Gravity waves from fronts and convection

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1)Stochastic GWs scheme and application to convection

2)GWs from fronts

3)Tests against observations

Gravity waves from fronts and convection
1) Stochastic GWs scheme and application to convection

Subgrid scale parametrizations are based on Fourier series decomposition of the waves field over the model gridbox of sizes δx, δy, and δt (δt can be larger than the model time-step).

$$w' = \sum_a \sum_b \sum_c \hat{w}\left(k_a, l_b, \omega_c\right) e^{i\left(k_a x + l_b y - \omega_c t\right)}$$

a, b, c are integers, (dropped in the following) and $k_a = a\frac{2\pi}{\delta x}, l_b = b\frac{2\pi}{\delta y}, \omega_c = c\frac{2\pi}{\delta t}$

Since a lot of waves with different caracteristics are needed this triple Fourier series can be very expensive to evaluate each timestep

Multiwaves schemes:

Garcia et al. (2007),
Alexander and Dunkerton (1999)
Treat the large ensemble of waves but each quite independently from the others and using Lindzen (1981) to evaluate the breaking.

Globally spectral schemes:

Treat the spectra globally, and using analytical integrals of its different parts

Hine (1997),
Manzini and McFarlane (1997)

Warner and McIntyre (2001)

Gravity waves from fronts and convection
1) Stochastic GWs scheme and application to convection

Classical arguments: see 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:

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

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

Gravity waves from fronts and convection
1) Stochastic GWs scheme and application to convection

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):

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

$k_n, l_n\, \omega_n$ chosen randomly

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

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

Heavyside function for critical levels

Eliasen-Palm theorem with dissipation

Breaking

$$m = \frac{N\left|\vec{k}\right|}{\Omega}$$ Vertical wavenumber

$$\Omega = \omega - \vec{k}\cdot\vec{u}$$ Intrinsic frequency

$\boxed{S_c, k^*: \text{ Tunable parameters}}$ (could be chosen randomly)

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1) Stochastic GWs scheme and application to convection

$P' = \sum_{n=1}^{\infty} C_n P_n'$ 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:

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

EP-flux at the launch level z_l :

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

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

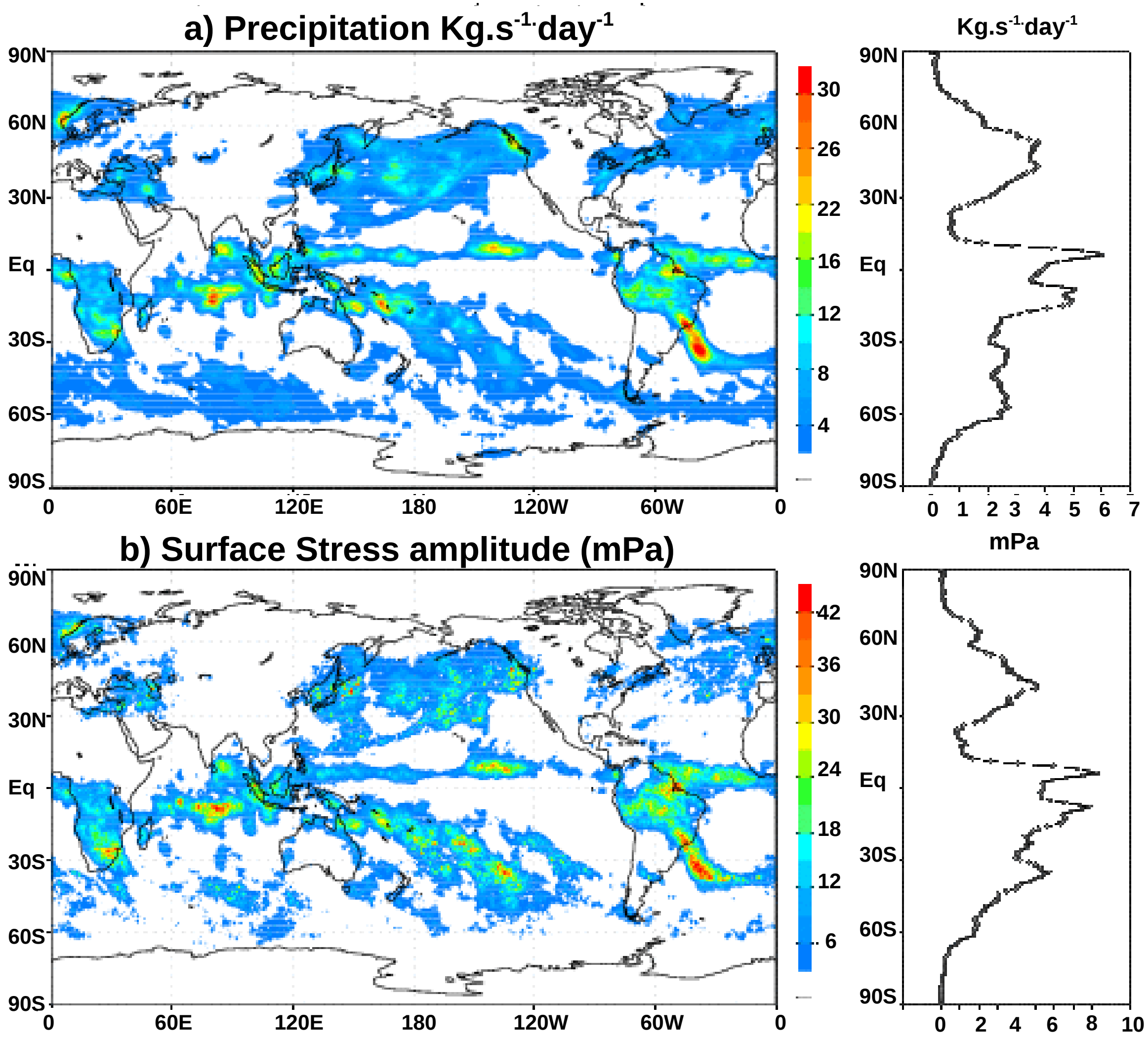
G_{uw}: New tuning parameter (could be a random number)

Gravity waves from fronts and convection
1) Stochastic GWs scheme and application to convection

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)

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



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.

Gravity waves from fronts and convection

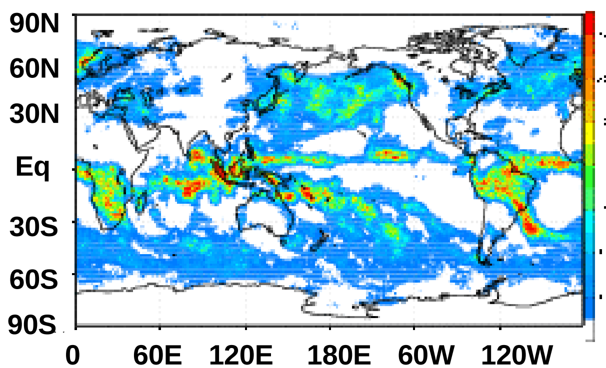
1) Stochastic GWs scheme and application to convection

Offline tests with ERAI and GPCP

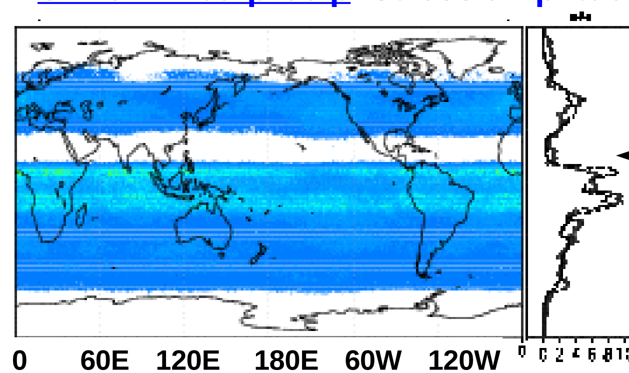
Benefit of having few large GWs rather than a large ensemble of small ones:

CGWs stress

Real precip. Stress amplitude (CI=2mPa)



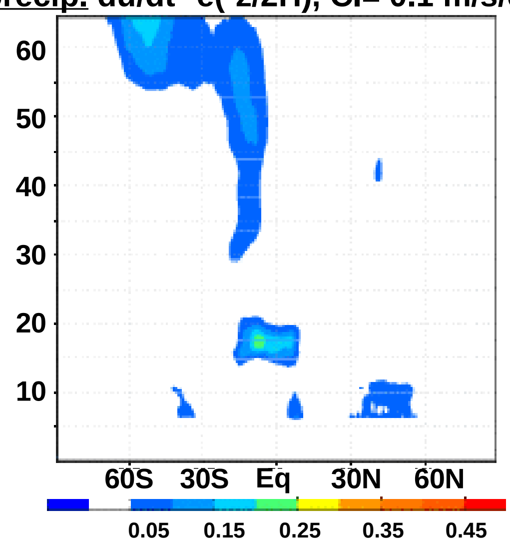
Uniformized precip. Stress amplitude (CI=2mPa)



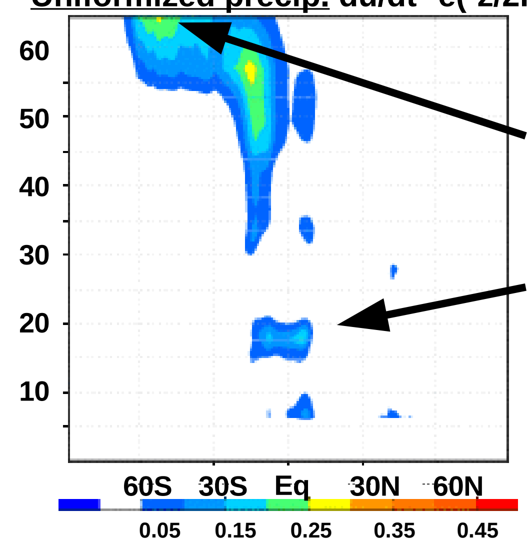
Same zonal mean stress

CGWs drag

Real precip. du/dt *e(-z/2H), CI= 0.1 m/s/d



Uniformized precip. du/dt *e(-z/2H), CI= 0.1 m/s/d



More drag near and above stratopause

Slightly less drag in the QBO region

Lott and Guez, JGR 2013

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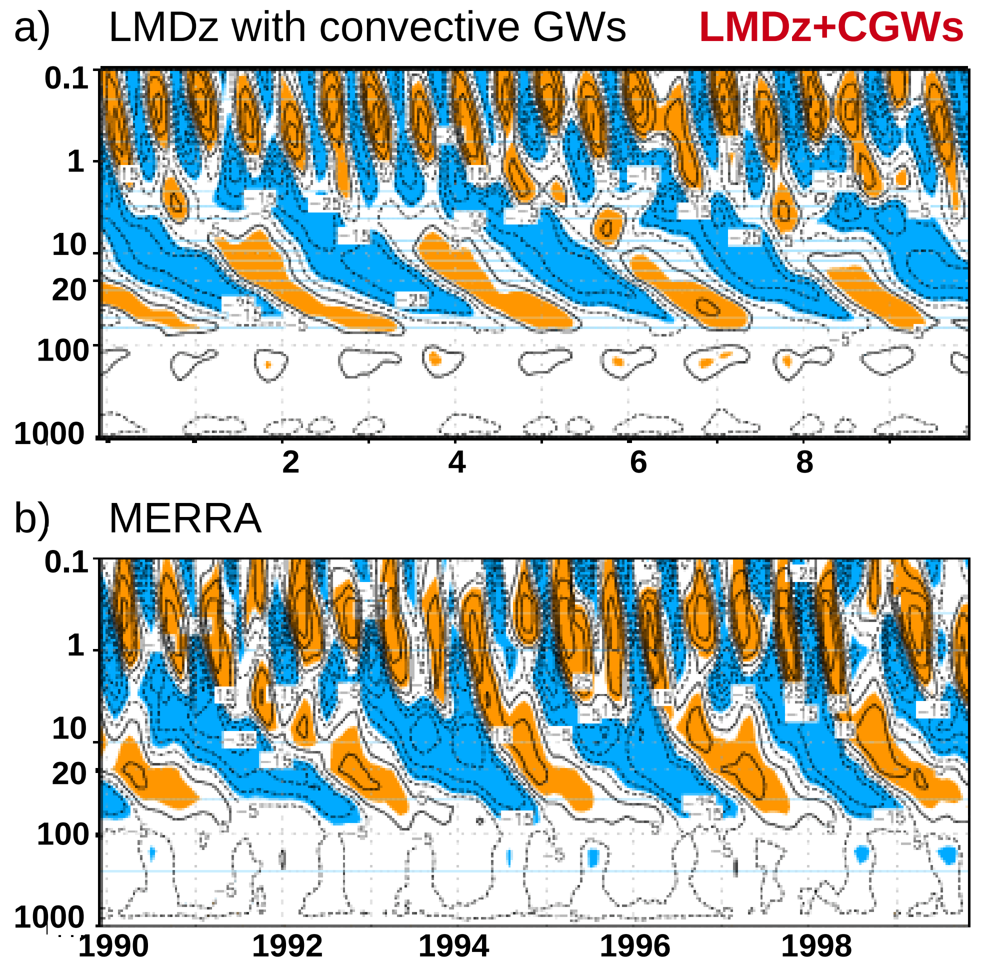
Online results with LMDz

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

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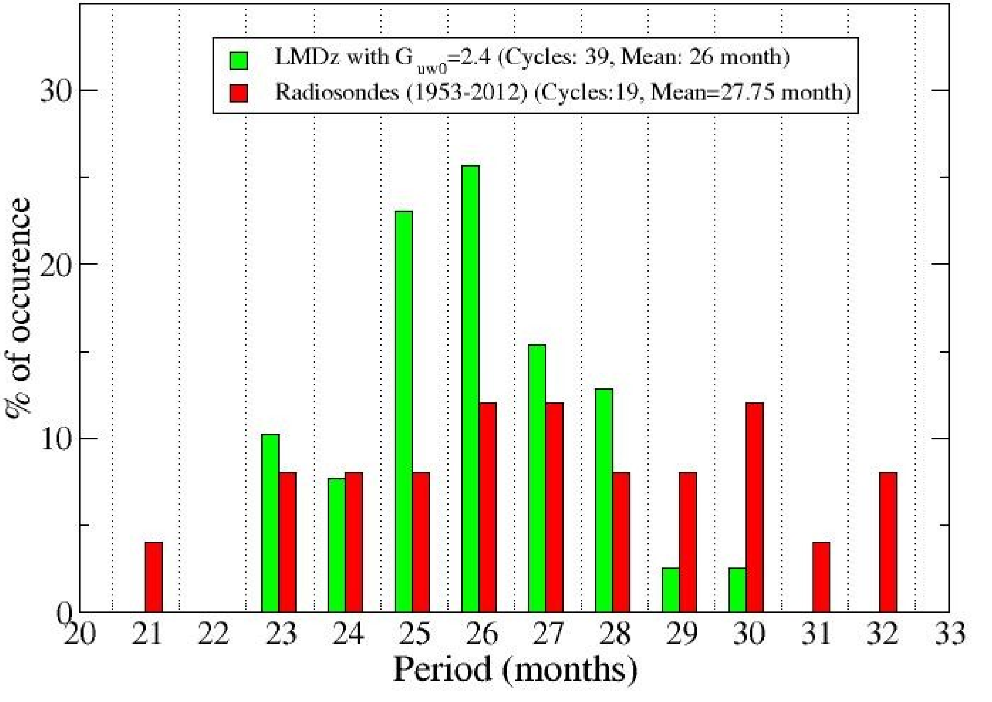
Online results with LMDz

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 favourec probably related to the weak relations with the SAO



Lott and Guez, JGR13

Gravity waves from fronts and convection
1) Stochastic GWs scheme and application to convection

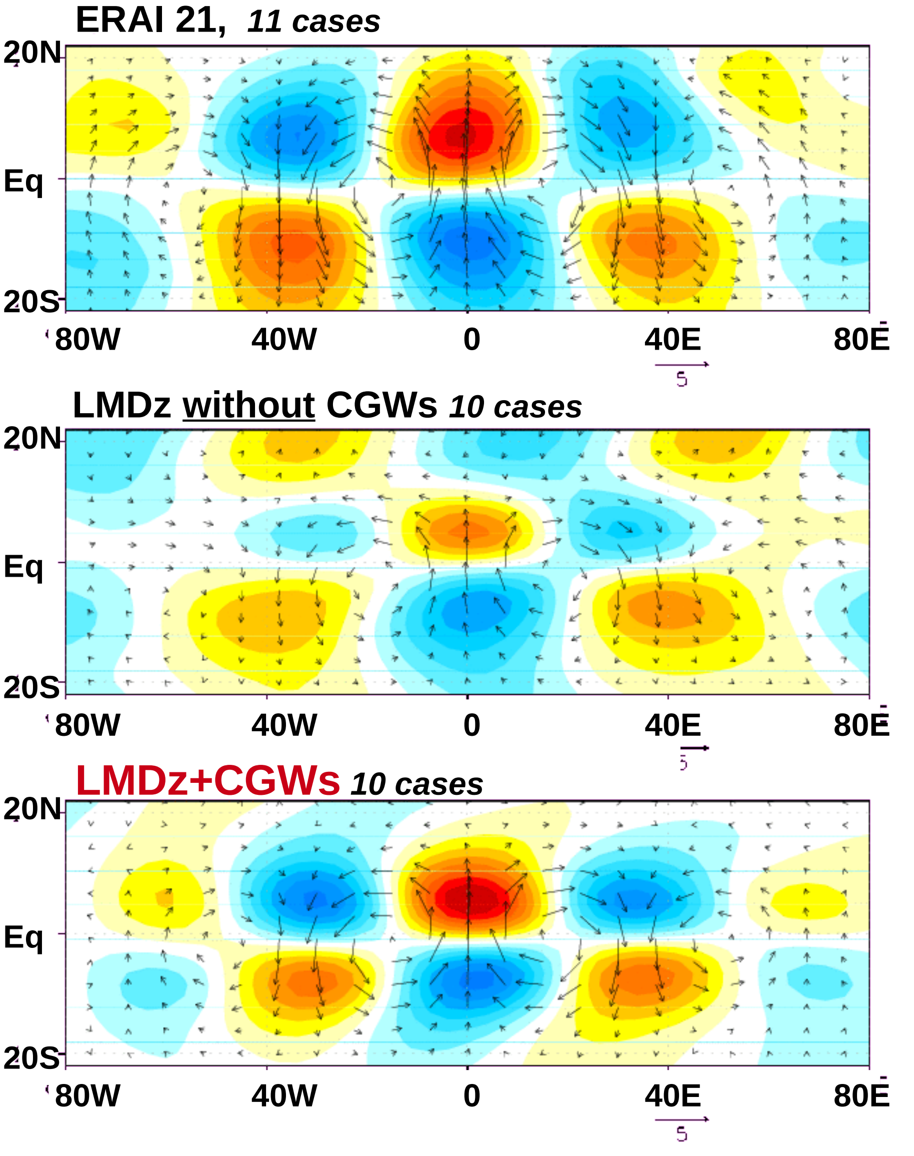
Composite of Rossby-gravity waves with s=4-8
Temp (CI=0.1K) and Wind at 50hPa & lag = 0day

<u>**Equatorial waves:**</u>

Remember also that when you start to have positive zonal winds, **the planetary scale Yanai wave is much improved**

(the composite method is described in Lott et al. 2009)

Zero longitude line arbitrary



Lott et al. 2012 GRL

Gravity waves from fronts and convection
2) GWs from fronts

For waves from front, the situation is more complex because it is the large scale flow itself that produces a dynamical "ageostrophic" forcing. In the response to this forcing it is still an issue to determine the part that is constituted of GWs from the balanced part.

Some nevertheless uses this frontogenesis function as an indicator. For instance in Richter et al.~(2010), it is said that when

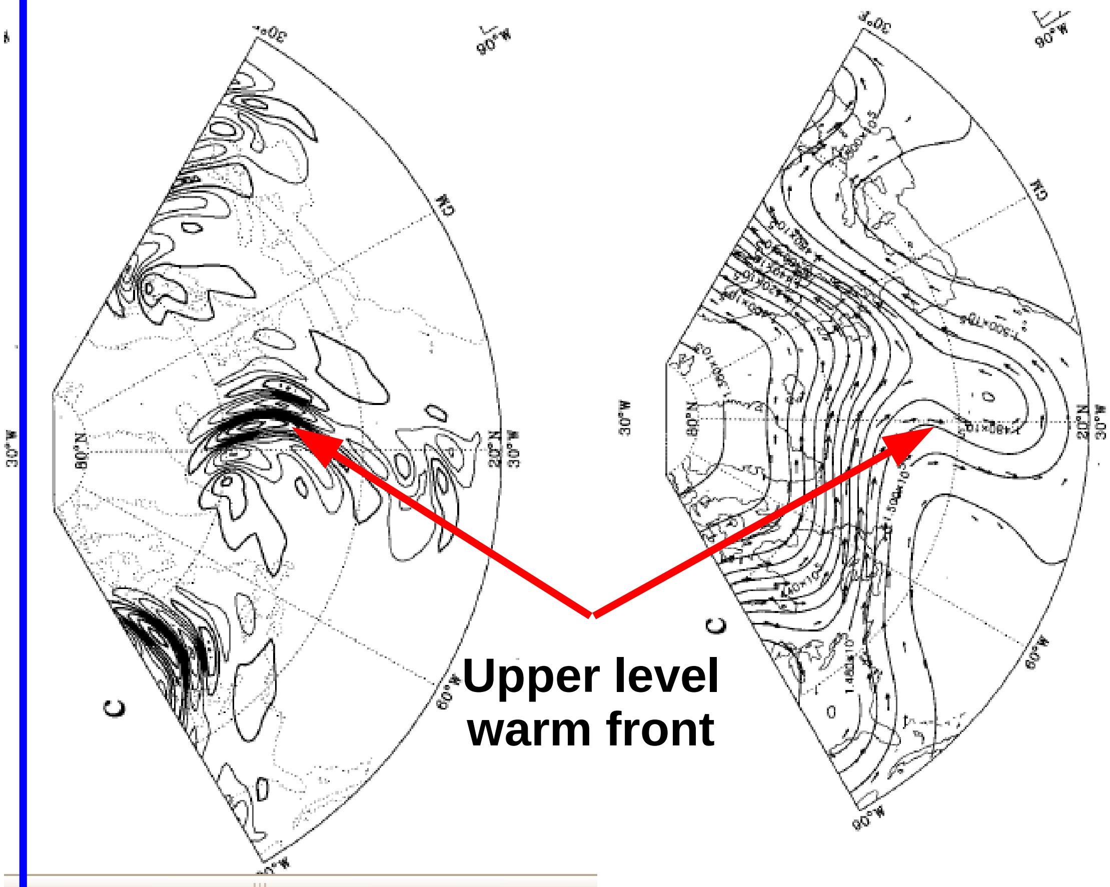
$$F=-\left(\frac{1}{a\cos\varphi}\frac{\partial\theta}{\partial\lambda}\right)^2\left(\frac{1}{a\cos\varphi}\frac{\partial u}{\partial\lambda}-\frac{v\tan\varphi}{a}\right)-\left(\frac{1}{a}\frac{\partial\theta}{\partial\varphi}\right)^2\left(\frac{1}{a}\frac{\partial v}{\partial\varphi}\right)$$
$$-\left(\frac{1}{a\cos\varphi}\frac{\partial\theta}{\partial\lambda}\right)\left(\frac{1}{a}\frac{\partial\theta}{\partial\varphi}\right)\left(\frac{1}{a\cos\varphi}\frac{\partial v}{\partial\lambda}+\frac{1}{a}\frac{\partial u}{\partial\varphi}+\frac{u\tan\varphi}{a}\right)$$

Exceeds 0.045 (K^2 $(100km)^{-2}$ h^{-1}), GWF=1.5 mPa!

Justification for being so vague :
"the relation between frontal characteristics and wave amplitude have not been established to date"

Gravity waves from fronts and convection
2) GWs from fronts

Simulations to support these parameterizations:



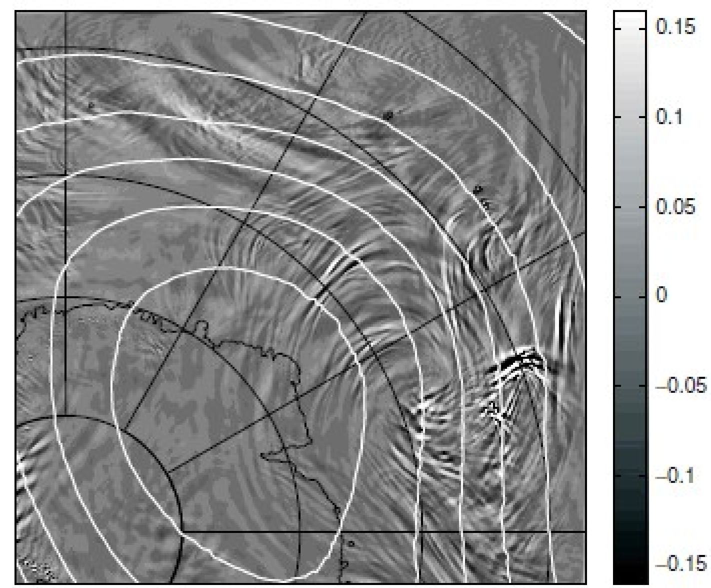


Figure 16. As Figure 2(b), but from a simulation with doubled horizontal resolution ($\Delta x = 10$ km).

Results confirmed by much higher resolution simulations

Plougonven Hertzog and Guez (2012)

O'Sullivan and Dunkerton (1995)

Gravity waves from fronts and convection
2) GWs from fronts

This is somehow related to the "Geostrophic Adjustment" process

In the "classical adjustment" an initial unbalanced flow radiates GWs as it returns to a balanced situation. In this case, the initial imbalance is the ultimate source of the GWs: the problem is to know what causes this imbalance (Lott, JAS 2003)

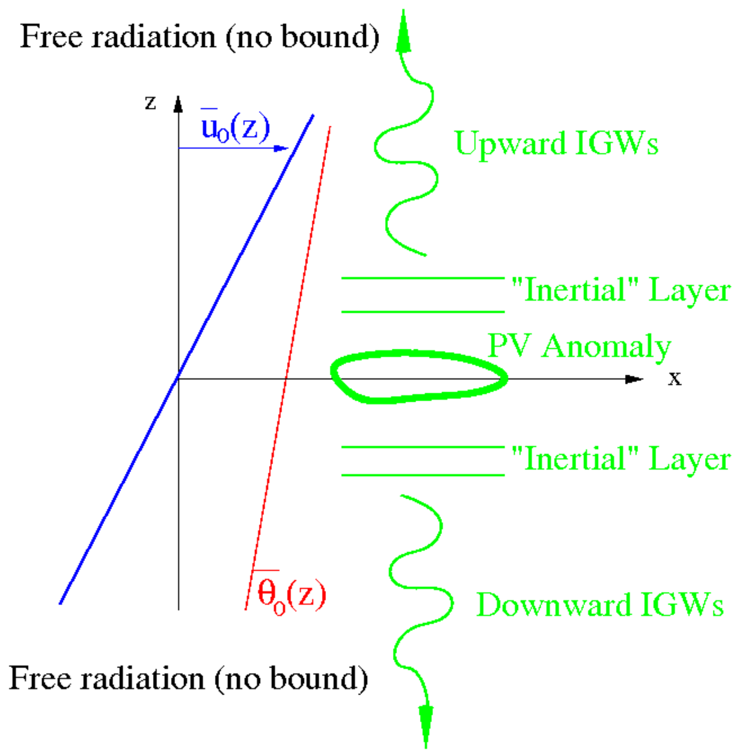
«Spontaneous adjustment» where a well-balanced flow radiates GWs in the course of its evolution. Here the adjustment itself is the GWs source.

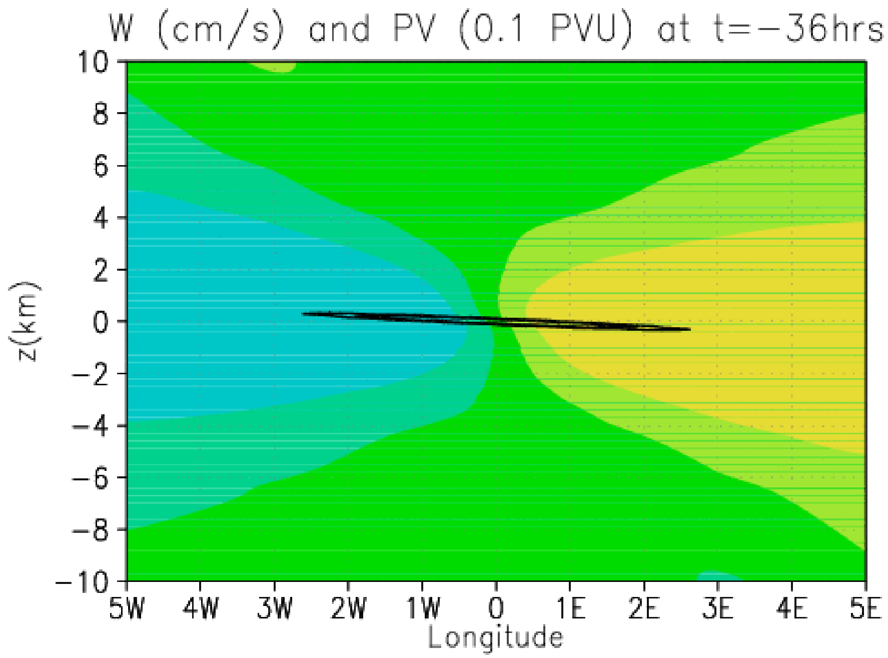
In the two cases, there is at the place of largest emission a pronounced PV anomaly, either it is present because the initial conditions are highly perturbed, or it is produced internally

But we know that PV anomalies can spontaneously emit Gravity Waves, and we have exact quantitative estimate of this emission (Lott et al., 2010, 12012). So we can use the PV anomalies themselves as predictors of the GWs emission.

Gravity waves from fronts and convection
2) GWs from fronts

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





For the 2D results: *Lott, Plougonven and Vanneste, JAS 2010*.

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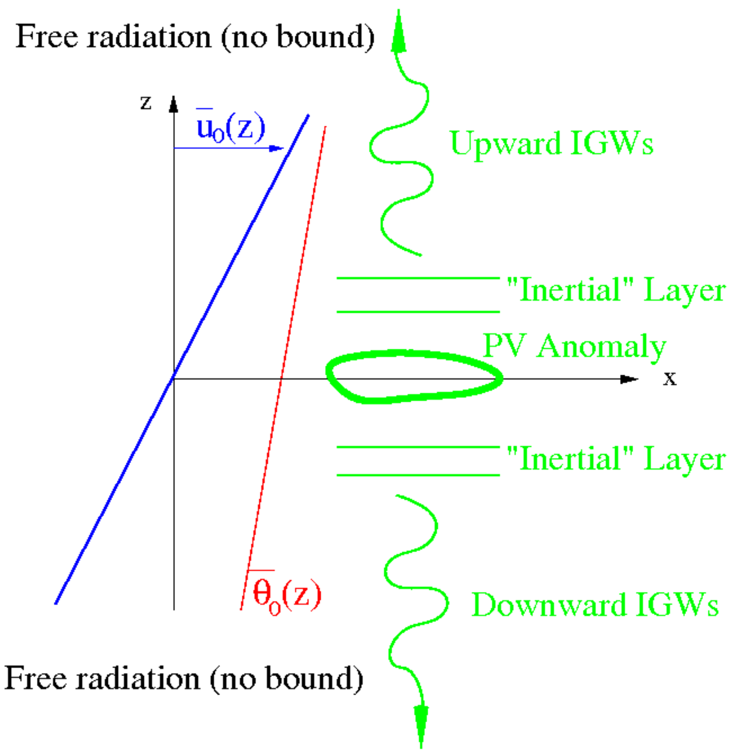

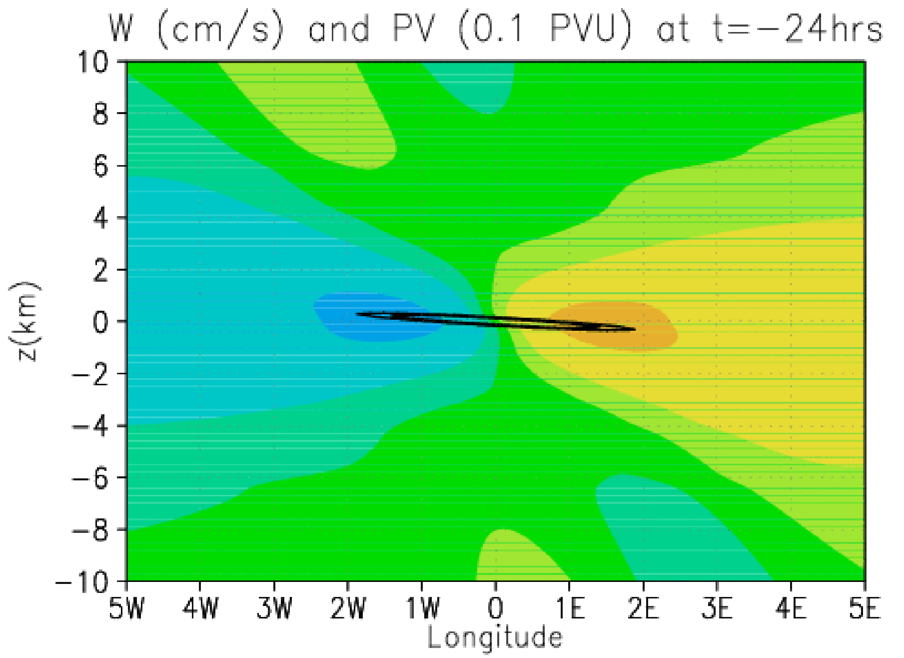

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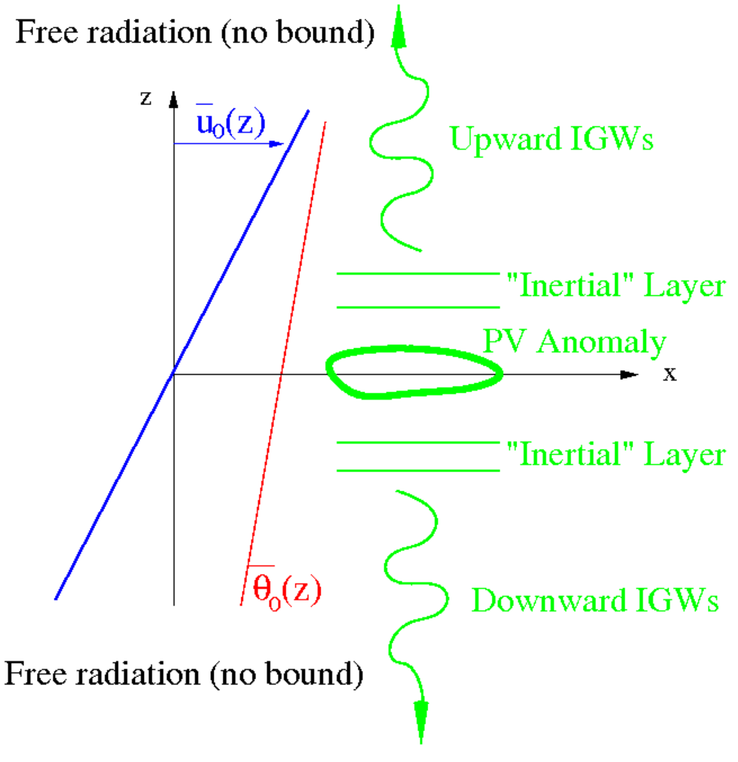

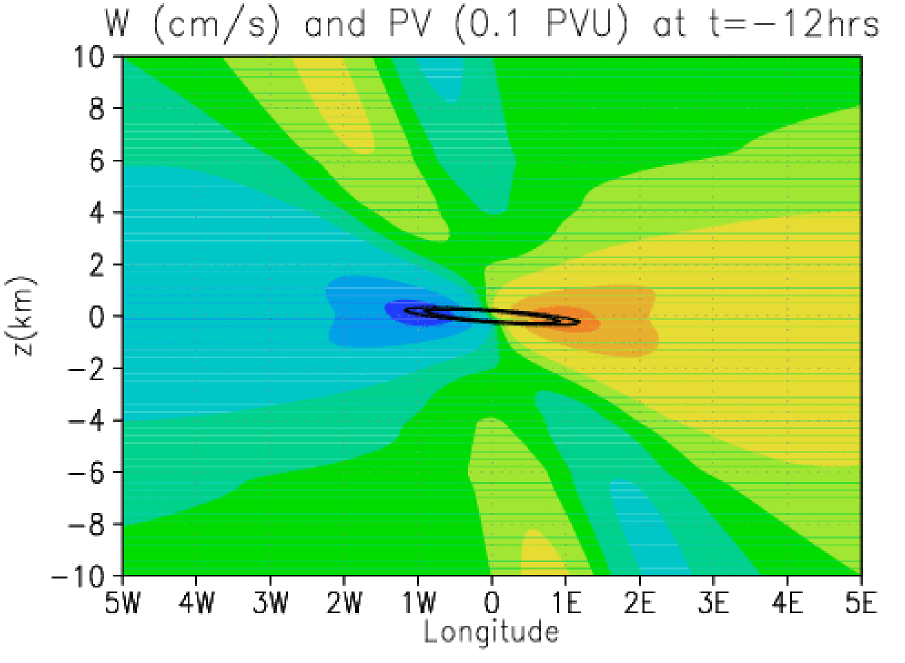

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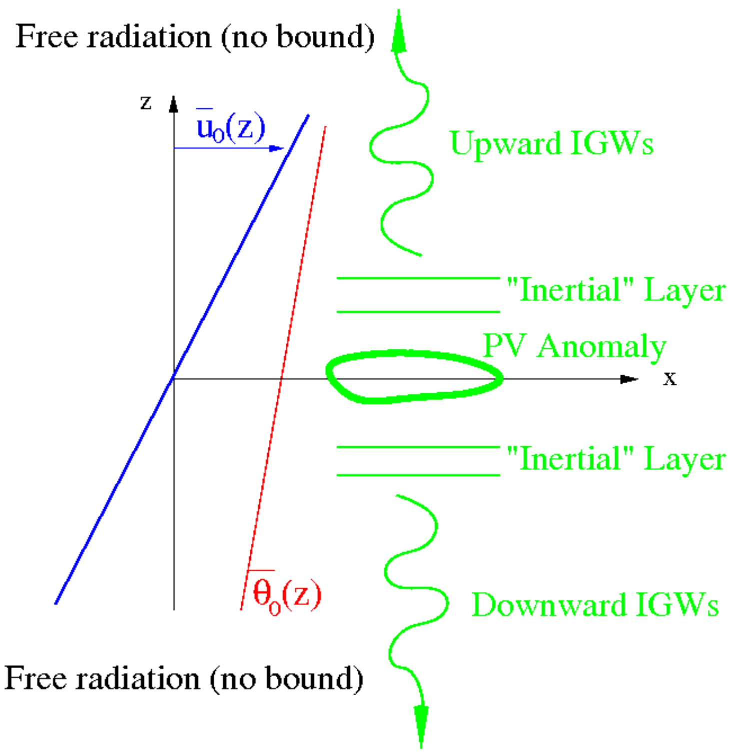

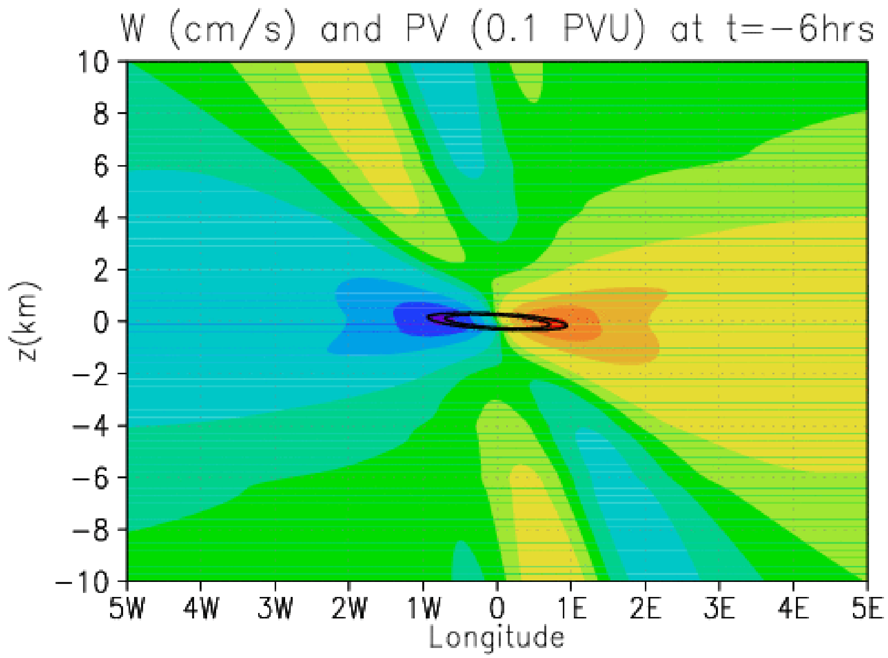

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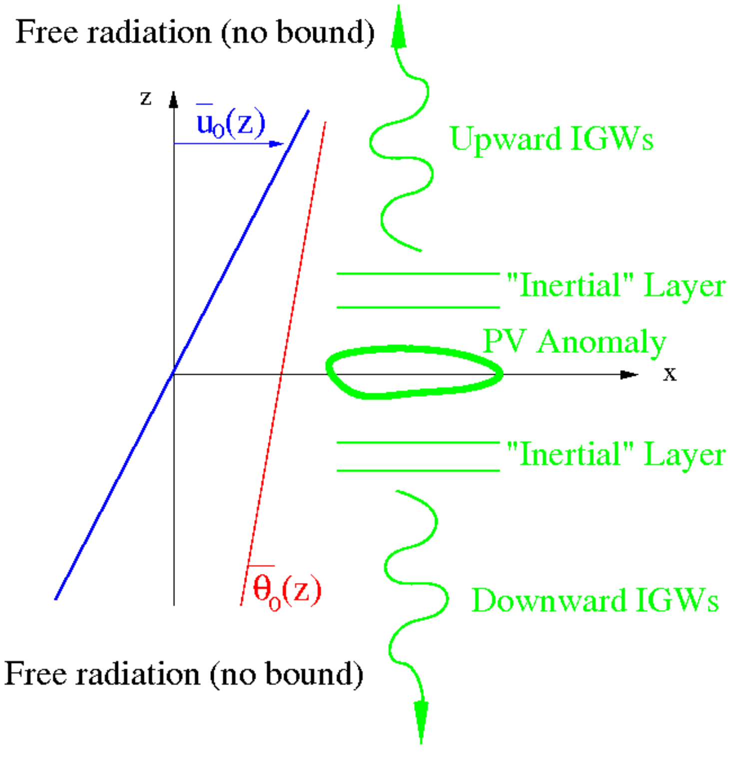

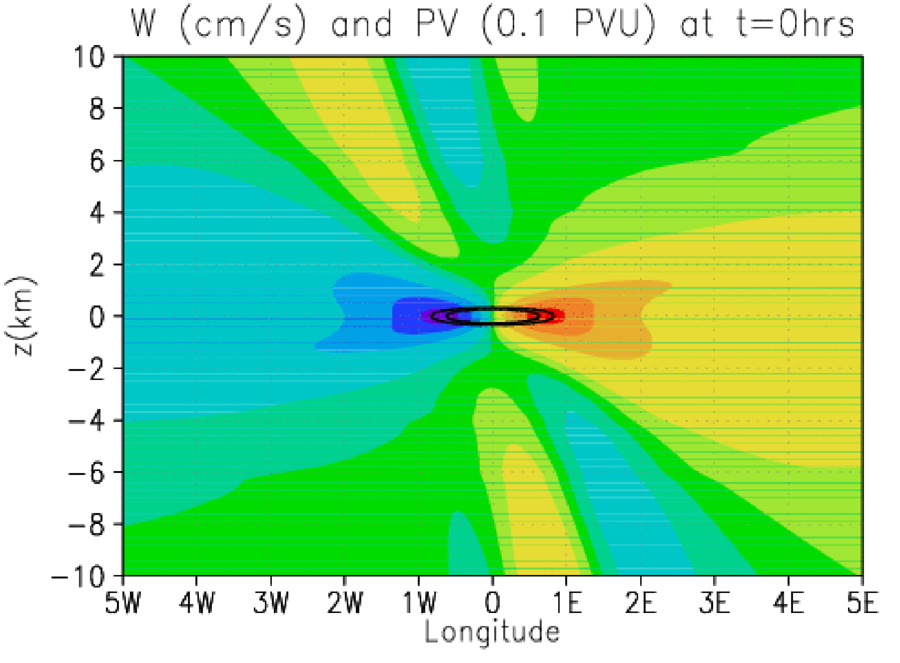

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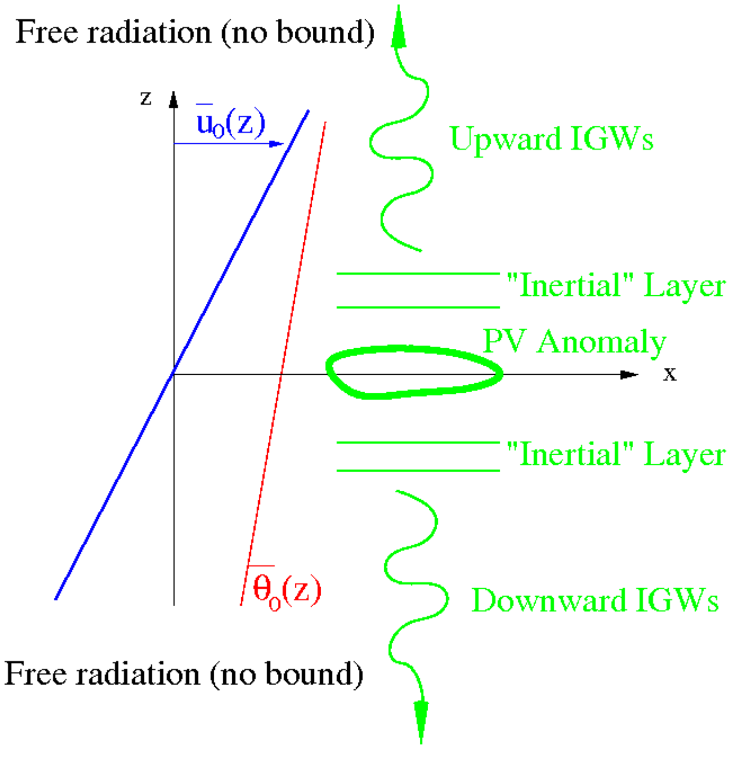

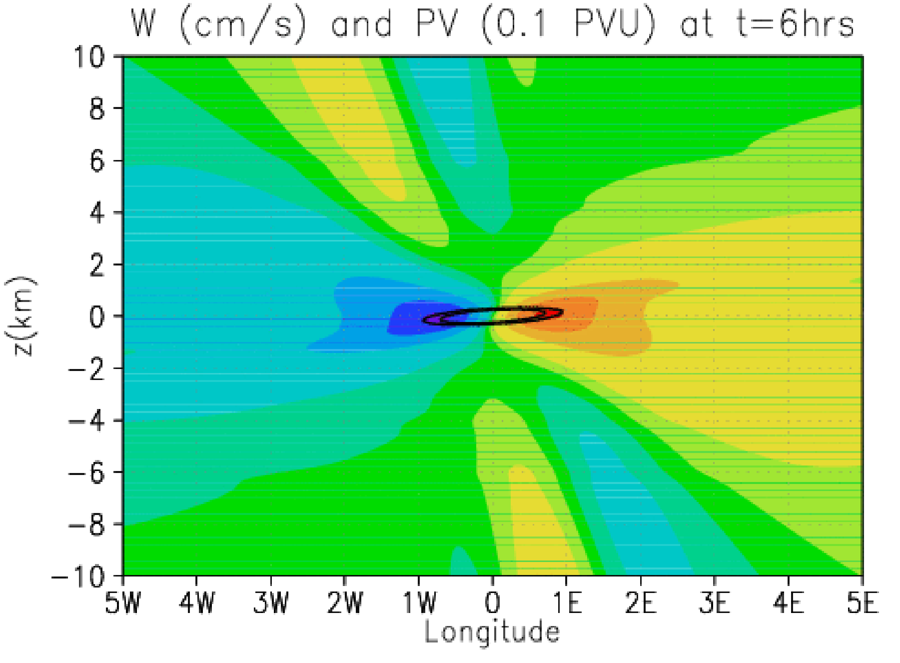

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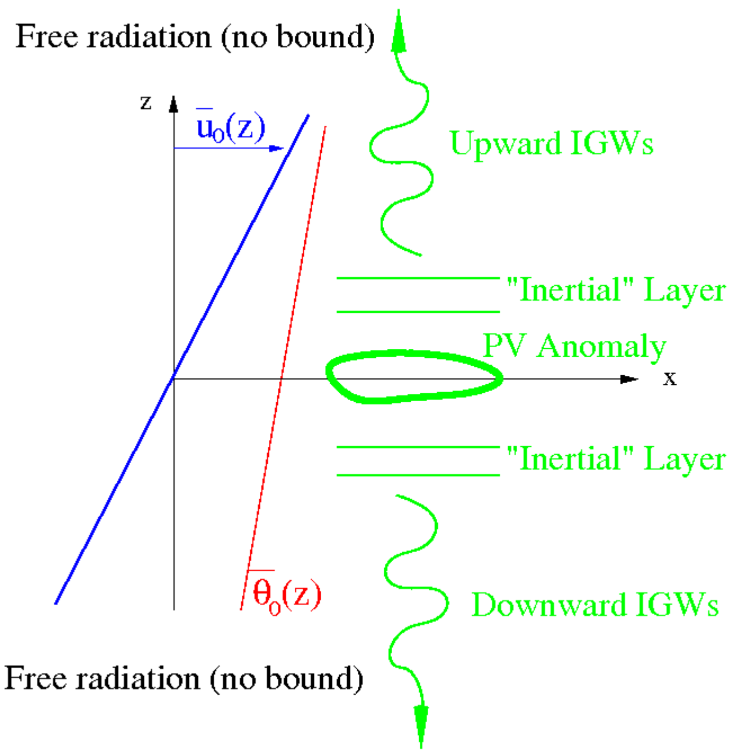

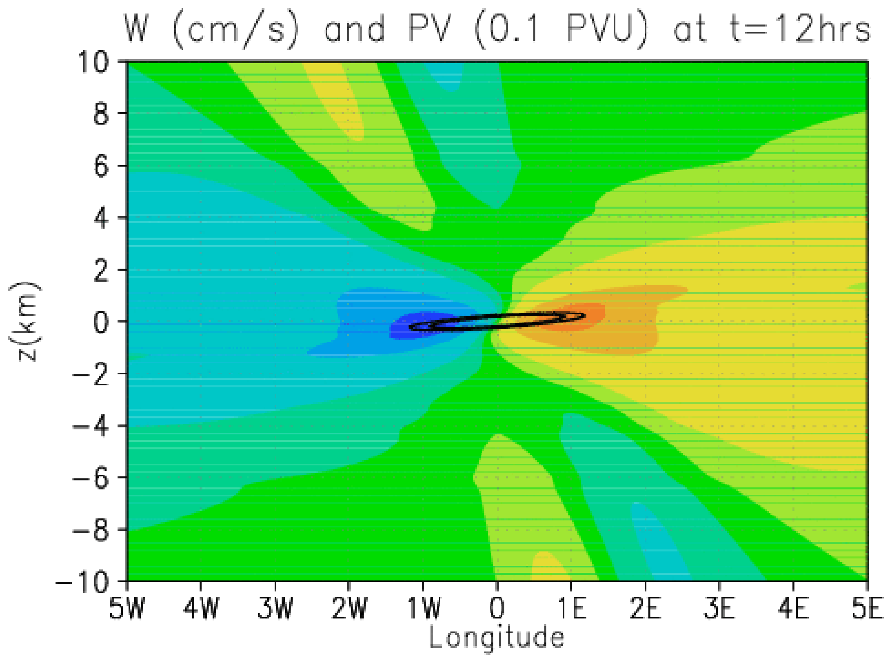

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Gravity waves from fronts and convection
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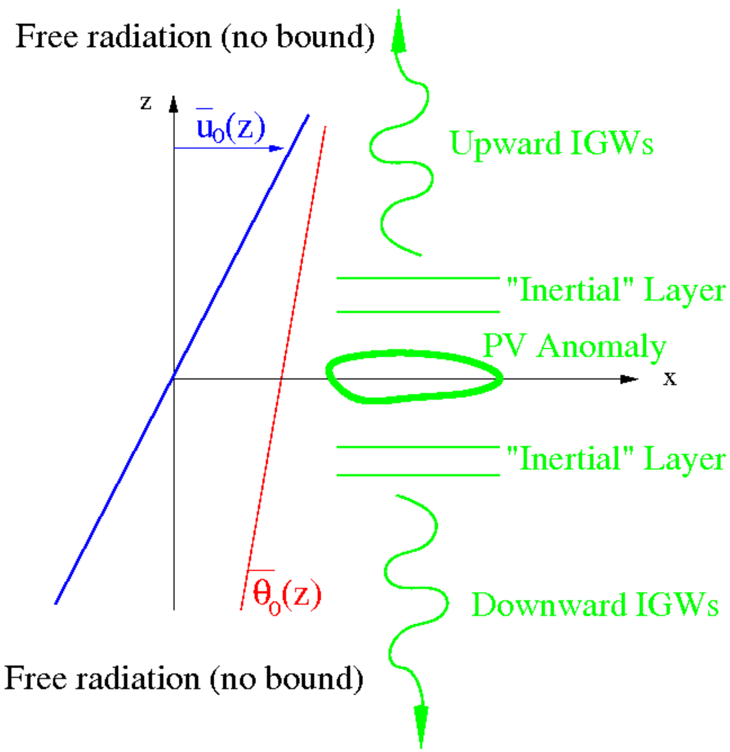

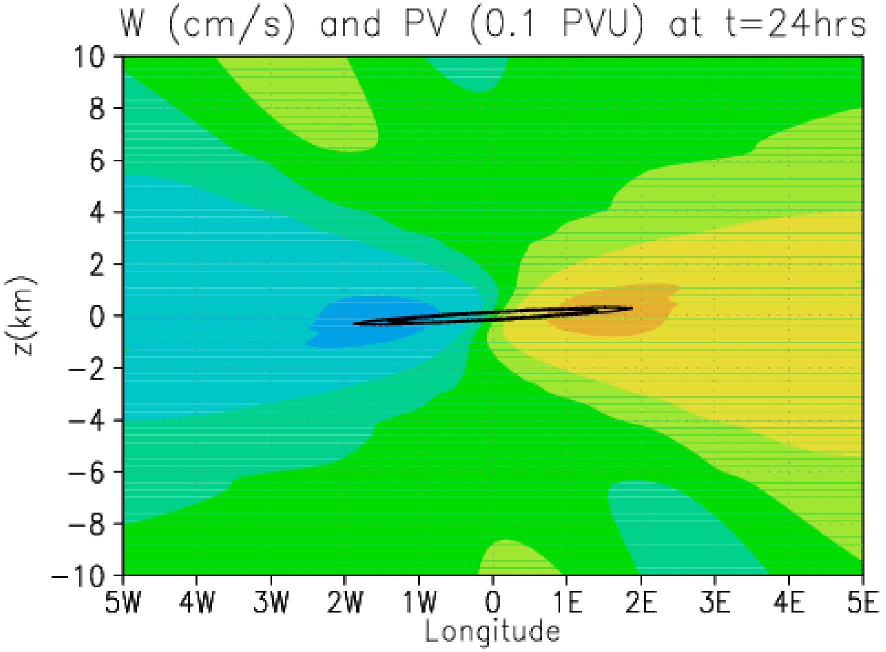

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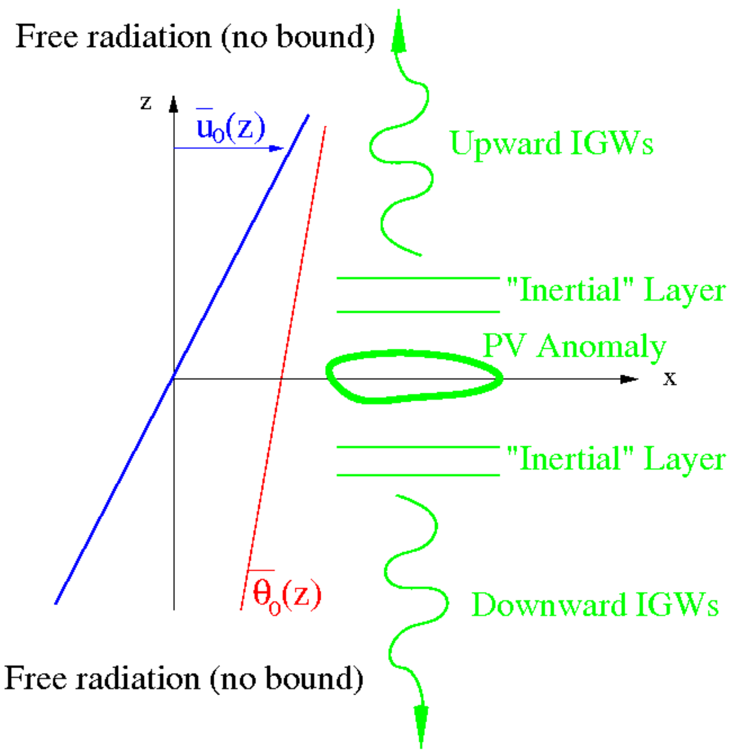

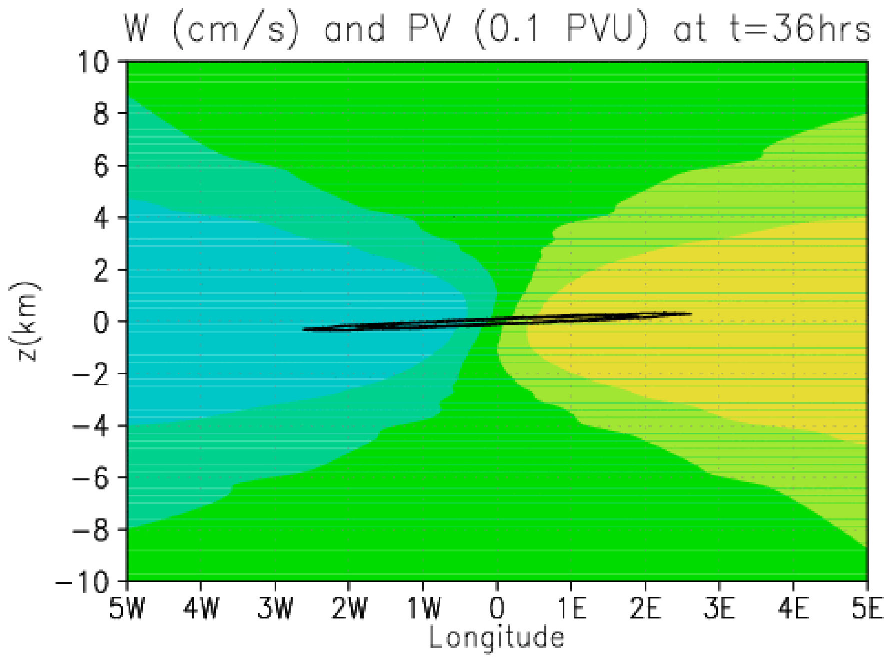

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Gravity waves from fronts and convection
2) GWs from fronts

The complete solution can be reconstructed from a single monochromatic solution:

$$w'(x,y,z,t) = \hat{w}_0(k,l,\omega) W(\xi) e^{i(kx+ly-\omega t)}$$

$$\xi = \frac{k\Lambda}{f}(z-z') = \frac{k\overline{u}_0(z)-\omega}{f}$$

$\xi=0$ Ordinary critical level
(Intrinsic frequency=0)

$\xi=-1,+1$ Inertio critical levels
(Intrinsic frequency $=-f,+f$)

Its vertical structure satisfies the PV conservation Eq:

$(\partial_t + \overline{u}_0 \partial_x)$
Advection

Disturbance PV

$$\xi \left(\boxed{-W_{\xi\xi} + \left(\frac{W_\xi}{\xi^2}\right)_\xi + \left(\frac{2i\nu W}{\xi^2}\right)_\xi - \frac{J(1+\nu^2)}{\xi^2} W} \right) = 0$$

QG PV: $f\partial_z\theta' + \overline{\theta}_{0z}(\partial_x v' - \partial_y u')$

Richardson number $J=N^2/\Lambda^2$; Hor. Wavenumber ratio $\nu = l/k$

Gravity waves from fronts and convection
2) GWs from fronts

The canonical solution $W(\xi)$ corresponds to a $\delta(\xi)$-PV distribution:

$$-W_{\xi\xi} + \left(\frac{W_\xi}{\xi^2}\right)_\xi + \left(\frac{2i\nu W}{\xi^2}\right)_\xi - \frac{J(1+\nu^2)}{\xi^2} W = \delta(\xi)$$

$\xi \gg 1$: $E\,\xi^{1/2+i\mu}$ (upward GW)

$\xi > 1$: $E\,(1+\xi)^{-i\nu}\xi^{1/2+i\nu+i\mu} F(1-\xi^{-2})$

In $\xi=1$ the CL continuation links E with A and B

$0<\xi<1$: $(1+\xi)^{-i\nu}(A\,F'(\xi^2)+B\xi^3 F''(\xi^2))$

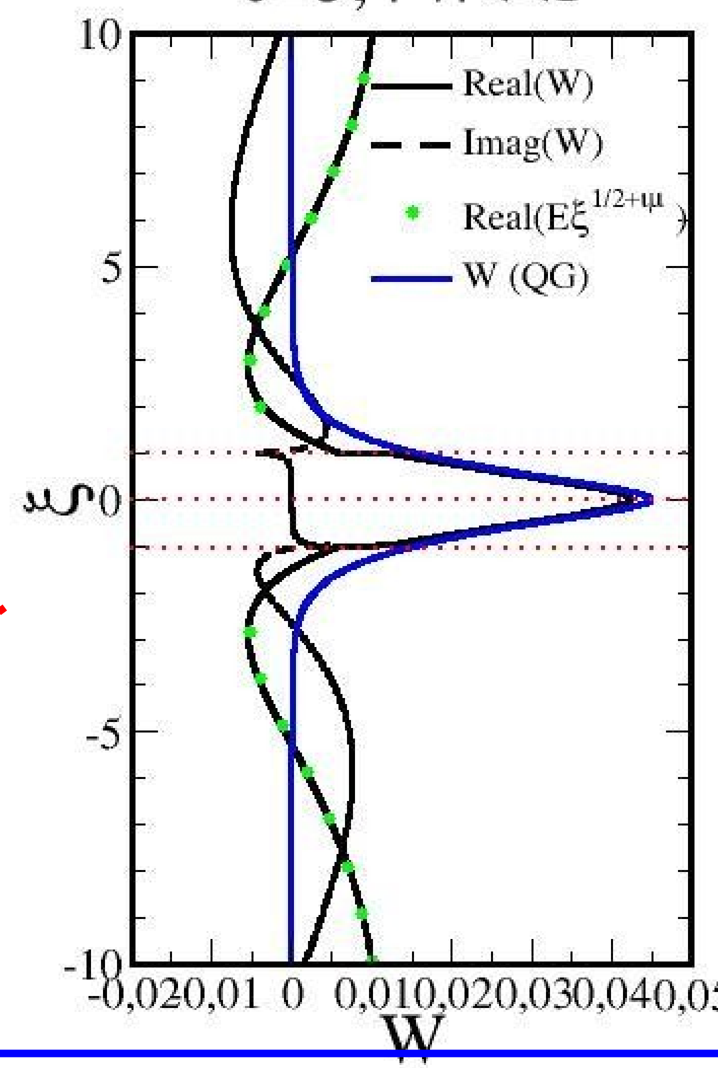
B and A such that $W_\xi/\xi^2(0^+) - W_\xi/\xi^2(0^-) = 1$

$-1<\xi<0$: $(1-\xi)^{+i\nu}(A^*\,F'^*(\xi^2)-B^*\xi^3 F''^*(\xi^2))$

$\xi \ll -1$: $E^*|\xi|^{1/2-i\mu}$ (downward GW)

F, F', and F'' Hypergeometric functions

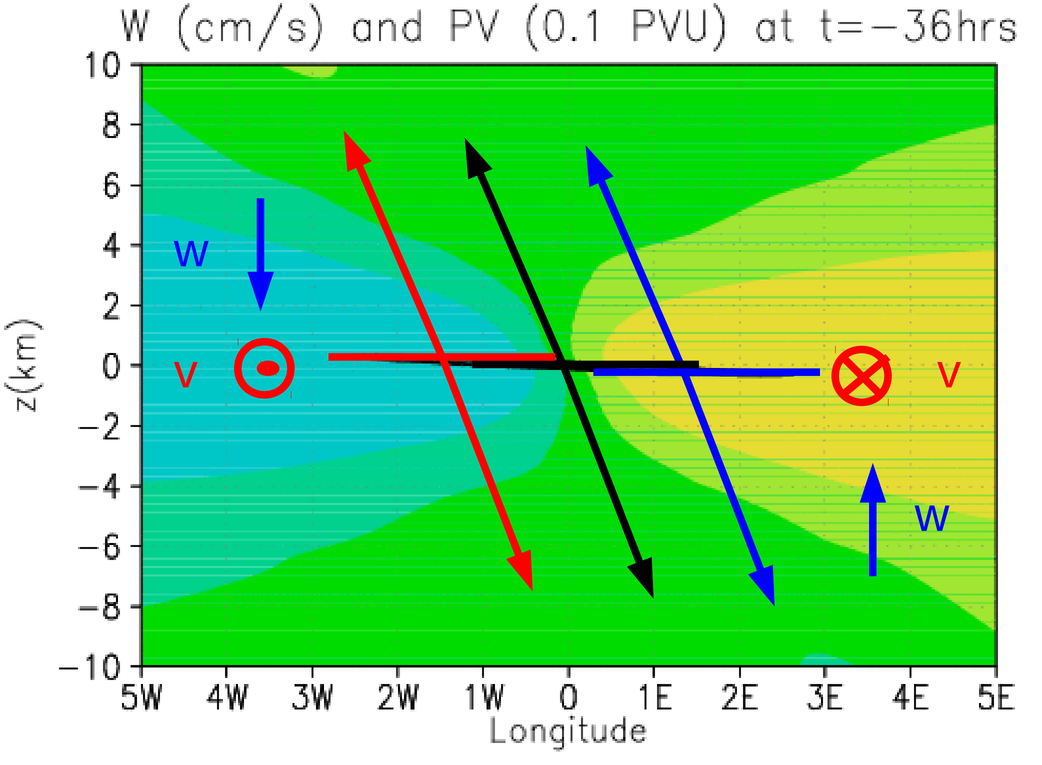
J=5, | ν|<<1



Gravity waves from fronts and convection
2) GWs from fronts

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

$wN^2 \sim f\Lambda v$



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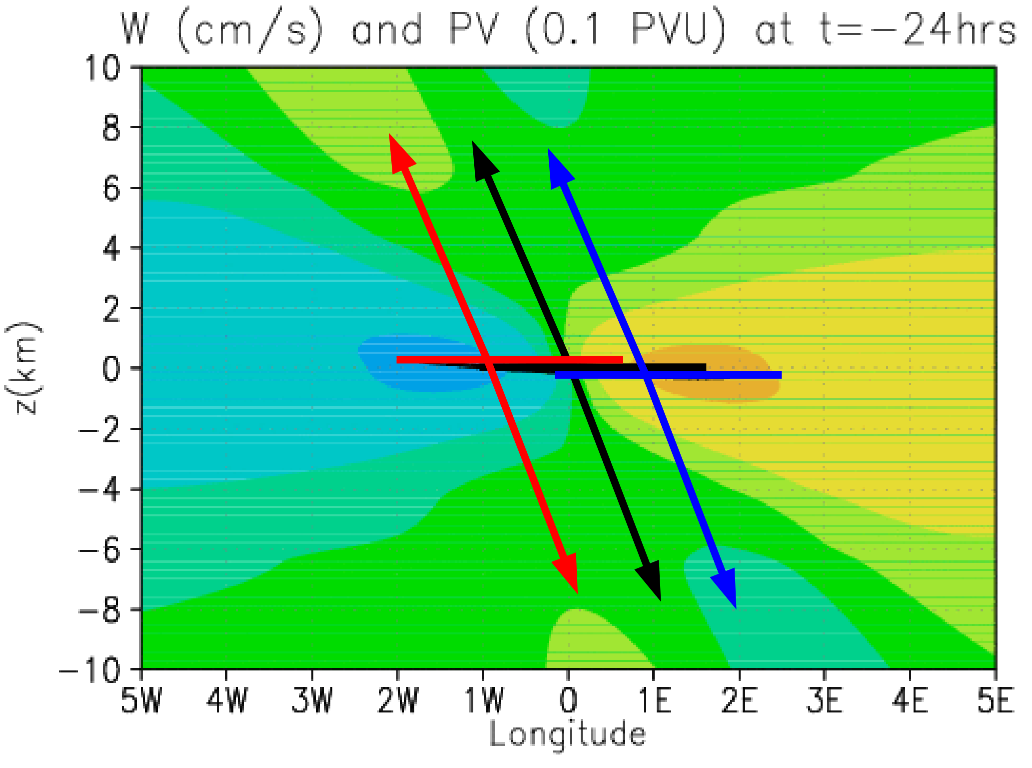

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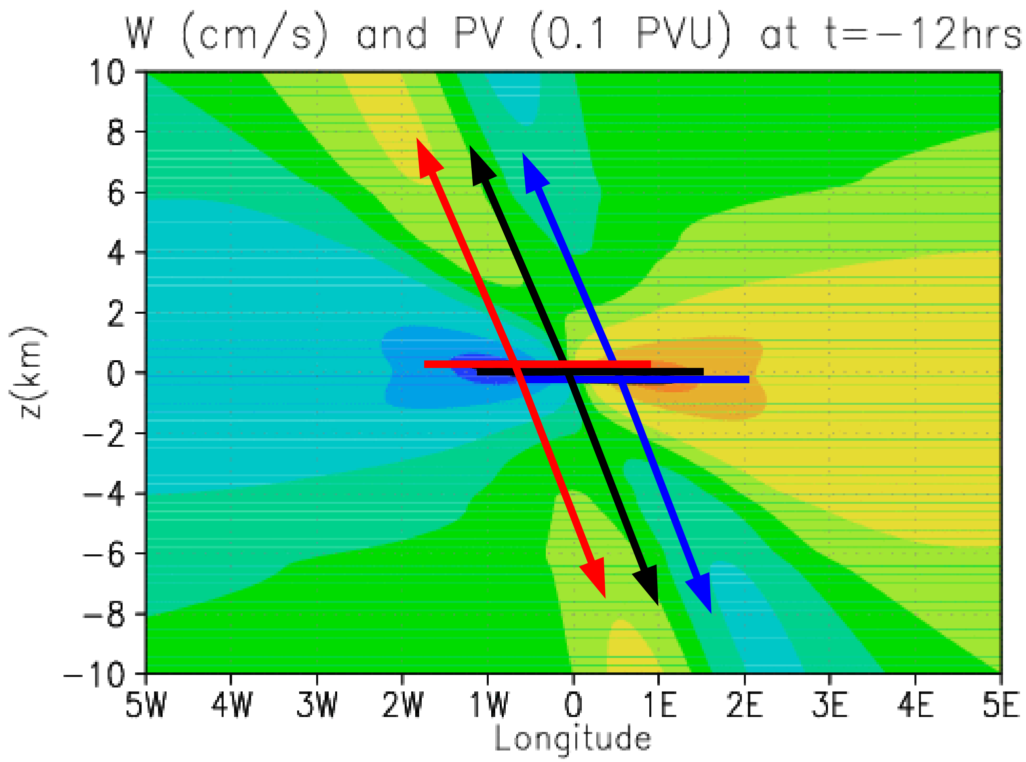

Gravity waves from fronts and convection
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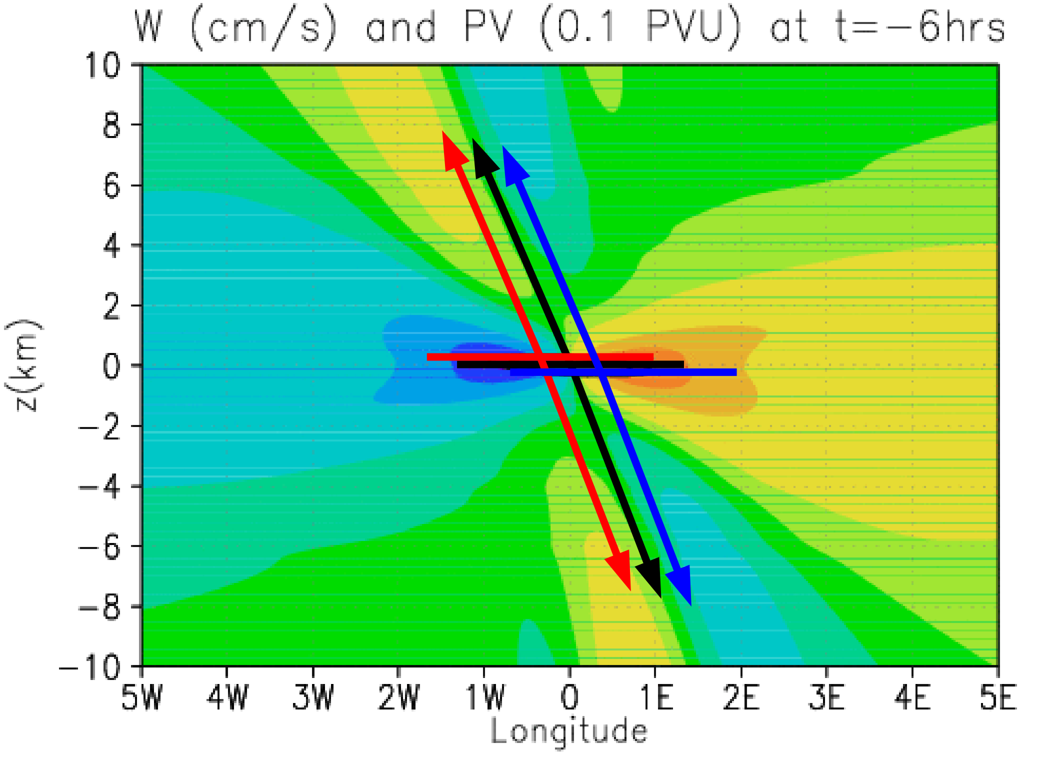
<u>General setup:</u> A 3D (x,y,z) PV anomaly advected in a rotating (*f*=cte), stratified (BV freq *N*=cte) shear flow (vertical shear Λ=cte).



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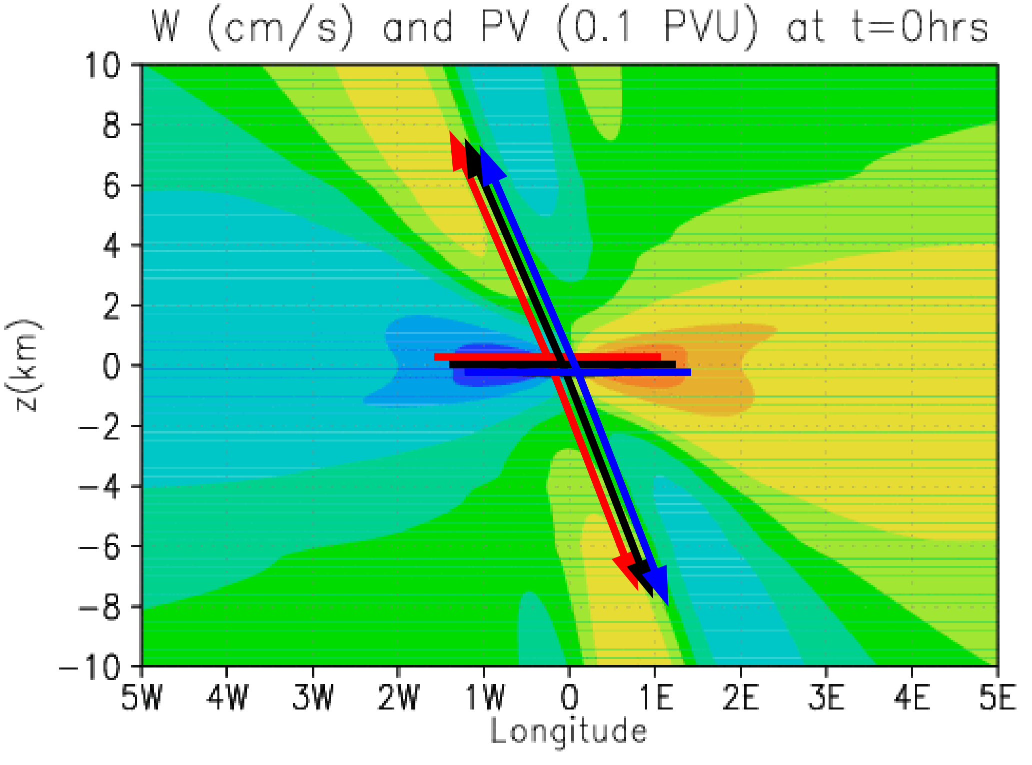

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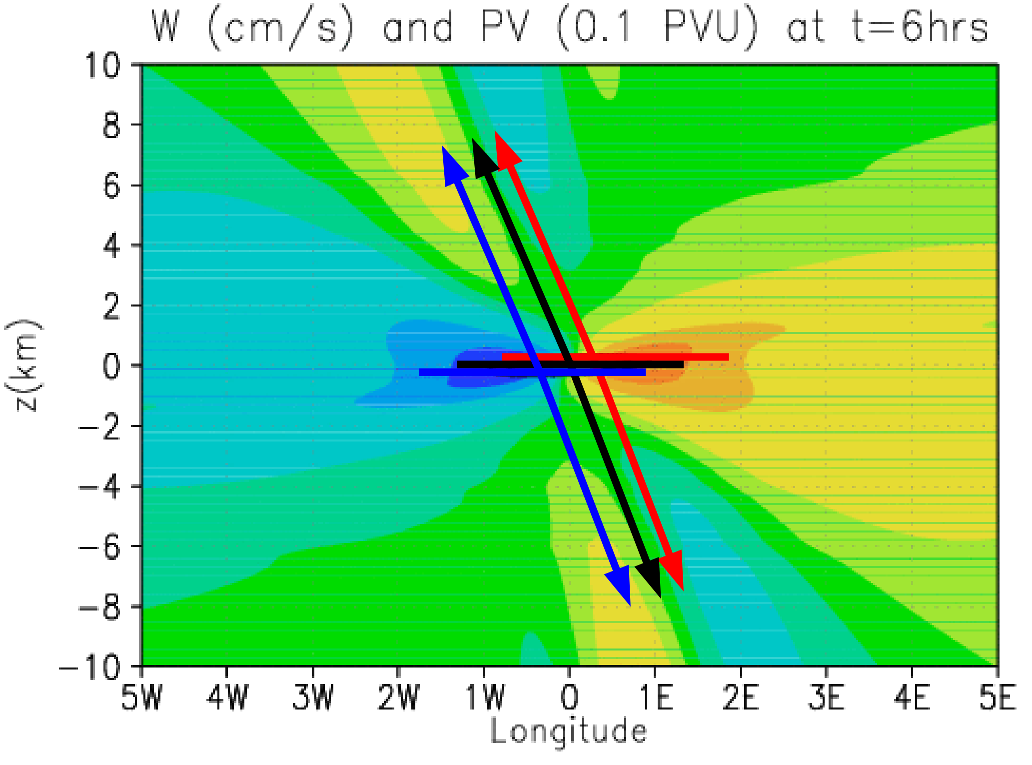

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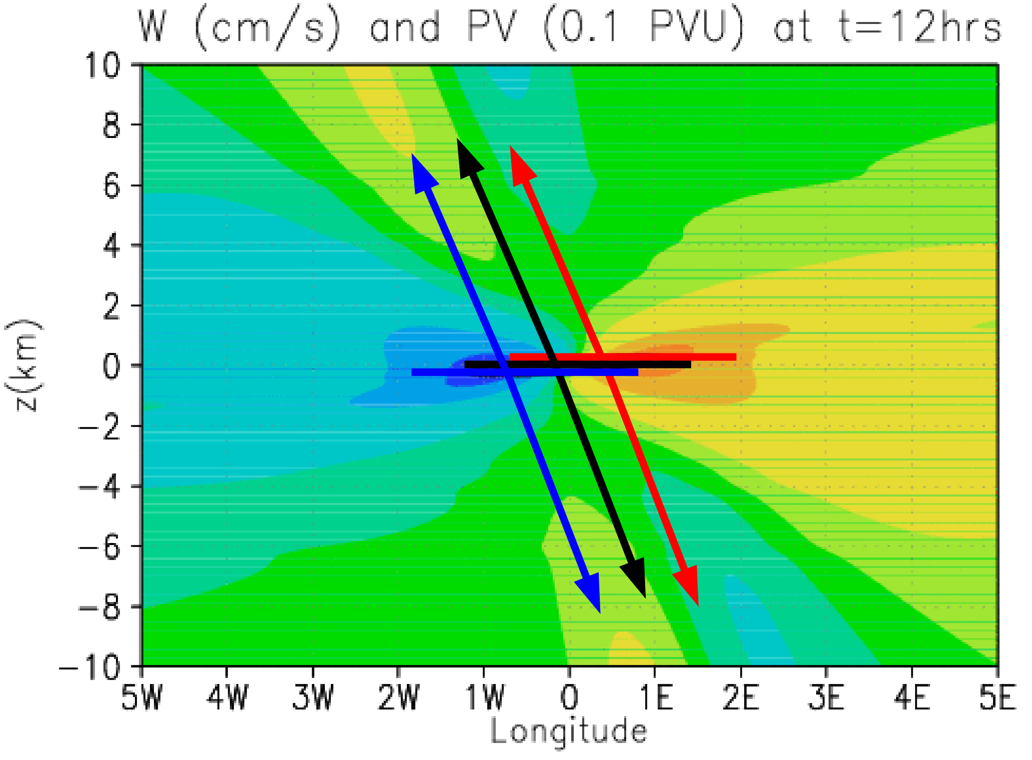

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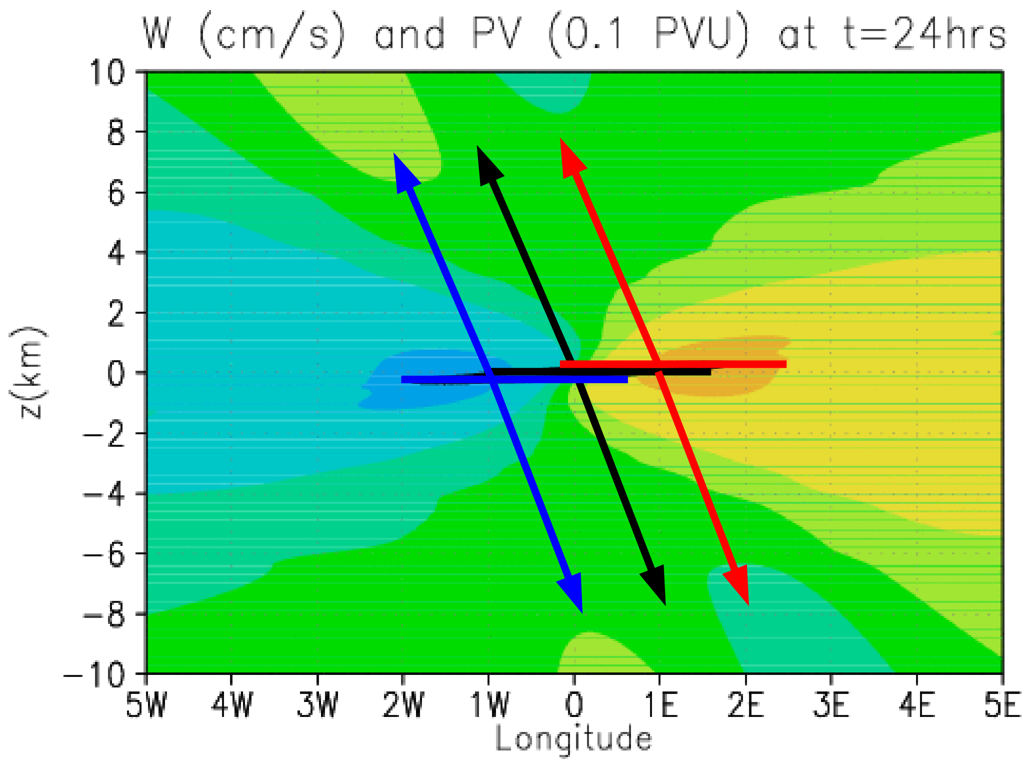

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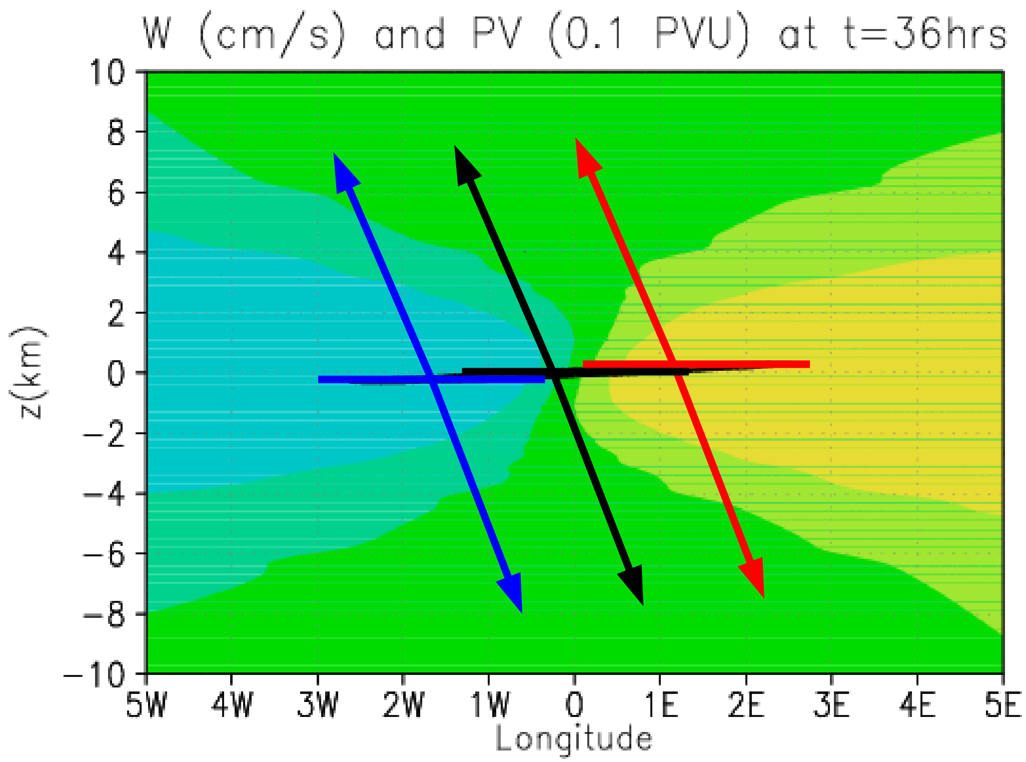


Gravity waves from fronts and convection
2) GWs from fronts

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*)

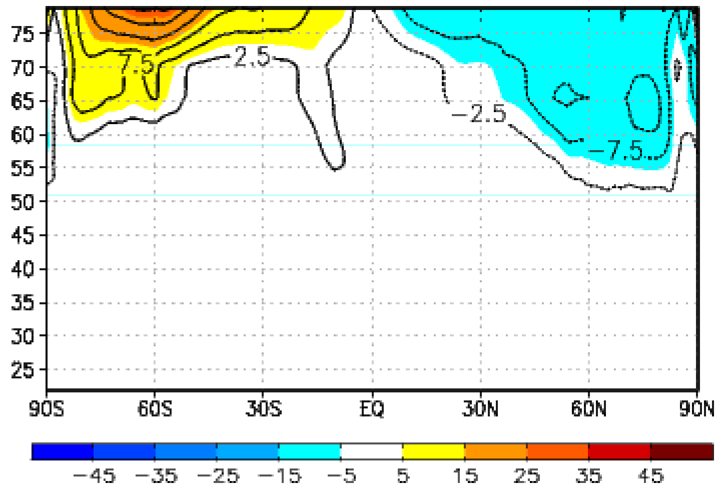
Including the frontal waves, see next presentation, now it is the subgrid scale vorticity which is considered as a “white” stochastic series:

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

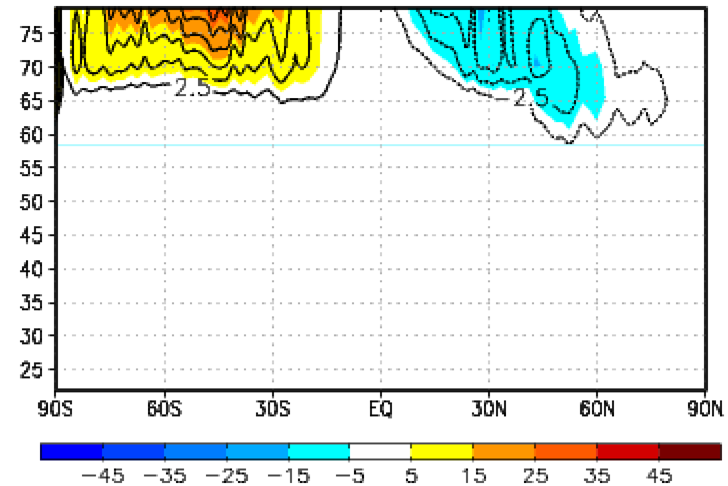
Gravity waves from fronts and convection
2) GWs from fronts

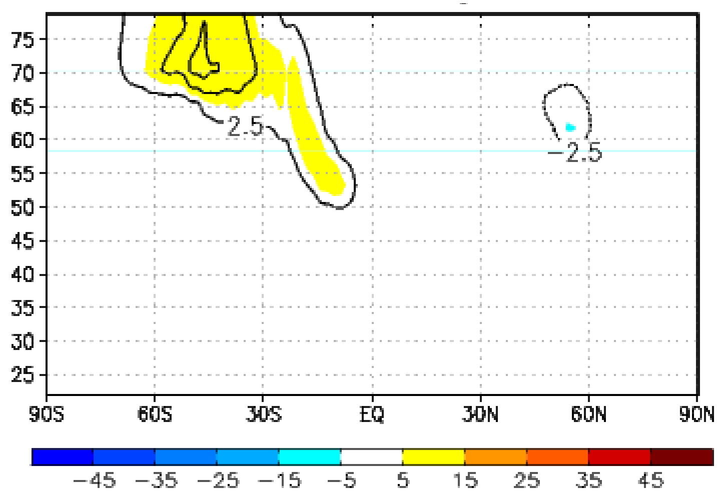
The “smoking gun” theory predicts about the right amount of drag compared to a highly tuned globally spectral scheme (January, all in m/s/day)

Globally spectral scheme

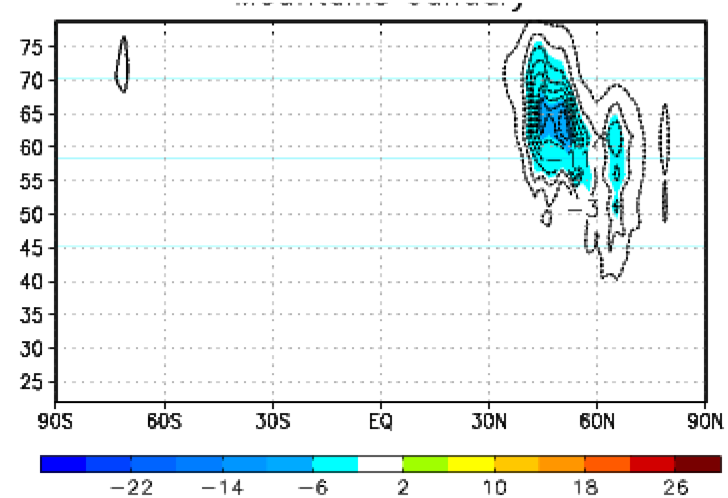


From fronts





Convective GWs

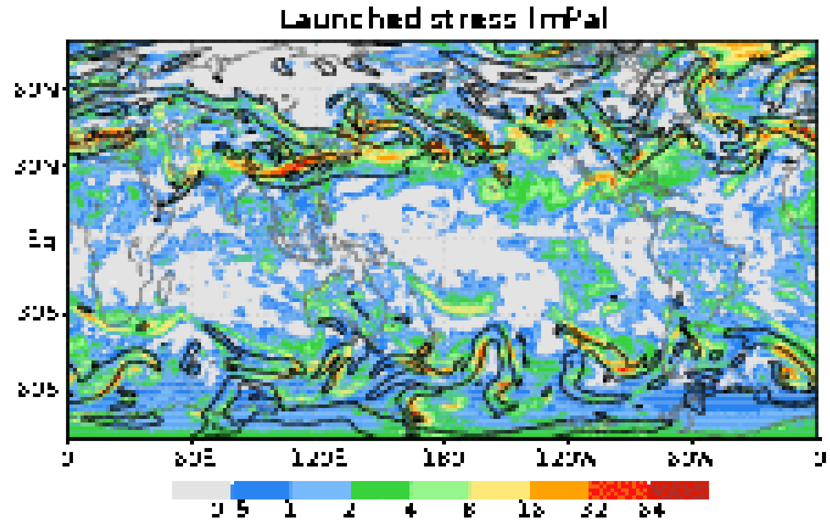


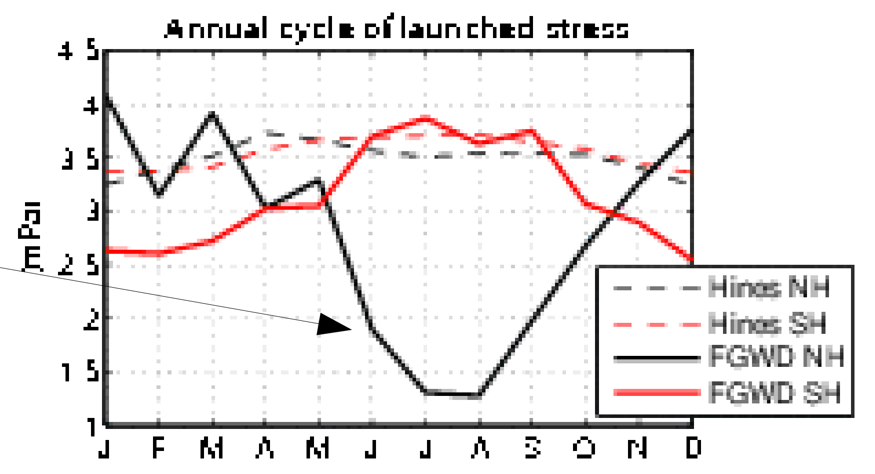
Mountains GWs

Gravity waves from fronts and convection
2) GWs from fronts

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

The waves predicted come from frontal zones





The wave stress now has an annual cycle...

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

Gravity waves from fronts and convection
2) GWs from fronts

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

U at 30hPA

ERAI 1980-2005

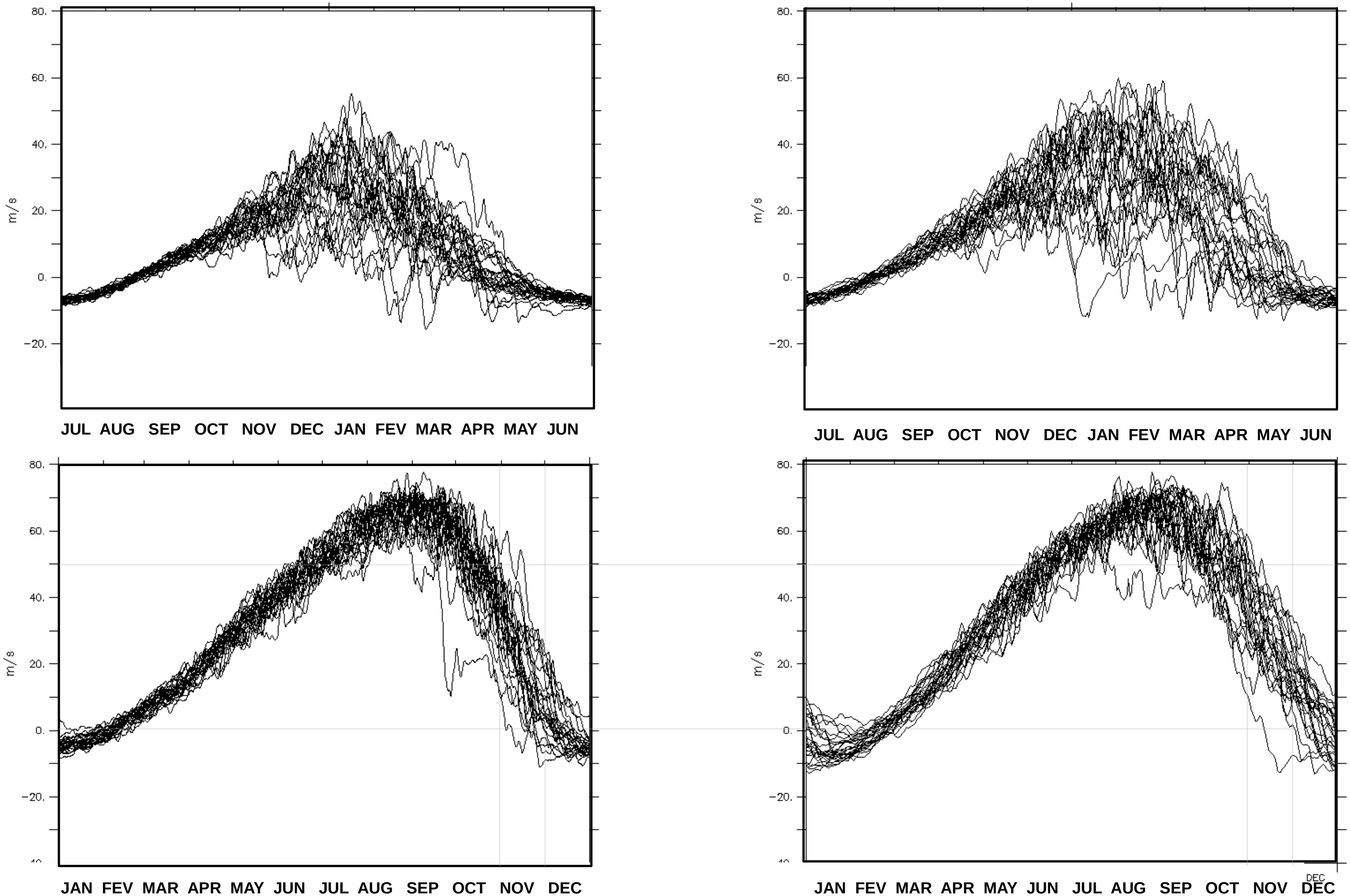
LMDz toward CMIP6

NH

60°N

SH

60°S



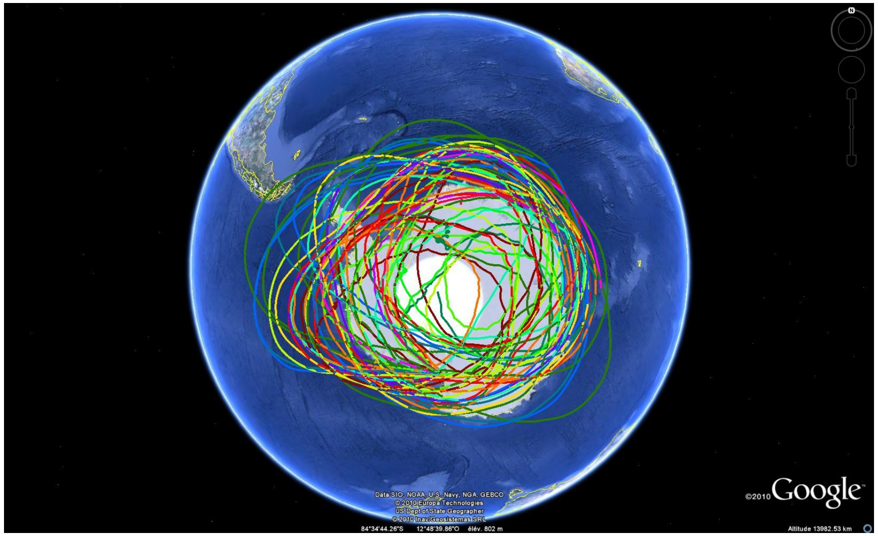
Gravity waves from fronts and convection
3) Tests against observations

<u>GWs from the scheme:</u>

Offline runs using ERAI and GPCP data corresponding to the Concordiasi period.

Important: Satellite (partial) observations in the tropics support what is shown next.

www.lmd.polytechnique.fr/VORCORE/Djournal2/Journal.htm



<u>**CONCORDIASI** (2010)</u>

Rabier et al. 2010 BAMS

19 super-pressure balloons launched from McMurdo, Antarctica, during Sep and Oct 2010.

The balloons were at ~ 20 km height.

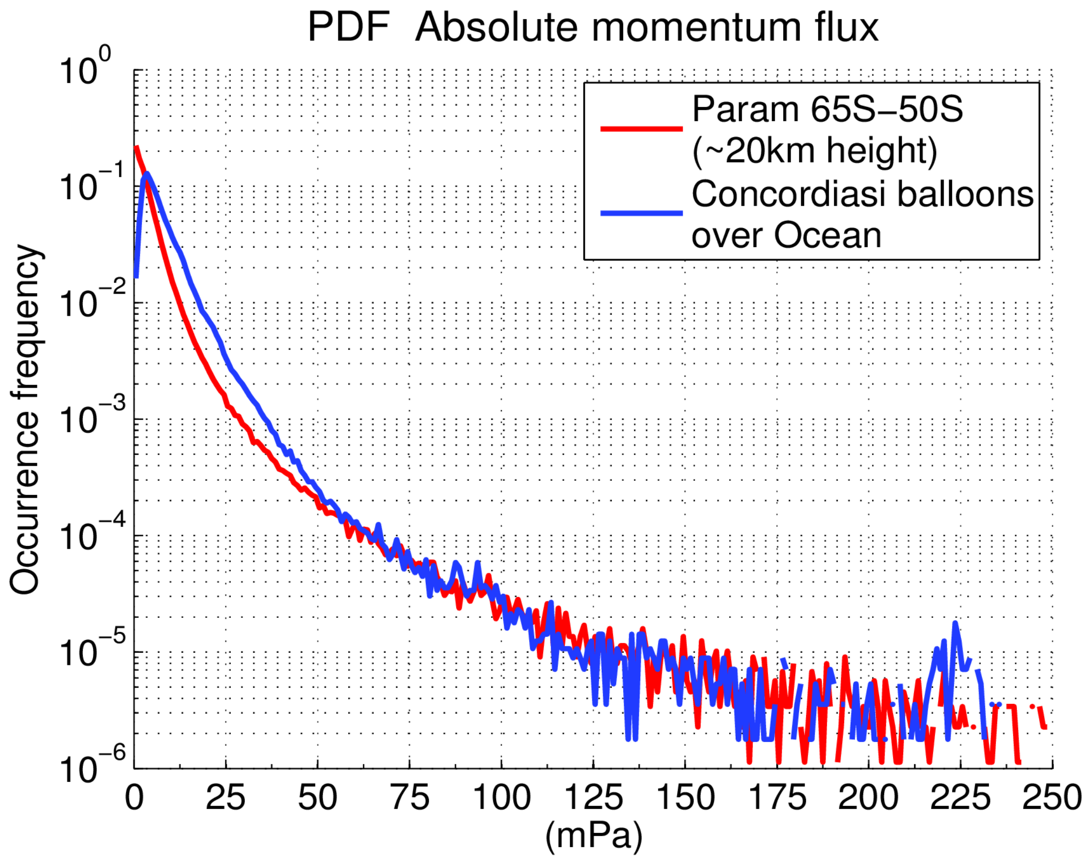
www.lmd.polytechnique.fr/VORCORE/Djournal2/Journal.htm

Dataset of GW momentum fluxes *(as by Hertzog et al. 2008)*

Gravity waves from fronts and convection
3) Tests against observations

Intermittency of GW momentum flux

The stochastic scheme parameters can be tuned to produce fluxes as intermittent as in balloon observations.



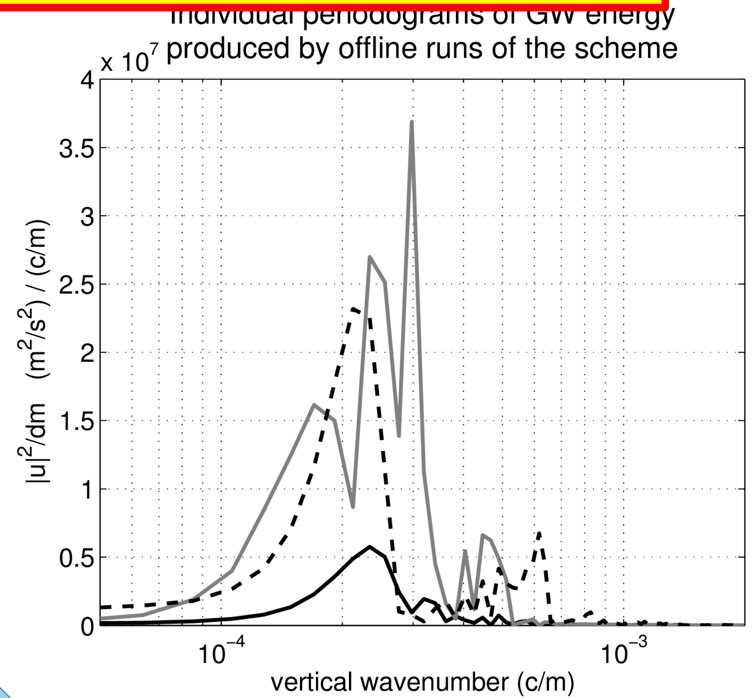
Remember that intermittency is important because it produces GW breaking at lower altitudes *(Lott&Guez 2013)*

de la Cámara et al. 2015

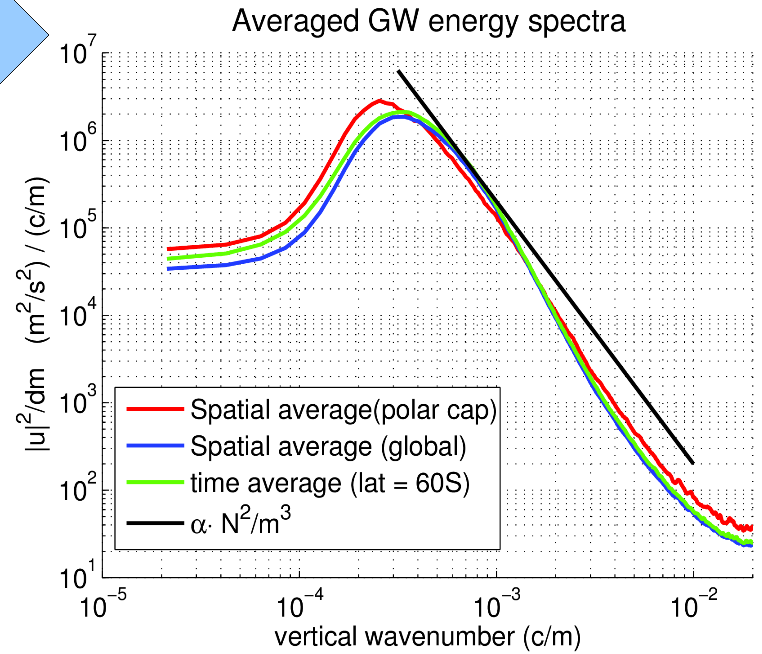
Gravity waves from fronts and convection
3) Tests against observations

Vertical spectra of GWs energy

The observed "universal spectra" can be obtained with a "multiwave scheme" as a superposition of individual periodograms of GW packets.



Average of periodograms



de la Cámara et al. 2015

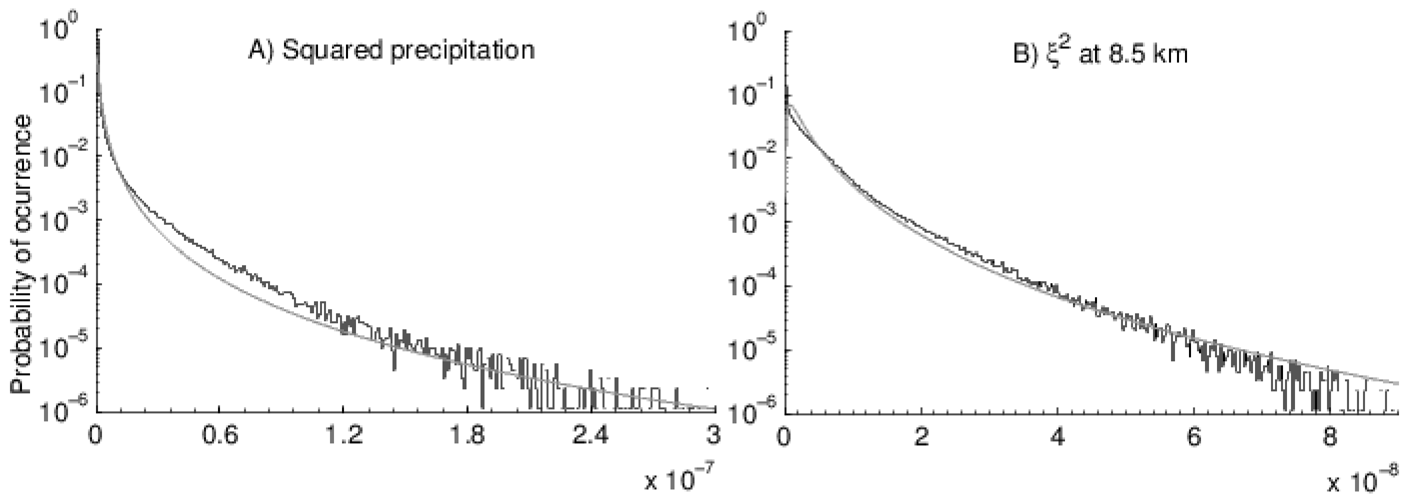
Gravity waves from fronts and convection
3) Tests against observations

What causes the intermittency?

Sources, like P^2 for convection or ξ^2 for fronts have lognormal distributions

(P precipitation, ξ relative vorticity)

For waves produced by PV see Lott et al.~(2012)



Results for intermittency suggest to relate the GWs to their sources

de la Cámara et al. 2015

Gravity waves from fronts and convection
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.

For instance on how the QBO changes when the climate change

Need for direct observations of GWs momentum fluxes in the equatorial stratosphere

Why the momentum fluxes measured by constant level balloons are 5 times larger than those Imposed in parameterizations?