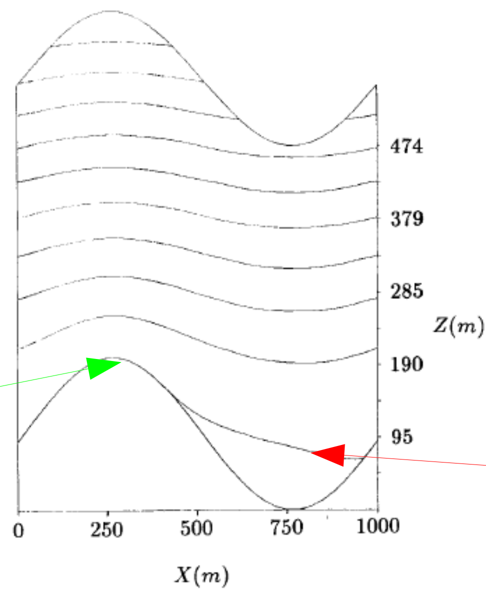
Nonlinear effets for mountains of small horizontal scale: $Fr^{-1} = \frac{N\,d}{U} \ll 1$

Nonlinear dynamics for $S = h_{max}/d \sim 0(1)$

,the slope parameter, it is almost never small!

Streamlines from a 2D Neutral Simulations
From Wood and Mason (QJ 1993)
$S=0.2,\ Fr^{-1}=0$

H(x)




Note the separation streamline

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.

Hydrodynamic « bluff body »drag: $Dr \sim \rho\, C_d \frac{h_{max}}{d} \frac{U|U|}{2}$

(enhanced roughness length in some model)

**If the valley is ventilated!! Otherwise the free atmosphere passes over the valleys and hardly see them (this is still an issue)**

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

**This is the type of dynamics we are talking about**

Neutral or Fast Flows : $Fr^{-1} = \frac{N\,d}{U} \ll 1$

Nonlinear dynamics for $S = h_{max}/d \sim 0(1)$

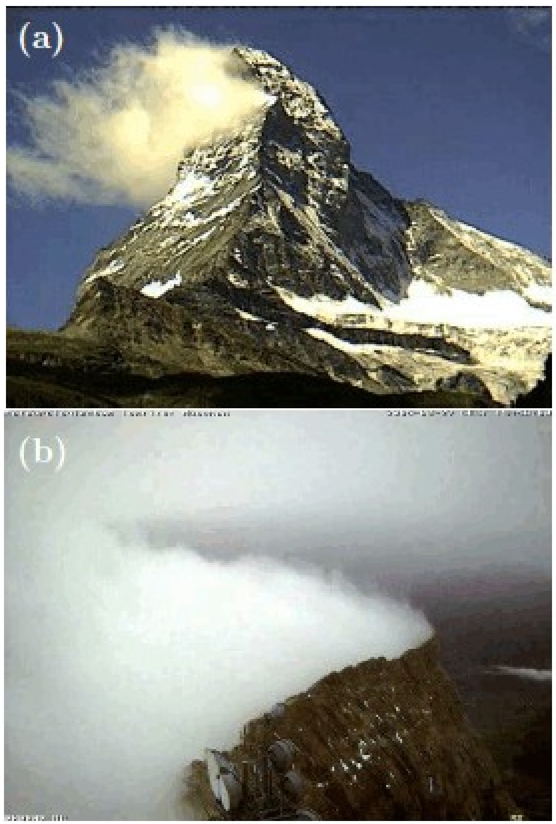
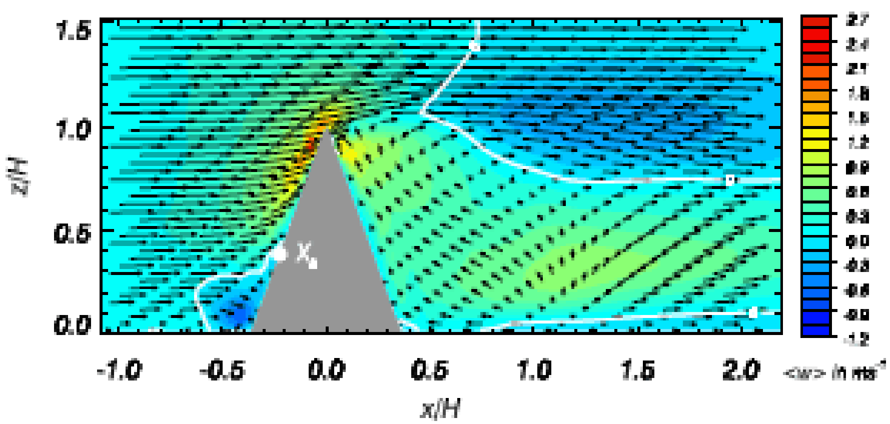



**Figure 1:** *Banner clouds forming leeward of a pyramidal shaped mountain peak or a quasi 2D ridge. (a) Banner cloud at Matterhorn (Switzerland). (b) Banner cloud at Mount Zugspitze (Bavarian Alps). Mean flow from right to left.*

The dynamics at these scales explain the formation of the « banner » clouds alee of elevated and narrow mountain ridges (Reinert and Wirth, BLM 2009)




Large eddy simulation

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

**A parameterization to improve directly the planetary and synopic scales**:

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

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

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

NCEP

No forces

Drag forces

Lift forces

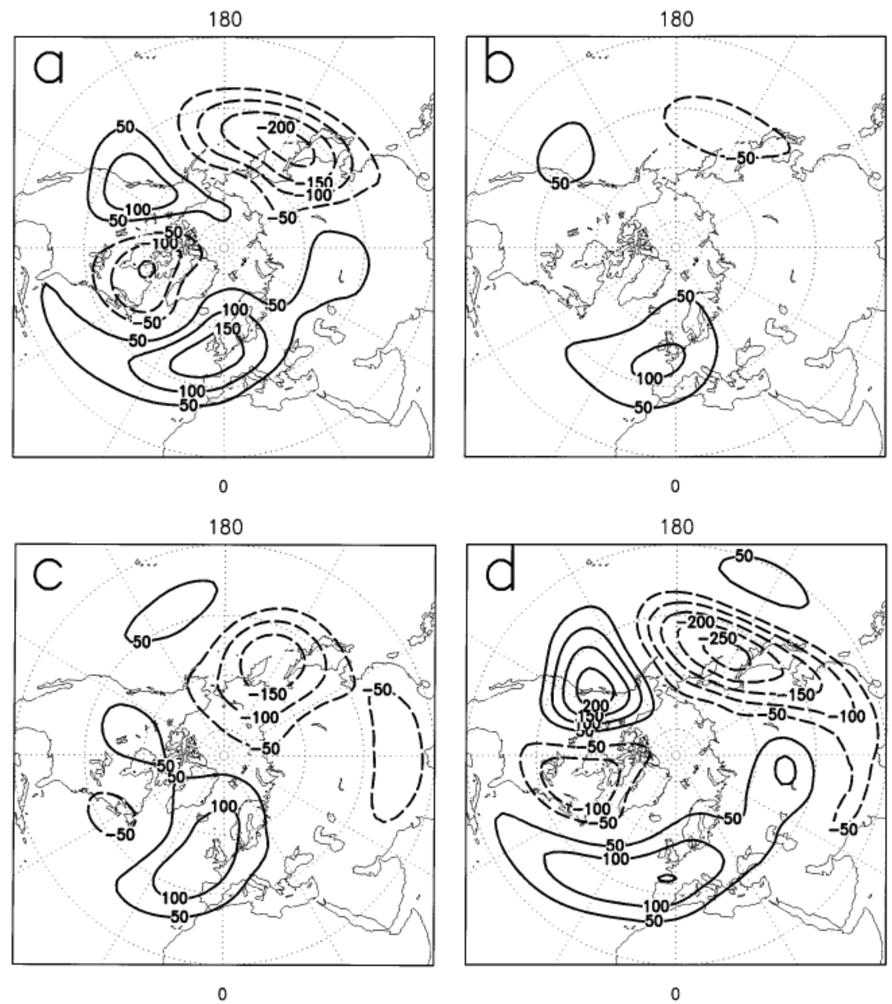
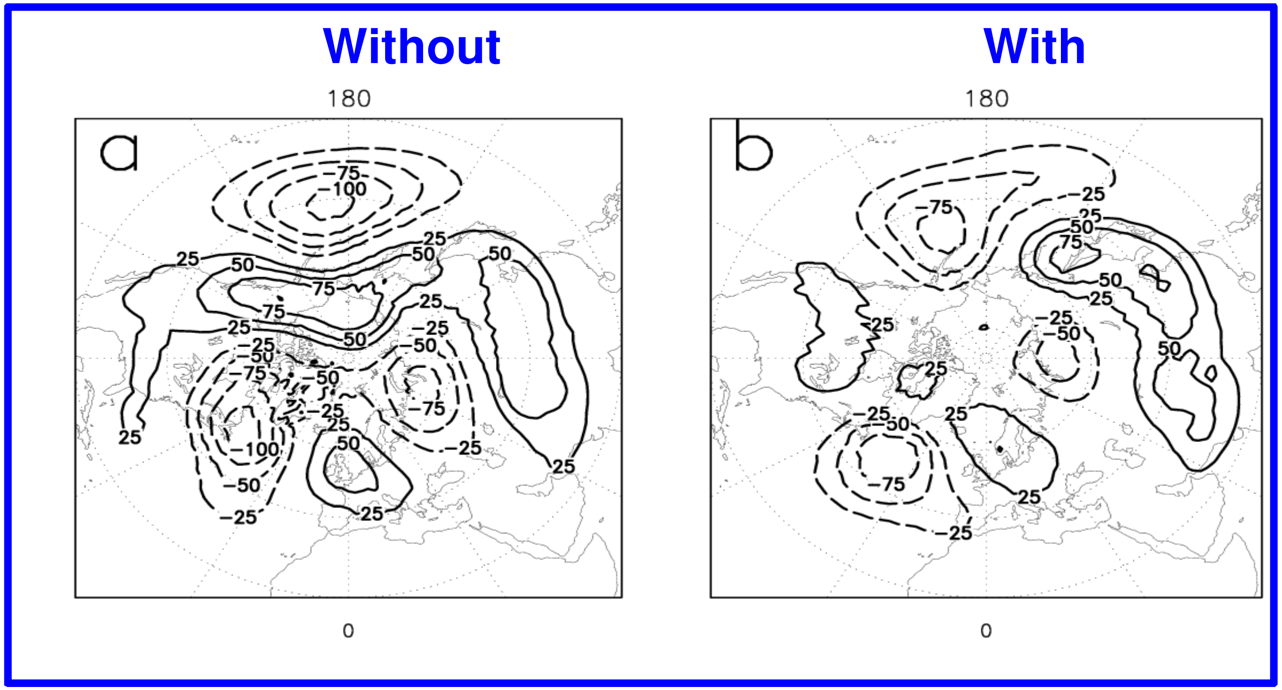



FIG. 3. Anomaly to the zonal mean of the geopotential height at 500 hPa averaged over the winter months (DJF) of the period 1985–90. LMD run with no explicit orography. (a) NMC analysis; (b) LMD no drag, no lift; (c) LMD low drag only; (d) LMD low lift only. Zero line not shown; negative values are dashed.

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

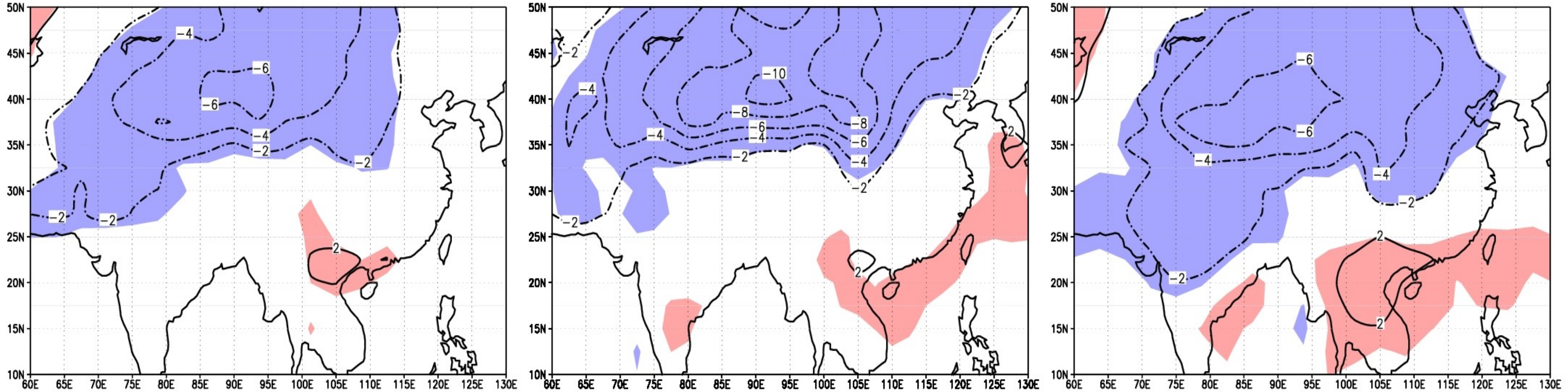
Simulation with mean explicit orography without and with the subgrid scale orographic drag scheme including enhanced lift

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



# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

DO



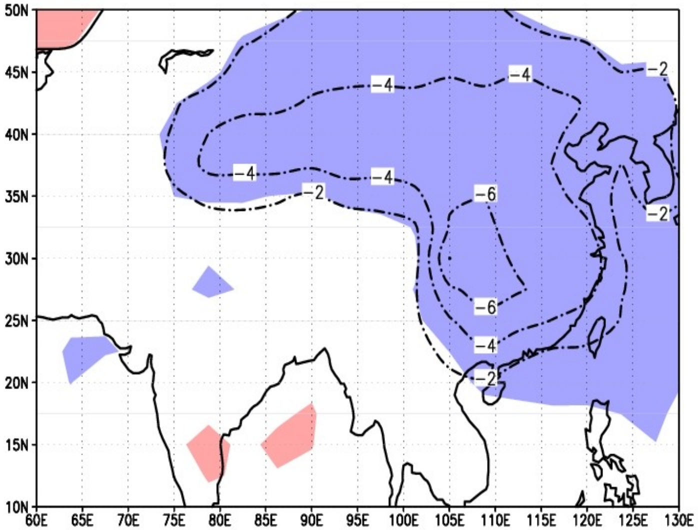

*Reference run* *NCEP reanalysis* *Without SSO param*

*Composites of surface temperature anomaly keyed on the total Equatorial Torque (LMDz) and on the Equatorial Mountain Torque (NCEP)*

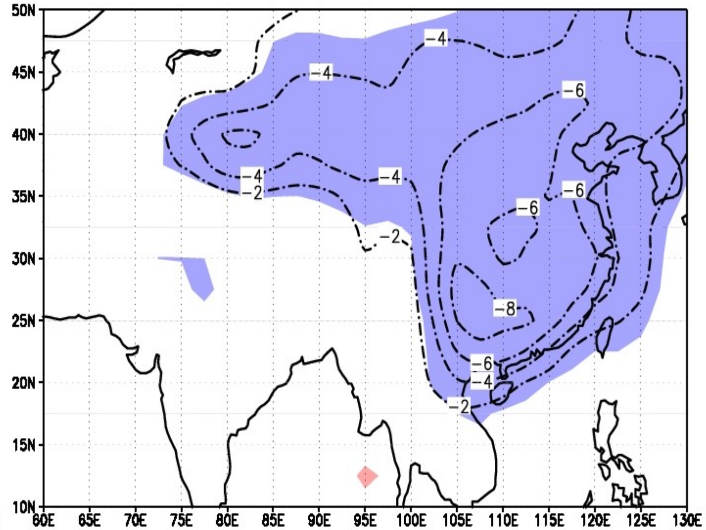
**Issue : does the same imoprovement occurs for the south-American cold surges?**

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

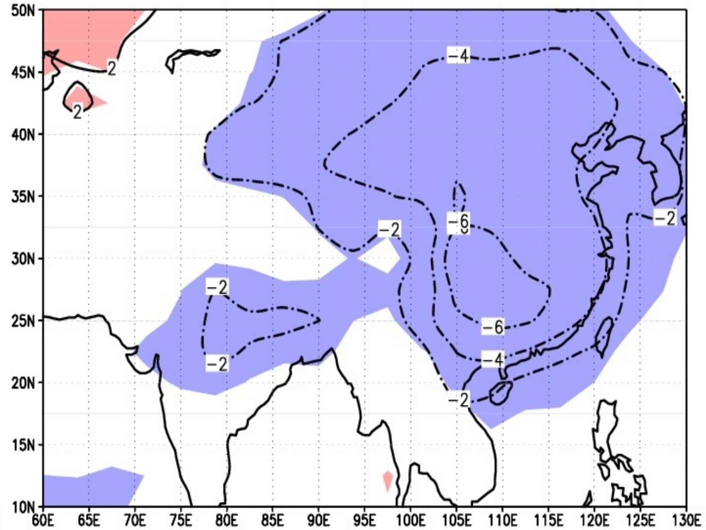
D+2




*Reference run*




*NCEP reanalysis*



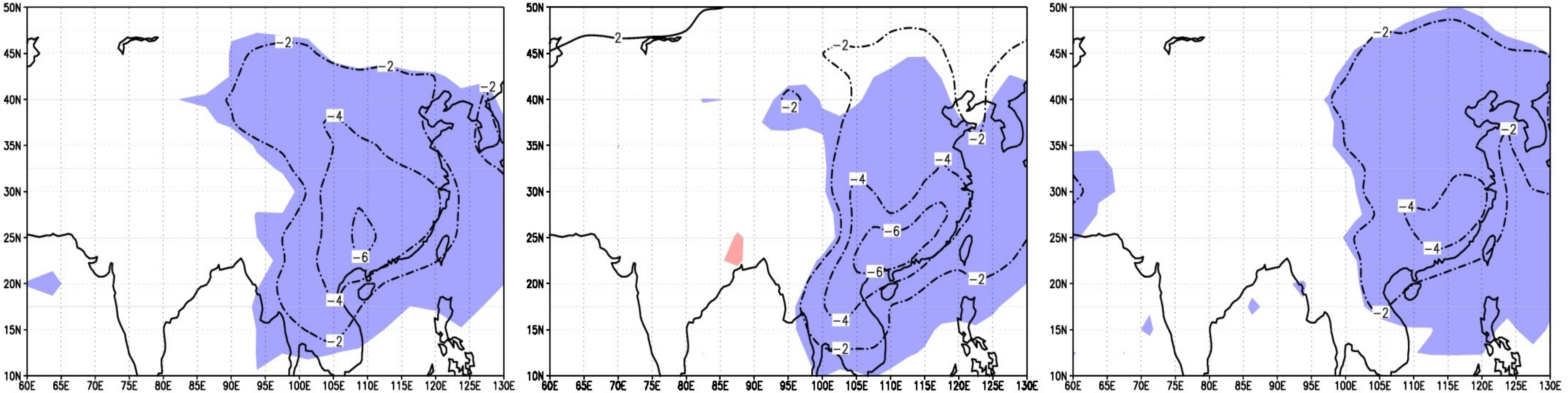

*Without SSO param*

*Composites of surface temperature anomaly keyed on the total Equatorial Torque (LMDz) and on the Equatorial Mountain Torque (NCEP)*

**Issue : does the same imoprovement occurs for the south-American cold surges?**

# Dynamical impact of mountains on atmospheric flows
## e) Improving the synoptic and planetary scales

D+4



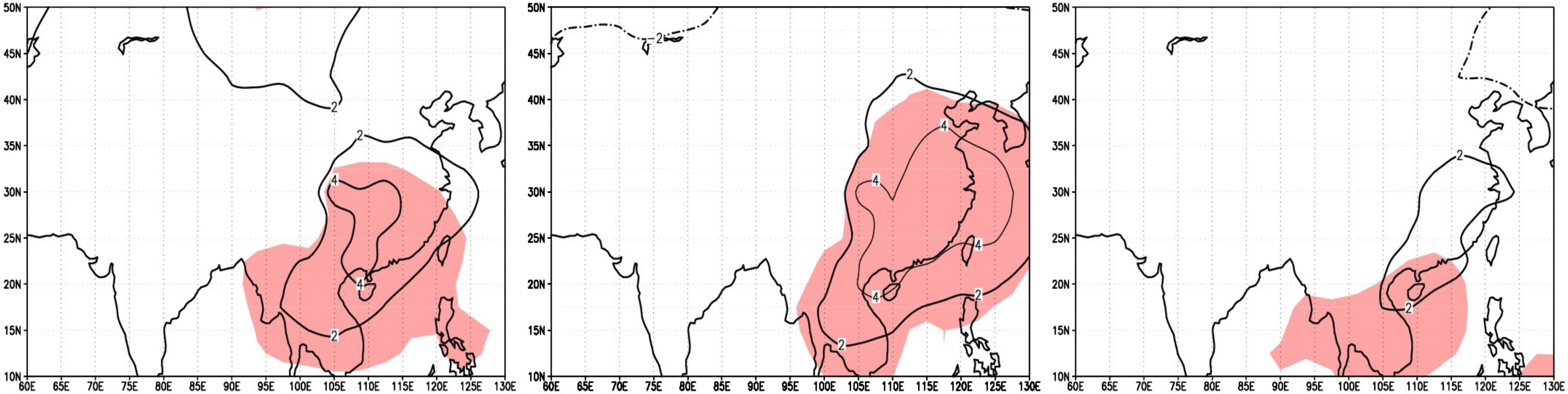

*Reference run* *NCEP reanalysis* *Without SSO param*

*Composites of surface temperature anomaly keyed on the total Equatorial Torque (LMDz) and on the Equatorial Mountain Torque (NCEP)*

**Issue : does the same imoprovement occurs for the south-American cold surges?**

# Dynamical impact of mountains on atmospheric flows
# e) Improving the synoptic and planetary scales

D+4



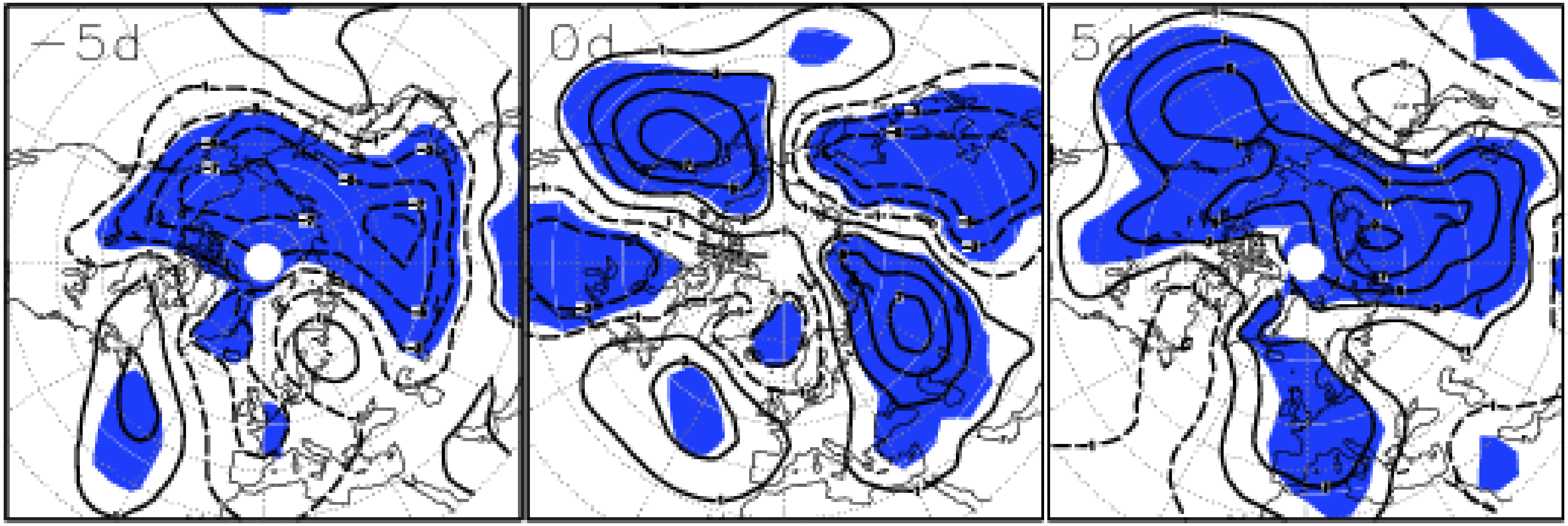

*Reference run* *NCEP reanalysis* *Without SSO param*

*Composites of surface pressure anomaly keyed on the total Equatorial Torque (LMDz) and on the Equatorial Mountain Torque (NCEP)*

**Issue : does the same imoprovement occurs for the south-American cold surges?**

# Dynamical impact of mountains on atmospheric flows
# f) Planetary scales dynamics

Interaction between a s=2-3 planetary wave in surface pressure and the large scale mountains. See the global deceleration within 10 days associated with the negative mountain torque produced by the wave.



# Dynamical impact of mountains on atmospheric flows
## g) Summary of issues

Theory (and or mesoscale modelling): trapped lee waves and PBL, interaction between valley weather and the large scale weather ?

SSO parameterization : Directionnal effects, trapped waves, stochastic formulation

Impacts :

- On local weather events like cold surges and (most of all) precipitations !
- On the southern hemisphere stratosphere, rôle of the isolated islands?
- In a changing climate

Analysis of the influence of mountains in the on-going CMIP simulations ? In order to list the errors to be corrected ?

Observations (?)

Mesoscale modelling approach (?)