Parameterization of non orographic gravity waves in large scale models
Formalism, Impacts, and test against observations

François Lott,

LMD/IPSL/PSL (Ecole Normale Supérieure)-Paris

1) Impact of gravity waves on the middle atmosphere climate
2) Spectral parameterizations and impact
3) Multiwave stochastic parameterizations and application to convective gravity waves
4) Application to gravity waves generated by fronts
5) Validation against balloon observations
6) Perspective

Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

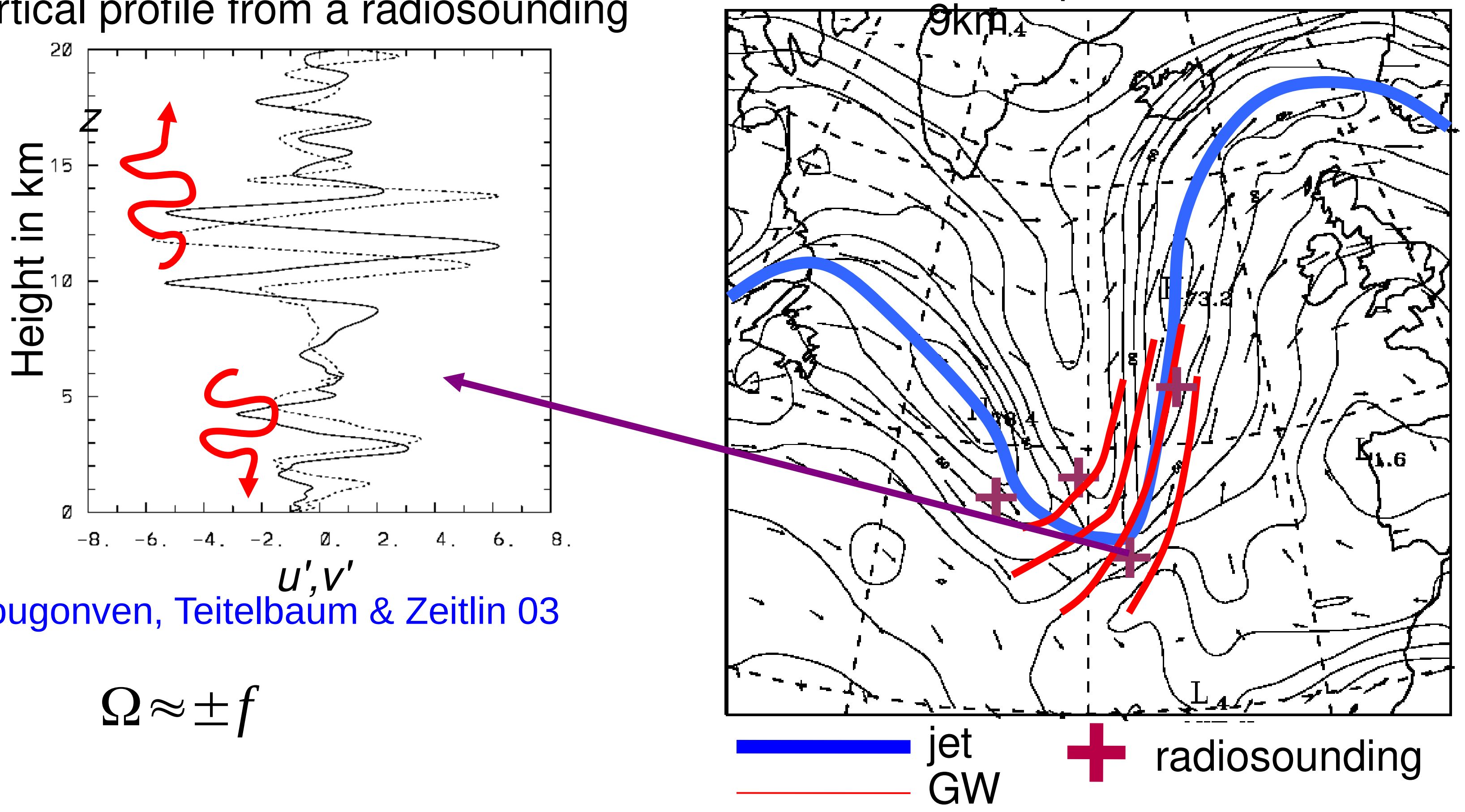
Inertio internal gravity waves, intrinsic frequency : $f < \Omega = \omega - \vec{k} \cdot \vec{U} < N$

Source 1 (fronts):

- Observation of a low frequency, large amplitude wave emitted in jet exit region (geostrophic adjustment?):

Vertical profile from a radiosounding

Wind speed at 9km



Plougonven, Teitelbaum & Zeitlin 03

$\Omega \approx \pm f$

Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

Inertio internal gravity waves, intrinsic frequency : $f < \Omega = \omega - \vec{k} \cdot \vec{U} < N$

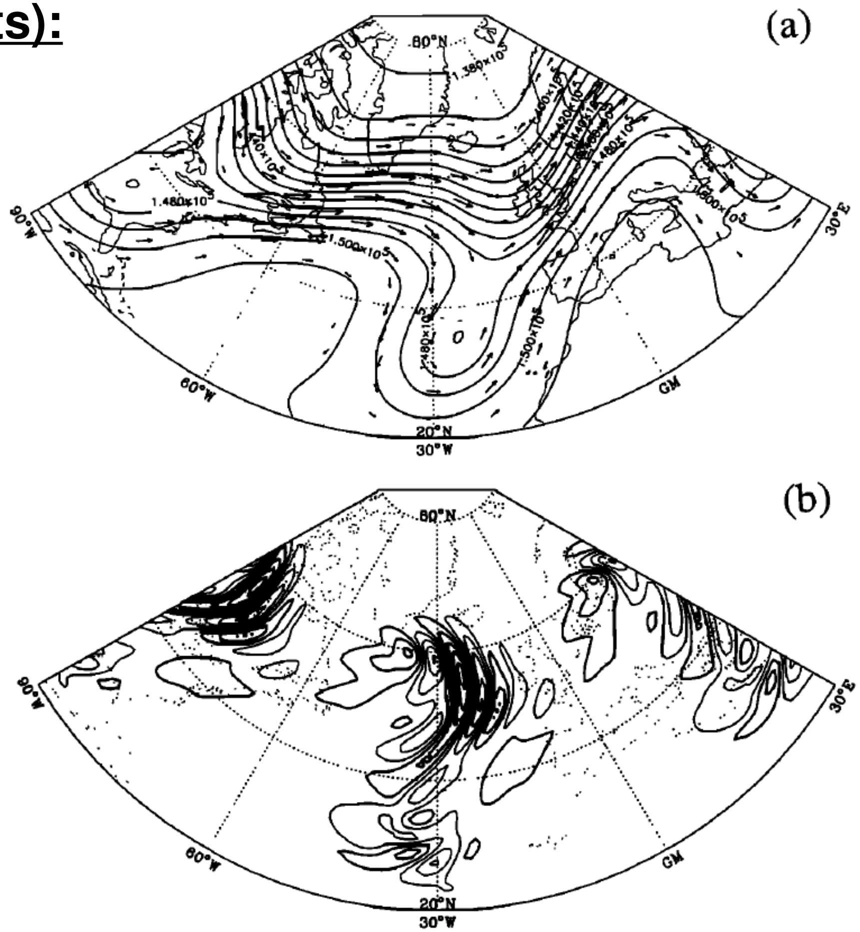
Source 1 (fronts):

Idealized numerical studies

O'Sullivan and Dunkerton 1995

Waves in Jet exit region

$$\Omega \approx \pm f$$



Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

Inertio internal gravity waves, intrinsic frequency : $f < \Omega = \omega - \vec{k} \cdot \vec{U} < N$

Source 2: Mountains

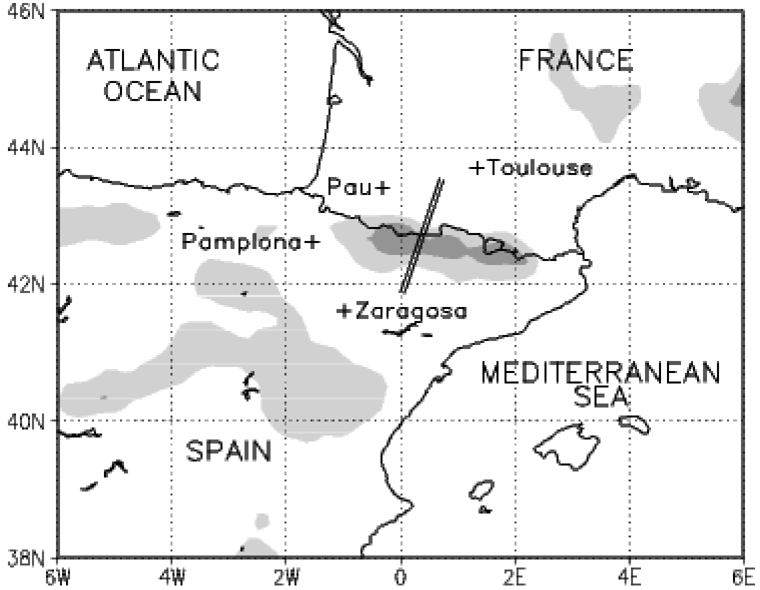


Figure 1: Smoothed terrain elevation and PYREX data used. + denotes the location of the high resolution soundings. The two thick lines indicate the airplane pathes during the IOP 3. The light and dark shaded areas denote terrain elevation above 1000m and 1500m respectively.

$$\Omega \approx -\vec{k} \cdot \vec{U} < 0$$

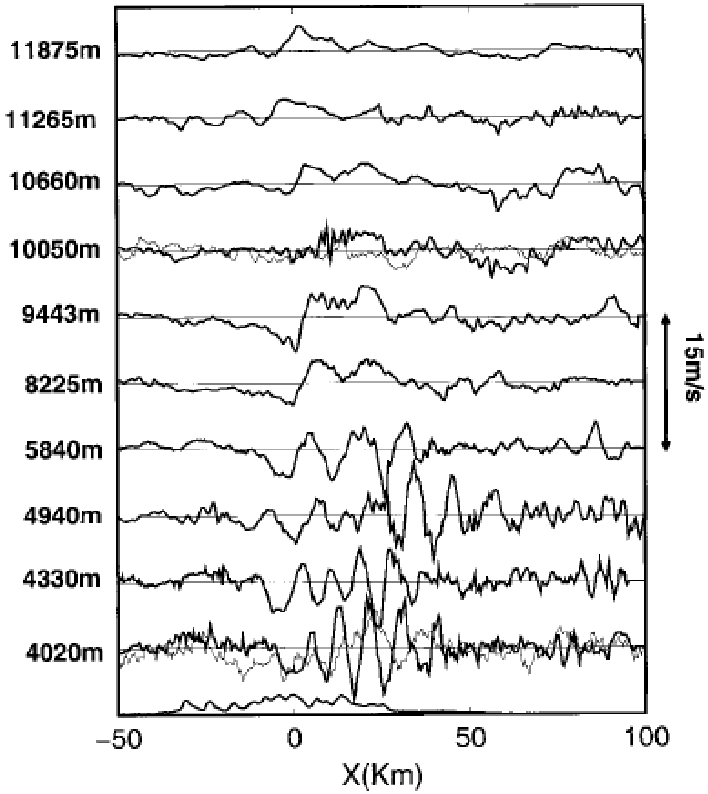


FIG. 2. Observed vertical velocities from different aircraft legs, from 15 Oct 1990 around 0600 UTC. Thick lower curve represents the Pyrénées; the thin curve at the $Z = 4$ km and $Z = 10$ km are red-noise surrogates with characteristics adapted to the measured vertical velocity at that level.

Parameterization of GWs in large scale models
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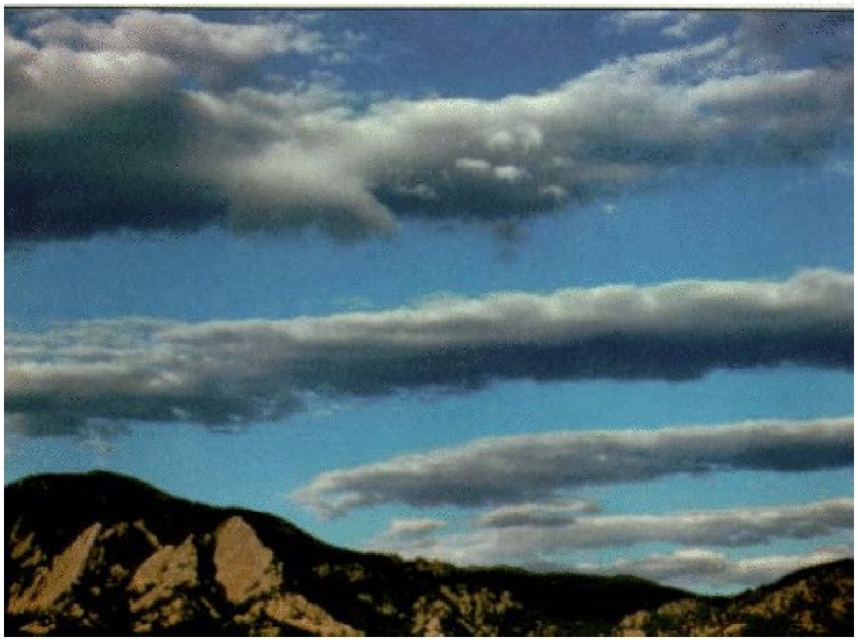
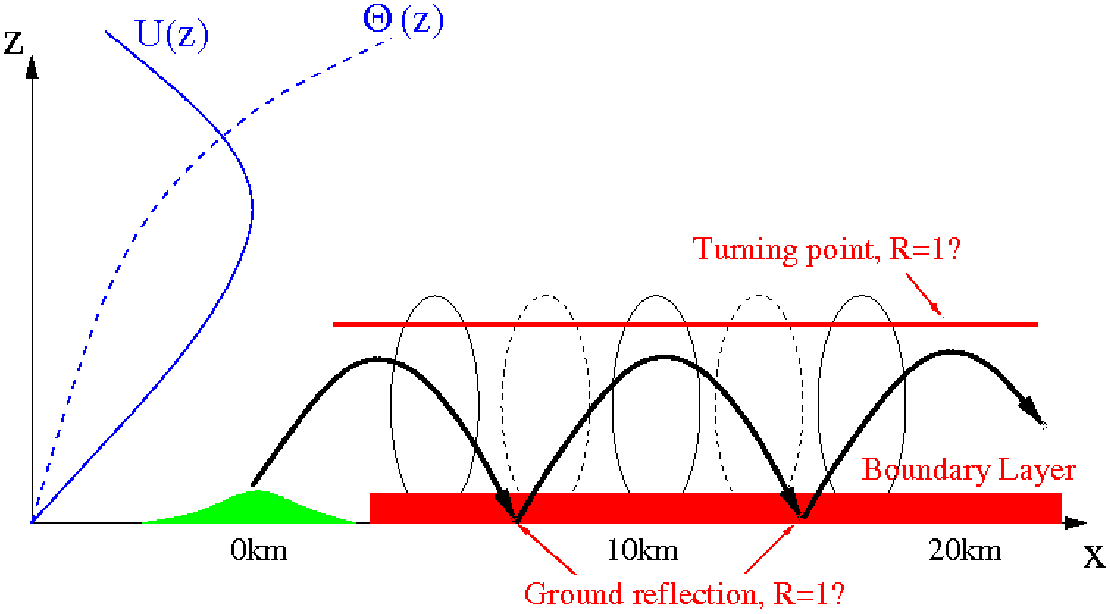
Inertio internal gravity waves, intrinsic frequency : $f < \Omega = \omega - \vec{k} \cdot \vec{U} < N$

Source 2: Mountains

Trapped lee-waves



Gravity waves trapping and lee waves (Scorer 1949)



$$\Omega \approx -\vec{k} \cdot \vec{U} < 0$$

Parameterization of GWs in large scale models
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Inertio internal gravity waves, intrinsic frequency : $f < \Omega = \omega - \vec{k} \cdot \vec{U} < N$

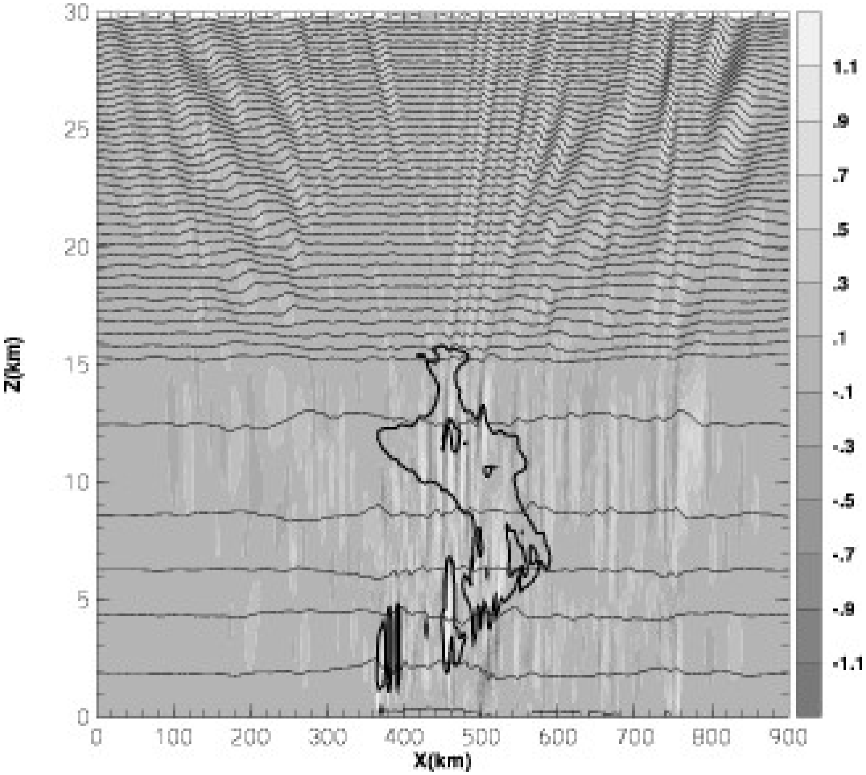
Source 3: Convection

The heating produce waves in both directions of propagation

$$\Omega > 0 \text{ and } \Omega < 0$$

Sources 1, 2, and 3 :

All these waves have horizontal scale much smaller than the scales resolved by climate models (still today !), they need to be parameterized



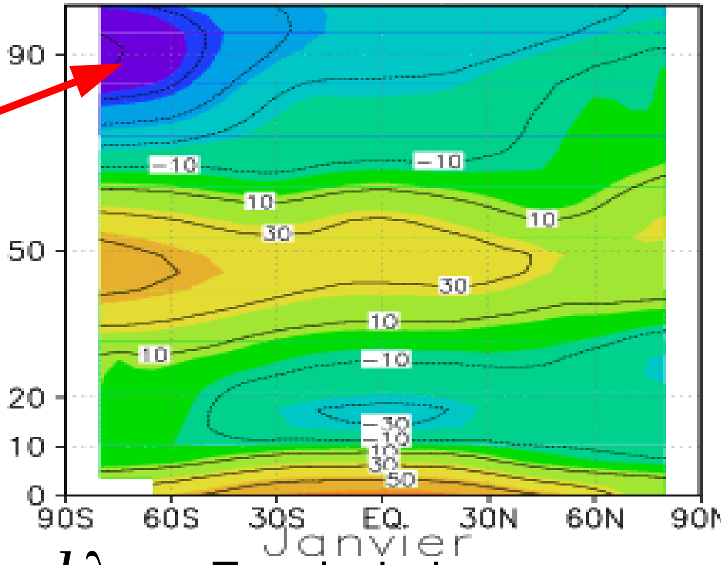
Gravity waves above a convective cloud (Alexander et Holton 1997)

Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

Midlatitudes. minima of T at the summer pole near the mesopause

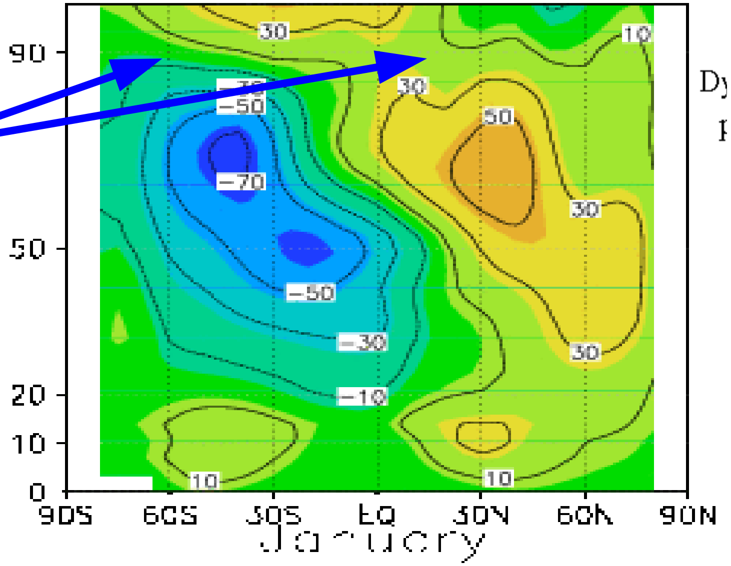
Closure of the midlatitude jets

$$\bar{T}=\frac{1}{2\pi}\int_0^{2\pi} T\,d\lambda$$

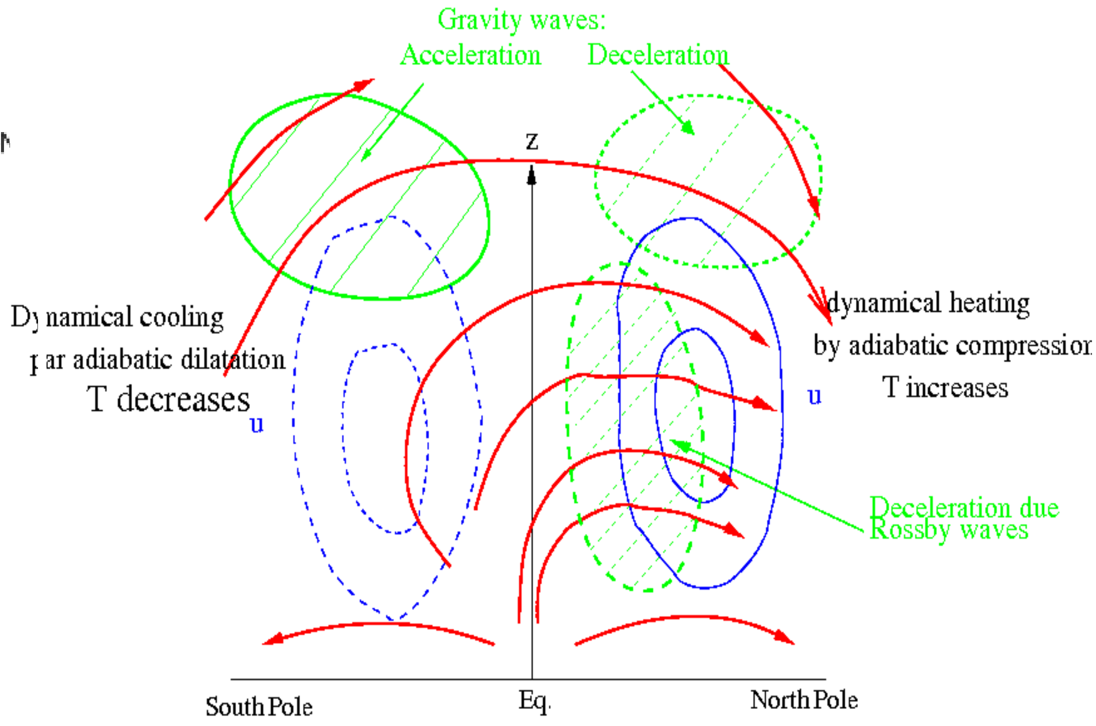


$$\bar{u}=\frac{1}{2\pi}\int_0^{2\pi} u\,d\lambda$$

Zonal wind

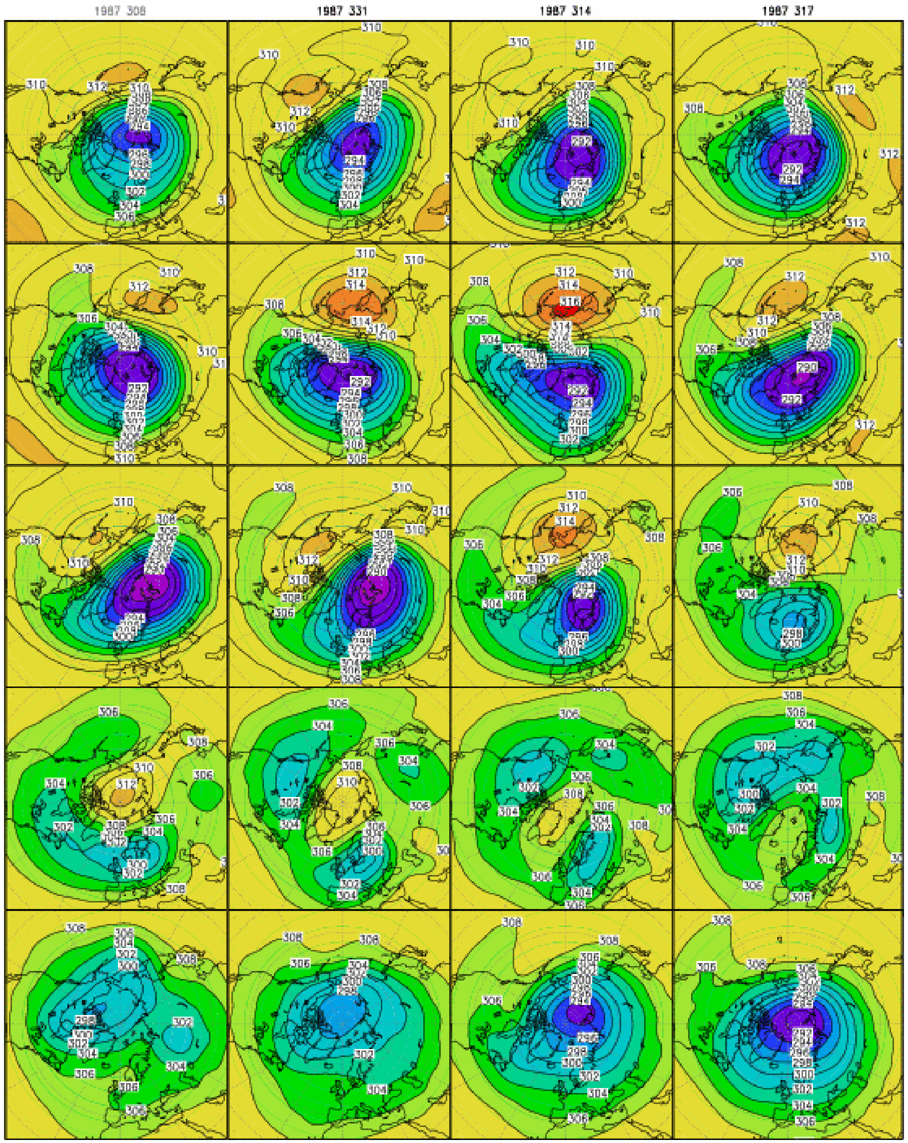


The meridional circulation driven by waves and the « downward control » (review in Haynes et al.~1991)

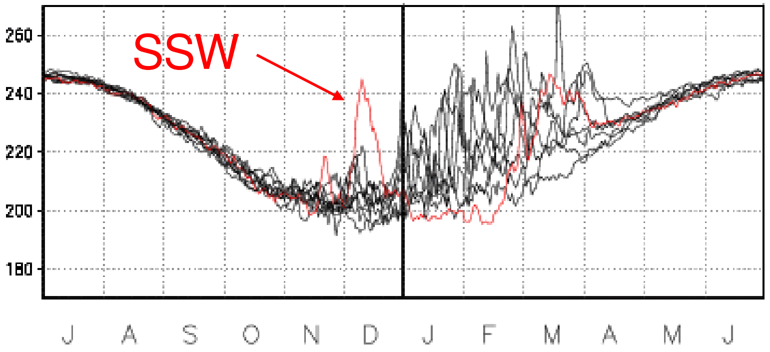


Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

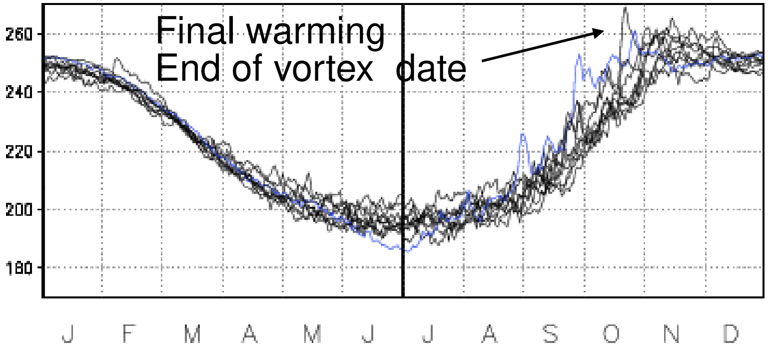
<u>The gravity waves are not alone:</u> planetary scale Rossby waves also provide a large Deceleration in the middle atmosphere, here Z at around 32km every 3 days in 1987-1988 early winter, and when occur Sudden Stratospheric Warmings



Temperature at the North pole, z=32km



Temperature at the South poles, z=32km



Vertical Structure Equation for Rossby waves

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

Parameterization of GWs in large scale models
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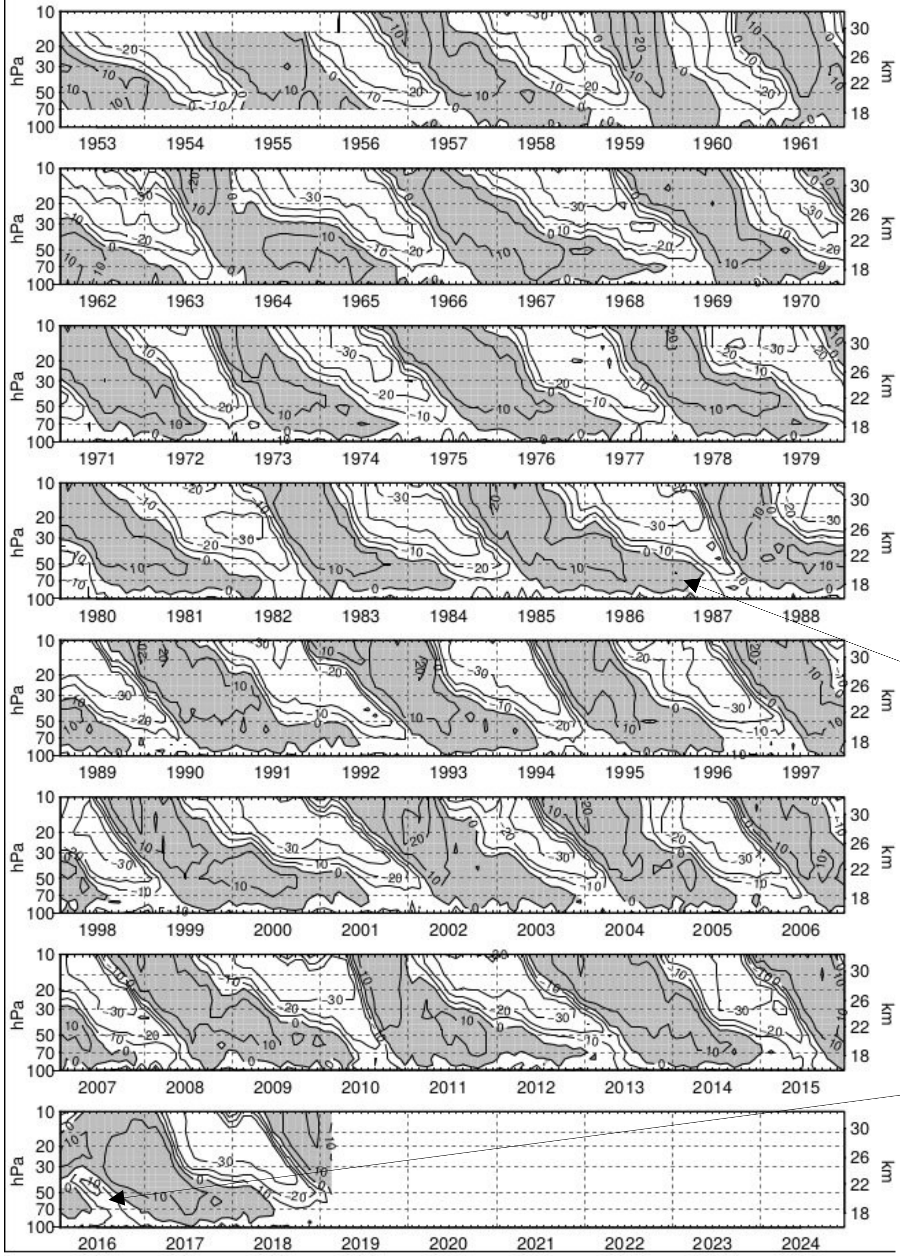


Tropics : Quasi biennial oscillation

of the zonal mean zonal wind at the equator,

$$\overline{u}(t, 0, z)$$

Radiosonde observations at Singapour since 1952

Aperiodic decent of zonal mean zonal Winds
(mean period 27.5 month)

Stalling of the westerlies near above the tropopause
Not well reproduce in models around 100hPa

Recent disruptions that may be caused by the changing climate

See QBO Initiative
Butchart et al. (GMD 2017)

Parameterization of GWs in large scale models
1) Impact of Gravity Waves on the middle atmosphere climate

Plumb (1977)'s model with 2 GWs interacting with the zonal wind:

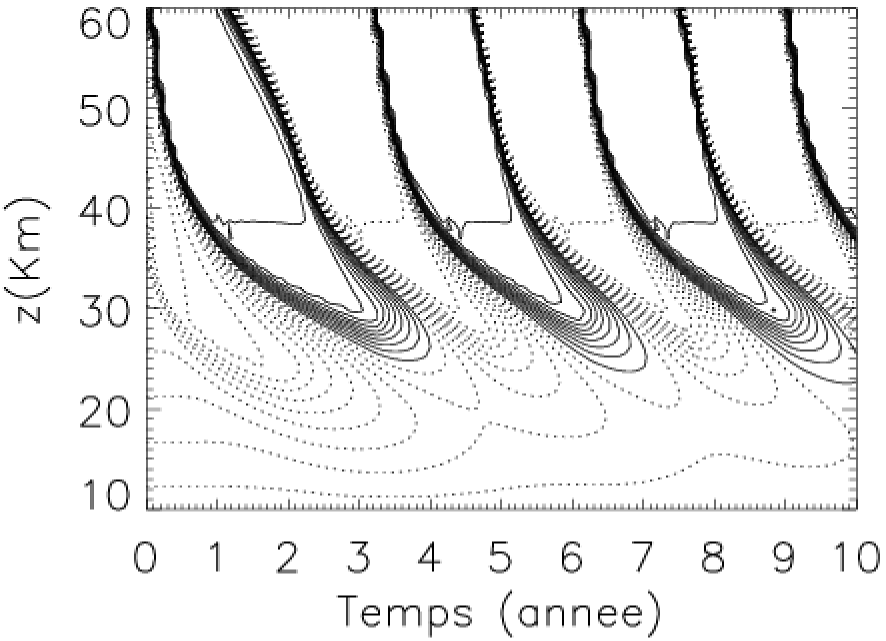
$$\frac{\partial \bar{u}}{\partial t} = \sum_{i=1}^{2} \frac{\partial \overline{F}_i^{z}}{\partial z} + \nu \frac{\partial^2 \bar{u}}{\partial z^2}$$

F momentum flux of a single wave
(planetary or gravity)
(explicit or parameterized)

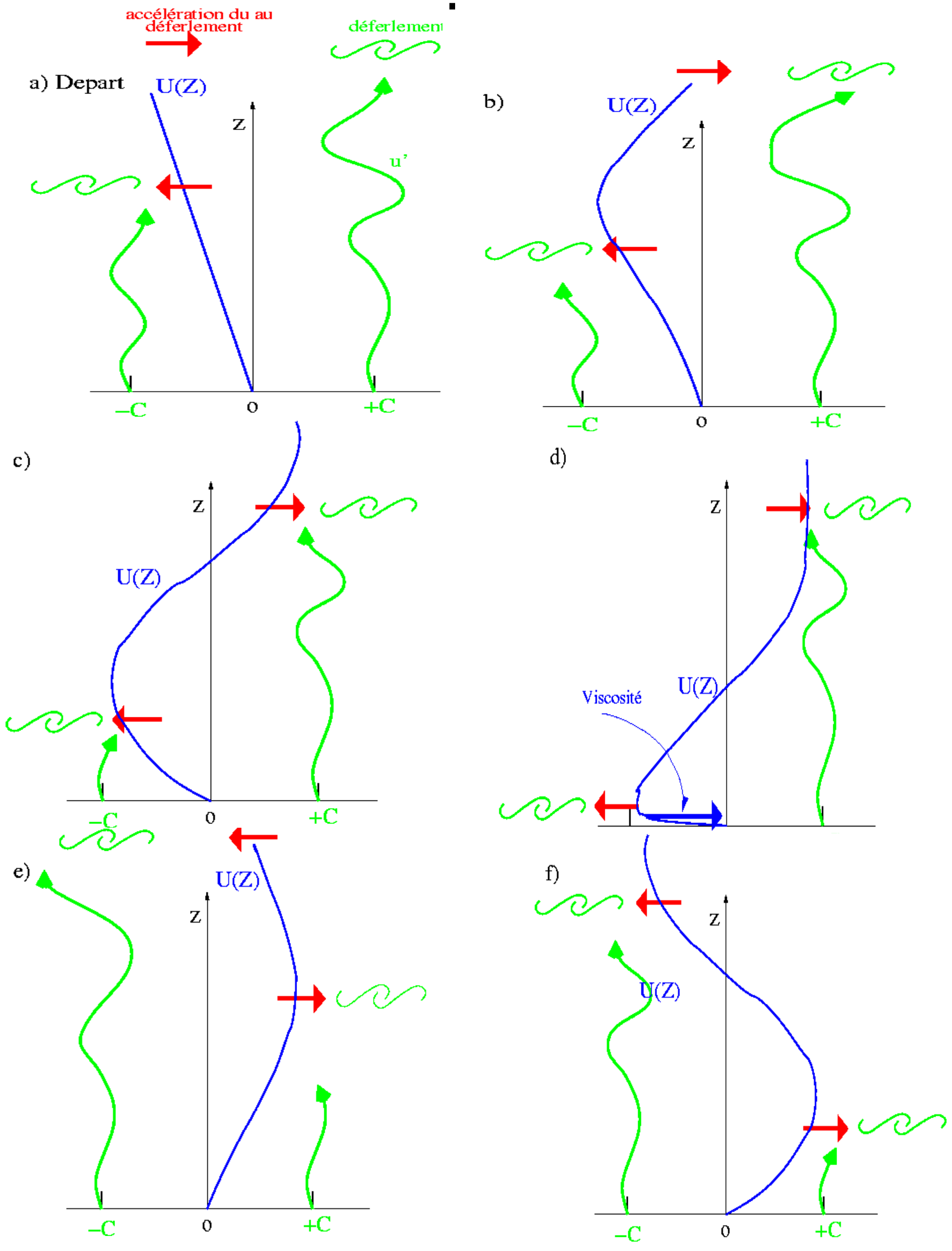
$$\overline{F}_i = \overline{\rho u_i' w_i'}$$

Result from the theoretical model:

$\bar{u}(z,t)$



Interpretation:

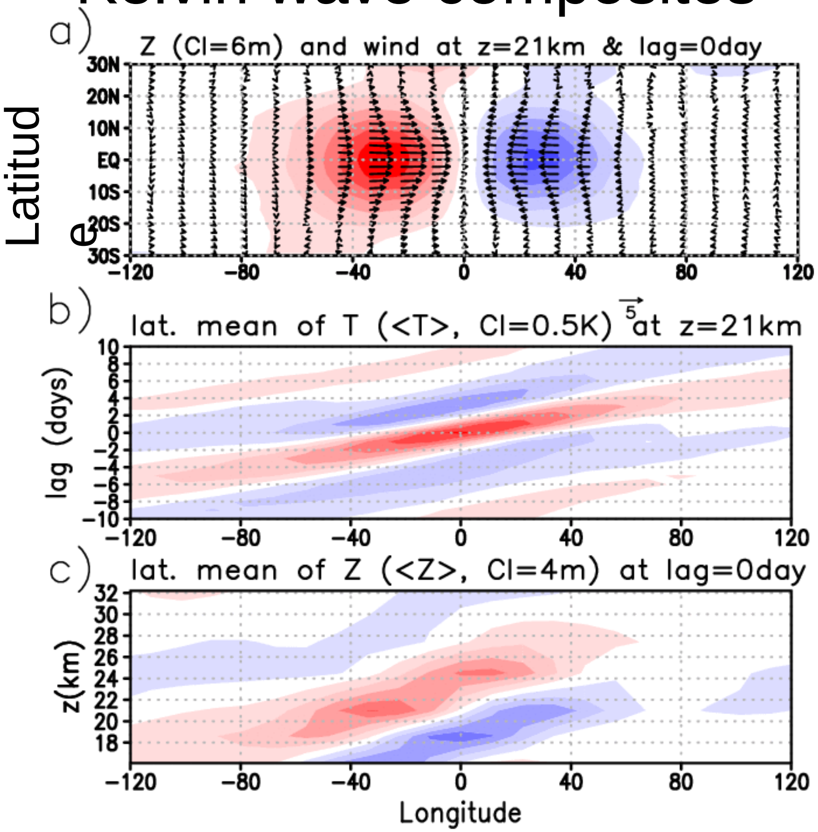


Parameterization of GWs in large scale models

1) Impact of Gravity Waves on the middle atmosphere climate

The gravity waves are not alone !

Kelvin wave composites

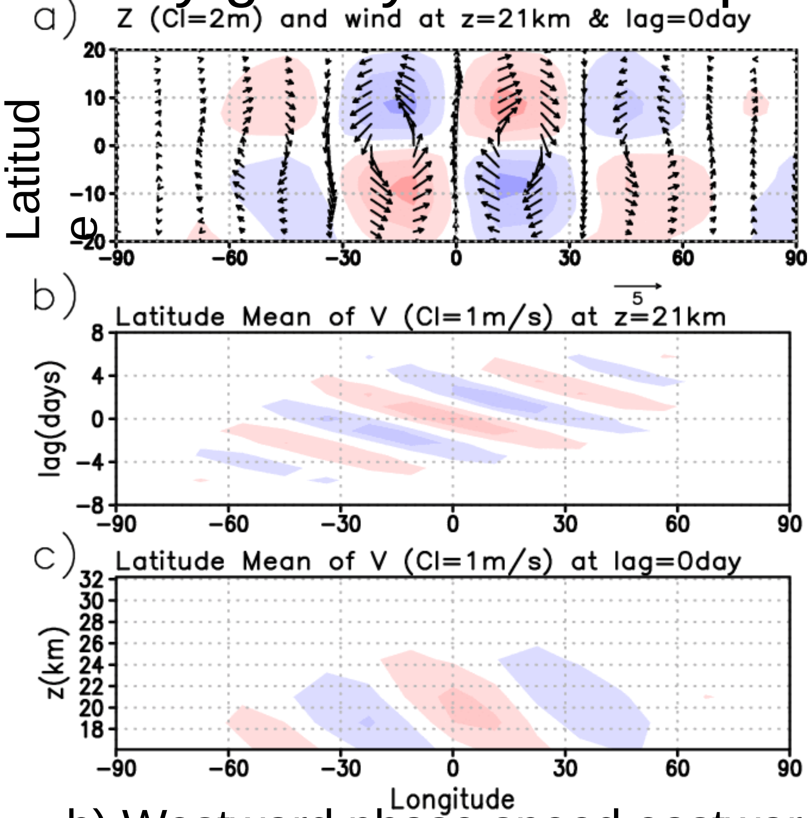


a) Pressure and wind structure at 21 km

b) Eastward propagation

c) Phase lines inclined eastward with altitude: upward propagation

Rossby gravity wave composites



b) Westward phase speed eastward group speed

c) Phase lines inclined westward with altitude : upward propagation

Extraction of equatorial waves in reanalysis (for instance MERRA) and models :
Lott Kuttipurath and Vial (JAS 2007) ; Lott et al.~(JGR 2014) ; Holt Lott et al. (QJRMS 2021)

Parameterization of GWs in large scale models
2) Spectral parameterization and impact

Subgrid scale parametrizations are based on Fourier series decomposition of the waves field over the model gridbox of sizes δ*x*, δ*y*, and δ*t* (δ*t* 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)

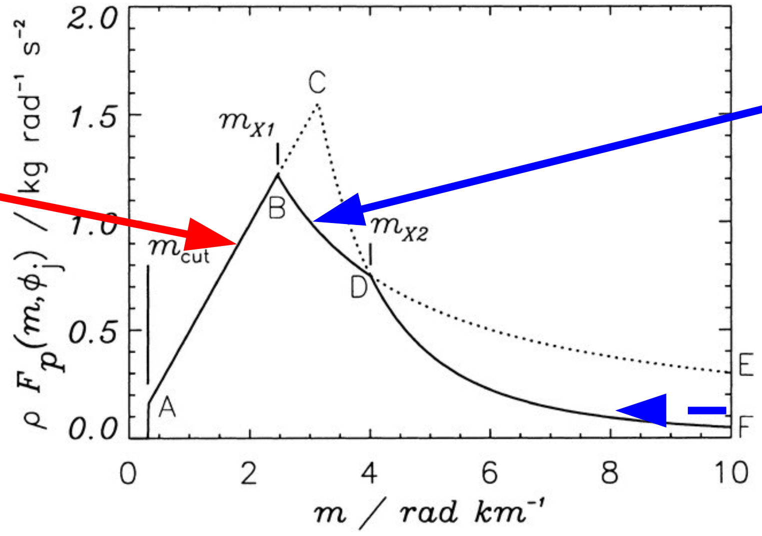
Warner and McIntyre (2001)

Parameterization of GWs in large scale models
2) Spectral parametrizations and impact

Globally spectral schemes,

Use that the observed GWs vertical (m-)spectra have a quasi-universal shape, with a m^{-3} slope for the $m>m^*$ part of the spectra that correspond to breaking waves

The **Warner and McIntyre (2001)** scheme propagate initial gravity wave spectra according to wave action conservation rules and troncate the propagated when it exceeds the m^{-3} saturated spectra to fit observed spectra



Conservative propagation

Quasi-saturated m^{-3}

Wave-breaking followed by conservative propagation

Fig. 1, from Warner and McIntyre (2001)

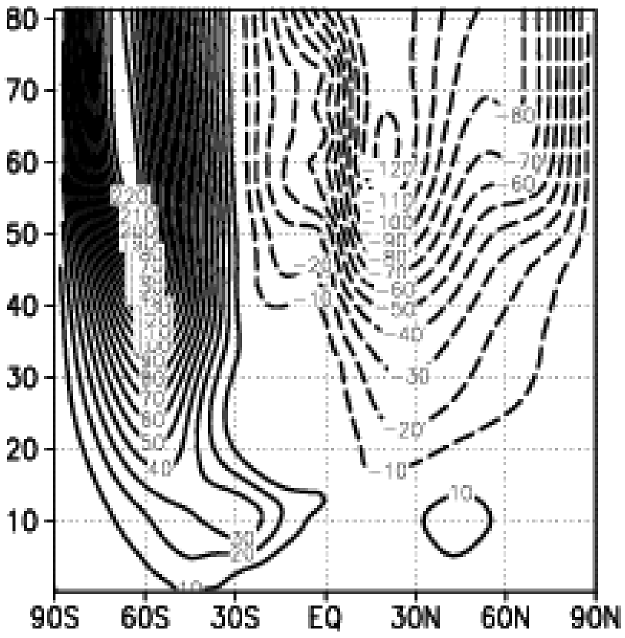
Parameterization of GWs in large scale models
2) Spectral parametrizations and impact

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 and Millet 2010).
Here are used the Hines' scheme developped by Manzini et al.(1997) and the Lott and Miller (1997) orographic scheme.

$$\bar{u}=\frac{1}{2\pi}\int_{0}^{2\pi} u\, d\lambda$$

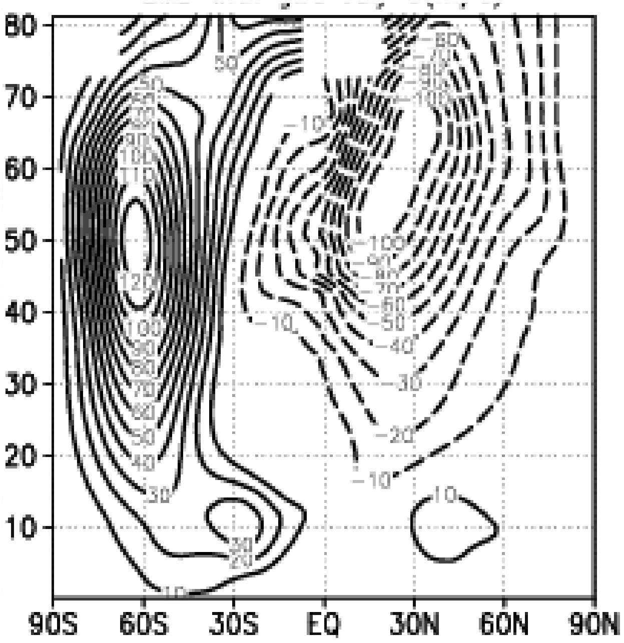
without

July



with

July



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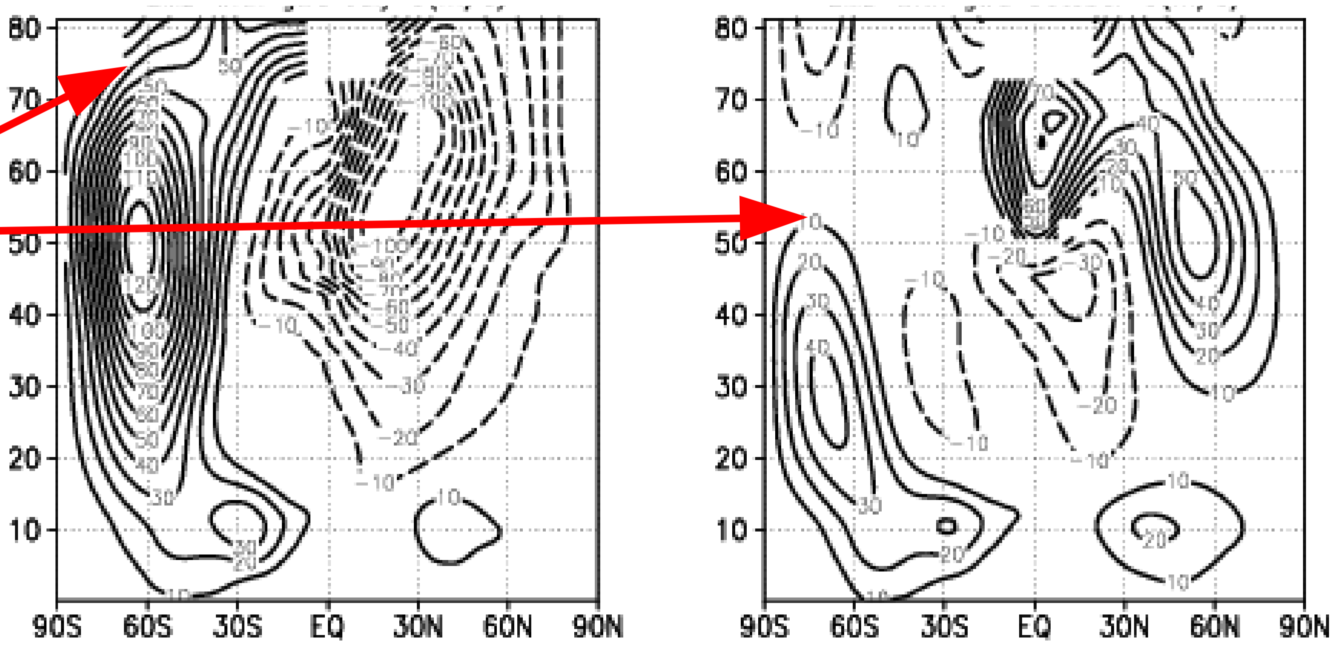
July **October**



Descend of the
$\bar{u}=0$
Line.

Date when it arrives
At 10hPa :
Final warming

Systematic Error !

Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

Exemple of the stochastic and « Multiwave » convective gravity wave scheme used in LMDz6 / IPSLCM6 model [Lott Guez and Maury GRL, 2012, Lott and Guez 2013]

Stochastic series with intermittency coefficients An's :

$$w' = \sum_{n=1}^{\infty} A_n \; \hat{w}_n(z) e^{z/2H} e^{i(k_n(x-C_n t))} \qquad \sum_{n=1}^{\infty} A_n^2 = 1$$

k_n, c_n chosen randomly, tunable parameter : **C_0** characteristic intrinsic phase speed

Launched flux :

$$\rho \hat{w}_n \hat{u}_n^*(z_l) \approx \rho_r \frac{\vec{k}_n}{|\vec{k}_n|} \; \exp(-m_{nl}^2 \Delta z^2) \; G_{uw} \quad P_r^2$$

Pr : gridsccale precipitation

Δz : Source depth

G_{uw} : amplitude parameter

Z_l : Launching altitude

Saturation criteria (dynamical filtering):

$$|\rho \hat{w}_n \hat{u}_n^*| \le \rho_r S_c^2 |c_n - U(z)|^3 \frac{k_m}{N|k_n|^3}$$

Sc : Saturation parameter

Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

Online results with LMDz

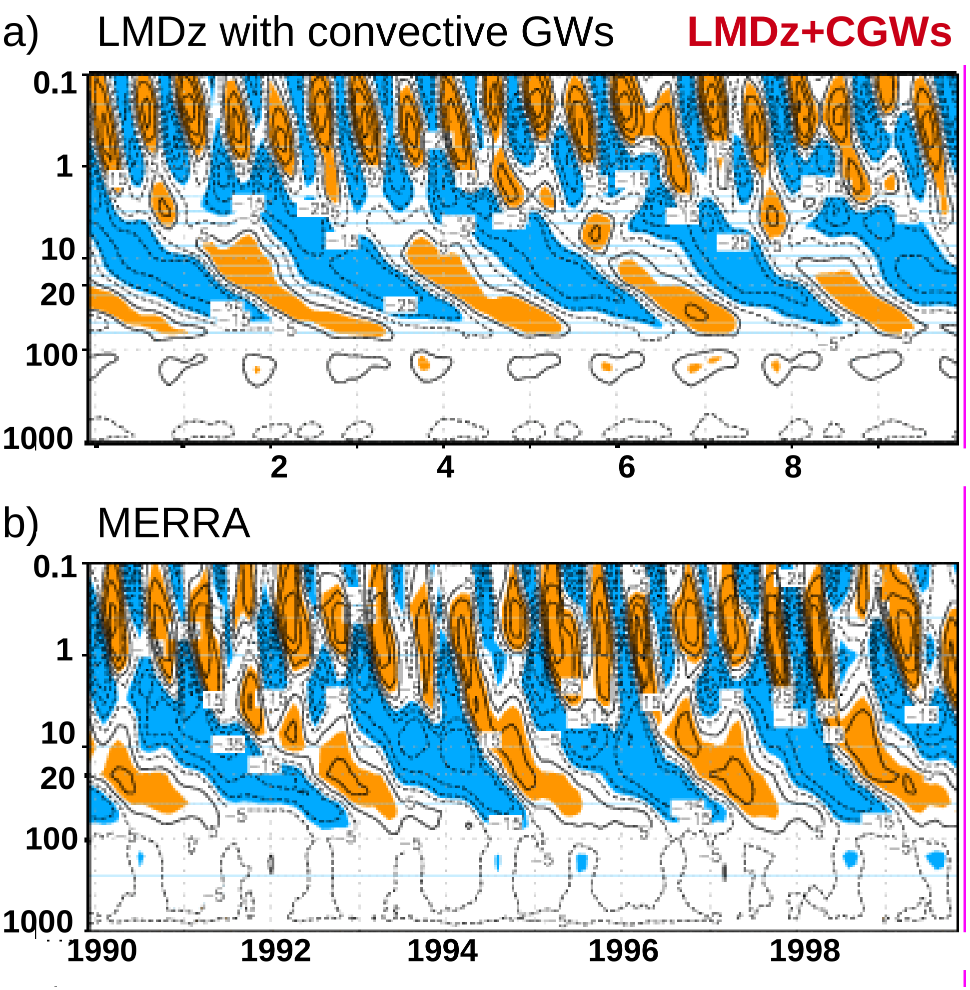
LMDz version with 80 levels, dz<1km
In the stratosphere

QBO of irregular
period with mean
around 26month,

20% too small amplitude

Systematic Error :
To small amplitude westerlies near
Above 100hPa
(Problem : this is probably the altitude
At which the QBO correlated with
the midllatitudes

(Anstey et al. 2021,
The Holton-Tan (1980) effect)



Lott and Guez, JGR13

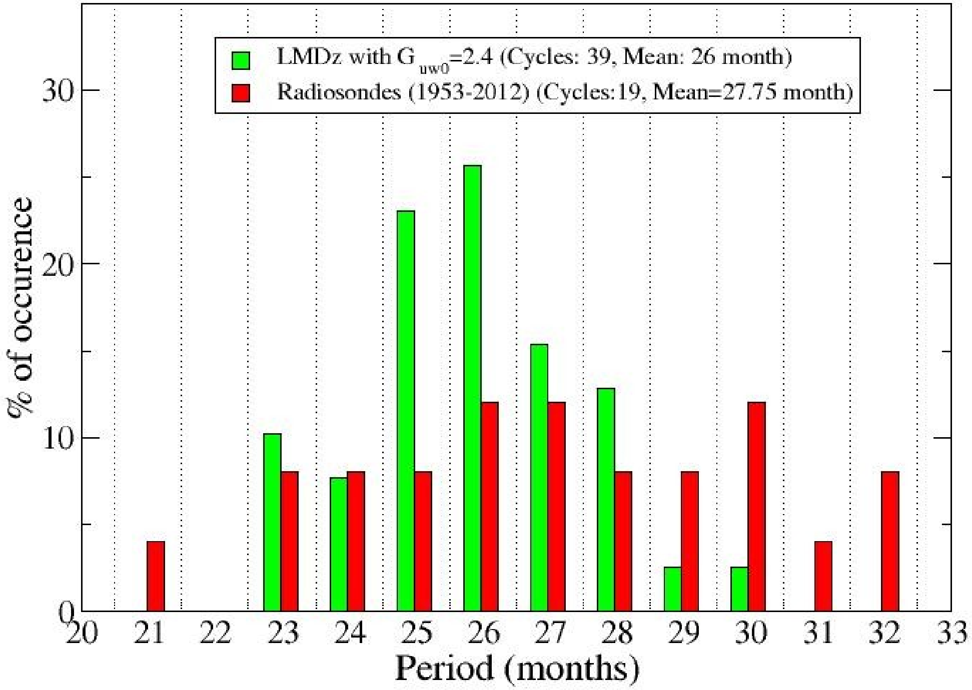
Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

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

Parameterization of GWs in large scale models
3) Multiwave stochastic param. and application to convective GWs

Equatorial waves:

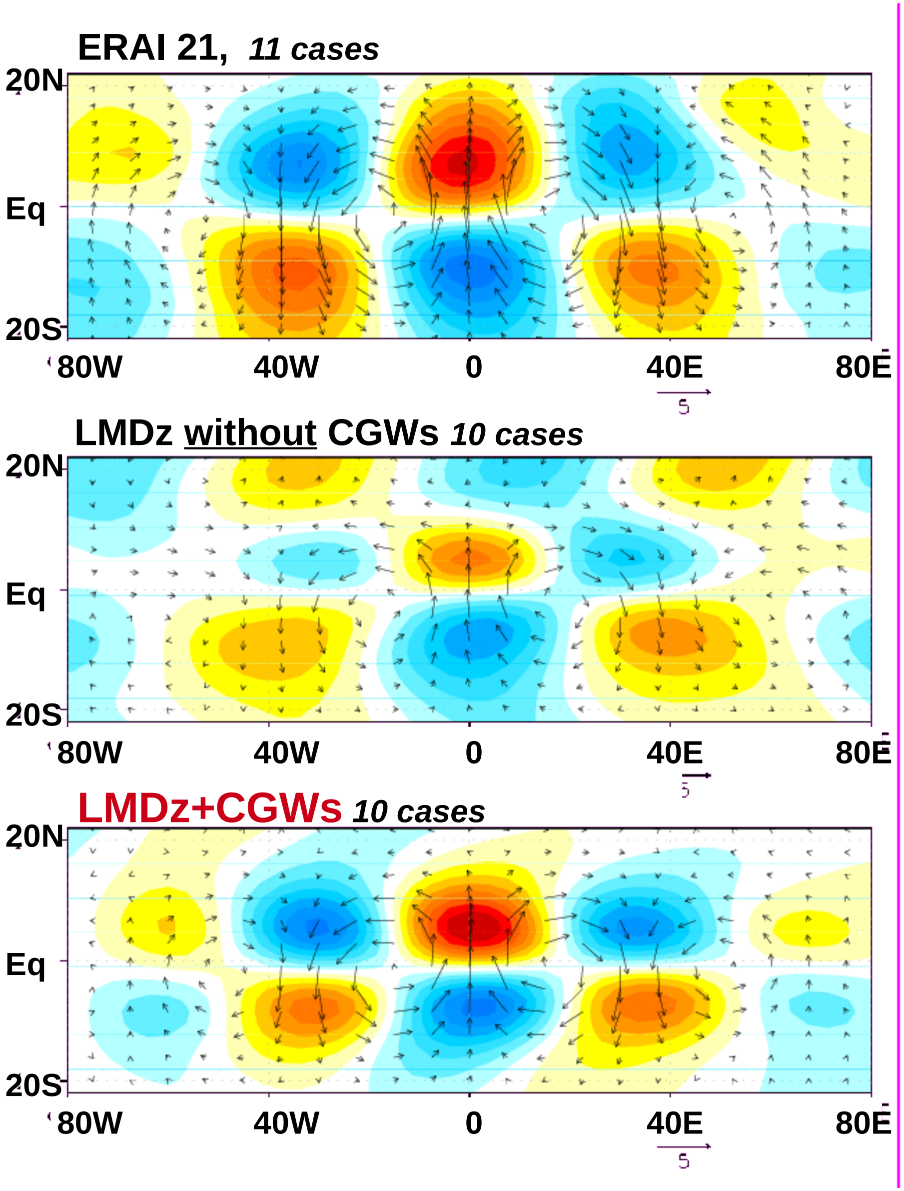
Remember also that
when you start to have
positive zonal winds, **the
planetary scale Yanai wave
is much improved**

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

Zero longitude line arbitrary

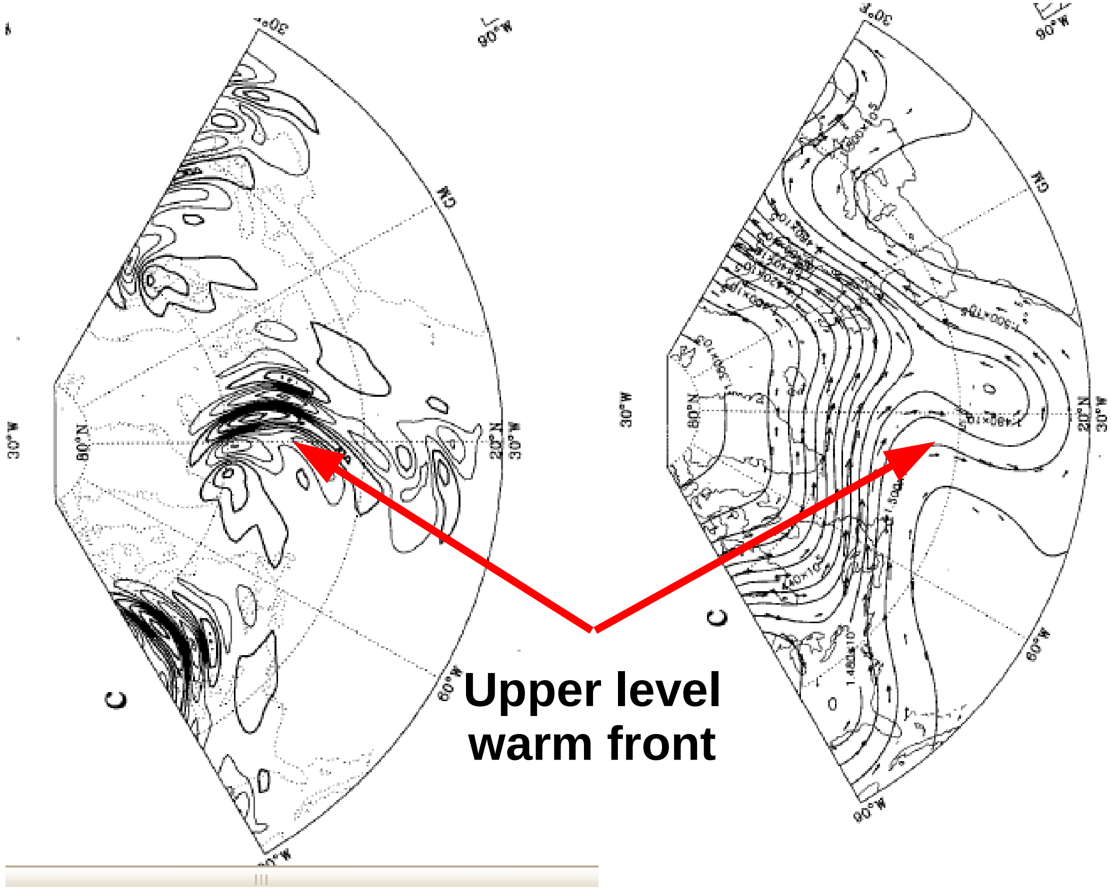
Lott et al. 2012 GRL

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



Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Simulations to support these parameterizations:



Upper level warm front

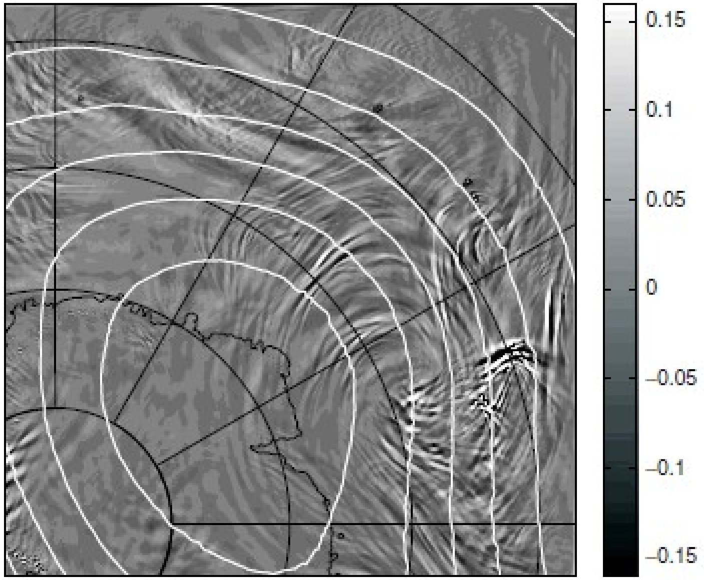


Figure 16. As Figure 2(b), but from a simulation with doubled horizontal resolution ($\Delta x = 10$ km).

Results confirmed by much higher resolution simulations

O'Sullivan and Dunkerton (1995)

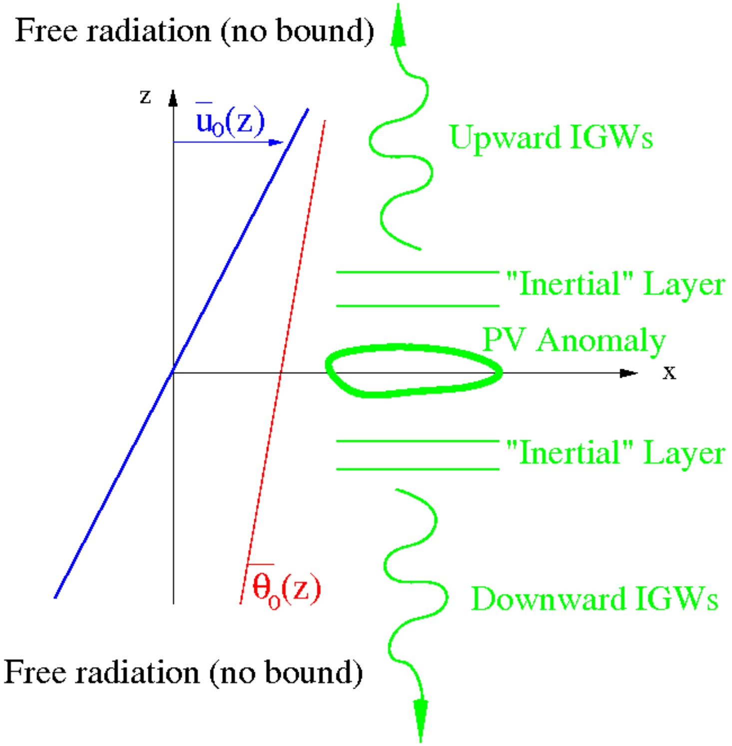
Plougonven Hertzog and Guez (2012)

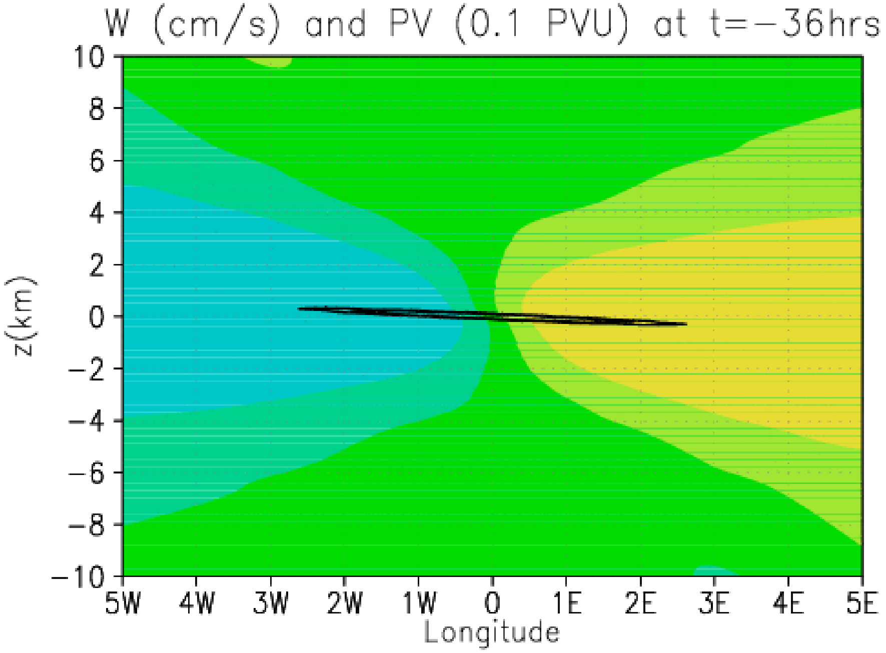
This is somehow related to the "Geostrophic Adjustment" process.
Part of It, the so-called «Spontaneous adjustment» where a well-balanced flow radiates GWs can be handled analytically
Lott, Plougonven, Vanneste (2010, 2012)

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Well balanced means entirely described by the Potential vorticity distribution:

Spontaneous emission : GW emission from 3D (x,y,z) Potential Vorticity (PV) anomaly advected in a rotating (*f* =cte), stratified (***N*****=cte**) shear flow (vertical shear $\Lambda = \bar{u}_{0z}$ **=cte**).





Underlying justification : fronts are characterized by strong PV anomalies and wind shears

Lott, Plougonven and Vanneste, JAS 2010, 2012.

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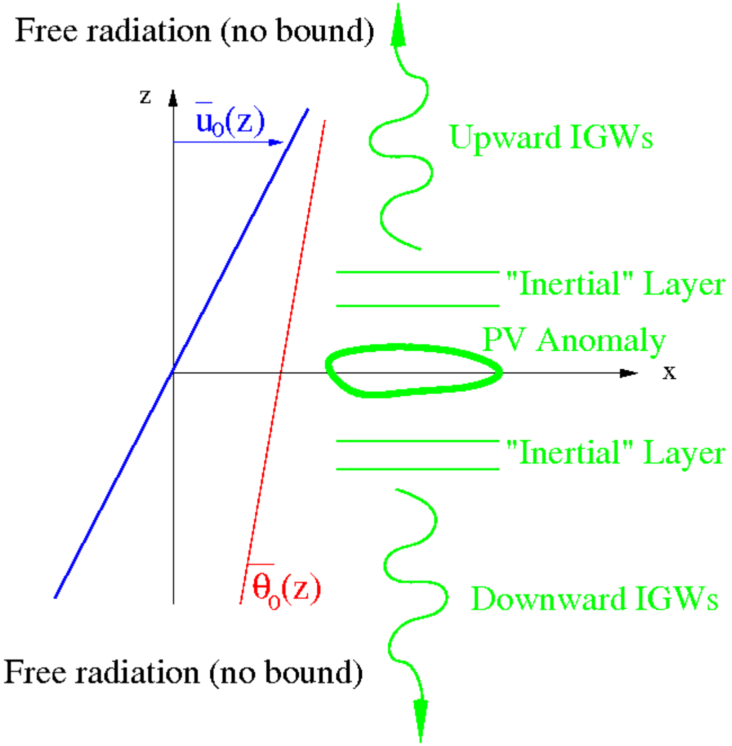

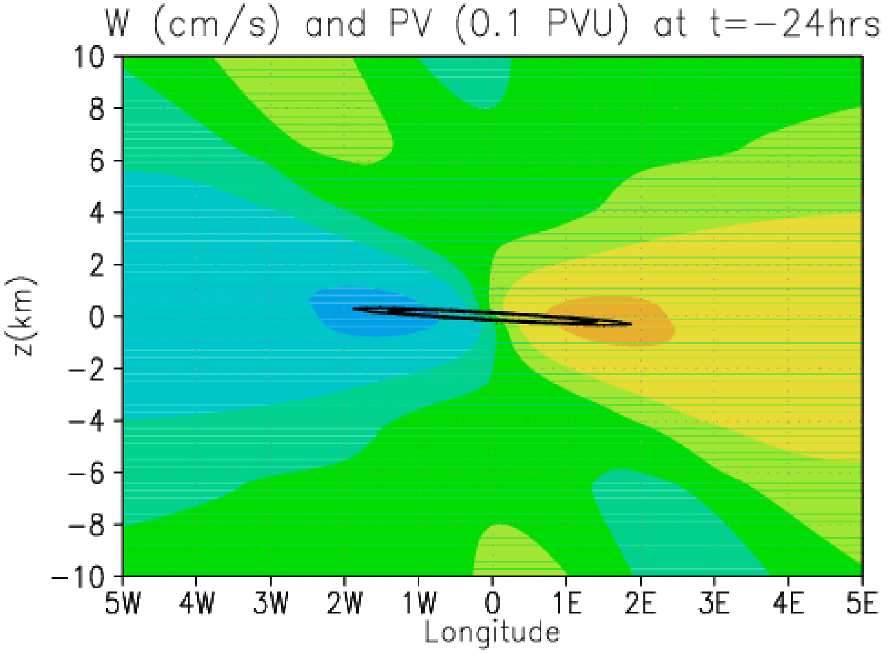

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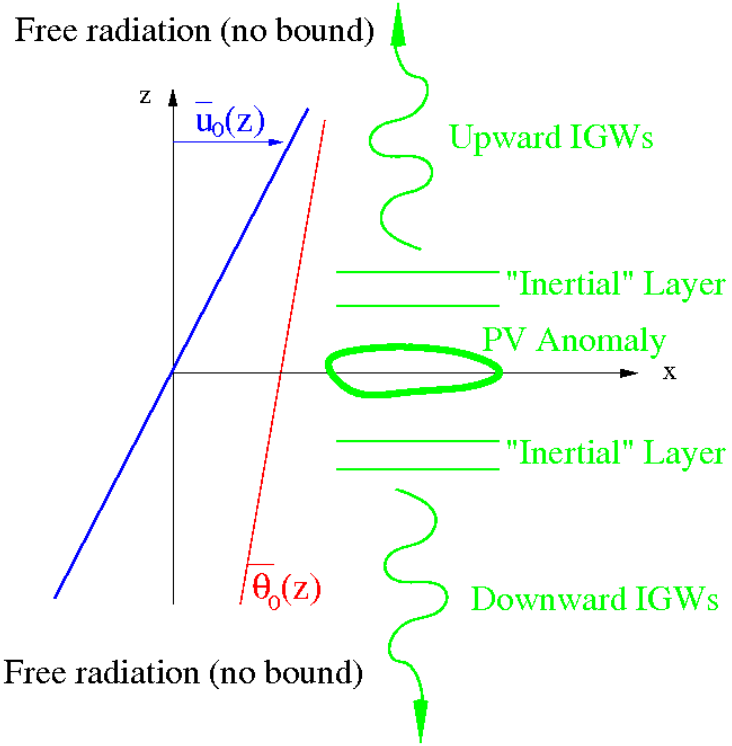

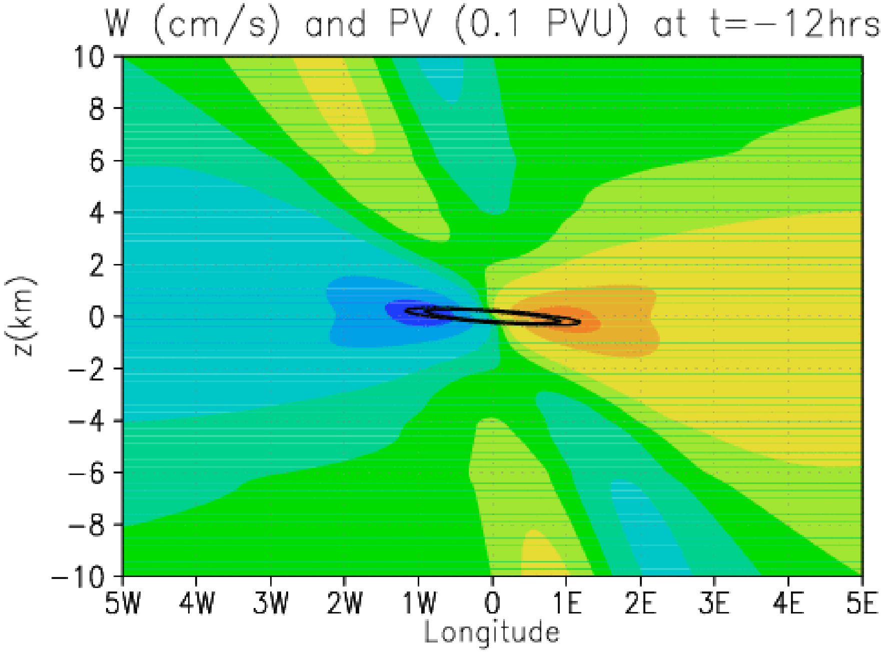

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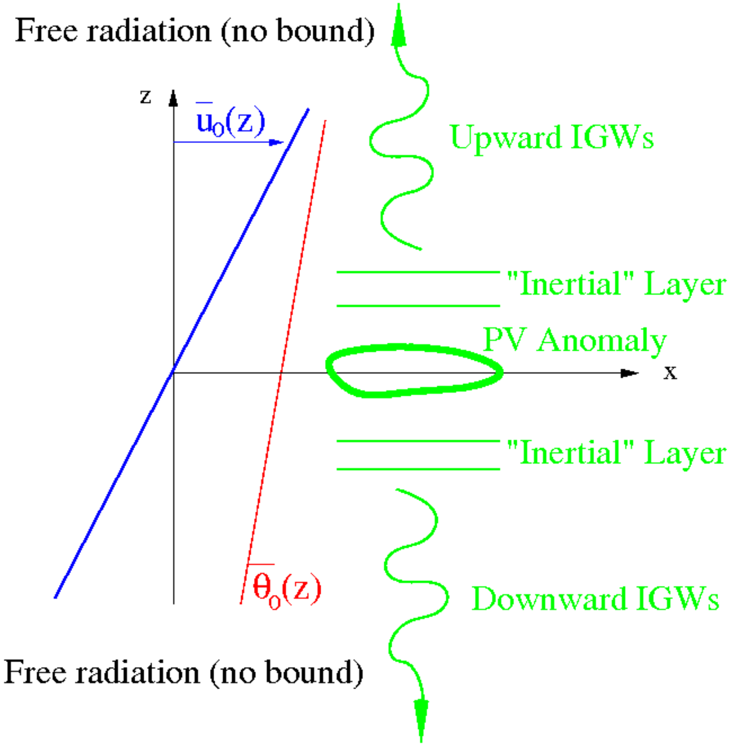

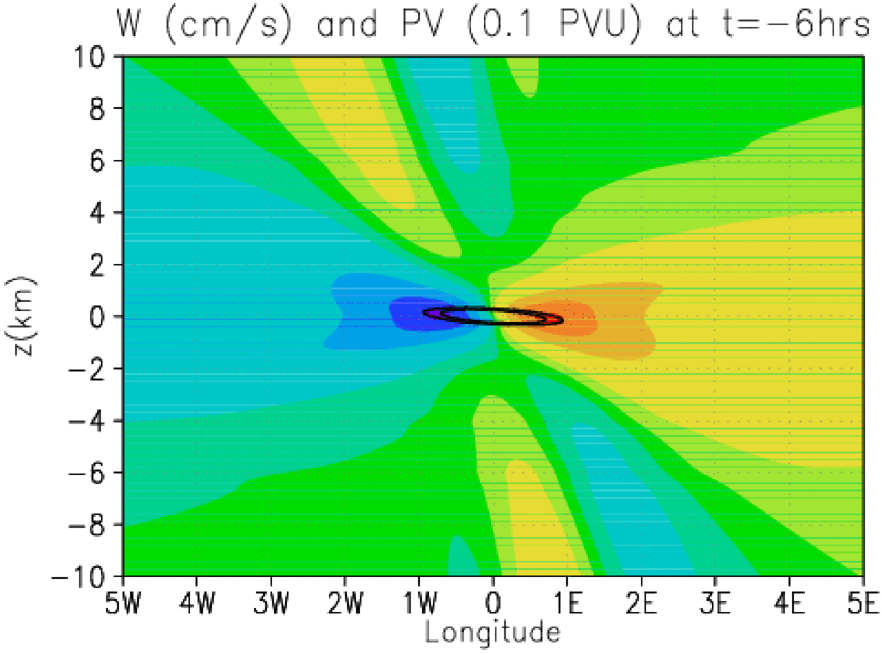

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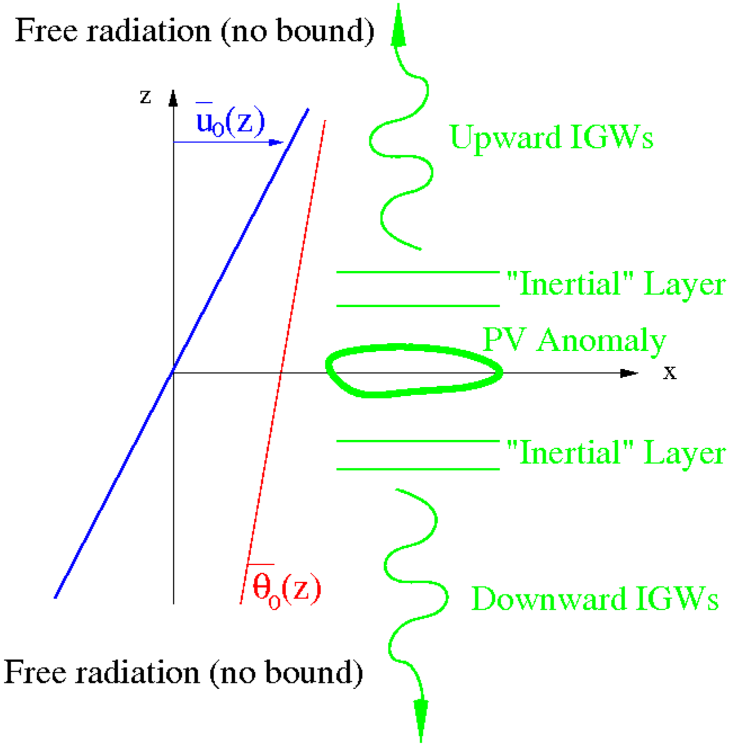

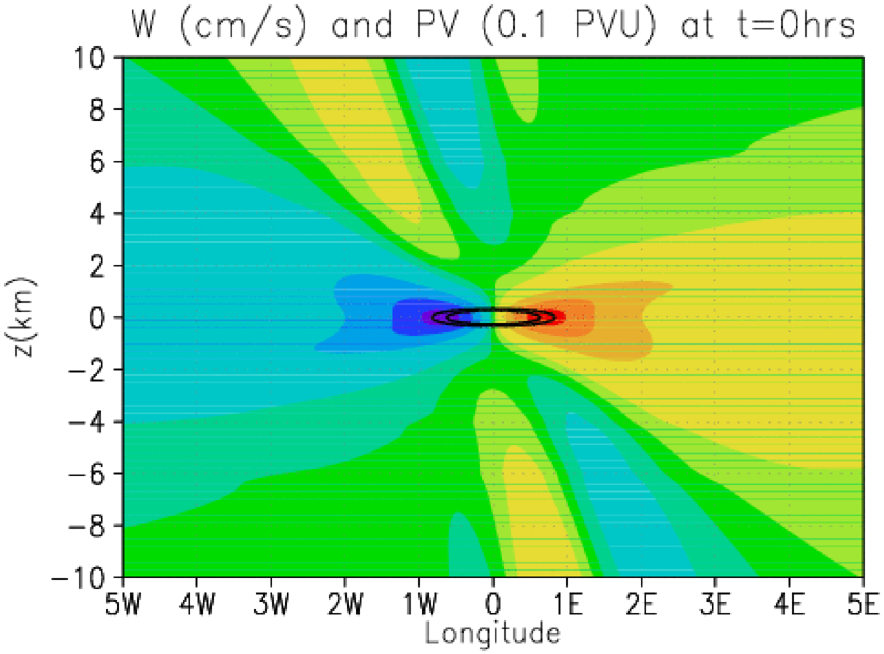

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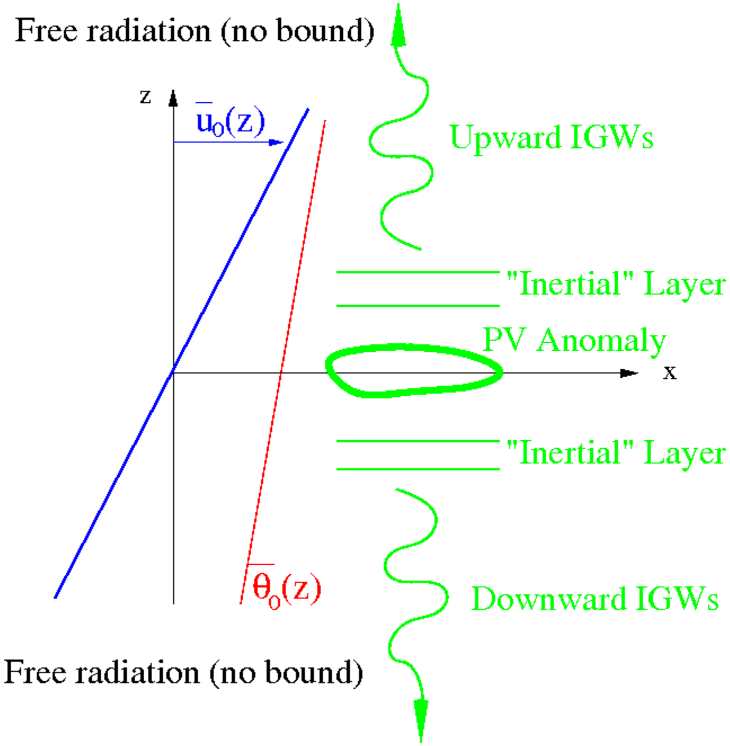
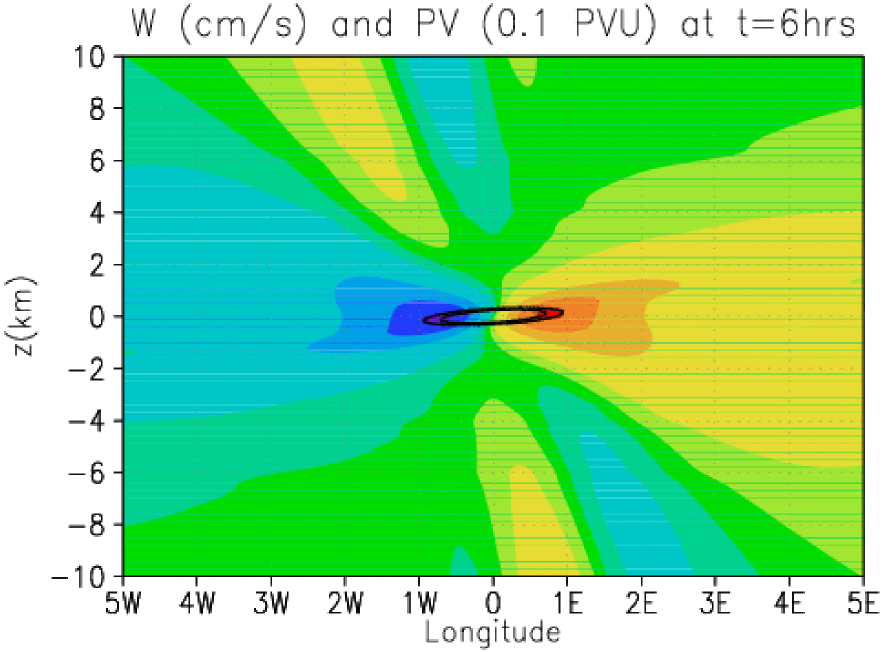
Spontaneous emission : GW emission from 3D (x,y,z) Potential Vorticity (PV) anomaly advected in a rotating (*f* =cte), stratified (***N*=cte**) shear flow (vertical shear $\boldsymbol{\Lambda = \overline{u}_{0z}}$ **=cte**).





Underlying justification : fronts are characterized by strong PV anomalies and wind shears

Lott, Plougonven and Vanneste, JAS 2010, 2012.

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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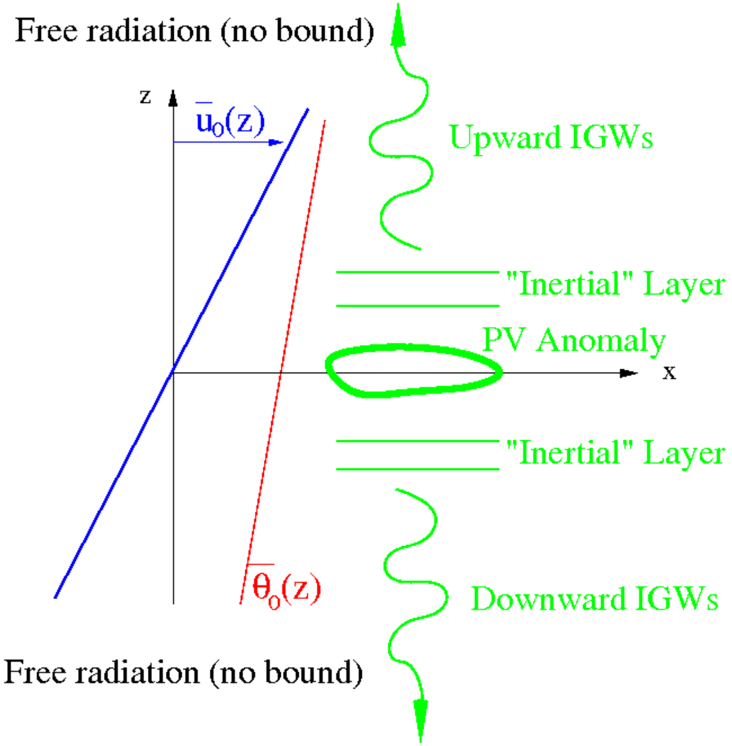

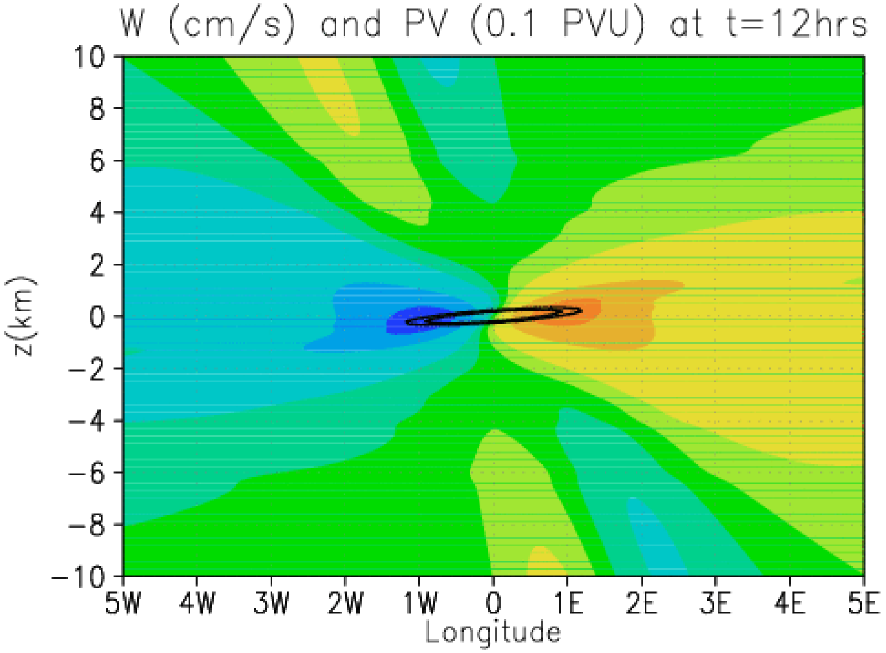

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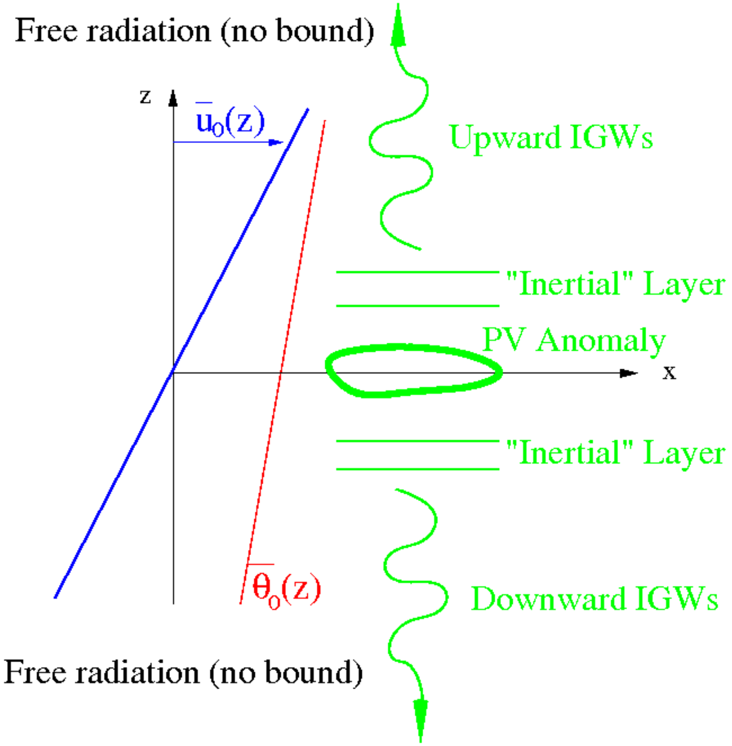

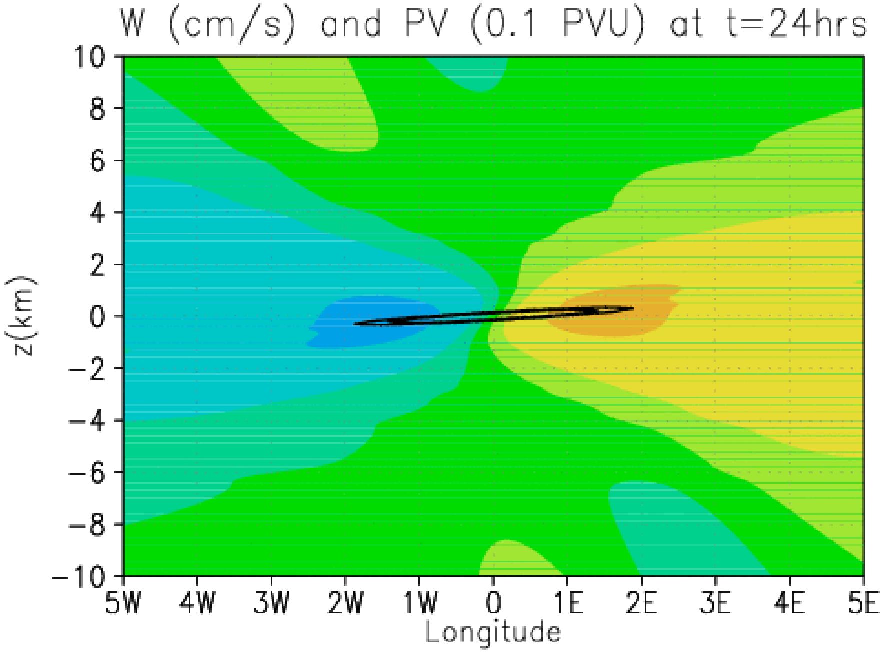

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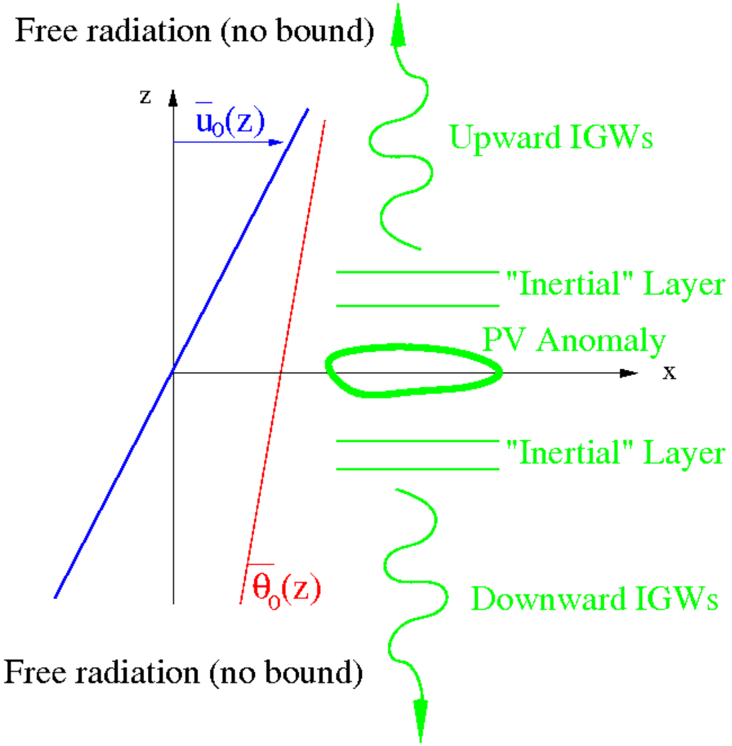

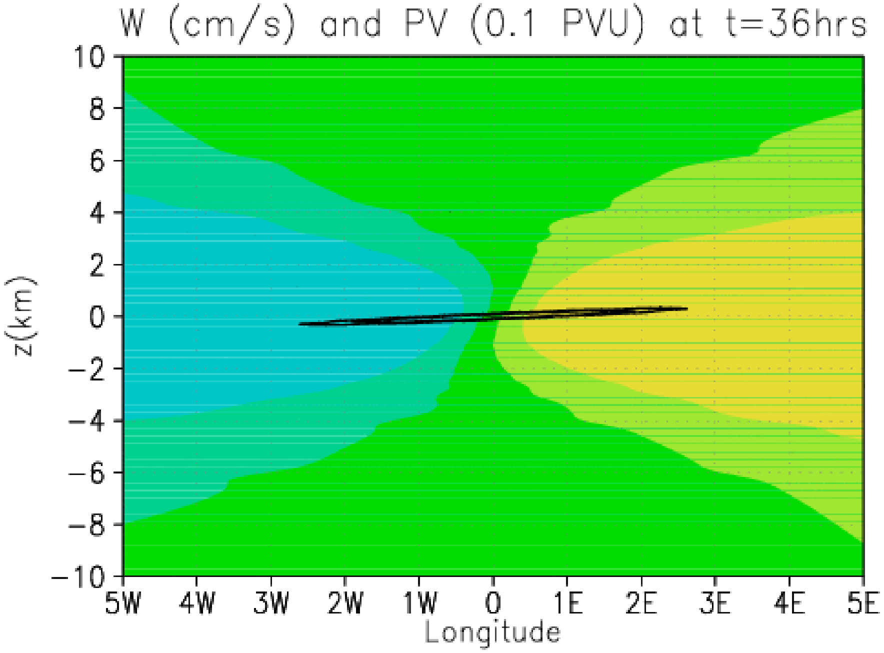

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Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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

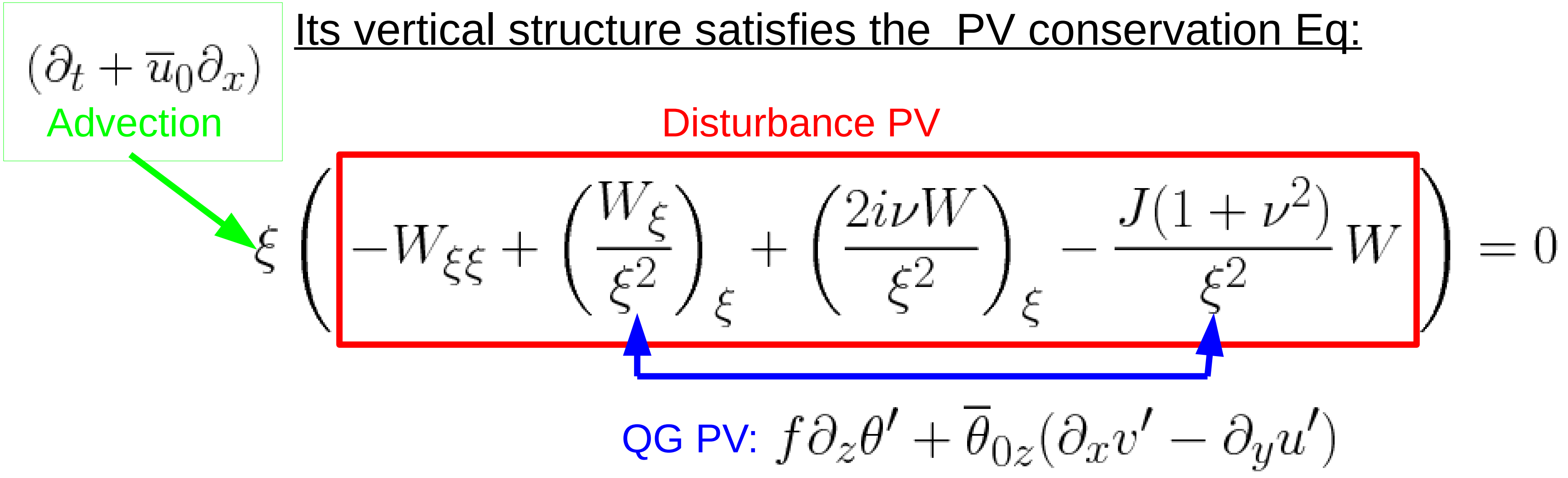
$$w'(x,y,z,t)=\hat{w}_0(k,l,\omega)W(\xi)e^{i(kx+ly-\omega t)}$$

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

ξ=0 Ordinary critical level
(Intrinsic frequency=0)

ξ=-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 $\nu=l/k$

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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

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

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

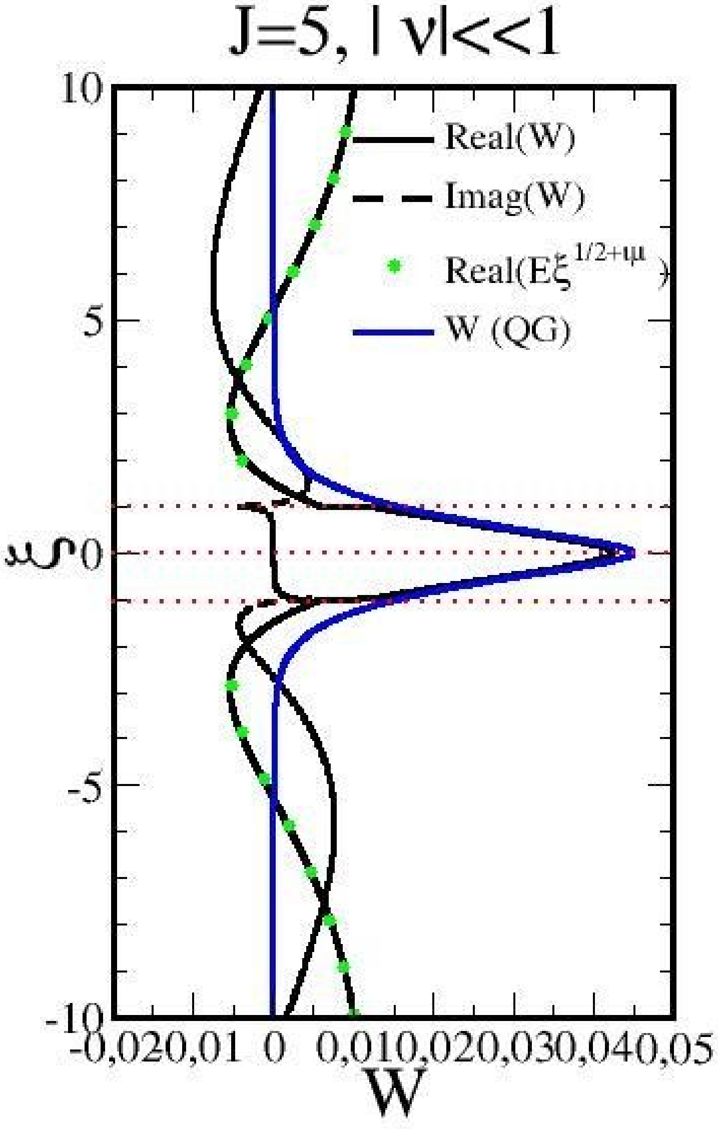
$0<\xi<1$: $(1+\xi)^{-i\nu}(A\, F'(\xi^2)+B\xi^3 F''(\xi^2))$

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

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

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

F, F', and F'' Hypergeometric functions



Parameterization of GWs in large scale models
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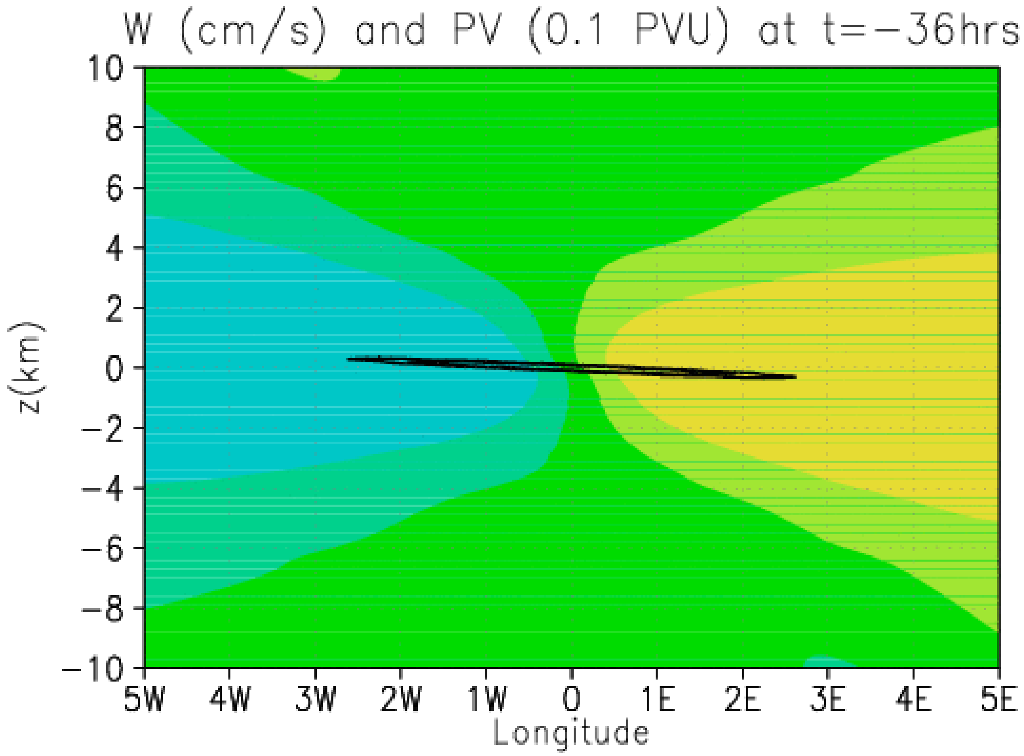

$wN^2 \sim f\Lambda v$

Lott, Plougonven and Vanneste, JAS 2010, 2012.

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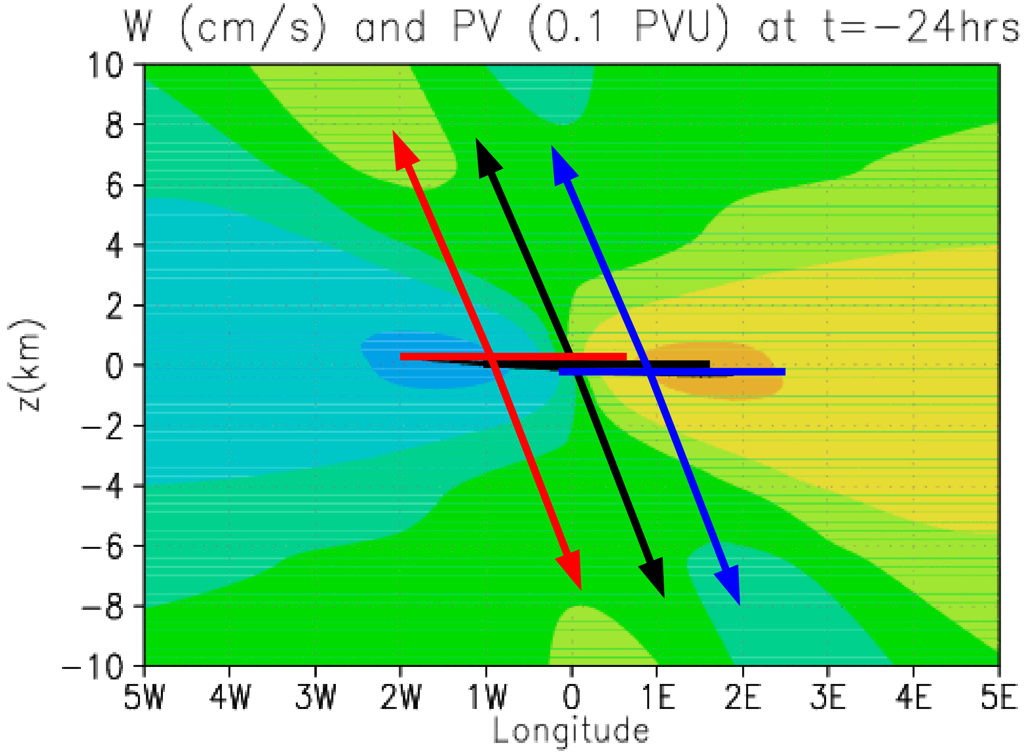

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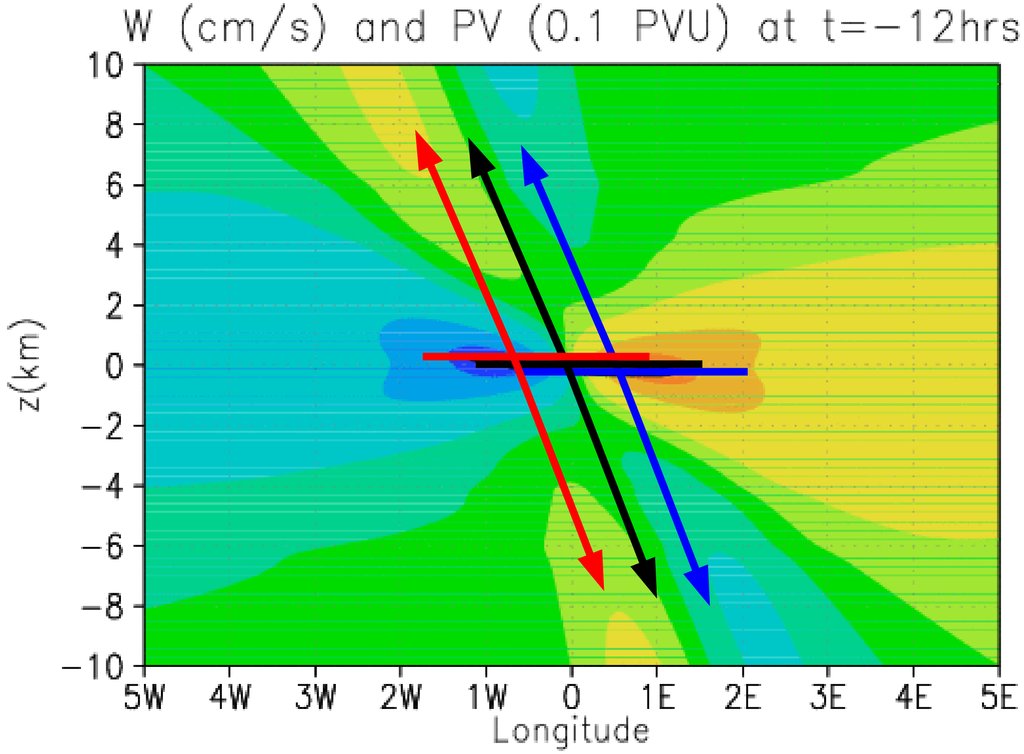

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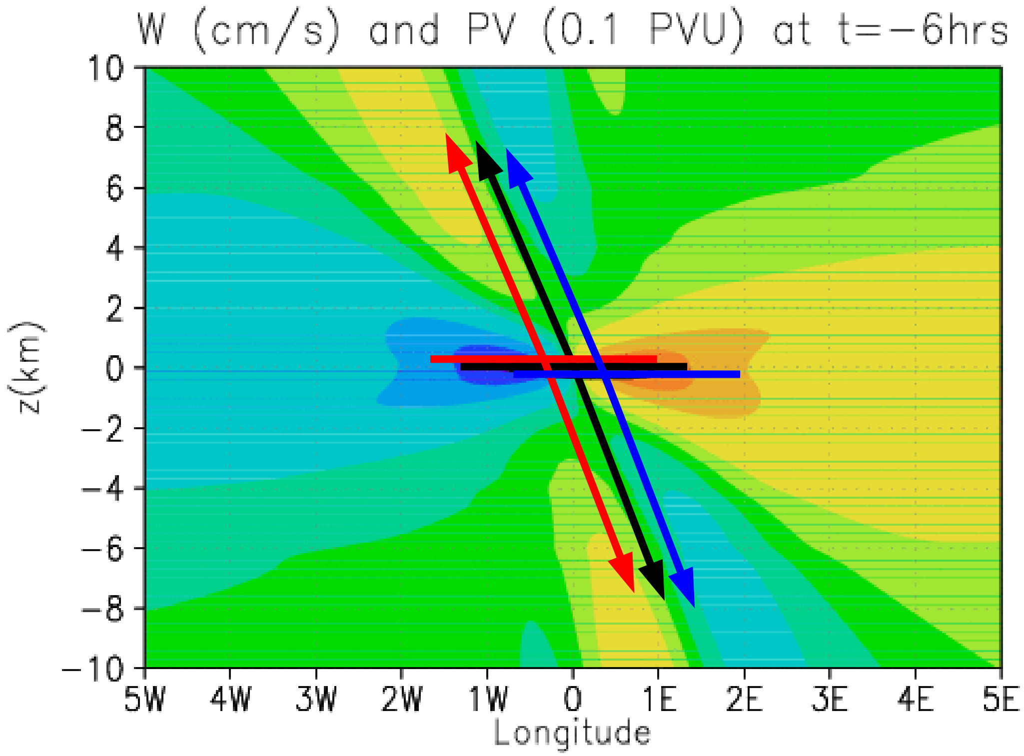

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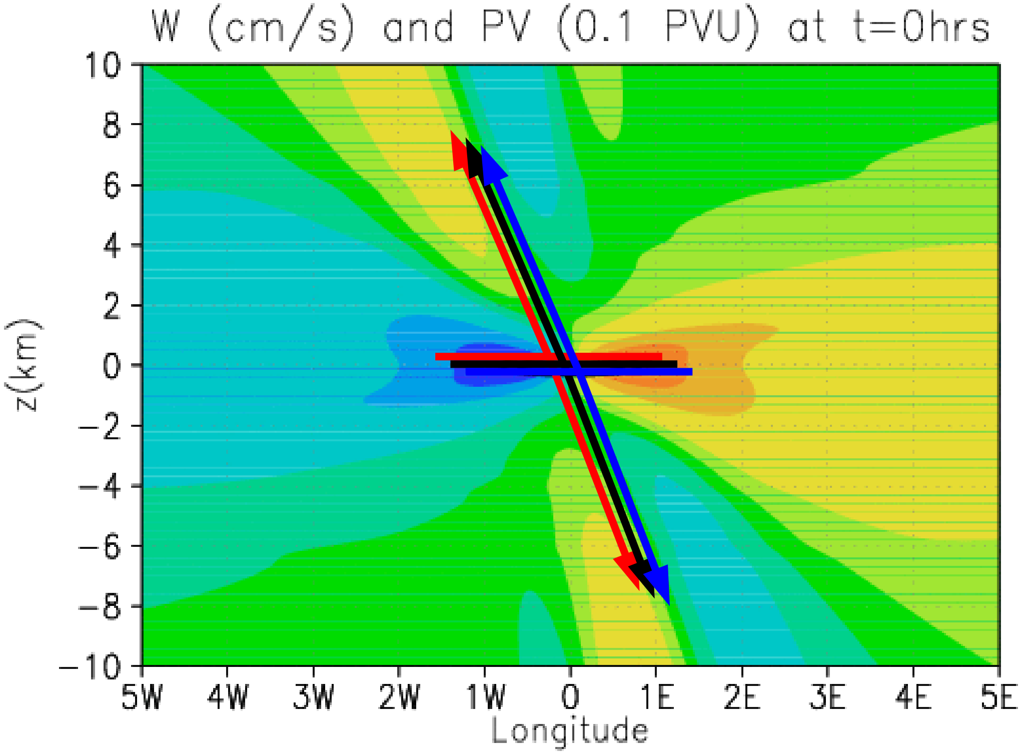

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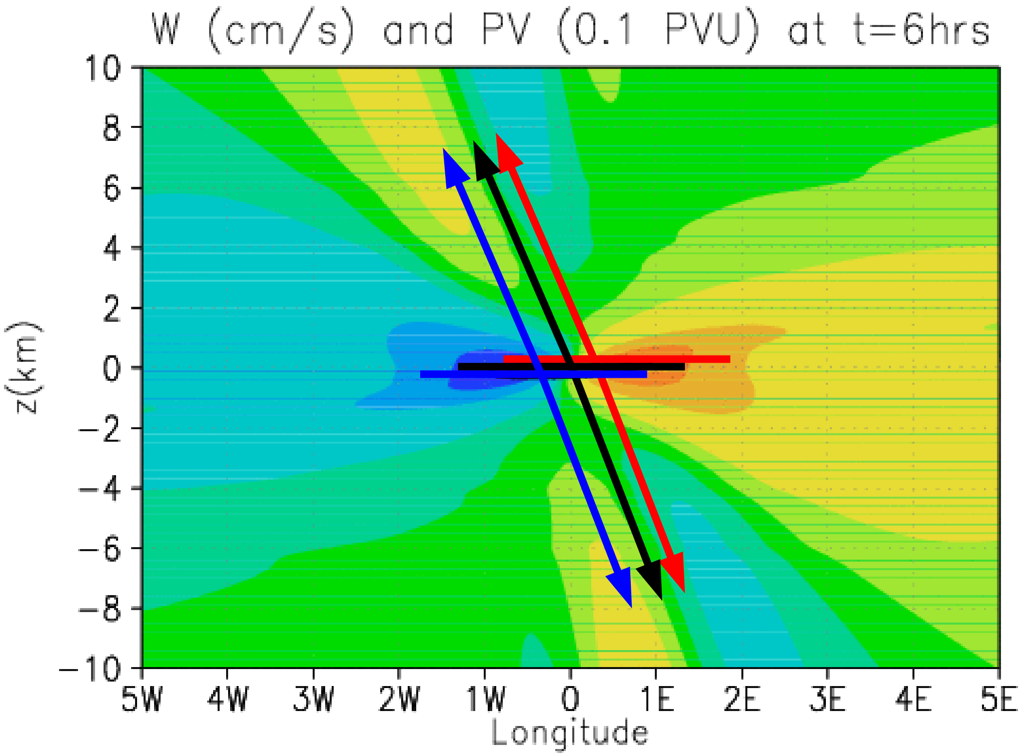

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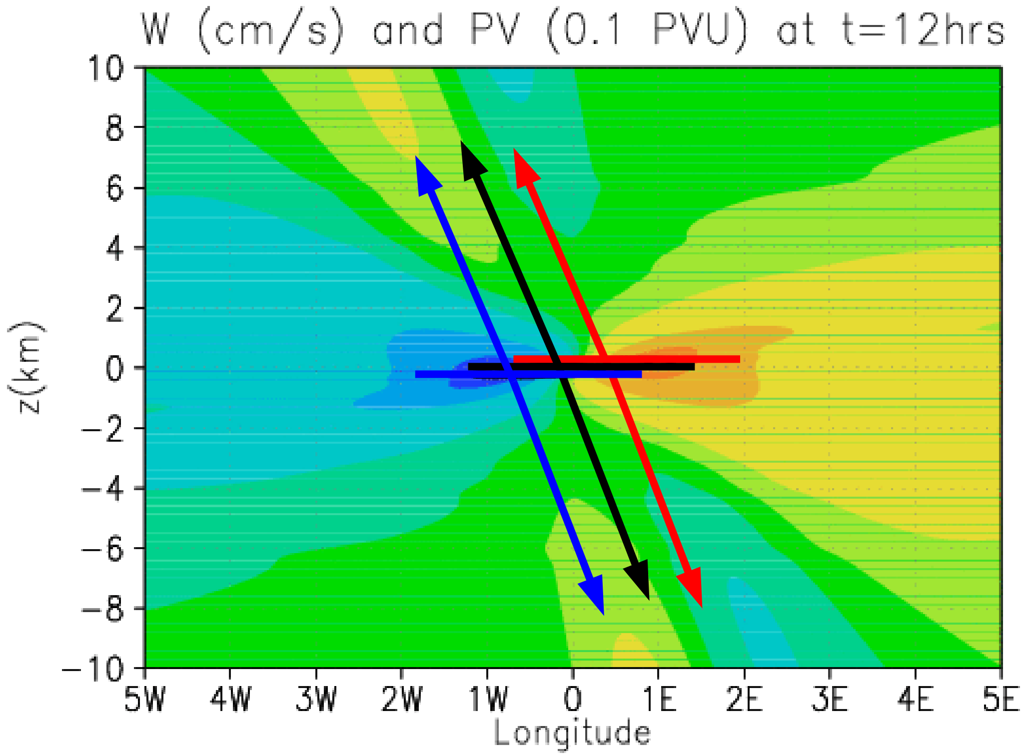

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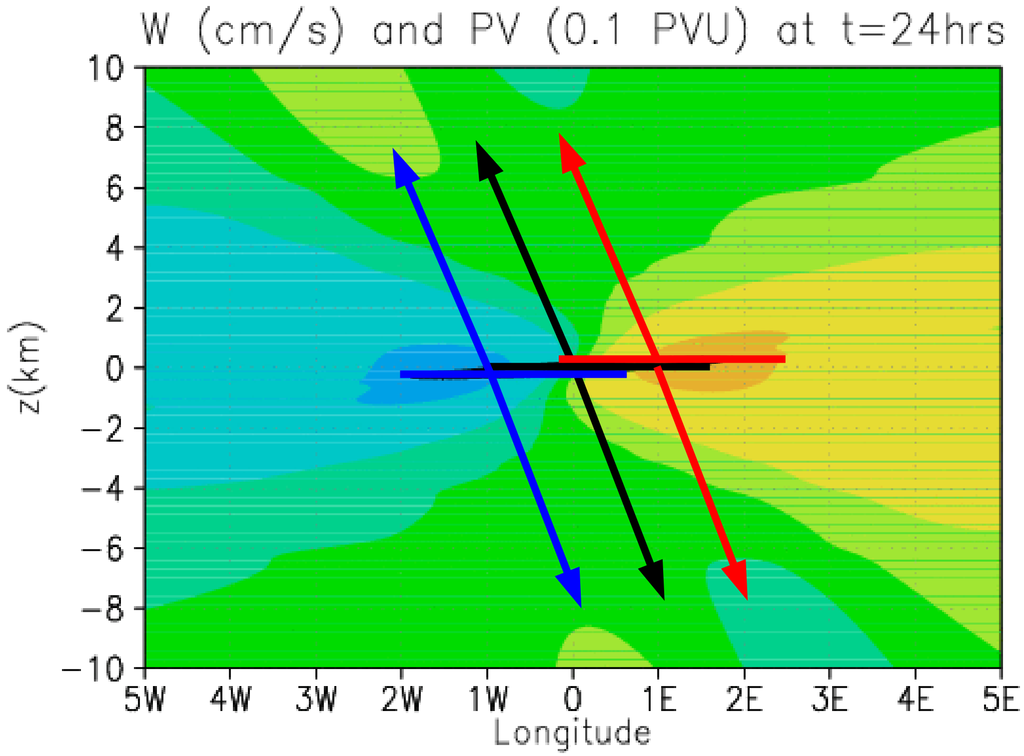

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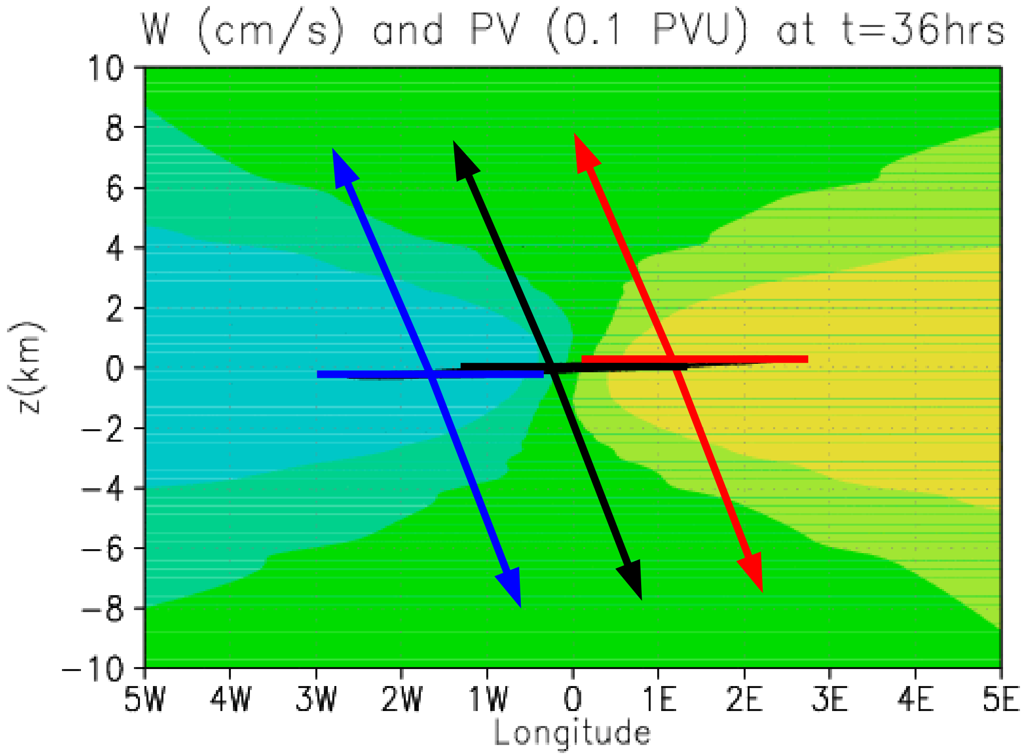


Lott, Plougonven and Vanneste, JAS 2010, 2012.

Parameterization of GWs in large scale models
4) Application to gravity waves generated by 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 routinesare 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:

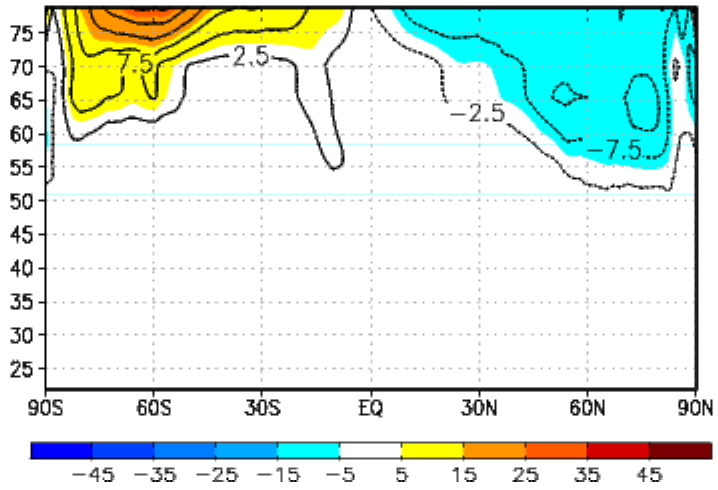
$q' = \sum_{n=1}^{\infty} C_n q_n'$ where $q_n' = \Re\left[\hat{q}_n e^{i(\vec{k}_n \cdot \vec{x} - \omega_n t)}\right]$ taking $|\hat{q}_n| = |q_r|$

de la Camara and Lott 2015

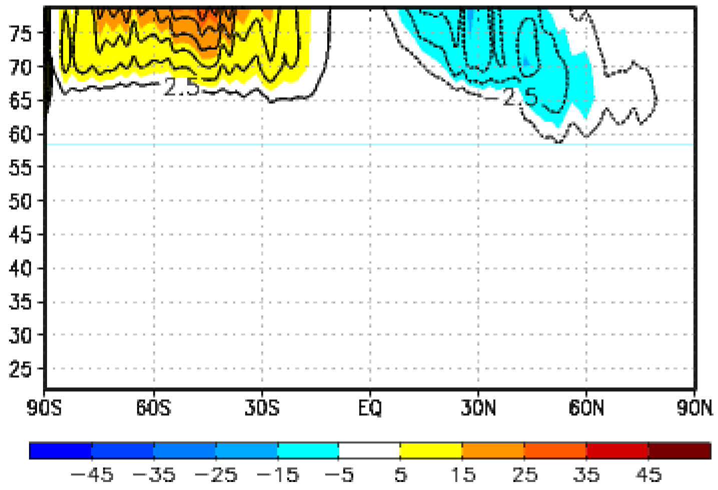
Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

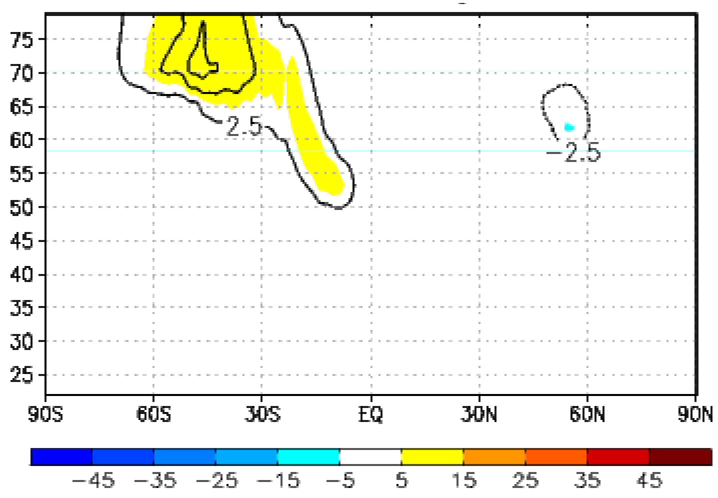
The theory predicts about the right amount of drag compared to a highly tuned globally spectral scheme (January, all in m/s/day)

Globally spectral scheme

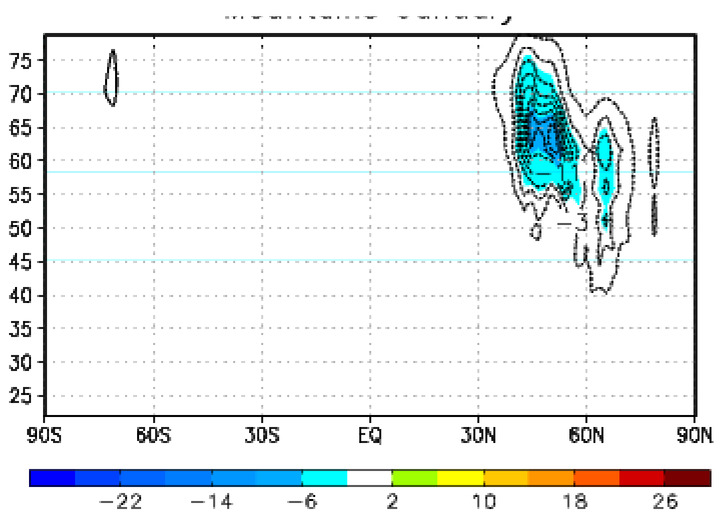


From fronts





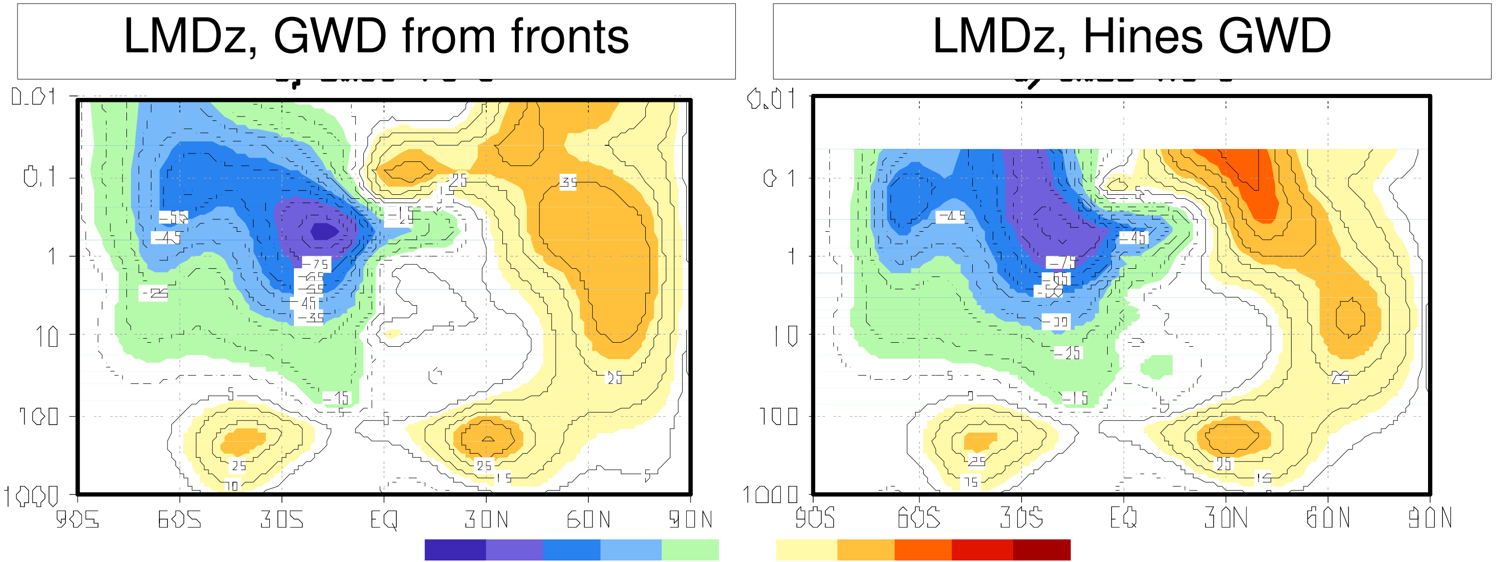
Convective GWs



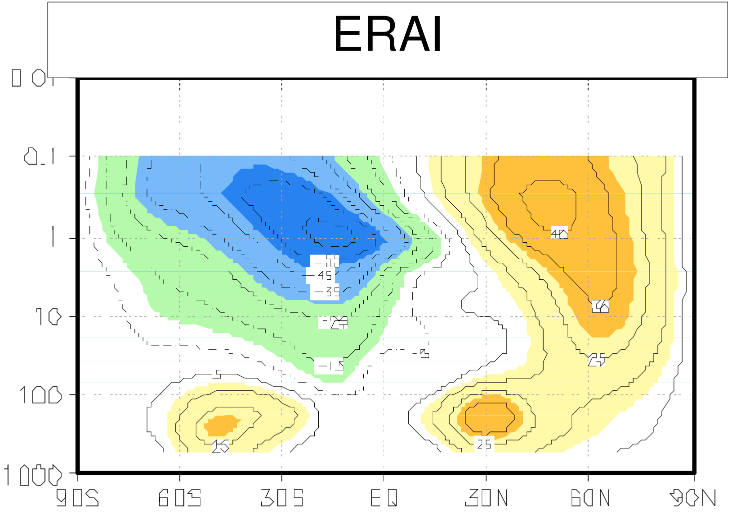
Mountains GWs

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Zonal wind U, January climatology


LMDz, GWD from fronts

LMDz, Hines GWD

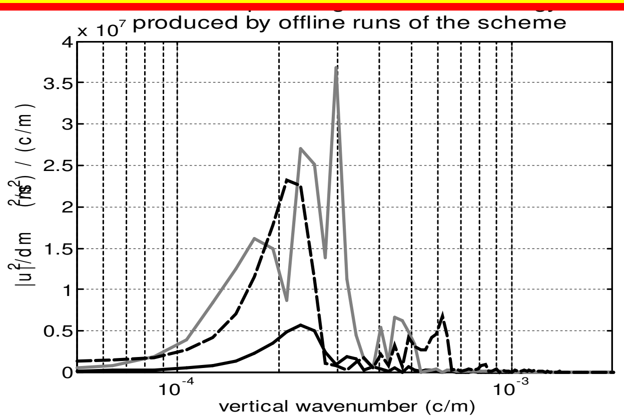

ERAI

The performance of the scheme Compares with what was obtained with the Hines Scheme in Lott et al. (C. Dyn.2005,)

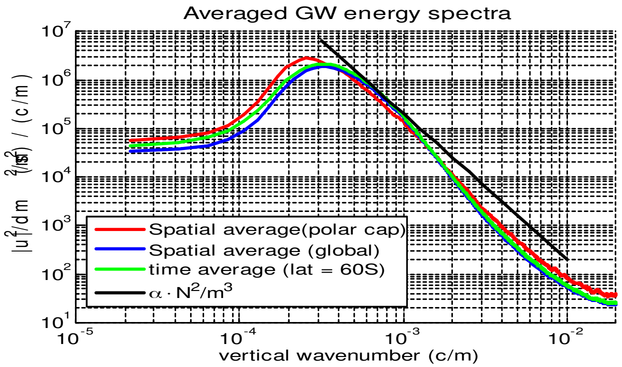
Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

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.



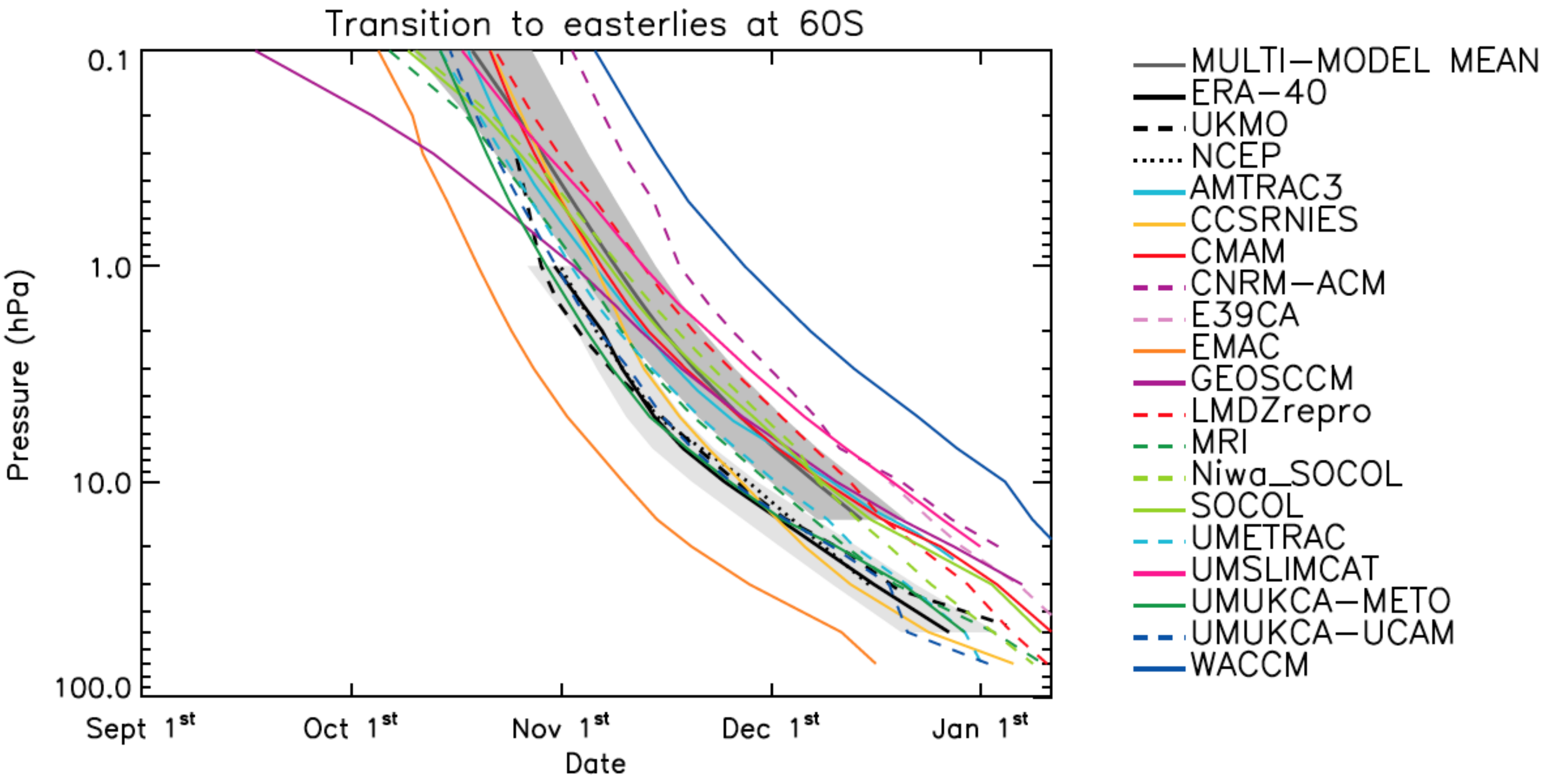
Average of periodograms



de la Cámara et al. 2015

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Butchart et al. 2011, *JGR*, *date when u(60S) fall below 10m/s*



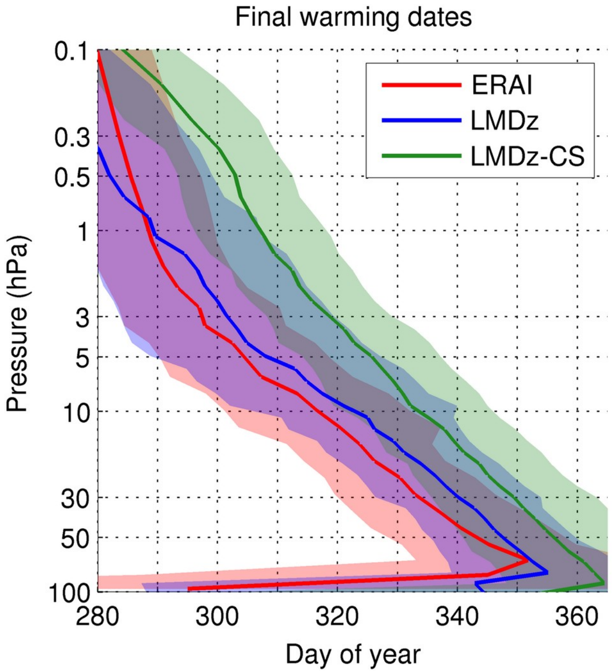
Insufficient parameterized GW drag at 60°S as cause of late final warming bias

(McLandress et al., 2012 *JAS*)

Due to lateral propagation of orographic waves? (Sato et al. 2009)

Parameterization of GWs in large scale models
4) Application to gravity waves generated by fronts

Test with constant sources (CS) against source related Gws.
Source related GWs predict an earlier breakdown
(Effect due to intermittency again?)



In the SH, the final warming dates times the winter vortex breakdown:
date when u(60S) fall below 10m/s

de la Camara et al. JAS 2016

Parameterization of GWs in large scale models
5) Validation against balloon observations

Mid latitudes and Concordiasi

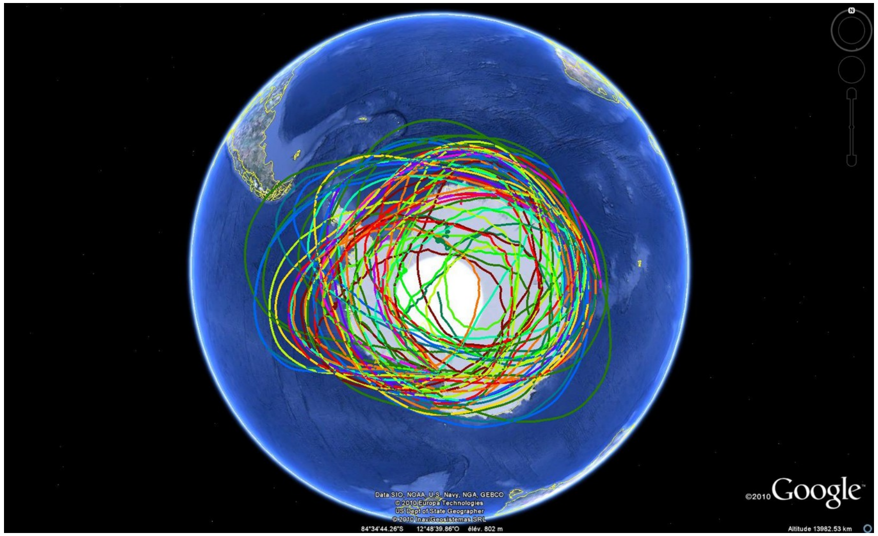
GWs from the scheme:

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

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



CONCORDIASI (2010)

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.

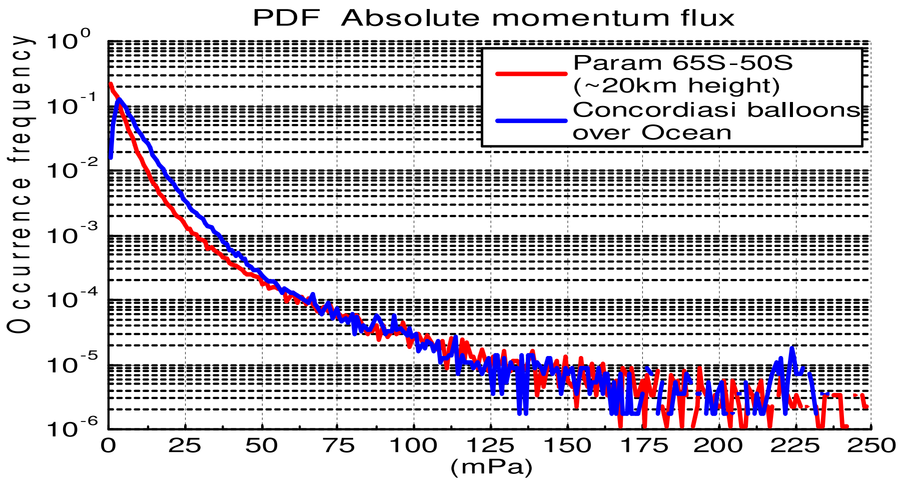
Dataset of GW momentum fluxes *(as by Hertzog et al. 2008)*

Parameterization of GWs in large scale models
5) Validation against balloon observations

Mid latitudes and Concordiasi

Intermittency of GW momentum flux

The stochastic scheme parameters can be tuned to produce fluxes as intermittent as in balloon observations.
An effect in good part due to the inclusion of the sources (convective and frontal)



Intermittency is important because it produces GW breaking at lower altitudes *(Lott&Guez 2013, de la Cámara et al. 2015*

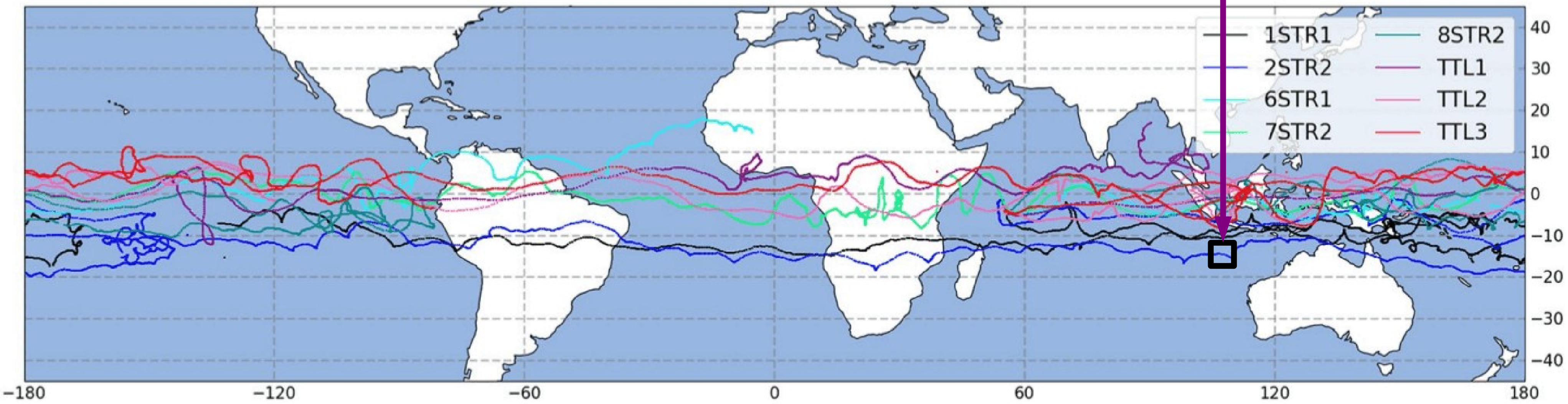
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Strateole 2, period 1 (Nov.2019-Feb. 2020, Corcos et al. 2021)

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2



5°x5° ERA5 1° data
Centered on balloon

Strateole 2 phase 1, Nov 2019-Feb . 2020
8 Balloon 2- to 3 months flights at about z=20km

Ma

Adapted from Corcos et al. JGR2021

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

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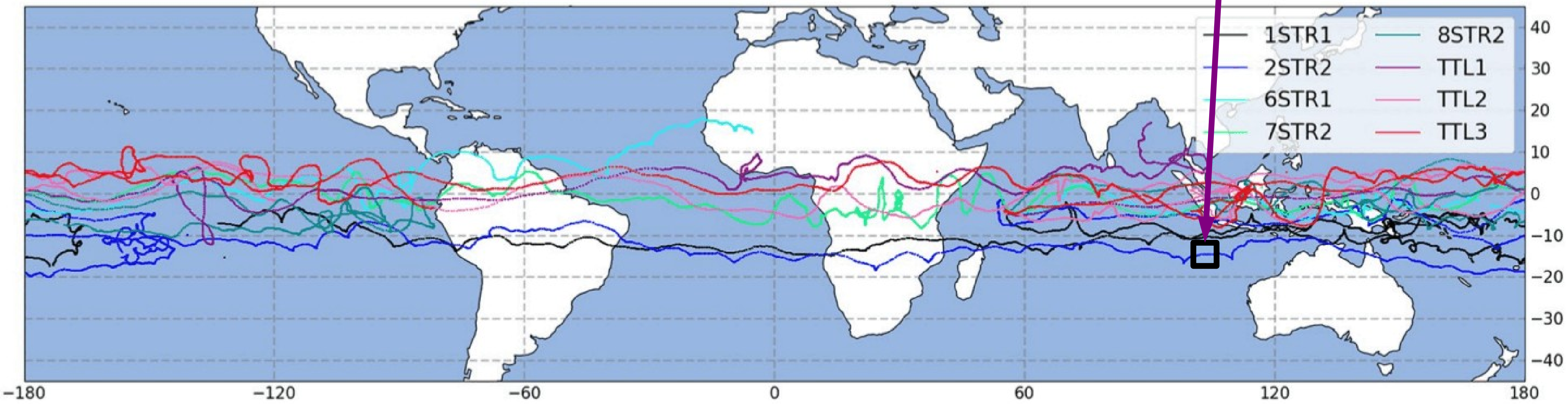

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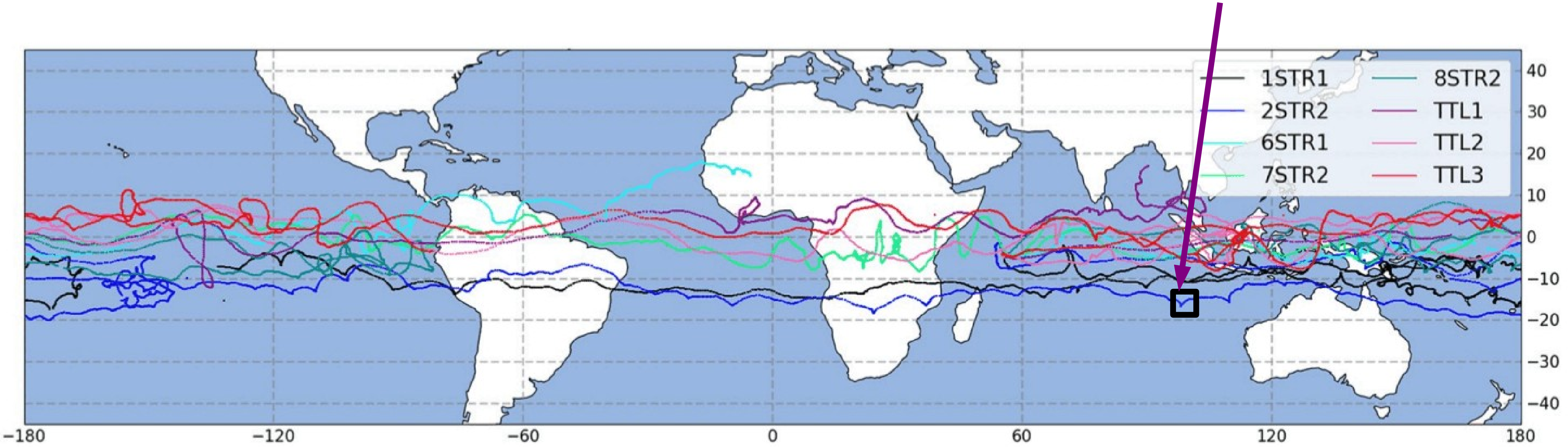
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2



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Parameterization of GWs in large scale models
5) Validation against balloon observations

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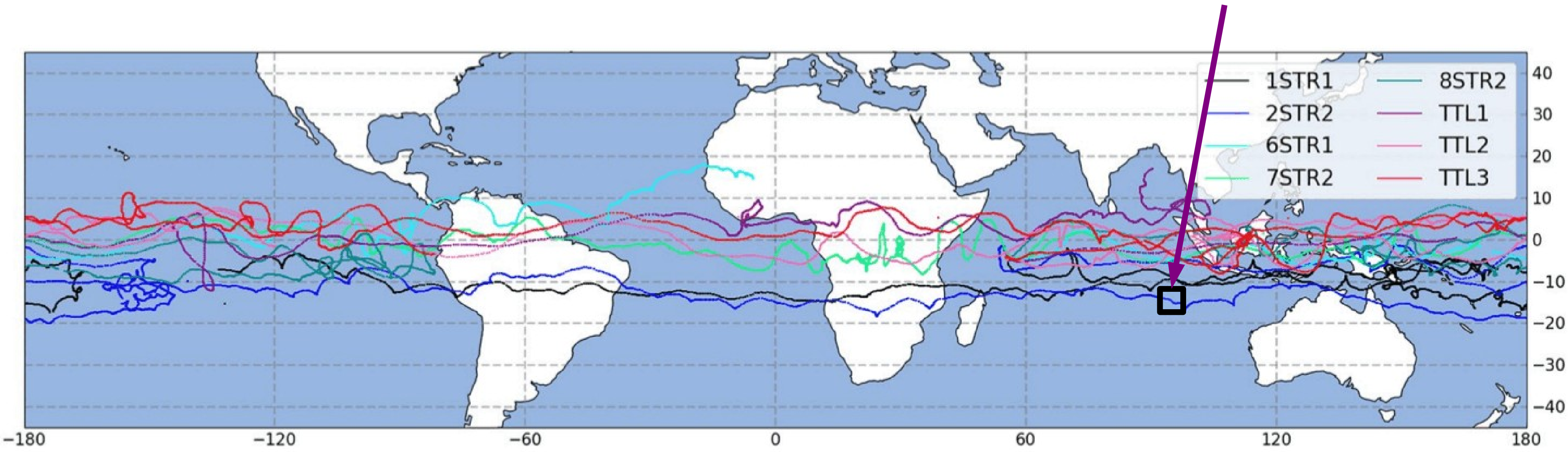


Strateole 2 phase 1, Nov 2019-Feb . 2020
8 Balloon 2- to 3 months flights at about z=20km

Adapted from Corcos et al. JGR2021

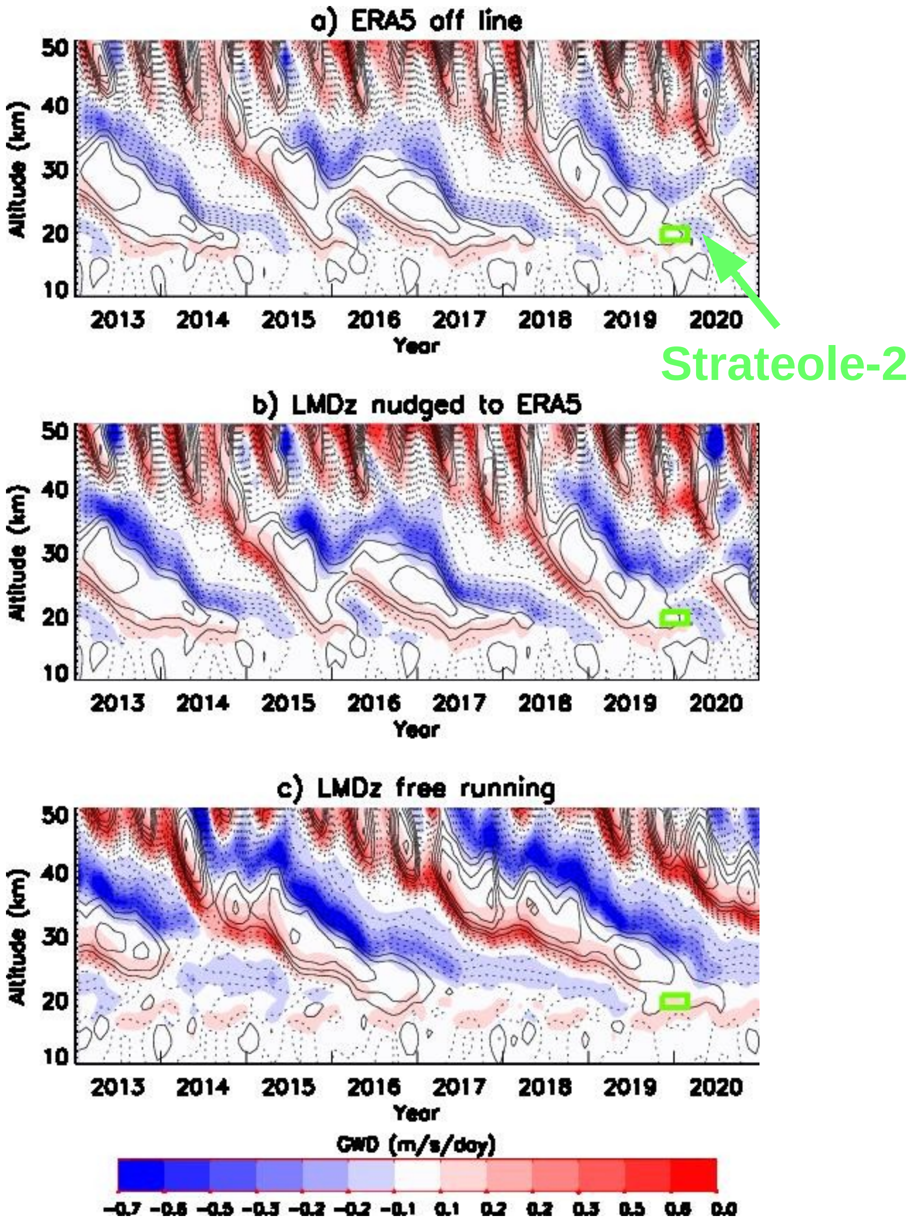
Ma

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Online-offline
and nudge results
with LMDz, large scale
Fields from ERA5

GWD tendencies from Lott et al. (2013),
adapted to IPSLCM6 Hourdin et al. (2020)



Strateole-2

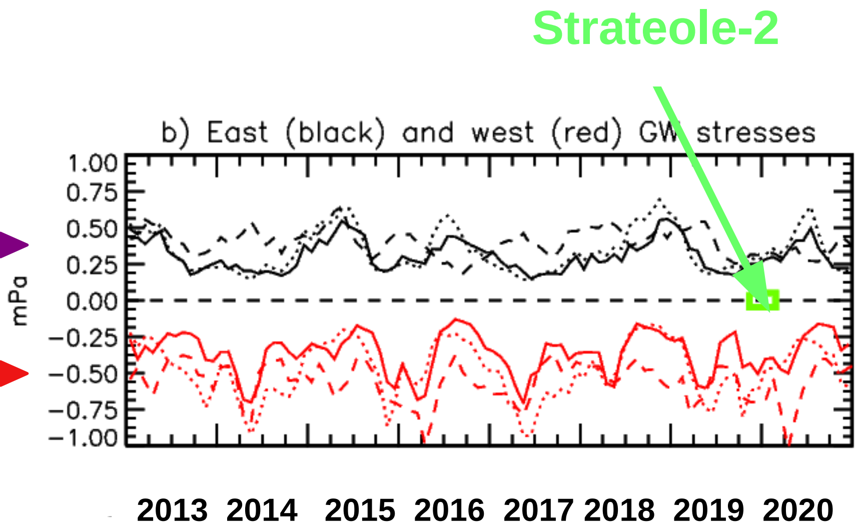
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Online-offline
and nudge results
with LMDz, large scale
Fields from ERA5

East and west stress at z=20km

Strateole-2



+0.4mPa

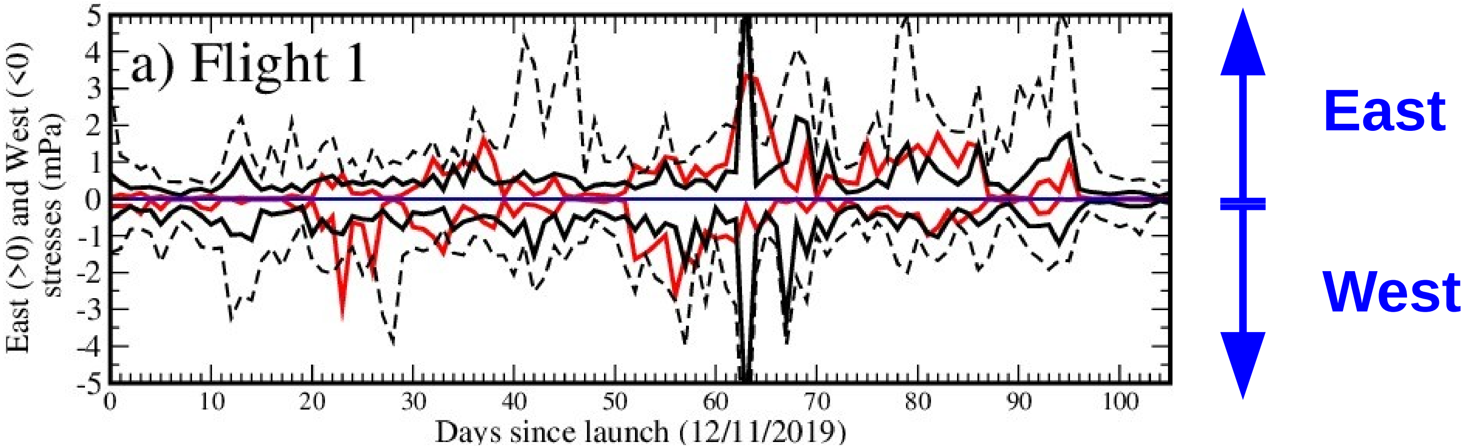
-0.5mPa

Zonally Averaged fluxes at about z=20 km have values around 0.4-0.5mPa

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

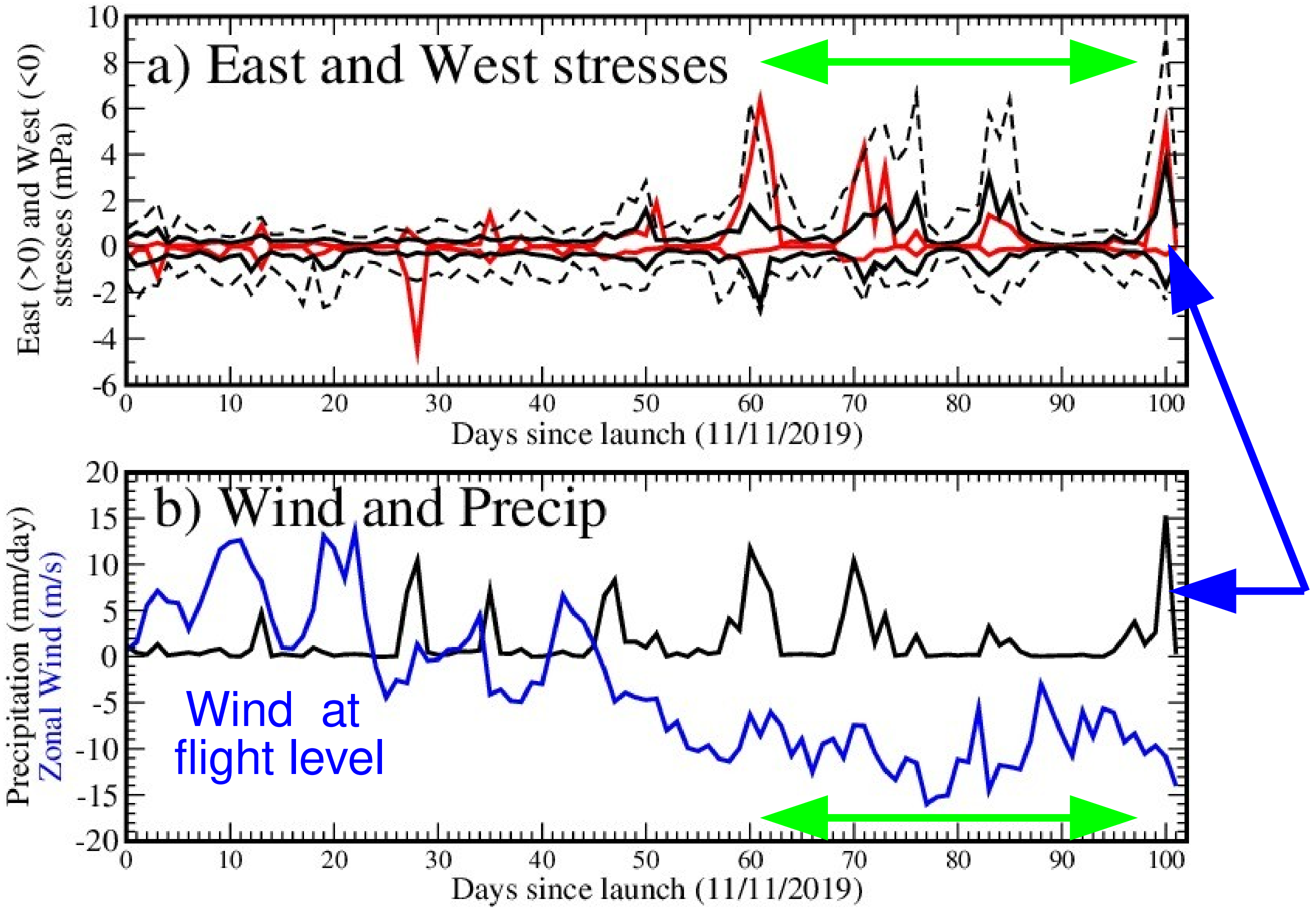
Good correspondance between observation and prediction (15mn-1hr waves)



Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Evidence of dynamical filtering and relation with precipitation, case of Flight 2



More Eastward flux when Wind is westward

More flux when precipitation peaks

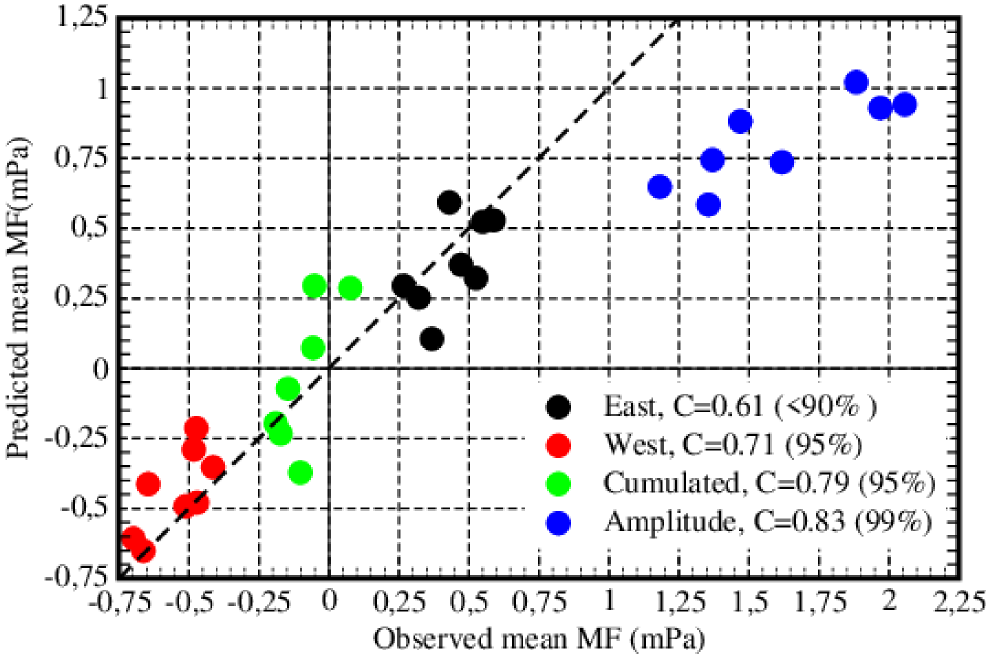
Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

East and West MF averaged over the entire (8) balloon flights
Offline predictions as function of observed momentum fluxes
(15mn-1hr)

+0.4mPa

-0.5mPa

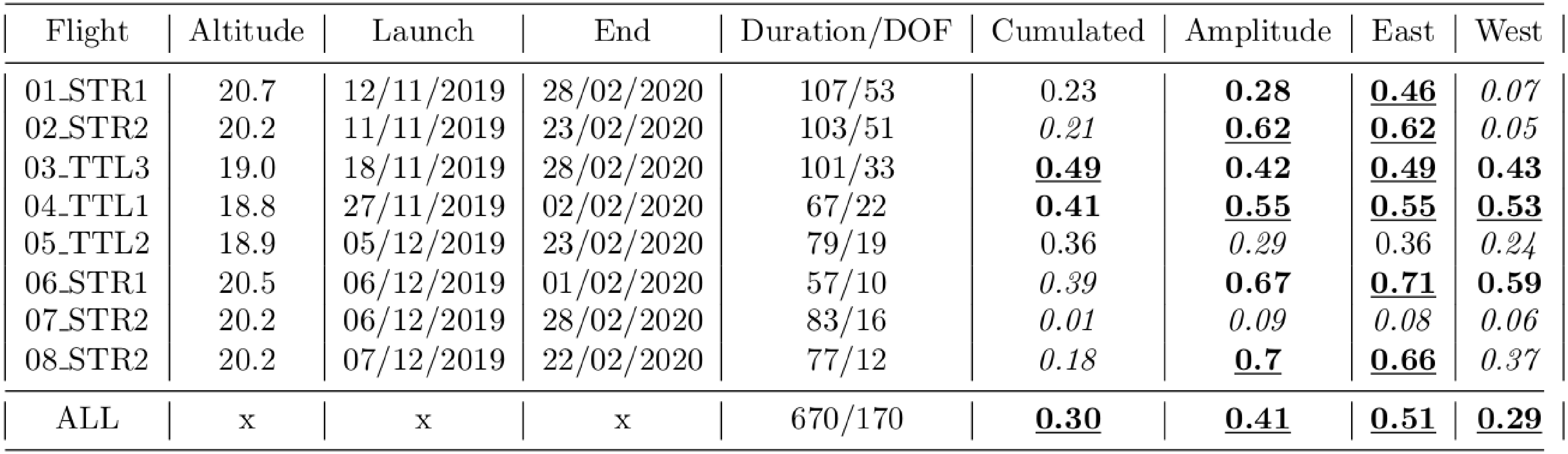


We scientists are not fools !

Parameterization of GWs in large scale models
5) Validation against balloon observations

Convective gravity waves and the tropics : Strateole 2

Correlation values daily data (“intraflight”),
flight by flight



Flight	Altitude	Launch	End	Duration/DOF	Cumulated	Amplitude	East	West
01_STR1	20.7	12/11/2019	28/02/2020	107/53	0.23	**0.28**	**0.46**	*0.07*
02_STR2	20.2	11/11/2019	23/02/2020	103/51	*0.21*	**0.62**	**0.62**	*0.05*
03_TTL3	19.0	18/11/2019	28/02/2020	101/33	**0.49**	**0.42**	**0.49**	**0.43**
04_TTL1	18.8	27/11/2019	02/02/2020	67/22	**0.41**	**0.55**	**0.55**	**0.53**
05_TTL2	18.9	05/12/2019	23/02/2020	79/19	0.36	*0.29*	0.36	*0.24*
06_STR1	20.5	06/12/2019	01/02/2020	57/10	*0.39*	**0.67**	**0.71**	**0.59**
07_STR2	20.2	06/12/2019	28/02/2020	83/16	*0.01*	*0.09*	*0.08*	*0.06*
08_STR2	20.2	07/12/2019	22/02/2020	77/12	*0.18*	**0.7**	**0.66**	*0.37*
ALL	x	x	x	670/170	**0.30**	**0.41**	**0.51**	**0.29**

1-sided Pearson test according to the DOF and for each flight :

<90, 90-95, **95-99**, **>99**

Parameterization of GWs in large scale models
5) Validation against balloon observations

Quasi-Biennal Oscillation Initiative (QBOi) Models

Three standard non-orographic gravity waves (GWs) parameterizations tuned to produce a realistic tropical Quasi-Biennial Oscillation in 12 global climate models are used to predict in-situ balloon observations.

	Parameterization schemes	**Climate Models**
Global Spectral scheme	Warner and McIntyre (WMI)	CMAM, IFS, ECEarth, UMGA7gws
	Hines Doppler Spread (HDS)	ECham5, MIROC, MPIM, MRI-ESM, EMAC
	Multiwaves (Lindzen’s type)	LMDz, HadGEM2, WACCM

used relate GWs to their convective sources

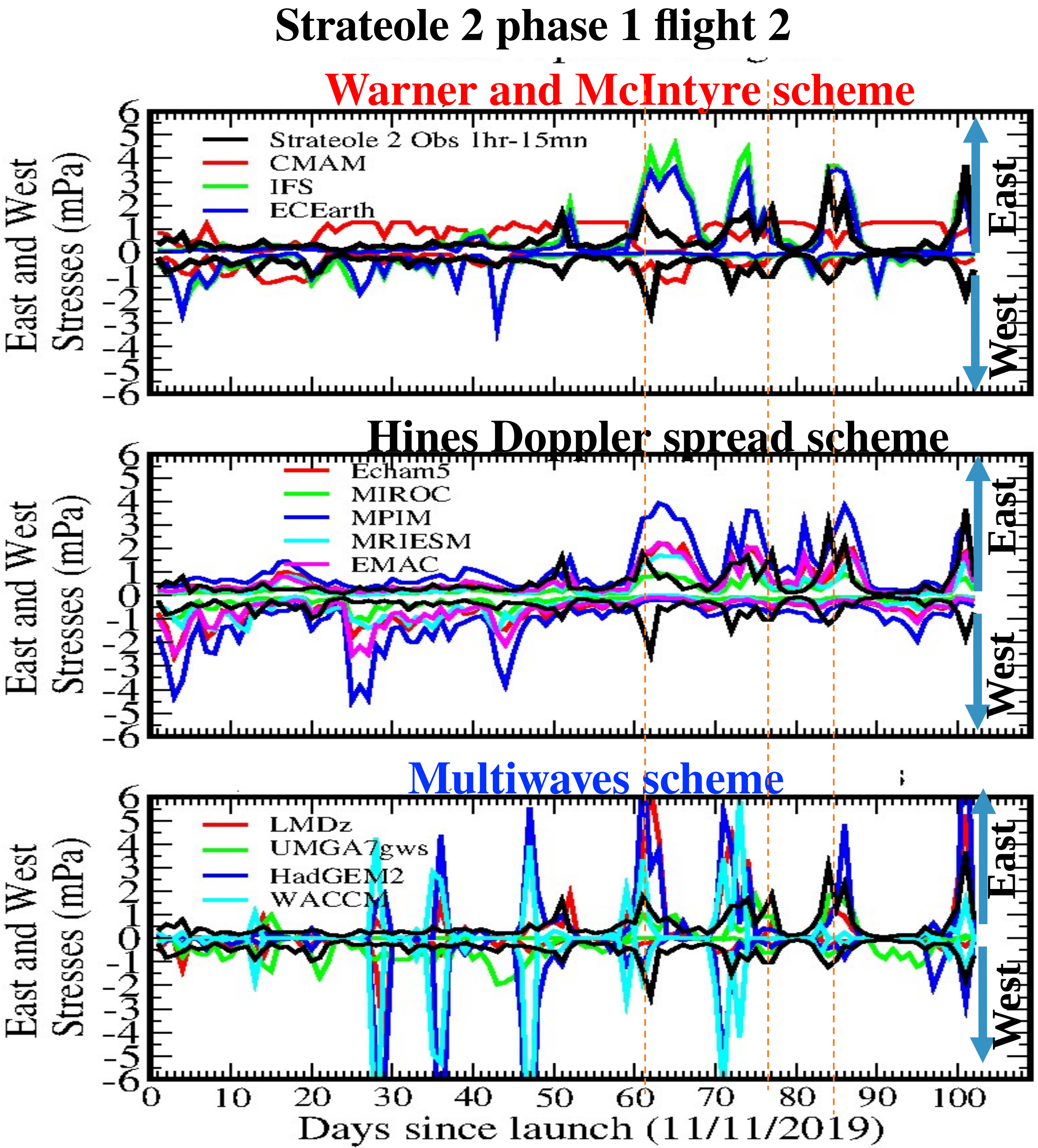
Parameterization of GWs in large scale models
5) Validation against balloon observations

Quasi-Biennal Oscillation Initiative (QBOi) Models

Predictions with the parameterizations using ERA5 data at the balloon location.

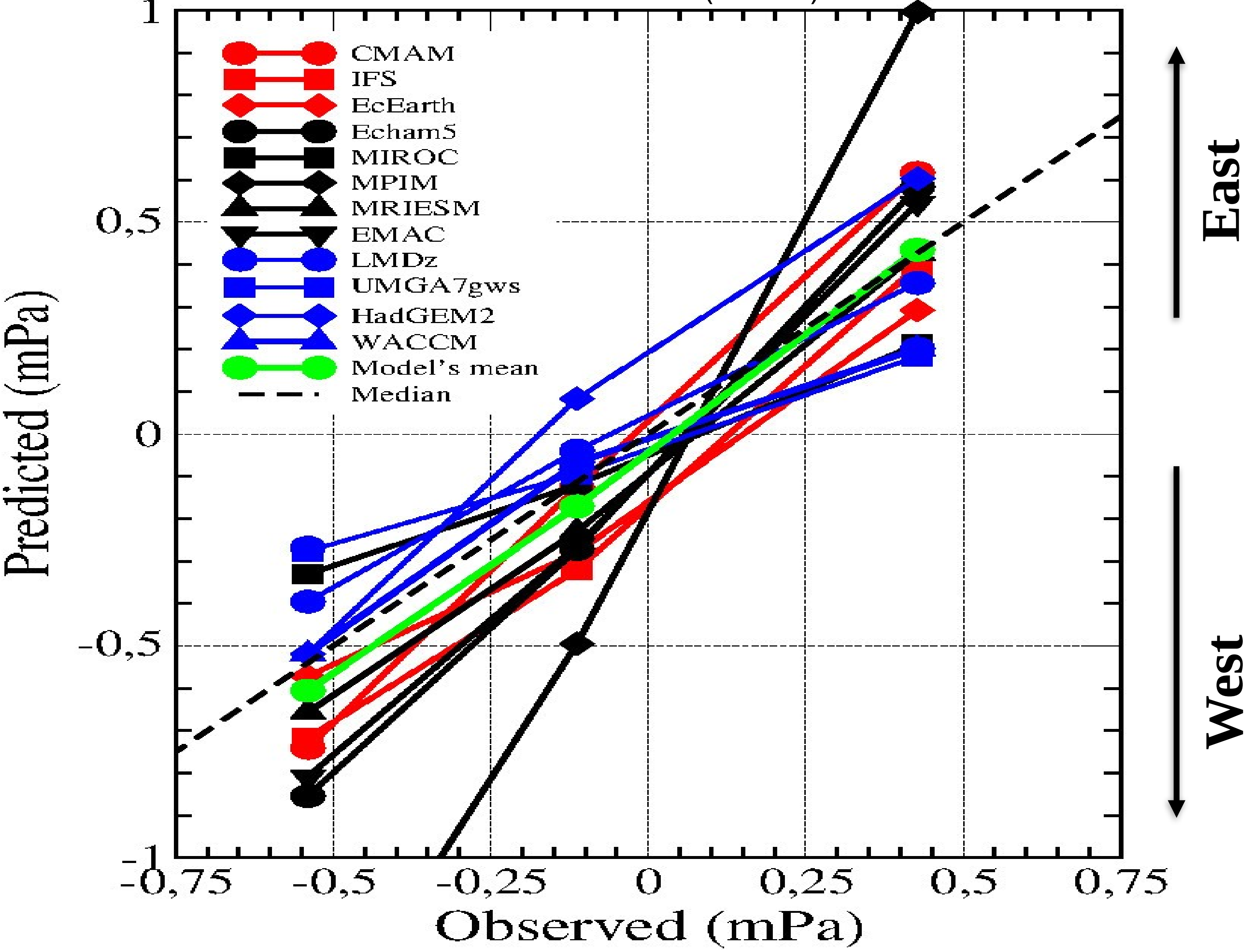
Large variety of bahaviours, but some correspondance with **observation** in terms of amplitude.

More Flux when more precipitation near to balloon location (day 60, 75 and 83)



Parameterization of GWs in large scale models
5) Validation against balloon observations

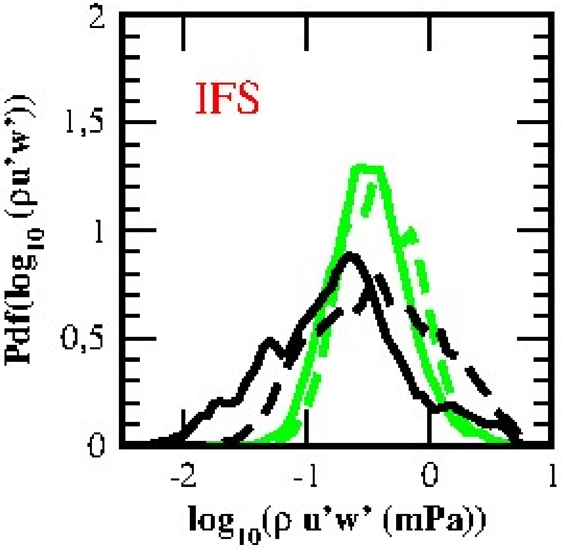
Quasi-Biennal Oscillation Initiative (QBOi) Models



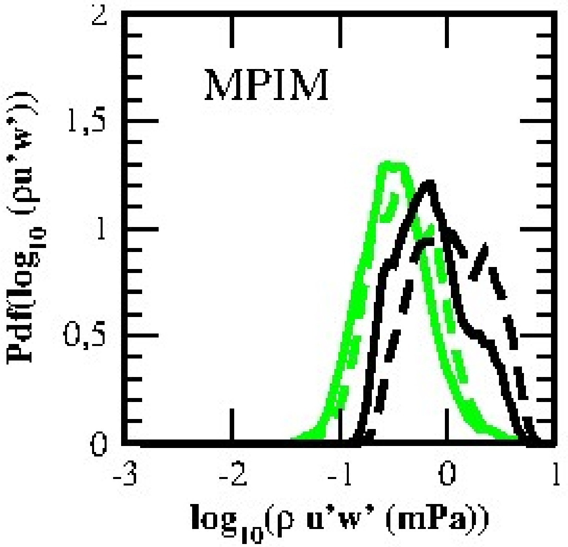
Parameterization of GWs in large scale models
5) Validation against balloon observations

Quasi-Biennal Oscillation Initiative (QBOi) Models

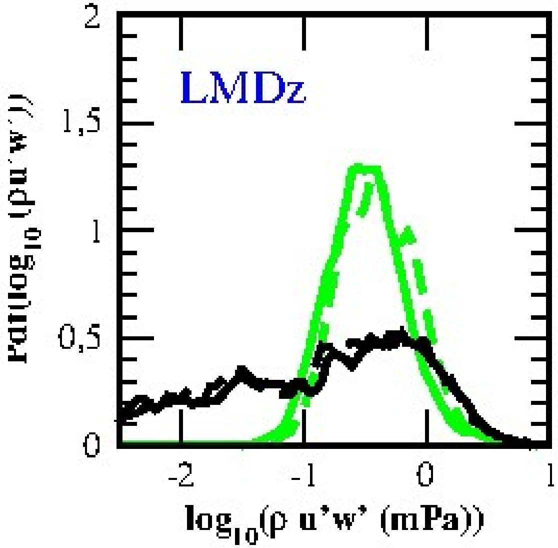
Warner and McIntyre scheme



Hines Doppler spread scheme



Multiwaves scheme



Observation are in green and predictions are in black.
Solid lines are for eastward and dashed lines are for westward.

Parameterization of GWs in large scale models
6) Perspectives

Take home message:

« We scientific are not fool »

Good example of theories verified by obs a posteriori

Perspective in terms of validation:

BAYESIAN estimate of parameters, including EnKF techniques?
Extent to Loon balloons
Extent to other GWs parameterization (frontal waves and mountain GWs)
Do improved schemes reduce model errors ?
Model tuning using uncertainty quantification (UQ)

Use of high resolution simul.s (DYAMON)
Use of Satellite observations that detect a fraction of the GW spectra (more global but coarser in resolution)

In terms of dynamics :

Interaction between the boudary layer and mountain gravity waves