Gravity waves:
introduction and global view

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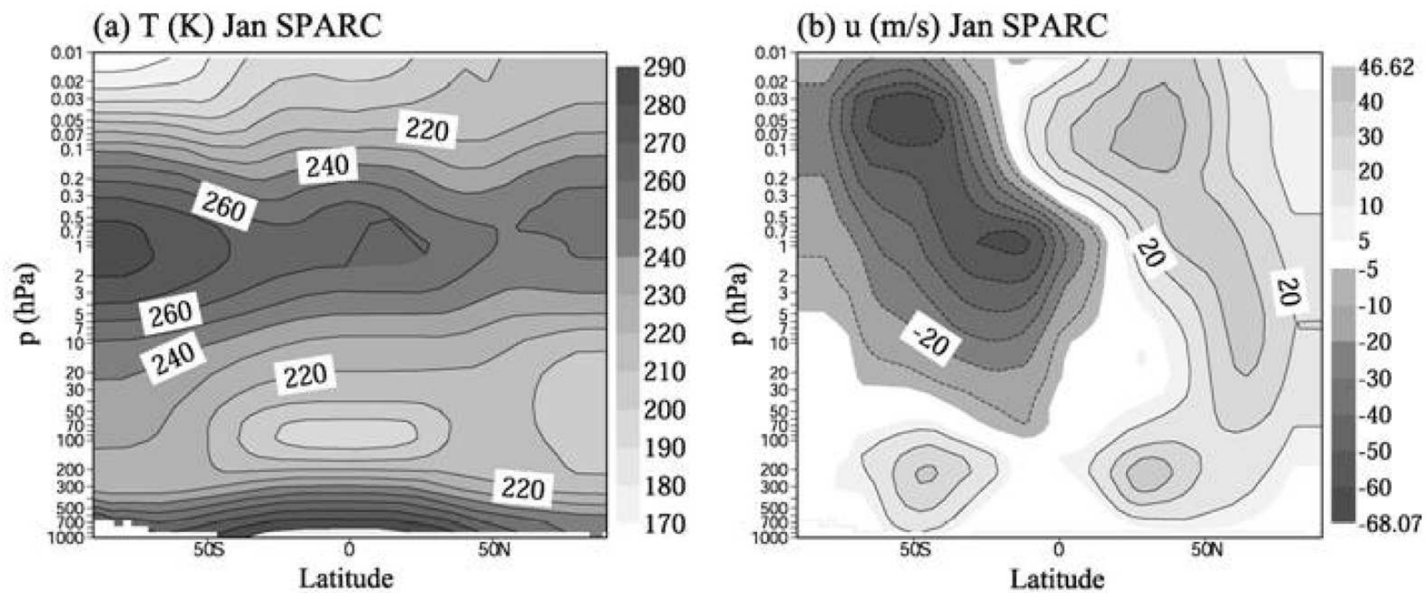
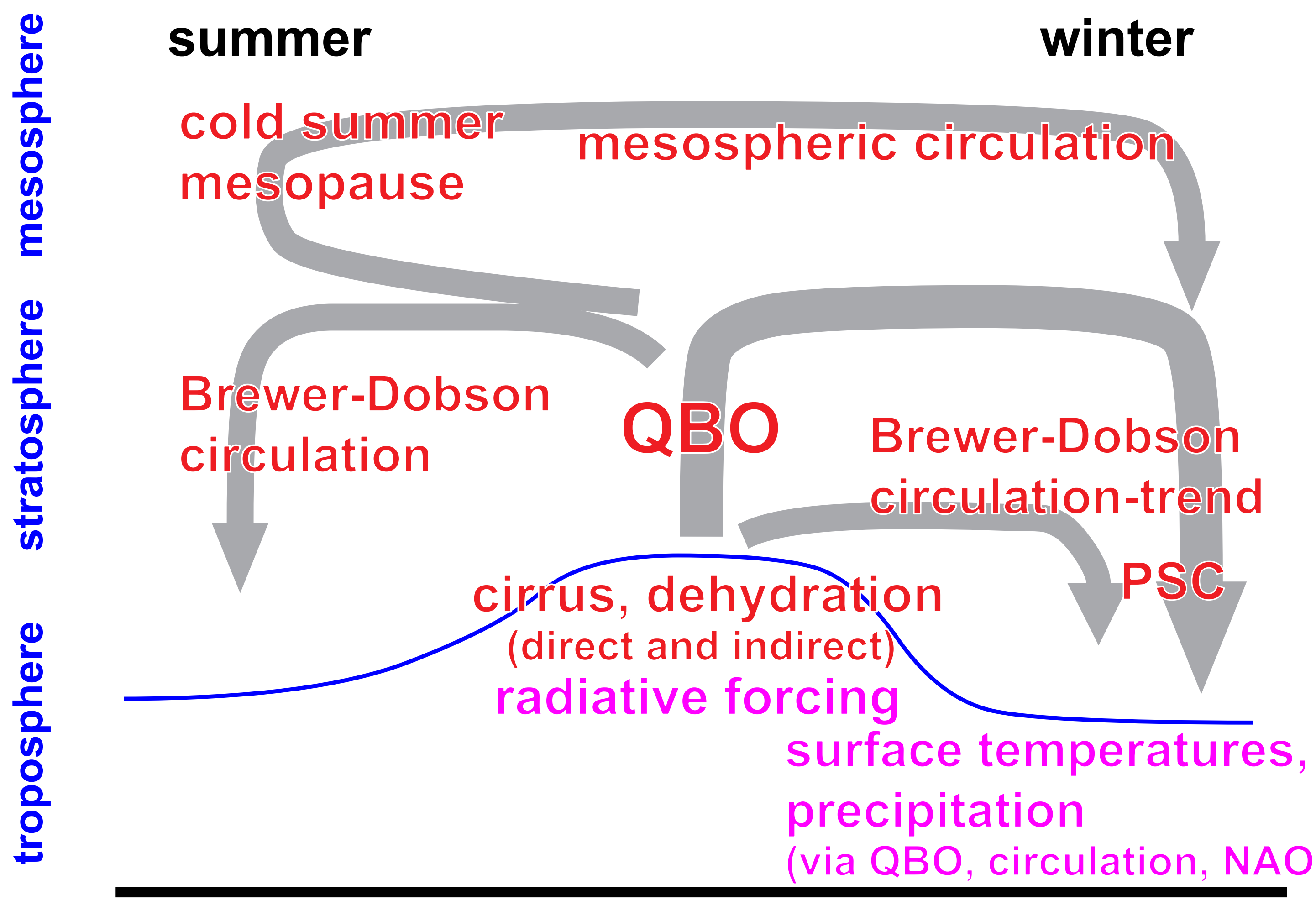
Structure of middle atmosphere



- $\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = X$
- steady state, zonal mean: $\Rightarrow -f\overline{v} = \overline{X}$
- X by planetary waves and gravity waves

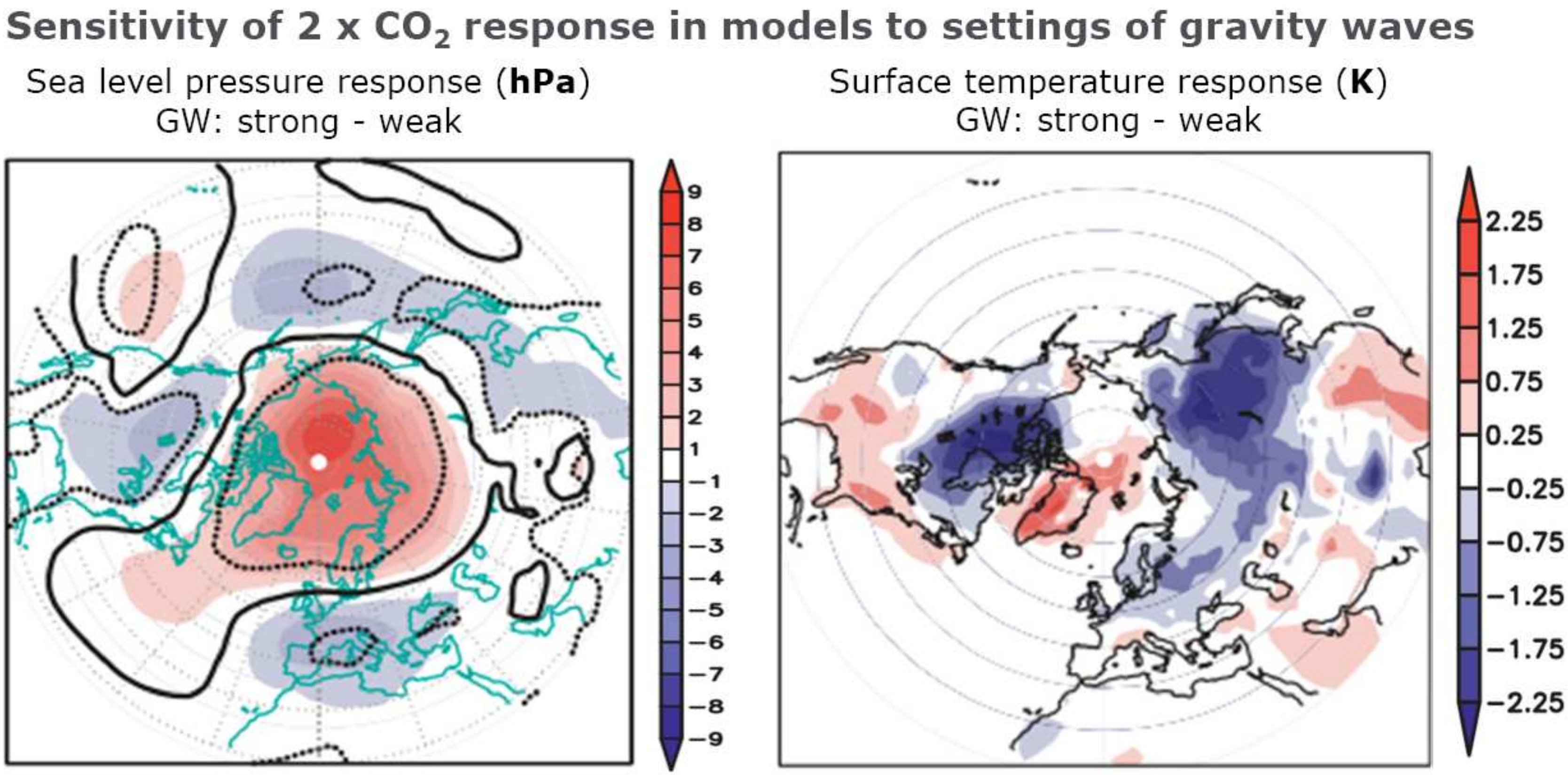
Decelleration of westerlies induces poleward circulation

GW impact on middle atmosphere



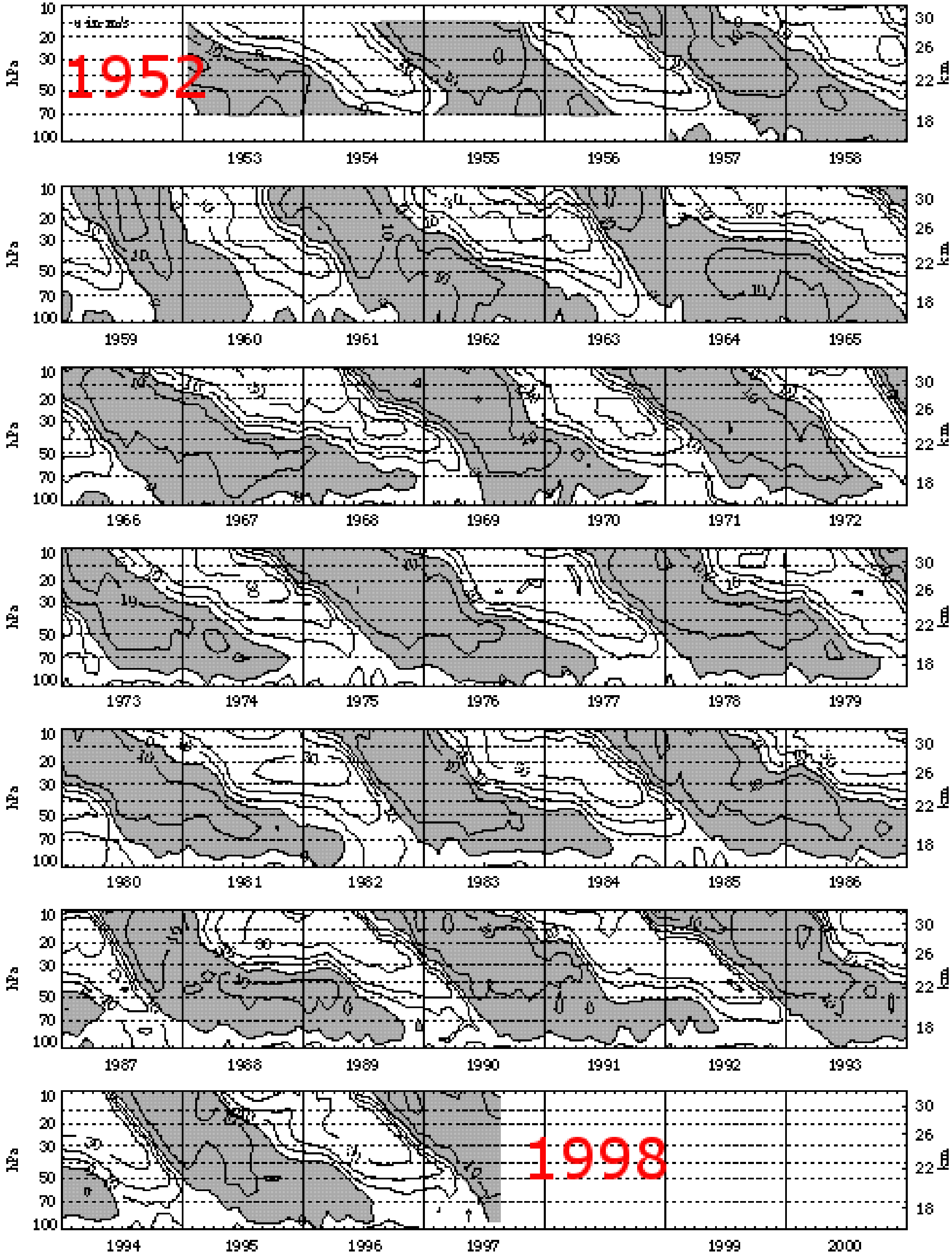
Red: Processes which are driven to >50 % by GWs
Purple: Indirect effects

General circulation → polar troposphere



Sigmond and Scaife, J. Clim., 2010

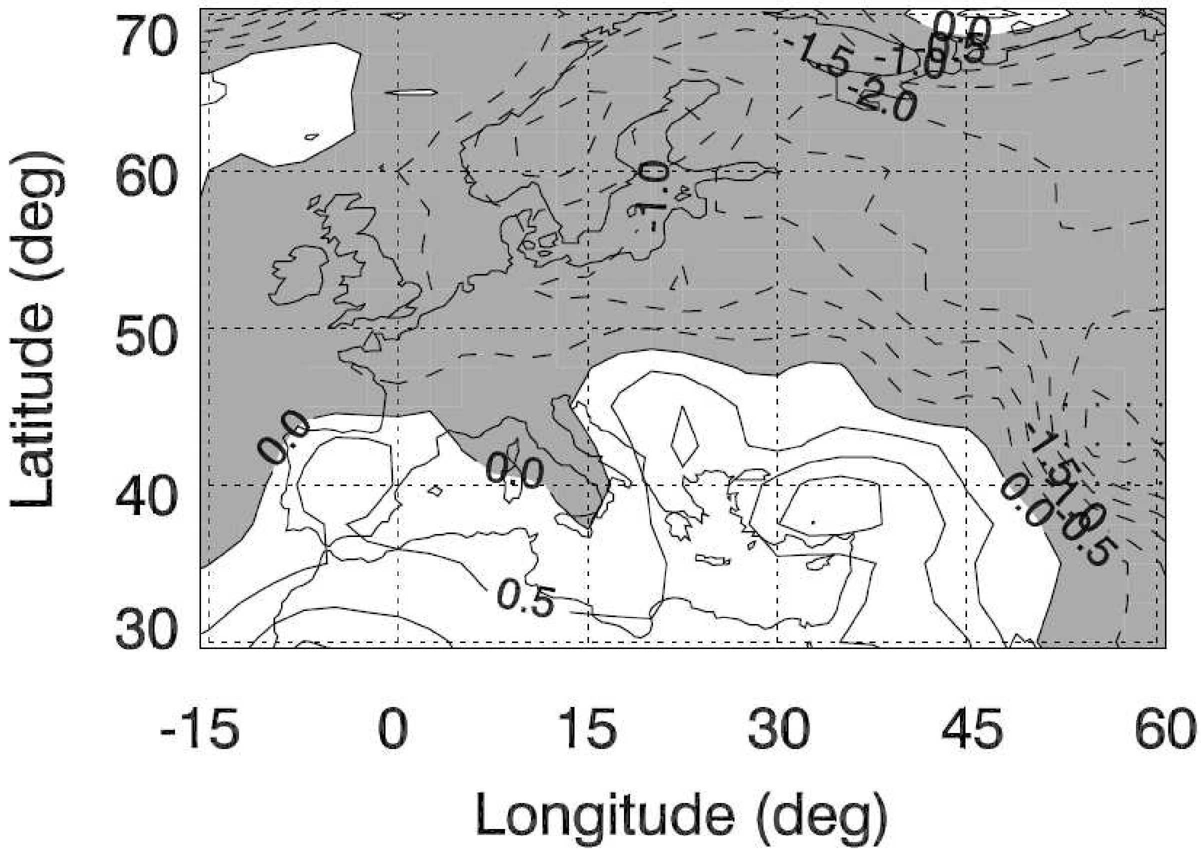
Sensitivity on the strength of GW momentum flux



Quasi Biennial Oscillation QBO

After:
B. Naujokat

QBO → tropospheric weather



from Marshall and Scaife, JGR, 2009

Difference of mean winter temperature between QBO phases in NCEP/NCAR reanalysis data.

gravity wave

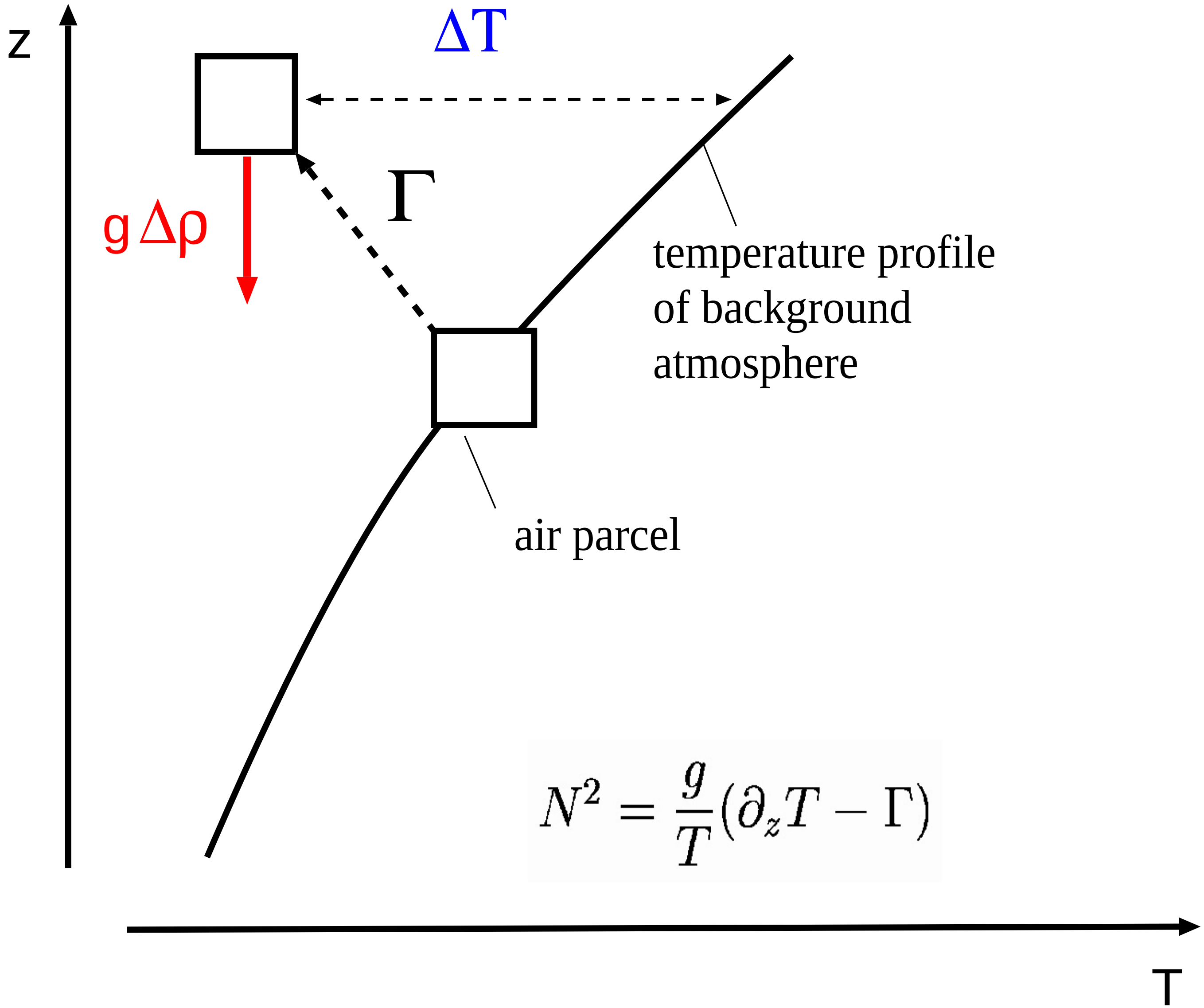
$$=$$

buoyancy wave

$$\neq$$

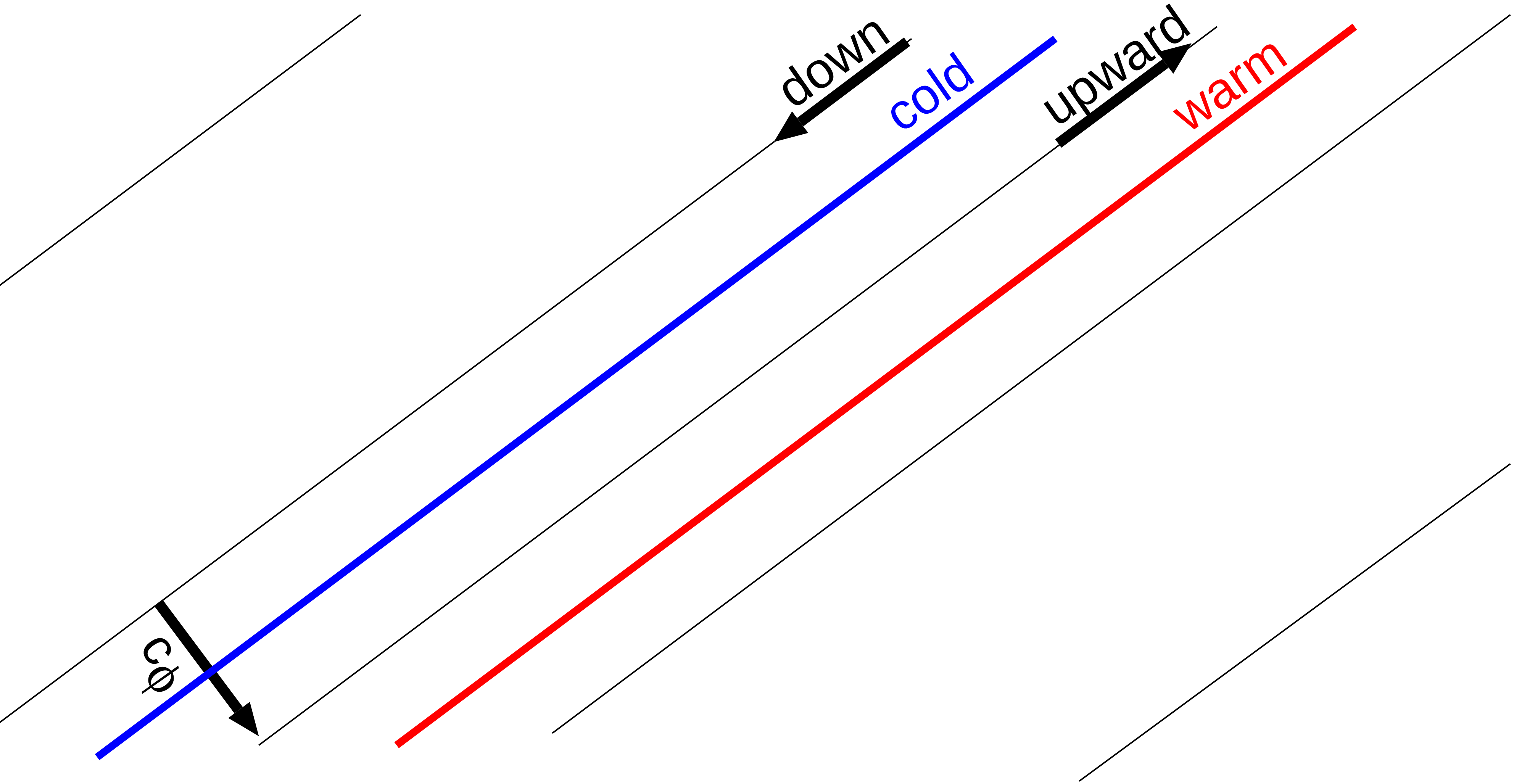
gravitational wave

Isolated Airparcel

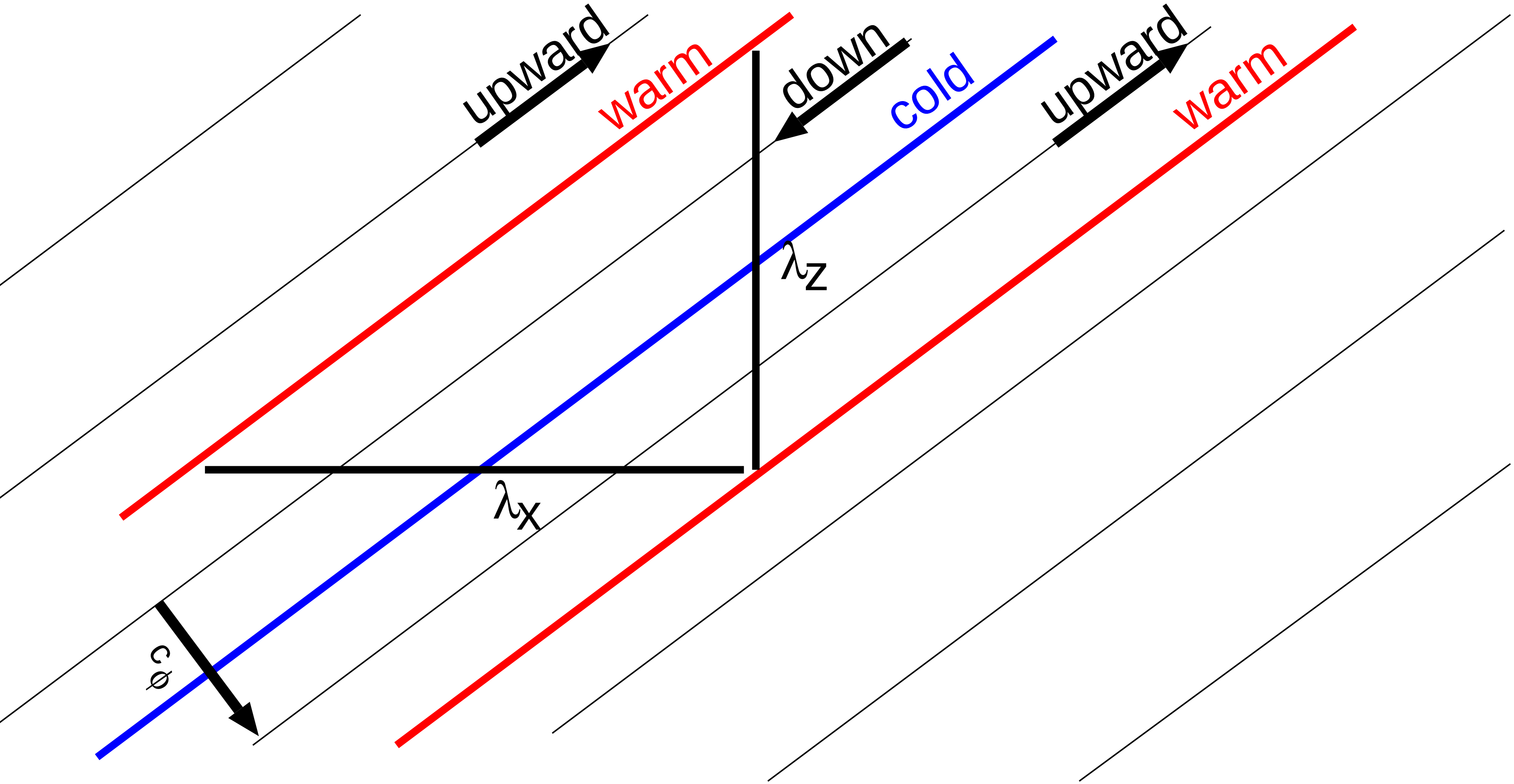


$$N^2 = \frac{g}{T}(\partial_z T - \Gamma)$$

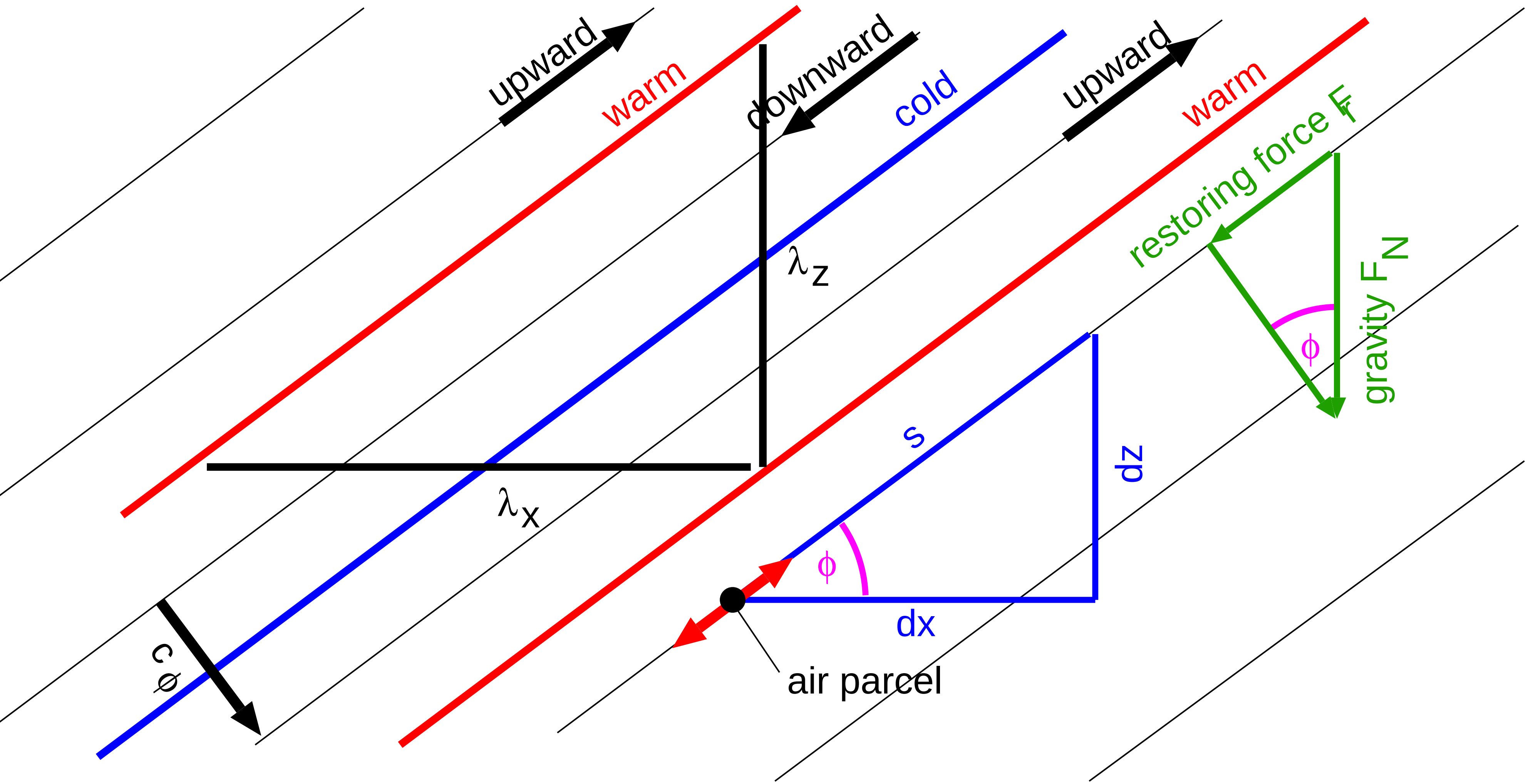
Plane Wave



Plane Wave



Plane Wave



$$\hat{\omega}^2 = \frac{k_h^2 N^2}{k_h^2 + m^2} \qquad (1)$$

Dispersion relation

The full dispersion relation in 3D, including exponential density decrease and Earth rotation is:

$$\hat{\omega}^2 = \frac{(k^2 + l^2)N^2 + f^2\left(m^2 + \frac{1}{4H^2}\right)}{k^2 + l^2 + m^2 + \frac{1}{4H^2}} \simeq \hat{\omega}^2 = \frac{k_h^2 N^2}{k_h^2 + m^2} + f^2 \quad (2)$$

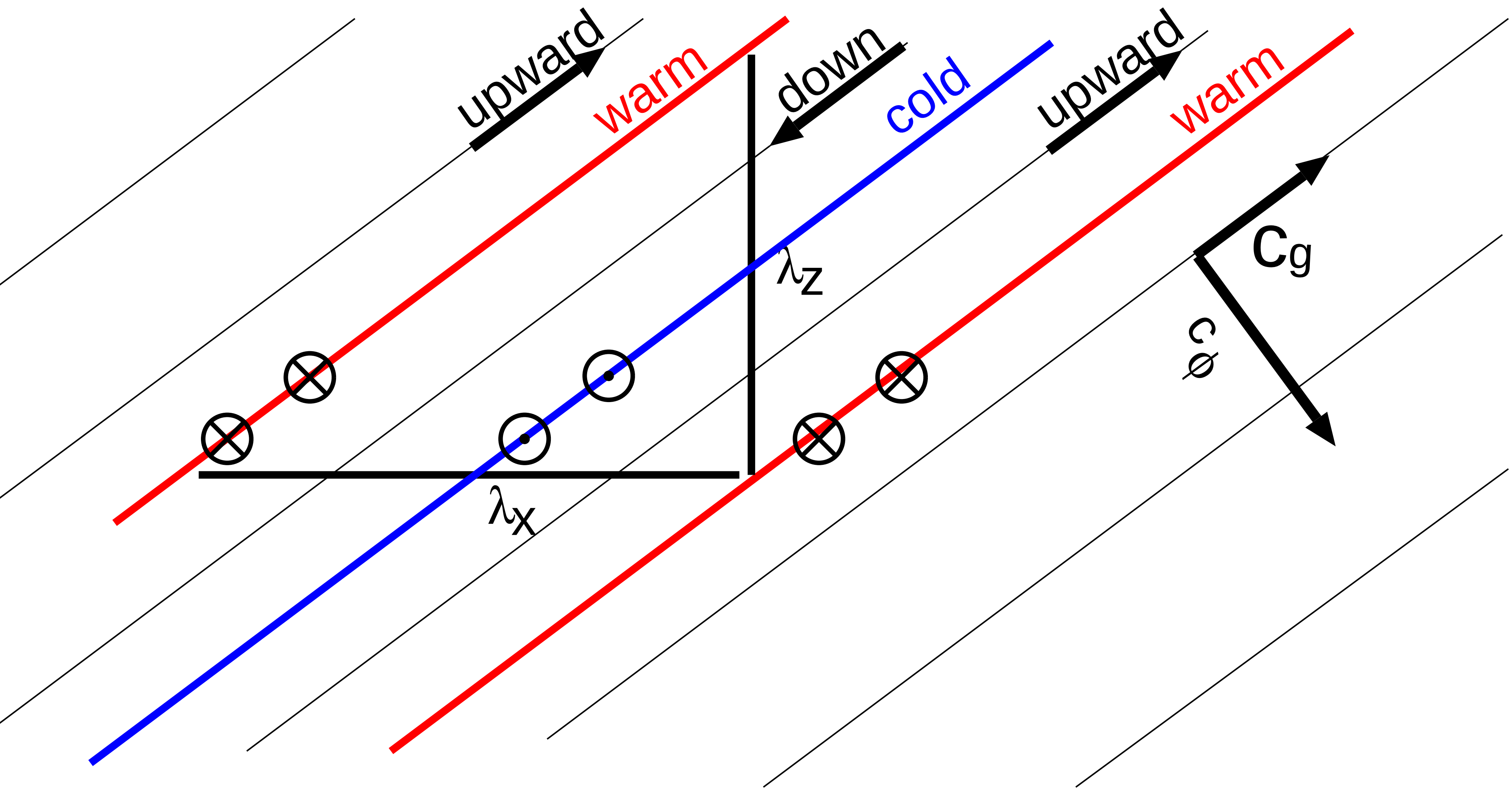
This implies

$$N^2 > \hat{\omega}^2 > f^2 \quad (3)$$

$\Rightarrow$ phase velocity and group velocity

$$\vec{c_\phi} = \frac{\omega}{|\vec{k}|}\left(\frac{k}{|\vec{k}|}, \frac{l}{|\vec{k}|}, \frac{m}{|\vec{k}|}\right), \quad \vec{c_g} = \left(\frac{\partial\omega}{\partial k}, \frac{\partial\omega}{\partial l}, \frac{\partial\omega}{\partial m}\right) \quad (4)$$

Plane Wave

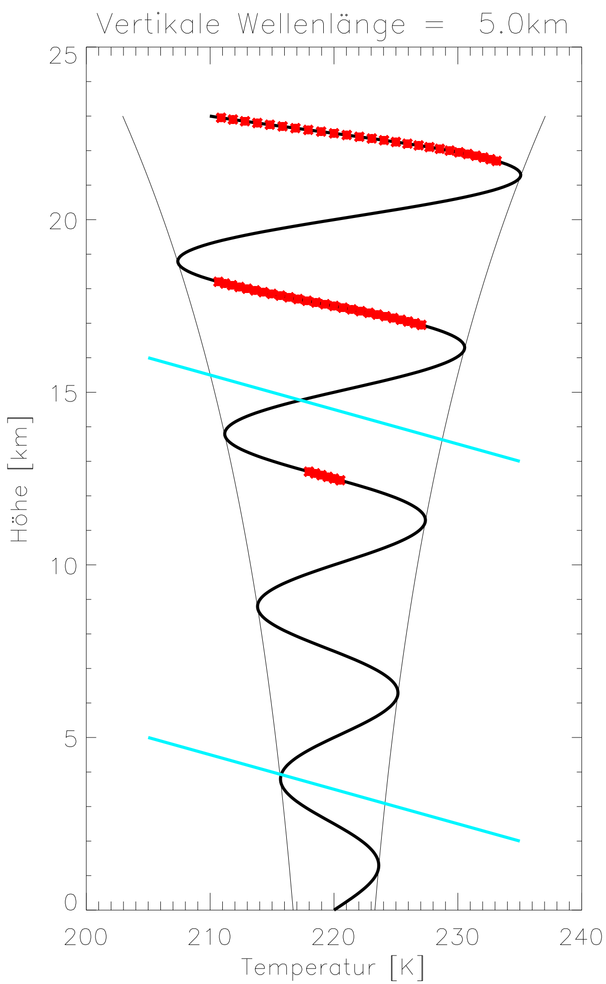


$$F_{px} = \bar{\rho}(1 - \frac{f^2}{\hat{\omega}^2})\overline{u'w'}; \quad \bar{X} = -\frac{1}{\rho}\frac{\partial}{\partial z}F_{px}$$

Wave clouds at Juelich

Wave clouds at Juelich

Saturation Amplitude



Too large amplitudes result in convectively instable layers.

Wave solution:

$$N^2 > 0 \Leftrightarrow \Gamma = -10\frac{K}{km} < \frac{\partial(\overline{T} + \hat{T}\sin(mz))}{\partial z} \tag{5}$$

$\Rightarrow$ Maximum stable amplitude:

$$\hat{T}_{max} = \frac{N^2\overline{T}}{gm} = \frac{N^2\overline{T}}{g2\pi}\lambda_z \tag{6}$$

Doppler shift

$$\hat{\omega} = \omega_{gb} - \vec{k_h}\vec{U} \tag{7}$$

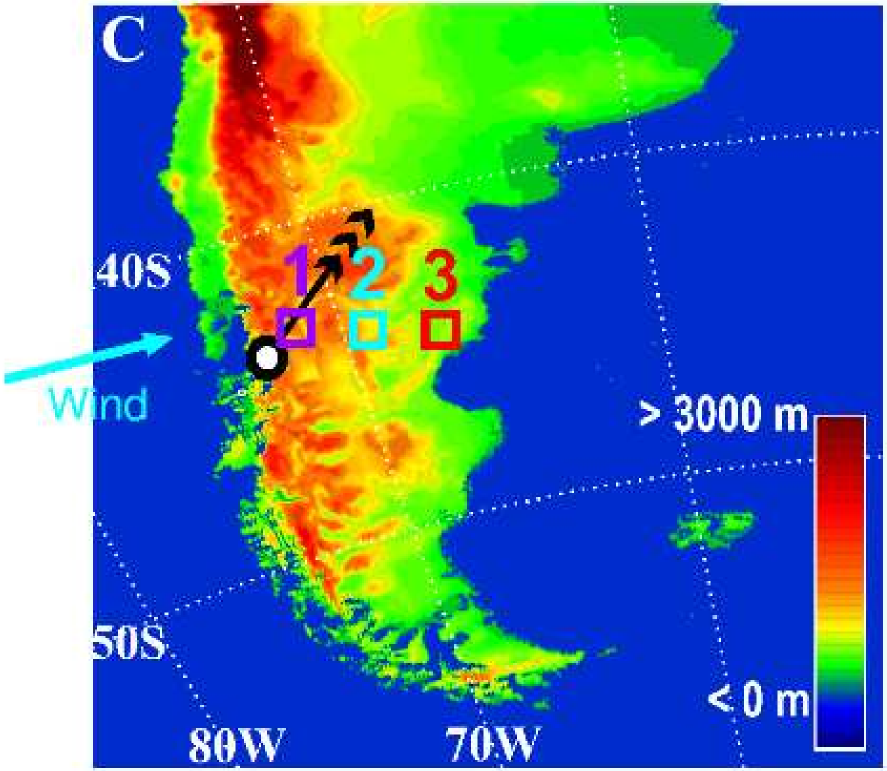
$$\hat{\omega}^2 = \frac{k_h^2 N^2}{m^2} \Rightarrow \lambda_z = \left| 2\pi\frac{c - U_{||}}{N} \right| \tag{8}$$

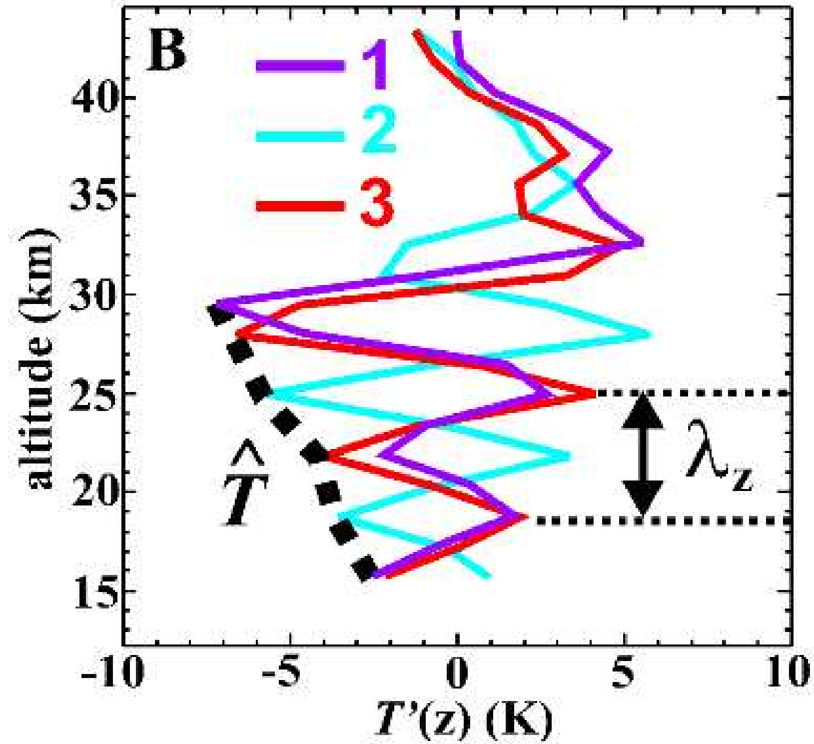
The key quantities

Very simplified:

- The momentum flux decides how much drag can be exerted
- The phase speed decides where the drag is exerted
- The direction decides whether the drag accelerates or decelerates the background flow

CRISTA-1 (1994)





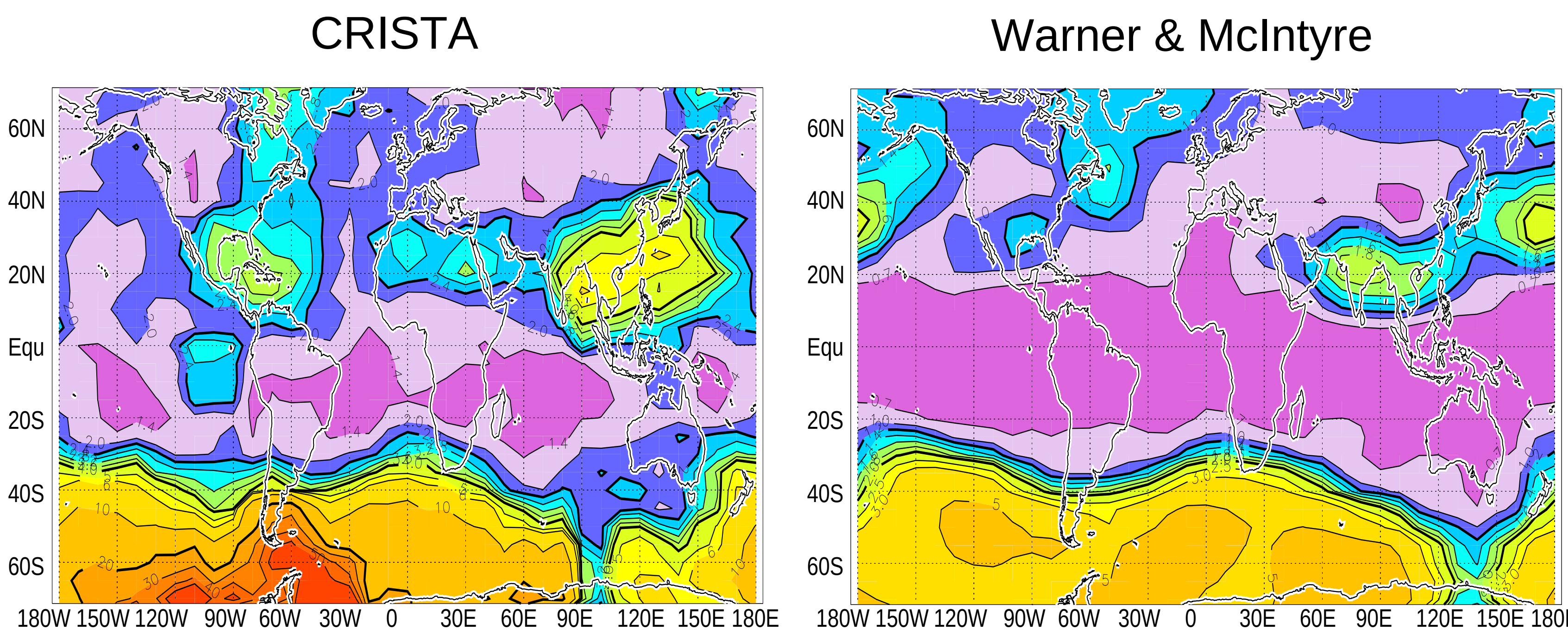
Eckermann and Preusse, Science, 1999

$$F \propto \frac{\lambda_z}{\lambda_h}(T')^2$$

Absolute values of momentum flux

CRISTA-2, August 1997

$$F \propto \frac{\lambda_z}{\lambda_h}(T')^2$$



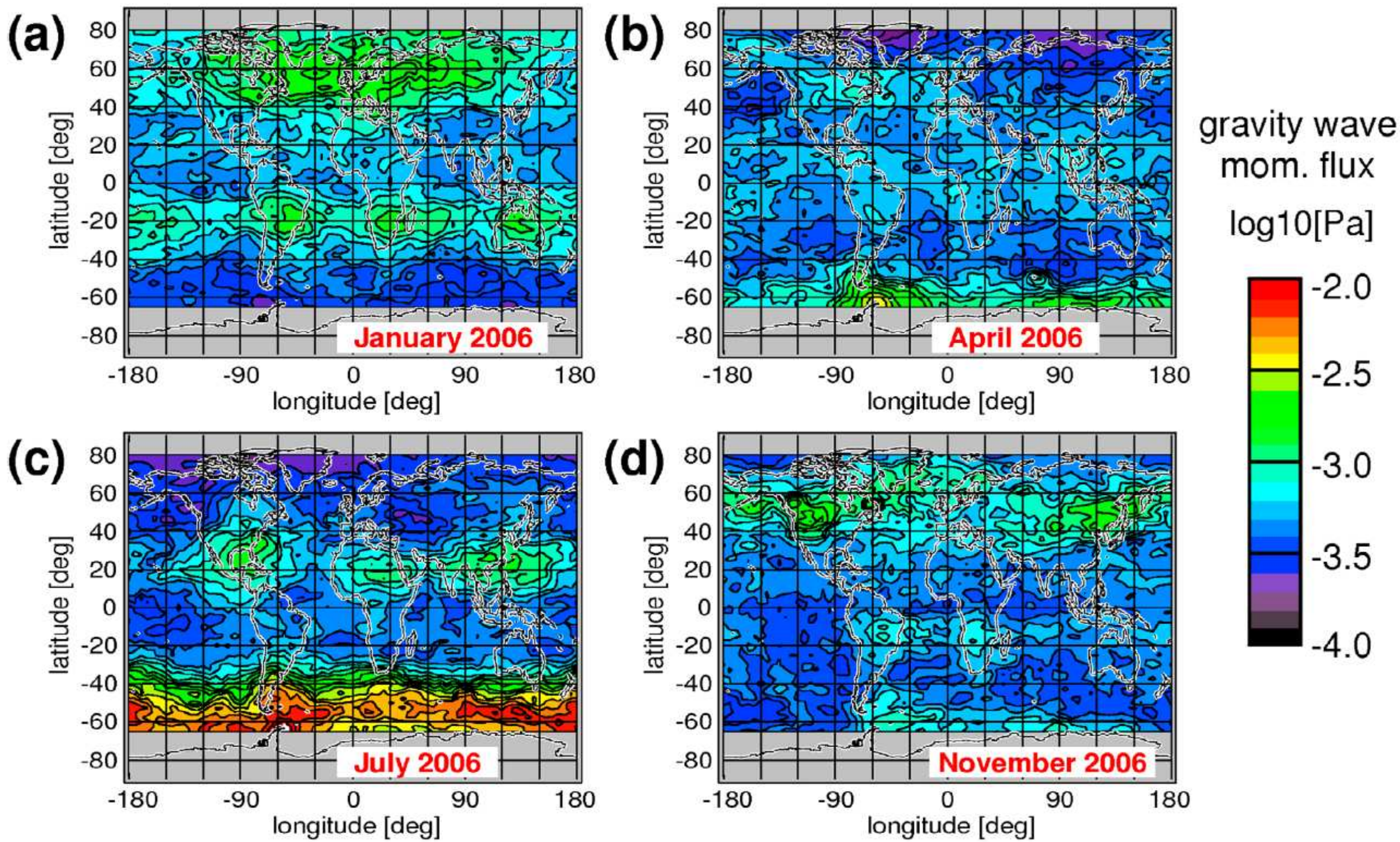
Absolute Values of Momentum Flux [mPa]

Ern et al., JGR, 2004

Orr et al., J. Clim., 2010 :

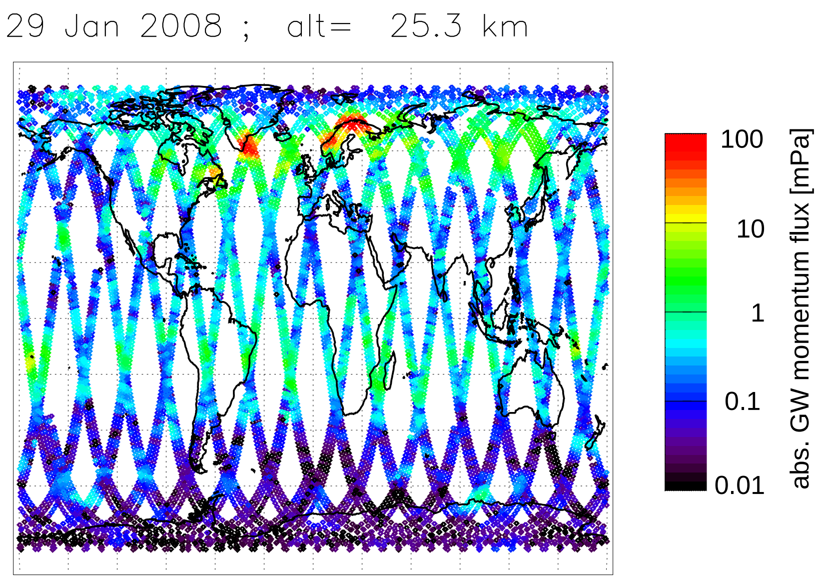
GW scheme in ECMWF confined by CRISTA

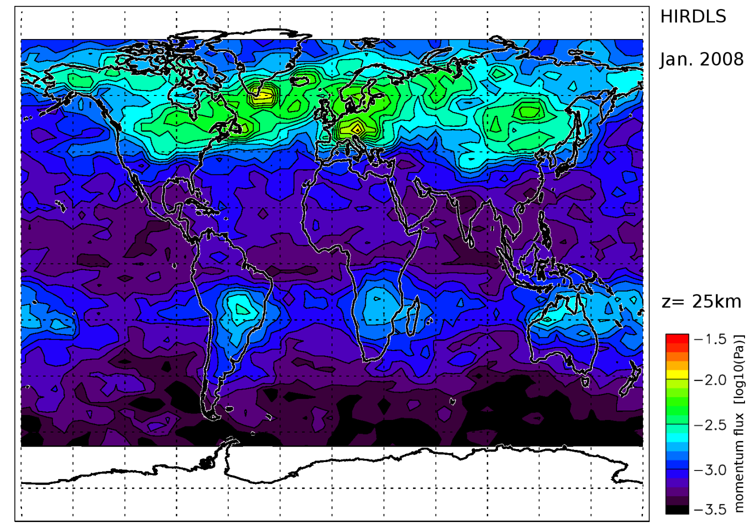
HIDLS: Annual cycle for 2006



Ern et al., JGR, 2011

ECMWF global data and HIRDLS

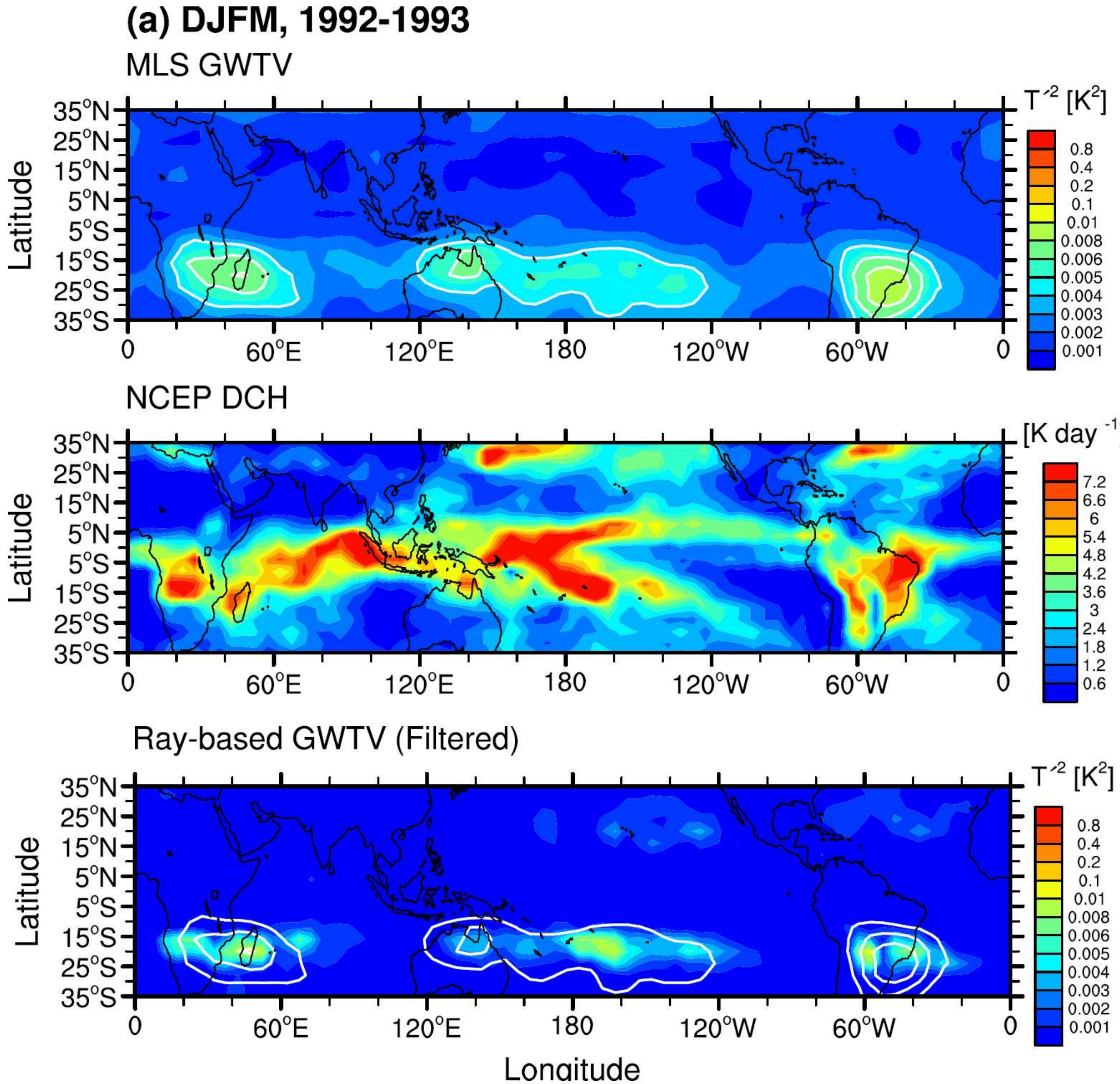




Preusse et al., ACP, 2014

- Single day vs. whole month
- General good agreement
- Low latitudes: Satellites show hot spots over continents

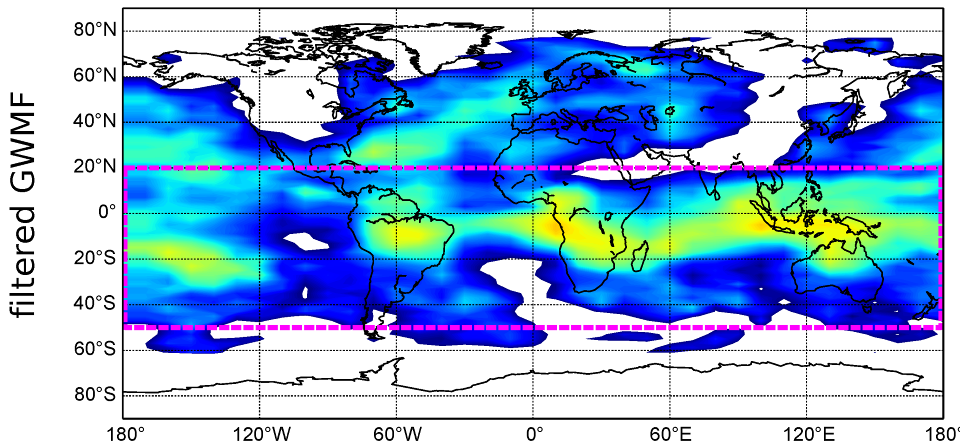
Yonsei Convective GW Source

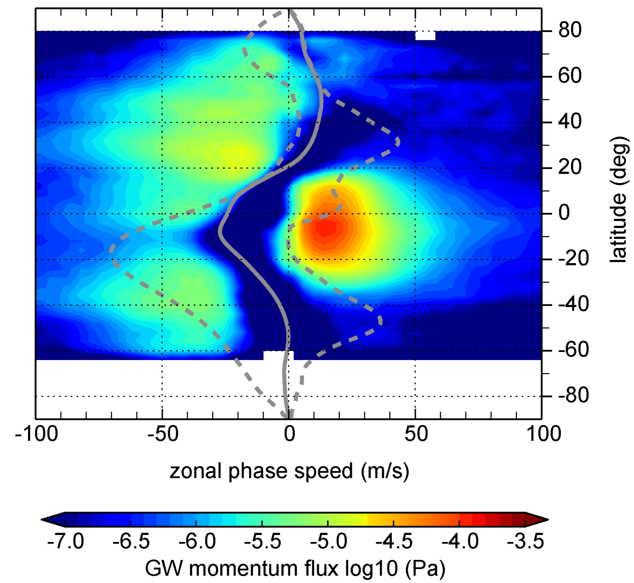


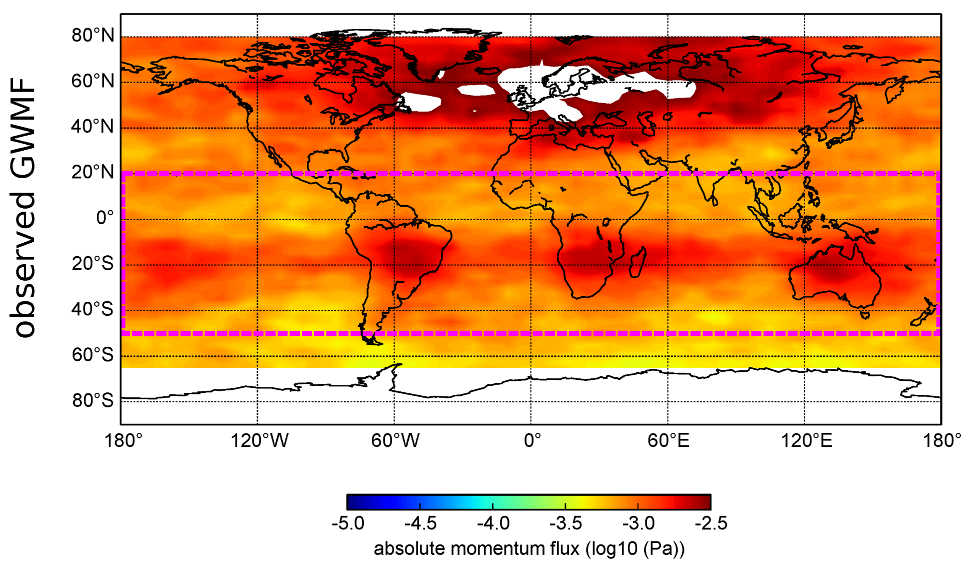
Choi et al., JGR, 2009

Yonsei Convective GW Source

Song and Chun, JAS, 2005



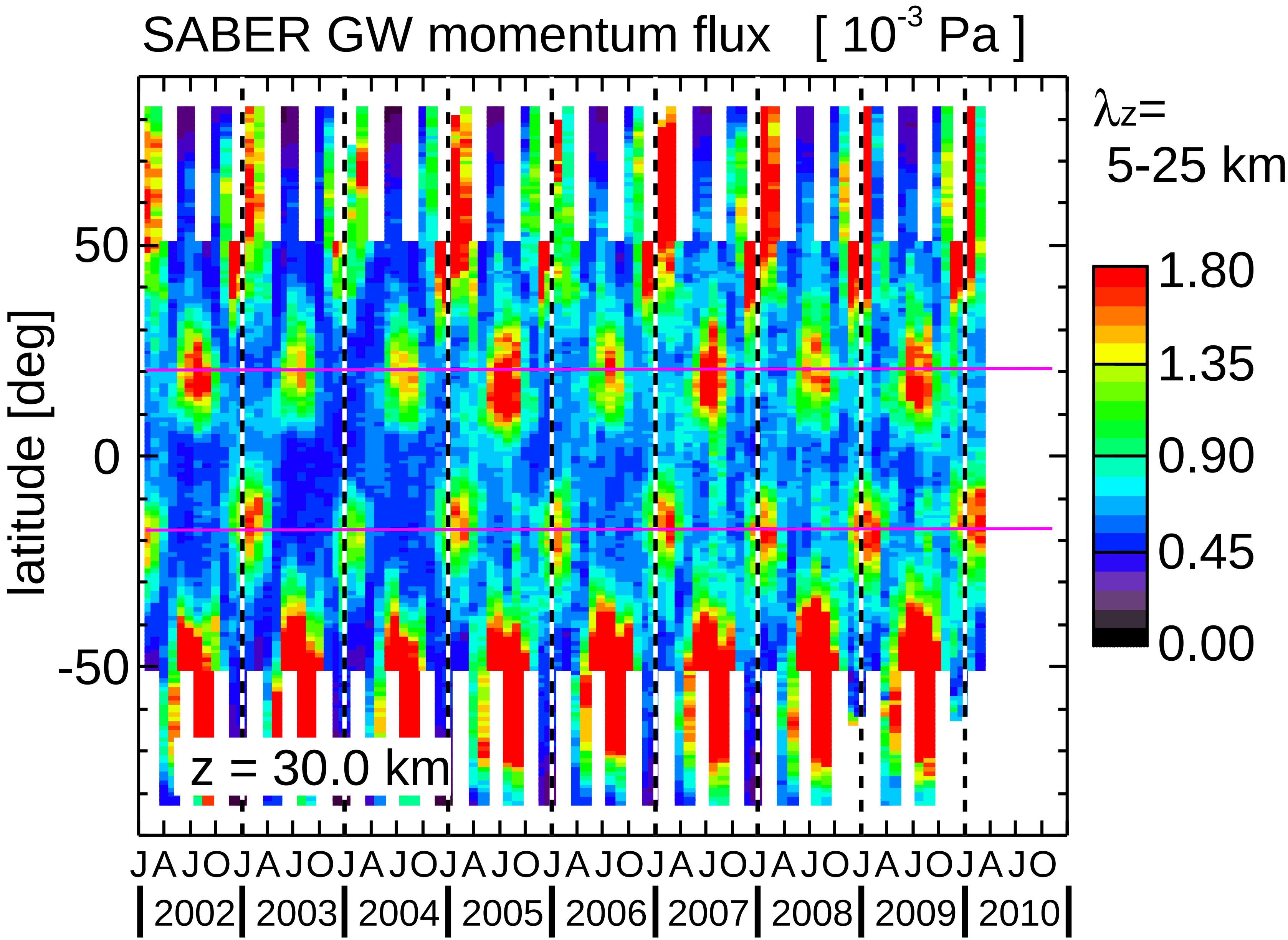




Jan 2006, z = 25 km

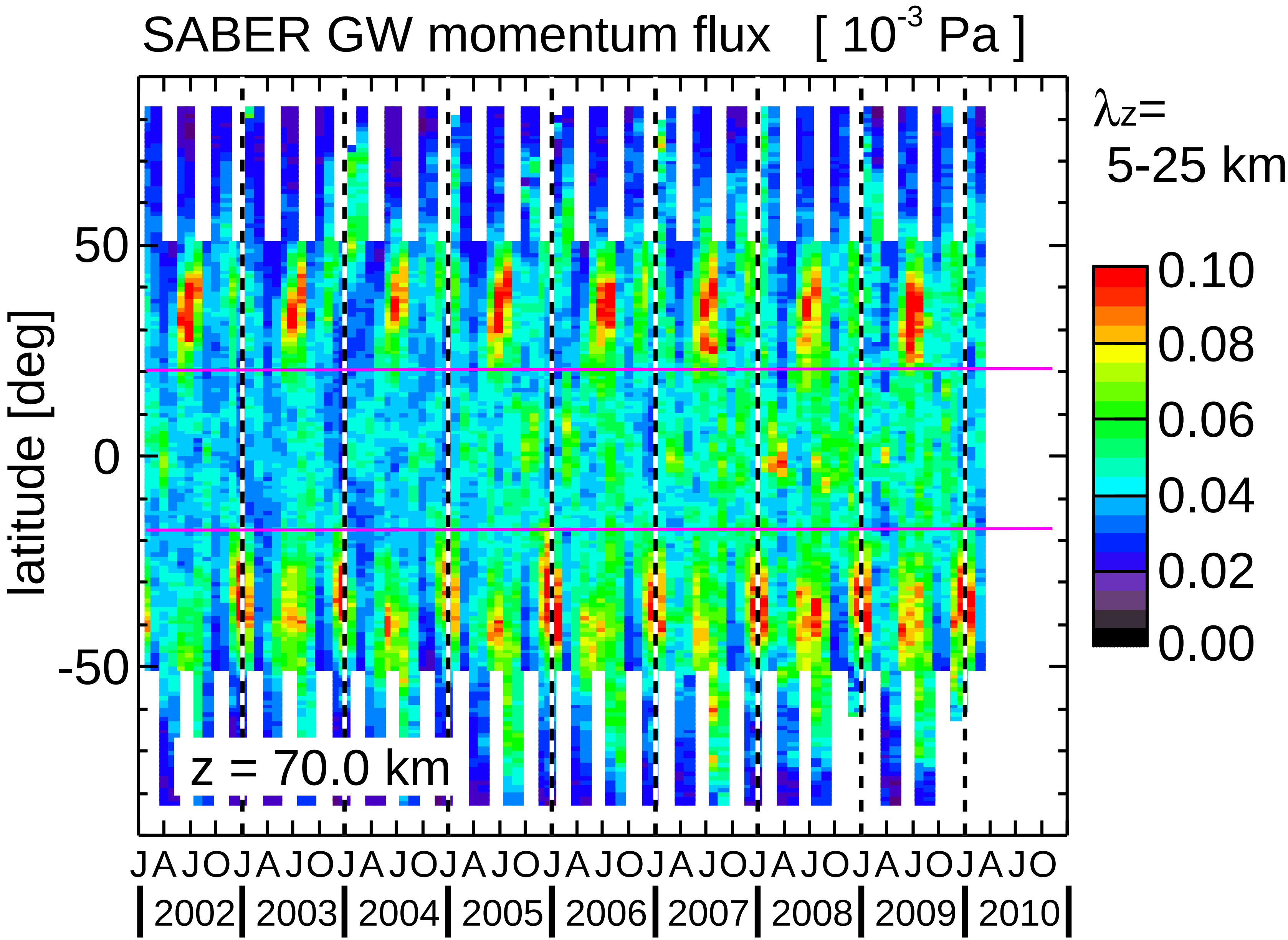
Trinh et al., in preparation

10 years of SABER



Ern et al., JGR, 2011

SABER: poleward shift

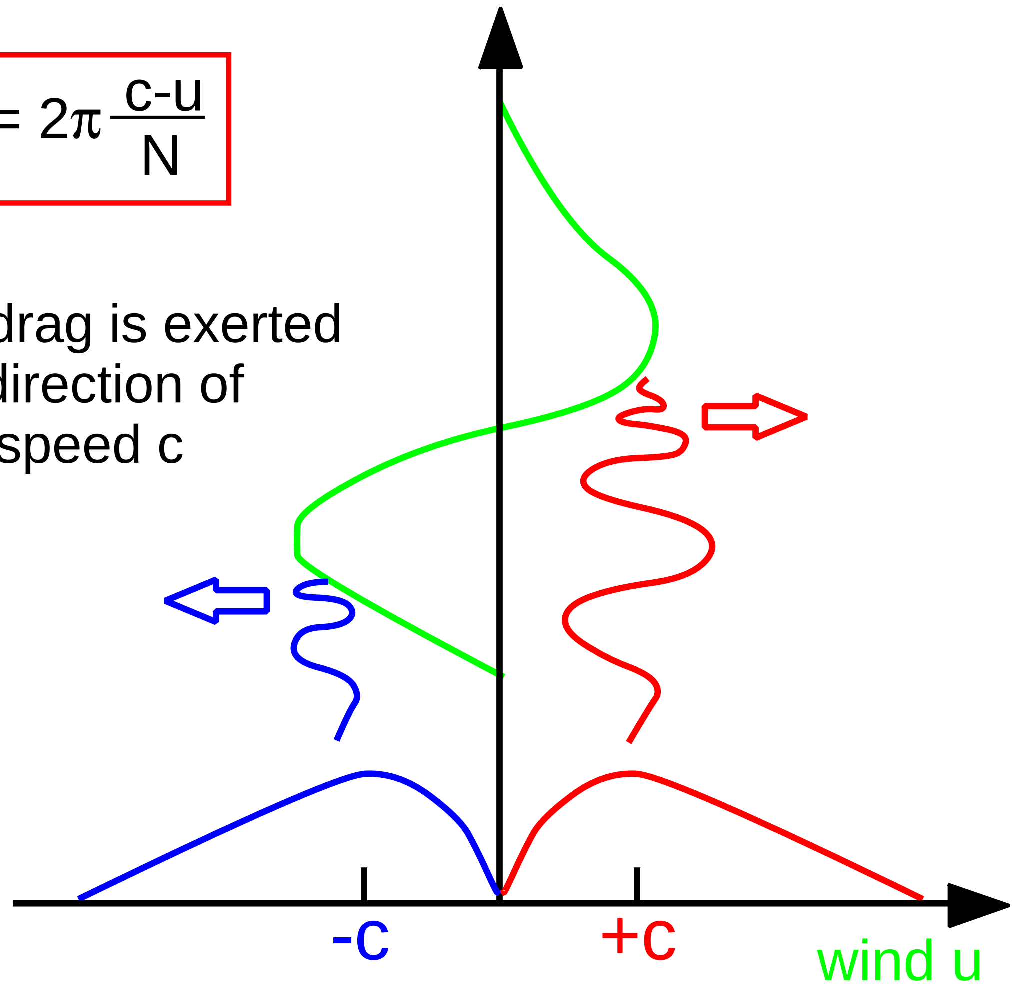


Ern et al., JGR, 2011

QBO is wave-driven

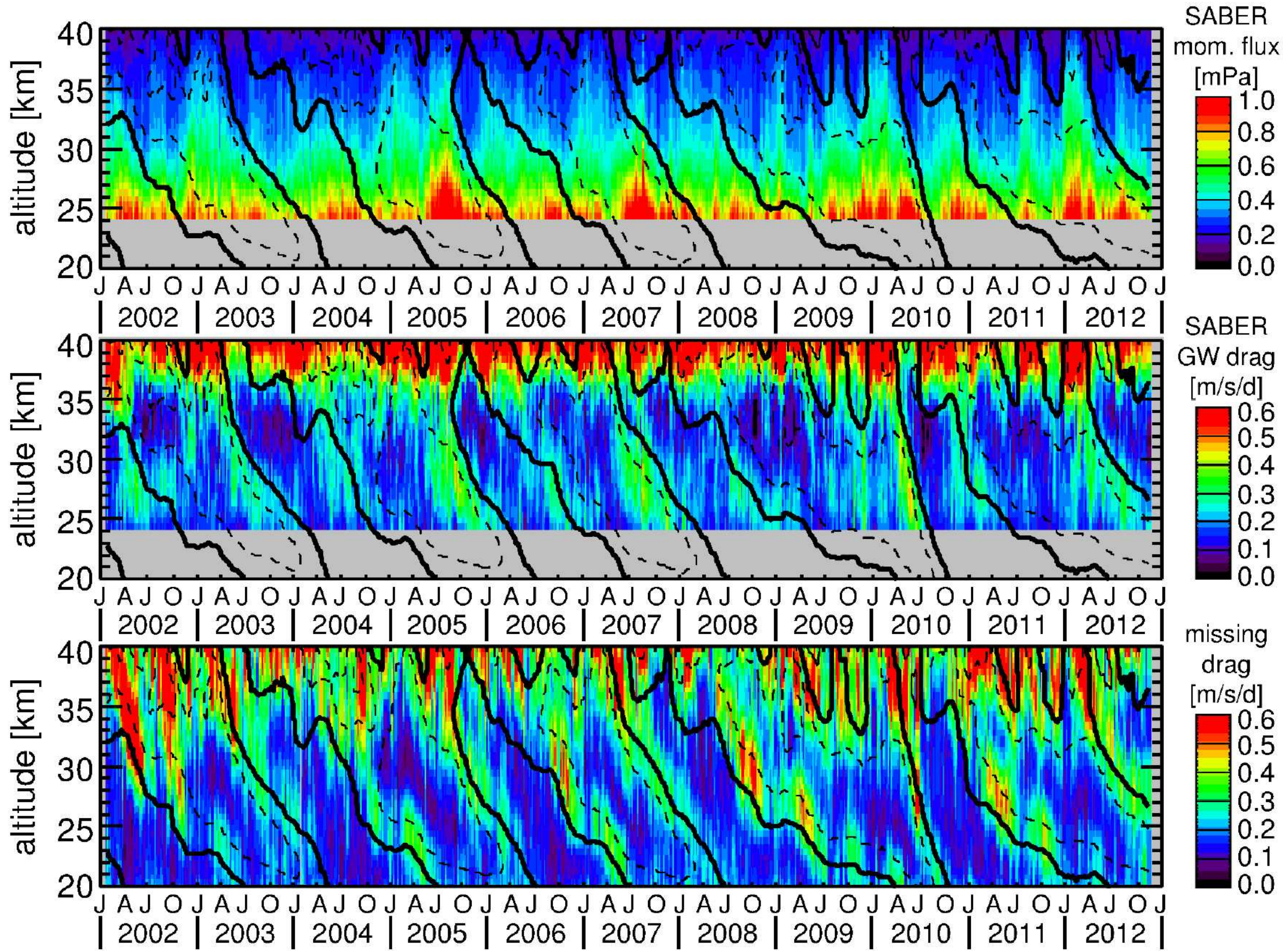
$$\lambda_z = 2\pi \frac{c-u}{N}$$

Wave drag is exerted
in the direction of
phase speed c



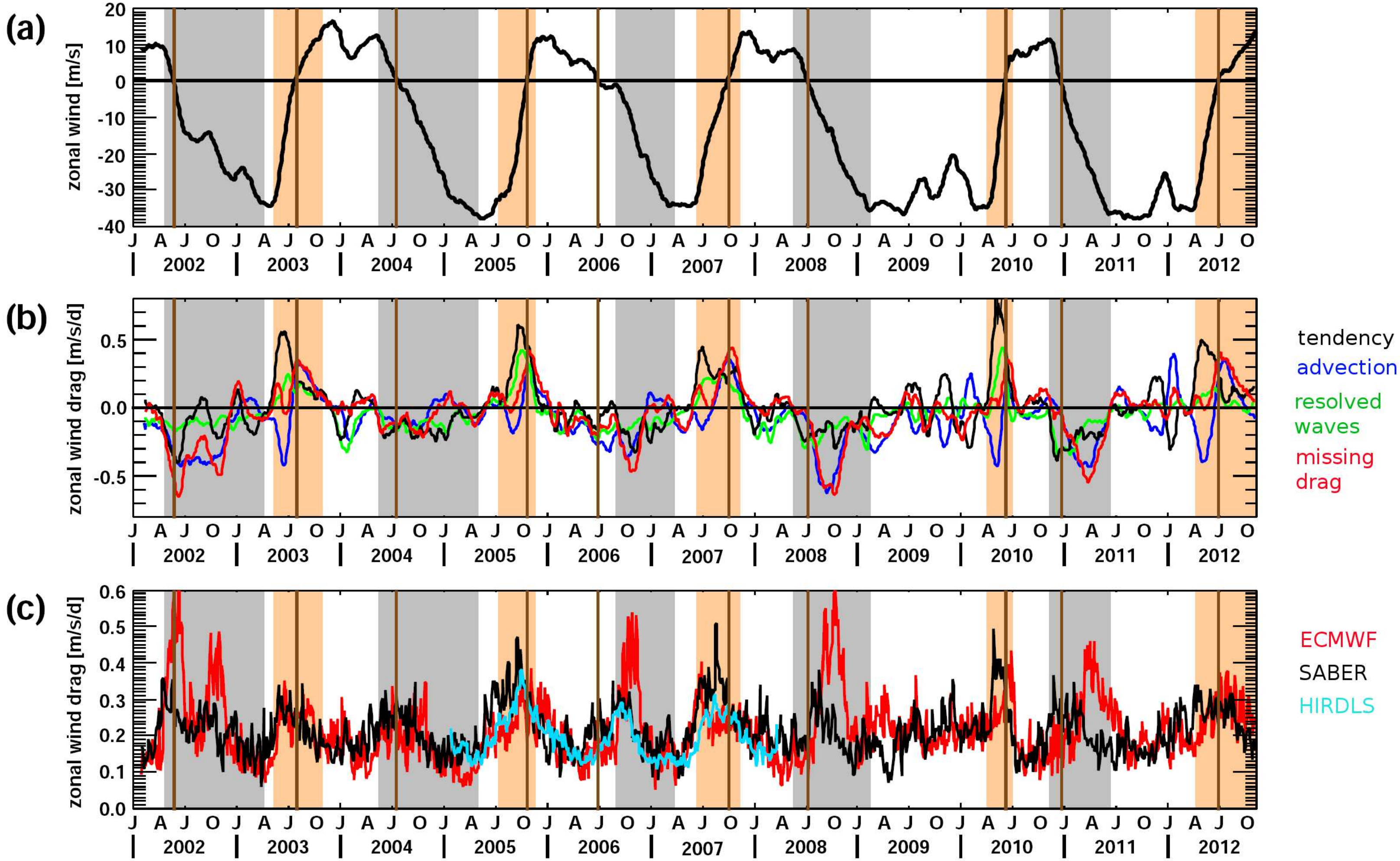
cf. Lindzen and Holton, A theory of the Quasi-Biennial Oscillation, JAS, 1968

QBO forcing



Ern et al., JGR, 2014

QBO forcing



Ern et al., JGR, 2014

Comparison of GCM and measurements

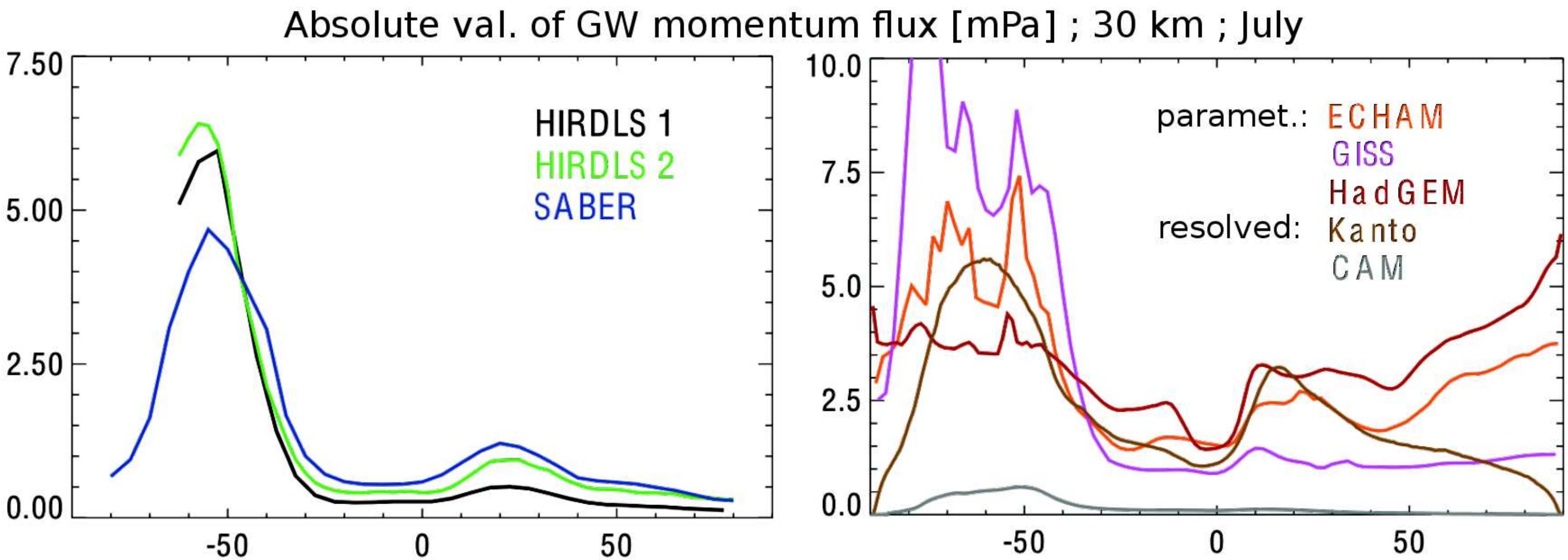
SPARC gravity wave initiative
(reinstated in 2008; lead Joan Alexander).

A Comparison Between Gravity Wave Momentum Fluxes in Observations and Climate Models

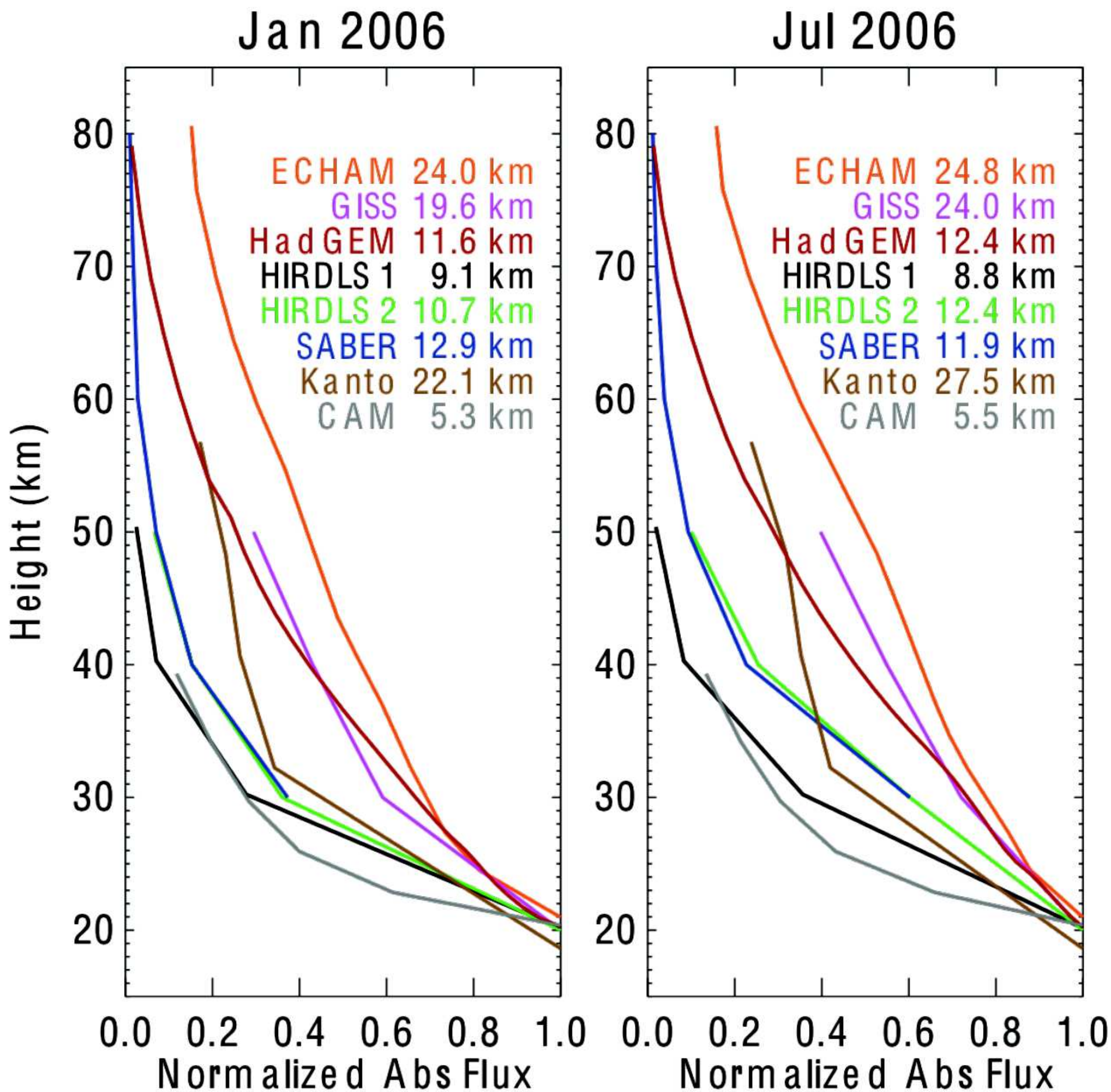
Marvin A. Geller, M. Joan Alexander, Peter T. Love,
Julio Bacmeister, Manfred Ern, Albert Hertzog, Elisa Manzini,
Peter Preusse, Kaoru Sato, Adam A. Scaife, and Tiehan Zhou

J. Clim., 2013

Zonal mean climatologies



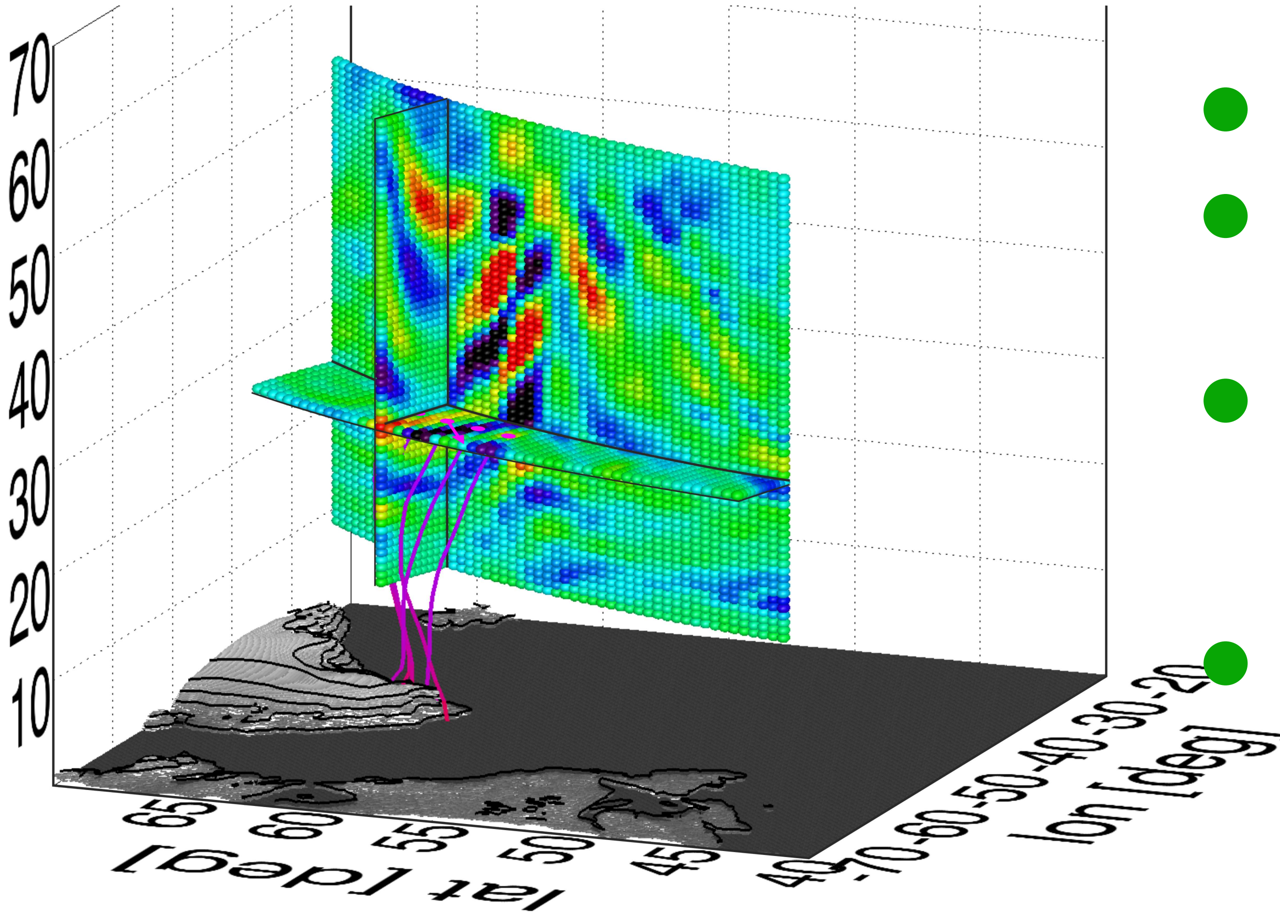
- general agreement of shape
- quantitative agreement (better factor 2) in winter vortex
- indicates problem at summer high latitudes


Jan 2006
Jul 2006
Height (km)
Normalized Abs Flux
ECHAM 24.0 km
GISS 19.6 km
HadGEM 11.6 km
HIRDLS 1 9.1 km
HIRDLS 2 10.7 km
SABER 12.9 km
Kanto 22.1 km
CAM 5.3 km
ECHAM 24.8 km
GISS 24.0 km
HadGEM 12.4 km
HIRDLS 1 8.8 km
HIRDLS 2 12.4 km
SABER 11.9 km
Kanto 27.5 km
CAM 5.5 km

Findings and challenges

- General shape of global distribution by
  - modulation of tropospheric GWs by background wind
  - individual sources such as orography, convection, spontaneous adjustment
  - large GWMF in southern winter: source still not fully explained
- sources need to be quantified
- QBO driving seams clear, but direction could induce artifacts
- vertical gradient, propagation and dissipation need good accuracy measurements

Infrared limb imaging from space



- 3D images of GWs
- vertical resolution about 1.0 km
- temperature precision 0.5-1.0 K
- sources by backward ray-tracing

Assessment

By simulated measurements (limb soundings) through ECMWF data fields:

- Infrared limb imaging will be able to measure all three key quantities:
  - GW momentum flux
  - direction
  - phase speed (inferred)
- zonal mean net GWMF accurate to $\sim$30 %
- independent values at several altitudes throughout entire stratosphere

Summary

- Gravity waves are important for e.g. QBO and Brewer-Dobson circulation and thus for climate projection
- Gravity wave sources include: orography, convection, spontaneous adjustment, ?
- Oblique propagation is important $\rightarrow$ parametrisation vs resolved?
- GCM $\leftrightarrow$ observations: General distributions between models and measurements are coarsly realistic
- Uncertainty ranges are large (factor 2 at best (e.g. 30km, SH winter), order of magnitude at worst).
- 3D distributions from limb imager would be most important break-through

Coupling by propagating waves

Global equation of motion (wind):

$$\frac{du}{dt} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} = X \qquad (9)$$

Separate into large scale $\bar{u}$ and GWs u', $u = \bar{u} + u'$.
Acceleration for $\bar{u}$ by GWs:

$$\bar{X} = -\frac{1}{\rho}\frac{\partial}{\partial z}F_{px} \qquad (10)$$

Pseudomentum flux:

$$F_{px} = \bar{\rho}(1 - \frac{f^2}{\hat{\omega}^2})\overline{u'w'} \qquad (11)$$