Mass and Wind Atmospheric Angular Momentum variations at intraseasonal and diurnal periodicities

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I) The Atmospheric Angular Momentum (AAM) budget

II) Intraseasonal

Links between the Mountain Torque (T_M) and the Artic Oscillation (AO)

The role of the mass AAM (M_O) in the relationship

III) Diurnal

Surface Pressure tides and axisymetric (s=0) modes of oscillation

Dynamical interpretation with a shallow water set of Eqs.

IV) Summary

Three <u>independent</u> datasets are used:

<u>Intraseasonal:</u>

- **The NCEP reanalysis (1958-2004) which is keyed to observations but does close very well the AAM budget**
- **A 30-year climatic integration with the LMDz-GCM which does close perfectly the AAM budget**
- **The cycles of the AAM during variations of the Antarctic Oscillation are also discussed (to contrast with the AO)**

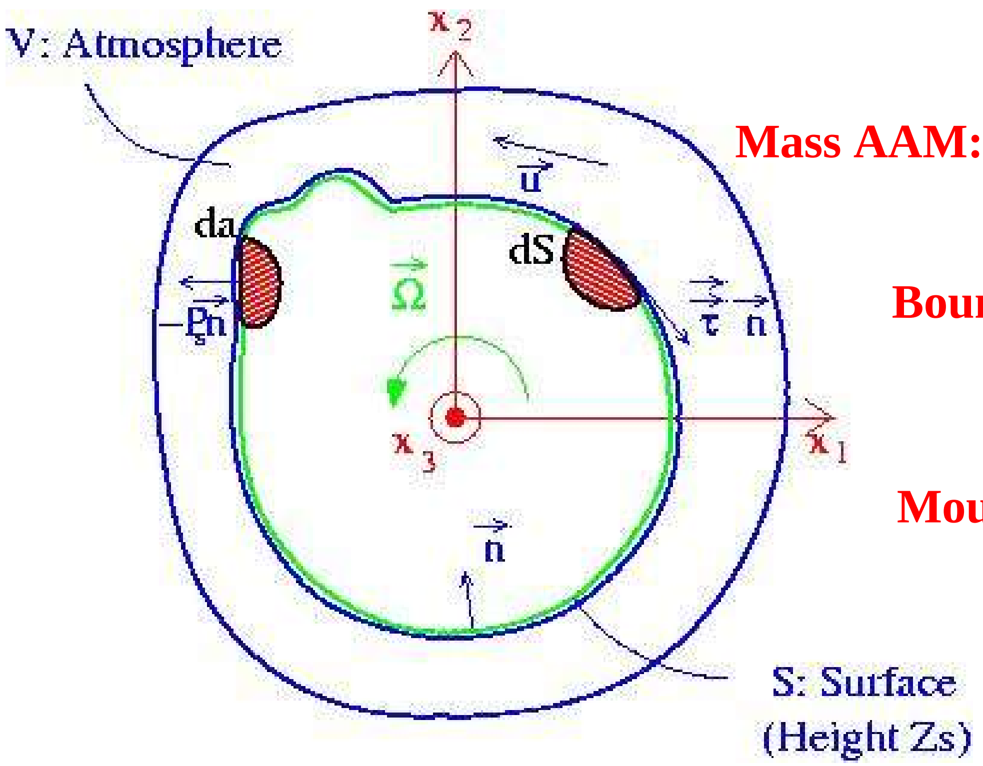
<u>Diurnal:</u>

- **A 1-year integration done with the LMDz-GCM (storage every 30 mns)**
- **Some ECMWF forecasts and operational analysis products**

The results are also dynamically intepreted with an axisymmetric shallow water model

I) 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

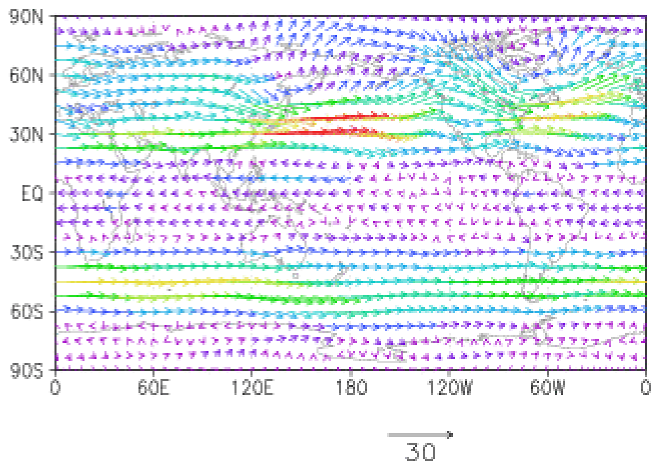
Almost perfectly with the LMDz model (1970-2000): r(dM/dt,T)=0.97

I) Atmospheric Angular Momentum (AAM) Budget:

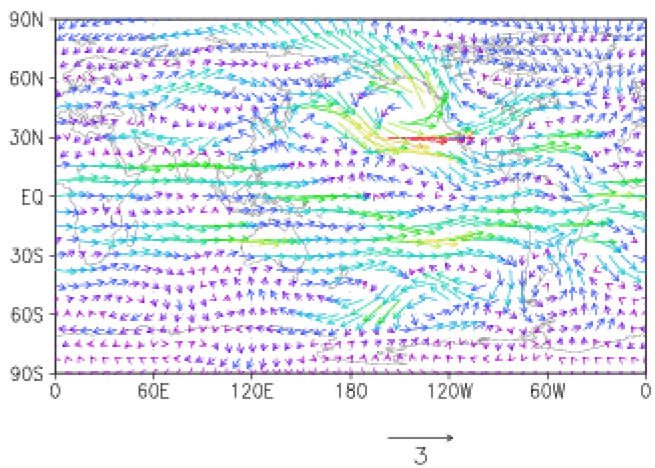
Composite of Barotropic Winds keyed to M_R:

NCEP data, DJF months.

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



Winter mean of the barotropic wind (u_b)



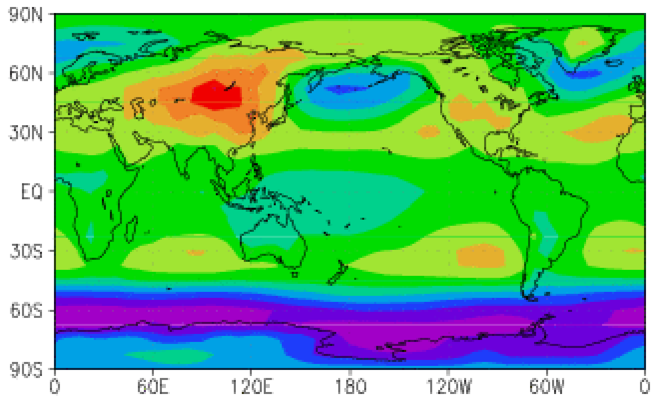
Regression of the barotropic wind (u_b) variations on the wind AAM (M_R) variations

I) <u>Atmospheric Angular Momentum (AAM) Budget</u>:

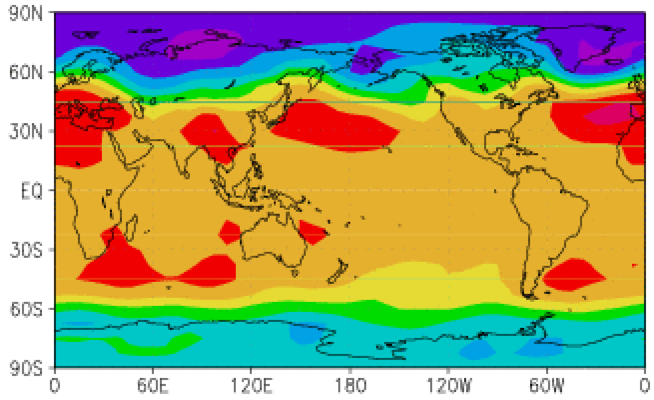
Composite of Sea Level Pressure (SLP) keyed to M_o:

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

NCEP data, DJF months.



Winter mean of the SLP



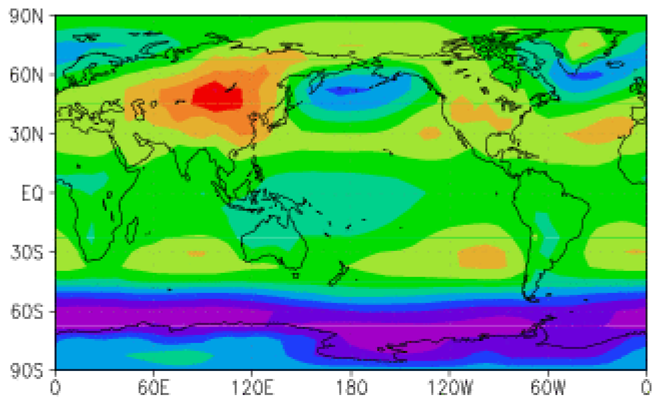
Regression of the SLP variations on the mass AAM (M_o) variations

I) <u>Atmospheric Angular Momentum (AAM) Budget</u>:

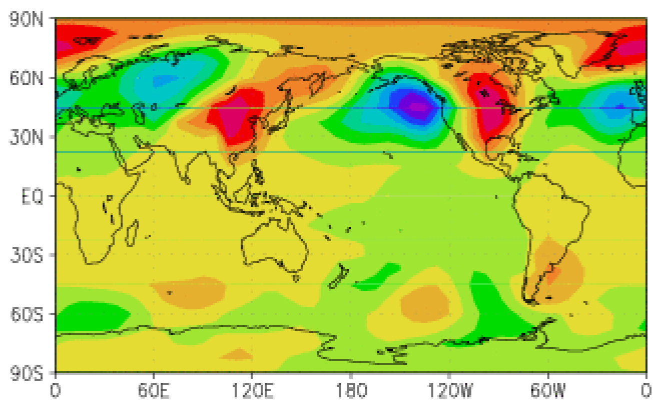
Composite of Sea Level Pressure (SLP) keyed to T_M:

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

NCEP data, DJF months.



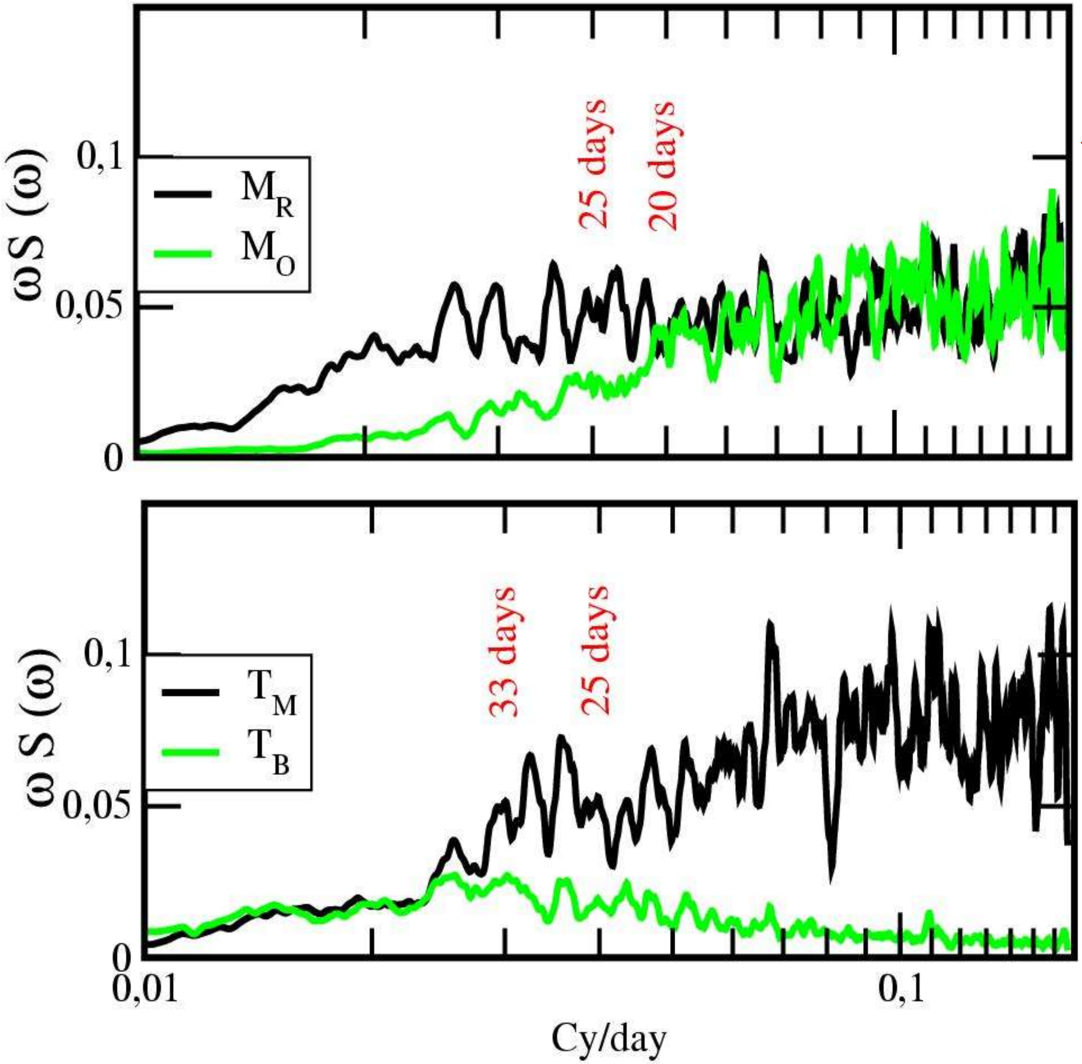
Winter mean of the SLP



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

I) Atmospheric Angular Momentum (AAM) Budget:

Spectral analysis of NCEP data



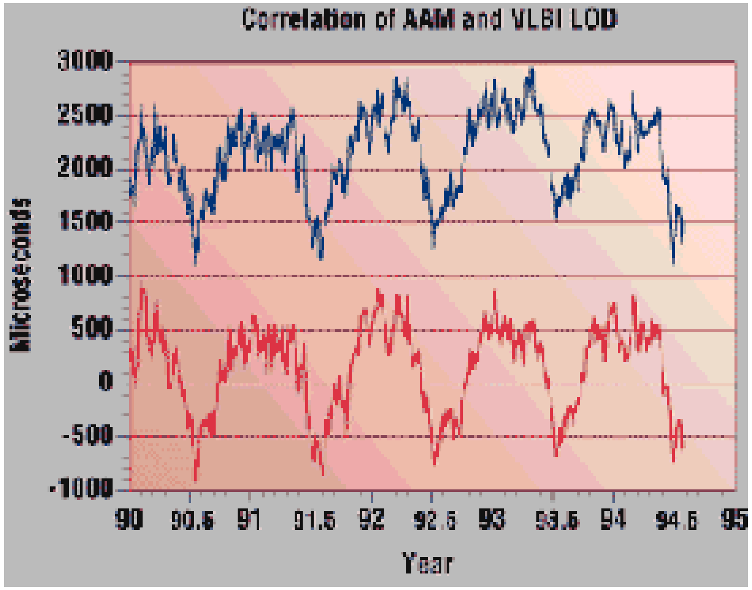
At periodicities below 30 days the Mass and Wind AAM fluctuations have comparable amplitude

At periodicities below 30 days the mountain Torque fluctuations are far larger than the boundary layer torque fluctuations

I) Atmospheric Angular Momentum (AAM) Budget:

Why it has been looked at over the last 30-years?

Length of day and AAM from reanalysis (NASA dataset)

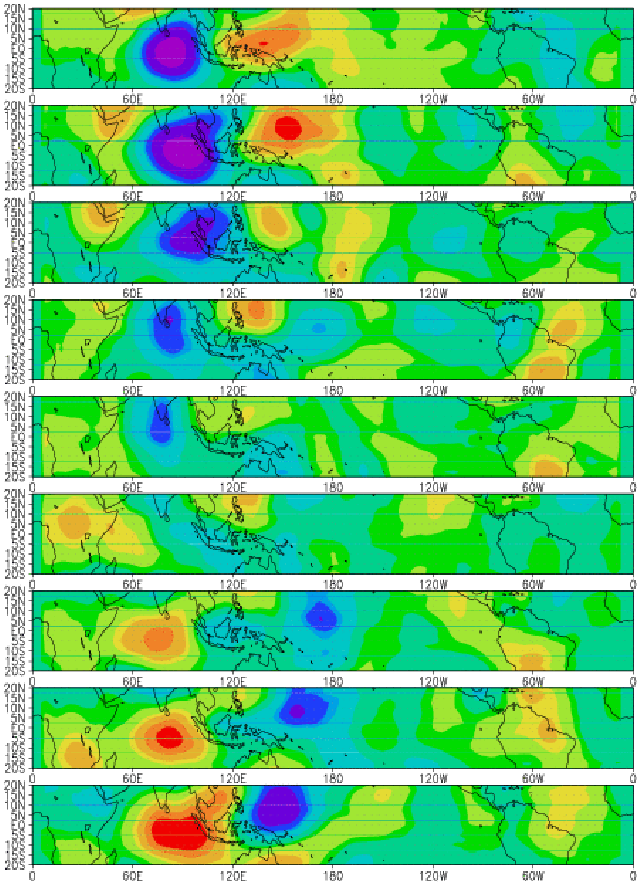


- M is a global quantity whose changes are related to observable changes of the Earth Rotation Parameters (EOP)
- At periodicities below few years, it follows the large scale oscillations of the Climatic system
- In our case, it also permits to evaluate the significance of mountains forcing on the global climate variability.

I) Atmospheric Angular Momentum (AAM) Budget:

AAM and large scale oscillations

Regression of NOA OLR on M_R (40-60 day band)



- EL-Nino: Wolf and Smith (1987)
- MJO Tropical oscillations, Madden (1987), Hendon (1995), essentially via M_R forced by T_B (but some role of T_M, Weickman et al. 1997)
- Mid-latitude oscillations and weather regimes (Lott et al. 2004a, b). Essentially via T_M, with $M_R \sim M_O$
- Synoptic disturbances (Iskenderian and Salstein, 1998) essentially via T_M

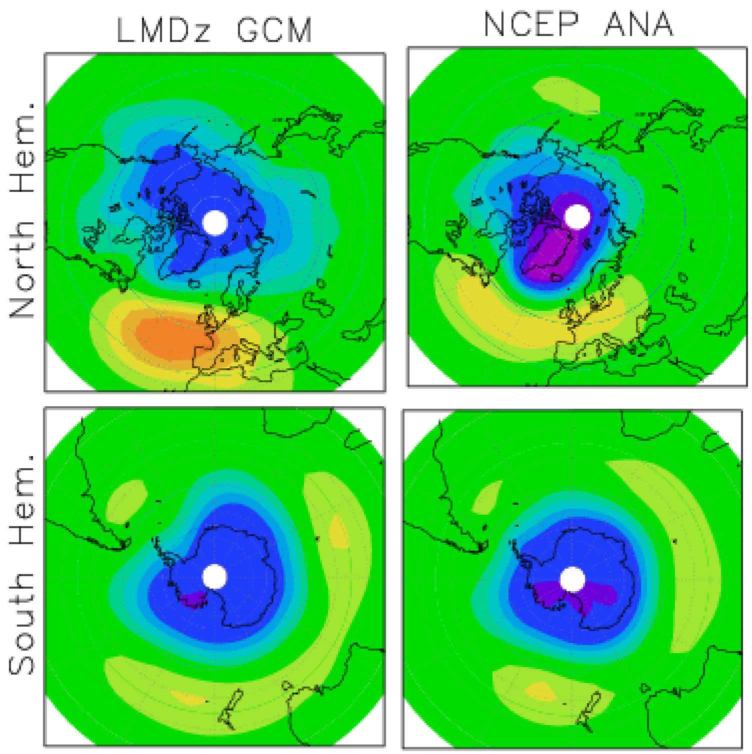
I) Atmospheric Angular Momentum (AAM) Budget:

AAM and large scale oscillations

- We will argue that the AAM budget studies can also be used to quantify the dynamical influence of mountains on atmospheric dynamics.
- To which extent the Charney de Vore (1979) model of mid-latitude low-frequency variability is relevant to the real atmosphere
- In Charney de Vore (1979) and following studies, the interaction between mountains and Rossby waves induce a mountain Torque which triggers Blocked regimes (the so-called topographic instabilities Ghil 1987)
- For T_M, M, and Rossby Waves, see also Lejenas and Madden (2000)

II.a) <u>Intraseasonal: relationship between T_M and the AO</u>:

AO and AAO in the NCEP data and in the LMDz model



We take for the AO and the AAO the first EOF of SLP daily variability for the NH and the SH respectively

- The model AO resembles that in the reanalysis although more dominated by the Atlantic Variability.
- The model AAO resembles that in the reanalysis although less zonally symmetric.
- The AO and the AAO first correspond here to reinforcement of the mid-latitude jet-stream (model and reanalysis)

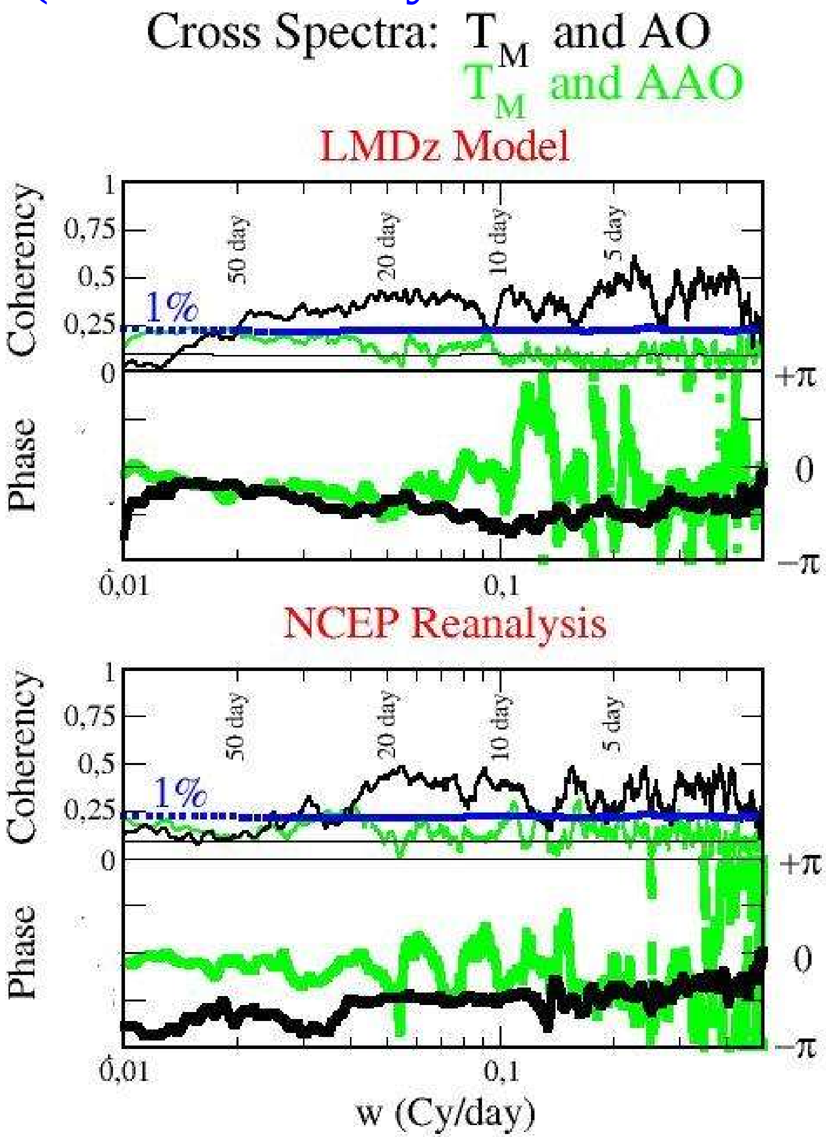
<u>Lott Goudard, and Martin (JGR 2005)</u>

<u>see also: Lott, Robertson, and Ghil (GRL 2001, JAS 2004)</u>

II.a) Intraseasonal: relationship between T_M and the AO:

Mountain Torque, the AO and the AAO, Co-Spectral Analysis

(NCEP Reanalysis and LMDz GCM data)



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

The coherency values are rather small:

It is important to confirm those found in the reanalysis with those from the LMDz-GCM

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

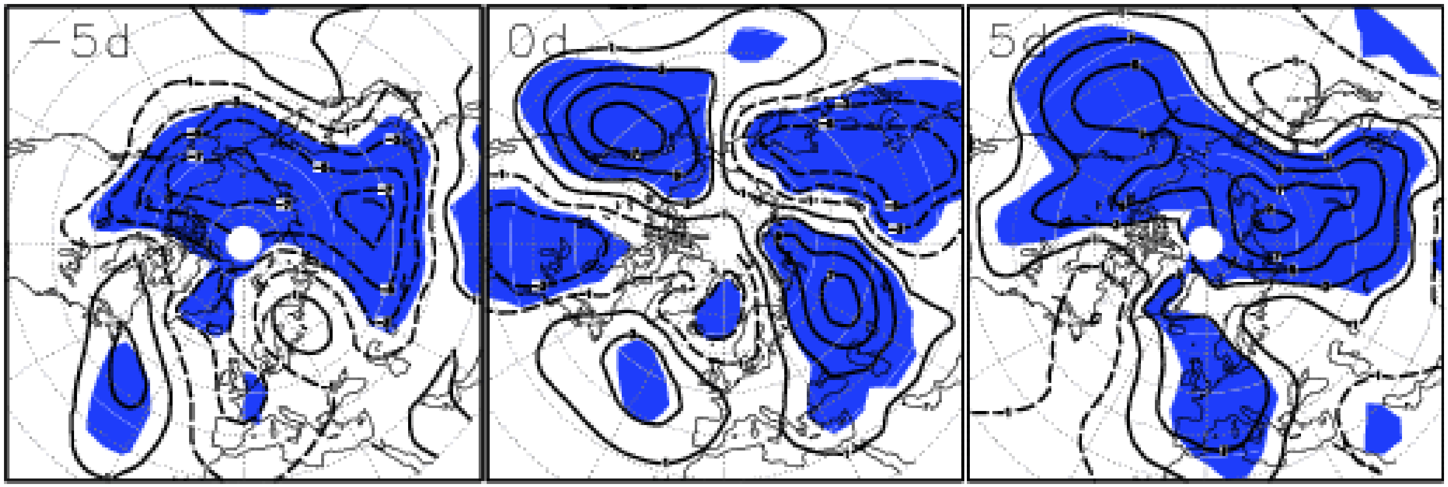
The case of the AAO can be viewed as a natural null hypothesis of our results for the AO

II.a) Intraseasonal: relationship between T_M and the AO:

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 negative mountain torque

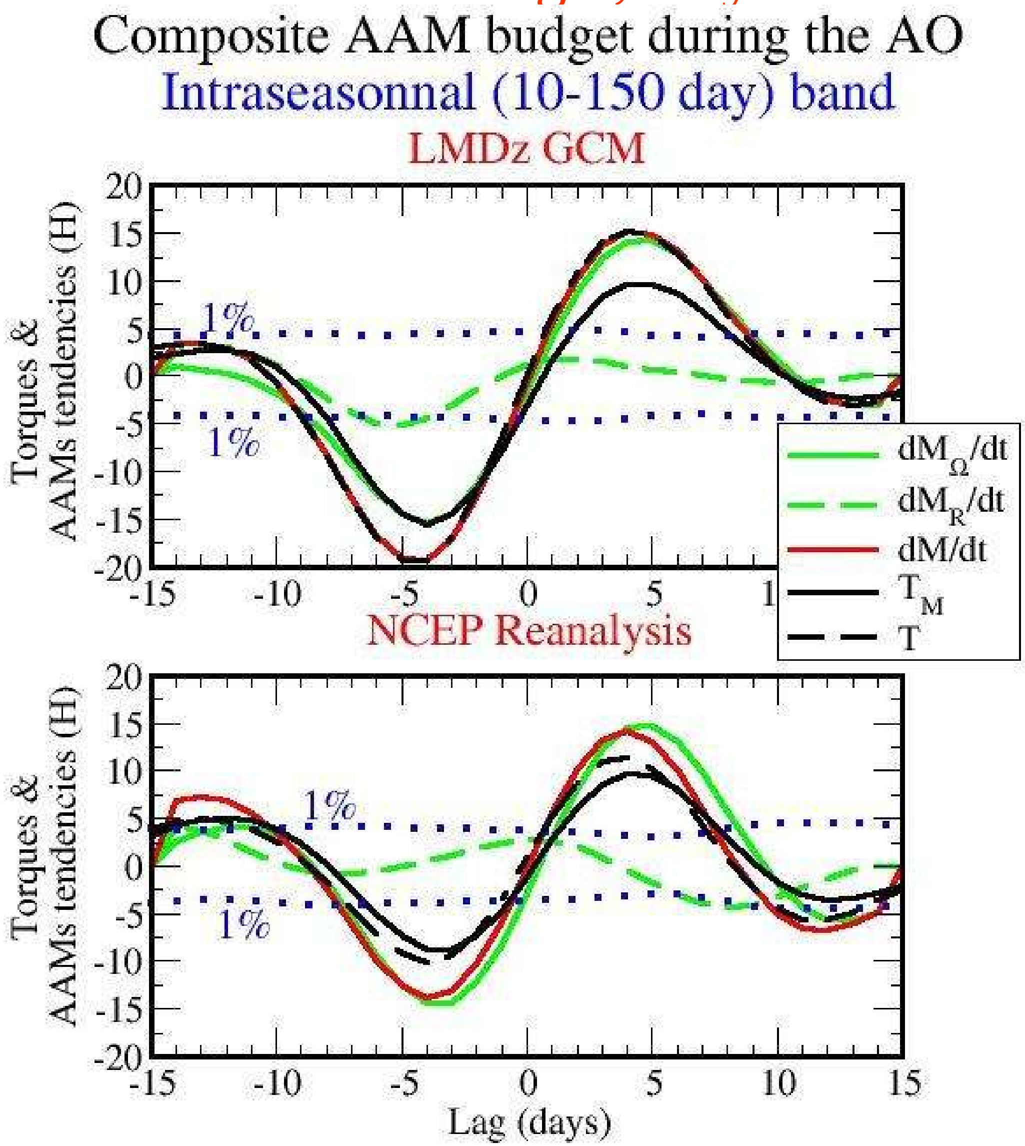
At negative lag the circulation over the NH is predominantly anticyclonic. It is predominantly cyclonic at positive lag: The negative mountain torque has decelerated the flow significantly.

The maps at -5 day lag and +5 day lag project somehow onto the AO.

II.a) Intraseasonal: relationship between T_M and the AO:

Composite analysis

AAM budget, keyed to minima in the AO:



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).

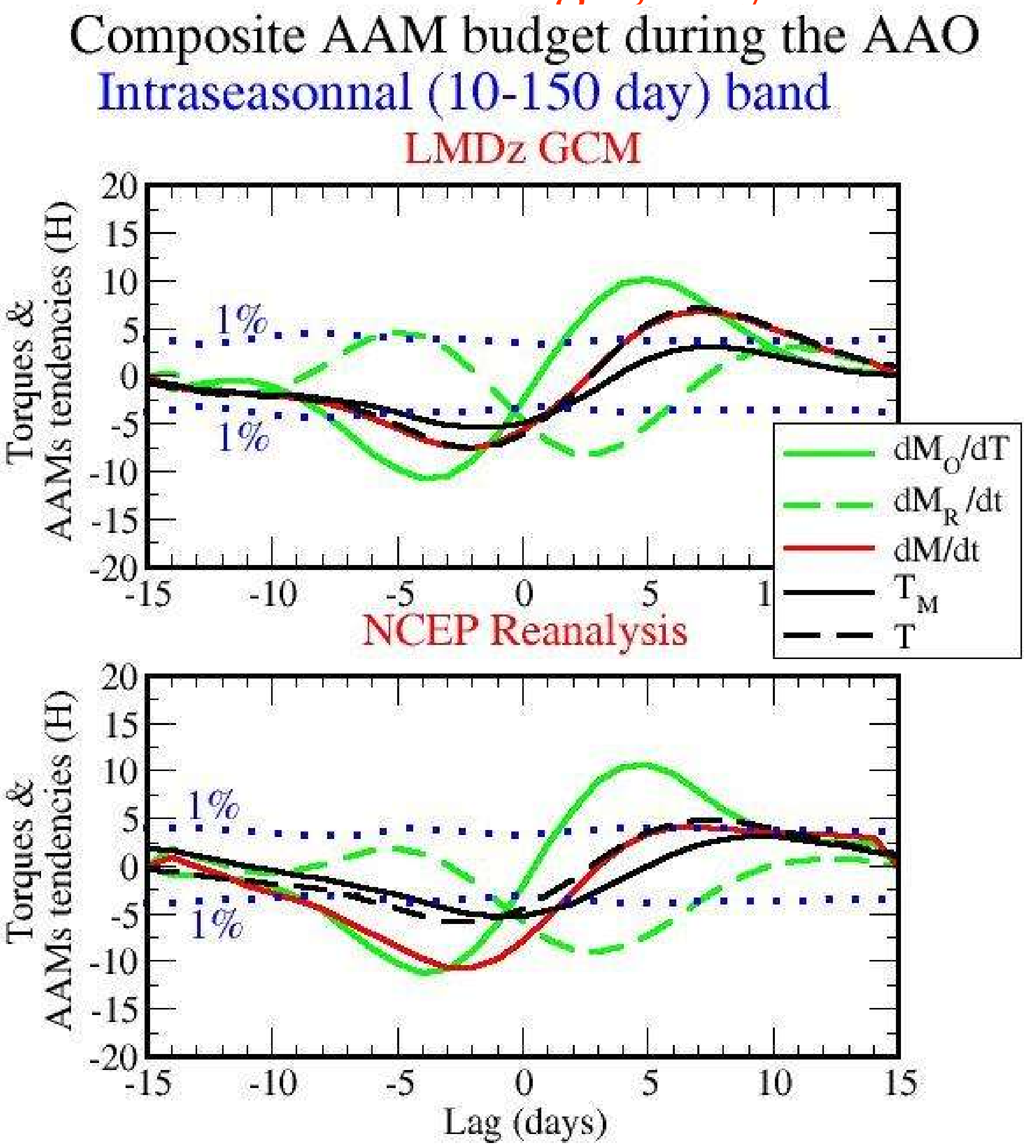
The model behaviour confirms the results from the reanalysis data.

This provides a quantitative evidence that the mountain torque can drive back and forth the AO

II.a) Intraseasonal: relationship between T_M and the AO:

Composite analysis

AAM budget, keyed to minima in the **AAO**:



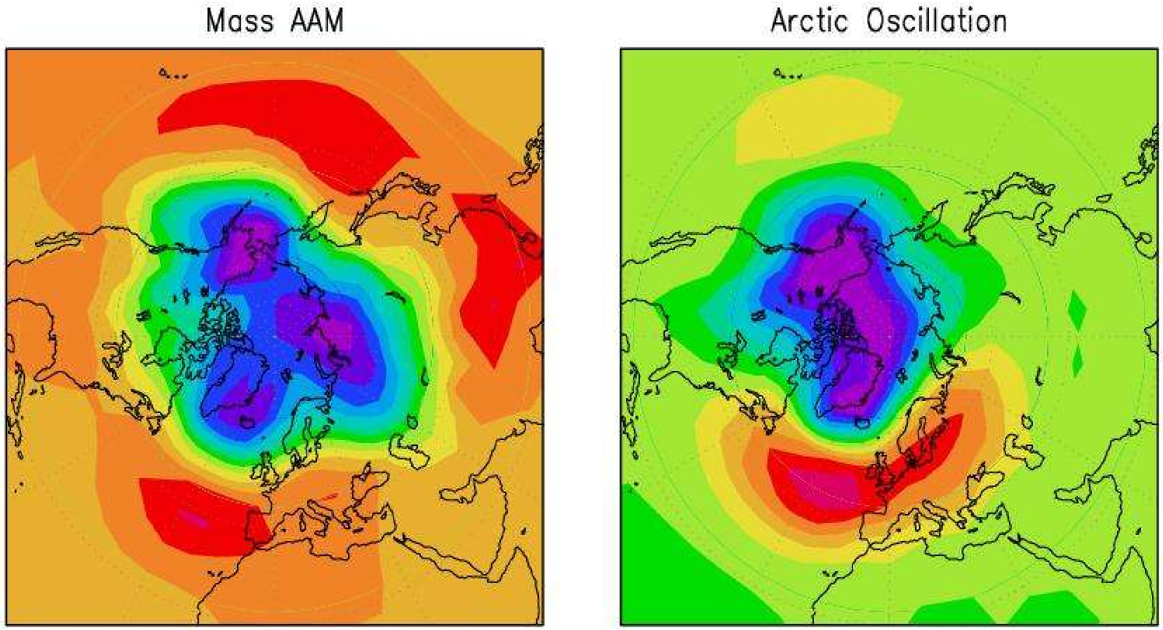
During cycles in AAO the AAM (M) varies little.

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.

II.b) 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

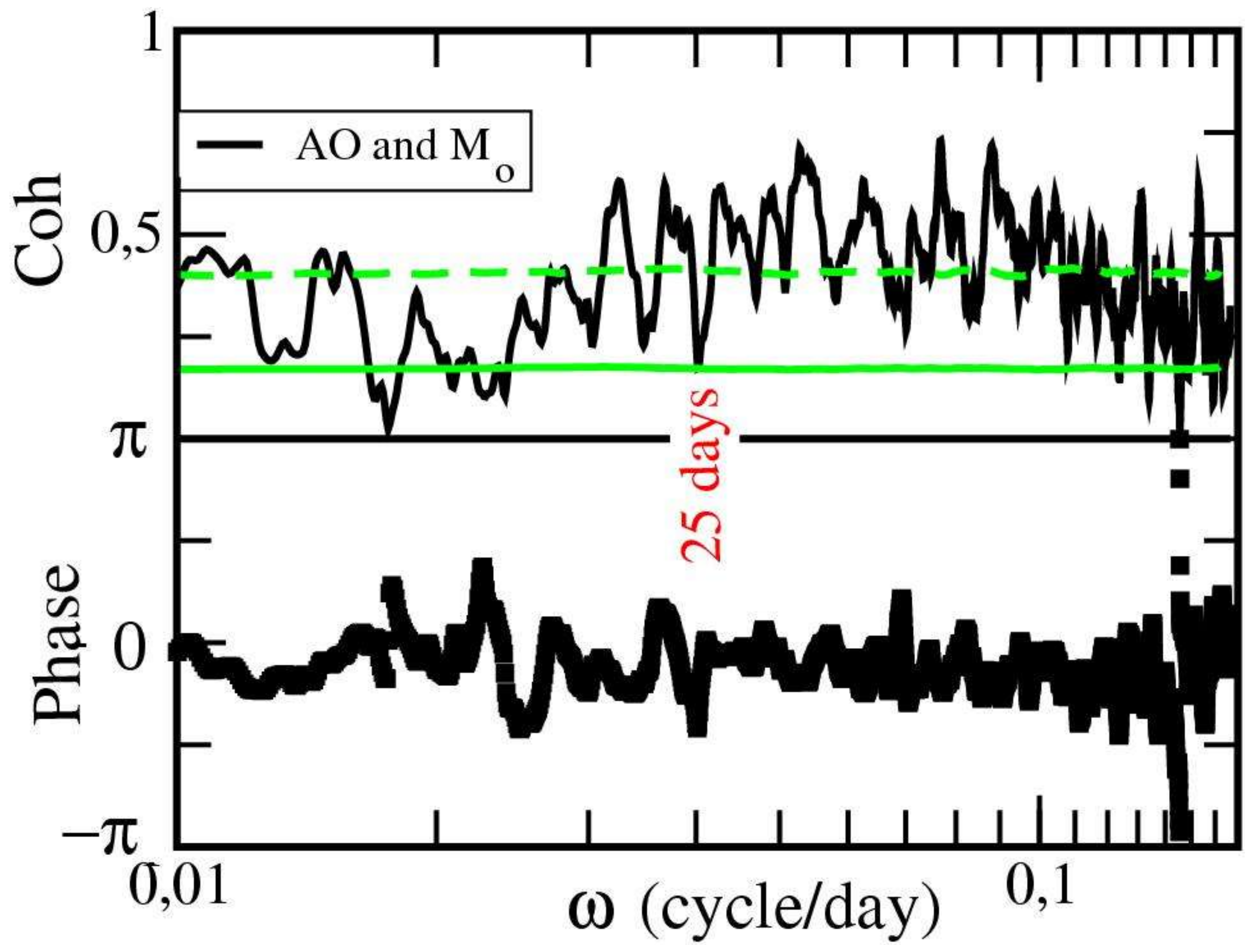
M_O (left) and the A0 (right).

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)

II.b) The role of M_O in the relationship between T_M and the AO?

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



Coherency between the AO and M_O.

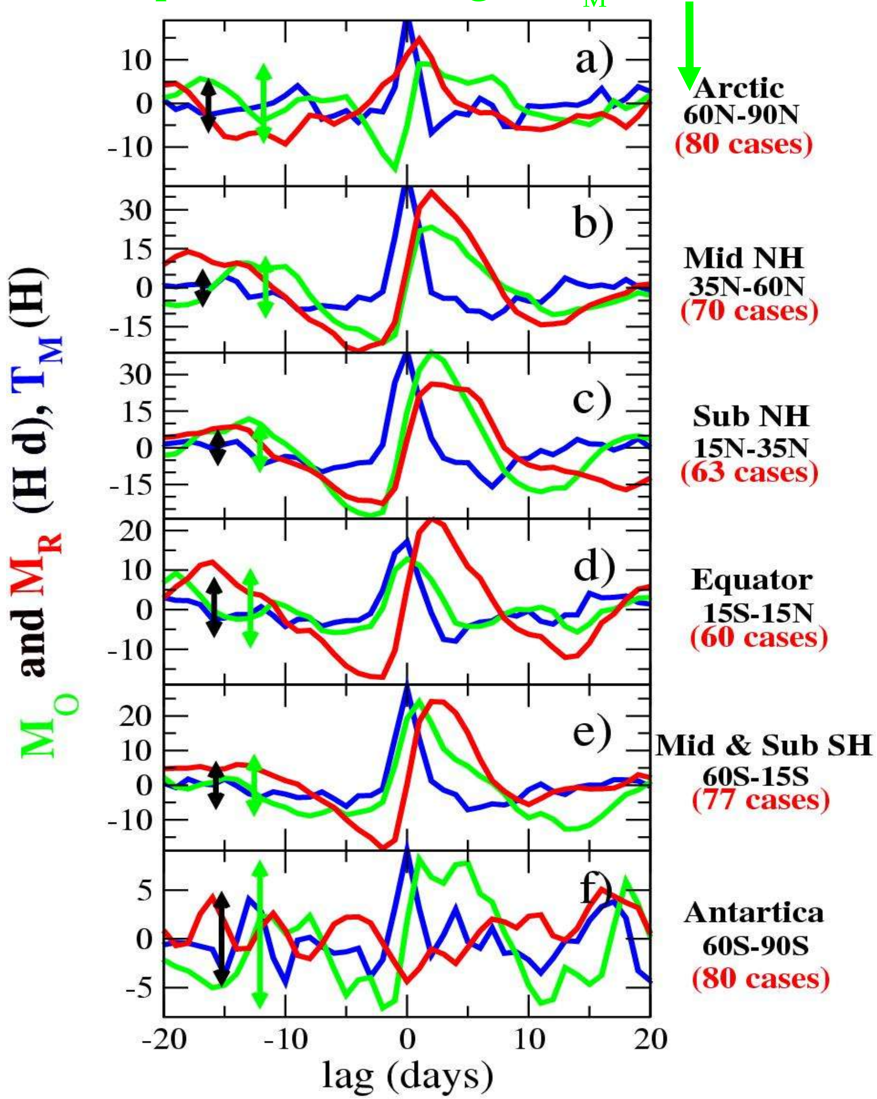
Only Significant for periodicities below 30 days

II.b) The role of M_O in the relationship between T_M and the AO?

Composites of the AAM budget, All data filtered to keep the 1-25 days band

Importance of the geostrophy to explain the partition between M_O and M_R

Composites according to T_M evaluated over 6 different latitude bands



a) and f): T_M due to mountains in the polar regions: $M_O > M_R$

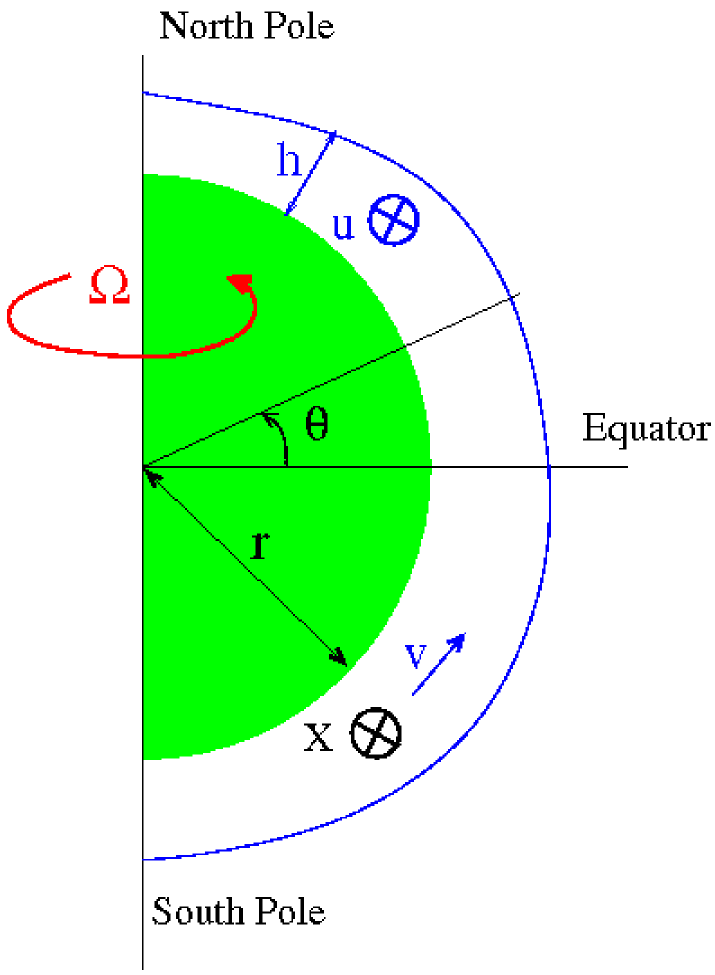
b), c), and e): T_M due to mountains in the mid-latitudes: $M_O \sim M_R$

here, geostrophy makes that a change in wind is equilibrated by a change in mass

f): T_M due to mountains in the tropics: $M_O < M_R$

II.b) The role of M_O in the relationship between T_M and the AO?

Interpretation with a shallow water model



"Dynamically Forced" Shallow Water Equations:

$$\left(\frac{\partial}{\partial t} + \frac{v}{r}\frac{\partial}{\partial \theta}\right) u - \left(2\Omega + \frac{u}{r\cos\theta}\right) v \sin\theta = X \ ,$$

$$\left(\frac{\partial}{\partial t} + \frac{v}{r}\frac{\partial}{\partial \theta}\right) v + \left(2\Omega + \frac{u}{r\cos\theta}\right) u \sin\theta = -\frac{g}{r}\frac{\partial h}{\partial \theta} \ ,$$

$$\frac{\partial h}{\partial t} + \frac{1}{r\cos\theta}\frac{\partial h v \cos\theta}{\partial \theta} = 0 \ .$$

AAM Budget:

$$\frac{d}{dt}(M_R + M_O) = T_X \ ,$$

Wind AAM:

$$M_R = 2\pi r^3 \int_{-\pi/2}^{+\pi/2} h u \cos^2\theta d\theta \ ,$$

Mass AAM:

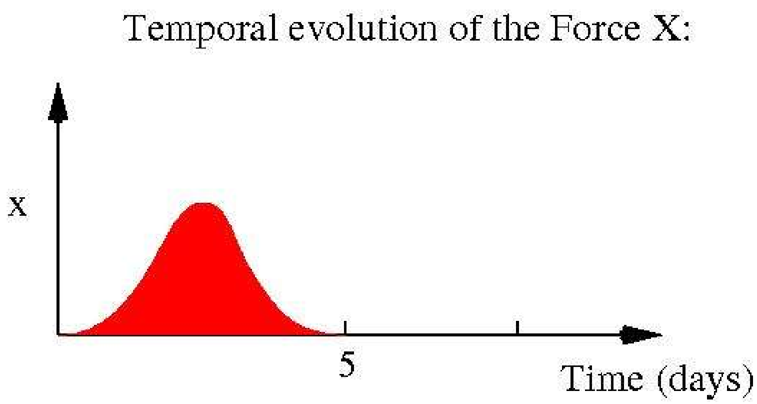
$$M_O = 2\pi r^4 \Omega \int_{-\pi/2}^{+\pi/2} (h - H_0) \cos^3\theta d\theta \ ,$$

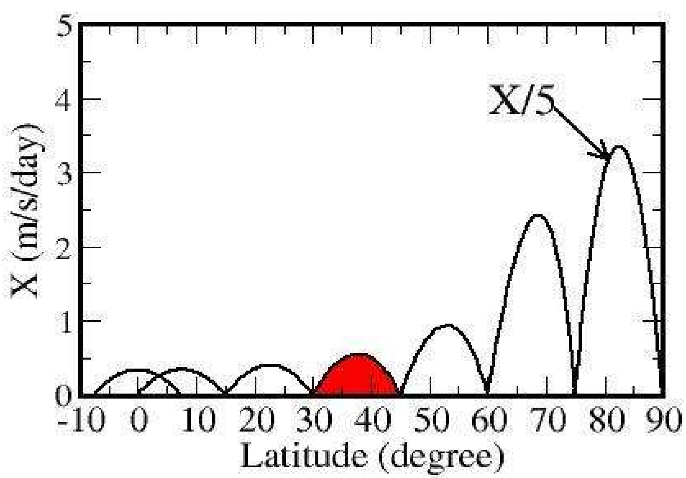
Torque:

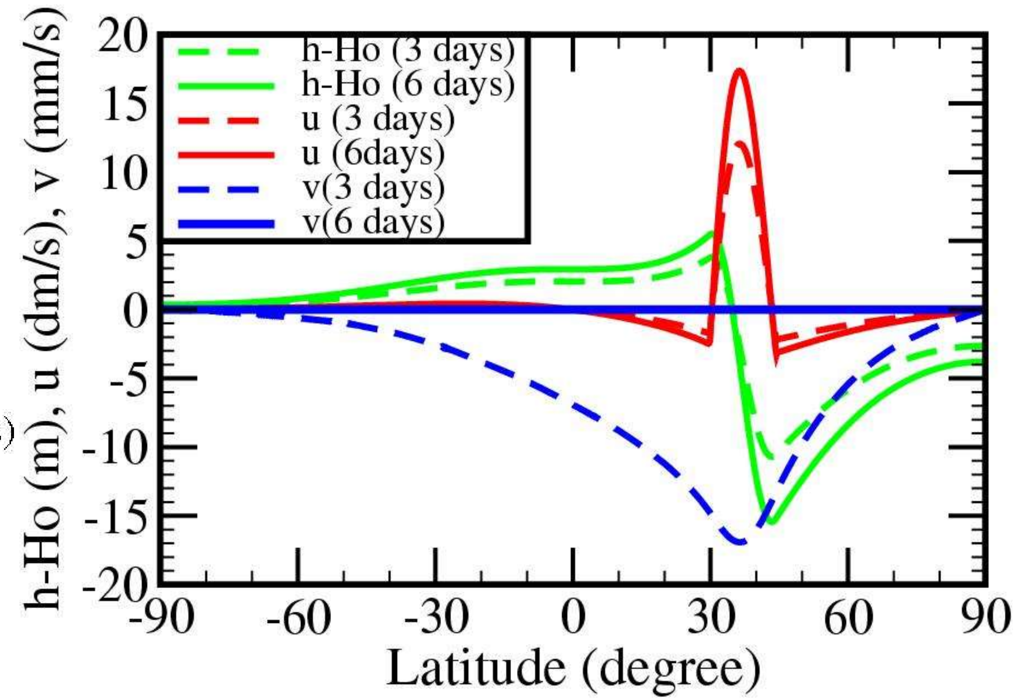
$$T_X = 2\pi r^3 \int_{-\pi/2}^{+\pi/2} \cos^2\theta h X d\theta \ .$$

II.b) The role of M_O in the relationship between T_M and the AO?

Interpretation with a shallow water model







<u>Flow fields (u,v, and h) :</u>

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

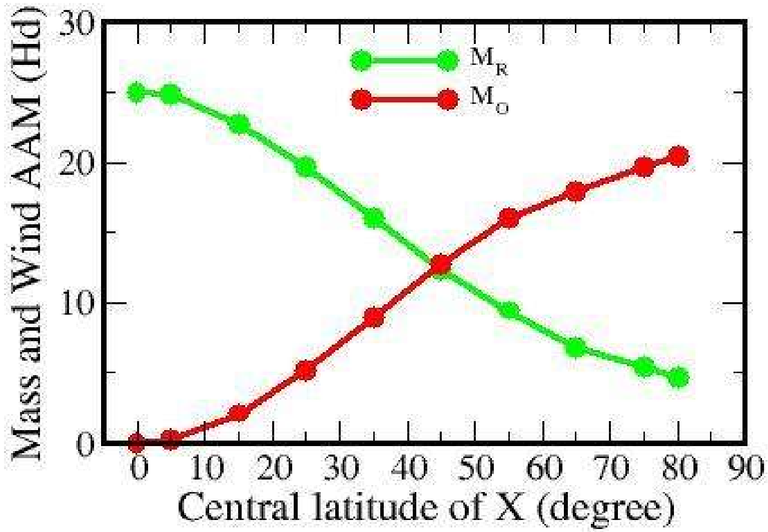
v transports mass from the polar latitude towards the Equator (h<0, north of 40°N, h>0 south of 40°N).

u is in geostrophic balance with h

II.b) The role of M_O in the relationship between T_M and the AO?

Interpretation with a shallow water model

M_R and M_O as a function of the latitude of the Force (X):



As in the Observations:

T_M due to polar regions: $M_O > M_R$

T_M due to mid-latitudes: $M_O \sim M_R$

T_M due to tropics: $M_O < M_R$

As the AO is a mode of variability confined to the mid and high latitudes, its relationships with T_M is primarily due to mountains located at mid and high latitudes.

Those mountains produce a stress distributed to the atmosphere (our forcing X) at mid and high latitudes (to be tested though!).

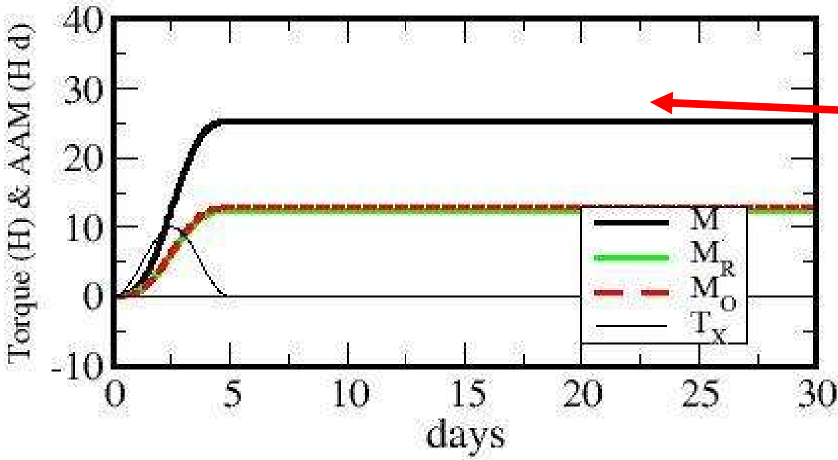
Those mountains produce a torque which modify the AAM, and a good fraction of it is in the mass AAM.

The AO, by its structure is associated to large changes in mass AAM.

III) Diurnal variations in mass and wind AAM

Preliminary: Shallow water model response when the forcing varies rapidly

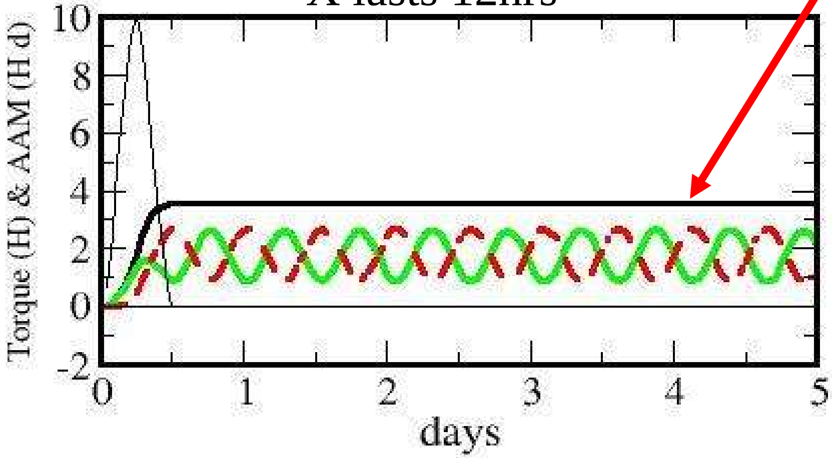
X lasts 5 days

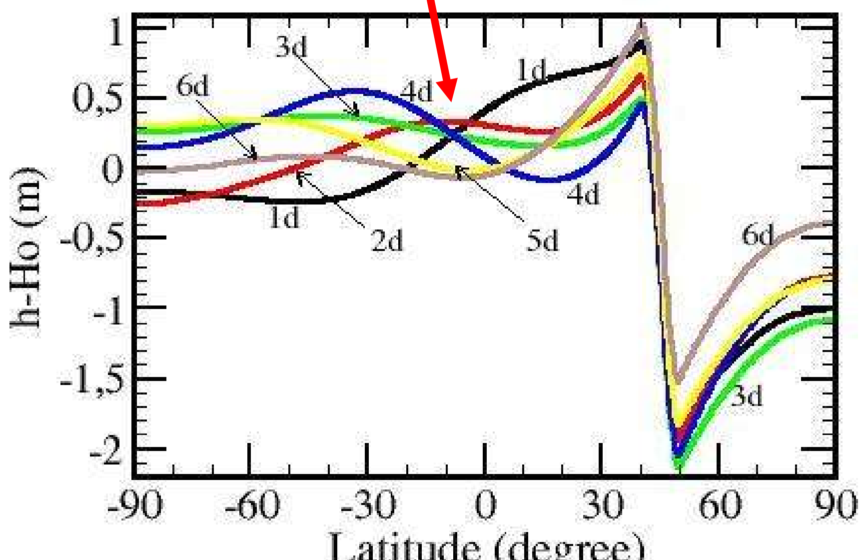


When the forcing varies slowly, the response to the force is adjusted to global Gravity Waves with s=0 (preceding cases)

When the forcing varies rapidly the M_O and M_R responses present near inertial oscillations associated with global scales gravity waves

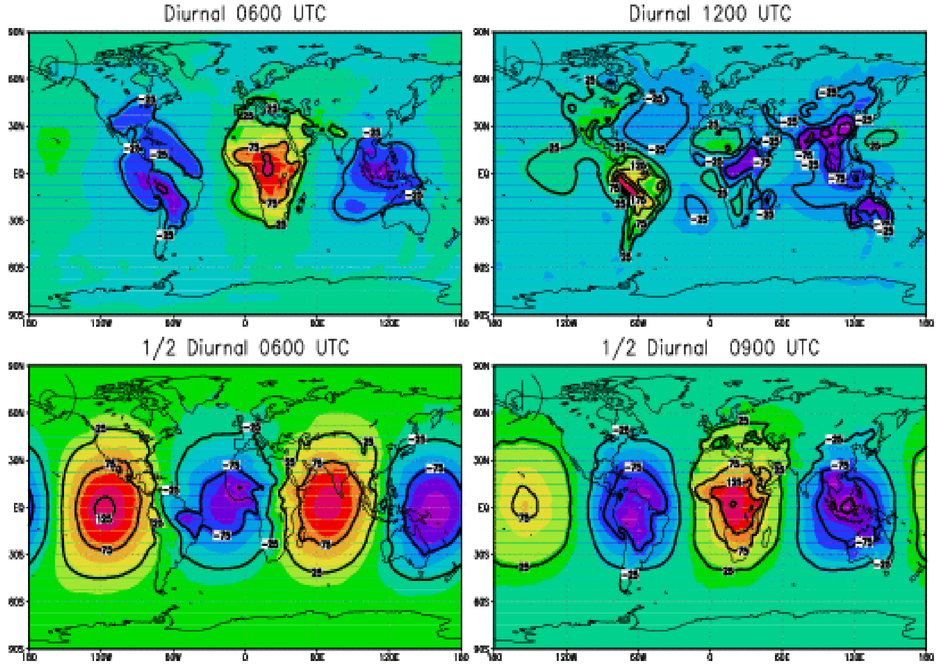
X lasts 12hrs





III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

Diurnal and semi diurnal Surface Pressure tides in LMDz



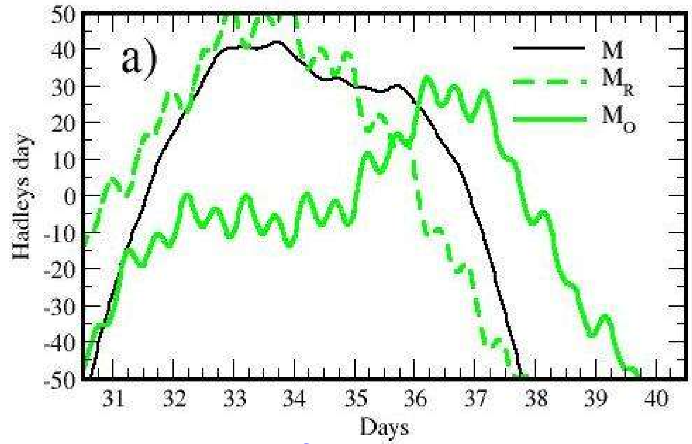
The diurnal tide is dominated by a non-propagating signal that is pronounced over land and deserts.

The semi diurnal tide is dominated by a propagating signal with wavenumber s=2.

Those tidal signals produce a daily cycle in the zonal mean barotropic dynamical forcings of the zonal flow (for instance through interaction with mountains)

III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

AAM budget in LMDz.



Note the daily fluctuations in M_O and M_R

AAM Budget:

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

Mass and Wind AAM:

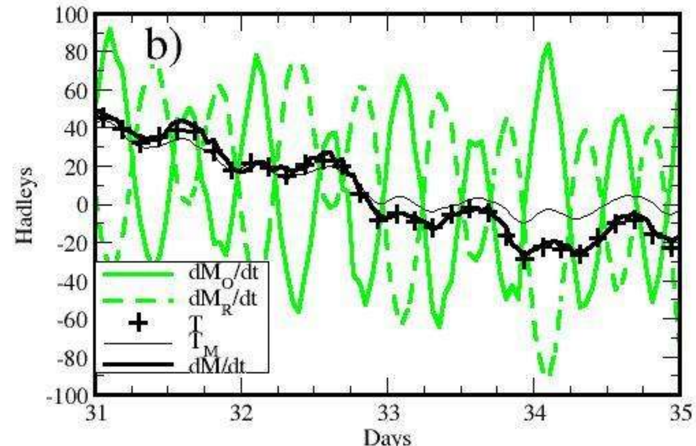
$$M_O = 2\pi r^4 \Omega \int_{-\pi/2}^{\pi/2} \cos^3\phi \, \mathcal{M} \, d\phi$$

$$M_R = 2\pi r^3 \int_{-\pi/2}^{\pi/2} \cos^2\phi \, \mathcal{U} \, d\phi.$$

Mountain and Friction torques

$$T_M = 2\pi r^3 \int_{-\pi/2}^{\pi/2} \cos^2\phi \, \mathcal{T} \, d\phi$$

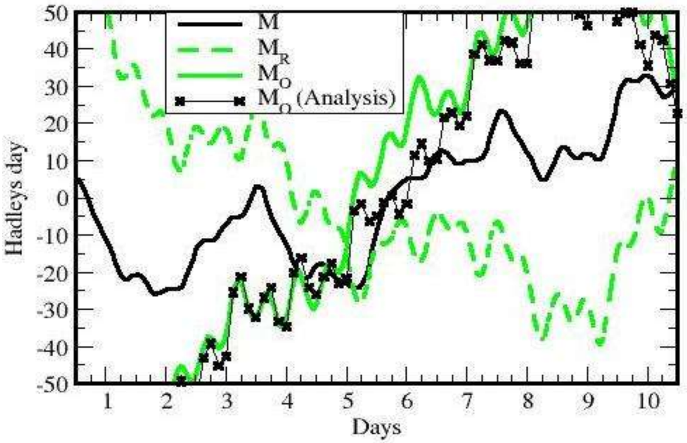
$$T_B = 2\pi r^3 \int_{-\pi/2}^{\pi/2} \cos^2\phi \, \mathcal{B} \, d\phi.$$



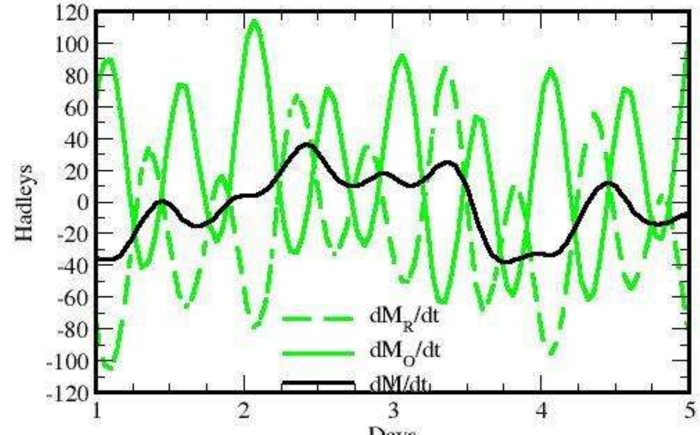
Note the large daily fluctuations in M_O and M_R tendency (almost 100H) compared to the rather small daily cycles in the Torques

III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

AAM in the ECMWF model, 2004 operational version: 10 days forecasts and operational analysis



Note the daily fluctuations in M_O and M_R (10 day Forecast and reanalysis)$_t$



Note the large daily fluctuations in M_O and M_R tendency (almost 100H) compared to the rather small daily cycles in the M tendency

III.a) Diurnal in M_R and M_O:

AAM in the ECMWF model,

2004 operational version:

12 10 days forecasts.

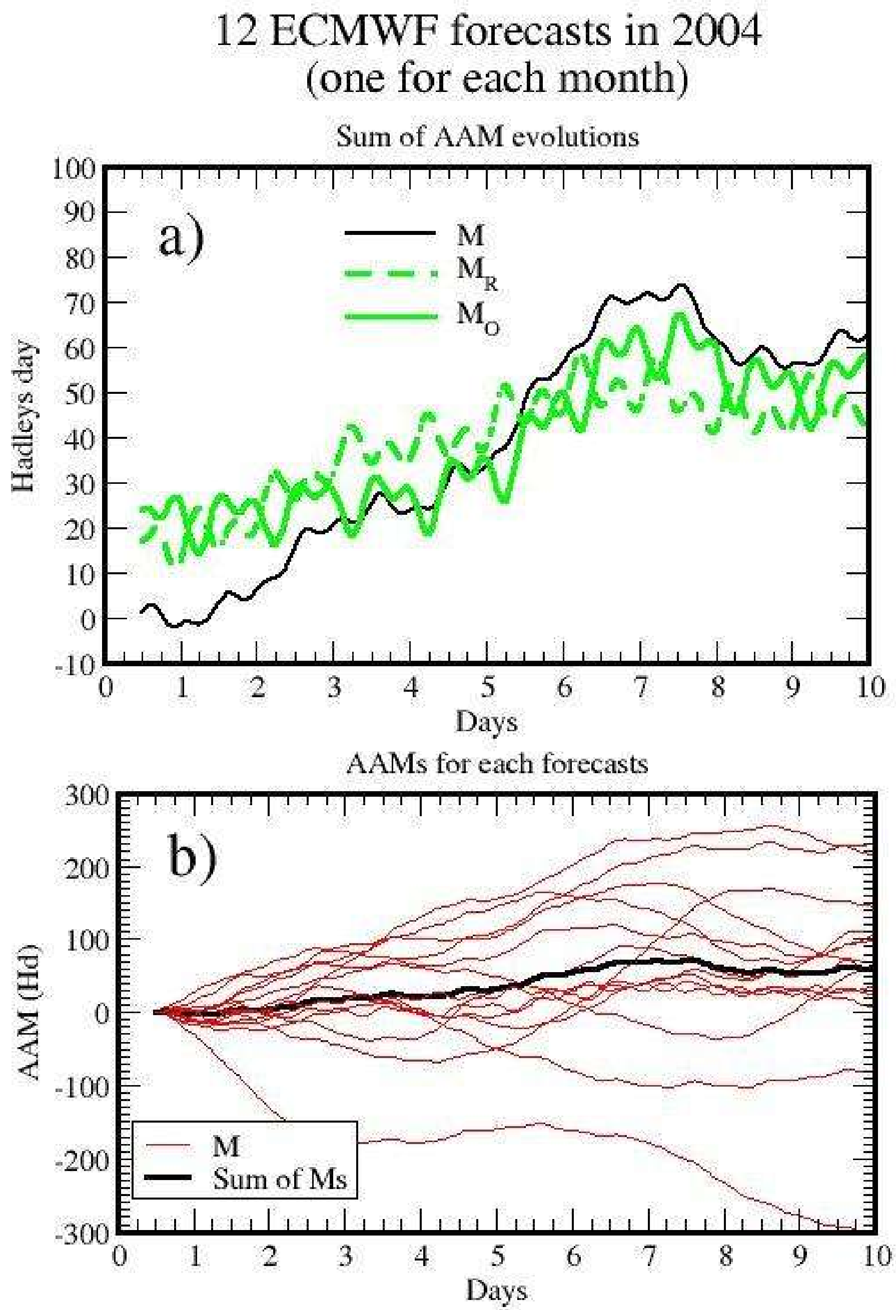
Note the robustness of the daily oscillations: tidal signal rather than initial adjustment.

The drift of M during the first 5-7 days

The drift of the mean M is above 50Hd, it is 1% significant out of the 12 cases here.

The associated torque dM/dt ~10H, compares with the magnitude of a the frictional torque

(see also Huang et al. For the NCEP/NCAR model)



III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

Diurnal and ½ diurnal mass AAM budget

Splitted AAM budget:

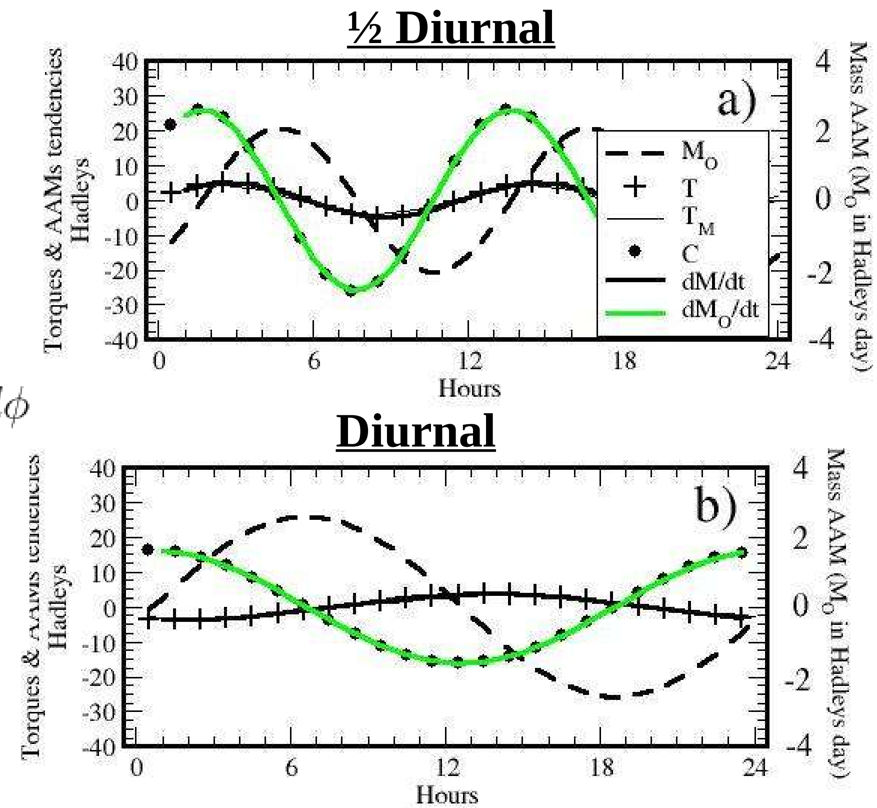
$$\frac{dM_O}{dt} = C\ ,\quad \frac{dM_R}{dt} = -C + T$$

Coriolis Conversion term:

$$C = -4\pi r^3 \Omega \int_{-\pi/2}^{\pi/2} \cos^2\phi \sin\phi\, \mathcal{V}\, d\phi$$

Vertical and zonal mean of ρv:

$$\mathcal{V} = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{P_S} v\frac{dp}{g} d\lambda.$$



Note the very large Coriolis conversion term (compared to the Torque).

Only patterns for $\mathcal{V}$ antisymetric with respect to the Equator can yield to a large Coriolis conversion term.

III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

Axisymmetric (s=0) and barotropic semi diurnal tides

Zonal mean and barotropic Eqs:

$$\frac{\partial \mathcal{U}}{\partial t} - 2\Omega \sin\phi \mathcal{V} = \mathcal{X}$$

$$\frac{\partial \mathcal{M}}{\partial t} + \frac{1}{r\cos\phi}\frac{\partial}{\partial\phi}\cos\phi\mathcal{V} = 0.$$

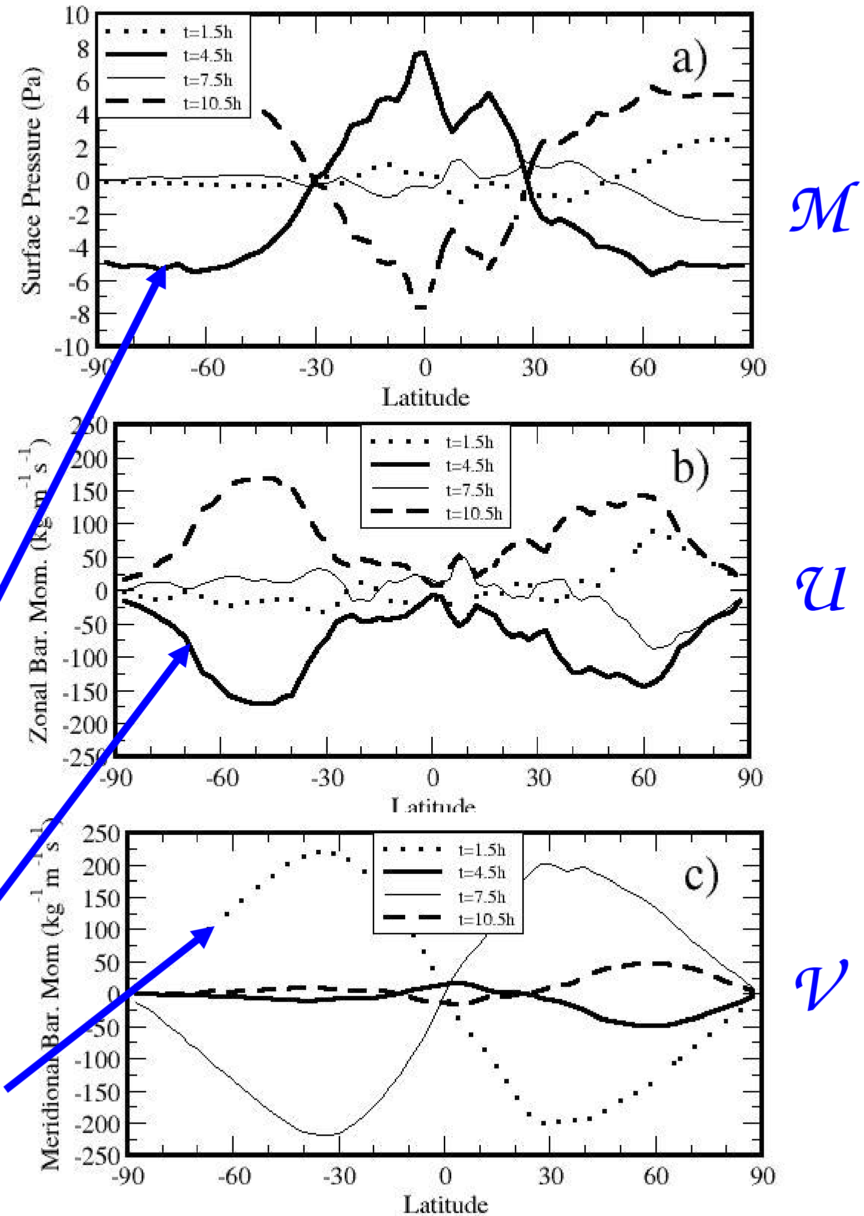
Zonal mean mass:

$$\mathcal{M} = \frac{1}{2\pi}\int_0^{2\pi}\frac{P_s}{g}d\lambda \quad ,$$

Vertical and zonal mean of ρu:

$$\mathcal{U} = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{P_S} u\frac{dp}{g}d\lambda$$

$\mathcal{X}$: Friction stress+mountain stress + div AAM flux

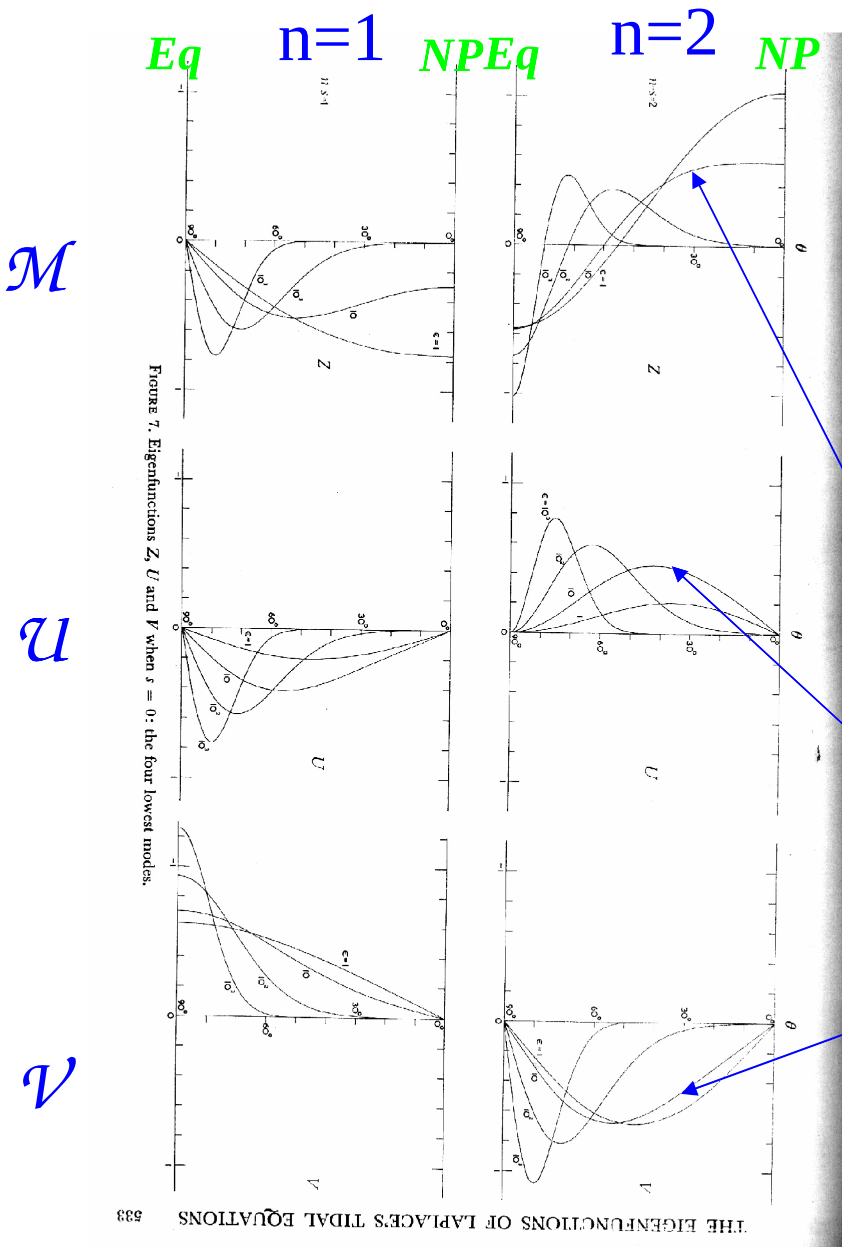


When the mass AAM is >0 (t=4.5hr) there is an excess of mass $\mathcal{M}$ in the tropics

The wind AAM is < 0 at the same time and the barotropic and zonal wind $\mathcal{U}$ is everywhere<0

In quadrature before (t=1.5hr) $\mathcal{V}$ is positive in the SH and negative in the NH bringing mass from the Midlat. toward the Eq. band

III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes



Eigensolutions of the s=0 Laplace tidal Eqs. (Figures and results here are from Longuet Higgins 1969).

Note the resemblance of the ½ diurnal signal with the <u>second gravest (n=2)</u> Eigensolution of the Laplace Tidals Eqs. with s=0 (axisymmetric)

ε=10 corresponds to an equivalent depth H_0~8km (barotropic tidal signal)

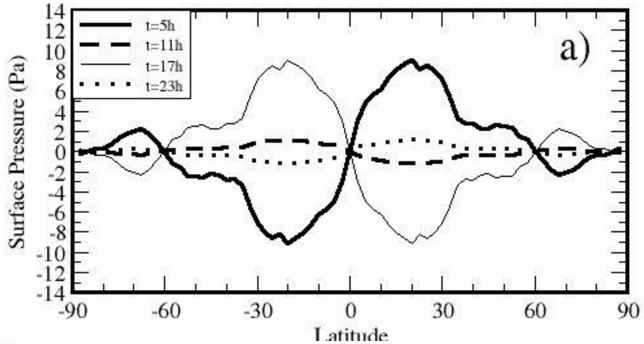
III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes

Axisymetric (s=0) and barotropic <u>diurnal</u> tides in LMDz

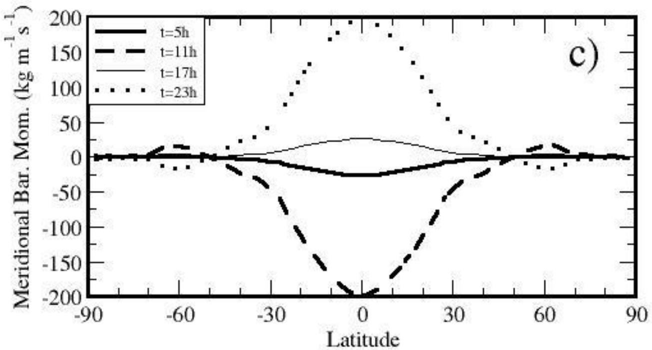
Pattern for M antisymetric with respect to the Equator

and for V symetric with respect to the Equator

M



V

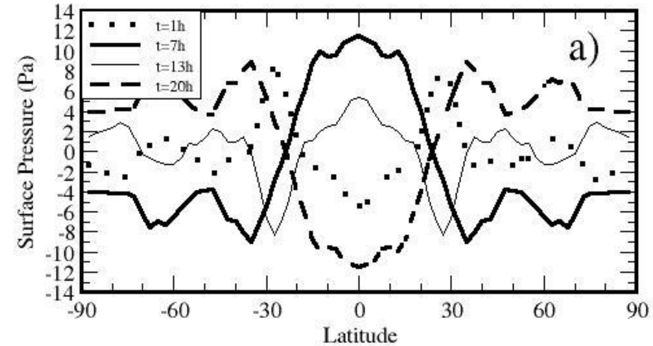


- **No signal on the mass AAM M_O: an excess of mass M in one hemisphere is compensated by a deficit in the other.**
- **V is of uniform sign and max at the Equator**
- **Looks like an n=1, s=0 tidal Eigensolution**

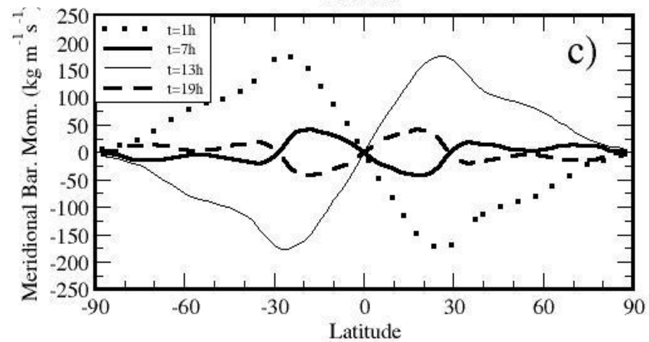
Pattern for M symetric with respect to the Equator

and for V antisymetric with respect to the Equator

M

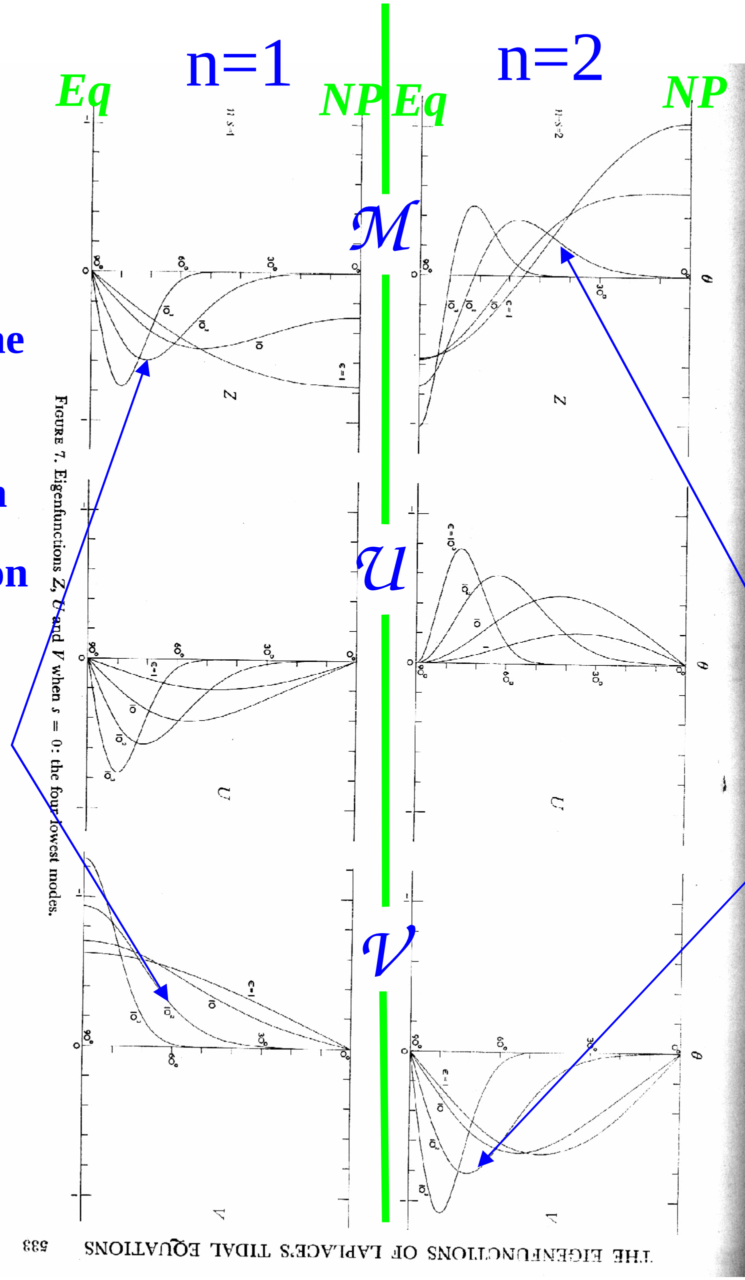


V



- **When the mass AAM M_O >0 (t=7hr) there is an excess of mass M in the tropics**
- **In quadrature before (t=1hr) V >0 in the SH and V<0 in the NH**
- **Like an n=2, s=0 tidal Eigensolution**

III.a) Diurnal in M_R and M_O: Surface pressure tides and s=0 modes



Note the resemblance of the Equatorial Antisymetric diurnal signal in ℳ with the first (n=1) Eigensolution of the s=0 tidals Eqs.

ε=100 corresponds to an equivalent depth H_0~1km (baroclinic tidal signal)

Note the resemblance of the Equatorial Symetric diurnal signal in ℳ with the first (n=2) Eigensolution of the s=0 tidals Eqs.

ε=100 corresponds to an equivalent depth H_0~1km (baroclinic tidal signal)

III.b) Dynamical interpretation with a shallow water set of Eqs.

Hypothesis: the dynamical forcings of the barotropic Zonal wind induce tidal signals

Zonal mean and barotropic Eqs:

$$\frac{\partial \mathcal{U}}{\partial t} - 2\Omega \sin\phi \mathcal{V} = \mathcal{X} = \mathcal{T} + \mathcal{F} + \mathcal{B},$$

Divergence of the AAM flux:

$$\mathcal{F} = -\frac{1}{r\cos^2\phi}\frac{\partial}{\partial\phi}\frac{\cos^2\phi}{2\pi}\int_0^{2\pi}\int_0^{P_S} uv\frac{dp}{g}d\lambda$$

Surface stress due to friction:

$$\mathcal{B} = \frac{1}{2\pi}\int_0^{2\pi}\tau_B d\lambda$$

Surface stress due to mountains:

$$\mathcal{T} = -\frac{1}{2\pi}\frac{1}{r\cos\phi}\int_0^{2\pi} P_s\frac{\partial Z_s}{\partial\lambda}d\lambda$$

Linear Eqs. for an axisymmetric atmosphere:

$$\rho_0\frac{\partial\overline{u}}{\partial t} - 2\Omega\sin\phi\,\rho_0\overline{v} = \overline{X},$$

$$\rho_0\frac{\partial\overline{v}}{\partial t} + 2\Omega\sin\phi\,\rho_0\overline{u} = -\frac{g}{r}\frac{\partial\overline{h}}{\partial\phi}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial\overline{h}}{\partial z} + (1-\kappa)\frac{\overline{h}}{H}\right) + \frac{\kappa}{H}\rho_0\overline{w} = 0$$

If $\overline{X}$ is of the form:

$$\overline{X} = \tilde{X}(t,\phi)\exp(-z/2H - \beta z),$$

A particular solution is of the form:

$$(\rho_0\overline{u}, \rho_0\overline{v}, \rho_0\overline{w}, \overline{h}) = \left(\tilde{u}, \tilde{v}, \tilde{w}, \tilde{h}\right)(t,\phi)\exp(-z/2H - \beta z)$$

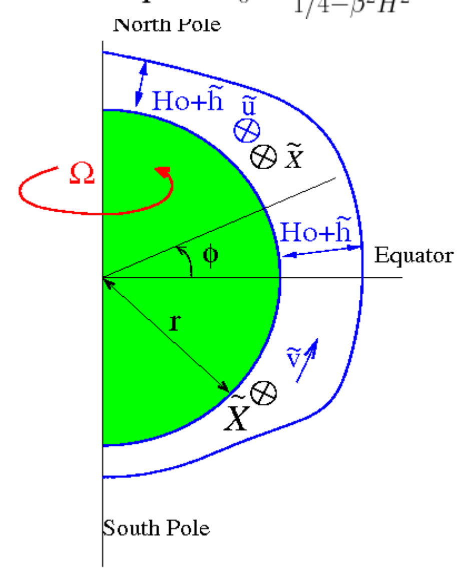
Yielding to the linearized shallow water Eqs:

$$\frac{\partial\tilde{u}}{\partial t} - 2\Omega\sin\phi\,\tilde{v} = \tilde{X},$$

$$\frac{\partial\tilde{v}}{\partial t} + 2\Omega\sin\phi\,\tilde{u} = -\frac{g}{r}\frac{\partial\tilde{h}}{\partial\phi},$$

$$\frac{\partial\tilde{h}}{\partial t} + \frac{H_0}{r\cos\phi}\frac{\partial}{\partial\phi}\cos\phi\,\tilde{v} = 0,$$

H_0 **is the equivalent depth:** $H_0 = \frac{\kappa H}{1/4 - \beta^2 H^2}$.



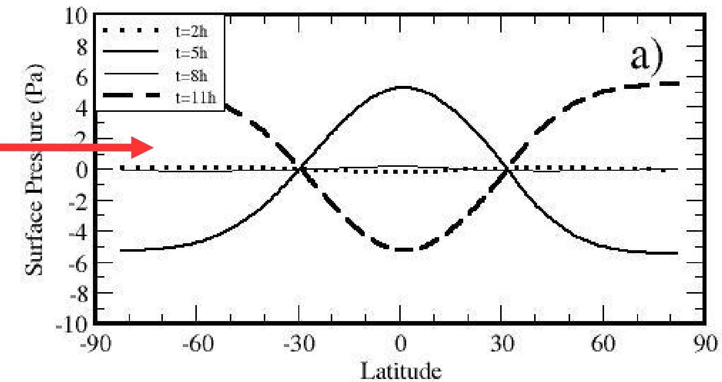
III.b) Dynamical interpretation with a shallow water set of Eqs.

Hypothesis: the dynamical forcings of the barotropic Zonal wind induce tidal signals

Mass response to the 1/2-Diurnal $\mathcal{T}$,

Ho=9.5km (barotropic case).

½ diurnal mass AAM cycle of the correct phase and amplitude



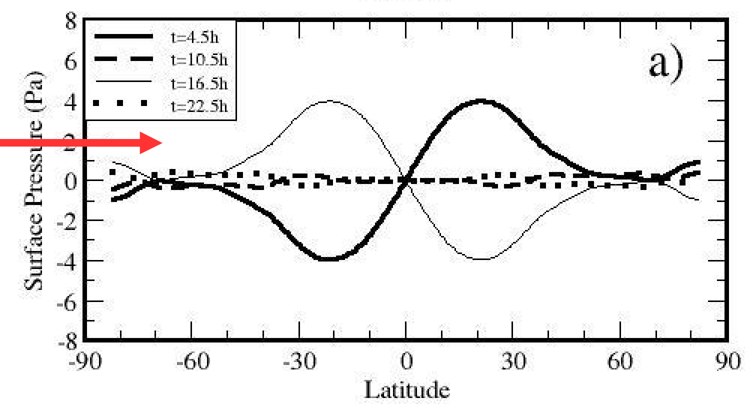
$\mathcal{M}$

Mass response to the Diurnal $\mathcal{T}$,

Ho=2.5km (baroclinic case 1).

No mass AAM cycle,

agreement in phase and amplitude with the diurnal mass pattern $\mathcal{M}$ from the GCM

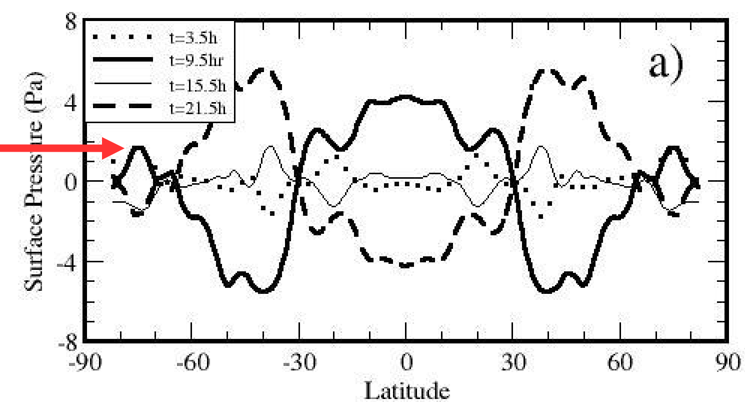


$\mathcal{M}$

Mass response to the Diurnal $\mathcal{F}$,

Ho=1km (baroclinic case 2).

Mass AAM cycle in agreement <u>in amplitude only</u> with that from the GCM. Mass pattern $\mathcal{M}$ in qualitative agreement with that from the GCM



$\mathcal{M}$

Summary (Intraseasonal):

- The NCEP reanalysis and a 30-year integration done with the LMDz GCM have been used to evaluate the relationships between the mountain Torque $\mathbf{T_M}$ and the Arctic Oscillation (**AO**).

- We find that $\mathbf{T_M}$ affects the **AO** via the mass Angular momentum $\mathbf{M_O}$, and because the AO redistributes mass from the polar regions toward the mid-latitudes and subtropics.

- The role of $\mathbf{M_O}$ in the relationships between $\mathbf{T_M}$ and the **AO** are explained by the fact that Mountain Forces applied in the mid and high latitudes induce changes in mass AAM that compare or that are larger than the corresponding changes in wind AAM $\mathbf{M_R}$.

- As the Antarctic Oscillation (**AAO**) is also associated with such a redistribution of the air masses, we show that the changes in $\mathbf{M_O}$ during variations of the AAO are in good part equilibrated by changes of opposite sign in $\mathbf{M_R}$ (which is not the case for the AO, where the $\mathbf{M_O}$ changes are driven by $\mathbf{T_M}$).

The interest of these results is that the mountain torque drives the changes in AAM, so it can actively participate to changes of the AO.

Summary (Diurnal):

- **M_O** and **M_R** in atmospheric models present large diurnal and semi-diurnal compensating oscillations associated with the n=2 axisymmetric (s=0) component of the atmospheric surface pressure tides.
- The axisymmetric diurnal tidal signal also present a substantial n=1 patterns that do not affect **M_O** and **M_R**.
- A small error in the evaluation of those terms can lead to a poor estimation of the diurnal cycle of the AAM budget: see the problems in conciliating the AAM budget approach and the torque approach to evaluate the diurnal forcings of the axial AAM by mixing forecasts and analysis products **(deViron et al. 2005).**
- Still in geodesy, the axisymmetric n=2 component can affect the Earth ellipcity, and the n=1 component the geocenter position.
- A shallow water model driven by zonal mean forces which vertical integral equal the zonal mean stresses issued from the LMDz-GCM reproduces a good part of this tidal signals. This suggests that the axisymmetric surface pressure tides can in good part be due to a dynamical forcing of the zonal mean flow.

Lott, de Viron, Vial and Viterbo (JAS 2008)