General Circulation of the Stratosphere and modelisation

a) Basic climatologies

b) Interpretation of the dynamics with a heuristic model

c) Brewer Dobson circulation

d) Middle latitudes dynamics
Stratospheric sudden warmings

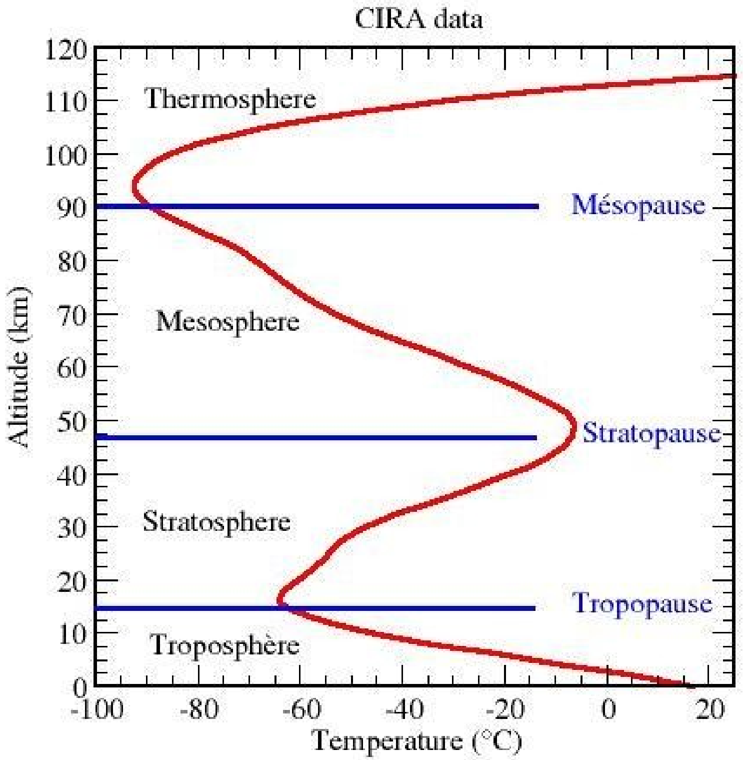
e) Equatorial dynamics
Semi annual and quasi-biennal oscillations

f) Convective gravity waves parameterization and impact in the tropics

g) Frontal gravity waves parameterization and impacts in the midlatitudes

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

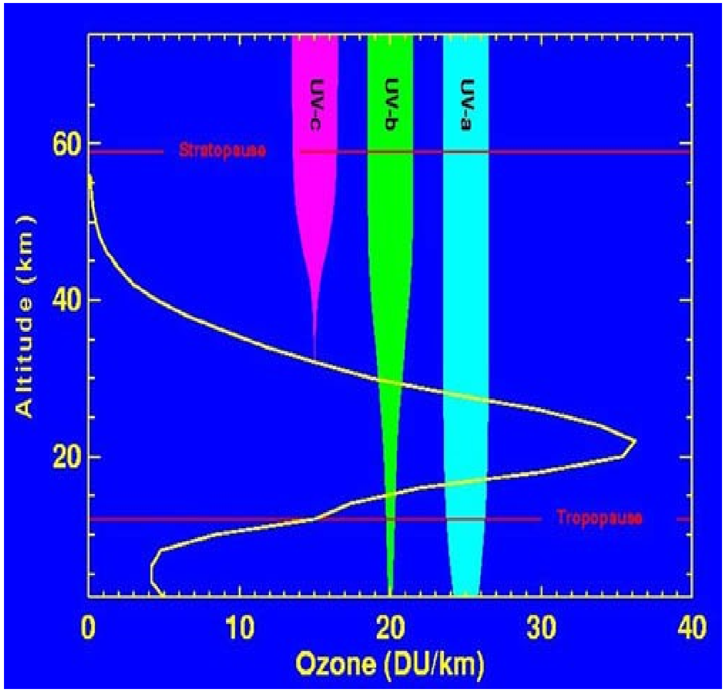
Global average of Temperature as a function of altitude



- CIRA data (1988): Rockets, rasiosondes, satellites above 110km.
- Troposphere: T decreases with z*, the heating comes from the surface, whereas the water vapor and clouds cool the atmosphere above via infrared emission (IR).
- The middle atmosphere:
  - contain 2 of the 3 layers of the neutral atmosphere: the stratosphere and the mesosphere.
  - Les chemical major constituant are still well mixed
  - There is a Max in T at 50km due to 03. This defines the stratopause separating the stratosphere and the mesosphere
- Above 90km lies the thermosphere, a layer highly exposed to sun radiation and the X-rays ionised the constituents. It contains the ionosphere (80-500km) where Aurora Borealis occur.
- Extremely thin in mass, T can vary from 600K to 1800K in one day.
- The atmosphere there is no longer neutral, is no longer well mixed: the composition varies according to the mass of the molecules because of the large distance between them.

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

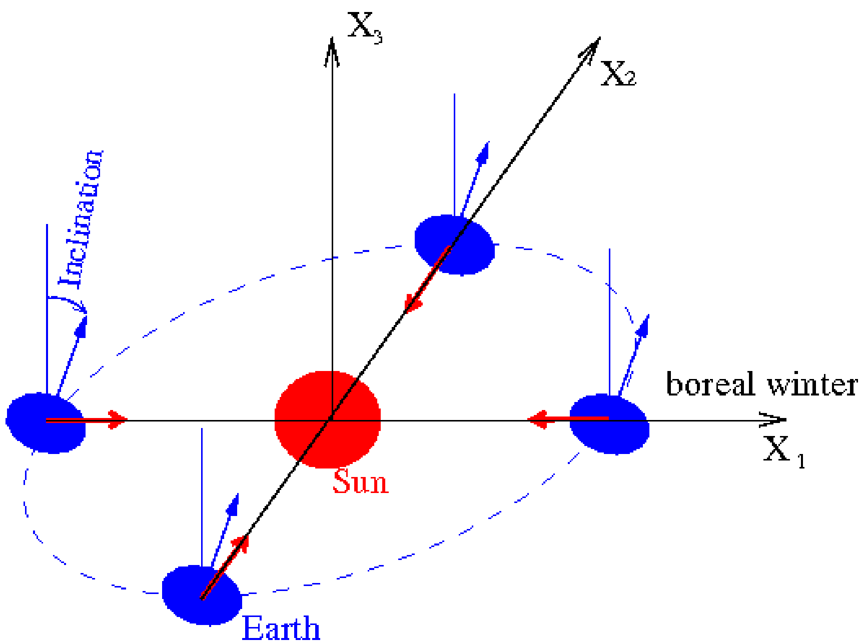
- Absorption of Uv-b by 03 is driving the middle atmosphere circulation

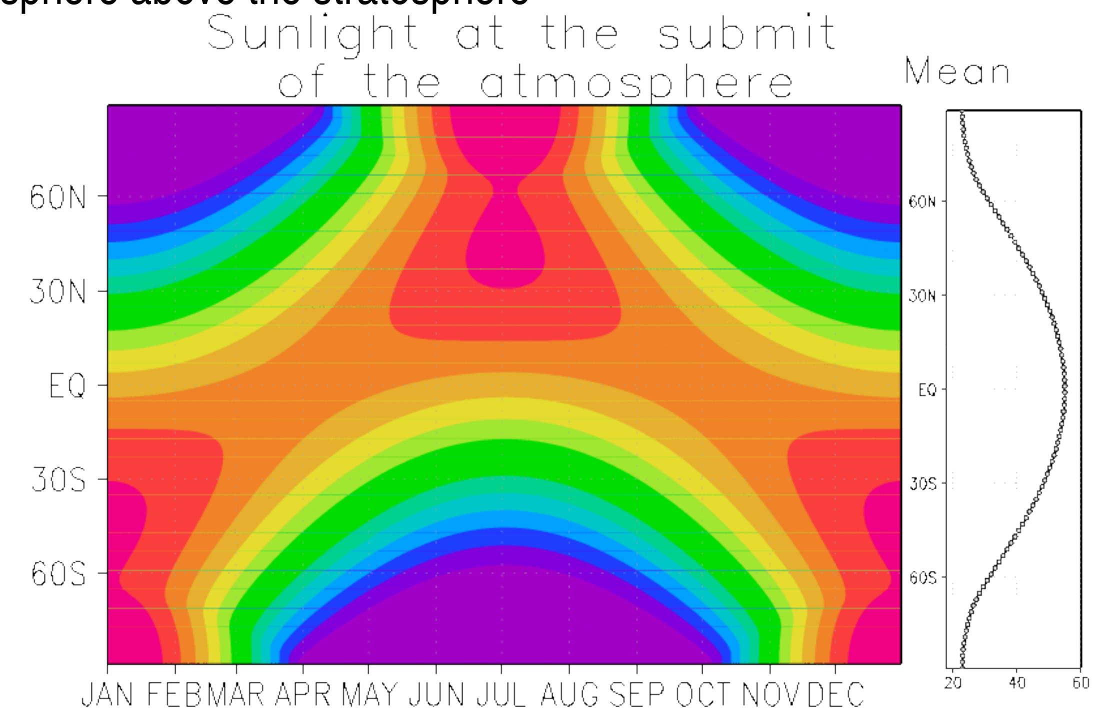


Profil d'Ozone aux moyennes latitude et
Altitude de pénétration des UV-a, UV-b, UV-c

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

Heating by ozone build-up the stratosphere above the stratosphere



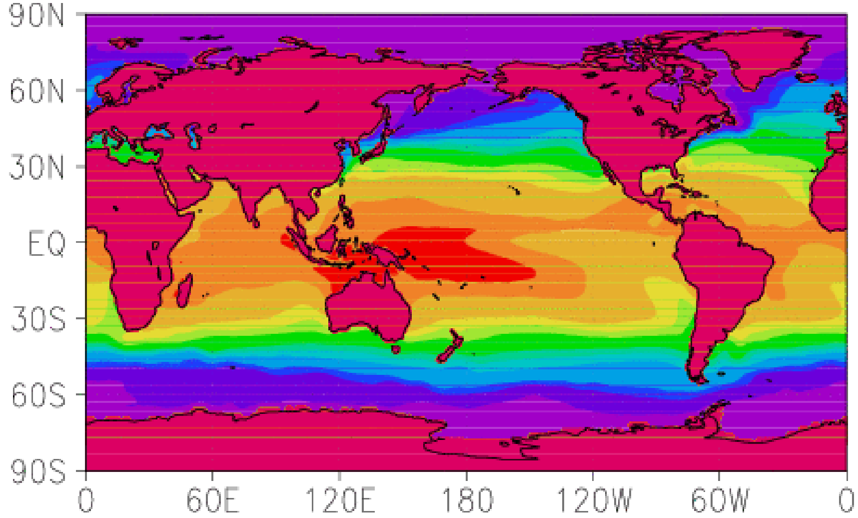


Ozone re-emit quasi immediatly, and through chemical heating the UV-radiation it absorbs ($O+O_2 \rightarrow O_3$)

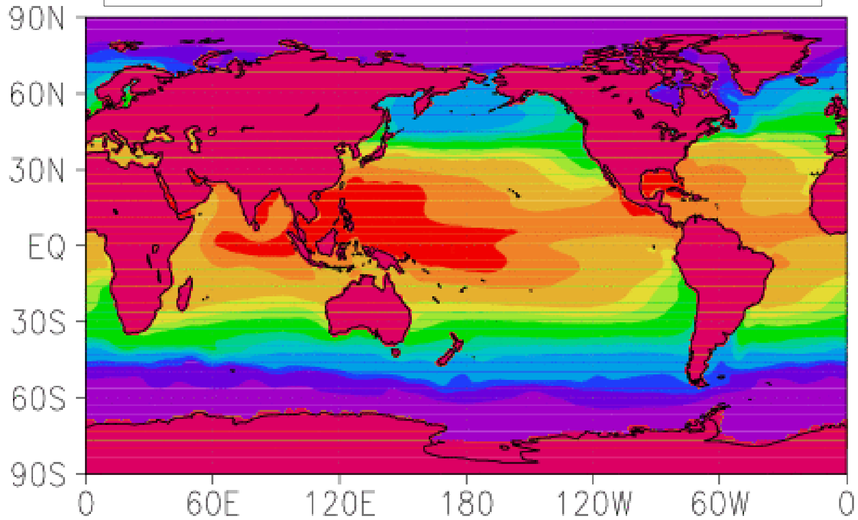
The daily average sunlight is maximum at the pole in summer
In mean over the year the sunlight stays maximum at the Equator

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

Sea surface T in January
ECMWF (1993-1997)



July



SST is always warmer in the tropical regions

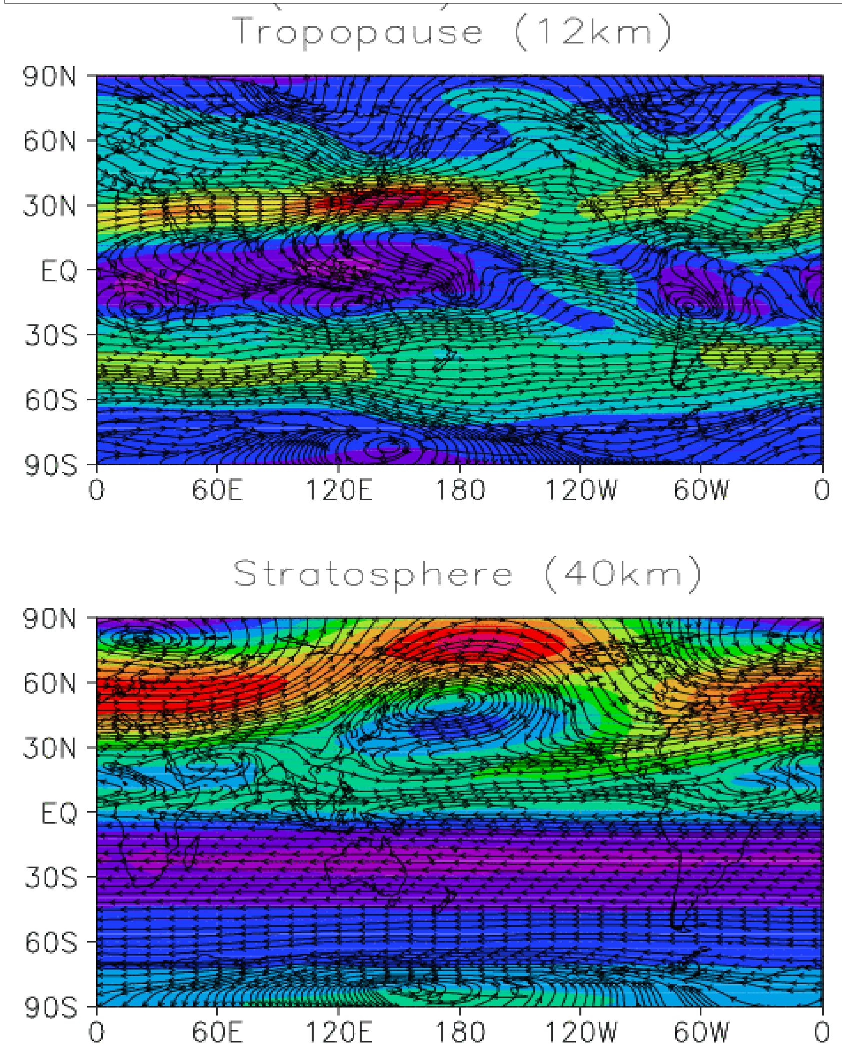
It also maintain a high rate of humidity and therefore a strong greenhouse effect in the tropical regions

Troposphere is in first place forced by the bottom, and will therefore has an annual cycle much less dramatic than the middle atmosphere

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

An extremely remarkable example of the difference between the general Circulations in the troposphere and in the stratosphere

ECMWF (93-97) winter wind

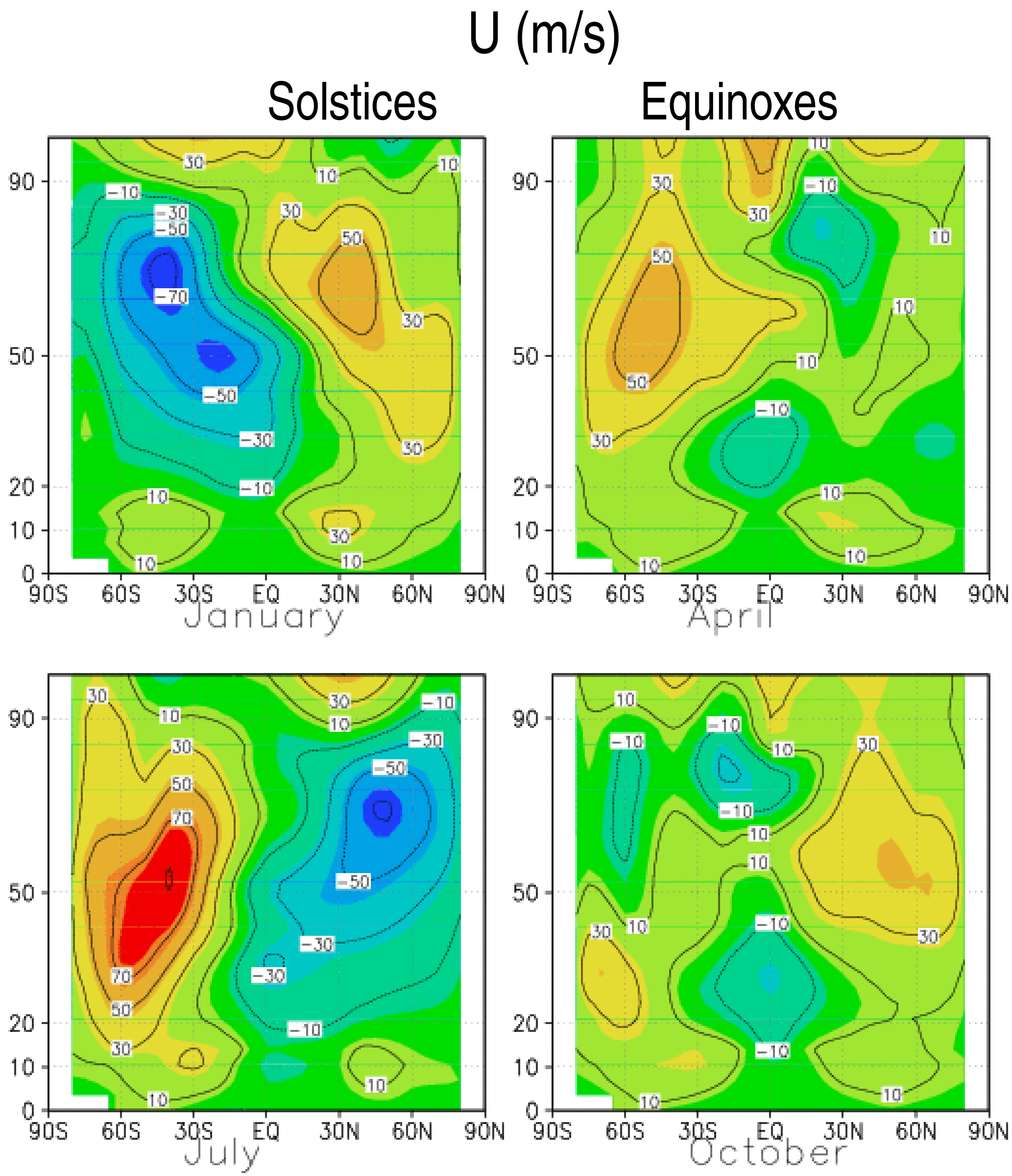


Winter time mean climatologies:

- The winds in the troposphere are eastward in both hemisphere and in the mid-latitudes.
- In the stratosphere the winds are eastward in the winter hemisphere and westward in the summer hemisphere.

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

Zonal mean zonal wind climatologies (CIRA dataset)



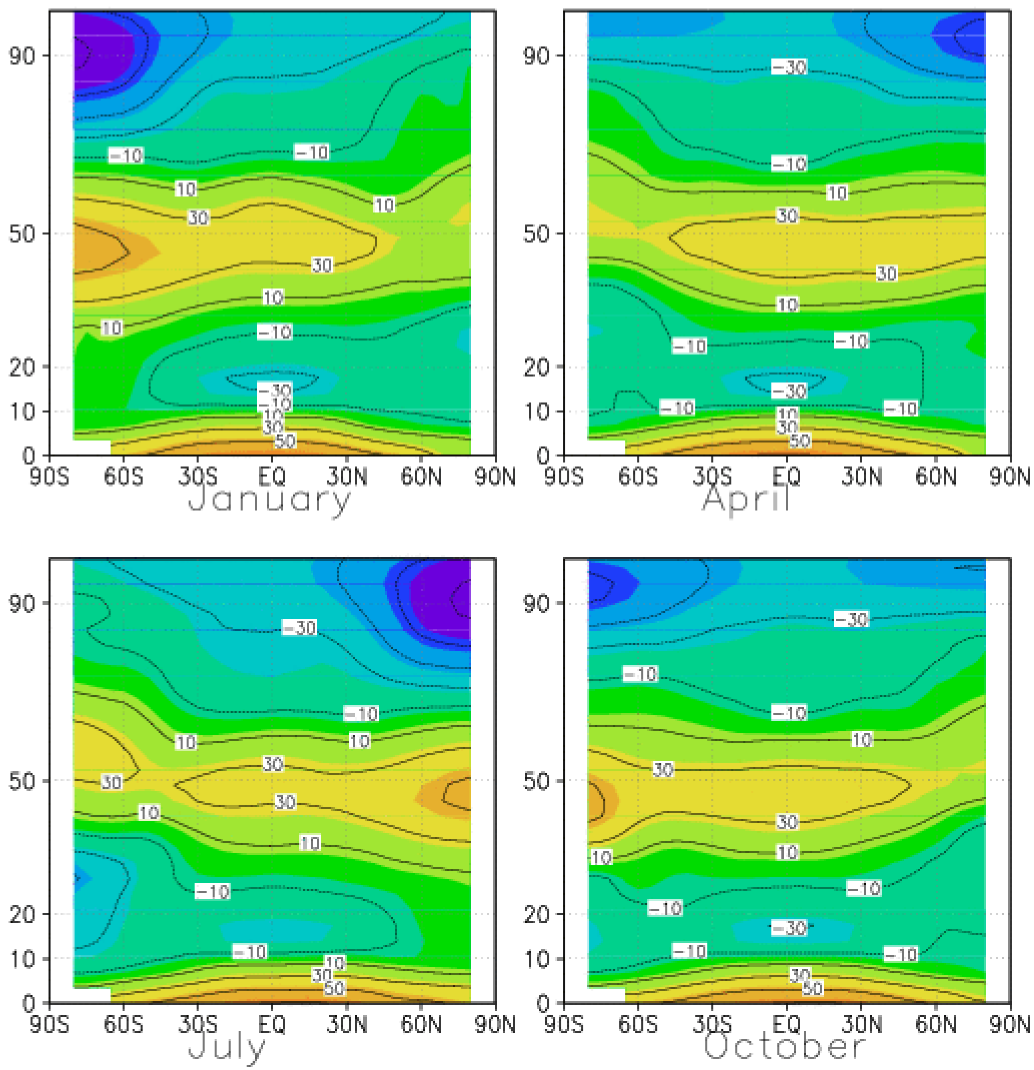
- In all seasons there are two westerly jets near below the subtropical tropopause. These westerlies extent almost down to the surface (0-16km) and characterize the midlatitude circulations.
- Still in troposphere, the winds tend to be slightly westward (easterly) in the tropics.
- In the middle atmosphere (20-90km), the winds are eastward (westerlies) in the winter hemisphere and westward in the summer hemisphere.
- In spring and fall the middle atmosphere jets are eastward in both hemisphere (equinox).
- Note, that during the winters, the jets in the southern hemisphere (July) are stronger than in the northern hemisphere (January).

General Circulation of the Stratosphere and modelisation
a) Basic climatologies

Zonal mean temperature climatologies (CIRA dataset)

T-230 (K)

Solstices Equinoxes



- Temperature decay with altitude in the troposphere.
- There is a minimum at the tropical tropopause (a greenhouse effect due to the presence of water vapour).
- In the stratosphere (20km<z<50km), T decreases from the summer pole to the winter pole.
- At the stratopause (50km) in the summer hemisphere, there is a max in T.
- During solstices and in the upper mesosphere (70-90km) T increases from the summer pole to the winter pole!
- Still in the solstices and at the mesopause, (90km) there are pronounced minima in T (~180K) over the summer pole!!

General Circulation of the Stratosphere and modelisation
b) Interpretation with a simplified model

Equations

$$\left(\frac{\partial}{\partial t} + \frac{v}{a}\frac{\partial}{\partial \phi}\right) u - \left(2\Omega + \frac{u}{a\cos\phi}\right) v \sin\phi = 0$$

$$\left(\frac{\partial}{\partial t} + \frac{v}{a}\frac{\partial}{\partial \phi}\right) v + \left(2\Omega + \frac{u}{a\cos\phi}\right) u \sin\phi = -\frac{1}{a}\frac{\partial \Phi}{\partial \phi}$$

$$\frac{\partial \Phi}{\partial t} + \frac{1}{a\cos\phi}\frac{\partial \Phi v \cos\phi}{\partial \phi} = Q_{0_3} - \overline{Q}^{\phi}_{0_3} - \alpha\left(\Phi - \Phi_0\right)$$

Angular momentum conservation:

$$\left(\frac{\partial}{\partial t} + \frac{v}{a}\frac{\partial}{\partial \phi}\right)\left(u\cos\phi + a\Omega\cos^2\phi\right) = 0$$

Donne pour des mouvements de petite amplitude (initialement):

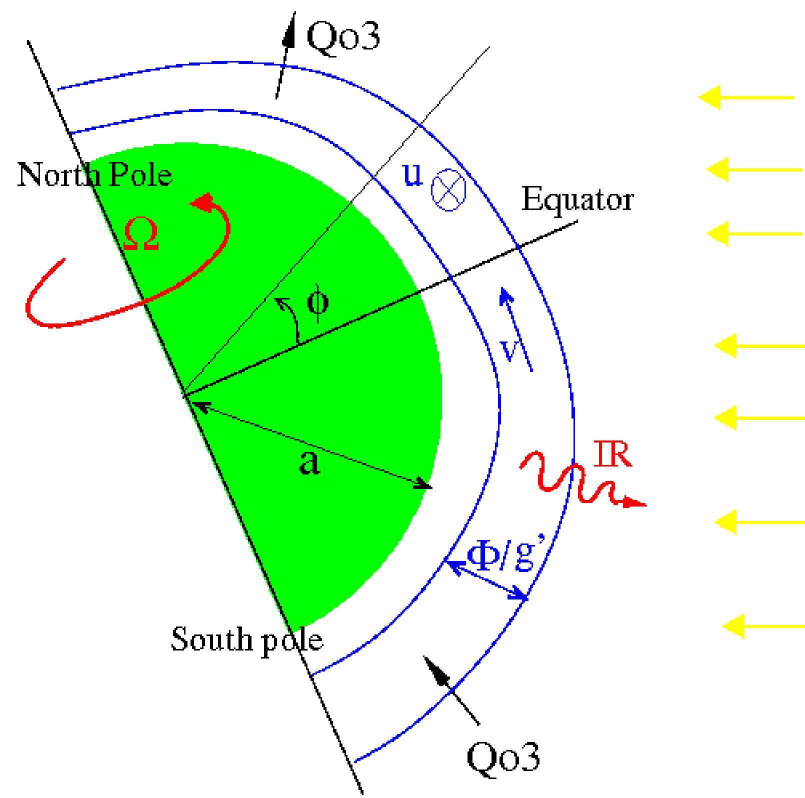
Geostrophic Equilibrium:

$$2\Omega \sin\phi \; u = -\frac{1}{a}\frac{\partial \Phi}{\partial \phi}$$

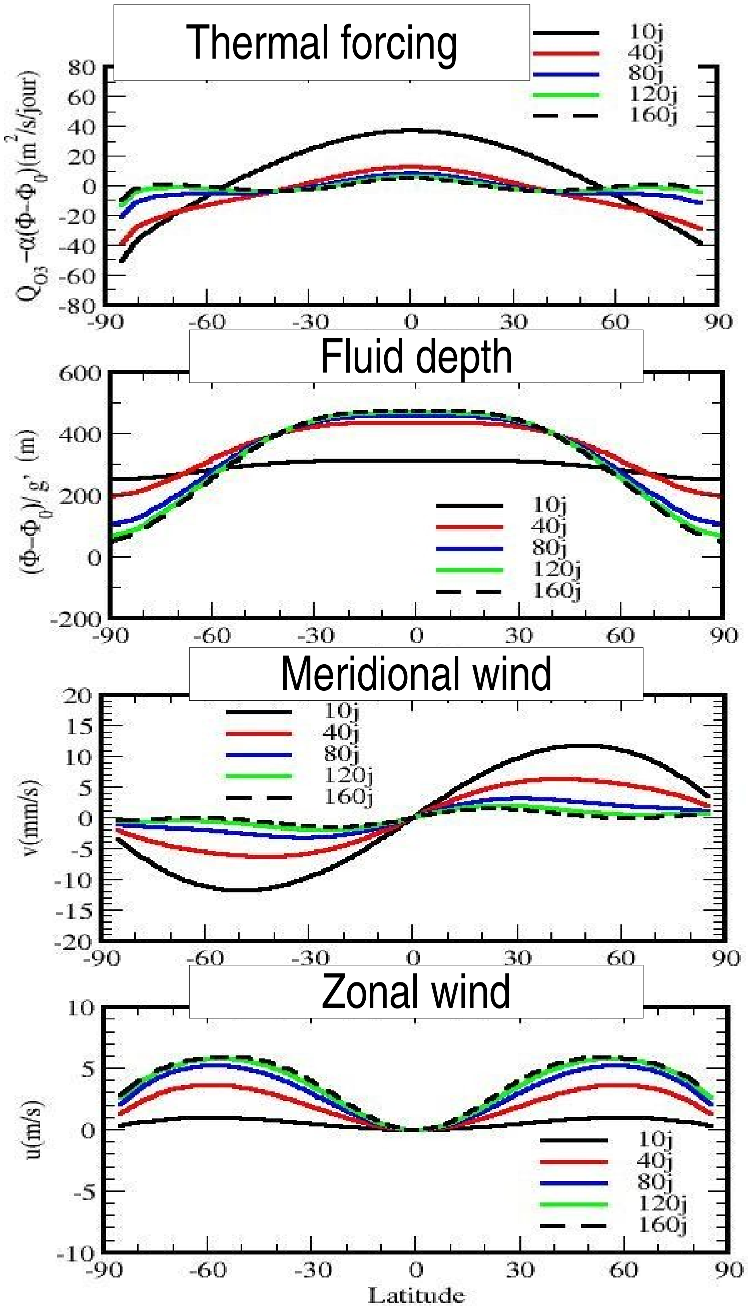
Thermal equilibrium

(propre à ce modèle et pour $t \to \infty$)

$$Q_{0_3} - \overline{Q}^{\phi}_{0_3} = \alpha\left(\Phi - \Phi_0\right)$$



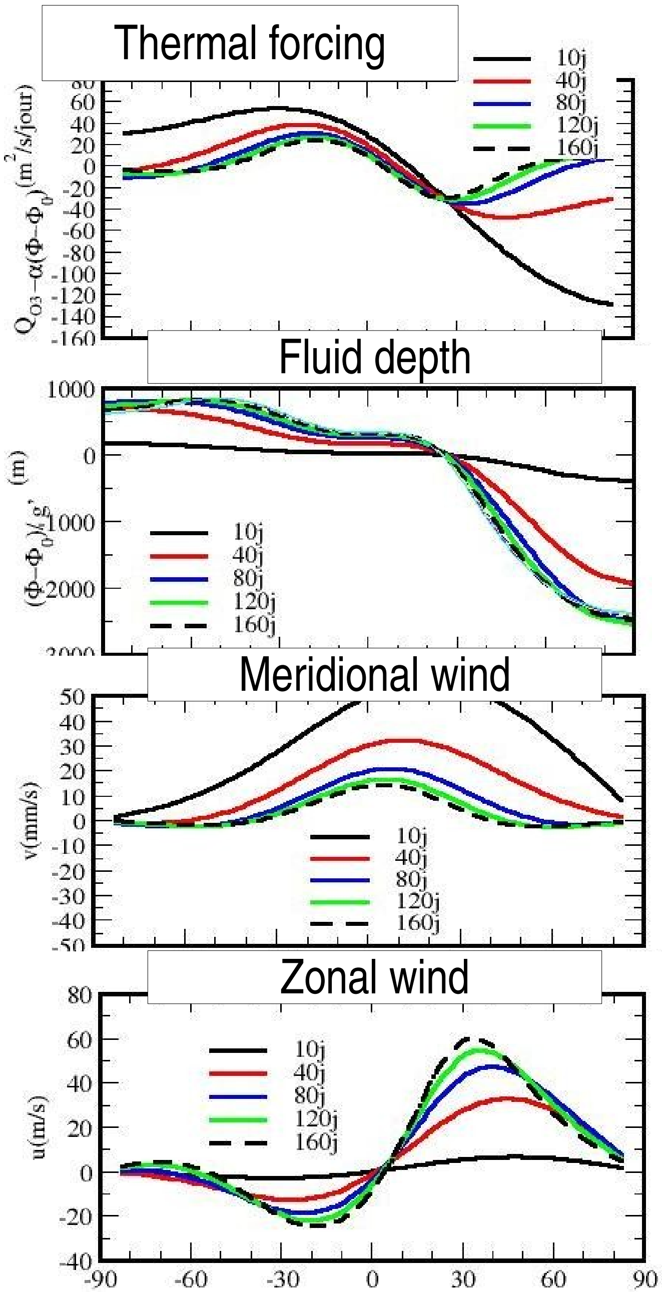
General Circulation of the Stratosphere and modelisation
b) Interpretation with a simplified model



Results for Equinoxes

- At the beginning (10d) the diabatic forcing is due to O_3 only, it induces an increase of Φ at the equator and a decrease in the mid and polar latitudes
- A radiative equilibrium between the diabatic Heating and the IR cooling is reached after 160d. The diabatic forcing is then very small.
- Initially, the heating induces a meridional motion (v) toward the north in the NH, toward the south in the SH.
- Although our model is for the middle atmosphere here during equinox, the results shown are also adapted to the tropospheric Hadley cells, and which are due to a diabatic heating in the mid troposhere centred near the equator during all seasons.
- Note that v becomes very small at equilibrium (160d). Does this question the existence of the Hadley cells except in the transient cases?
- By angular momentum conservation, this meridional displacement produced postive zonal winds in both hemisphere.
- Note that u is in geostrophic equilibrium with Φ in the midlatitudes.

General Circulation of the Stratosphere and modelisation
b) Interpretation with a simplified model



Results for January

•At the beginning (10d), the diabatic forcing is due to O_3 only. It induces an increase of Φ in the southern Hemisphere and a decrease in the Northern hemisphere.

• A radiative equilibrium between the forcing due to 0_3 and the IR cooling is reached after 160d.

•The initial forcing due to 03 induce a meridional displacement (v). v becomes very small when we get near the steady state (160d).

•Again the model is not efficient to explain steady-state meridional circulations.

•By angular momentum conservation, these displacements induced negative zonal winds (u) in the SH and positive zonal winds in the NH.

•Note that:

- The westerlies in the NH are much stronger in amplitude than the easterlies in the SH.
- U is in geostrophic balance with Φ in the midlatitudes:

General Circulation of the Stratosphere and modelisation
b) Interpretation with a simplified model

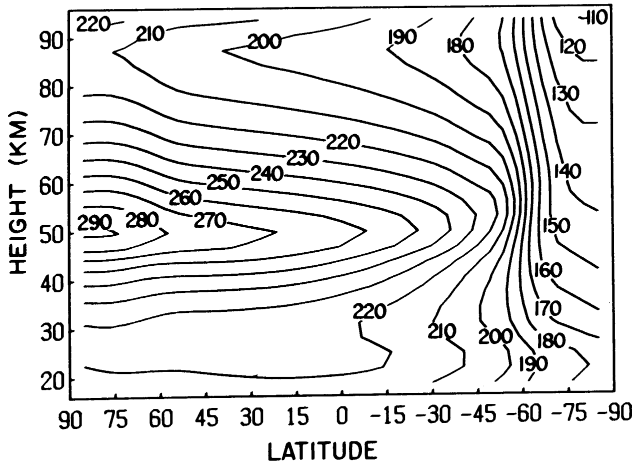


Fig. 2.34. Radiative equilibrium temperature distribution for northern (left) summer solstice. [From Wehrbein and Leovy (1982), with permission.]

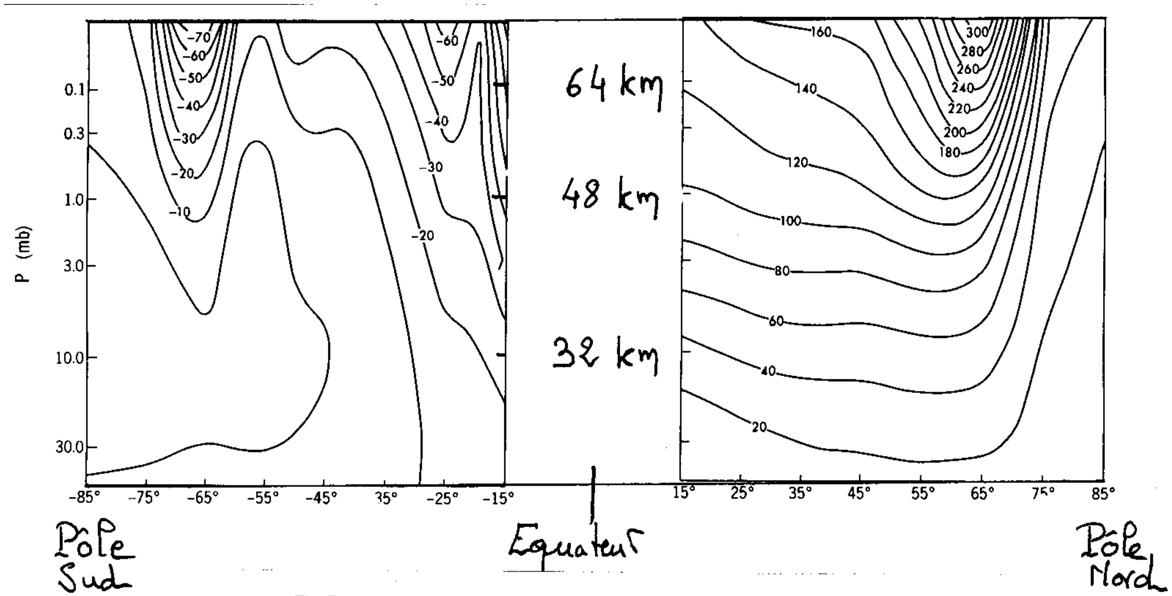


Fig. 7.1. Zonal gradient wind u_{gr} that is in thermal-wind balance with the temperature field T_r of Fig. 1.2 and equals the observed climatological zonal wind at 100 mb. (a) Northern Hemisphere (winter), (b) Southern Hemisphere (summer). (Courtesy of Dr. S. B. Fels.)

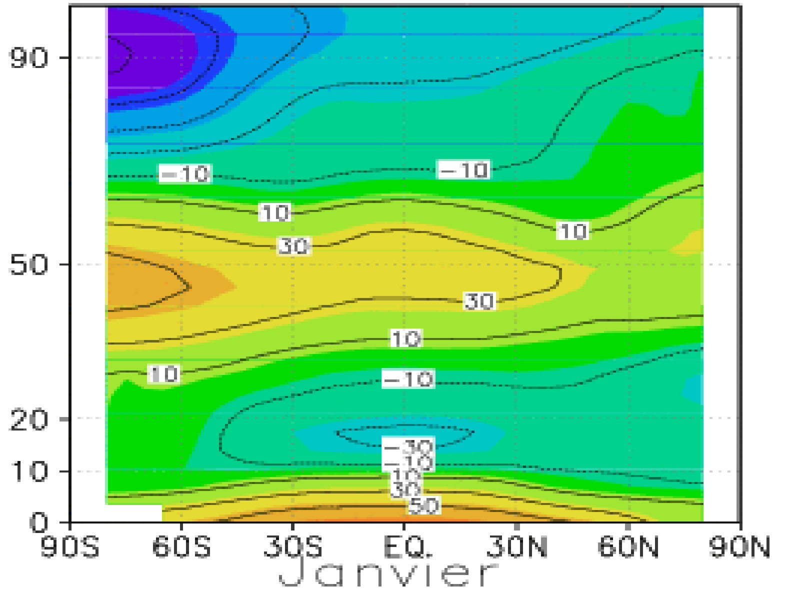
The middle atmosphere is not in thermal equilibrium

Result here from a radiative code alone,

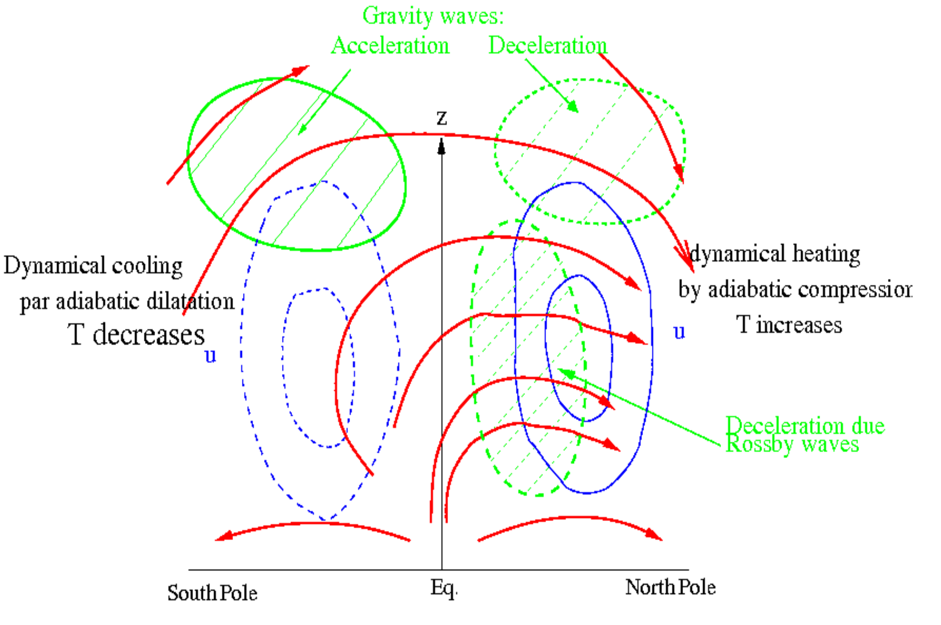
The zonal wind is evaluated from the T field via the thermal wind balance

General Circulation of the Stratosphere and modelisation
c) The Brewer Dobson Circulation

January Temperatures

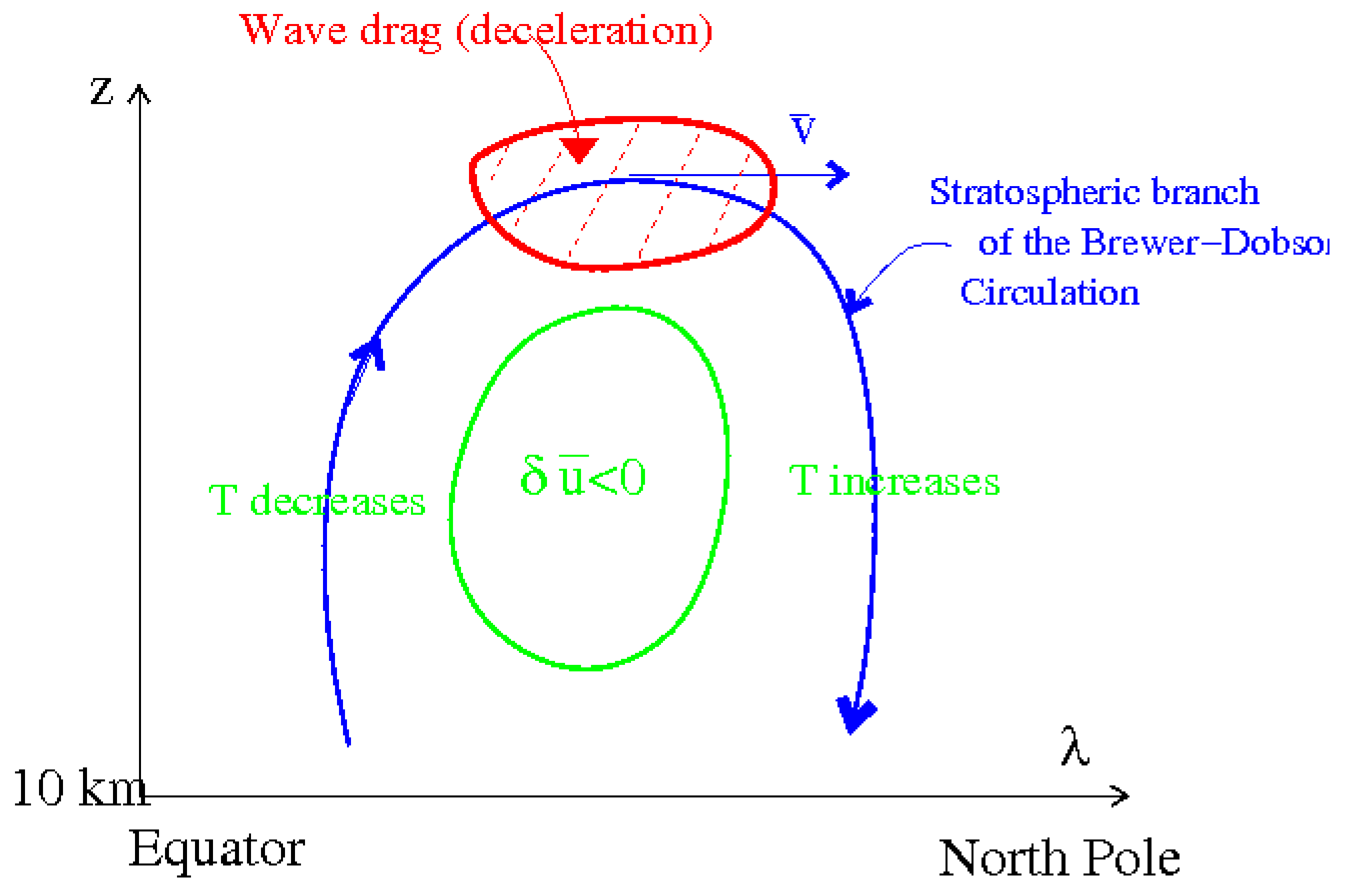


The meridional circulation driven by waves and the « downward control »



General Circulation of the Stratosphere and modelisation
c) The Brewer Dobson Circulation

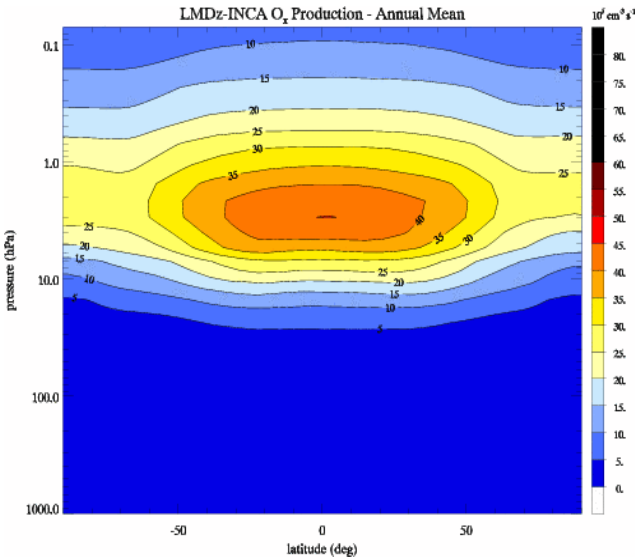
More about the downward control, or how to decelerate a rapidly rotating fluid on a sphere!



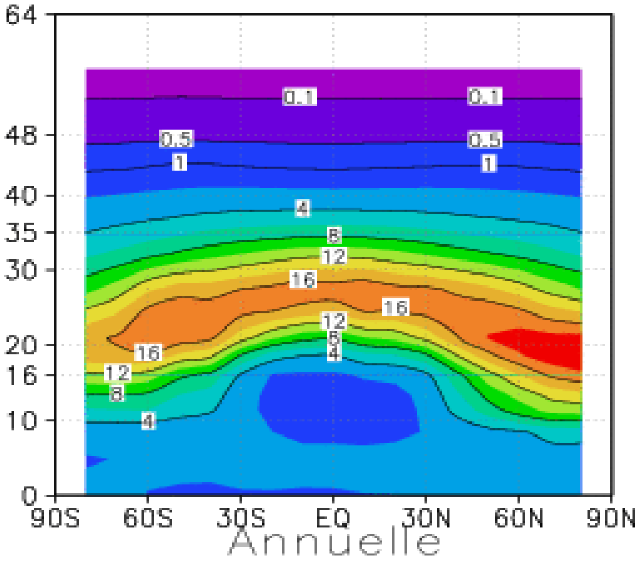
General Circulation of the Stratosphere and modelisation
c) The Brewer Dobson Circulation

The ozone is produced in majority around
the equatorial trpopause, but accumulates up at much
lower altitudes and latitudes!

Annual mean production
Of Ox



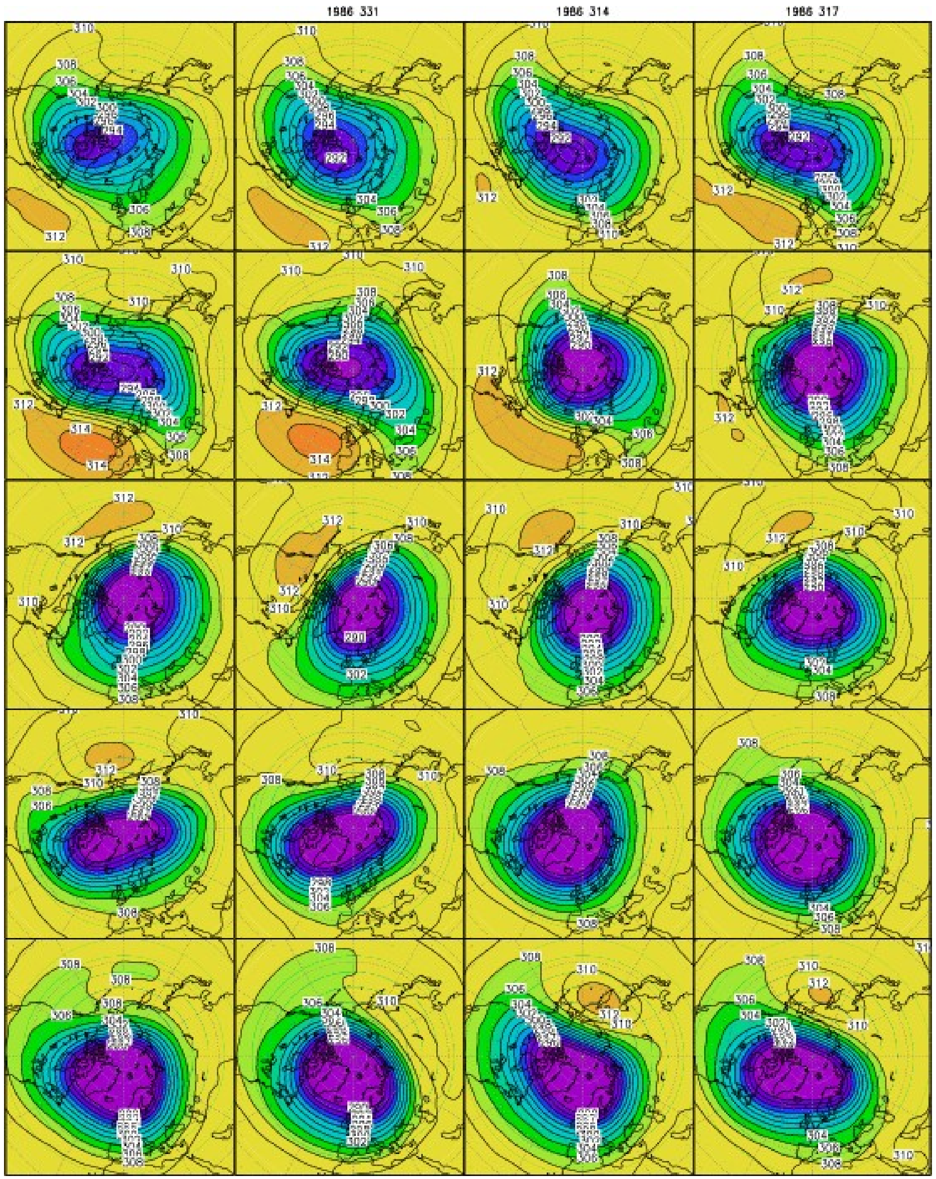
Annual mean of O3



General Circulation of the Stratosphere and modelisation
d) Midlatitude Dynamics

In the stratosphere
the Rossby waves
also play a very large rôle
on the mean climate
and variability

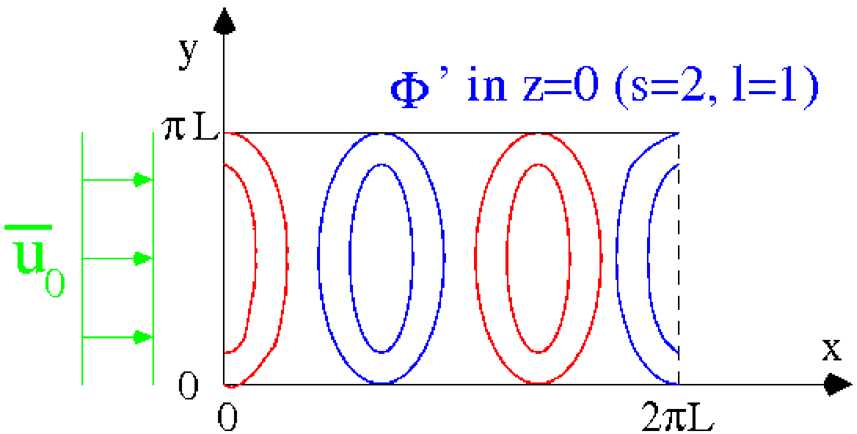
(here evolution of a
geopotentiel map
at z=32km every
3 days)



General Circulation of the Stratosphere and modelisation
d) Midlatitude Dynamics

These Rossby waves are very slow, they are quite intermittent and are forced by the low frequency variability of the tropospheric weather.

Vertical structure equation of a quasi-steady Rossby wave on a laterally bounded beta plane. Quasi-Geostrophic approximation is made.



$$\hat{\Phi}_{zz} + \left(\frac{N^2}{f^2} \left(\frac{\beta}{\overline{u}_0} - k^2 - l^2 \right) - \frac{1}{4H^2} \right) \hat{\Phi} = 0$$

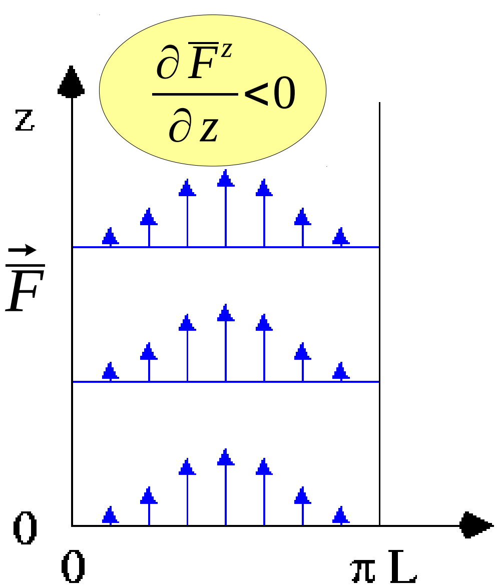
Only vertical propagation if the mean wind is >0 (in winter)

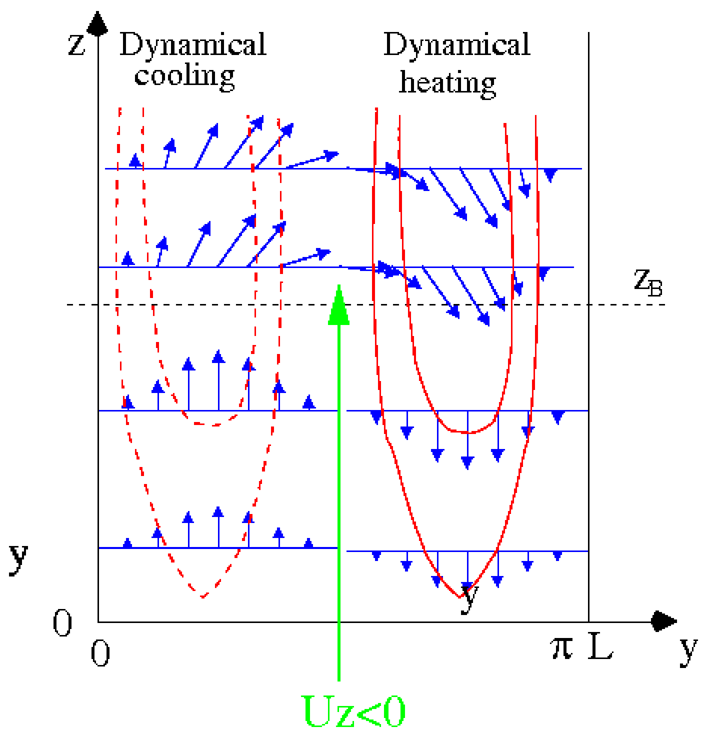
Only the very long modes can propagate vertically

General Circulation of the Stratosphere and modelisation
d) Midlatitude Dynamics

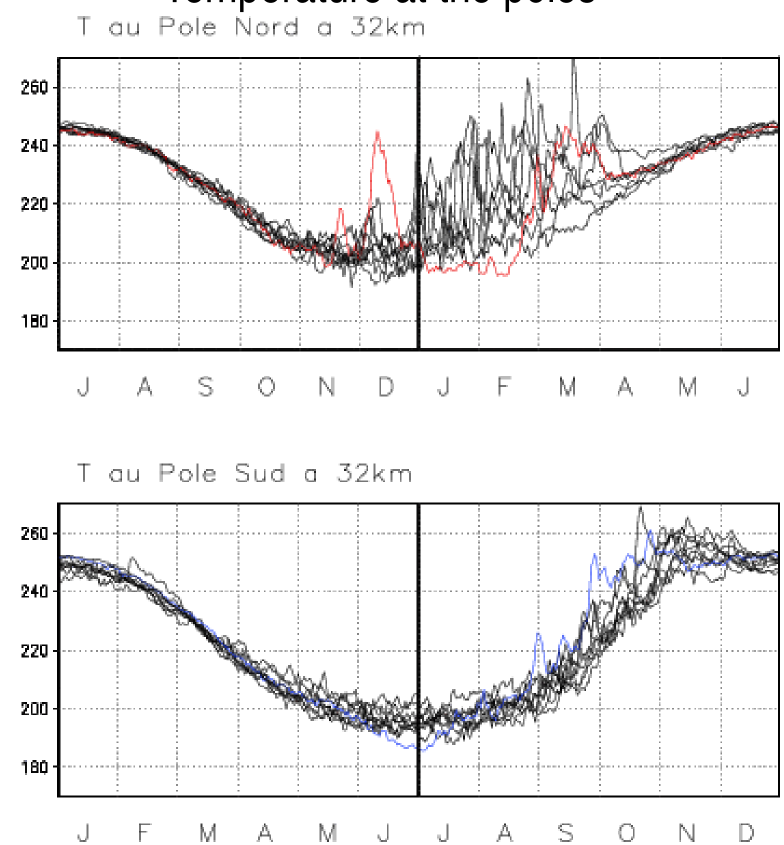
These Rossby waves as well break (in this case via barotropic instabilities rather than by convective instability for the Gws). This yields to the Stratospheric warmings

Vertical structure equation of a quasi-steady Rossby wave on a laterally bounded beta plane. Quasi-Geostrophic approximation is made.





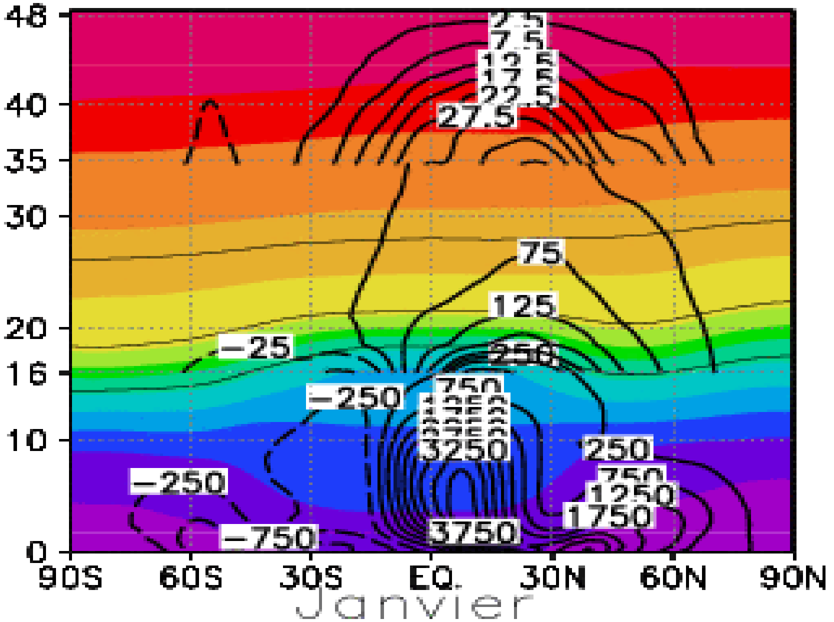
Temperature at the poles



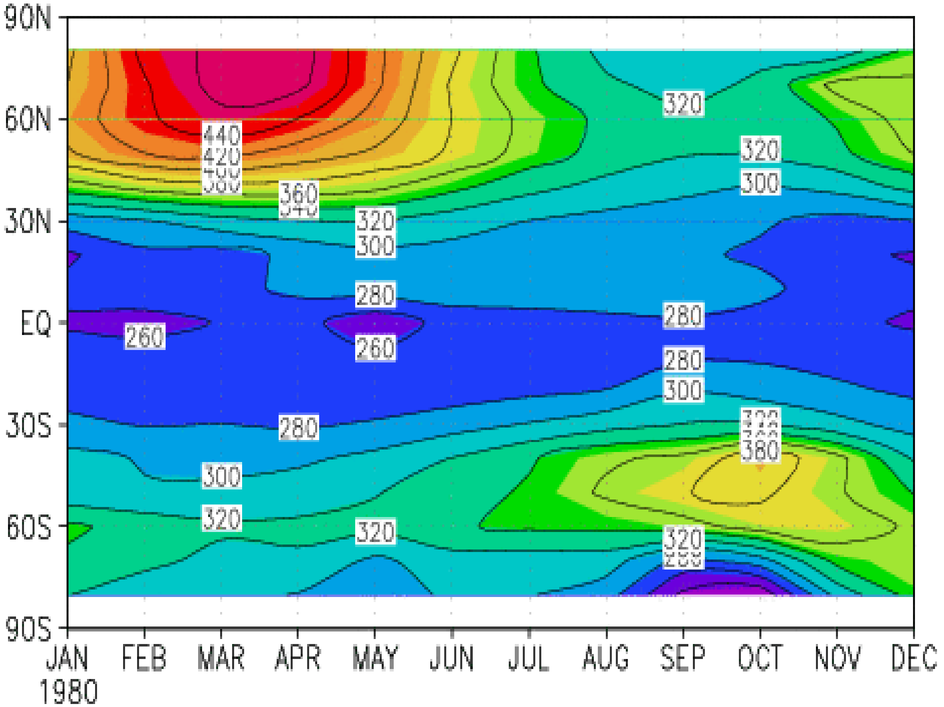
General Circulation of the Stratosphere and modelisation
c) The Brewer Dobson Circulation

The ozone is produced in majority around
the equatorial trpopause, but accumulates up at much
lower altitudes and latitudes!

Streamfunction of the meridional
circulation, January
(TEM formalism)



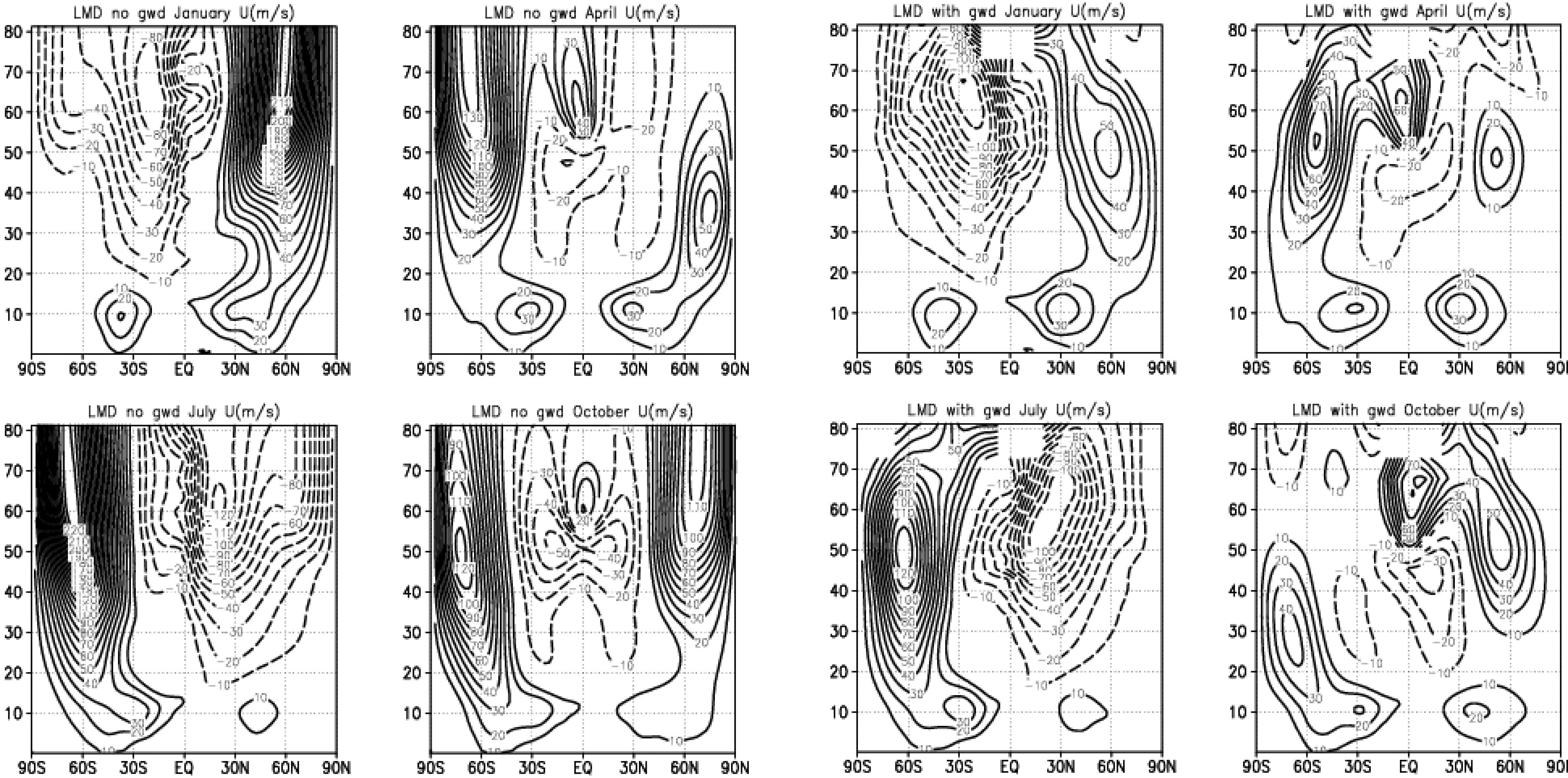
Annual Cycle of O3



General Circulation of the Stratosphere and modelisation
c) The Brewer Dobson Circulation

The effect of gravity waves can be well seen in the mesosphere
if we compare simulations with and without parameterization LMDz
(Lott et al. 2005, Lott Millet 2010):

without with



General Circulation of the Stratosphere and modelisation
d) Equatorial Dynamics

Zonal wind at the Equator: Semi annual and quasi biennal oscillation

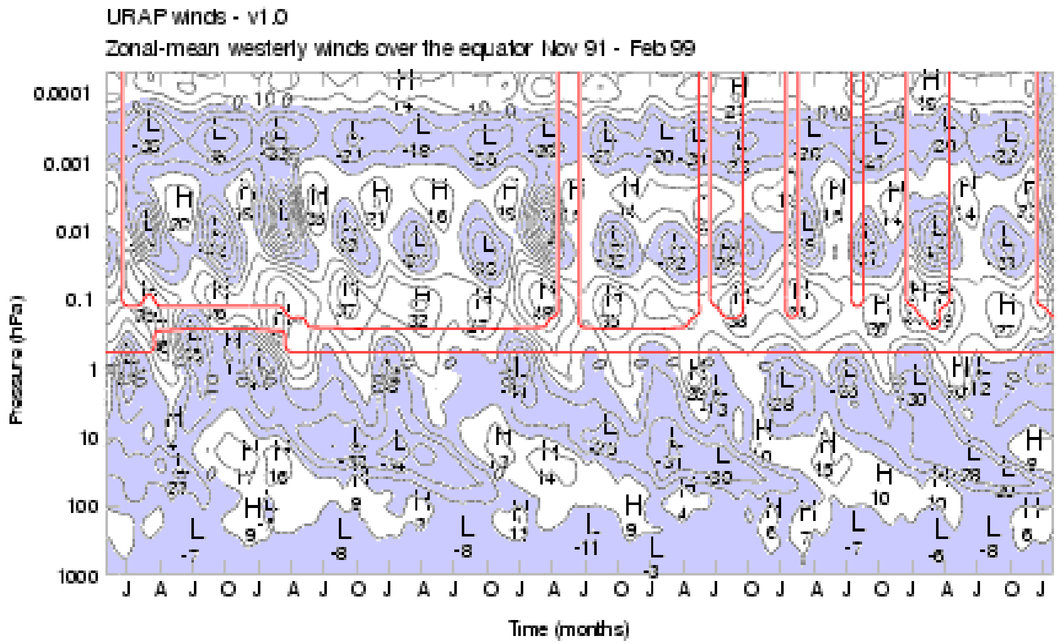


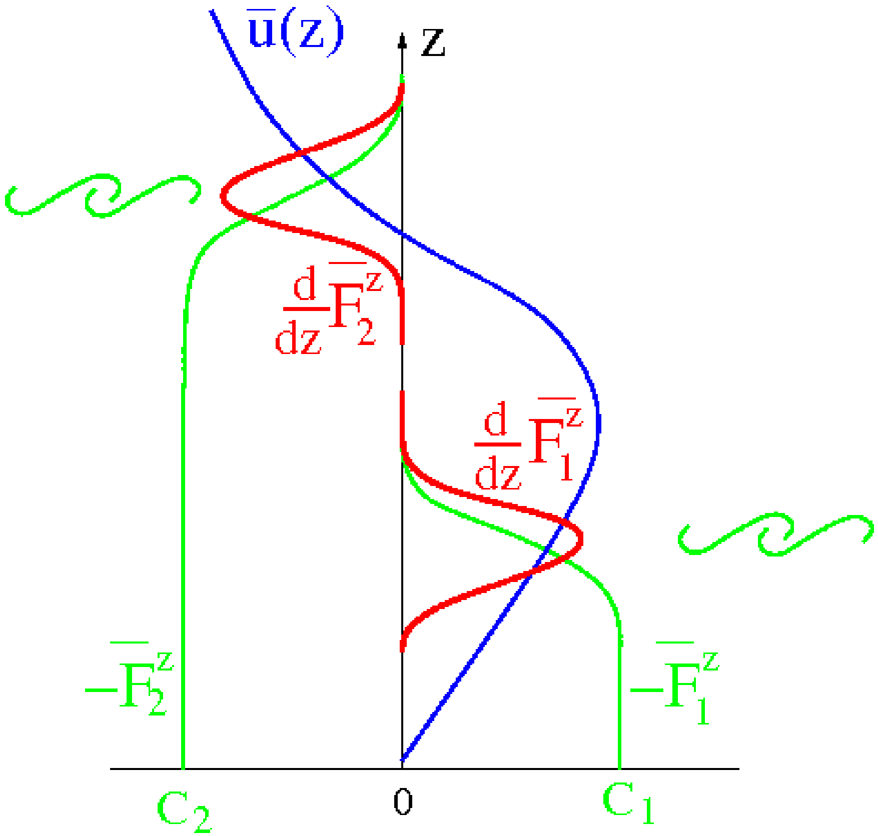
Figure 6. Time series of zonal-mean westerly winds over the equator, from November 1991 to February 1999. The tick marks along the x-axis mark each January, April, July and October. The additional lines show where the values are mainly derived from interpolated or climatogical data.

(UARS observations, Swinbank and Ortland, 1997)

General Circulation of the Stratosphere and modelisation
d) Equatorial Dynamics

The plumb model for a semi-annual oscillation driven by two gravity waves

$$\rho_0 \frac{\partial \bar{u}}{\partial t} = \sum_{i=1}^{2} \frac{\partial \bar{F}_i^z}{\partial z} + \frac{\partial}{\partial z} \nu \frac{\partial \bar{u}}{\partial z}$$



General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

Classical arguments to justify stochastic parameterizations
(Palmer et al. 2005, Shutts and Palmer 2007, for the GWs: Piani et al. (2005, globally spectral scheme) and Eckeman (2011, multiwaves scheme)

1) The spatial steps Δx and Δy of the unresolved waves is not a well defined concept (even though they are probably related to the model gridscales δx δy). The time scale of the GWs life cycle Δt is certainly larger than the time step (δt) of the model, and is also not well defined.

2) The mesoscale dynamics producing GWs is not well predictable (for the mountain gravity waves see Doyle et al. MWR 11).

These calls for an extension of the concept of triple Fourier series, which is at the basis of the subgrid scale waves parameterization to that of stochastic series:

$$w' = \sum_{n=1}^{\infty} C_n w'_n \qquad \text{where} \qquad \sum_{n=1}^{\infty} C_n^2 = 1$$

The C'_ns generalised the intermittency coefficients of Alexander and Dunkerton (1995), and used in Beres et al. (2005).

General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

For the w'_n we use linear WKB theory of hydrostatic GWs, and treat the breaking as if each w'_n was doing the entire wave field (using Lindzen (1982)'s criteria for instance):

$$w'_n = \Re\left\{\hat{w}_n(z)\, e^{z/2\mathrm{H}}\, e^{i(k_n x + l_n y - \omega_n t)}\right\} \qquad \hat{w}_n, k_n, l_n, \omega_n \quad \text{chosen randomly}$$

WKB passage from one level to the next with a small dissipation (Eliasen Palm flux):

$$\vec{F}(z+dz) = \frac{\vec{k}}{|\vec{k}|}\, sign(\Omega) \left(\frac{1 + sign(\Omega(z+\delta z)\cdot\Omega(z))}{2}\right) Min\left(|\vec{F}(z)|\, e^{-2\frac{\nu m^3}{\Omega}\delta z},\ \rho_r \frac{|\Omega^3|}{2N}\, e^{-(z+\delta z)/H}\, S_c^2 \frac{k^{*2}}{|\vec{k}^4|}\right)$$

Critical level

Eliasen-Palm theorem with dissipation

Breaking

S_c, k^*: Tunable parameters

$$m = \frac{N|\vec{k}|}{\Omega} \quad \text{Vertical wavenumber} \qquad\qquad \Omega = \omega - \vec{k}\cdot\vec{u} \quad \text{Intrinsic frequency}$$

Few waves (say M=8) are launched at each physical time step (δt=30mn), but their effect is redistributed over a longer time scale (Δt=1day), via an AR-1 protocole:

$$\left(\frac{\partial \vec{u}}{\partial t}\right)_{GWs}^{t+\delta t} = \frac{\Delta t - \delta t}{\Delta t}\left(\frac{\partial \vec{u}}{\partial t}\right)_{GWs}^{t} + \frac{\delta t}{M \Delta t}\sum_{n'=1}^{M} \frac{1}{\rho}\frac{\partial \vec{F}_n^z}{\partial z}$$

General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

$P'_r = \sum_{n=1}^{\infty} C_n P_n'$ where $P_n' = \Re\left[\hat{P}_n e^{i(\vec{k}_n \cdot \vec{x} - \omega_n t)}\right]$ taking $\left|\hat{P}_n\right| = P_r$

The subgrid scale standard deviation of the precipitation equals the gridscale mean

Distributing the related diabatic forcing over a depth Δz it is quite easy to place the forcing in the right hand side of a "wave" equation:

$$\rho c_p \left(\frac{DT'}{dt} + \frac{DT_0}{dz} w' \right) = L_w P' \frac{e^{-z^2/\Delta z^2}}{\Delta z} \rightarrow \frac{\Omega^2}{k^2} \hat{w}_{zz} + N^2 \hat{w} = \frac{R L_w}{\rho H c_p} \hat{P} \frac{e^{-z^2/\Delta z^2}}{\Delta z}$$

EP-flux at the launch level:

$$\vec{F}_{nl} = \rho_r \frac{\vec{k}_n}{\left|\vec{k}_n\right|} \frac{\left|\vec{k}_n\right|^2 e^{-m_n^2 \Delta z^2}}{N \Omega_n^3} G_{uw} \left(\frac{R L_W}{\rho_r H c_p} \right)^2 P_r^2$$

New tuning parameter (could be a random number)

k_n, l_n, ω_n Are still chosen randomly $m_n = \frac{N\left|\vec{k}_n\right|}{\Omega_n}, \Omega_n = \omega_n - \vec{k}_n \cdot \vec{U}$

General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

Offline tests with ERAI and GPCP

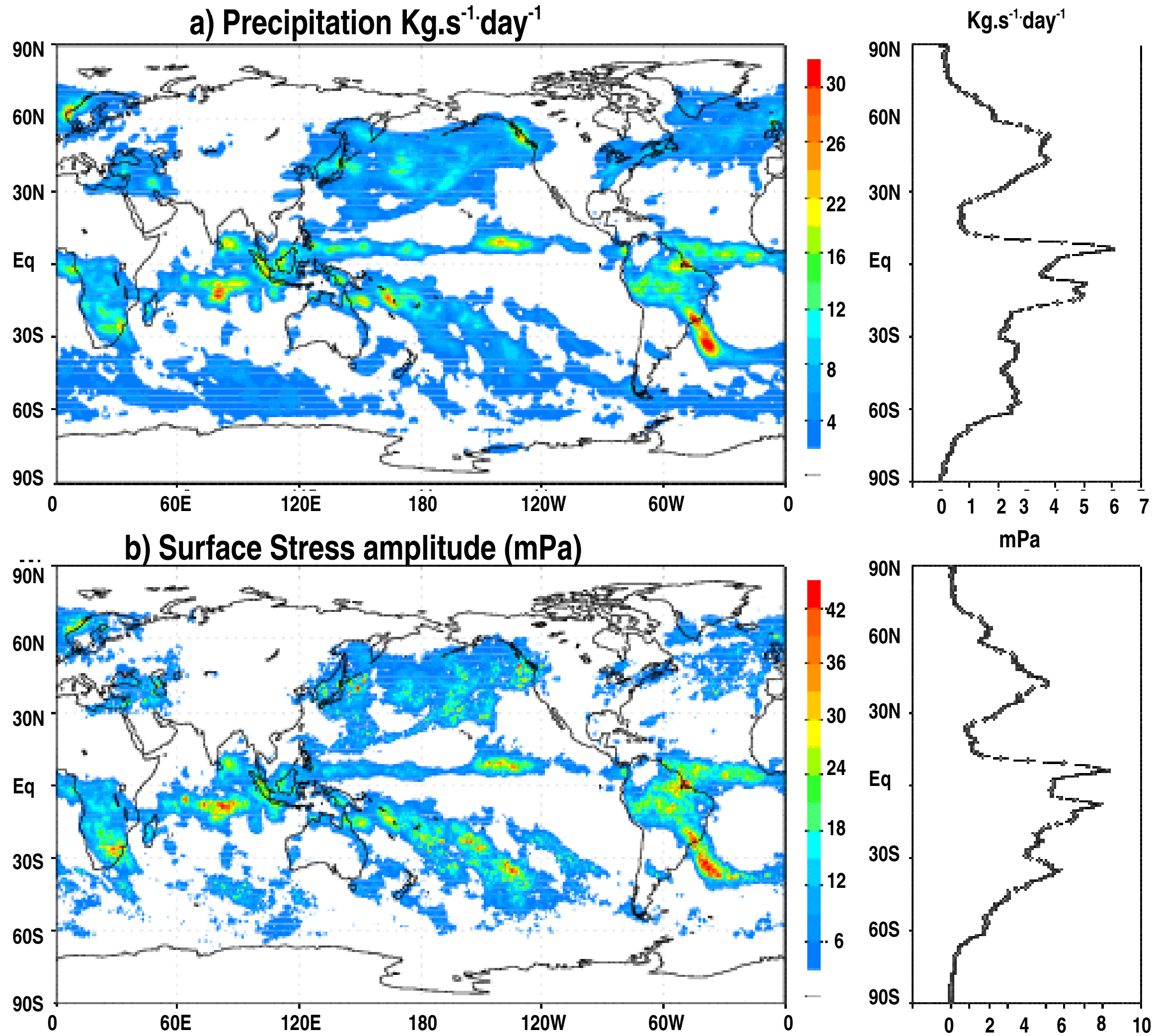
G_{uw}=2.4, S_c=0.25,
k*=0.02km^{-1},
m=1kg/m/s
Dt=1day and M=8
Dz=1km (source depth~5km)

The CGWs stress is now well distributed along where there is strong precipitations

It is stronger on average in the tropical regions, but quite significant in the midlatitudes.

The zonal mean stress comes from very large values issued from quite few regions.

Precipitations and surface stresses averaged over 1week (1-7 January 2000) **Results for GPCP data and ERAI**

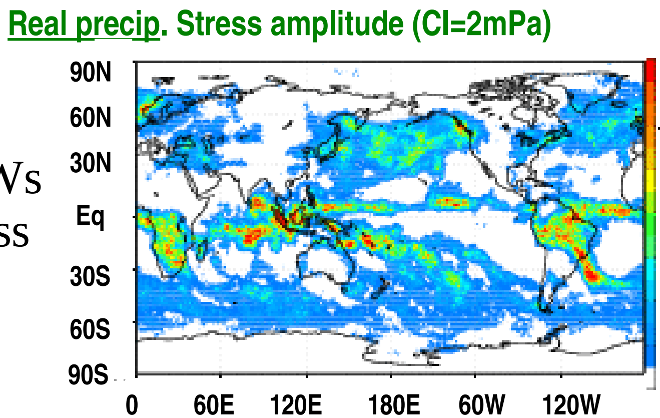


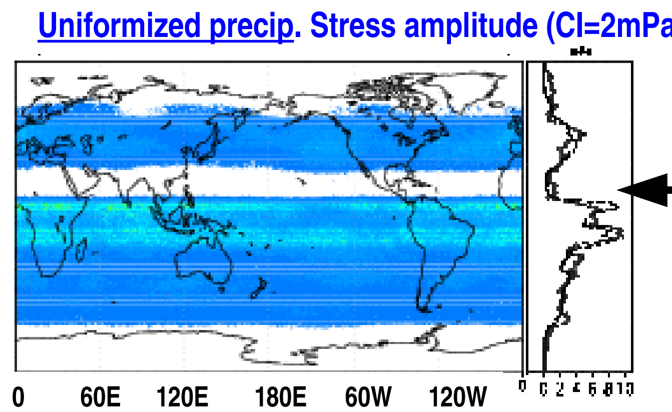
General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

Offline tests with ERAI and GPCP

Benefit of having few large GWs rather than a large ensemble of small ones:

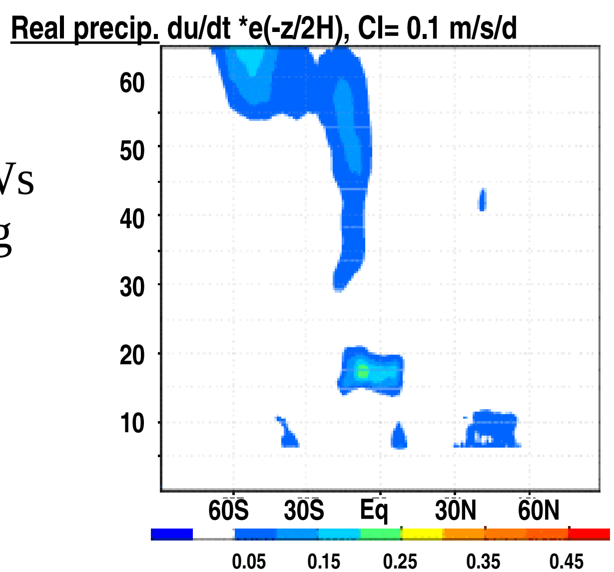
CGWs stress

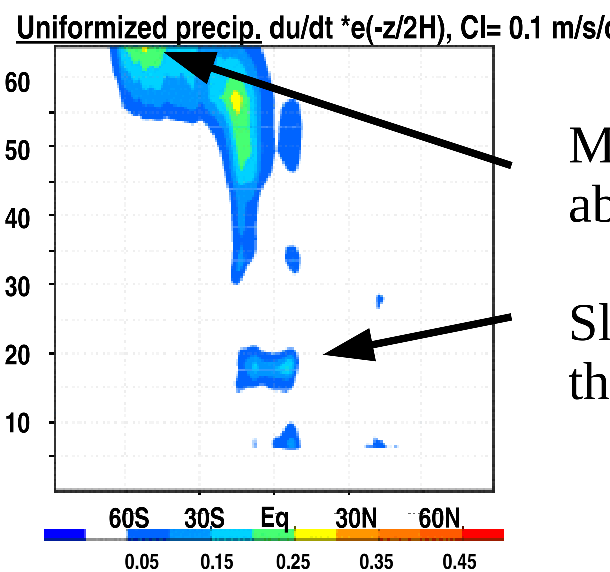




Same zonal mean stress

CGWs drag





More drag near and above stratopause

Slightly less drag in the QBO region

Lott and Guez, JGR 2013

General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

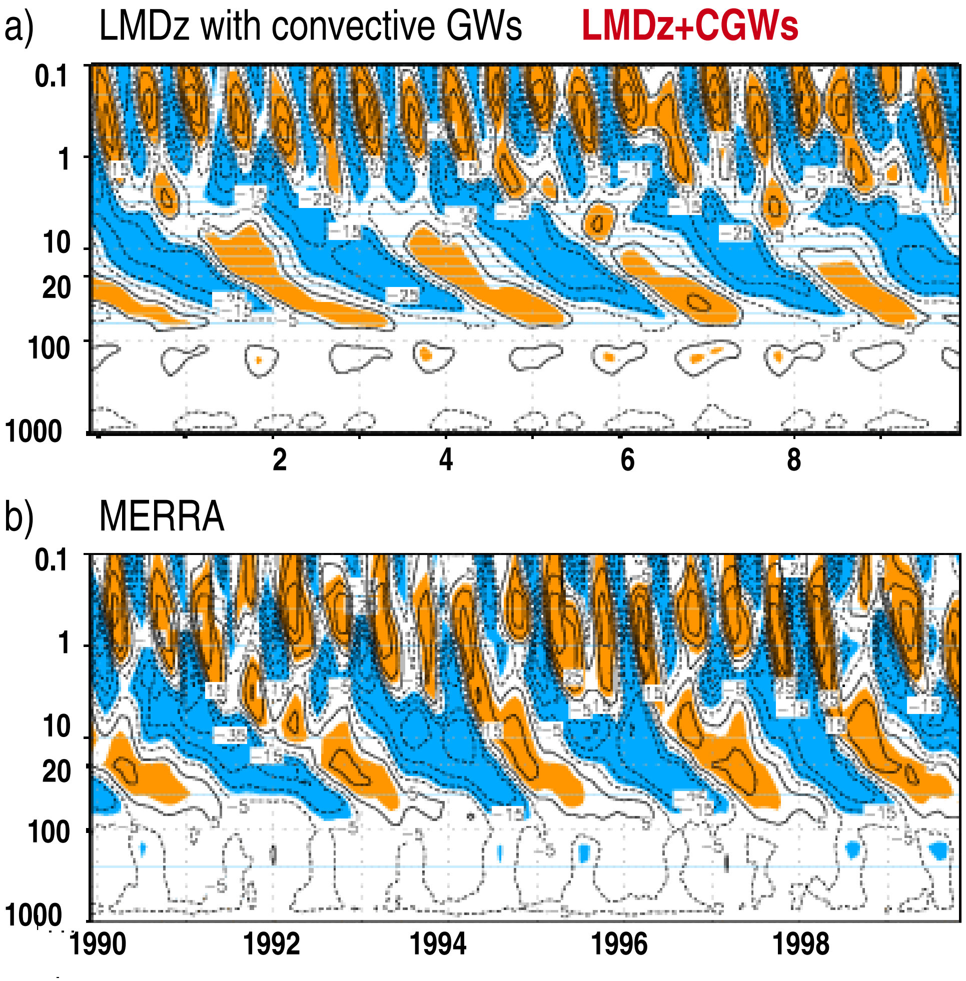
Online results with LMDz

LMDz version with 80 levels, dz<1km
In the stratosphere

QBO of irregular
period with mean
around 26month,

20% too small amplitude

Westerly phase lacks of connection
with the stratopause SAO



Lott and Guez, JGR13

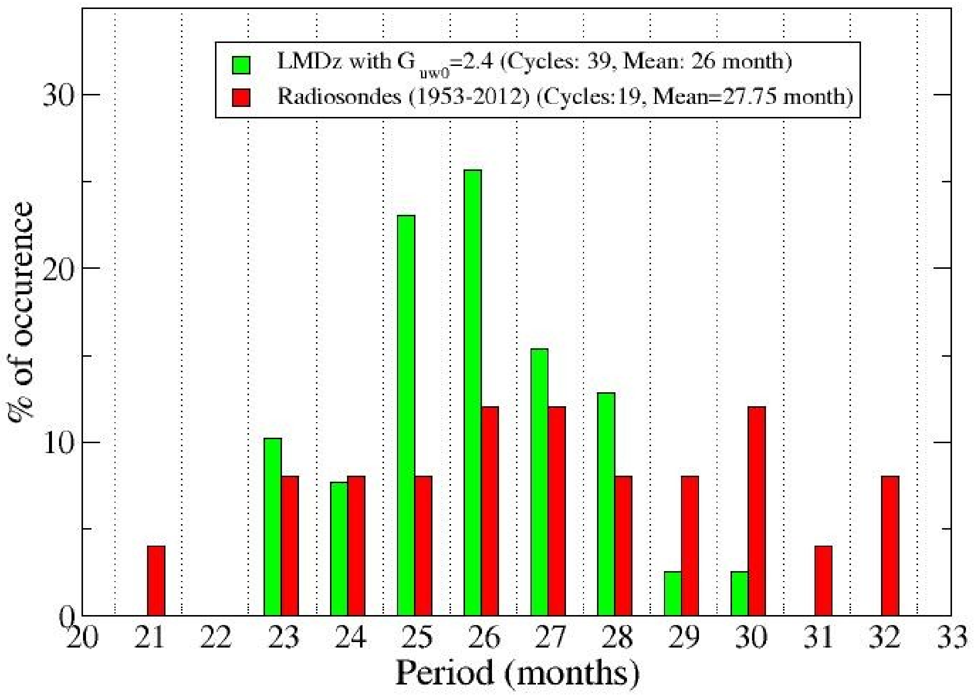
General Circulation of the Stratosphere and modelisation
e) Convective gravity waves parameterization

Online results with LMDz

Histogram of QBO periods

Relatively good spread of the periods taking into account that it is a forced simulation with climatological SST (no ENSO)

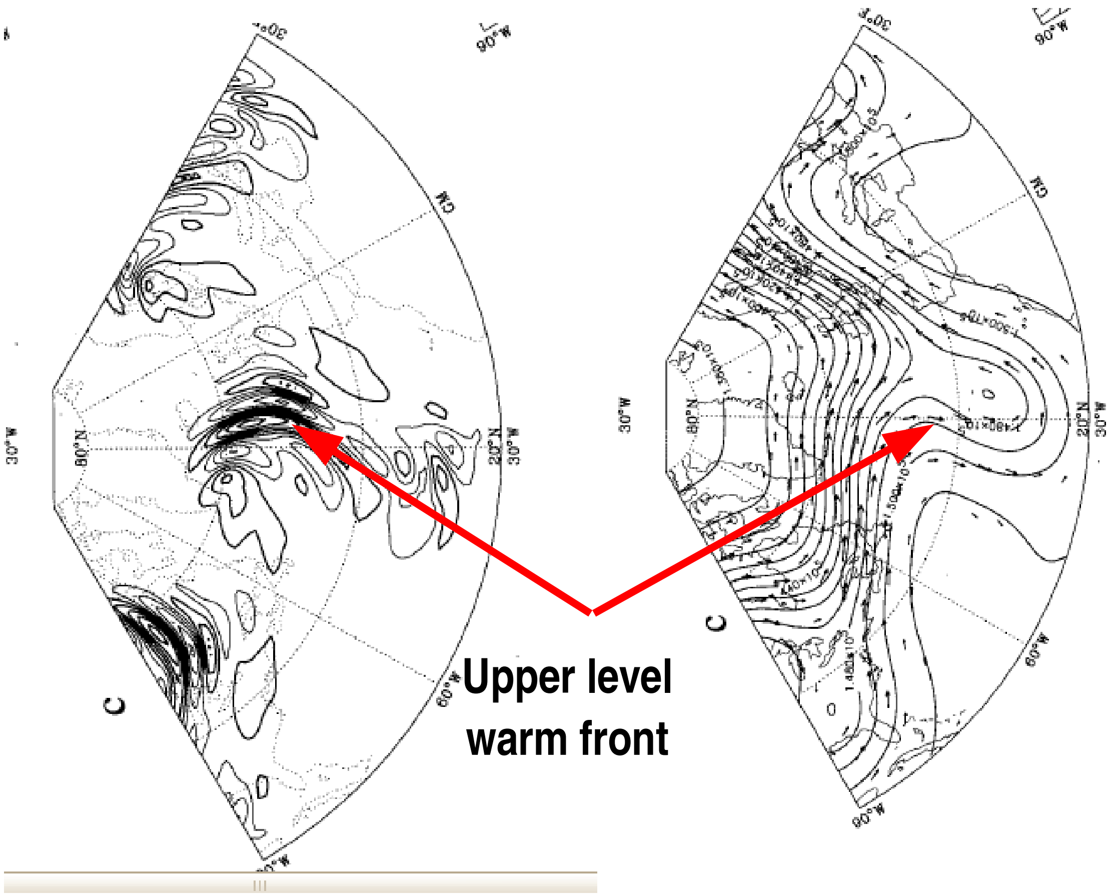
Periods related to the annual cycle (multiples of 6 months) are not favoured: probably related to the weak relations with the SAO



Lott and Guez, JGR13

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

Simulations to support these parameterizations:



O'Sullivan and Dunkerton (1995)

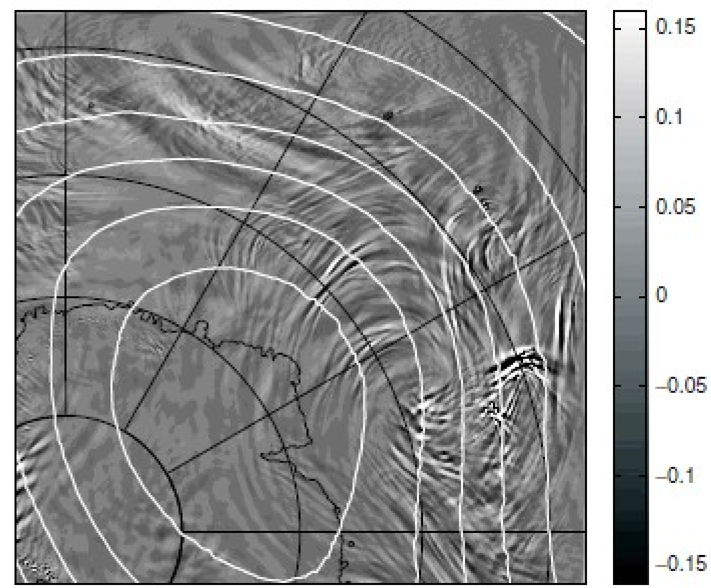


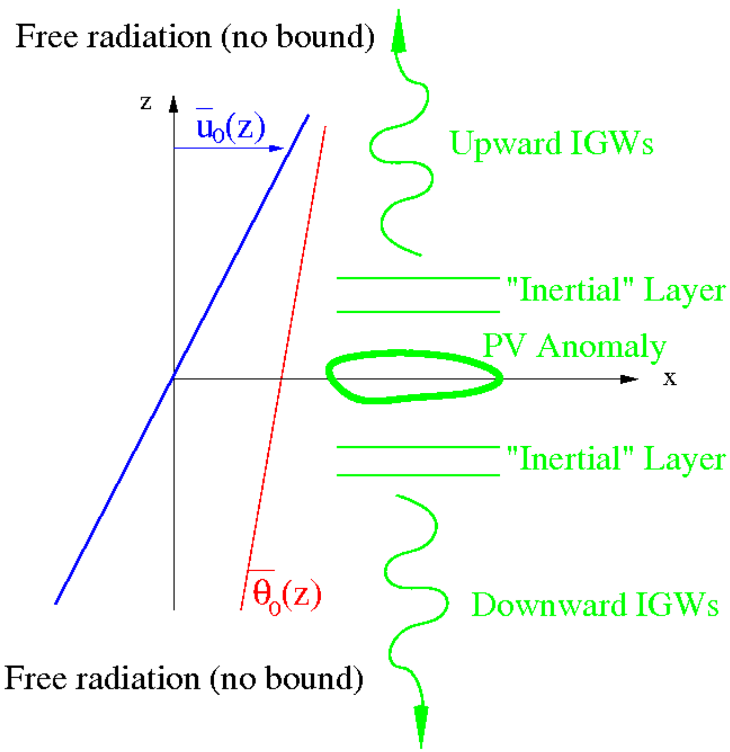
Figure 16. As Figure 2(b), but from a simulation with doubled horizontal resolution ($\Delta x = 10$ km).

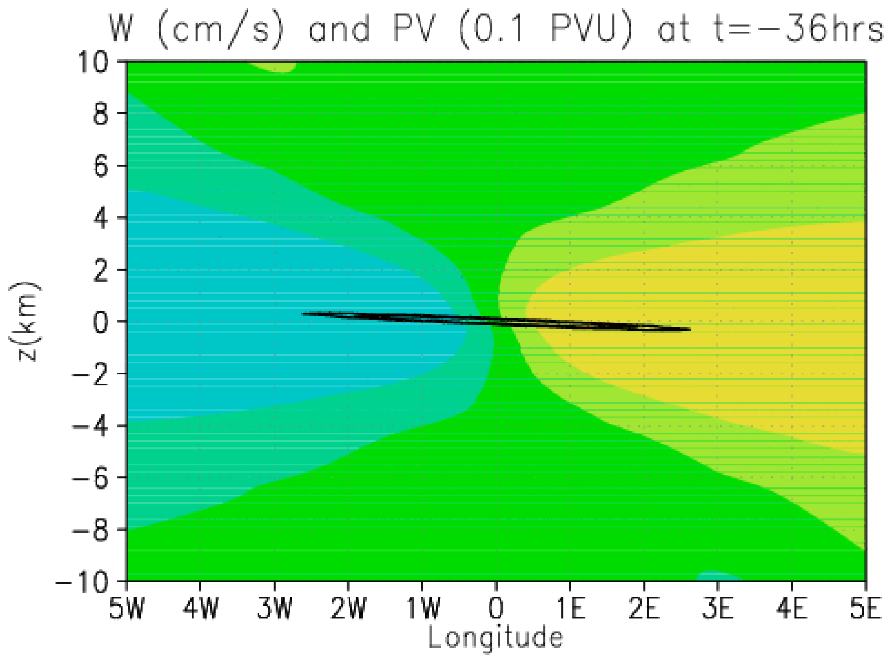
Results confirmed by much higher resolution simulations

Plougonven Hertzog and Guez (2012)

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

<u>General setup:</u> A 3D (x,y,z) PV anomaly advected in a rotating (*f* =cte), stratified (BV freq ***N*=cte**) shear flow (vertical shear **Λ=cte**).





Spontaneous adjustment theory: *Lott, Plougonven and Vanneste, JAS 2010, JAS 2012*.

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

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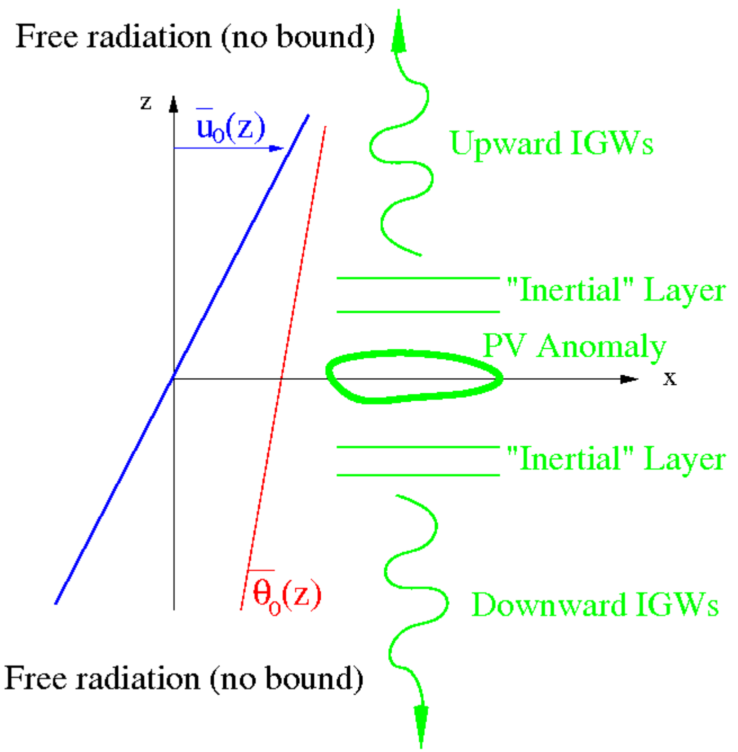

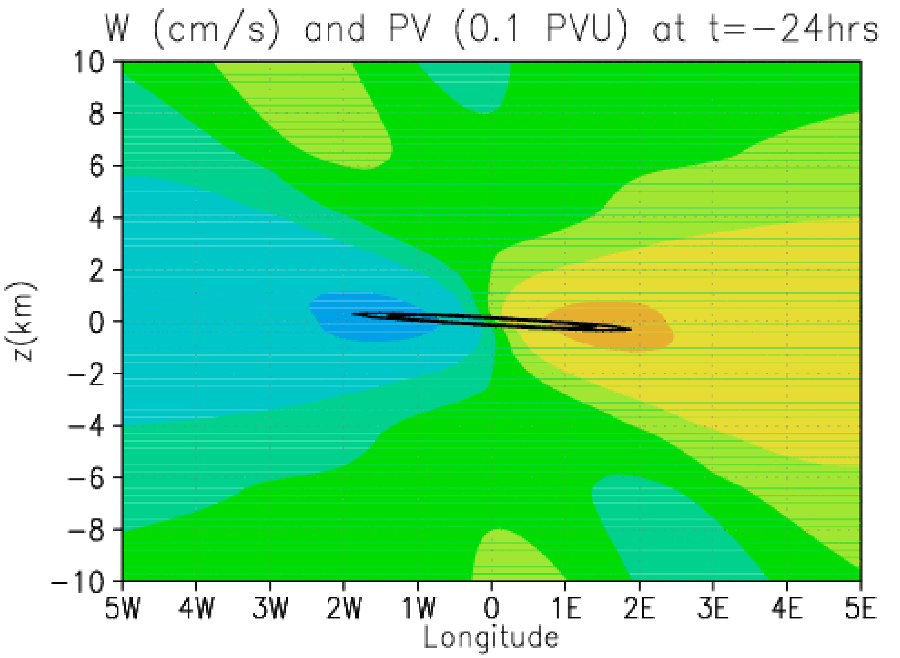

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General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

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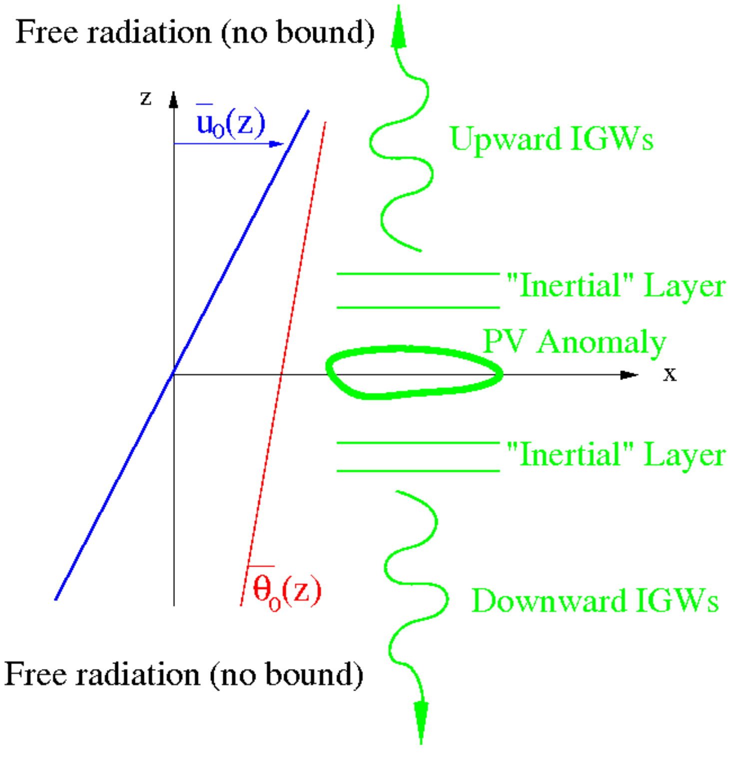

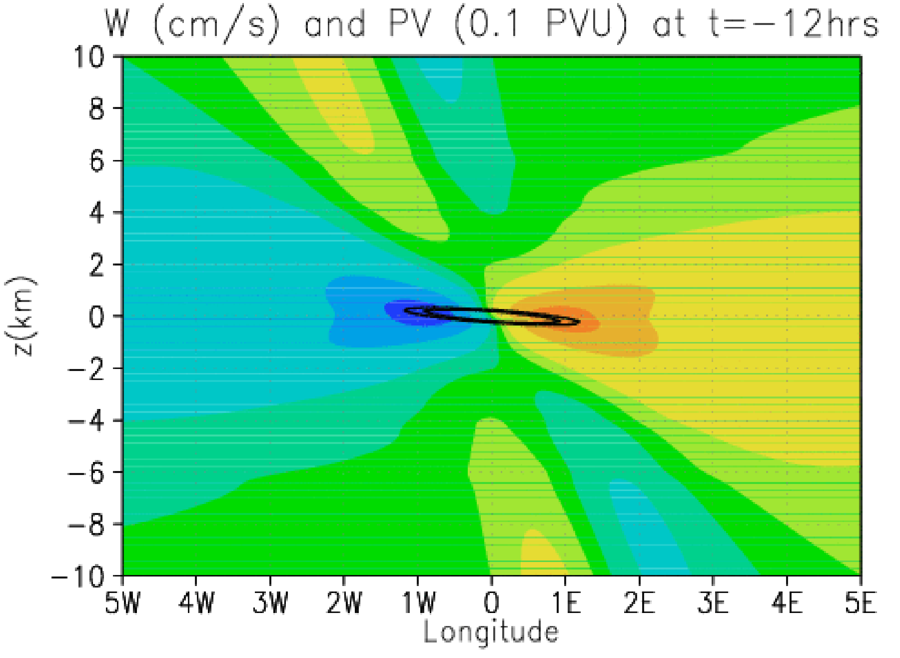

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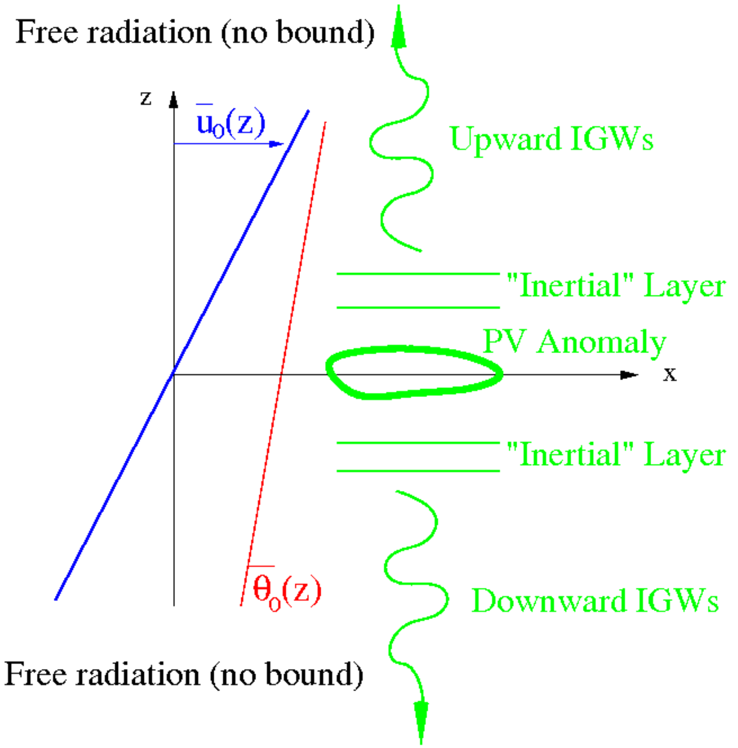

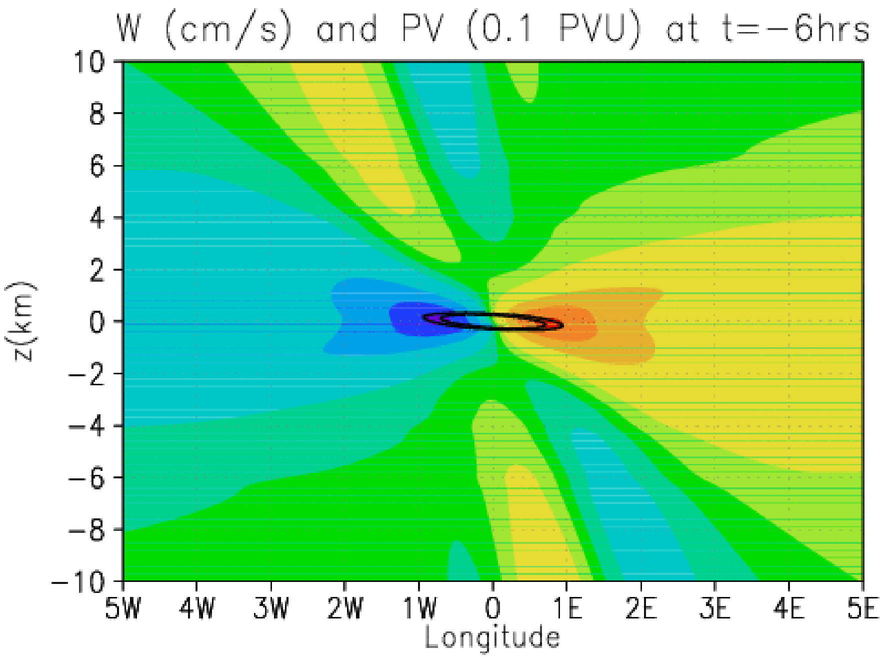

Spontaneous adjustment theory: *Lott, Plougonven and Vanneste, JAS 2010, JAS 2012.*

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

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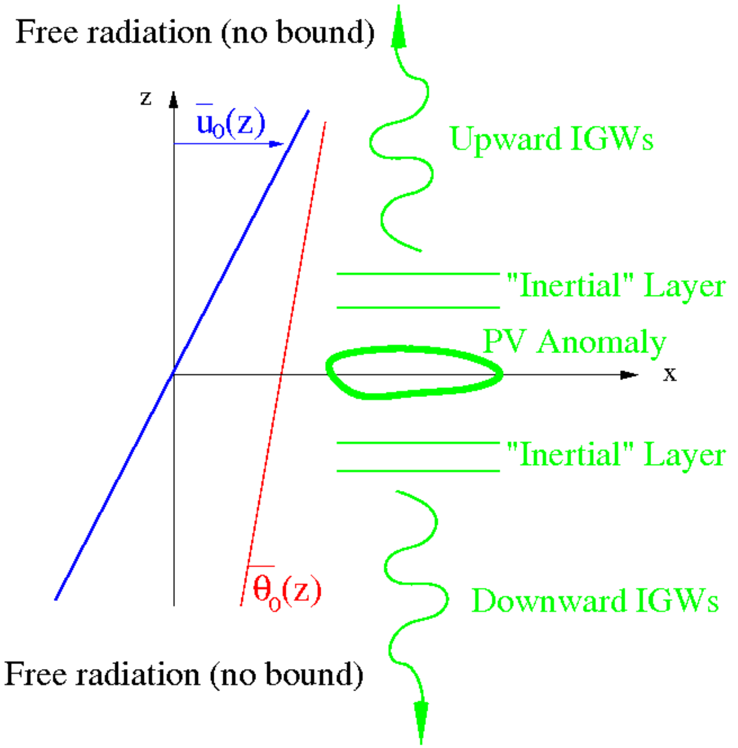

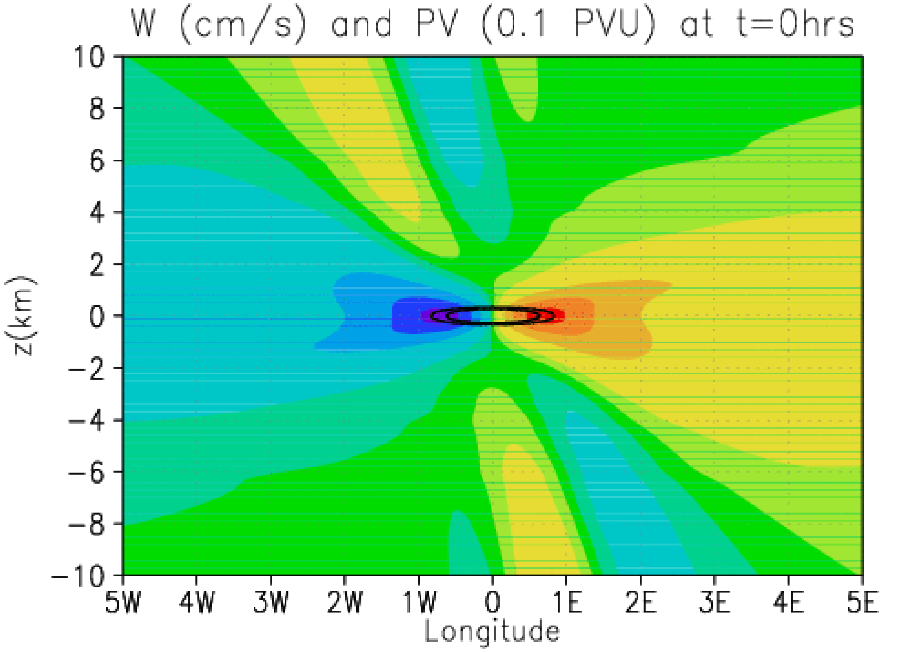

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General Circulation of the Stratosphere and modelisation
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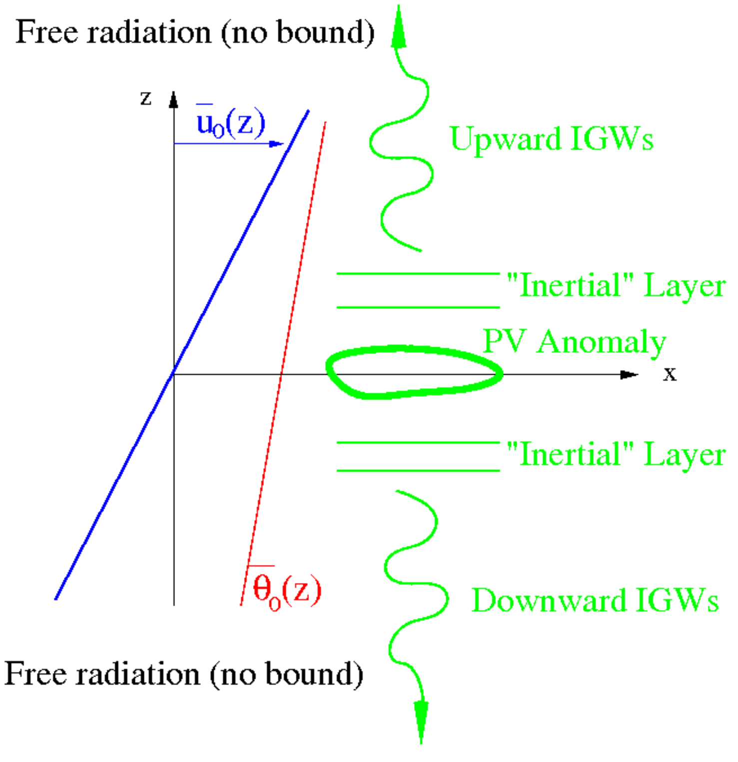

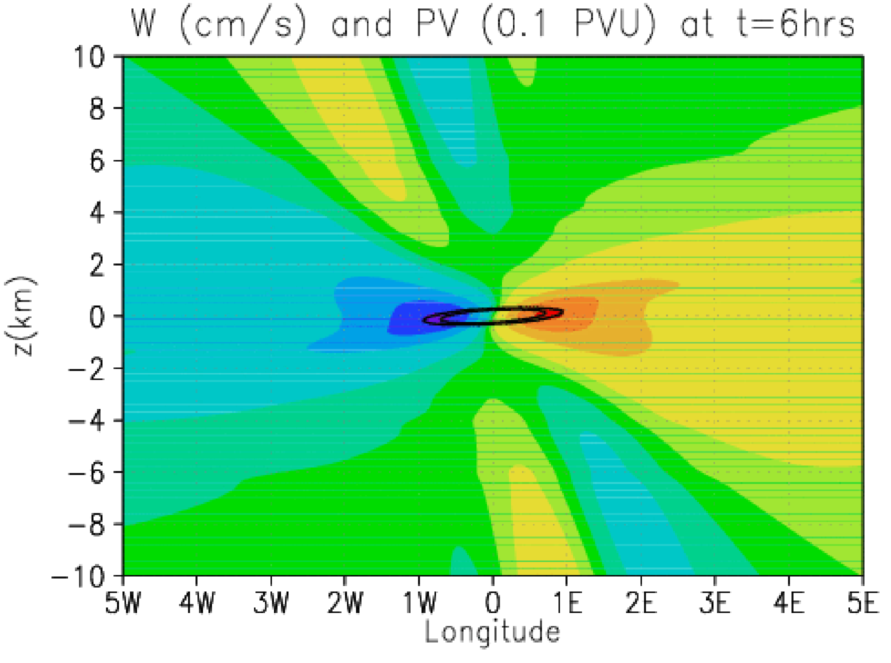

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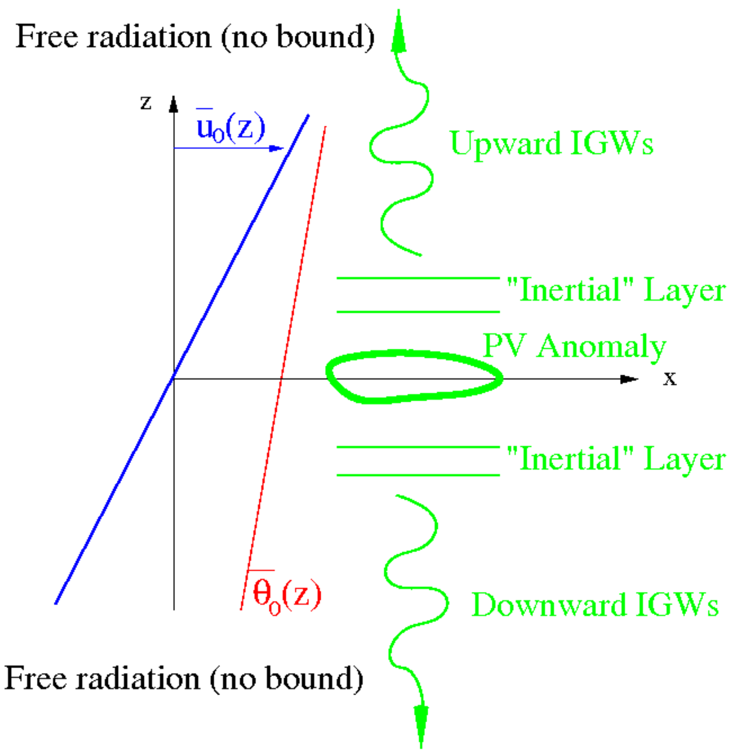

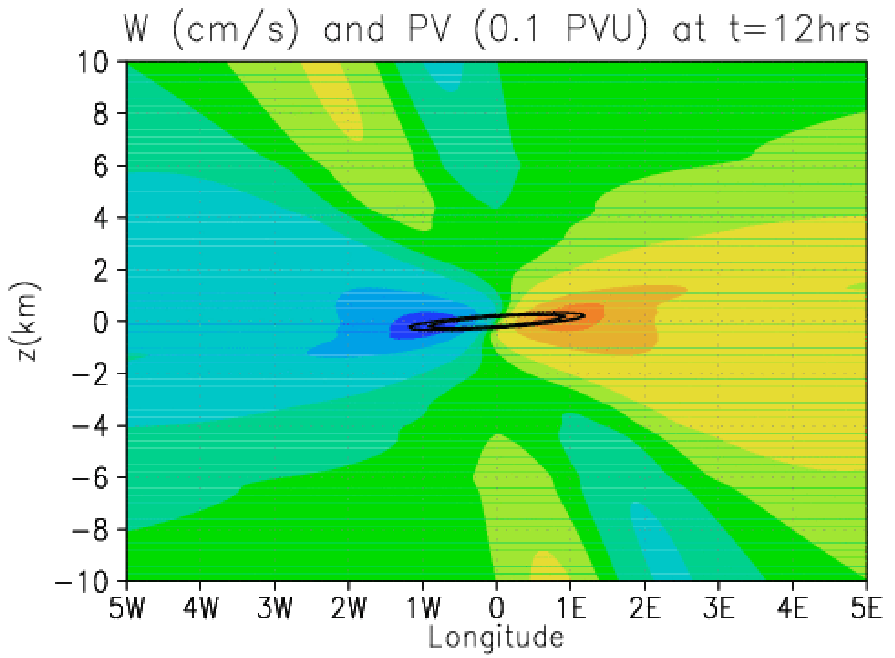

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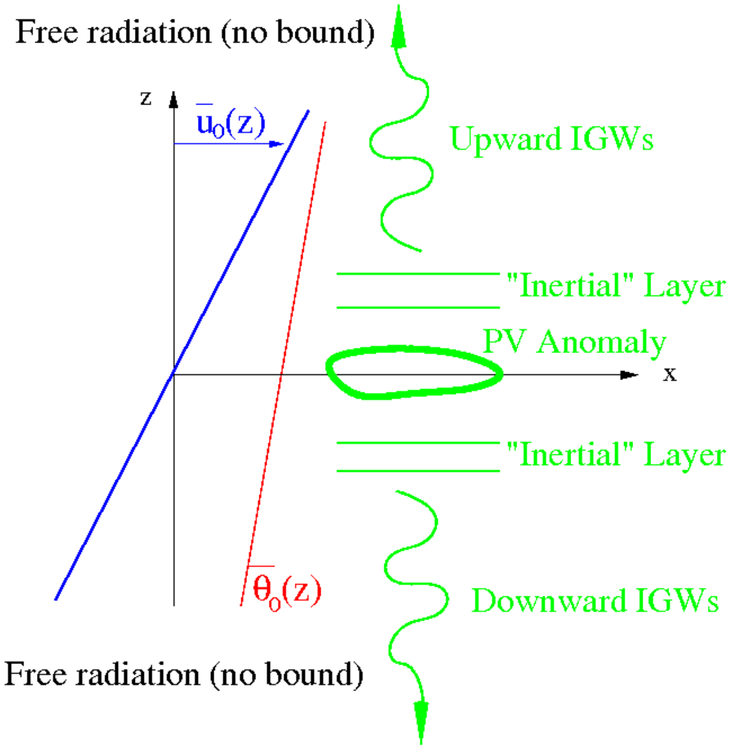

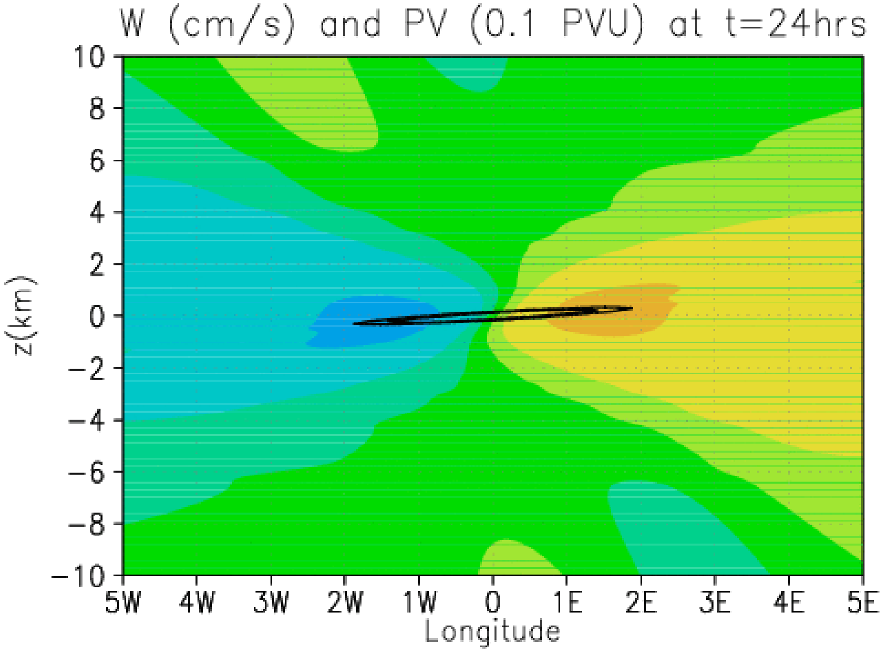

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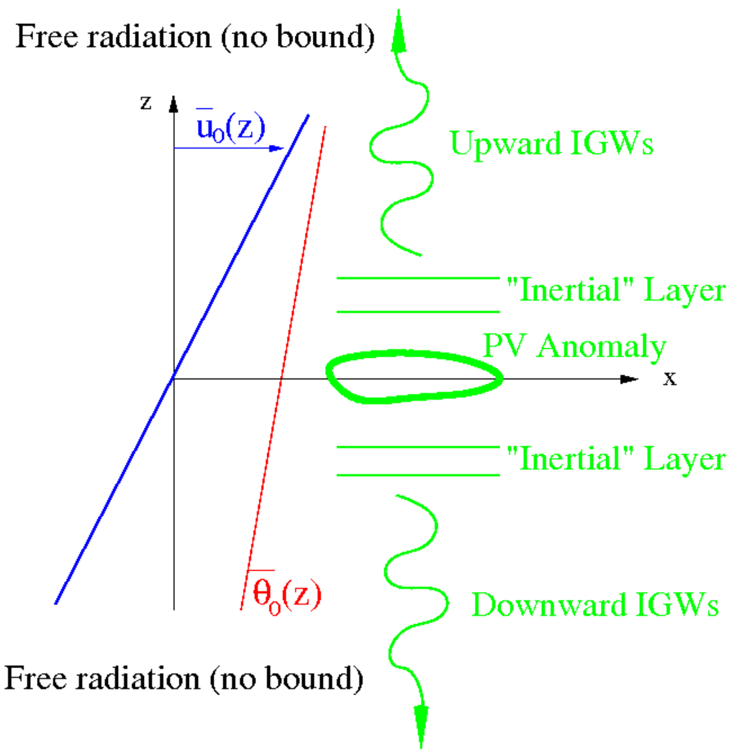

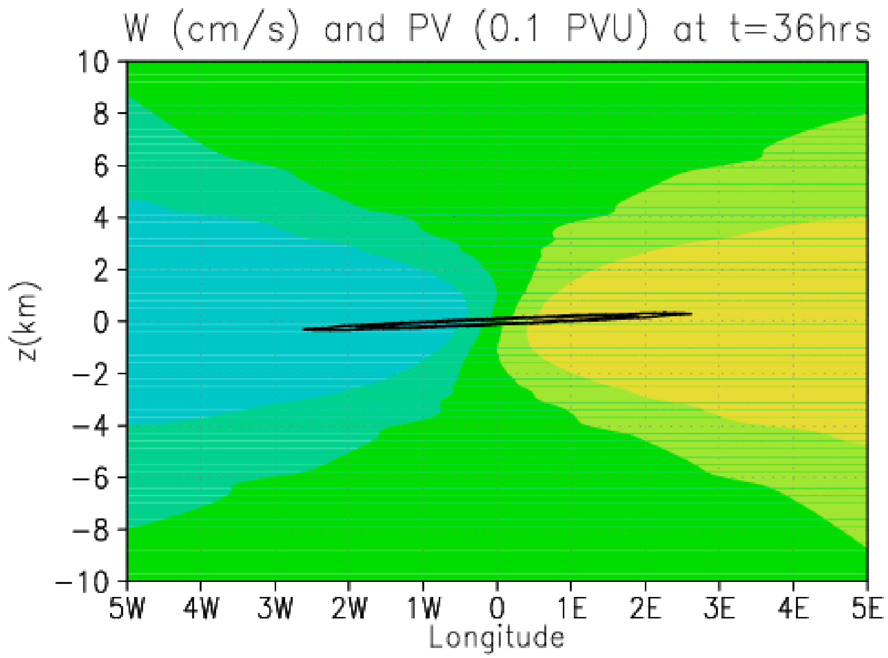

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General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

The wave stress is predictable in closed analytical form:

$$F \approx \frac{\rho g^2}{f \theta^2 N^3} \left(\rho q' \sigma_z\right)^2 \frac{e^{-\pi \frac{N}{\Lambda}}}{4}$$

PV anomaly

Characteristic depth of the PV anomaly

Valid for various PV distributions, and over long time scale (compared to the ½ hour interval at which subgrid-scale parameterisation routines are updated)

We next take for the PV q the GCM gridscale PV anomalies (as a measure of the subgrid scales one, again a "white" spectrum *hypothesis*)

Now it is the subgrid scale vorticity which is considered as a "white" stochastic series:

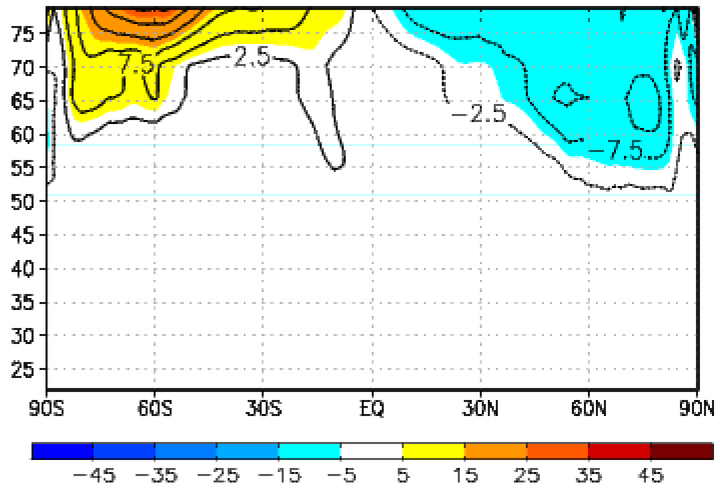
$$q' = \sum_{n=1}^{\infty} C_n q_n' \quad \text{where} \quad q_n' = \Re\left[\hat{q}_n e^{i(\vec{k}_n \cdot \vec{x} - \omega_n t)}\right] \quad \text{taking} \quad |\hat{q}_n| = |q_r|$$

For σ_z the GCM's layer depth, stochastic treatment of the k's, ω's, ect...

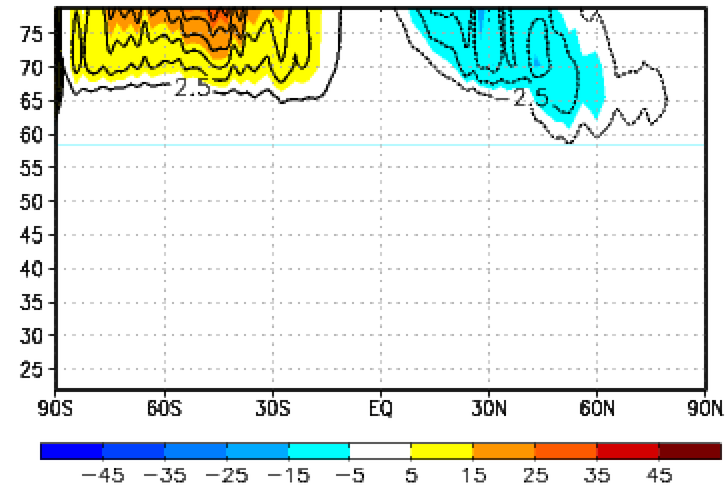
General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

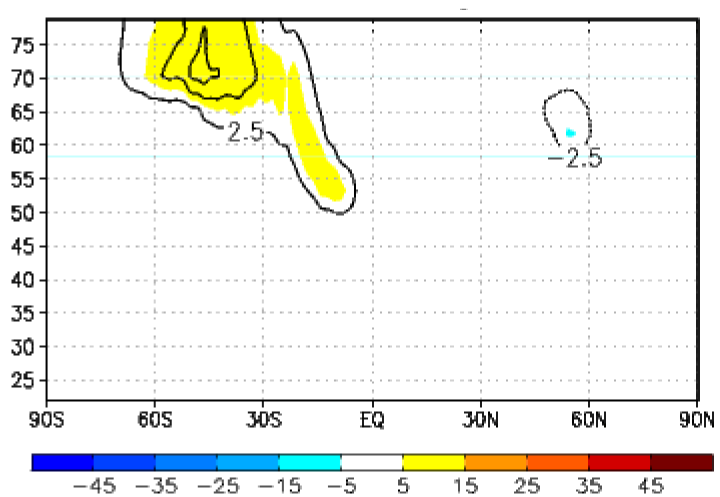
The "smoking gun" theory predicts about the right amount of drag compared to a highly tuned globally spectral scheme (January, all in m/s/day)

Globally spectral scheme

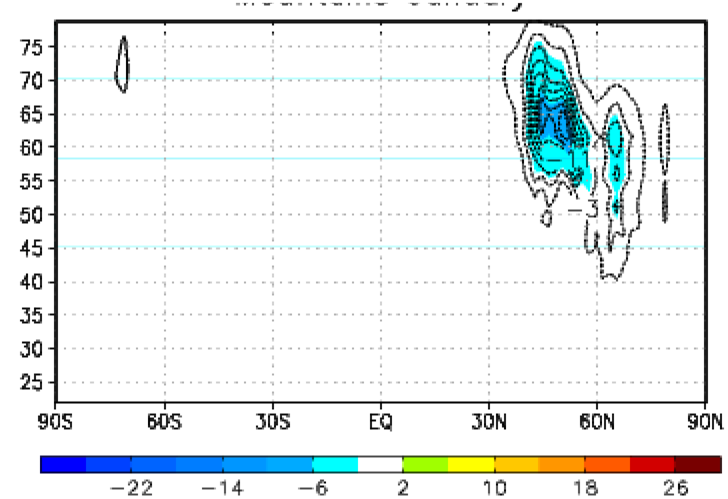


Smoking fronts





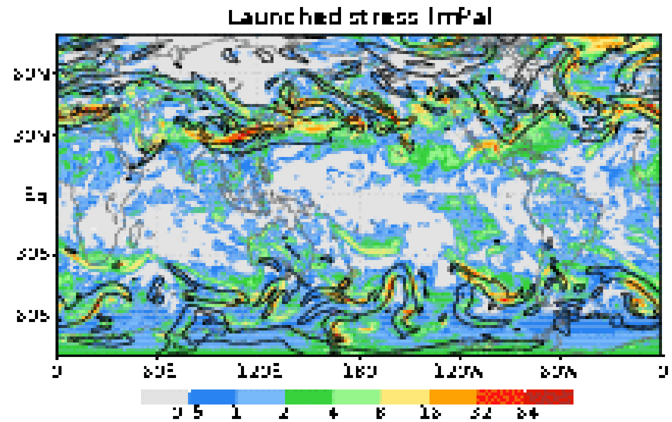
Convective GWs



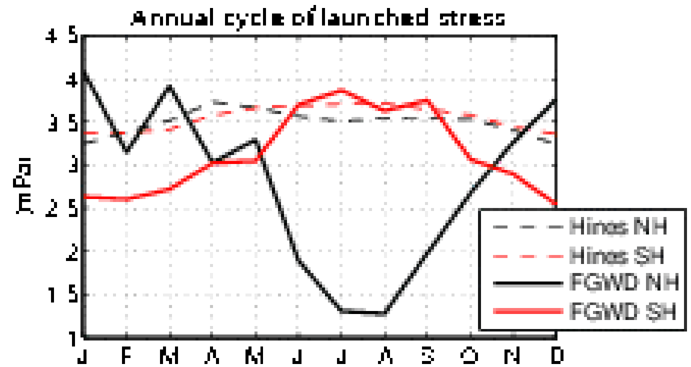
Mountains GWs

General Circulation of the Stratosphere and modelisation f) Frontal gravity waves parameterization

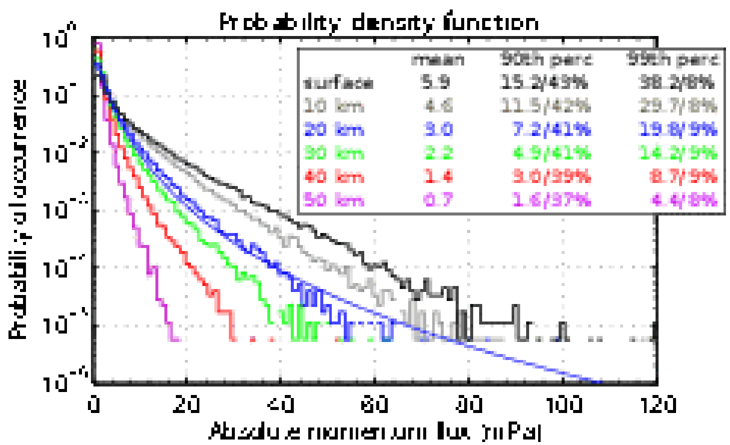
Launched GWs stress amplitude, and $\|\vec{\nabla} T\|$ at 600hPa:



The waves predicted come from frontal zones



The wave stress now has an annual Cycle...



and realistic intemittency

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

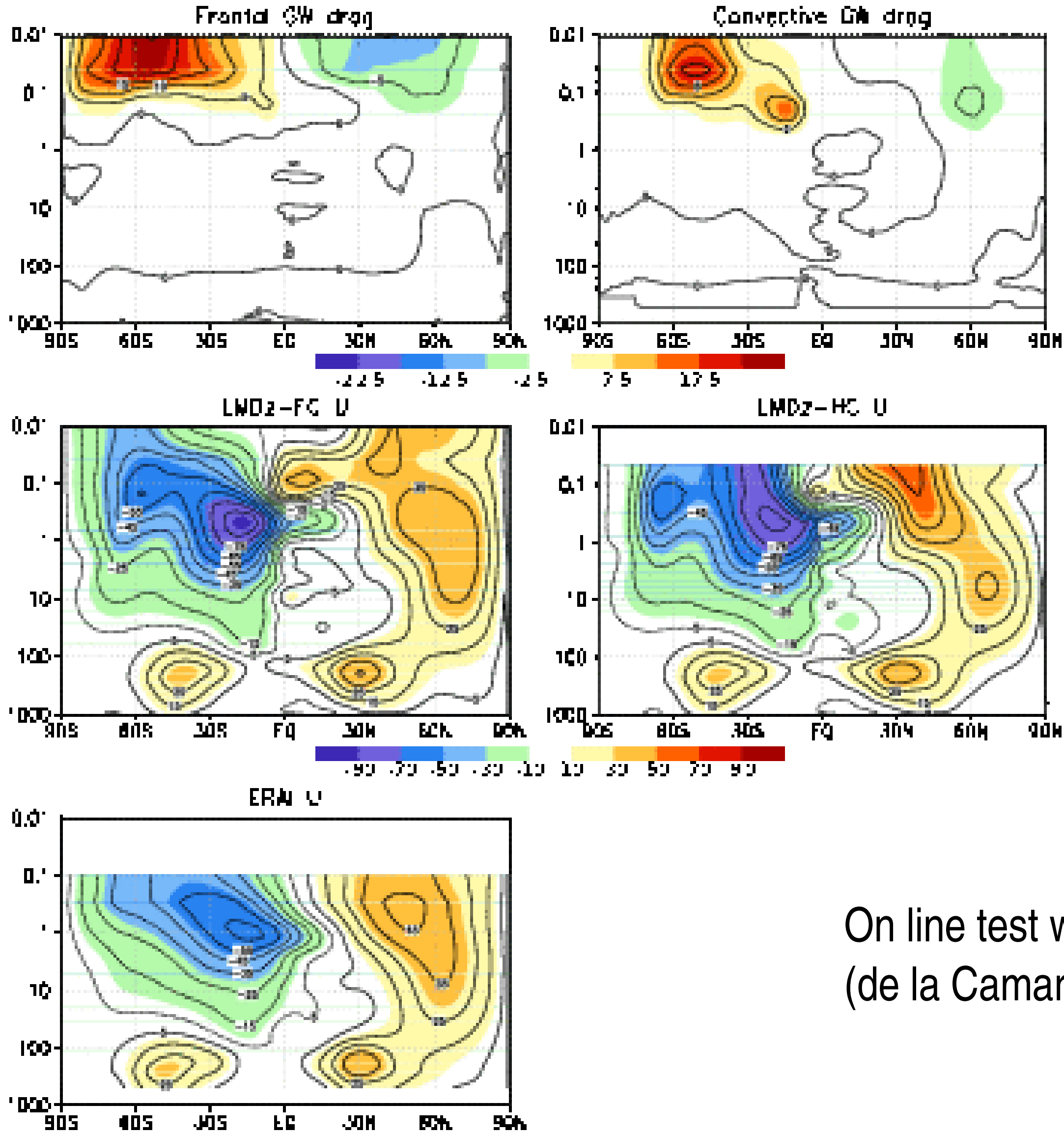
Frontal GWs drag

Convective GWs drag

Run with Hines + Convective waves

Frontal + Convective Stochastic GWs

ERA



On line test with LMDz GCM (de la Camara and Lott 2015)

General Circulation of the Stratosphere and modelisation
f) Frontal gravity waves parameterization

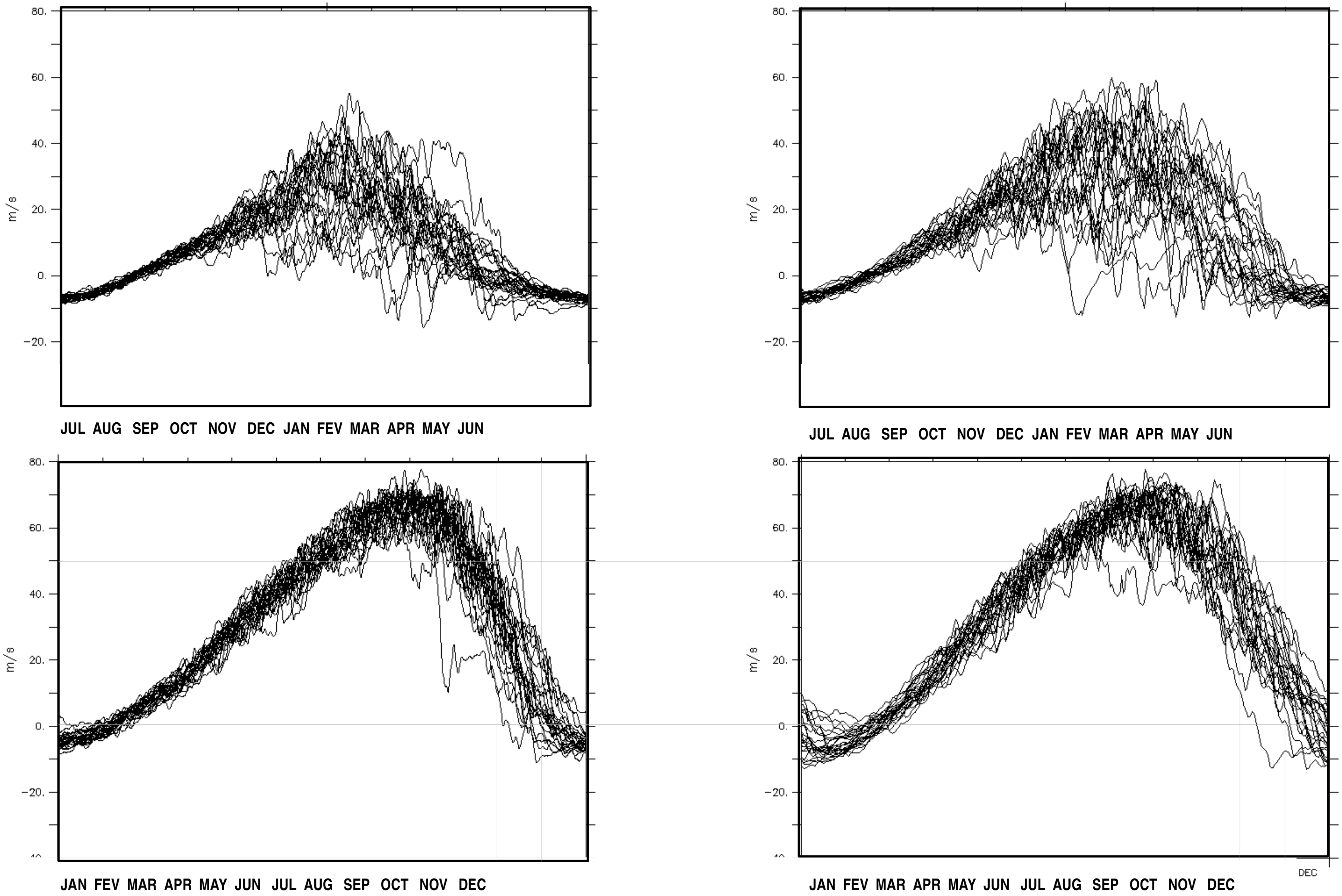
His the stronger GWs annual cycle impact the GCM's annual cycle?

U at 30hPA

ERAI 1980-2005 | LMDz toward CMIP6

NH 60°N

SH 60°S



General Circulation of the Stratosphere and modelisation Perspectives

Will this physically based stochastic approaches increase the spread of climate Simulations?

For instance via an improvement of the year to year variability of the SH stratospheric winter vortex breakdown?

Now that the GWs are tied to the tropospheric weather, we can address their contribution to the climate change in the middle atmosphere

Does our unbalanced responses to upper-level PV anomalies modify the triggering of surface synoptic waves?

Extent stochastic methods to mountain waves?