Some orographic effects on the large-scale circulation

1) The mid 1990's
   Enveloppe orography, the Pyrex campain and theoretical progresses

2) Impacts and limitations of the Lott & Miller (1997) scheme.
   drag versus lift forces

3) Mountain torques and low-frequency variability
   Observational evidences that mountain forces affect LFV

4) Mountain torques and synoptic scale flows
   Observational and model evidences that lift forces matters.

5) Perspectives

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

The envelope orography
(Wallace, Tibaldi, and Simmons 1983)

Case I

Case II

500mb Geopotential

7-10 day error

7-10 day error

Mean orography

Envelope orography

Needed to be replaced in the 1990's (data assimilation, radiation problems...)

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

The Pyrénées Experiment (Bougeault et al. 1990)

The central transect of PYREX

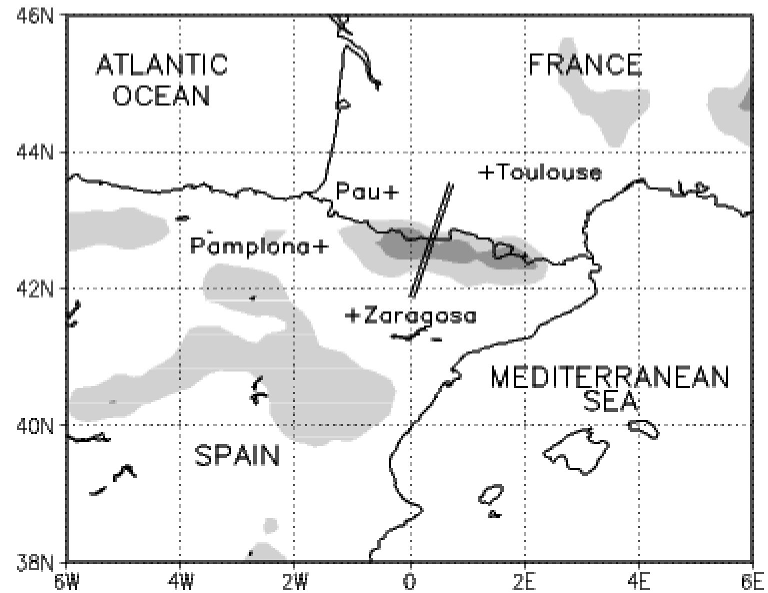
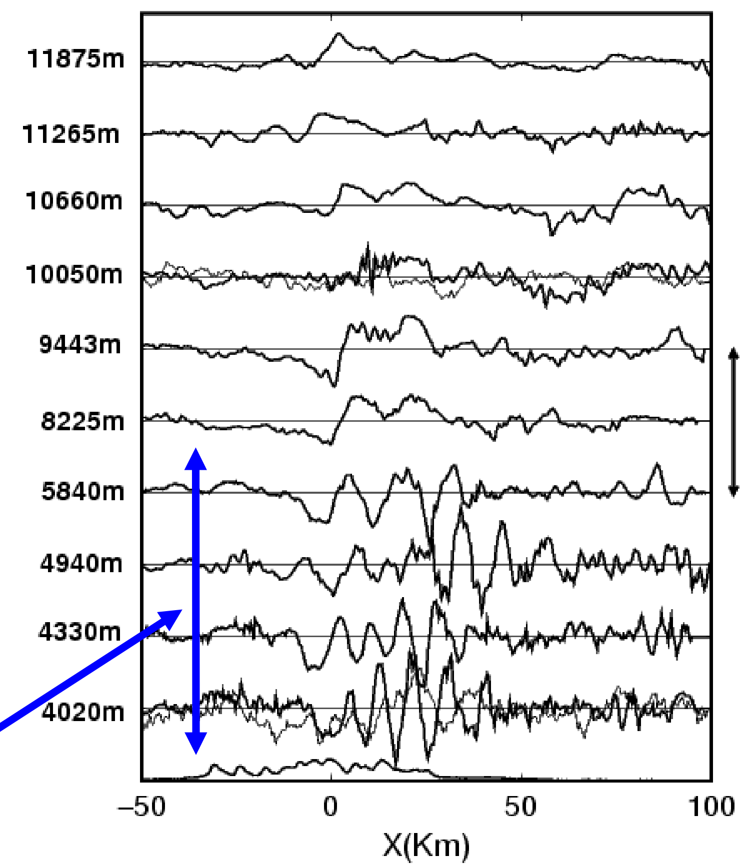


Figure 1: Smoothed terrain elevation and PYREX data used. + denotes the location of the high resolution soundings. The two thick lines indicate the airplane pathes during the IOP 3. The light and dark shaded areas denote terrain elevation above 1000m and 1500m respectively.

Mountain waves seen by 10 aircrafts flights above the transect



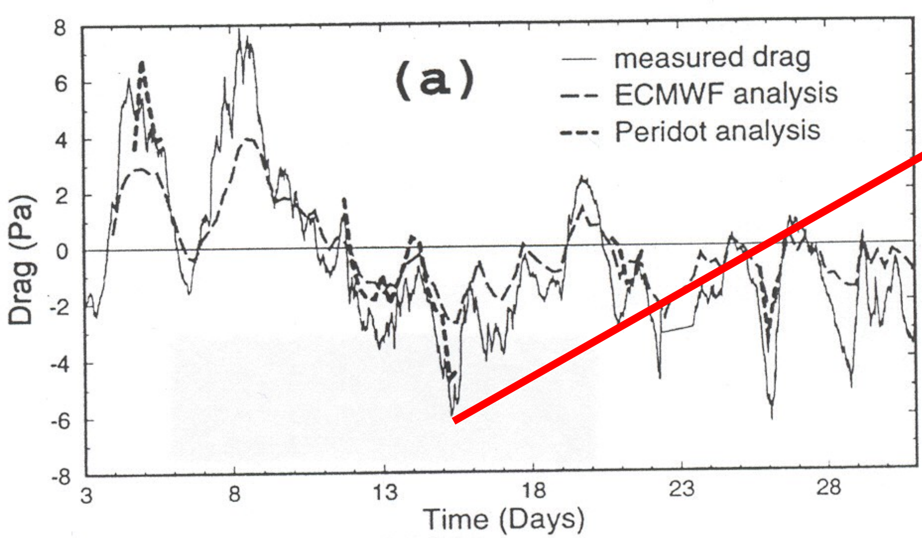
Trapped waves
(Georgelin et Lott 2001)

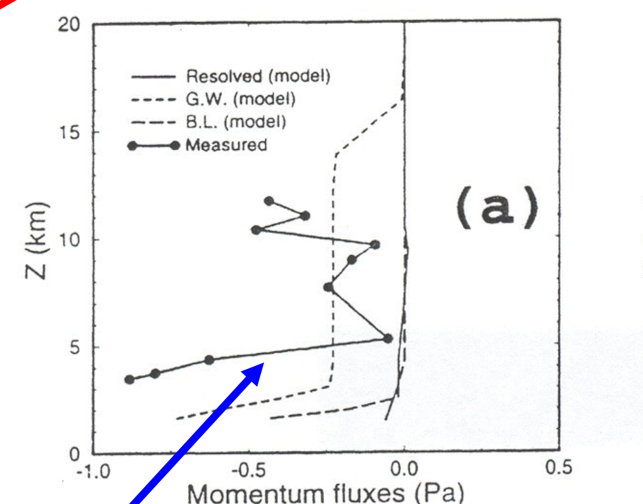
Figure 2: Observed vertical velocities from different Aircraft legs. 15 October 1990 around 6 UTC. Thick lower curve represent the Pyrénées, the thin curve at the Z=4km and Z=10km are red noises surrogate with characteristics adapted to the measured vertical velocity at that levels.

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

Momentum flux measured by
the aircrafts aloft the transect, the
15 October 1990

Surface pressure drag
measured by micro barographs located
along the transect (0ctobre 1990)
Comparison with ECMWF and Pyrex analysis (Lott 1995)





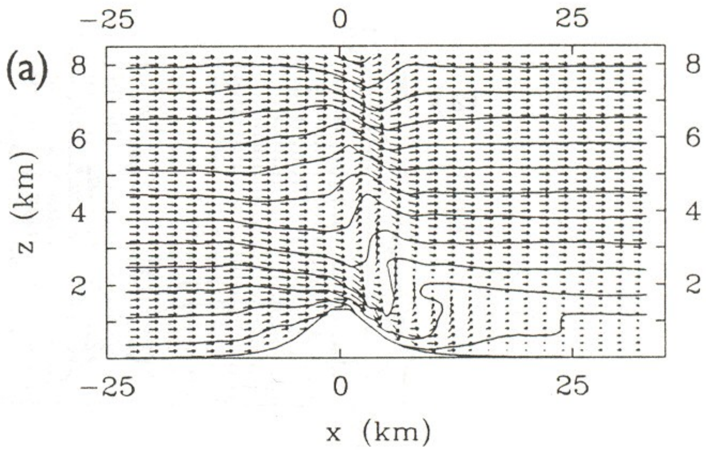
Effect of the trapped lee waves
(Georgelin et Lott 2001)

Note that the momentum flux aloft is one order
of magnitude smaller than the surface drag.

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

Mountain Waves (non-linear 3D effects from Miranda and James (1992))

U=10m/s, N=0.01s^{-1}, h_{max}~1km

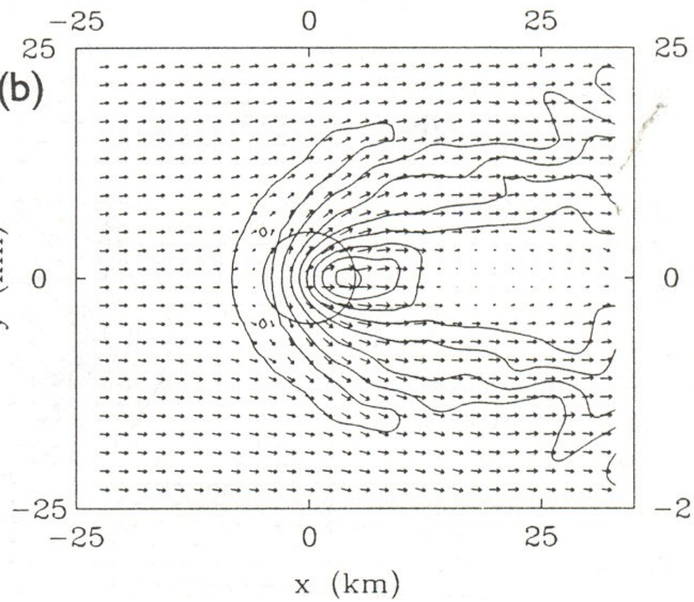


Note:

The fact that the isentropic surfaces are almost vertical dowstream and at low level: this indicates wave breaking

The strong “Foehn” downstream

The residual gravity waves propagating aloft



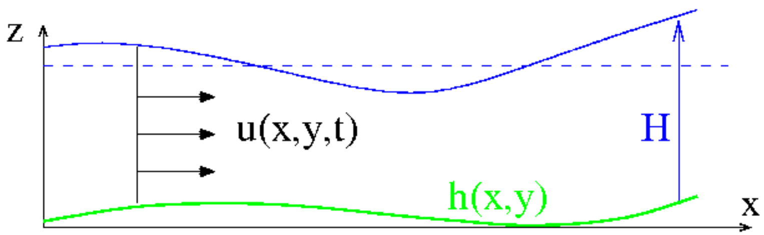
The apparent deceleration of the low-level winds far dowstream of the obstacle.

Question:

How can we quantify the reversible motion (due to the presence of the wave) from the irreversible effects that are due to wave breaking?

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

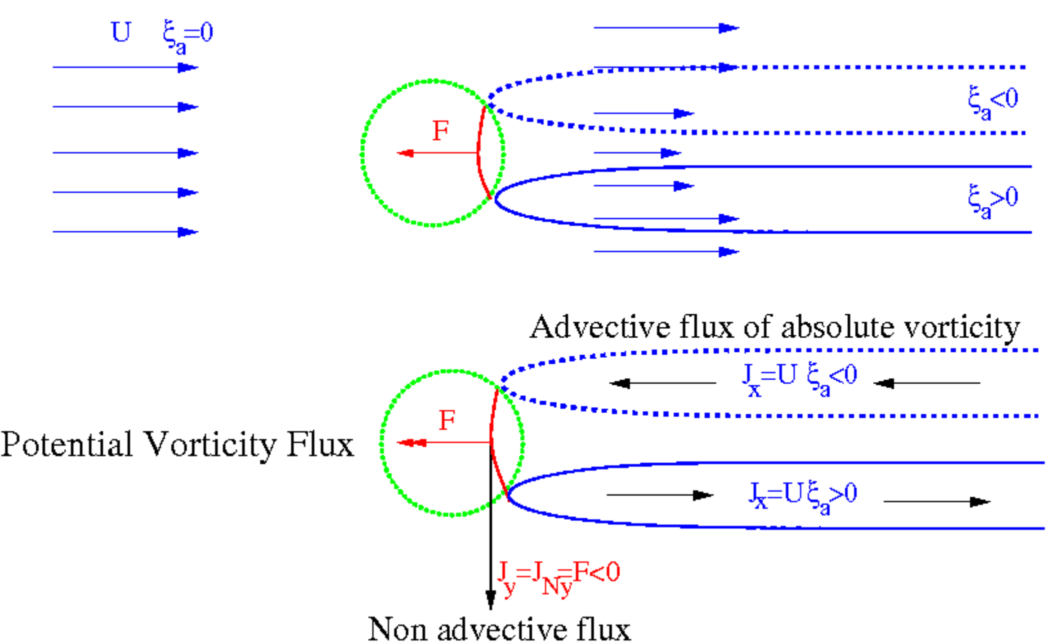
Hydraulic Jumps in Shallow water

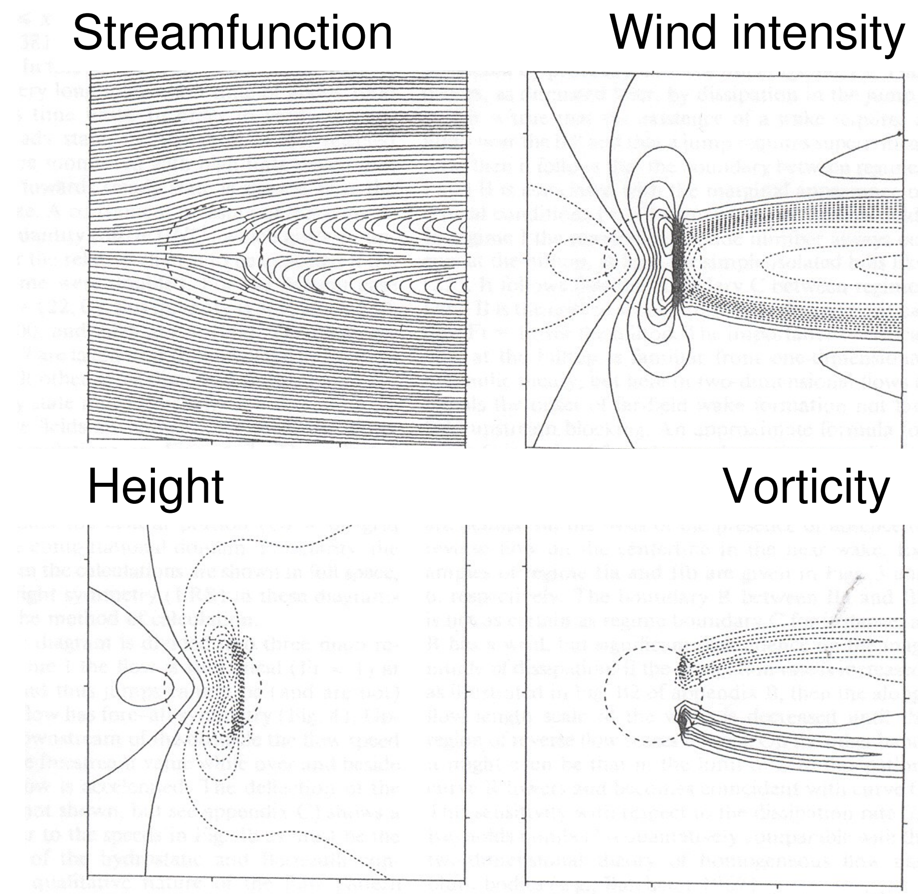


Equation for the absolute vorticity :

$$\frac{\partial \xi_a}{\partial t}+\vec{\nabla}\cdot\left(\vec{u}\,\xi_a+\vec{J}_N\right)=0$$

$\vec{J}_N$: Non advective flux perpendicular to the drag.





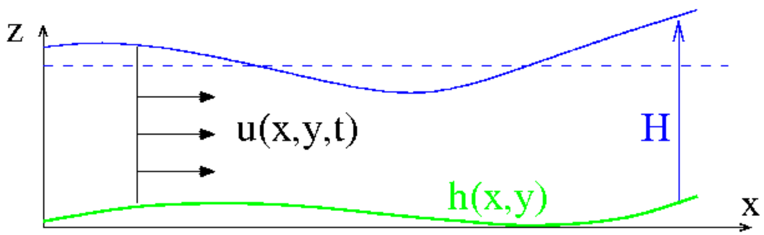
Schar et Smith 1992

This is related to PV production :

$$\frac{D}{Dt}\frac{\xi_a}{H}=-\frac{\vec{\nabla}\cdot\vec{J}_N}{H}$$

Some orographic effects on the large-scale circulation, F. Lott
1) Envelope orography, the Pyrex campain and theoretical progresses

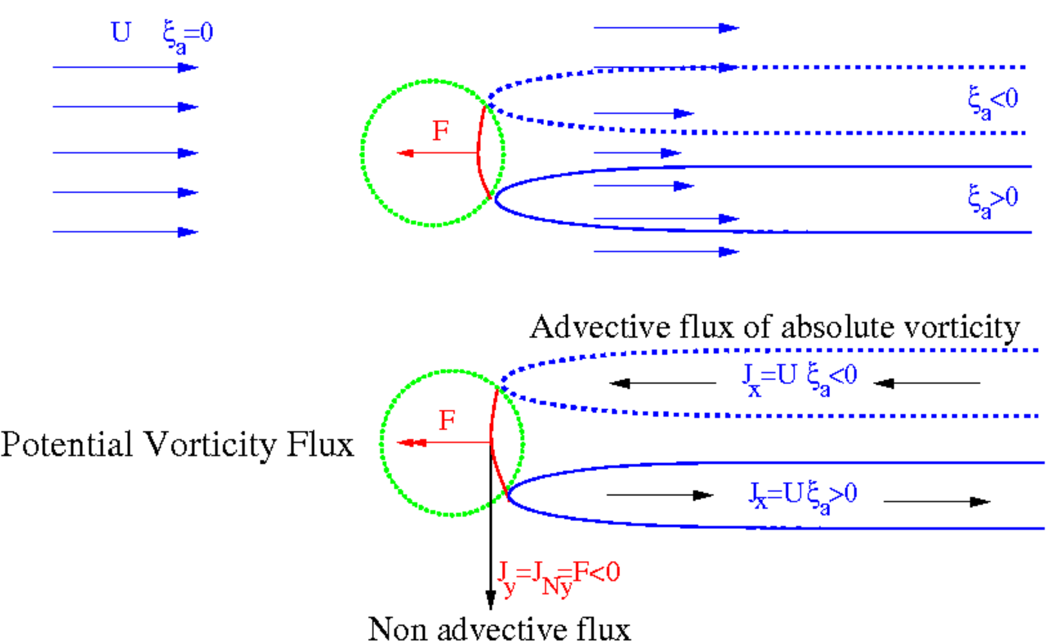
Hydraulic Jumps in Shallow water

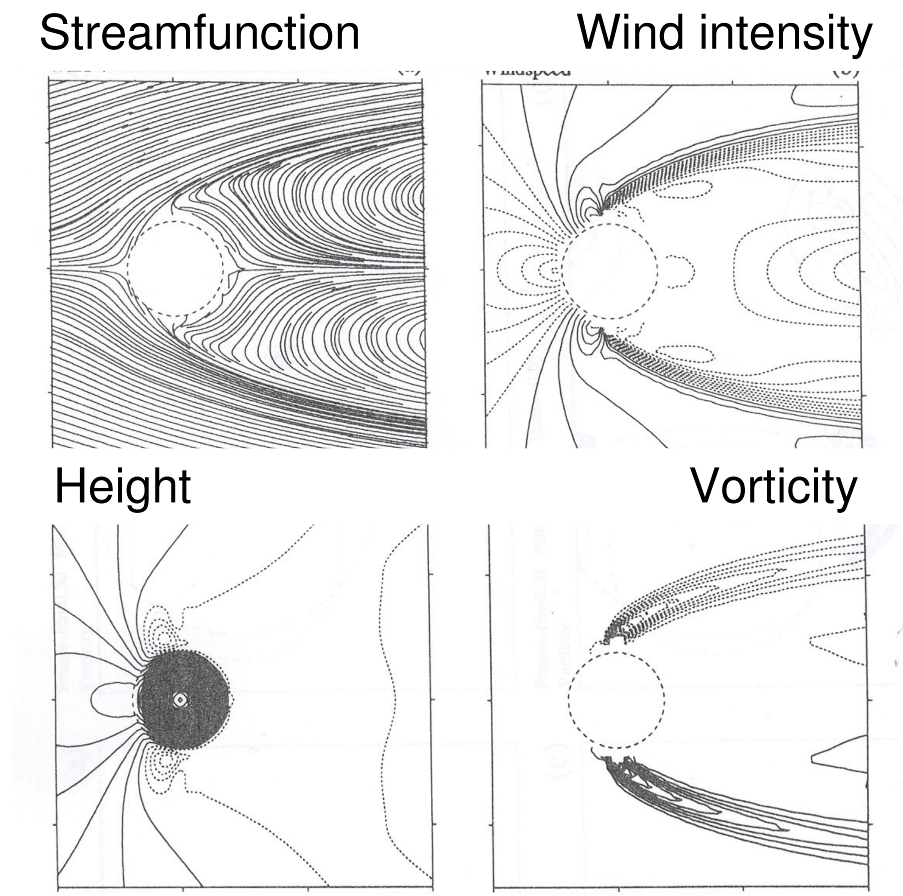


Equation for the absolute vorticity :

$$\frac{\partial \xi_a}{\partial t} + \vec{\nabla} \cdot \left(\vec{u}\, \xi_a + \vec{J}_N \right) = 0$$

$\vec{J}_N$: Non advective flux perpendicular to the drag



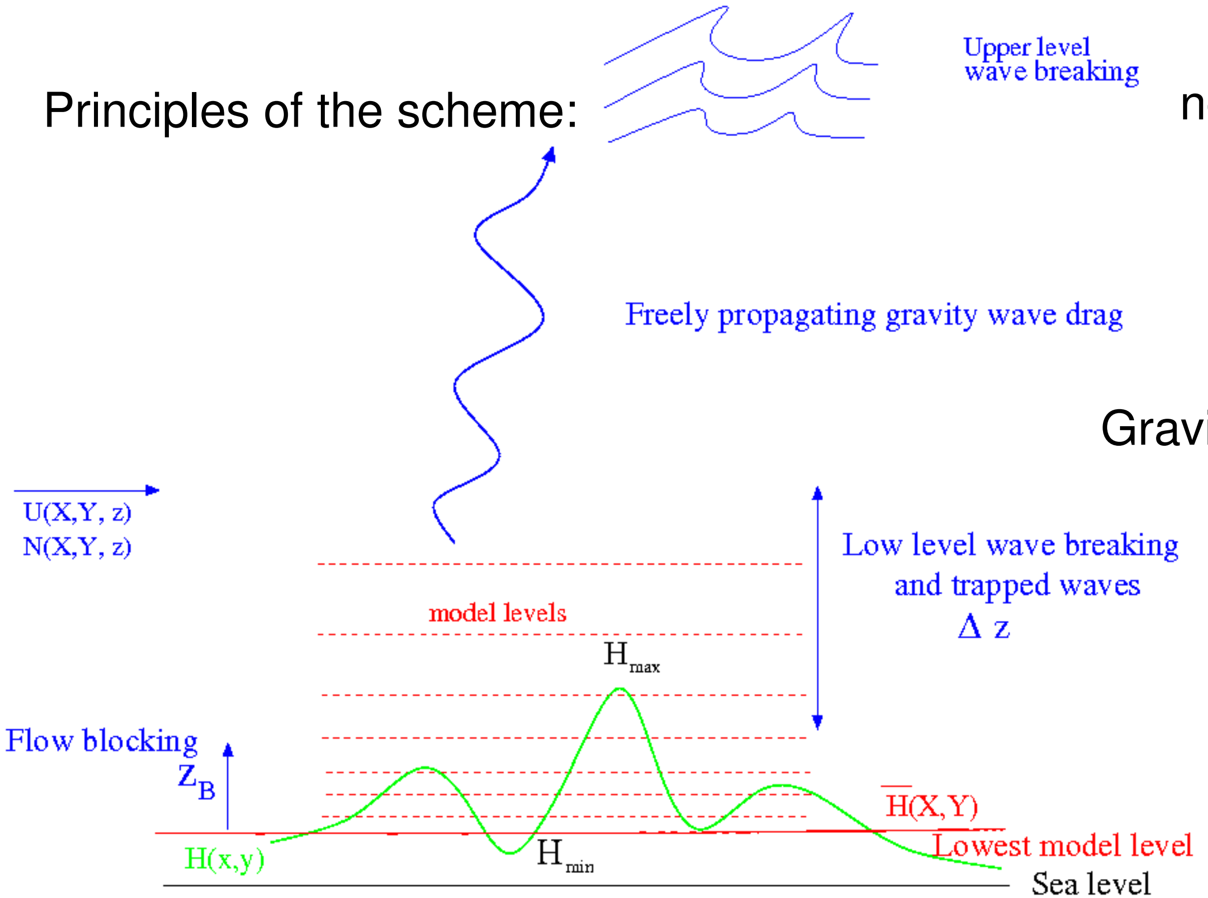


Schar et Smith 1992

This view of a fluid force producing a flux of PV can well be applied when the obstacle pierces the free surface

2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

Principles of the scheme:



The scheme relies on few tunable non-dimensional parameters, all of Order 1

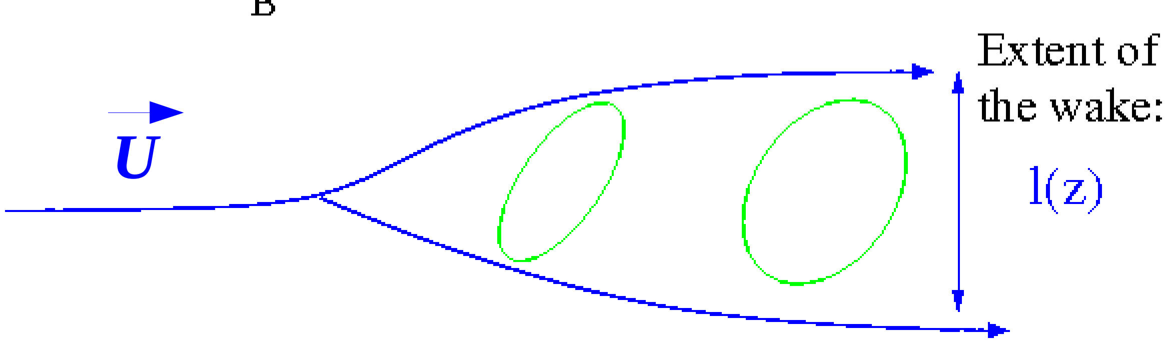
Breaking based on a total Richardson number criteria (***Ric***):

Gravity wave drag (***G***) $\rho\, G\, N\, U\, (H_{SSO} - Z_B)^2$

With directional effects and all SSO parameters calculated !
(Baines and Palmer 1990)

Flow blocking ($\boldsymbol{H_{NC}}$) $\int_{Z_B}^{H_{max}} \frac{N}{U}\, dz < H_{NC}$

Below Z_B



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

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

2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

At a truncature T106, the SSO drag scheme makes up the total drag due to the Pyrénées (the resolution is too coarse to see this mountain explicitely).
At T213, operational in 1997, the parametererized drag also made up well the differences between the explicit model drag and the measured (PYREX) drag

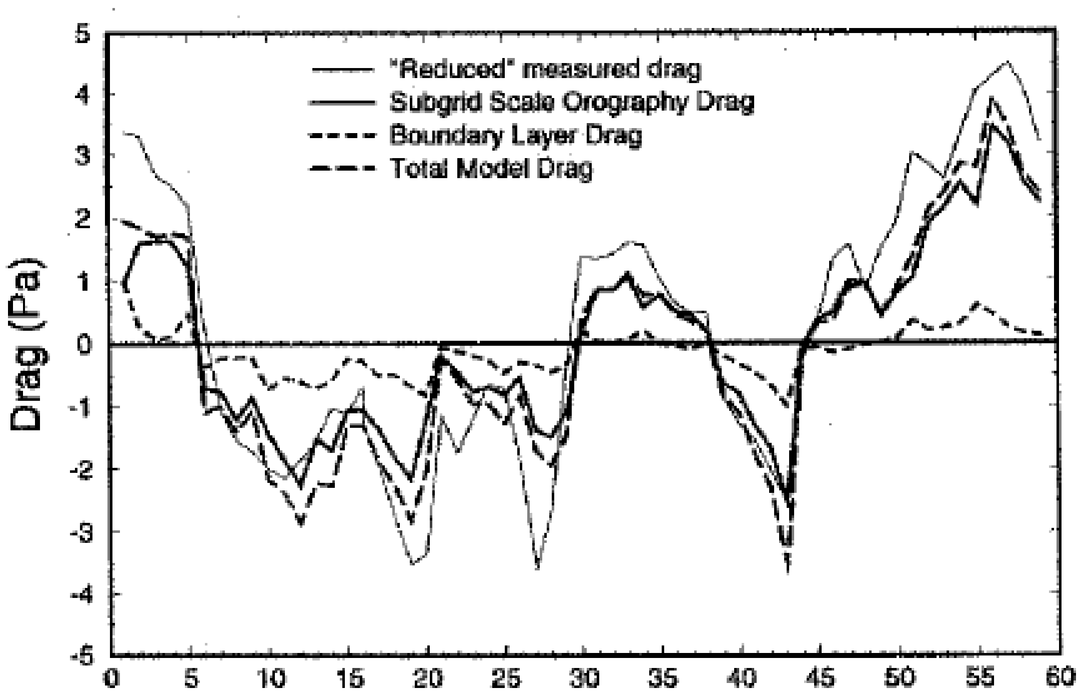
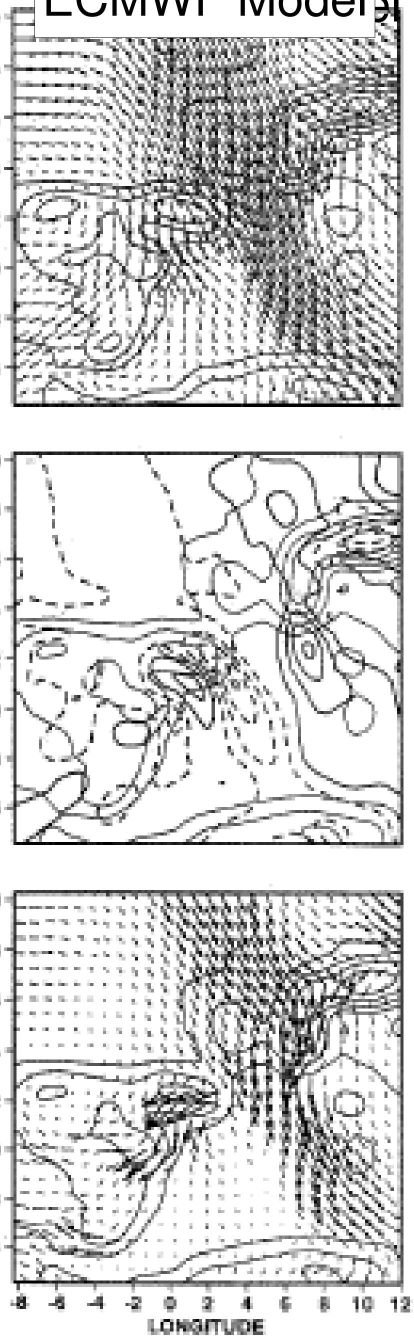


Figure 8. T106 forecasts: ECMWF model with mean orography and the new subgrid-scale orographic drag scheme. Parametrized mountain drags during PYREX. The comparison is limited to the 60 PIO cases defined in the text.

The scheme also improved the ECMWF forecast performances in terms of score, ect...

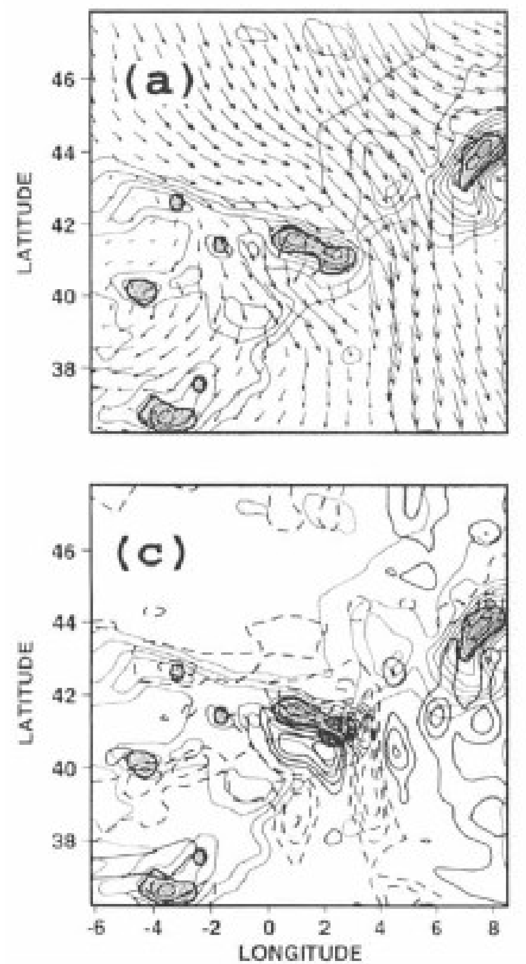
Some orographic effects on the large-scale circulation, F. Lott
2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

ECMWF Model

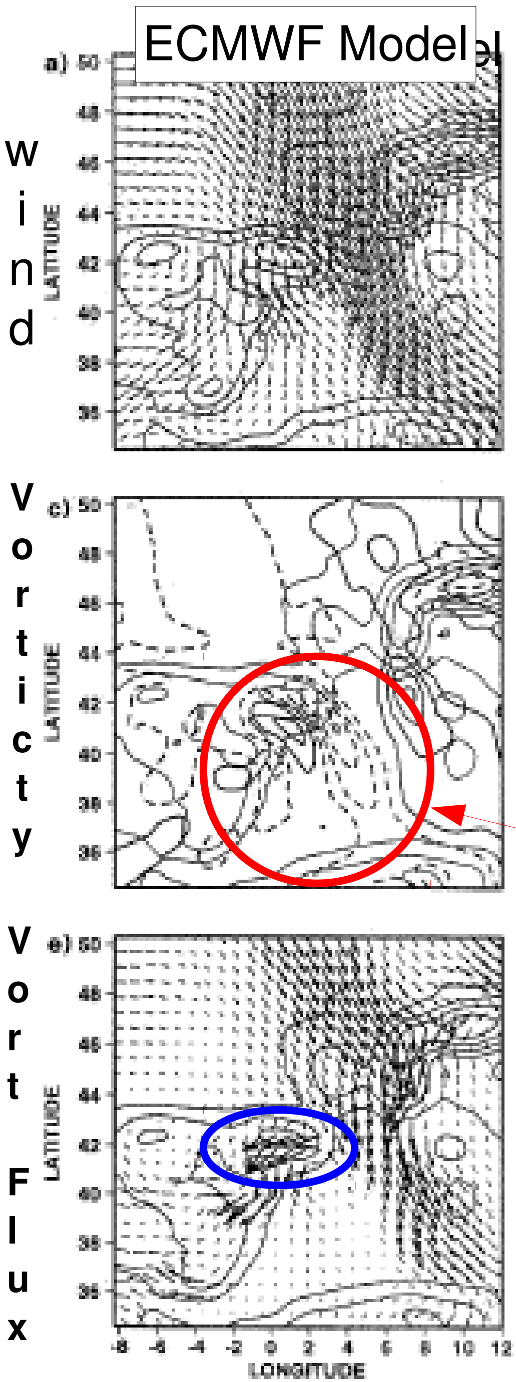


The effect of the low level drag is to produce a low level wake, quite in agreementwith the higher resolutions analysis (Lott & Miller 1997)

θ=297K, 15 Nov 1990



Some orographic effects on the large-scale circulation, F. Lott
2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces



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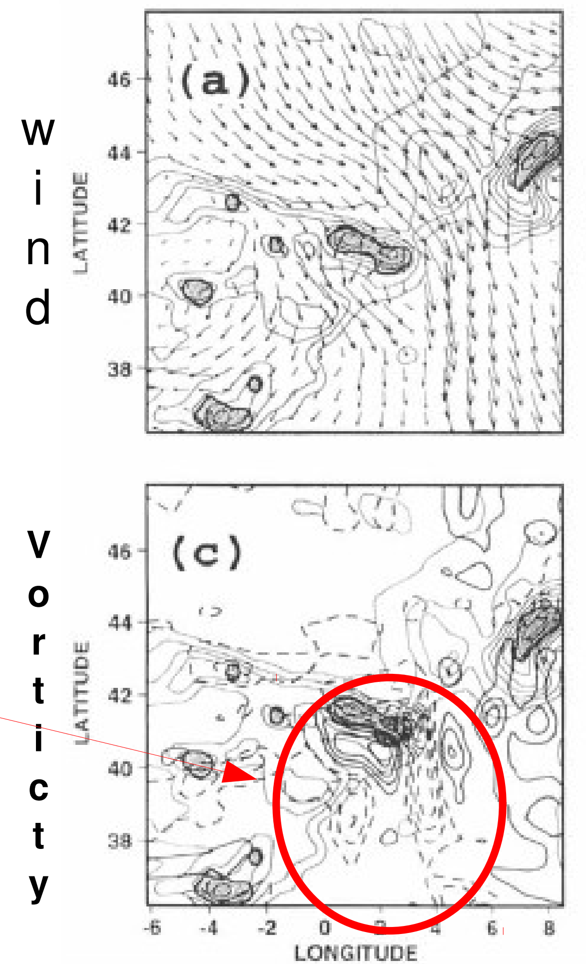


Non-advective PV flux due to low level drag

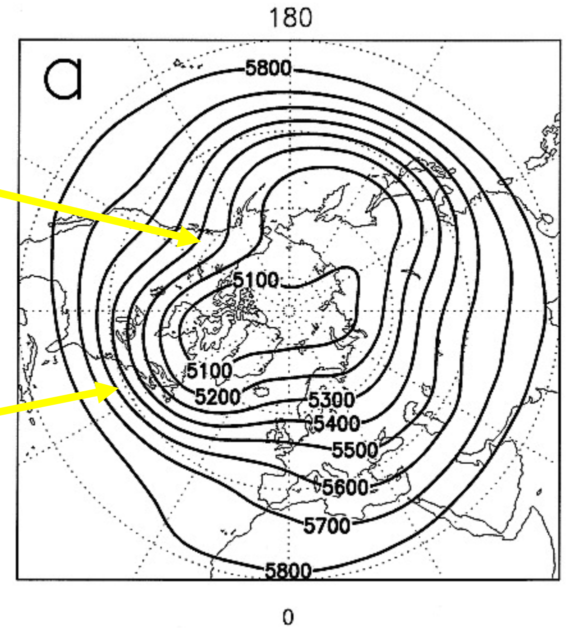
The scheme also improved the ECMWF forecast performances in terms of score, ect...

Some orographic effects on the large-scale circulation, F. Lott
2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

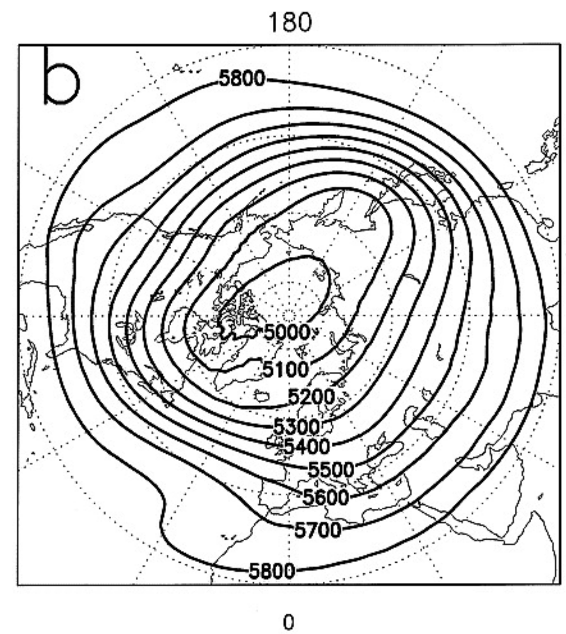
Although the Lott and Miller (1997) SSO drag scheme improve the performances of the ECMWF forecasts (e.g.few days simulations), it does not improve much the structure of the steady planetary waves in climate simulations.

Ridges (ξ<0)

Troughs (ξ>0)



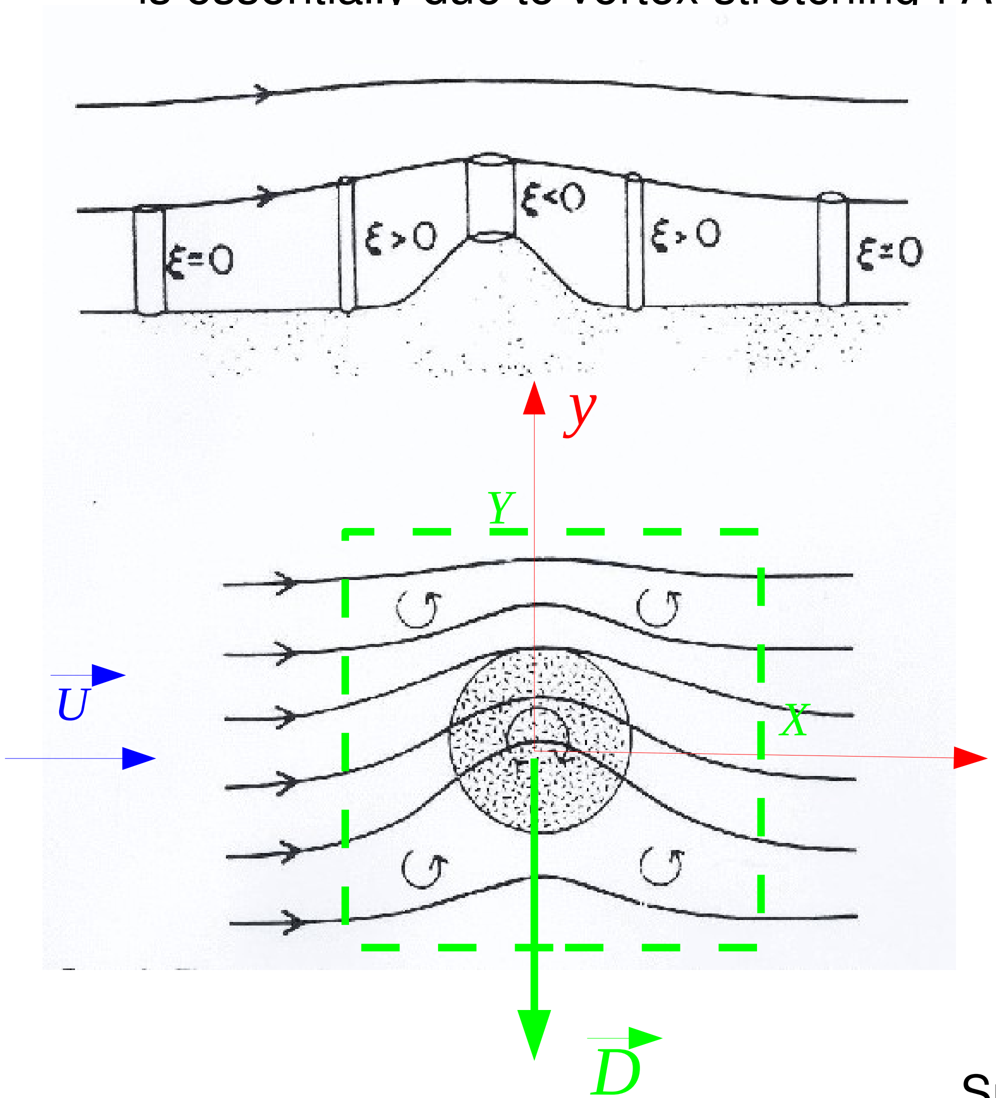
NCEP



LMDz, no SSO Scheme

Some orographic effects on the large-scale circulation, F. Lott
2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

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 :

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

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

In the linear case:

$$\vec{D} = \vec{L} = -\rho\,f\,U\,\bar{H}\,\vec{y}$$

Smith (1979)

Justification to enhance vortex stretching (almost the enveloppe orography concept)

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

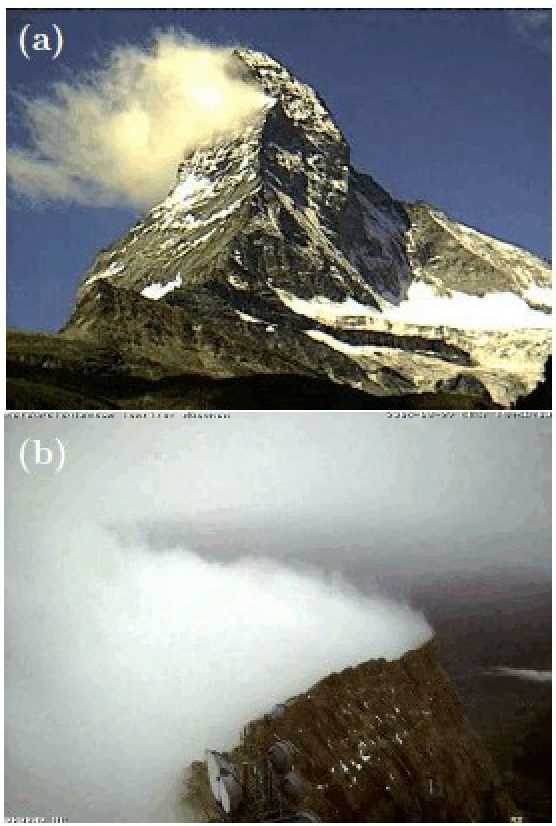
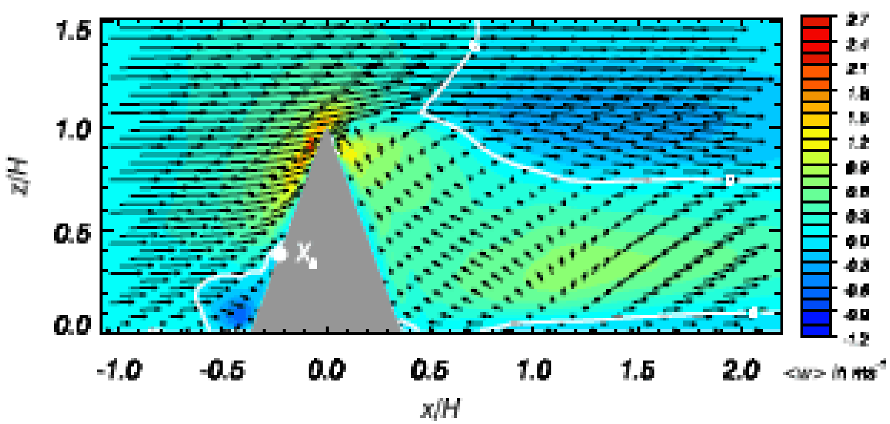


Figure 1: *Banner clouds forming leeward of a pyramidal shaped mountain peak or a quasi 2D ridge. (a) Banner cloud at Matterhorn (Switzerland). (b) Banner cloud at Mount Zugspitze (Bavarian Alps). Mean flow from right to left.*

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

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

A solution can be to higher up the mountains elevation by a fraction of its variance,
This the concept of envelope 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)

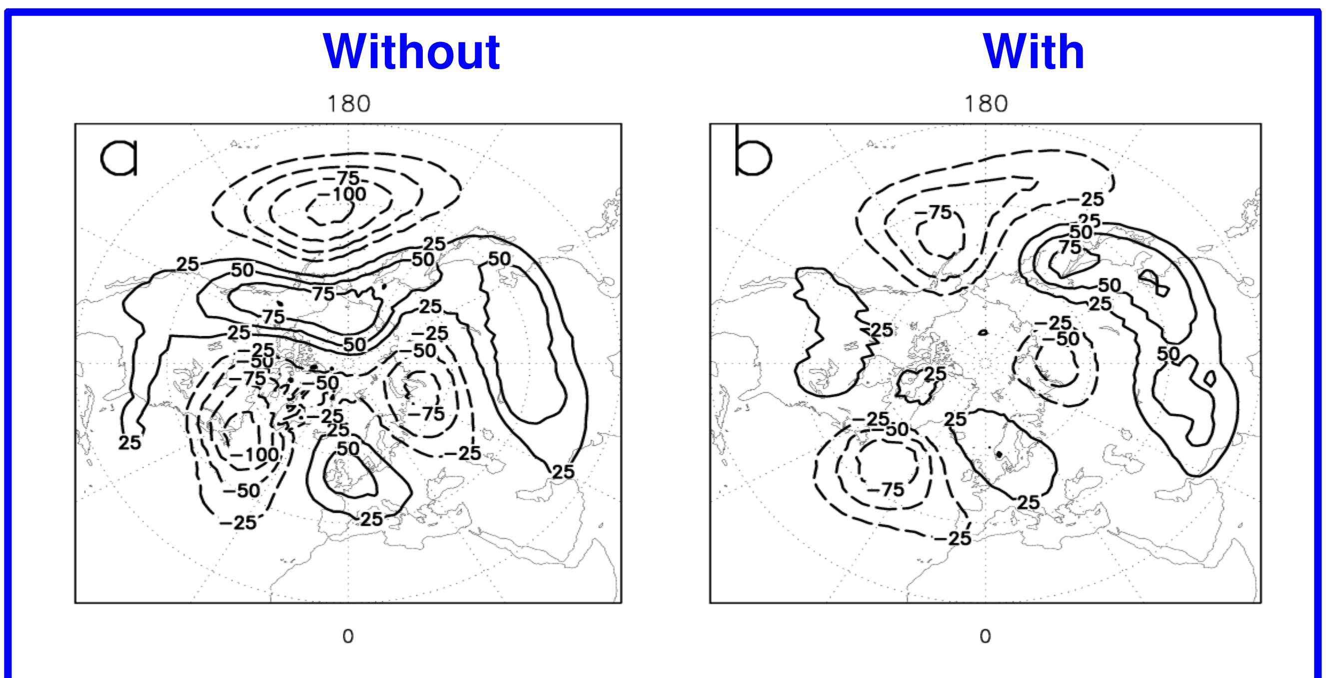
$$D_l = -\rho C_l f \left(\frac{H_{max} - z}{H_{max} - H_{mean}} \right) \vec{k} \, X \, \vec{U}$$

When integrated from H_{mean} to H_{max} this drag gives the Lift stress if C_l =2

Some orographic effects on the large-scale circulation, F. Lott
2) Impact and limitations of the Lott & Miller (1997) scheme: drag versus lift forces

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

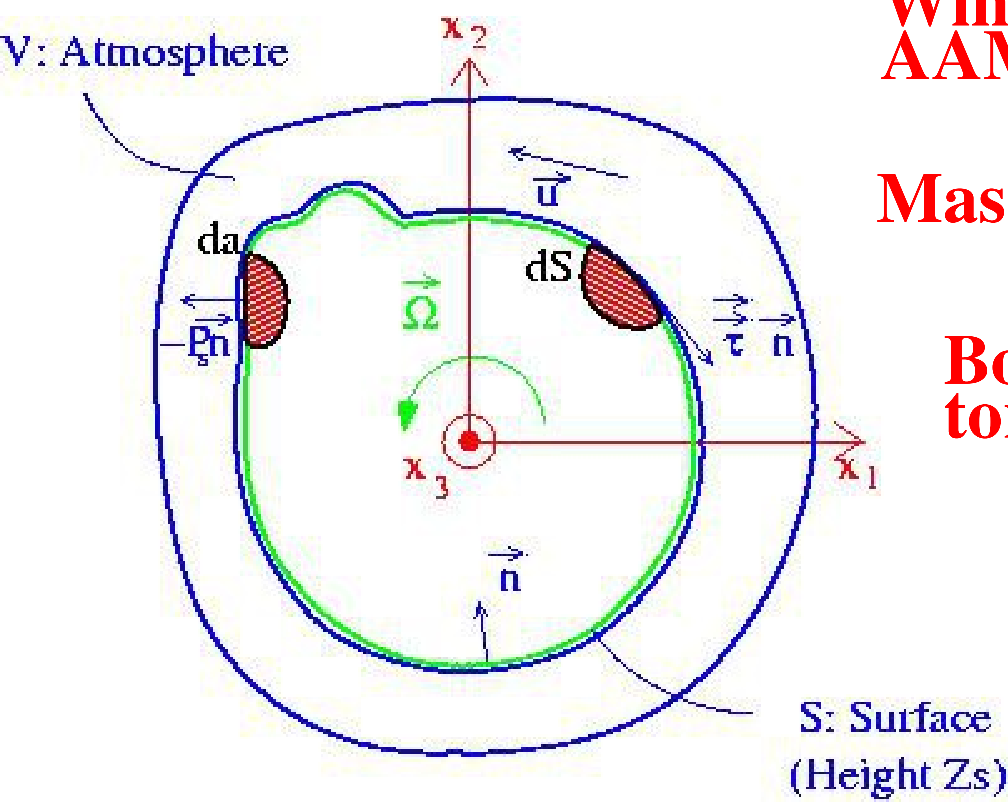
Error maps between the Geopotential height at 700hPa, NCEP reanalysis minus LMDz
Winter months out of a 10years long simulation



Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

Atmospheric Angular Momentum (AAM) Budget:

$$\frac{d}{dt}\left(M_R + M_O\right) = T_M + T_B$$



Wind AAM:

$$M_R = \int_V \rho \; r \; \cos\theta \; u \; dV$$

Mass AAM:

$$M_O = \int_V \rho \; \Omega \; r^2 \cos^2\theta \; dV$$

Boundary layer torque:

$$T_B = \int_S r \cos\theta \; \tau \; dS$$

Mountain torque:

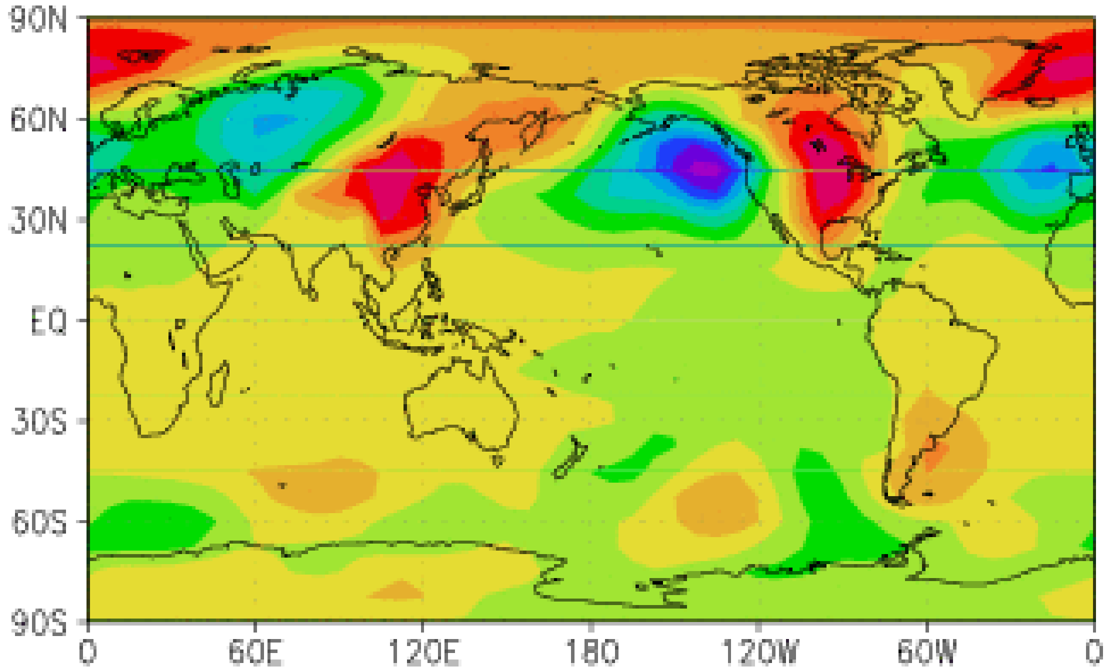
$$T_M = -\int_S P_S \frac{\partial Z_S}{\partial \lambda} dS$$

Budget well closed with the NCEP Data (1958-2003): r(dM/dt,T)=0.87

Almost perfectly with the LMDz model (1970-2000): r(dM/dt,T)=0.97

Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

Composite of Sea Level Pressure (SLP) keyed to T_M:



$$T_M = -\int_S P_S \frac{\partial Z_S}{\partial \lambda} dS$$

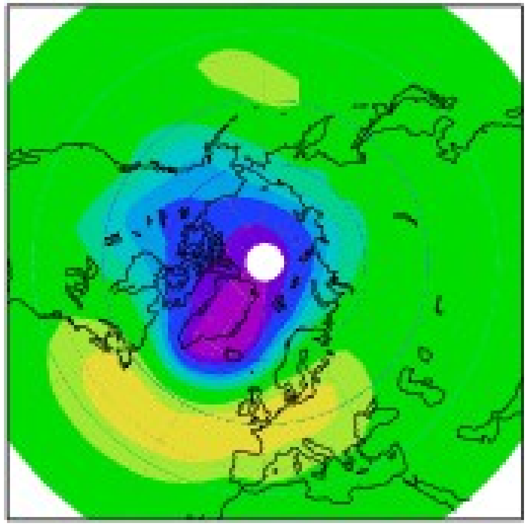
Regression of the SLP variations on the mountain torque (T_M) variations

DJF, NCEP data

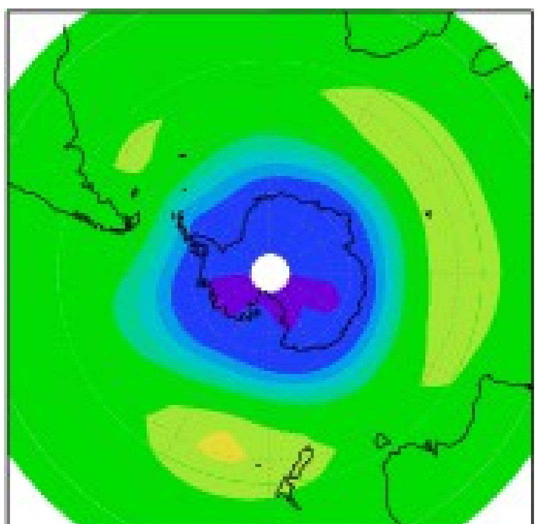
Arctic and Antarctic Oscillation

NCEP ANA

AO



AAO

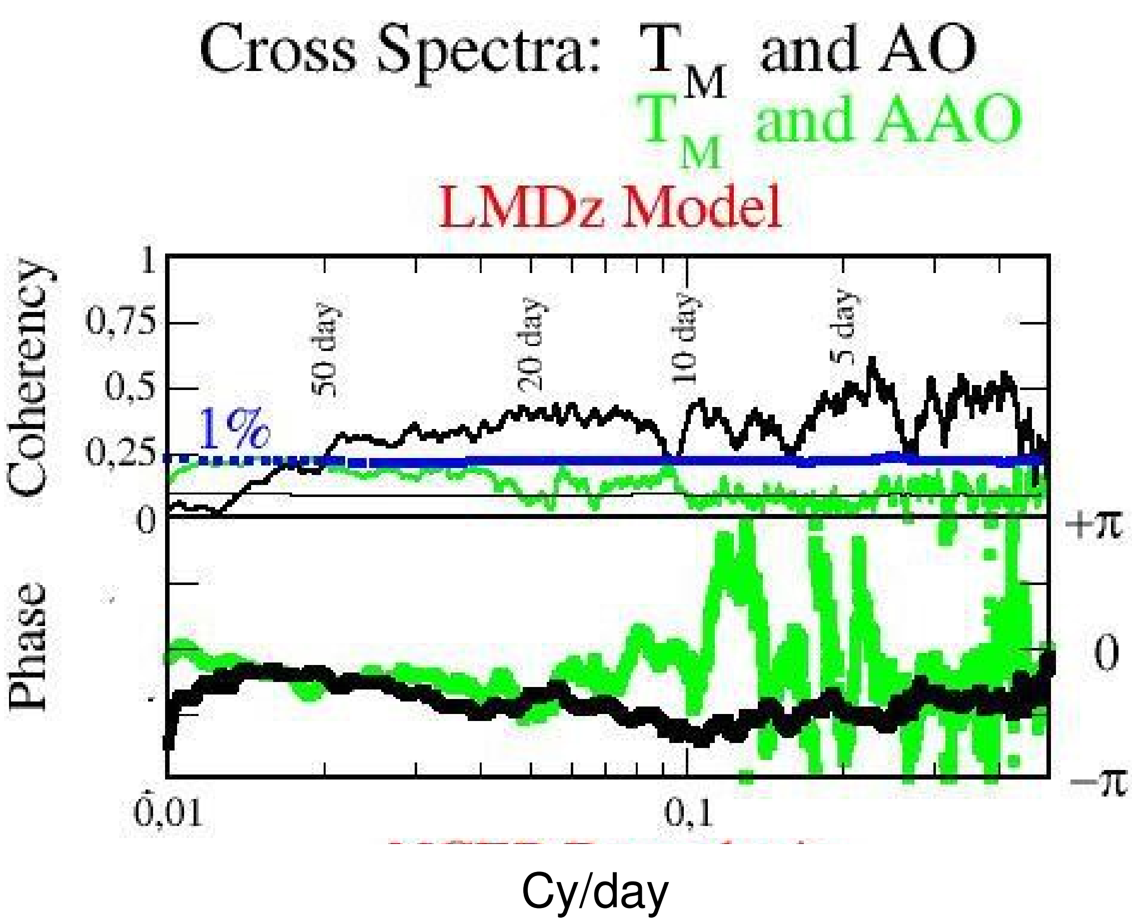


- **AO and the AAO: first EOF of SLP winter variability for the NH and the SH respectively**
- The AO and the AAO first correspond here to reinforcement of the mid-latitude jet-stream (model and reanalysis)

Lott, Goudard, and Martin (Model data, JGR 2005)

see also: Lott, Robertson, and Ghil (NCEP data, GRL 2001, JAS 2004a, b)

Mountain Torque, the AO and the AAO, Co-Spectral Analysis
(NCEP Reanalysis and LMDz GCM data)



<u>In the LMDz GCM and in the reanalysis, the mountain torque is in significant lead-lag quadrature with the AO</u>

It is also important to contrast the Southern Hemisphere (AAO) and the Northern Hemisphere (AO), because there are much less mountains in the SH

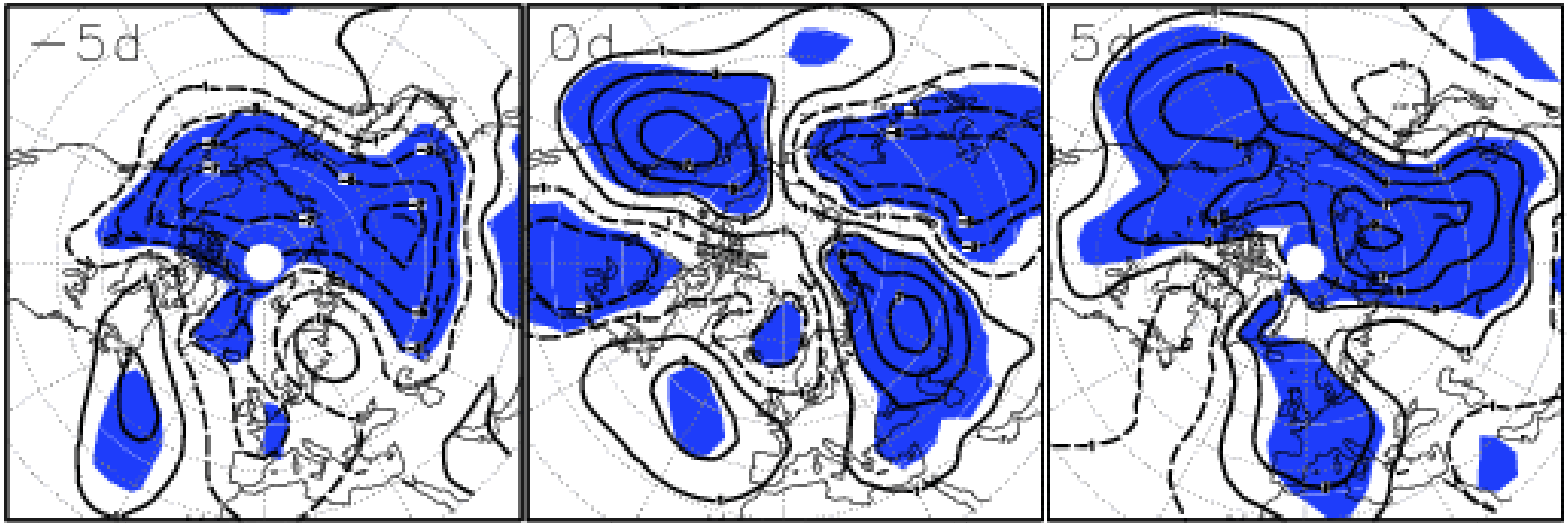
<u>The case of the AAO can be viewed as a natural null hypothesis of our results for the AO</u>

Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

Composite analysis

All datas are filtered to retain the 10-150 day band (IS), 80 maps per composites.

SLP MAPS from the LMDz-GCM, keyed to minima in the IS T_M



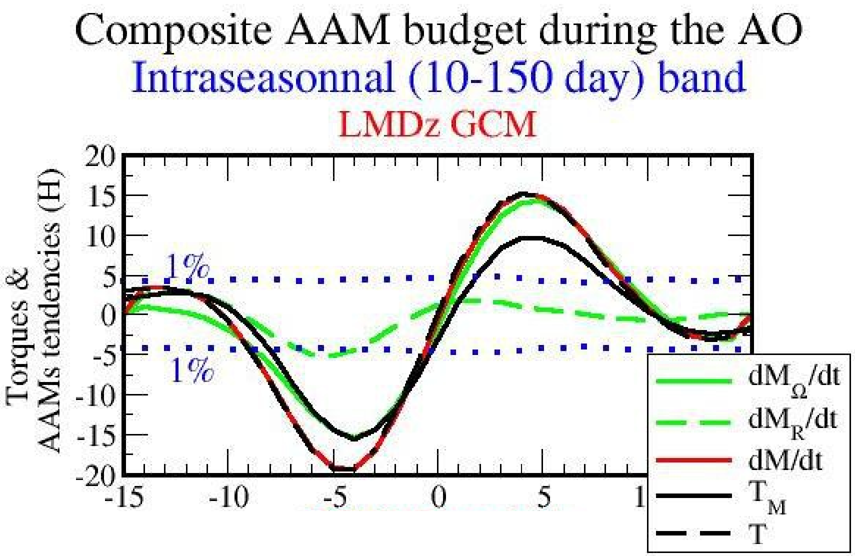
At 0day lag, the SLP composite presents a dipolar structure over the Rockies and the Himalayas corresponding to a <u>negative</u> mountain torque

At negative lag the circulation over the NH is predominantly anticyclonic. It is predominantly cyclonic at positive lag: <u>the negative mountain torque has decelerated the flow significantly.</u>

<u>The maps at -5 day lag and +5 day lag project somehow onto the AO.</u>

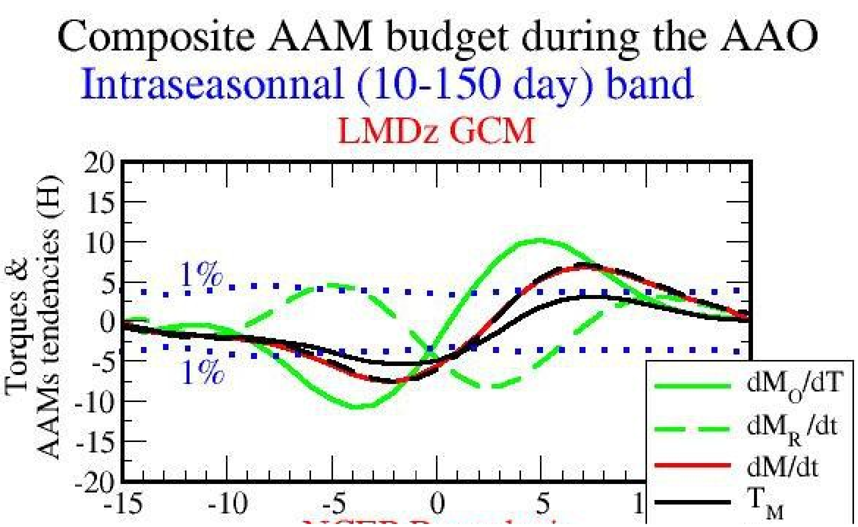
Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

Composite analysis



During AO cycles the AAM (M) varies, and its variations are in good part driven by the mountain torque (T_M).

The variations in M are essentially due to the mass AAM (M_O) (the relative AAM M_R varies little).



During cycles in AAO the AAM (M) varies little.

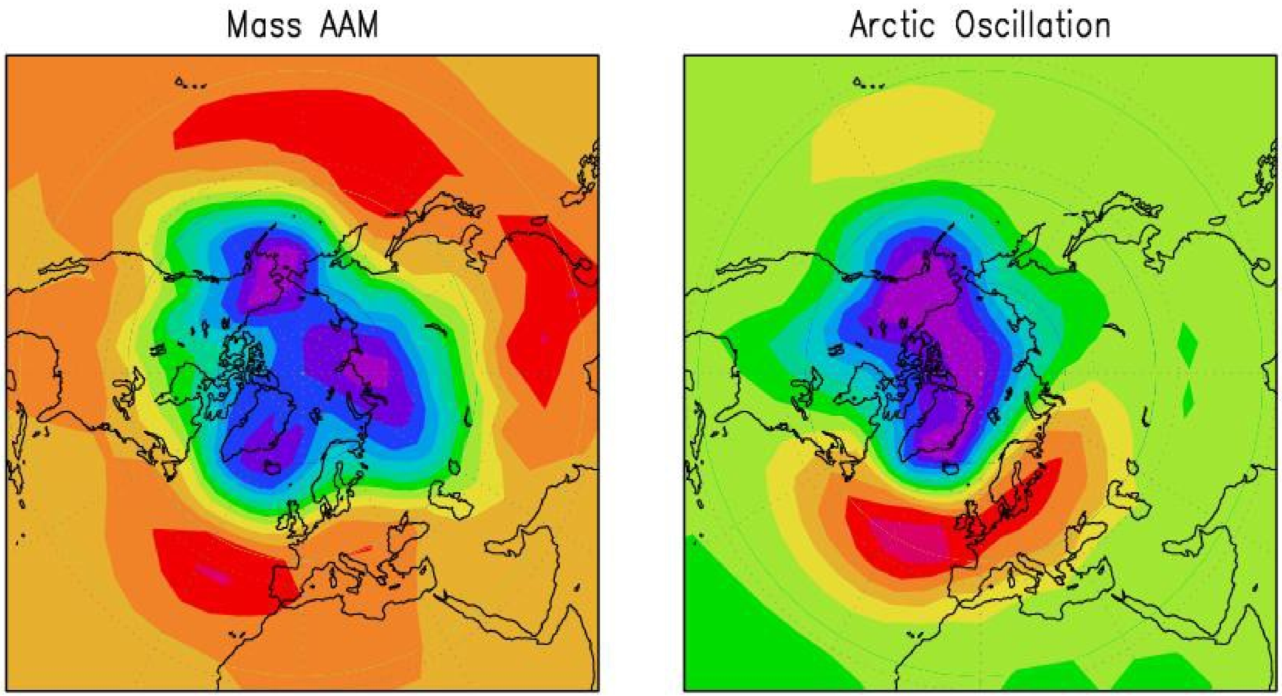
The mass AAM (M_o) varies near as much as during the AO.

In this case, the changes in mass AAM (M_o) are equilibrated by changes of opposite sign in wind AAM (M_R).

The mountain torque (T_M) does not play a substantial role.

The role of M_O in the relationship between T_M and the AO?

Mass AAM (M_O) and the Arctic Oscillation (AO)



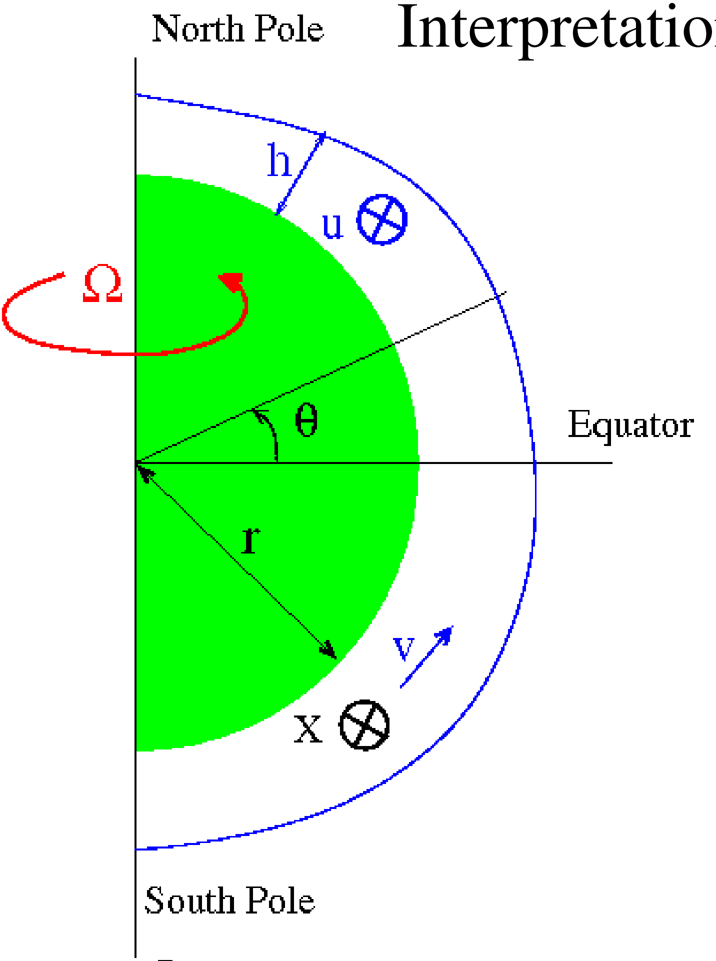
DJF Regression of sea level pressure onto M_O (left) and the A0 (right).

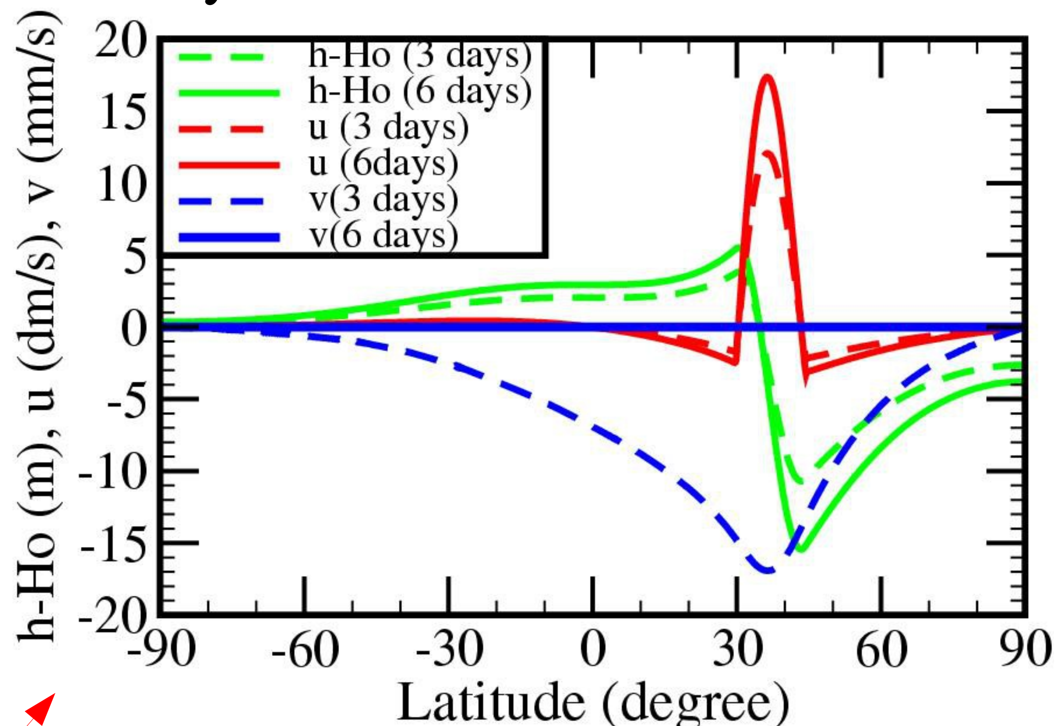
The good correlation between the two maps is at the origin of the relationships between the mountain torque (T_M) and the AO

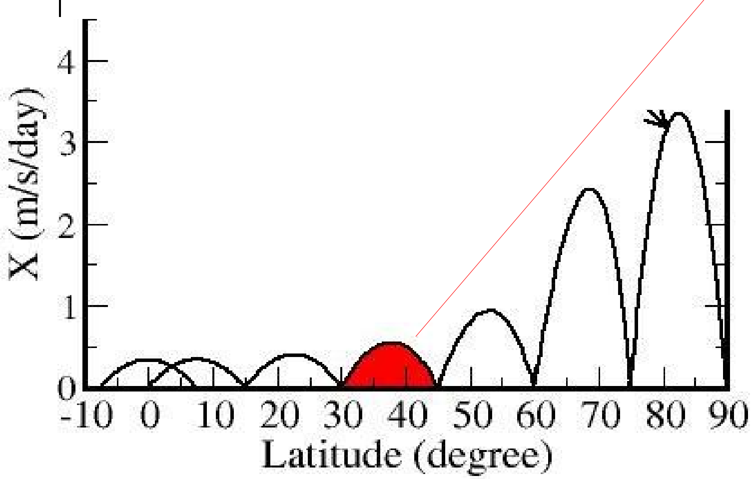
Lott and d'Andrea (QJ 2005)

Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

Interpretation with an axi-symmetric shallow water model







The force X (>0) is equilibrated by a meridional ageostrophic velocity v (<0) via the Coriolis torque.

v transports mass from the polar latitude towards the Equator (h<0, north of 40°N, h>0 south of 40°N) Mass AAM>0!.

u is in geostrophic balance with h WIND AAM >0

The relative amplitude of the mass and wind AAM depends on the latitude of the force

Some orographic effects on the large-scale circulation, F. Lott
3) Mountain torques and low frequency variability

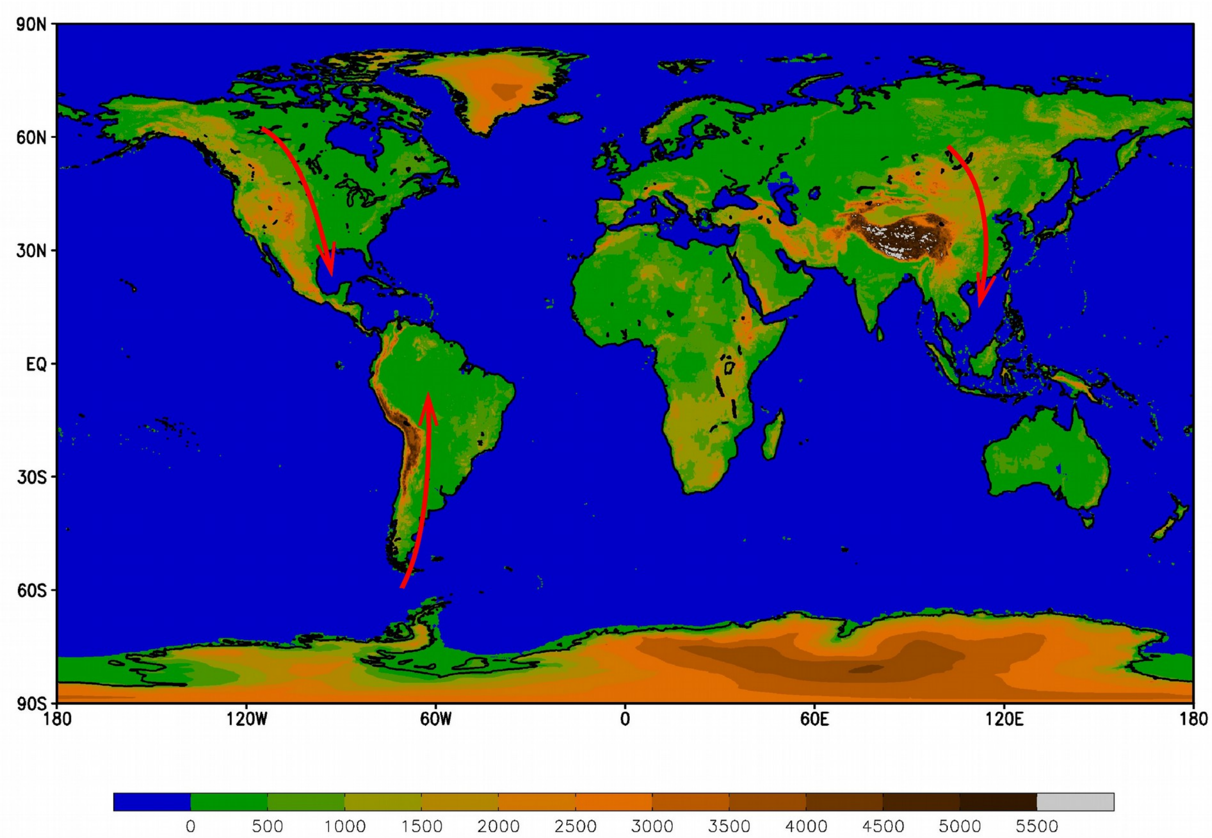
Extension : Relations with the local and global weather regimes also exist :
Pacific and Atlantic Blockings (Lott Robertson Ghil 2004b)

Limitations : Almost no evaluation of the parameterized forces. For reanalysis in Lott Ghil Roberstson (2001, 2004a, b) this is because the data do not close well enough the AAM budget.
For the model datas in Lott Goudard Martin (2005), it plays a small rôle lo,ger simulations are needed.

But more indirect more effect of the parameterized torques has not been analysed.
It can be done by modifications of the SSO scheme as in Sandu et al. ~(2015)

Some orographic effects on the large-scale circulation, F. Lott
4) Mountain torques and synoptic scale flows

Not cyclogenesis but **cold surges**:
regional scale phenomena present on 3 continents



World topography and location of the cold surges (adapted by S. Mailler from Garreaud, 2000)

- Dominant features of the winter climate in north and south America, and in east-Asia

- (not so) Recent examples :

•Cold wave in China (Jan.-Feb. 2008)
•
•Cold wave in the southern United States (jan. 2010)
•
•Cold wave in south America (Jun. 2010)

Some orographic effects on the large-scale circulation, F. Lott
4) Mountain torques and synoptic scale flows

Equatorial mountain torques can be viewed as dynamical forcing of the atmospheric motion?

$$\frac{d(\overrightarrow{M_\Omega}+\overrightarrow{M_r})}{dt}+\vec{\Omega}\times\overrightarrow{M_r}=\overrightarrow{T_M}+\overrightarrow{T_f}$$

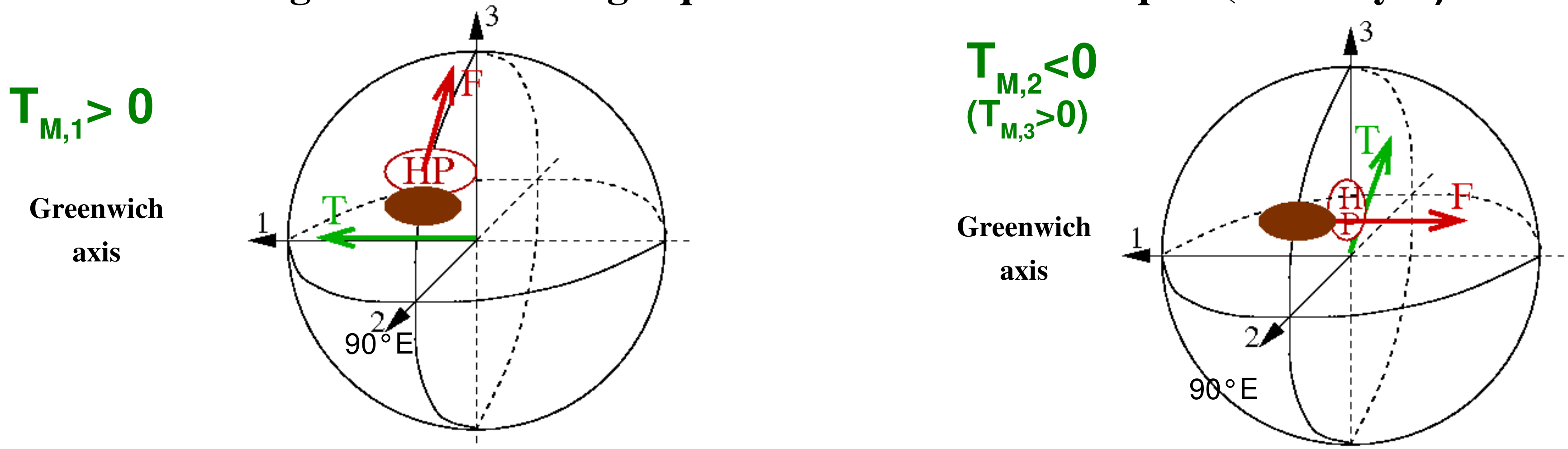
$\overrightarrow{M_r}$ **Wind angular momentum**

$\overrightarrow{M_\Omega}$ **Mass angular momentum**

$\overrightarrow{T_f}$ **Parameterized torque**

$\overrightarrow{T_M}$ **Pressure torque**

Configurations creating Equatorial Mountain Torques (Himalayas)

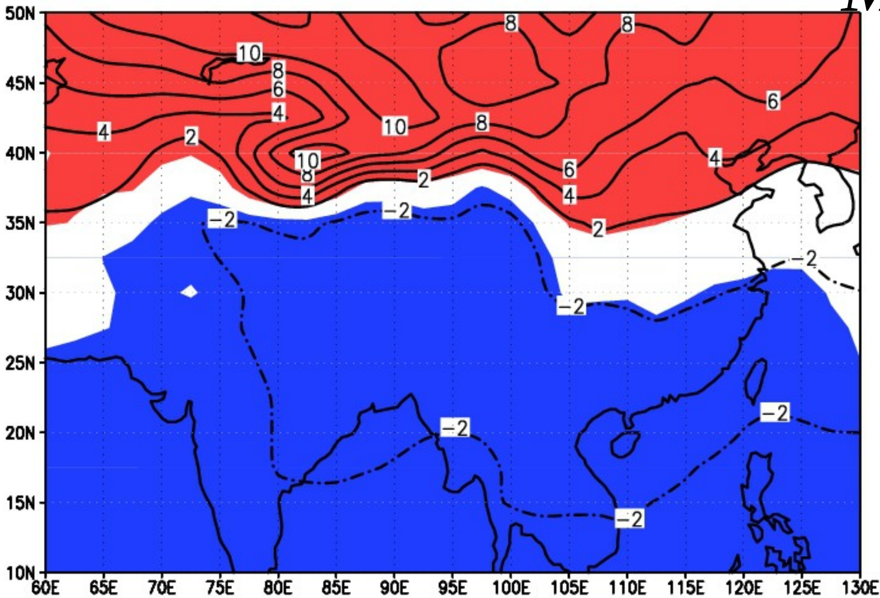


F: reactive force applied by the mountain on the atmosphere **T:** Torque applied by the mountain on the atmosphere

Mailler and Lott (Reanalysis JAS 2009, LMDz model MWR 2015)

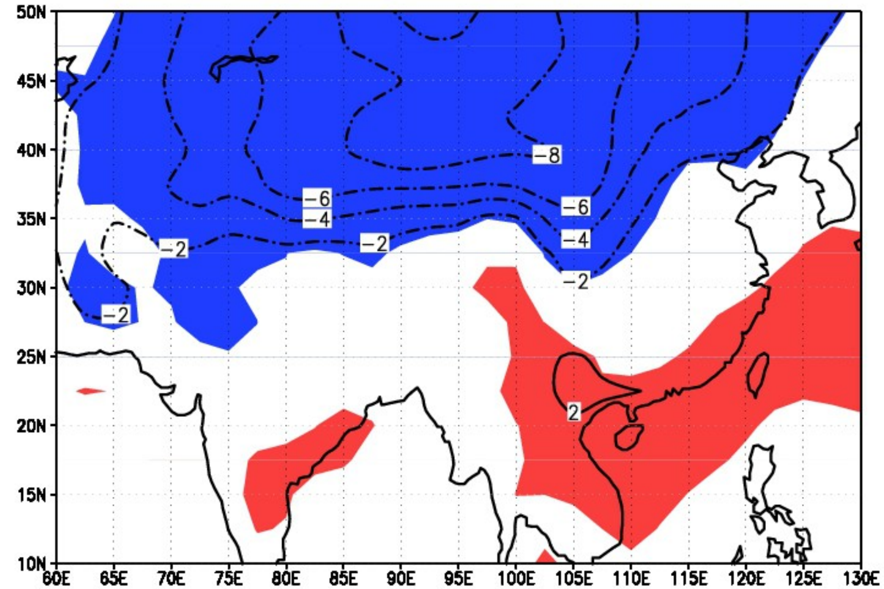
Some orographic effects on the large-scale circulation, F. Lott
4) Mountain torques and synoptic scale flows

Composite keyed on T_{M1}^{TP} Tibetan Plateau

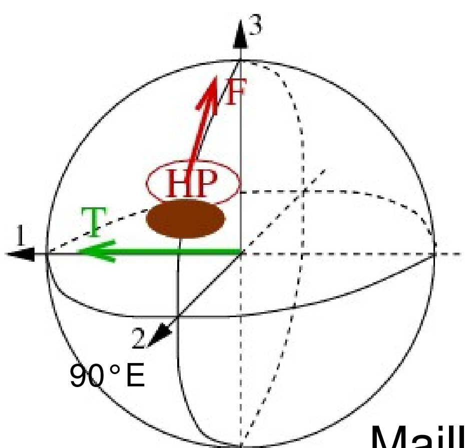


Surface pressure
CI :2hPa, 99% levels are shaded

Day 0



Surface T
CI : 1K, 99% significance levels shaded



Situation corresponding to positive peaks of : T_{M1}^{TP}
- High pressure and low temperature in Siberia, corresponding to a strengthening of the Siberian High
- Low pressure in the subtropics

Mailler and Lott (Reanalysis JAS 2009, LMDz model MWR 2015)

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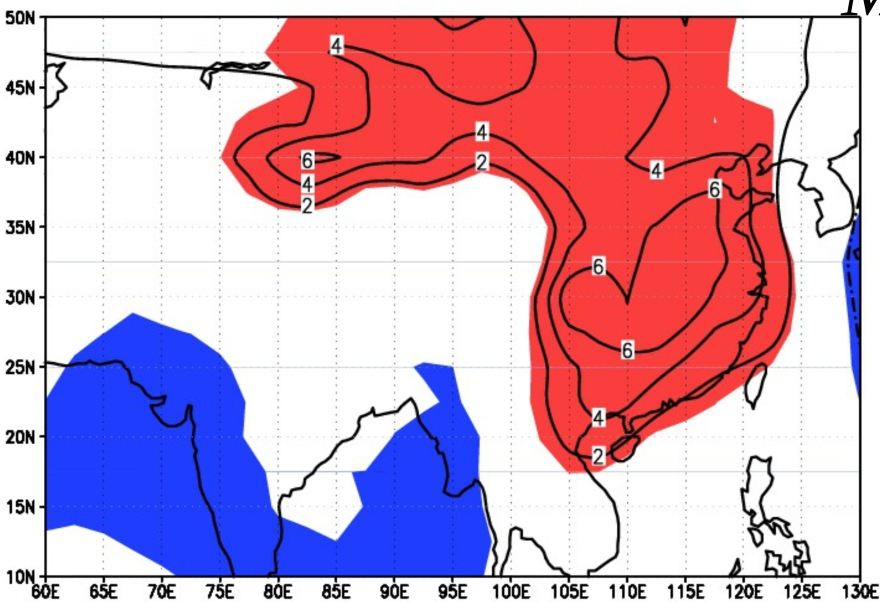
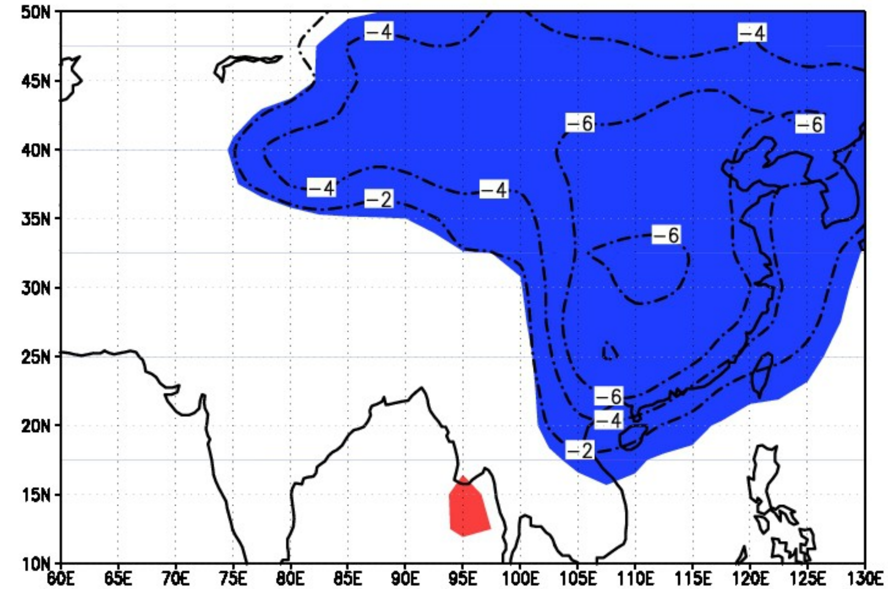
Composite keyed on T_{M1}^{TP} Tibetan Plateau

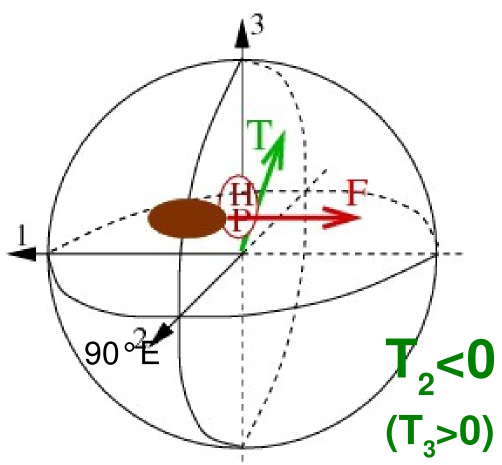


Day 2



Surface pressure
CI :2hPa, 99% levels are shaded

Surface T
CI : 1K, 99% significance levels shaded



Situation two days after positive peaks of T_{M1}^{TP}

- Significant high pressure and low temperature in eastern China
- Extends to the subtropics
- Typical of east-asian cold surges
- High pressure east of the TP explains the negative T_{M2}^{TP}

Mailler and Lott (Reanalysis JAS 2009, LMDz model MWR 2015)

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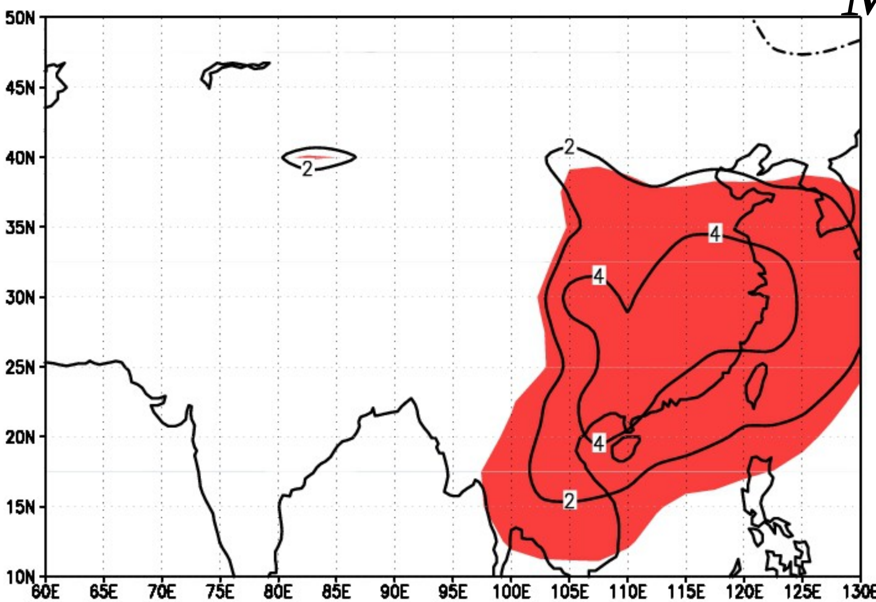
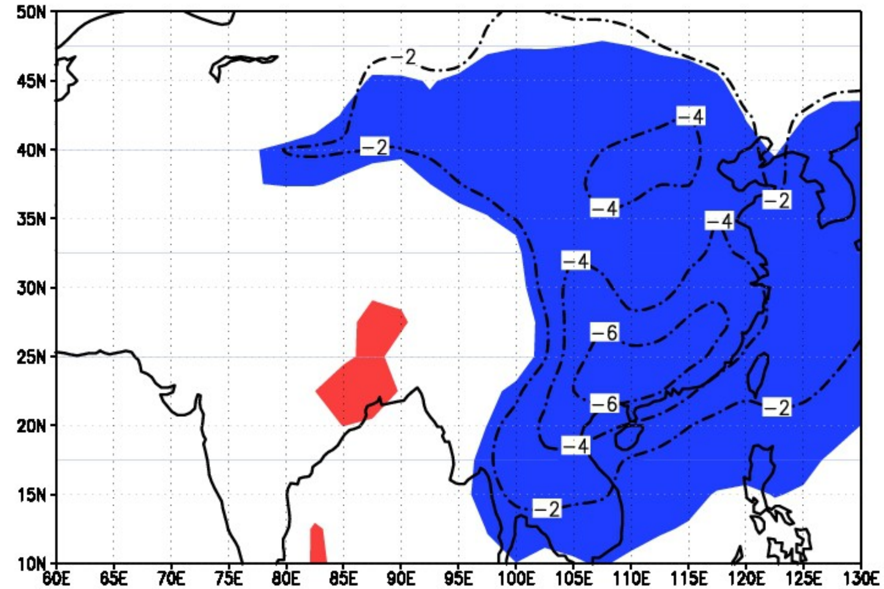
Composite keyed on T_{M1}^{TP} Tibetan Plateau

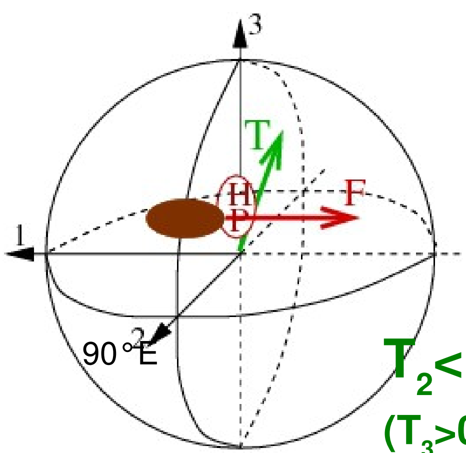


Day 4



Surface pressure
CI :2hPa, 99% levels are shaded

Surface T
CI : 1K, 99% significance levels shaded



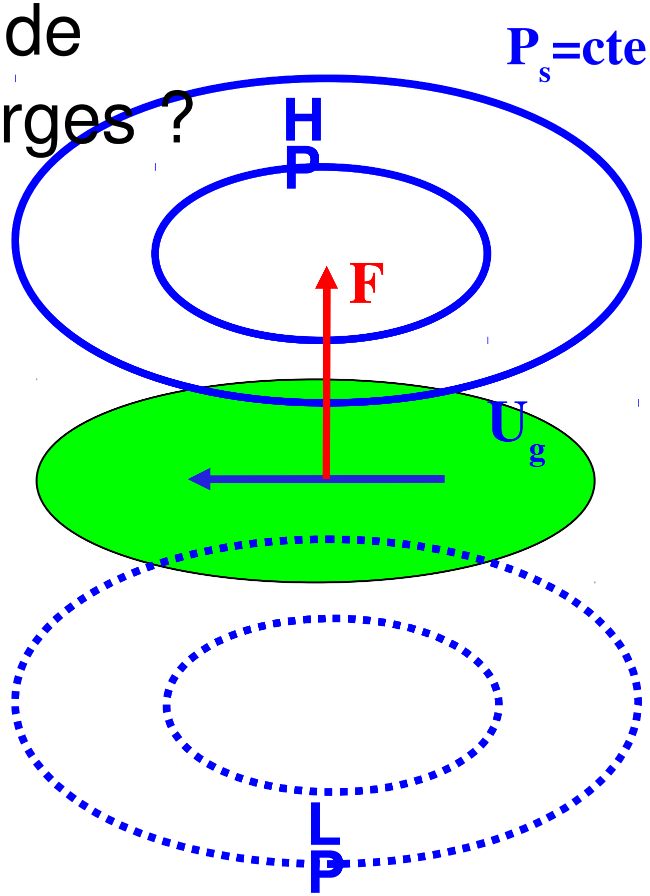
$T_2<0$
($T_3>0$)

Situation 4 days after positive peaks of $_1$: T_{M1}^{TP}

- Cold surge is mature and strongly affects tropical regions
- Anomalies of surface temperature and surface pressure reach 4 hPa and 6K respectively

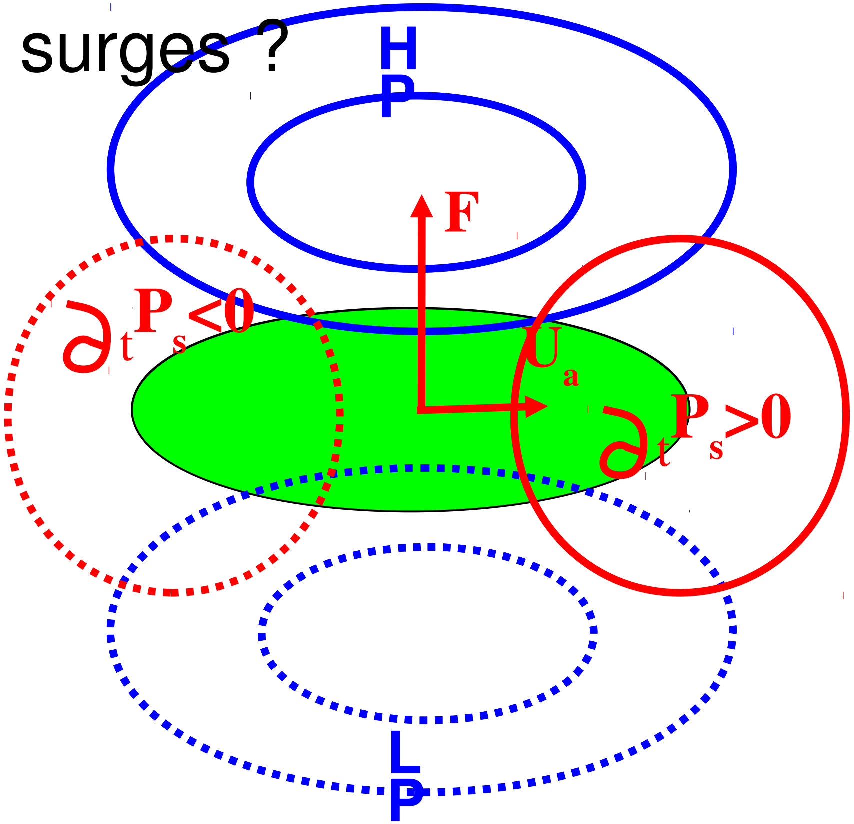
Impact on winter East Asia winter monsoon : Mailler and Lott (GRL 2009)

How a transverse torque
of the right amplitude
can produced Cold surges ?



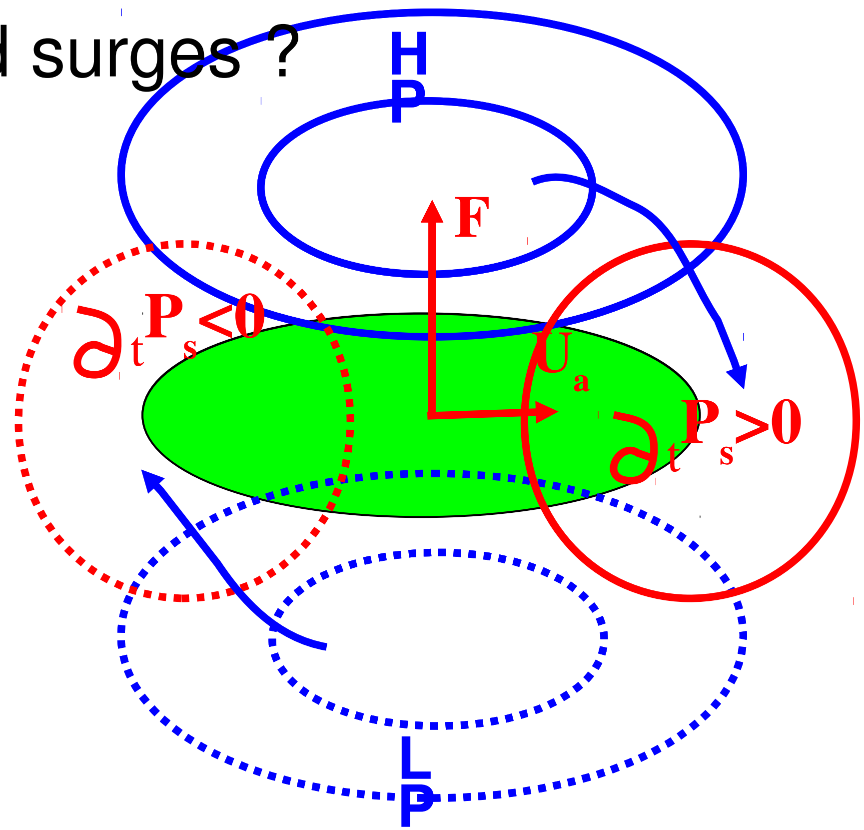
U_g: Geostrophic wind
F: Reactive force on the flow
Mountain is in green
P_s: Surface pressure

How a transverse torque
of the right amplitude
can produced Cold surges ?



U_a ageostrophic wind:
Equilibrate **F** via Coriolis
Transport mass from left to the right here

How a transverse torque
of the right amplitude
can produced Cold surges ?



U_a ageostrophic wind:
Equilibrate **F** via Coriolis
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How a transverse torque
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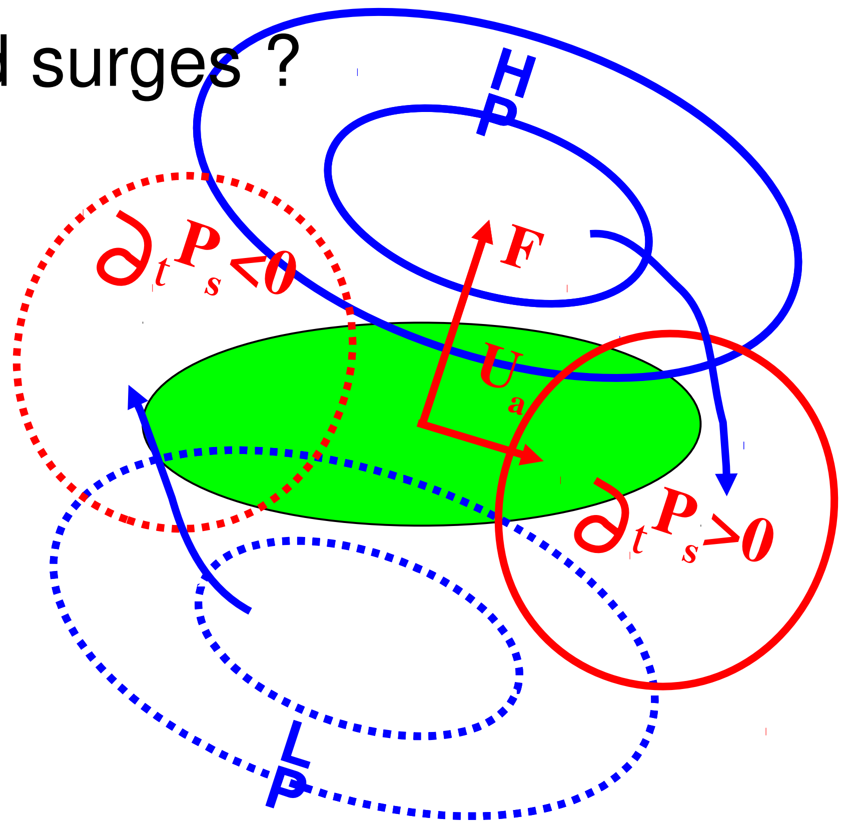

U_a ageostrophic wind:
Equilibrate **F** via Coriolis
Transport mass from left to the right here

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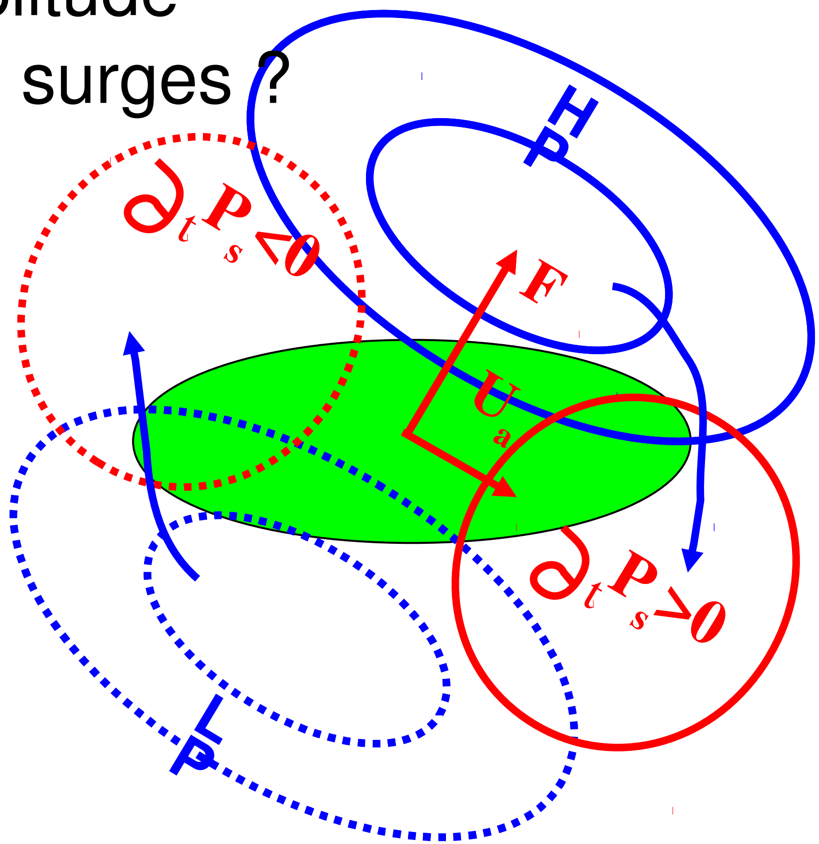
How a transverse torque of the right amplitude can produced Cold surges ?

Here we treat a pressure force on the same footing as a parameterized Force

Can be justified in the QG case.

Useful to tune parameterization ?



$\mathbf{U_a}$ ageostrophic wind:
Equilibrate $\mathbf{F}$ via Coriolis
Transport mass from left to the right here

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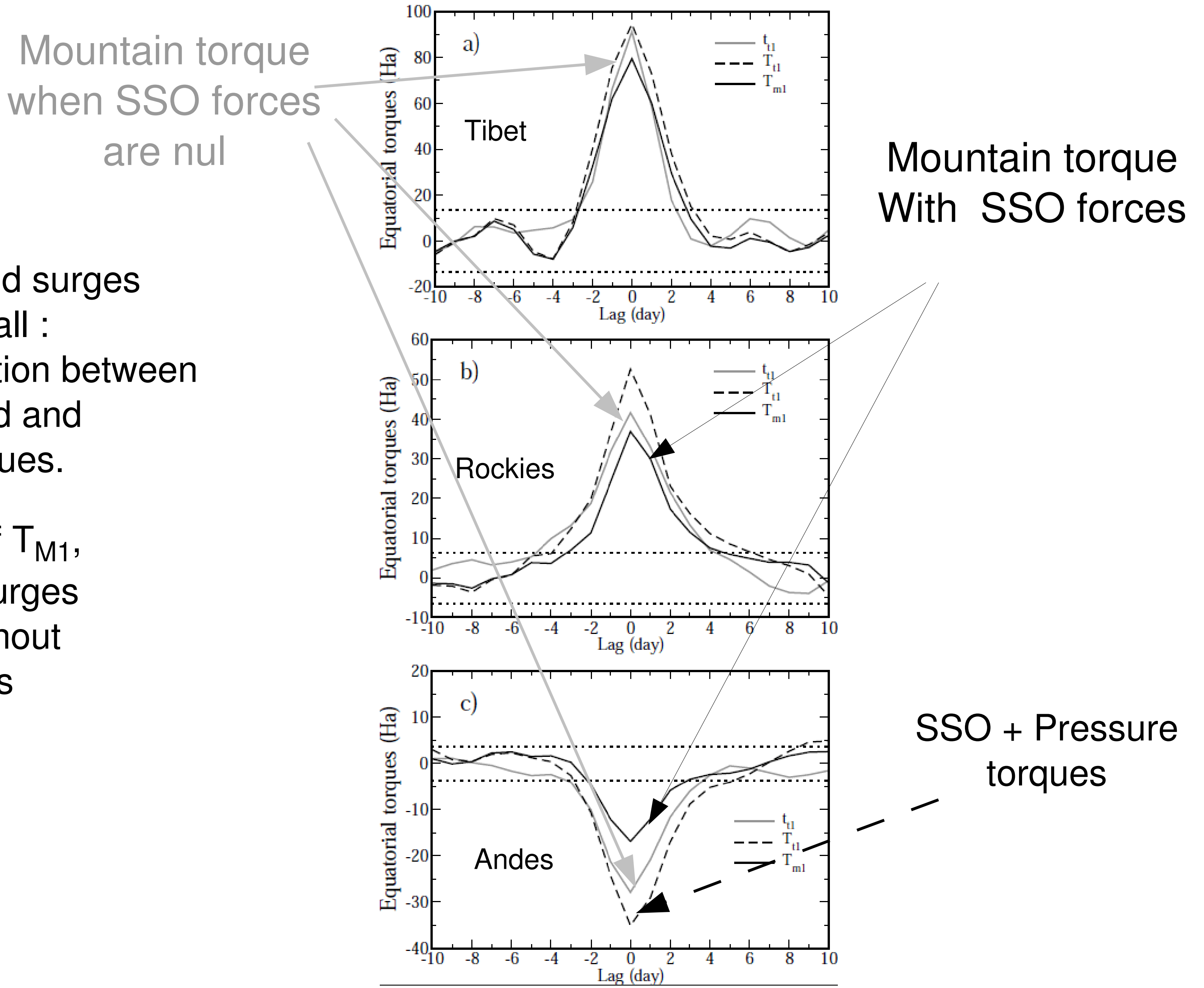
Contribution of the parameterized torques

SSO effects on cold surges are quite small : There is a compensation between parameterized and resolved torques.

Composites of T_{M1}, during cold surges with and without SSO forces



4) Perspectives

- Reconciliate SSO schemes and boundary layer schemes
  (They often do the same thinks at low level)

- How to treat large slope effects in global model (air isolation in valleys rather than in a adhoc way like envelope orography or enhanced lift)

- Make SSO schemes more stochastic to treat better a large ensemble of waves
  (3D-Critical levels and trapped waves need that, if significants....)

- Re-evaluate impacts of SSO on planetary waves and LFV (Sandu et al. 2015))
  Including interaction with the resolved drag (Van Nieckerk et al. 2016)

- Better understand the upscale route of orographic effects :
  mesoscale->synoptic->planetary->zonal mean
  (Even using theory : Martin and Lott (2007) shows that GWs
  reduce lee cyclogenesis in the Eady model forced by orography)