Atmospheric Circulation

(WAPE: General Circulation of the Atmosphere and Variability)

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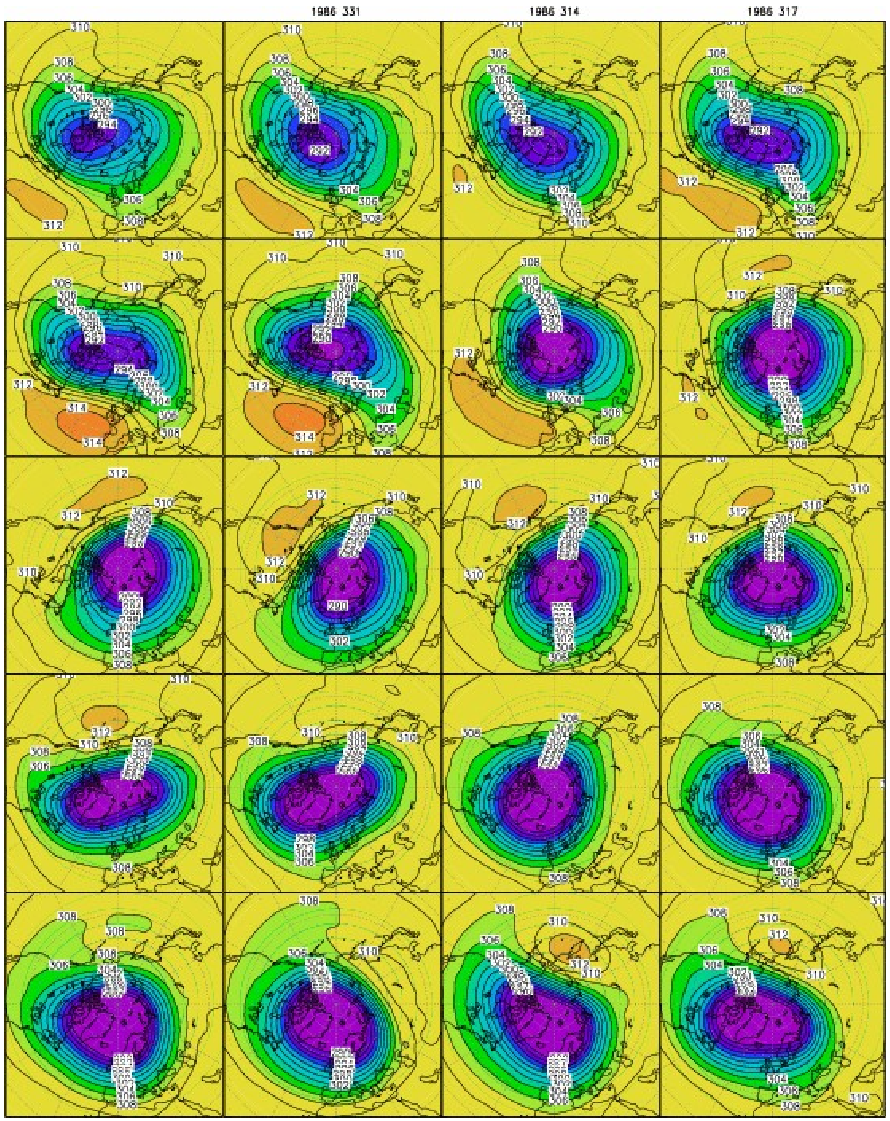
6) Midlatitude stratospheric variability and sudden stratospheric warmings

a) Observations: Rossby waves and stratospheric warming

b) Stratospheric warming resulting from Rossby wave breaking
Toy model 3

a) Observations: Rossby waves and stratospheric warming



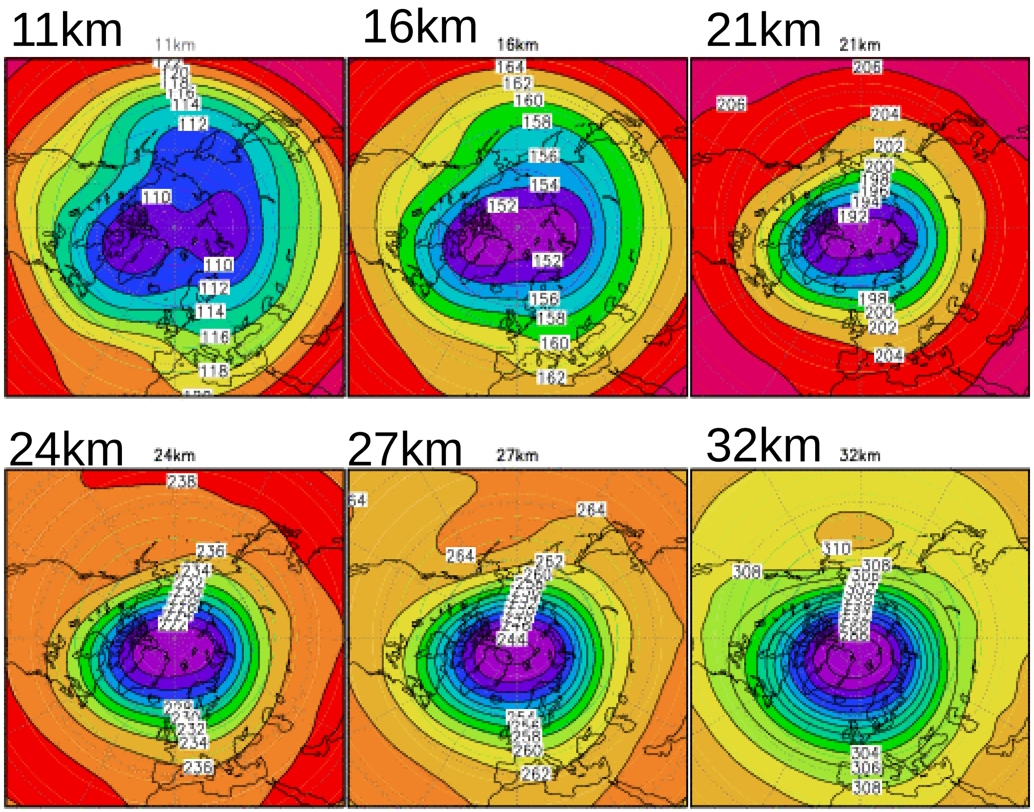
$Z = \Phi/g$ at 10hPa (z~32km)

Decembre 1986,
one map every 3 days,
NCEP data

- Evolution of the stratospheric Arctic Polar vortex
- Its deformation occurs over very large horizontal scales
- It evolves very slowly

The large-scale Rossby waves dominate the daily variability of the middle atmosphere in winter

a) Observations: Rossby waves and stratospheric warming



Vortex + stationnary planetary wave as seen on $\langle Z\rangle=\langle\Phi\rangle/g$, at different altitudes

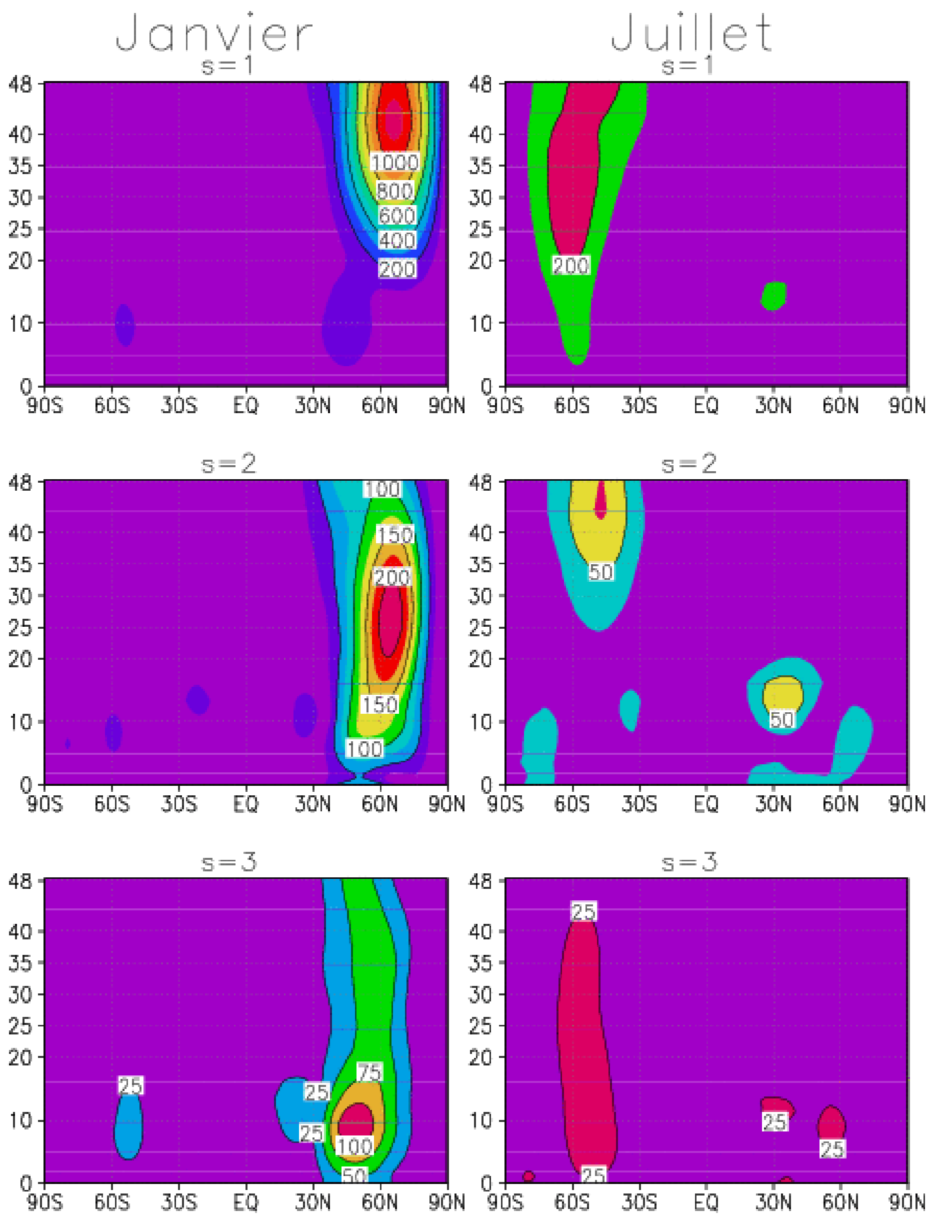
(NCEP data, 1980-2000)

- Note the slow phase change with altitude ($\sim -\pi/4$ between 16km and 32km)
- Note the very large scale of the deformation and the fact that it increases with altitudes

Phase variation with altitude indicates the upward propagation of Rossby waves

a) Observations: Rossby waves and stratospheric warming

Vertical propagation of the Rossby waves



Zonal harmonic analysis of the stationnary geopotential height NCEP data (1980-2000)

$$\langle Z\rangle(\lambda,\phi,z)=\sum_{s=0}^{\infty}\langle\hat{Z}_s\rangle(\phi,z)\,e^{is\lambda}$$

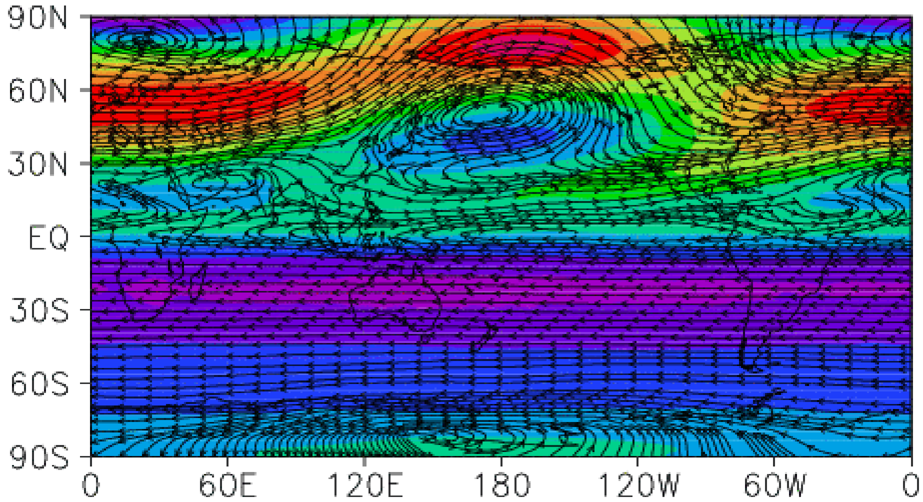
- Only the steady waves 1 and 2 penetrate in the stratosphere
- Only the planetary waves only penetrate in winter
- The wave s=1 dominates

a) Observations: Rossby waves and stratospheric warming

The planetary waves only penetrate in winter

No vertical propagation when the winds are westward ($\overline{u}_0 < 0$)

ECMWF wind in NH winter (93-97) (cf. cours 1)



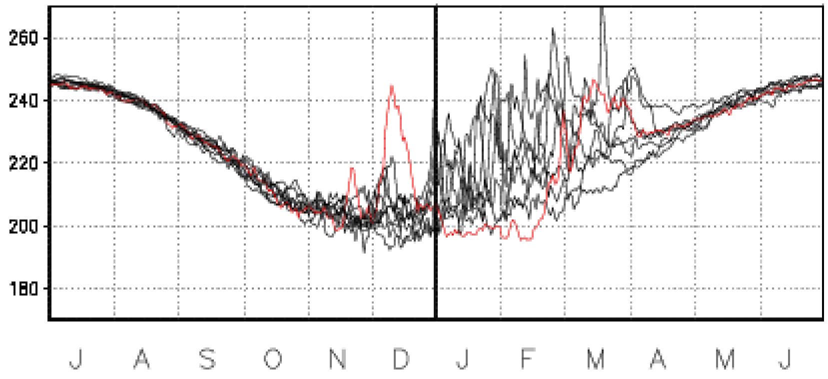
Notice the presence of a large scale s=1 wave only.

This wave is only present in the hemisphere where the winds are eastward

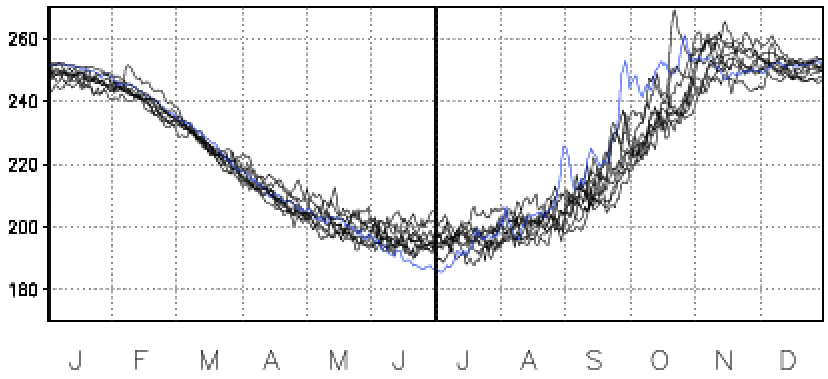
a) Observations: Rossby waves and stratospheric warming

Stratospheric warmings, 10 winters (1981-1990) shown

North Pole T at 32km



South Pole T at 32km



The zonal mean T
near the poles at z~32km

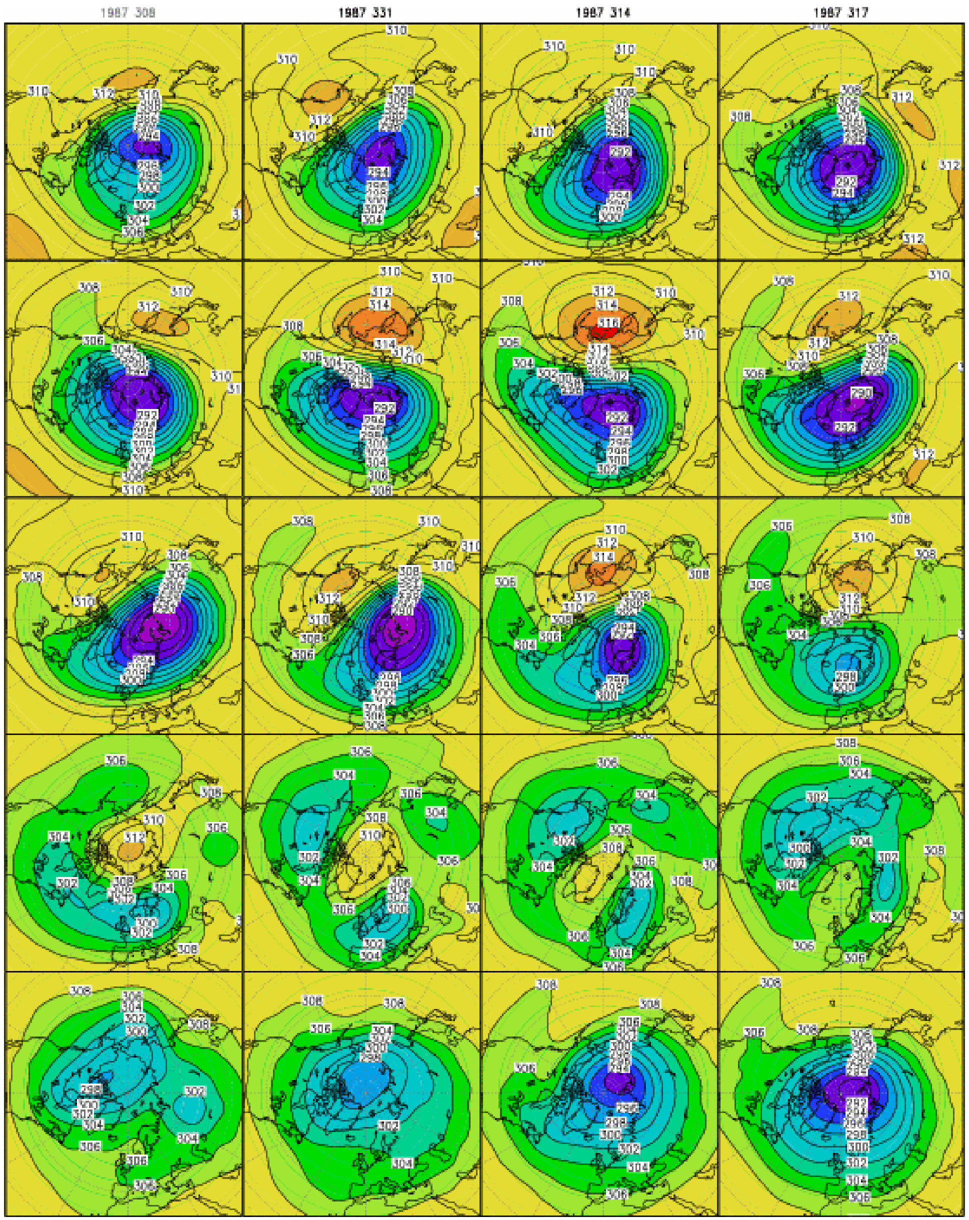
Some values in winter
exceed summer values

Essentially true in the
Northern hemisphere

In the southern hemisphere
only at the end of winter
(time of the southern polar vortex

a) Observations: Rossby waves and stratospheric warming

Evolution of the planetary waves during a sudden stratospheric warming



Z at 32km,
every 3 days in Déc. 1987

During certain months in winter the planetary waves in the stratosphere become very large

During these episodes the polar cap warms, and the polar jet can even reverse

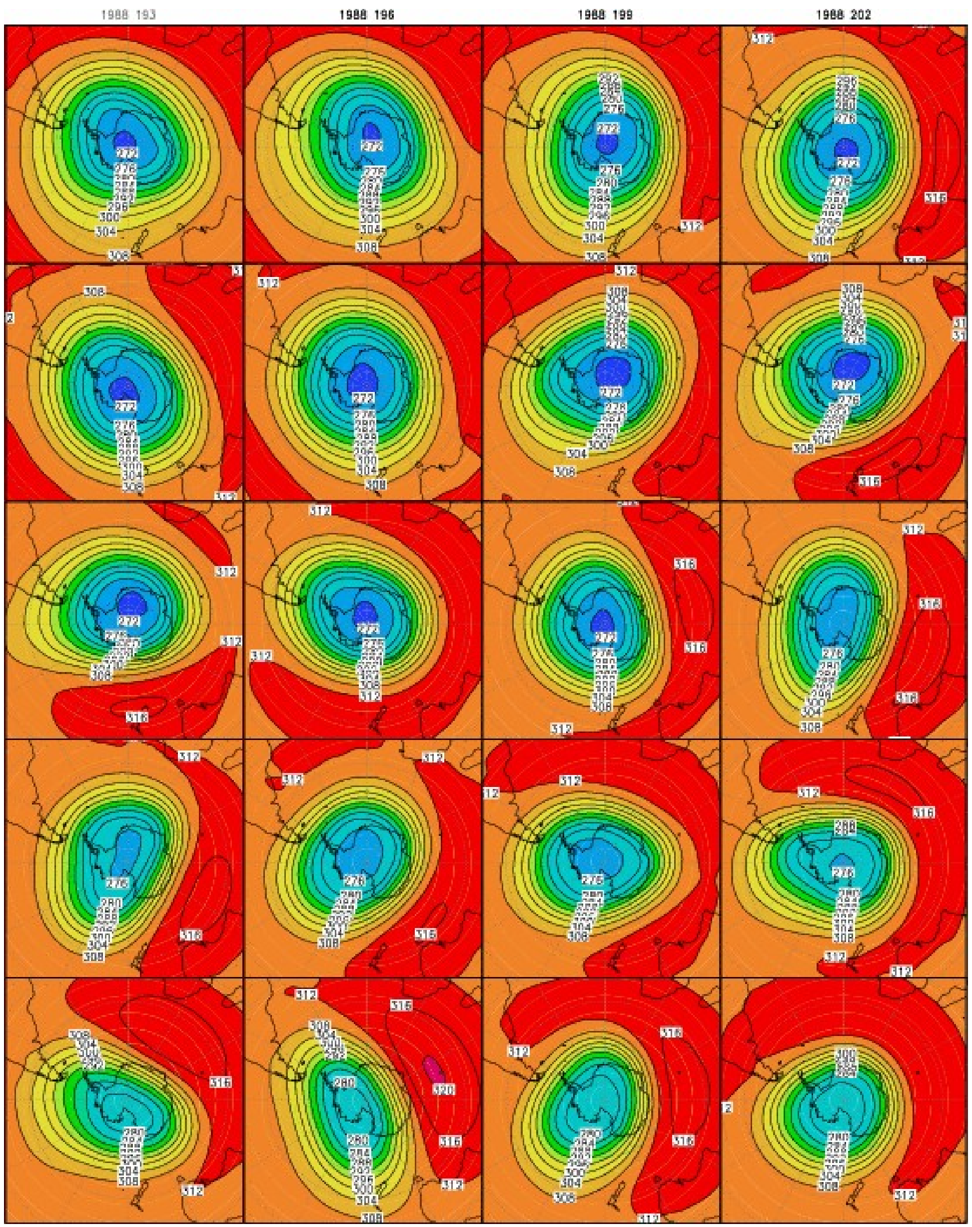
At the beginning, there are essentially waves with small wavenumber (s=1,2), in the end much larger wave numbers modulate rthe flow

Note in the end that the vortex reconstruct through radiative effects

Sometimes, when the warming occurs in late spring, the vortex does not reconstruct, this is a final warming!

a) Observations: Rossby waves and stratospheric warming

Southern Hemisphere winter



Aug.-Sept. 1988, Z at 32km, and every 3 days:

There is some variability in the vortex shape and location

But it almost never disappear

The air masses in the polar stratosphere stays isolated since the vortex never break. This help a systematic destruction of Ozone during the polar night (absence of light to produce ozone, and no exchange with the mid-latitudes).

<u>And:</u> the weakness of the planetary wave drag make that the Brewer Dobson circulation does not really penetrate in this vortex.

b) Stratosperic warming resulting from Rossby waves breaking

Toy model 3

Boussinesq equations, β plane approximation and separation $\tilde{\Phi} = \Phi_0(z) + \Phi(t, x, y, z)$

Quasi-geostrophic approximation:

$$u \approx u_g = -\frac{1}{f_0}\frac{\partial \Phi_e}{\partial y}, \quad v \approx v_g = \frac{1}{f_0}\frac{\partial \Phi_e}{\partial x}$$

The geostrophic wind is non-divergent

$$D_g u_g - \beta y v_g - f_0 v + \partial_x \Phi_e = 0$$
$$D_g v_g + \beta y u_g + f_0 u + \partial_y \Phi_e = 0$$
$$\partial_z \Phi_e = b_e$$
$$D_g b_e + N^2 w = 0$$
$$\partial_x u + \partial_y v + \partial_z w = 0$$

where $D_g = \partial_t + u_g \partial_x + v_g \partial_y$

$$N^2 = \frac{g}{\theta_s}\frac{d\theta_0}{dz}$$

The dynamics is described by the quasi-Geostrophic potential vorticity equation:

$$D_g \left(\underbrace{\frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} + f_0 + \beta y + f_0 \frac{\partial}{\partial z}\frac{b_e}{N^2}}_{q_g} \right) = 0$$

The flow is then entirely given by the q_g field and after inversion of the elliptic equation:

$$f_0 q_g = \frac{\partial^2 \Phi_e}{\partial x^2} + \frac{\partial^2 \Phi_e}{\partial y^2} + f_0(f_0 + \beta y) + \frac{\partial}{\partial z}\frac{f_0^2}{N^2}\frac{\partial \Phi_e}{\partial z}$$

b) Stratosperic warming resulting from Rossby waves breaking
Toy model 3

Wave mean-flow separation

Wave mean-flow separation:

$$u_g = \underbrace{\overline{u}_0(y,z)}_{O(1)} + \underbrace{u_g'}_{O(\alpha)} + \underbrace{\overline{u_g} - \overline{u_0}(y,z)}_{O(\alpha^2)}$$

$$\Phi_e(x,z,t) = \underbrace{\overline{\Phi}_0(y,z)}_{O(1)} + \underbrace{\Phi'}_{O(\alpha)} + \underbrace{\overline{\Phi_e}(y,z,t) - \overline{\Phi}_0(y,z)}_{O(\alpha^2)}$$

Equation for the wave (O(α)):

$$\left(\partial_t + \overline{u}_0 \partial_x\right) q' + \overline{q}_{0y} v_g' = 0$$

$$f_0 q' = \Phi'_{xx} + \Phi'_{yy} + \frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial \Phi'}{\partial z}\right)$$

Equation for the mean flow (O(α²)):

$$\partial_t \overline{u}_g - f_0 \overline{v} = -\frac{\partial \overline{v'_g u'_g}}{\partial y}$$

$$\partial_y \overline{v} + \partial_z \overline{w} = 0$$

$$\partial_t \overline{\Phi}_z + N^2 \overline{w} = -\frac{\partial \overline{v'_g \Phi'_z}}{\partial y} + \overline{Q}$$

Horizontal or zonal mean

$$\overline{u} = \frac{1}{L}\int_0^L u\,dx \quad \text{or} \quad \overline{u} = \frac{1}{2\lambda}\int_0^{2\pi} u\,d\lambda$$

L domain size (periodic)

λ longitude

The wave fluxes $\overline{u_g' v_g'}$ et $\overline{\Phi'_z v_g'}$ measure the action of the wave on the mean flow

b) Stratosperic warming resulting from Rossby waves breaking

Toy model 3

Waves vertical propagation in uniform flows: $\overline{u_0} = \text{const}\,, \quad N^2 = \text{const}\,, \quad \overline{q_y} = \beta$

We search solutions like

$$\Phi' = \Re\left\{\hat{\Phi}_r e^{i(kx+ly+mz-\omega t)}\right\}$$

Dispersion relation :

$$\hat{\omega} = \frac{-k\beta}{k^2+l^2+\frac{f^2}{N^2}m^2}$$

$$\hat{\omega} = \omega - k\overline{u_0} \qquad \text{Intrinsic frequency}$$

Vertical group velocity:

$$C_{gz} = \frac{\partial\hat{\omega}}{\partial m} = \frac{2km\beta f^2/N^2}{\left(k^2+l^2+\frac{f^2}{N^2}m^2\right)^2}$$

This imposes *km>0* to ensure vertical propagation

Note also that : $m^2 = \frac{N^2}{f^2}\left(\frac{\beta}{\overline{u}_0 - C} - k^2 - l^2\right)$

The phase lines are inclined toward the west

Only the long waves propagate upward vertically!

No vertical propagation when the winds are westward ($\overline{u}_0 < 0$)

A weak $\overline{u}_0 > 0$ favour the propagation of more waves (mature phase of a stratospheric warming)

b) Stratosperic warming resulting from Rossby waves breaking

Toy model 3

Transform Eulerian mean equations for the mean flow :

$$\partial_t \overline{u}_g - f_0 \overline{v}^* = \vec{\nabla} \cdot \vec{F}$$

$$\partial_t \overline{\Phi}_{ez} + N^2 \overline{w}^* = 0$$

$$\partial_y \overline{v}^* + \partial_z \overline{w}^* = 0$$

QG EP-flux :

$$\vec{F} = \left(-\overline{u_g' v_g'}, + \frac{f_0}{N^2} \overline{v_g' \Phi_z'} \right)$$

TEM meridional circulation

$$\overline{v}^* = \overline{v} - \frac{\partial}{\partial z} \frac{\overline{v_g' \Phi_z'}}{N^2}$$

$$\overline{w}^* = \overline{w} + \frac{\partial}{\partial y} \frac{\overline{v_g' \Phi_z'}}{N^2}$$

For our adiabatic stationnary monochromatic wave :

$$\Phi' = \Re \left\{ \hat{\Phi}_r e^{i(kx+ly+mz-\omega t)} \right\}$$

The EP flux is non-zero :

$$\vec{F} = \left(\frac{kl}{f_0^2} \frac{|\hat{\Phi}_r|^2}{2}, \frac{km}{N^2} \frac{|\hat{\Phi}_r|^2}{2} \right)$$

pointing up and **non divergent**

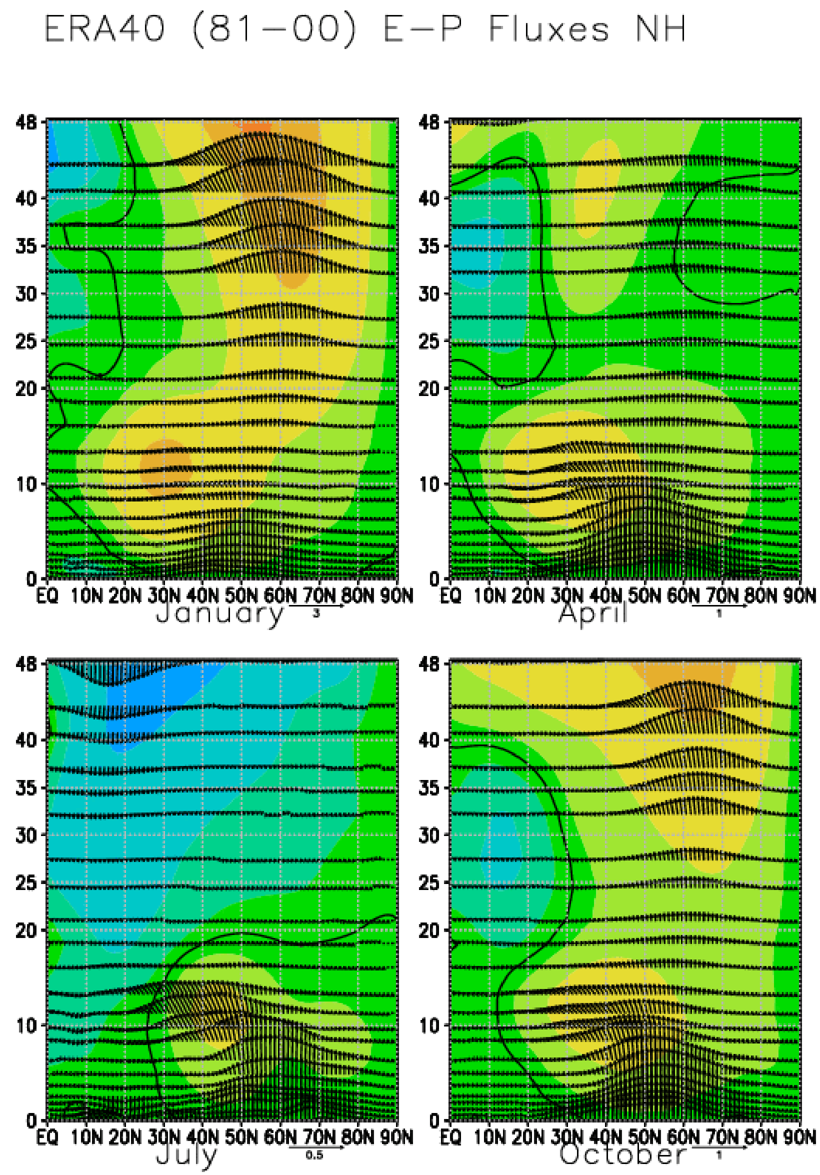
b) Stratosperic warming resulting from Rossby waves breaking

Toy model 3

Zonal mean zonal wind
and Eliasen Palm flux vector from
ERA40 reanalysis

$$\frac{\overline{F}^{\phi}}{\rho_0} = a\cos\phi\left(\overline{v'\theta'}\frac{\overline{u}_z}{\overline{\overline{\theta}}_z} - \overline{v'u'}\right)$$

$$\frac{\overline{F}^{z}}{\rho_0} = a\cos\phi\left(\frac{\overline{v'\theta'}}{\overline{\theta}_z}\left(f - \frac{(\overline{u}\cos\phi)_{\phi}}{a\cos\phi}\right) - \overline{w'u'}\right)$$



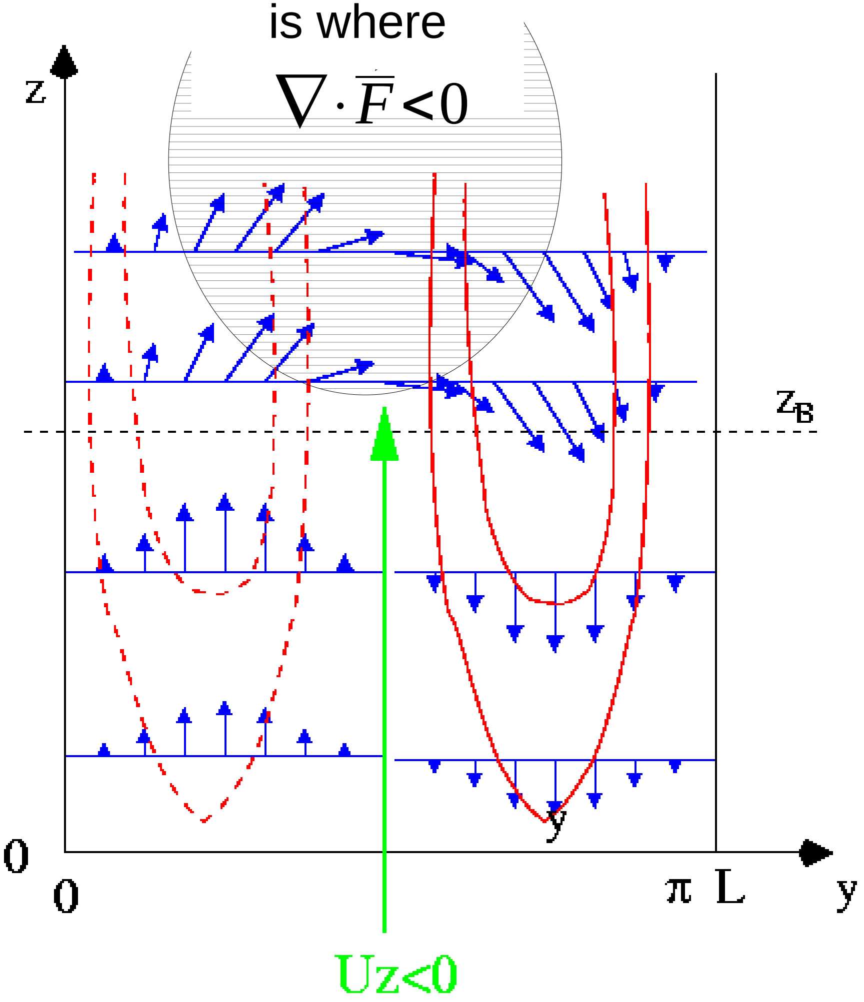
b) Stratosperic warming resulting from Rossby waves breaking

Toy model 3

Response of the mean flow
to anomalously large scale Rossby waves

Hatched zone
is where

$$\nabla \cdot \vec{F} < 0$$



Say that Rossby waves break above
a breaking altitude Z_B
the following balance can be proposed

$$-f_0 \overline{v}^* = \vec{\nabla} \cdot \vec{F}$$

Mass conservation close the meridional
circulation :

$$\overline{w}^* = \int_z^\infty \frac{\partial \overline{v}^*}{\partial y} dz$$

This warms the high latitudes :

$$\partial_t \frac{\partial \overline{\Phi}_e}{\partial z} = -N^2 \overline{w}^*$$

Reduce the wind via thermal wind
balance:

$$\frac{\partial \overline{u}_g}{\partial z} = -\frac{1}{f_0} \frac{\partial}{\partial y} \frac{\partial \overline{\Phi}}{\partial z}$$