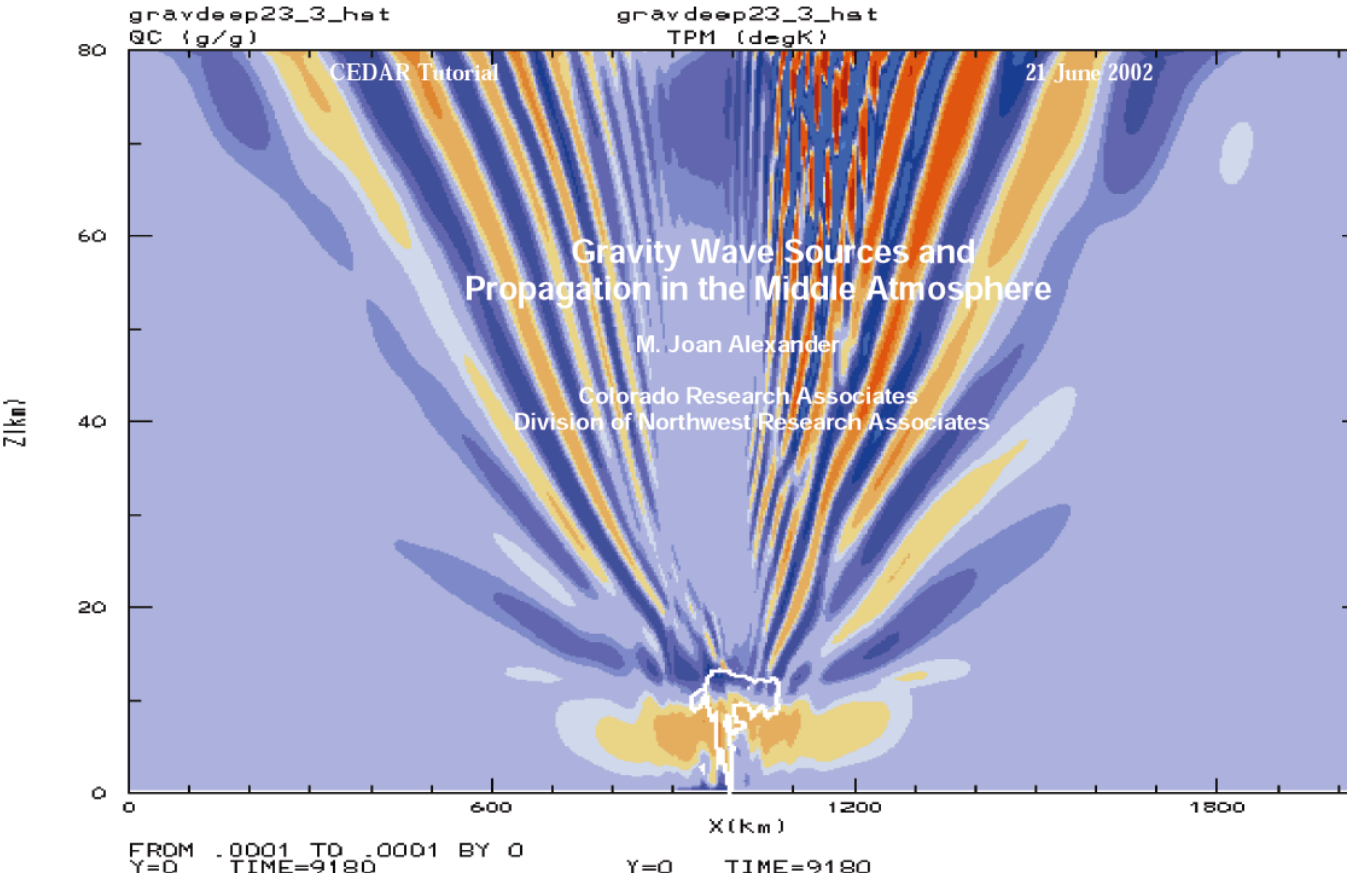
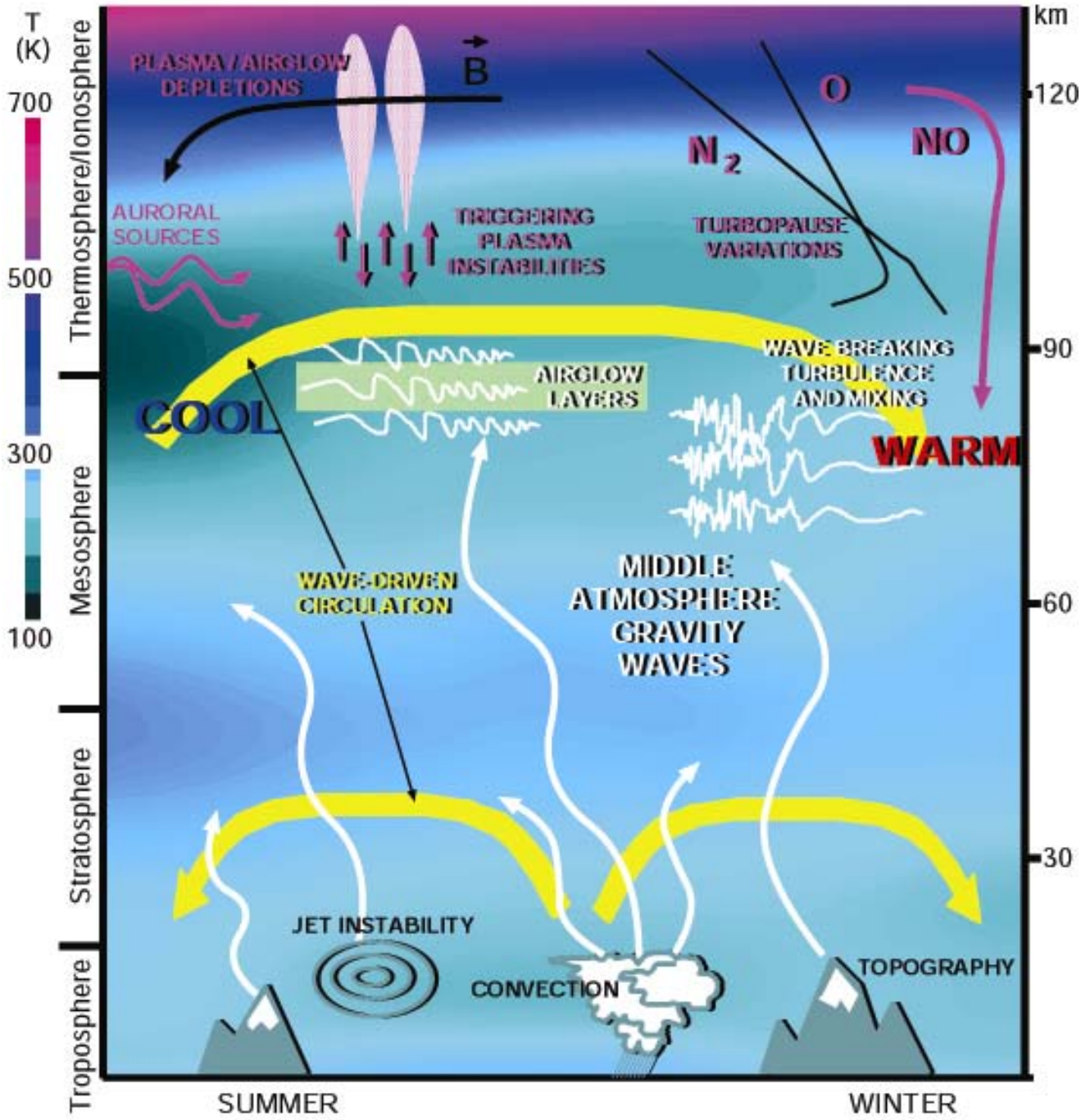

gravdeep23_3_hat
QC (g/g)
gravdeep23_3_hat
TPM (degK)
CEDAR Tutorial
21 June 2002
Gravity Wave Sources and
Propagation in the Middle Atmosphere
M. Joan Alexander
Colorado Research Associates
Division of Northwest Research Associates
Z(km)
80
60
40
20
0
0
600
1200
1800
X(km)
FROM .0001 TO .0001 BY 0
Y=0 TIME=9180
Y=0 TIME=9180

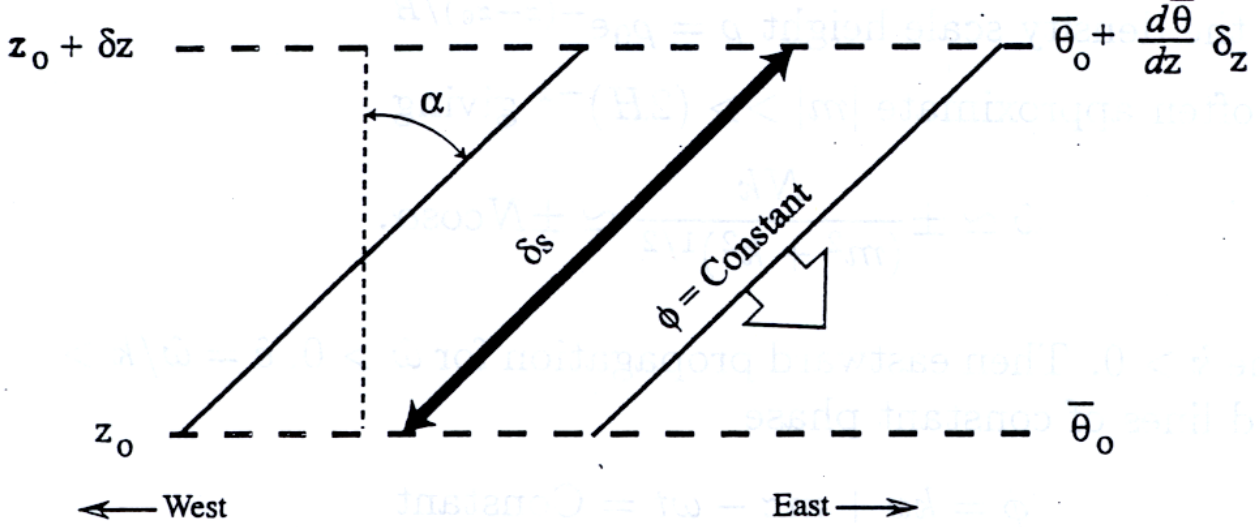

T
(K)
700
500
300
100
Thermosphere/Ionosphere
Mesosphere
Stratosphere
Troposphere
km
120
90
60
30
PLASMA / AIRGLOW
DEPLETIONS
B
AURORAL
SOURCES
TRIGGERING
PLASMA
INSTABILITIES
O
NO
N2
TURBOPAUSE
VARIATIONS
WAVE BREAKING
TURBULENCE
AND MIXING
AIRGLOW
LAYERS
COOL
WARM
WAVE-DRIVEN
CIRCULATION
MIDDLE
ATMOSPHERE
GRAVITY
WAVES
JET INSTABILITY
CONVECTION
TOPOGRAPHY
SUMMER
WINTER

Joan Alexander
Colorado Research Associates

GRAVITY WAVES

- Vertically propagating waves associated with the buoyancy restoring force in stably stratified fluids.

- Parcels oscillate parallel to phase lines and perpendicular to the direction of phase propagation.



$$\frac{d^2(\delta s)}{dt^2} = (N\cos\alpha)^2 \delta s$$

Parcel acceleration = Buoyancy force along δs

General solution δs=exp$[\pm i(N\cos\alpha)t]$.
Parcels oscillate at frequency $N\cos\alpha$ where N is the buoyancy frequency,

$$N = \left(\frac{g}{\bar{\theta}}\frac{d\bar{\theta}}{dz}\right)^{1/2}.$$

Detailed analysis starting from the linearized fundamental fluid equations neglecting the Coriolis force gives the *dispersion relationship*:

$$(\omega - \bar{u}k)^2 = \hat{\omega}^2 = \frac{N^2 k^2}{\left[m^2 + k^2 + 1/(4H^2)\right]}$$

$\hat{\omega} = (\omega - \bar{u}k)$ is the *intrinsic frequency*
k, m are the horizontal and vertical wavenumbers
$\bar{u}$ is the wind along the wave propagation direction
H is the density scale height $\rho = \rho_0 \mathrm{e}^{-(z-z_0)/H}$

Can often approximate $|m| >> (2H)^{-1}$ giving

$$\hat{\omega} \simeq \pm \frac{Nk}{(m^2 + k^2)^{1/2}} \simeq \pm N \cos\alpha.$$

Define $k > 0$. Then eastward propagation for $\hat{\omega} > 0$, $\hat{c} = \hat{\omega}/k > 0$, and lines of constant phase

$$\phi = kx + mz - \omega t = \text{Constant}$$

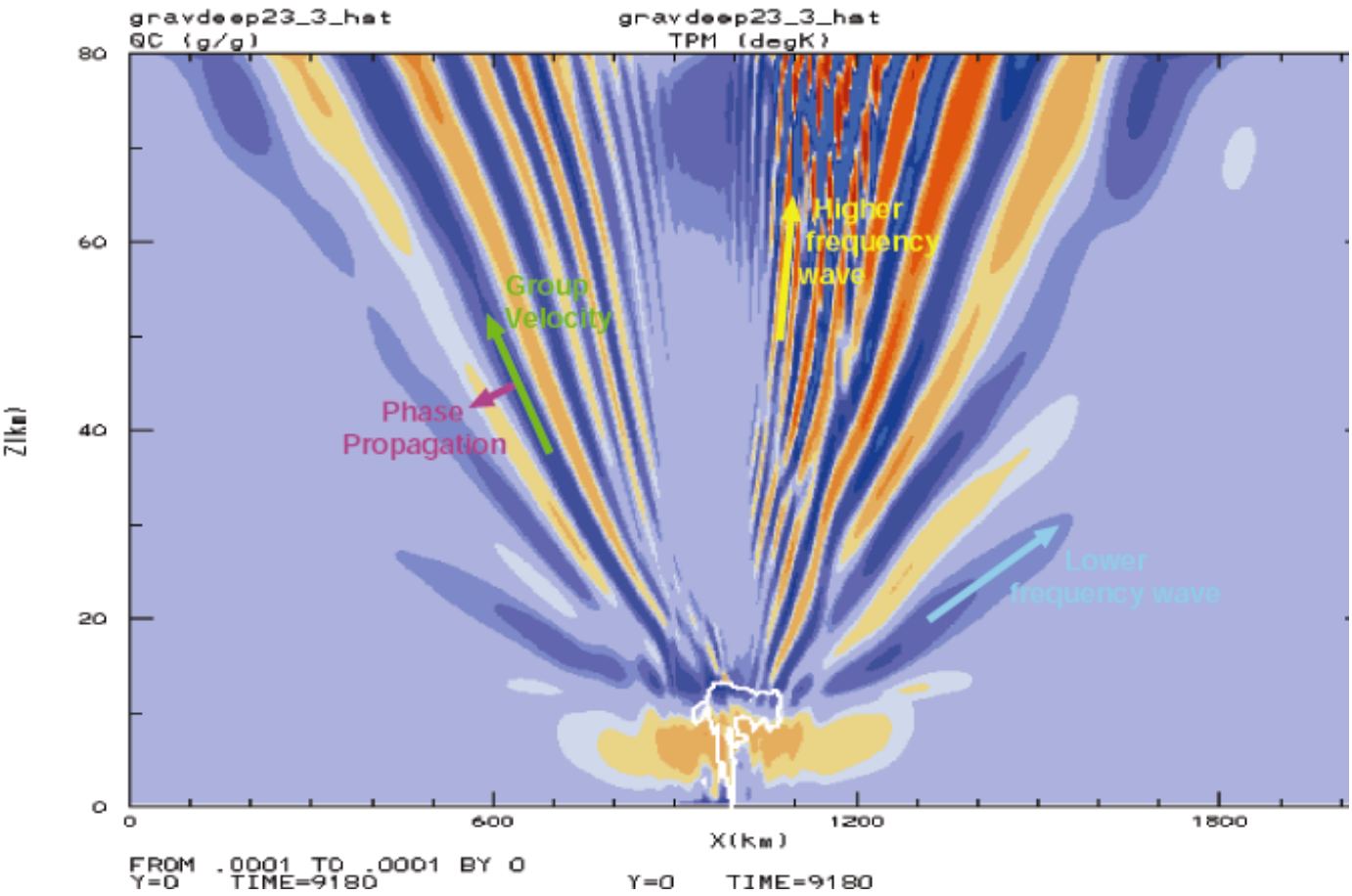
slope upward for $m < 0$.
Energy propagates at the *group velocity*

$$(c_{gx}, c_{gz}) = \left(\frac{\partial\hat{\omega}}{\partial k}, \frac{\partial\hat{\omega}}{\partial m}\right) = (\bar{u}, 0) \pm \frac{N}{(m^2 + k^2)^{3/2}}(-m, k)$$

So for eastward propagating waves (positive root) energy propagates upward and eastward relative to the mean flow. Since

$$\left|\frac{c_{gz}}{c_{gx} + \bar{u}}\right| = \left|\frac{k}{m}\right|$$

the group velocity vector is parallel to phase lines and perpendicular to phase propagation.


gravdeep23_3_hat
QC (g/g)
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TPM (degK)
Higher frequency wave
Group Velocity
Phase Propagation
Lower frequency wave
Z(km)
X(km)
0
20
40
60
80
600
1200
1800
FROM .0001 TO .0001 BY 0
Y=0 TIME=9180
Y=0 TIME=9180

Inertia-Gravity Waves

For low frequency gravity waves, the Coriolis force must be included, and the dispersion relationship becomes

$$\hat{\omega}^2 \simeq f^2 + N^2 k^2 / m^2$$

where f is the Coriolis parameter. The vertical to horizontal group velocity ratio

$$\left| \frac{c_{gz}}{c_{gx} + \bar{u}} \right| = \left| \frac{k}{m} \right| = (\hat{\omega}^2 - f^2)^{1/2} / N$$

So inertia-gravity waves propagate more closely to the horizontal than is the case for a pure gravity wave. Inertia-gravity waves also display horizontal wind perturbations both parallel and perpendicular to the propagation direction such that

$$\frac{v'}{u'} = -i \left(\frac{f}{\hat{\omega}} \right)$$

Vertical profiles plotted as $u'(z)$ vs $v'(z)$ (called a *hodograph*) trace an ellipse which becomes more circular as $\hat{\omega} -> f$.
f is a lower limit for vertical propagation of gravity waves, and in general

$$|f| < |\hat{\omega}| < Nk / \sqrt{k^2 + 1/(4H^2)}.$$

$\hat{\omega} = f$ represents a critical level where the phase speed $\hat{c} = \bar{u}$.

$\hat{\omega} = Nk / \sqrt{k^2 + 1/(4H^2)}$ is a turning point where the vertical group velocity changes sign and energy is reflected downward.

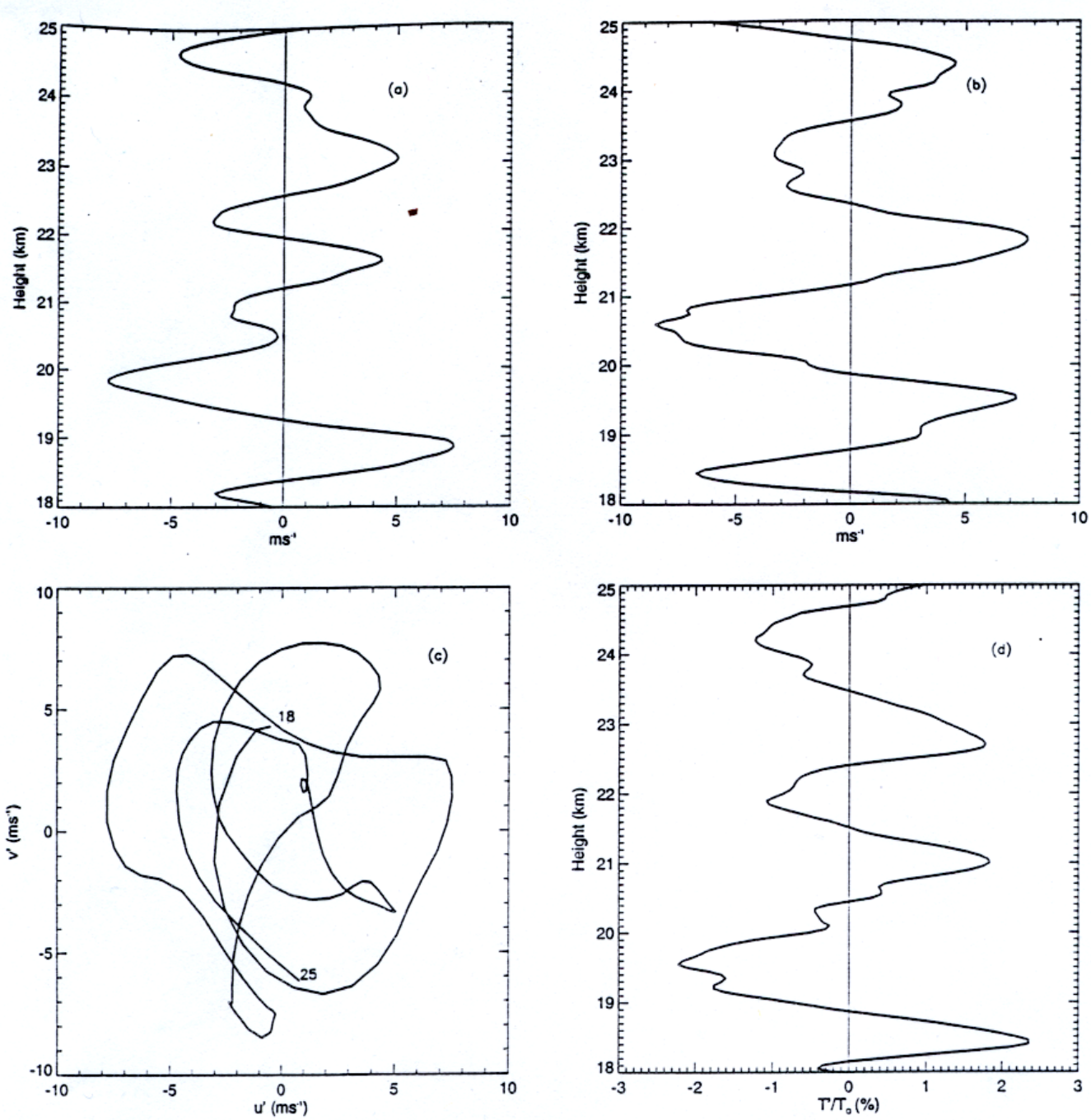


Figure 4. Vertical profiles of (a) zonal and (b) meridional wind perturbations, (c) hodograph of the perturbation motions, and (d) percentage normalized temperature fluctuations for 5 February, 1995 at 2200 UT. In (c) the numbers 18 and 25 inicate the start and stop heights of the profiles

Gravity Wave Breaking

Adiabatic waves, isentropes (θ=Constant) are material surfaces. Convective instability onset where

$$\frac{\partial\theta}{\partial z} = \frac{\partial\bar{\theta}}{\partial z} + \frac{\partial\theta'}{\partial z} = 0$$

where $\bar{\theta}$ and θ' are the background and disturbance potential temperature. The altitude where wave breaking will occur can be estimated from the linear solution.
The hydrostatic relationship in terms of the geopotential Φ

$$\frac{\partial\Phi}{\partial z} = RT/H = \frac{R}{H}\theta \mathrm{e}^{-(z-z_0)R/c_p H}$$

Separating $\Phi = \bar{\Phi} + \Phi'$ with

$$\Phi' = \Phi_0 \exp[(z - z_0)/(2H) + i(kx + mz - \omega t)]$$

and differentiating gives $\partial\theta/\partial z = 0$ when

$$N^2 = m^2 \Phi_0 \mathrm{e}^{z/2H}$$

So the breaking level is given by $z_b \simeq 2H \ln\left|N^2 m^{-2} \Phi_0^{-1}\right|$ where Φ_0 is the wave amplitude at the reference level z_0.
For larger Φ_0 or larger m (smaller vertical wavelength), wave breaking is lower in the atmosphere. Since

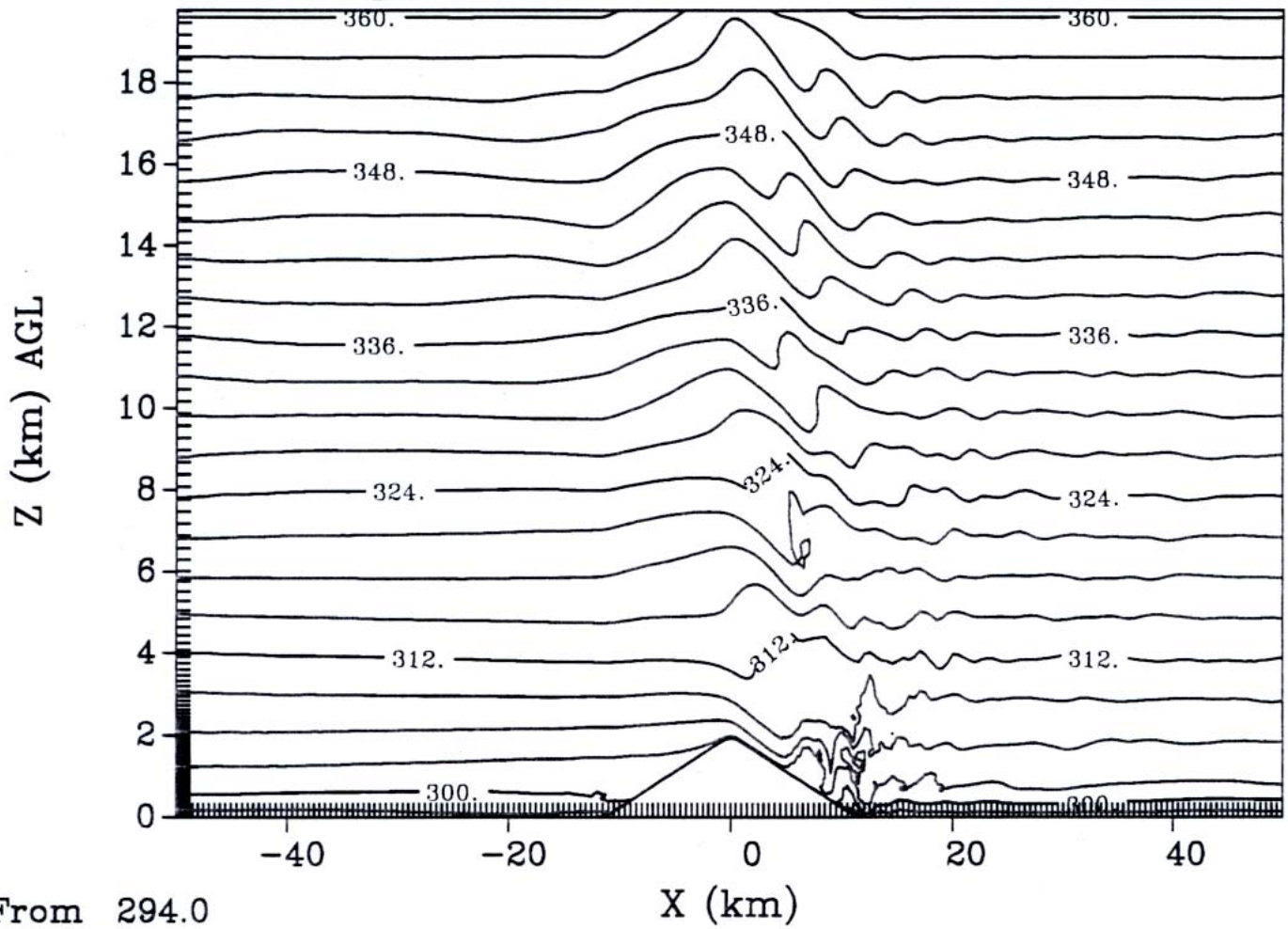
$$m \simeq \pm \frac{N}{c - \bar{u}}$$

even small amplitude waves break as they approach a critical level.

12/01/95
Grid 1
050000 UTC

Kat + and Mountain Wave only

2000m 10deg mtn dX500-125m dZ20-5m nest



From 294.0
to 360.0
by 3.0

Potential Temperature (K)

Model start 12/01/95 0300 UTC Y= .00 km

Gravity Wave Effects on the Atmosphere

Gravity waves carry momentum and energy vertically. Breaking or dissipation drives mean flow accelerations and can have vertical mixing and heating effects on the background atmosphere. Body force on the mean flow:

$$\bar{X} = -\frac{1}{\bar{\rho}} \frac{\partial M}{\partial z}$$

where $M = \bar{\rho}\overline{(u'w')}(1 - f^2/\hat{\omega}^2)$. M is -1 times the gravity wave component of the EP-Flux. $M > 0$ (< 0) for eastward (westward) propagating waves. $\bar{X}$ always in the direction of wave propagation. (Transience and nonlinearities can give rise to secondary wave emission from the breaking region.)

The EP-Flux is approximately conserved as a gravity wave propagates vertically. Then $\bar{X} \propto \bar{\rho}^{-1}$ means that very small amplitude waves in the troposphere can have huge effects in the mesosphere.

Stratosphere winds are eastward in winter, westward in summer. These winds filter the gravity wave spectrum such that westward propagating waves break in the mesosphere, eastward in summer. Resulting drag forces, through Coriolis torques, drive a summer-to-winter meridional circulation,

$$\partial \bar{u}/\partial t - f\bar{v}^* = \bar{X}$$

Atmospheric Gravity Wave Scales:

Horizontal wavelengths $\sim 10 - 1000$s km

Vertical wavelengths $\sim 1 - 30$ km, and possibly longer

Periods:

Intrinsic frequency $f < \hat{\omega} < N$

So $2\pi/\hat{\omega} \sim 5$ min $-$ several days

Observed from ground $\omega = \hat{\omega} + \bar{u}k$

Can extend outside this range

Phase speeds $\sim 0 - 100$ m/s, and possibly higher

Gravity Waves in Vertical Shear U(z)

Simplified linear theory gives insight into the effects of background wind and stability variations on gravity waves as they propagate vertically:

$$\text{Intrinsic frequency} \qquad \hat{\omega} = \omega_0 - kU(z) \sim \frac{N(z)k}{m(z)}$$

$$\text{Vertical wavelength} \qquad \lambda_Z(z) \sim \hat{c}(z)\frac{2\pi}{N(z)}$$

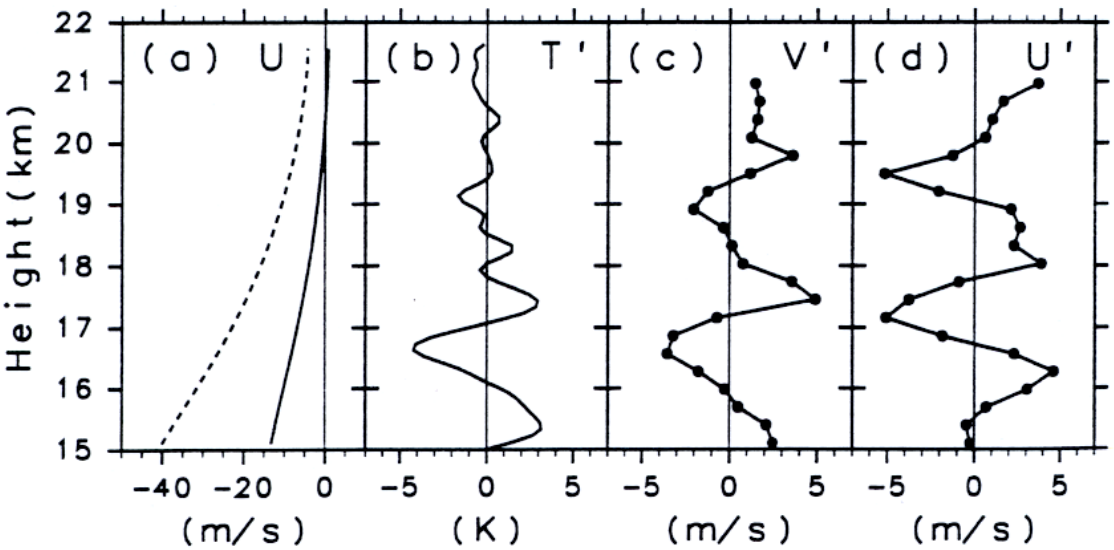
Intrinsic phase speed $\hat{c} = c - U(z)$

Critical level: $\hat{c} = c - U(z) \to 0$

horizontal wn $= k$, vertical wn $= m$, buoyancy freq $= N$

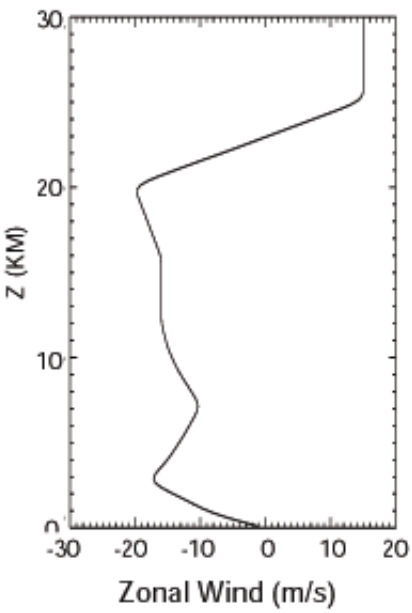
Observation of a gravity wave approaching a critical level [Sato and Yamada, 1994]:

For this case $c \sim 0$ so $\lambda_Z \to 0$ as $U(z) \to 0$.

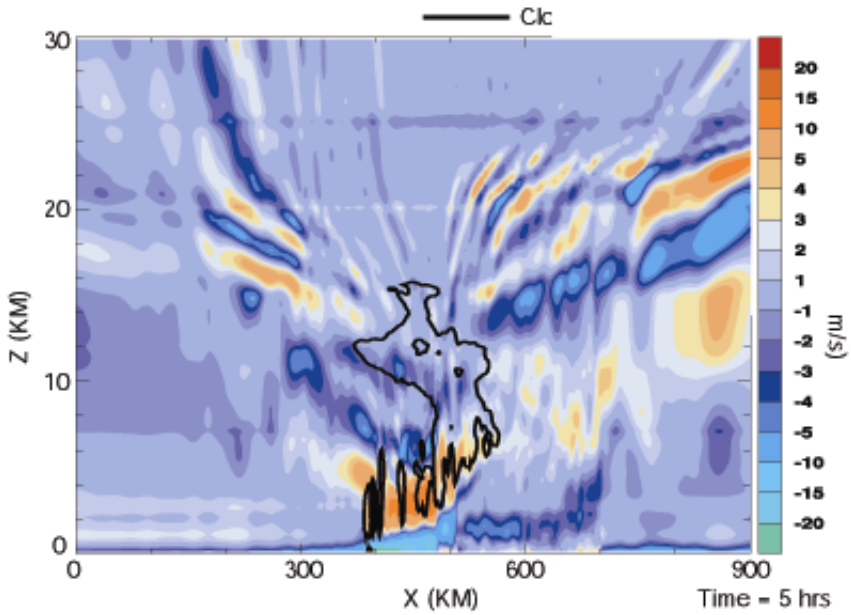


Doppler-Shifting / Refraction Effects

Strong Stratospheric Shear



Simulation of gravity waves generated by convection showing refraction of waves in the stratosphere :



Mean Flow U(z) Effects: Doppler-shifting and Refraction

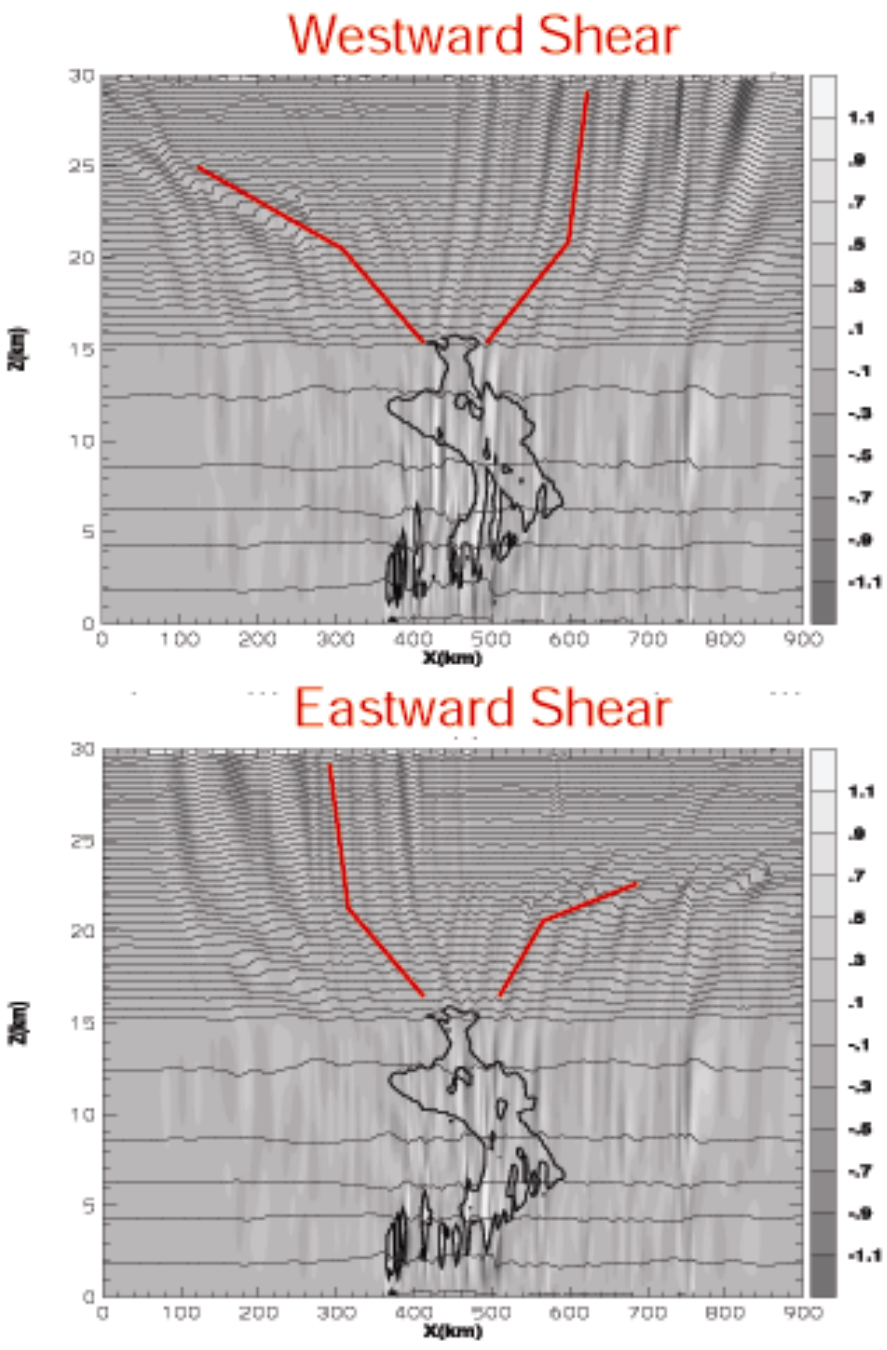
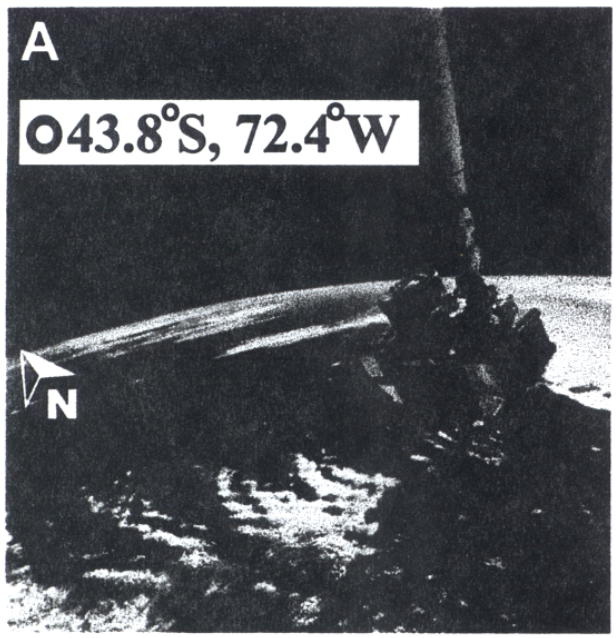
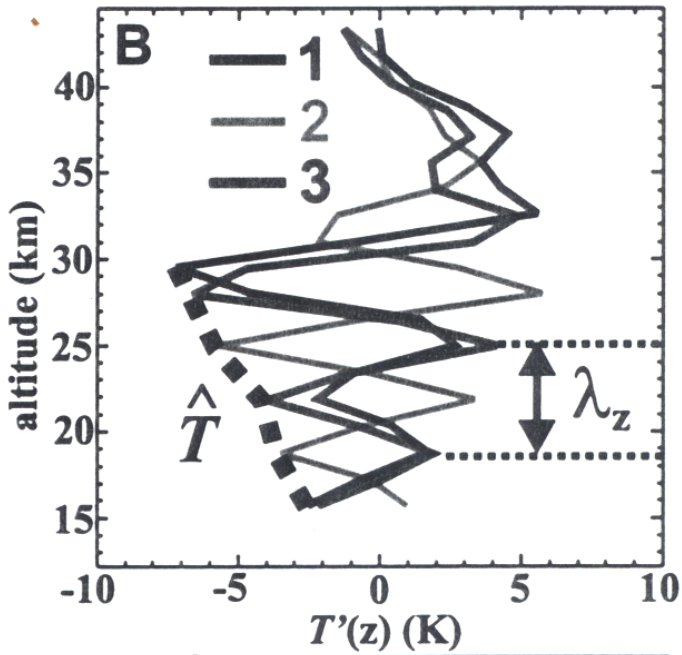


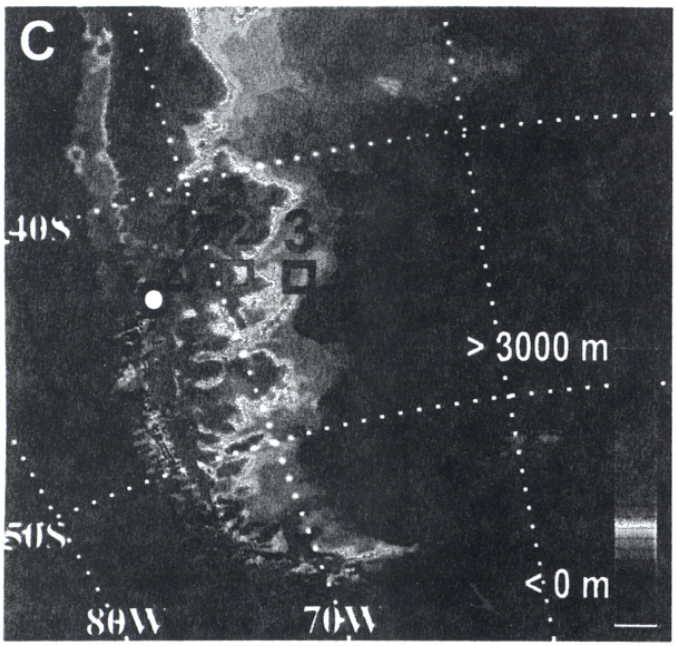
Figure 3. Two-dimensional simulations of tropical squall lines [Alexander and Holton, 1997]. The simulations are identical except for the shear in the stratosphere above 15 km altitude. (a) Case with easterly shear above 20 km. (b) Case with westerly shear above 20 km. The thick solid lines show the outline of the cloud water, the thin lines show potential temperature surfaces at 10K intervals, and the shading represents vertical velocity. The vertical velocity scale saturates at +/- 1.3 m/s to show detail in the stratosphere. Peak values in the troposphere are actually larger at +/- 5 m/s.

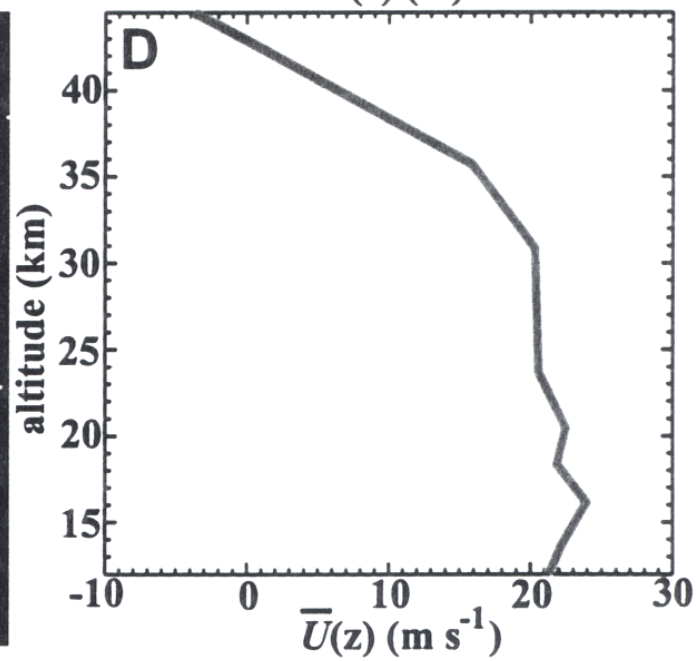
CRISTA

Eckermann & Preusse (1999)









Gravity Wave Sources

1. Topography
   - only stationary waves c=0
   - mainly northern hemisphere winter
   - note that the mesosphere effects depend on wave "saturation" assumptions

2. Jet instability
   - again mostly winter hemisphere
   - also more prevalent in northern hemisphere?

3. Convection
   - can produce high phase speed waves
   - will be common in the tropics & summertime extratropi
   - large momentum fluxes have been observed

4. Other
   shear generation, geostrophic adjustment, wave-wave interactions, secondary wave emission from wave breaking regions

Global Distribution of Topographic Waves

Bacmeister's [1993] topographic ridge-finding algorithm

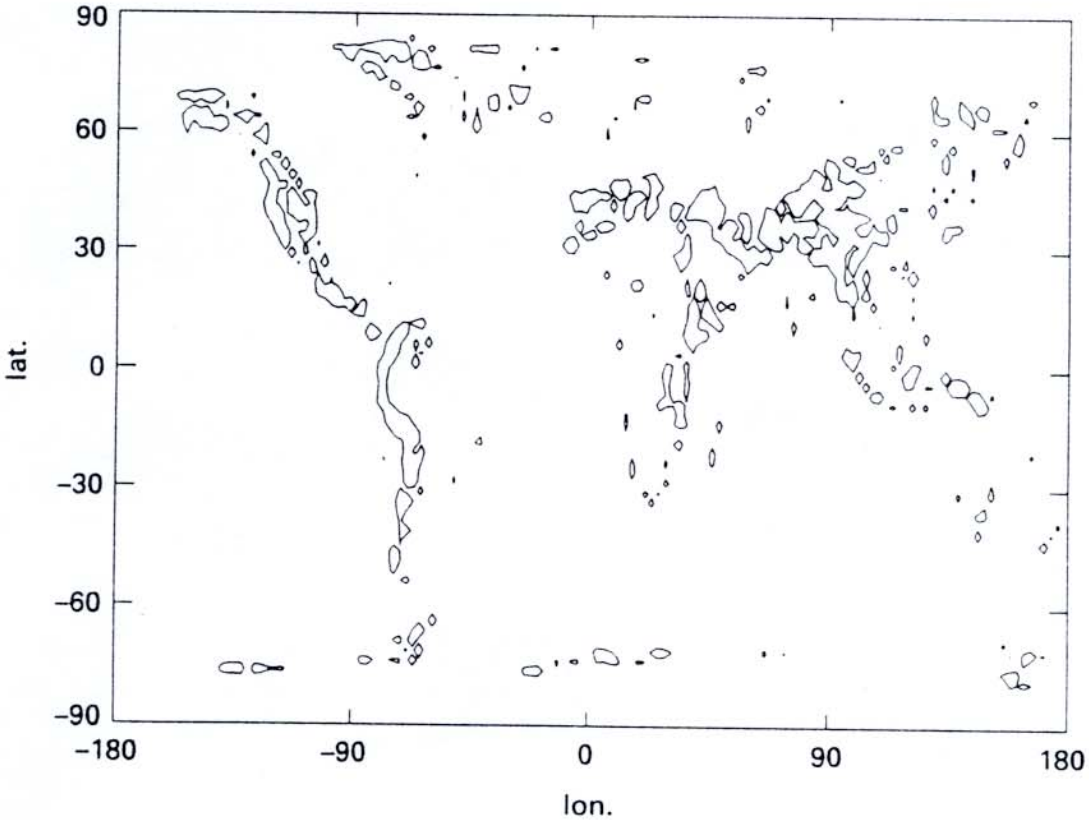


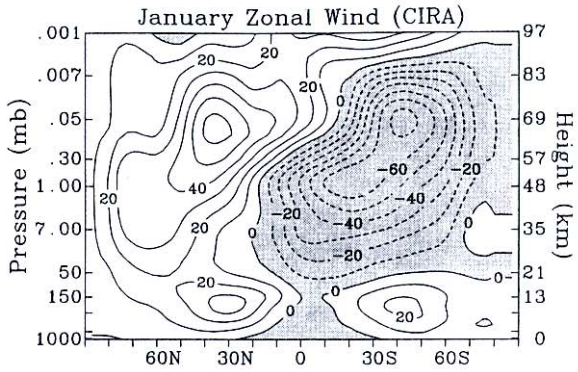
FIG. 3. Fractional area of 2.5° × 2.5° analysis boxes containing vertically propagating mountain waves S_w, which depends on a, as described in Eq. (4) of the text. Only 0.5 contour is drawn in the figure. This represents the maximum fractional area with waves allowed in the new parameterization.

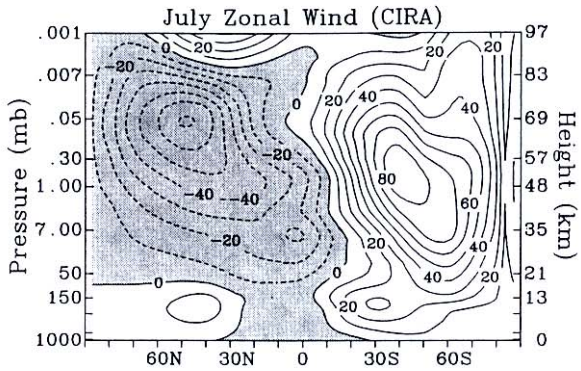
- Topography is a geographically limited wave source.
- Most sources are in the Northern Hemisphere.
- Stationary (c=0) mountain waves can only propagate through the stratosphere in winter.

Results from the Canadian Middle Atmosphere Model (CMAM) [McLandress, 1998]

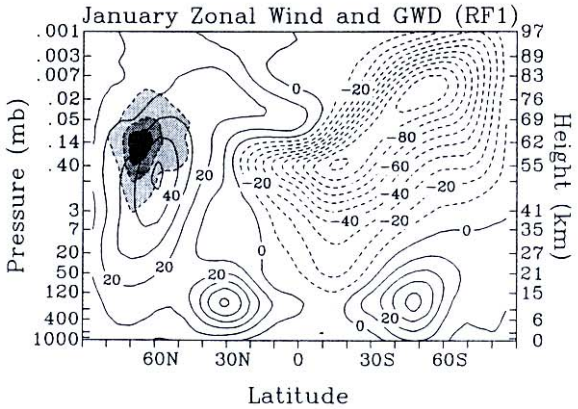
Includes topographic sources with a Lindzen-type [McFarlane, 1987] parameterization of gravity wave drag.

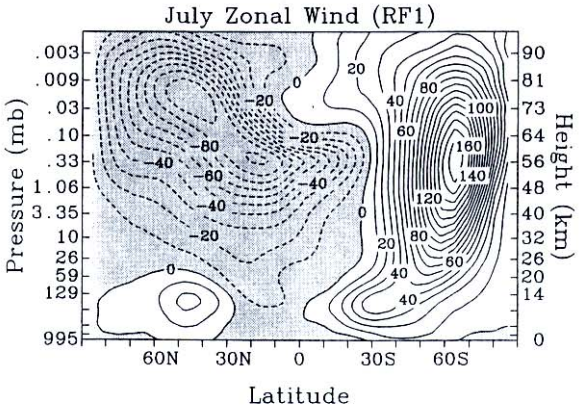
OBSERVATIONS



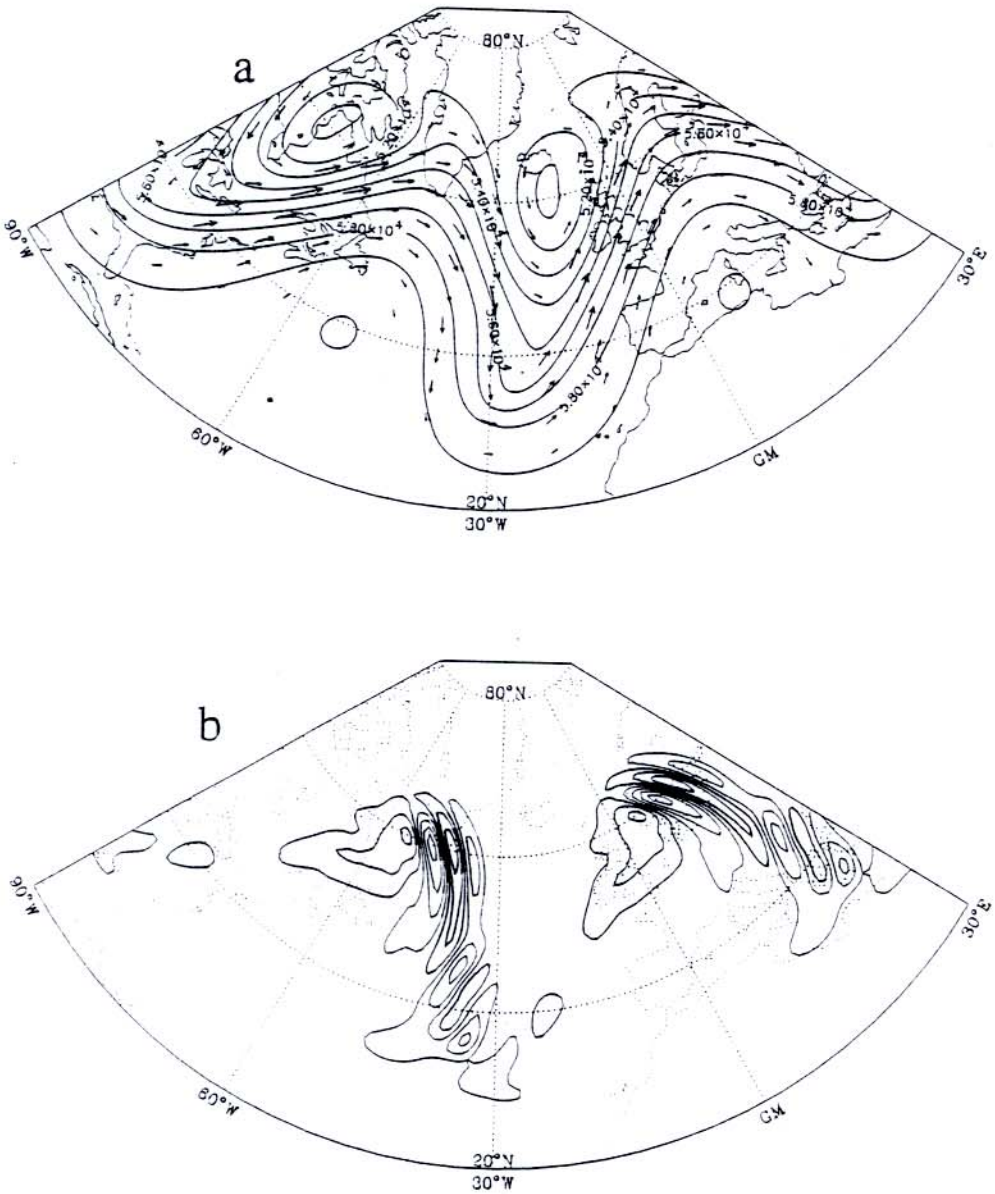


CMAM RESULTS

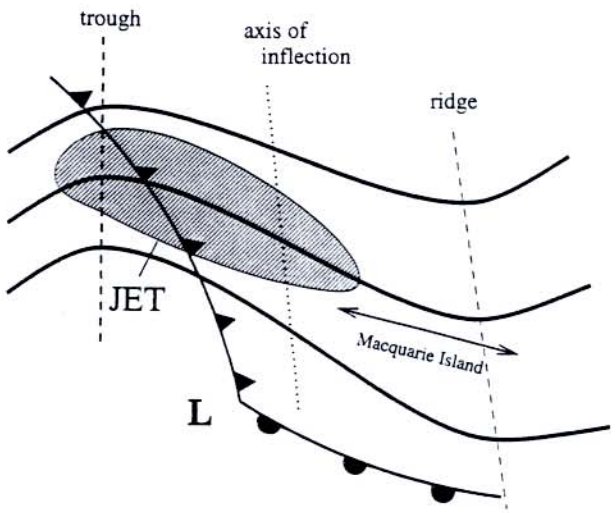




Model of jet stream baroclinic instability
[O'Sullivan and Dunkerton, 1995]



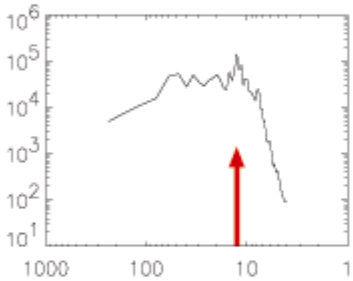
Similar to inferred source of inertia-gravity waves over Macquarie Island (55 S latitude) [Guest et al., 2000]



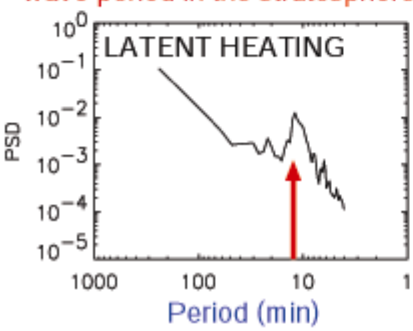
Numerical Simulations of Convection suggest relationships between:

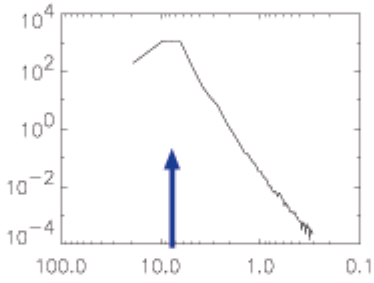
- -The storm characteristics, and
- -The characteristics of the waves generated in the stratosphere

VERTICAL VELOCITY POWER SPECTRA OF WAVES IN THE STRATOSPHERE:

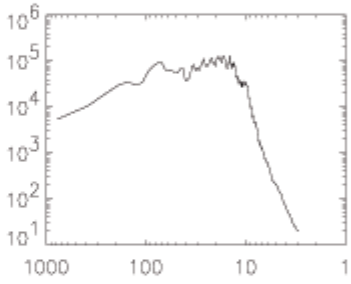


The period of Latent Heating oscillations matches the dominant wave period in the stratosphere:





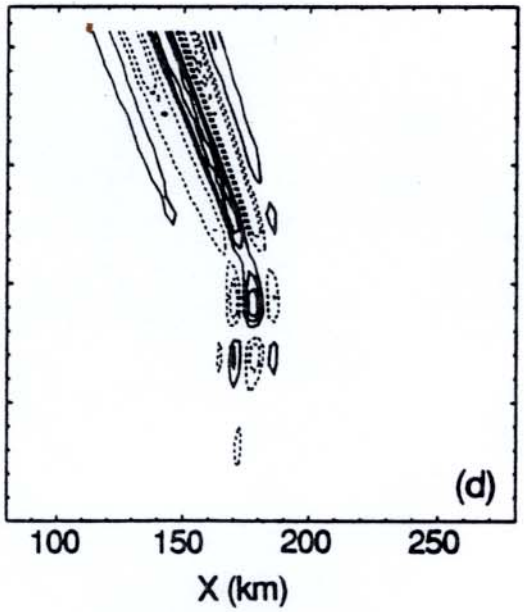
The dominant vertical wavelength in the wave spectrum is related to the depth of the latent heating in the storm.

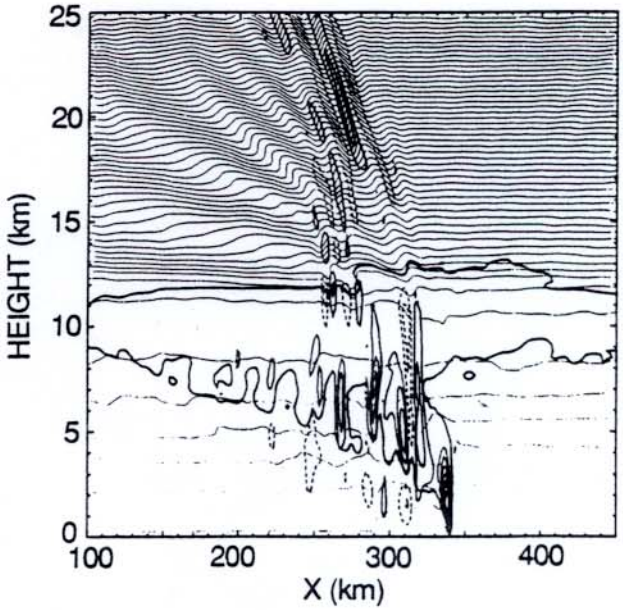


The horizontal wavelength spectrum is broad and is shaped by nonlinear processes in the numerical model.

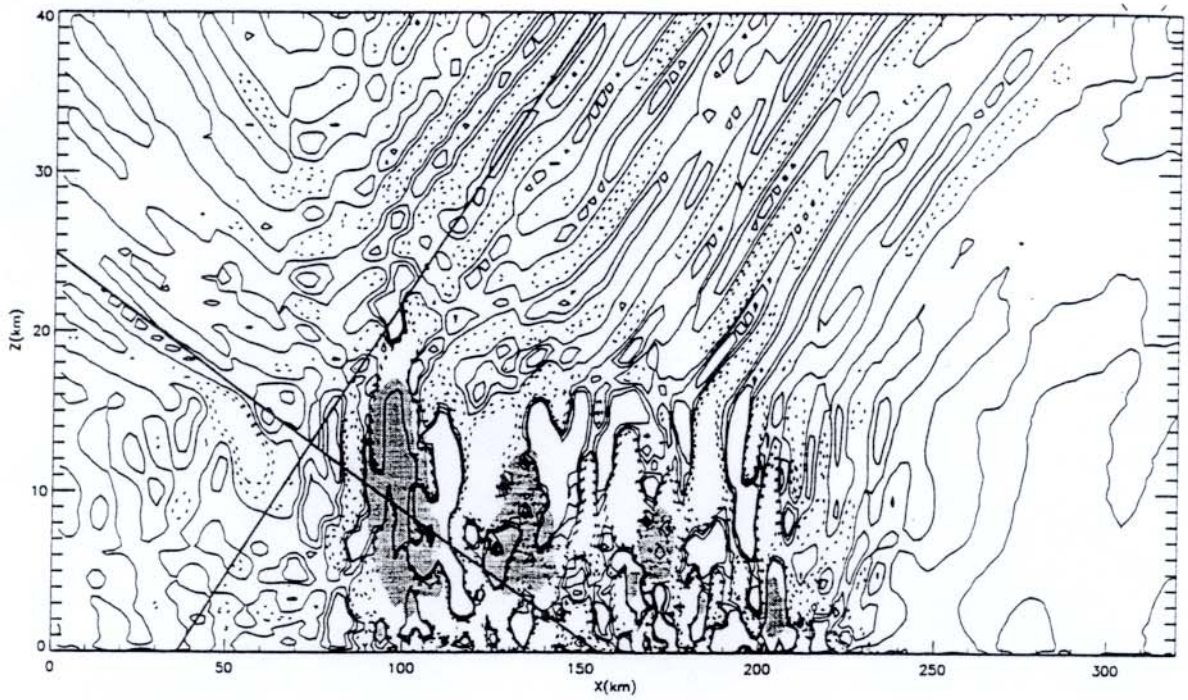
"Mechanical Oscillator" Mechanism

Fovell et al. (1992): 2-D Linear Mechanistic Model





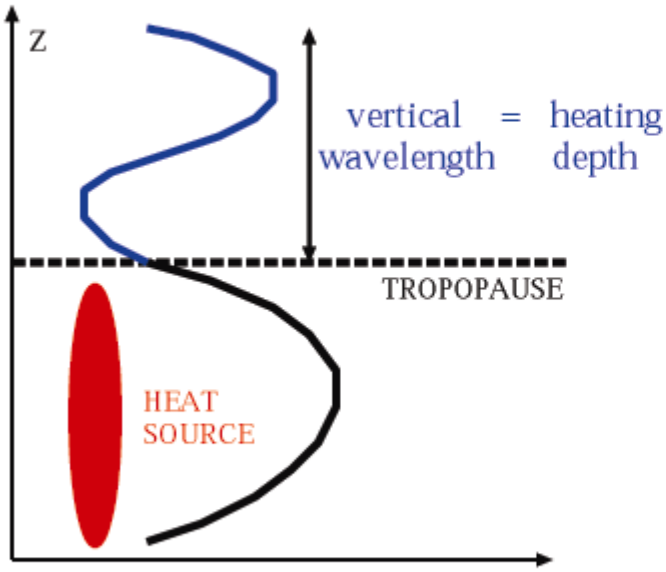
Lane et al. (1999): 3-D Numerical Simulation



Deep Heating Mechanism for Convectively Generated Waves

Salby & Garcia (1987)

For buoyancy frequency increase by 2X across the tropopause:

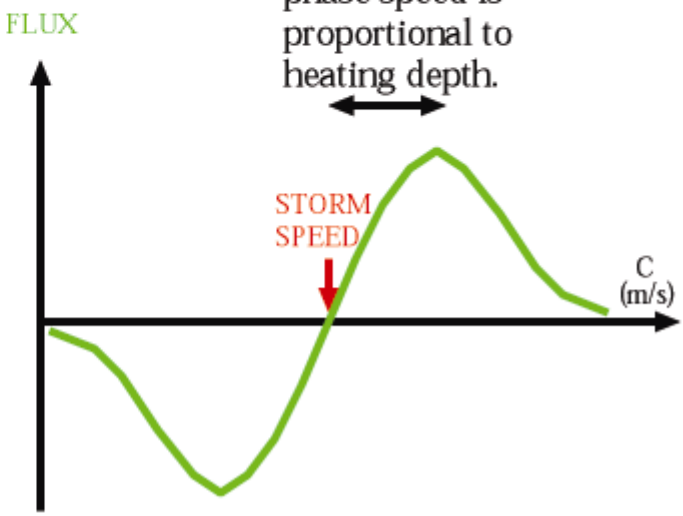


Gravity wave dispersion relation:

$\lambda_z \propto |c-U| / N$

MOMENTUM FLUX SPECTRUM

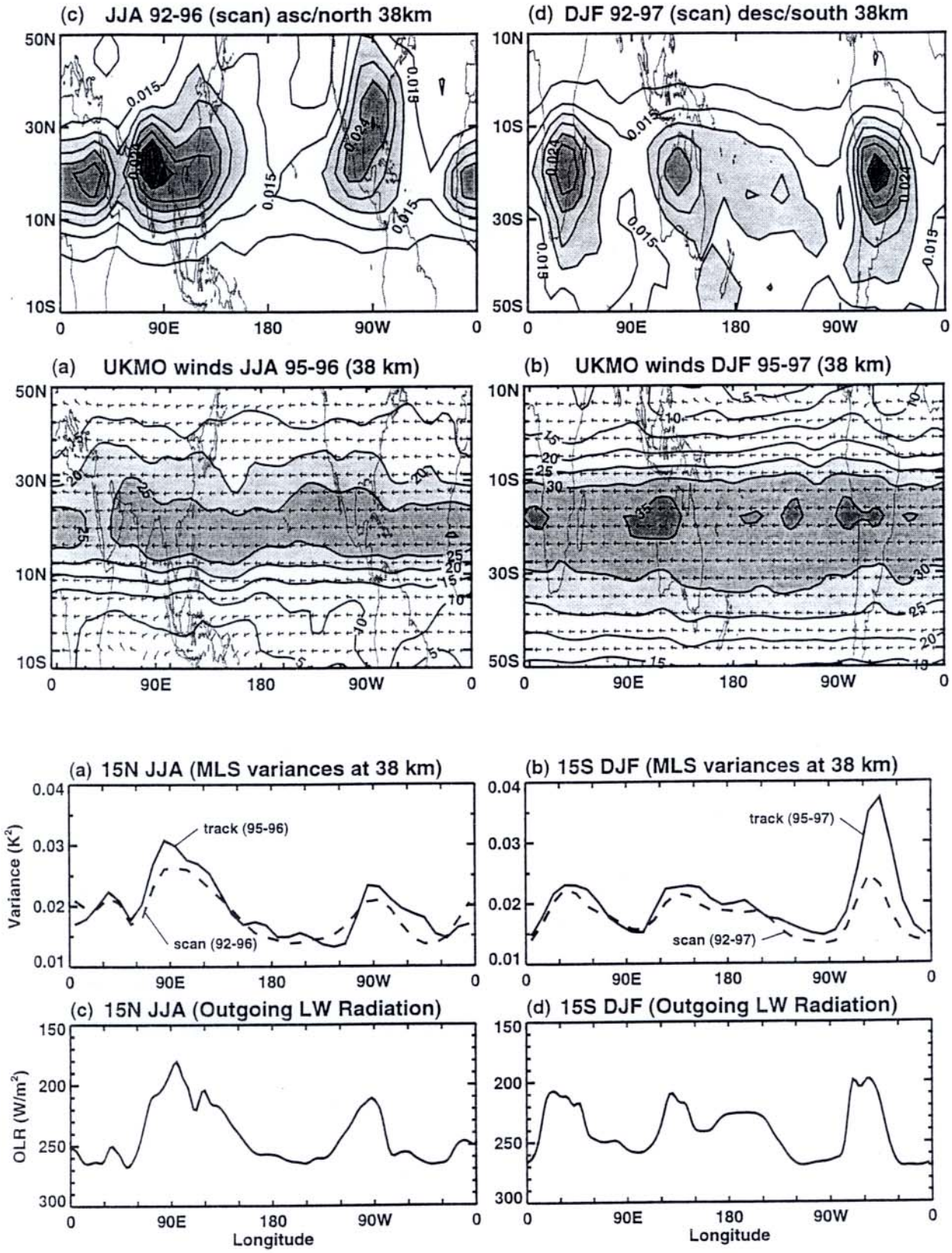
Peak storm-relative phase speed is proportional to heating depth.



MLS Temperature Variance - Summer Subtropics

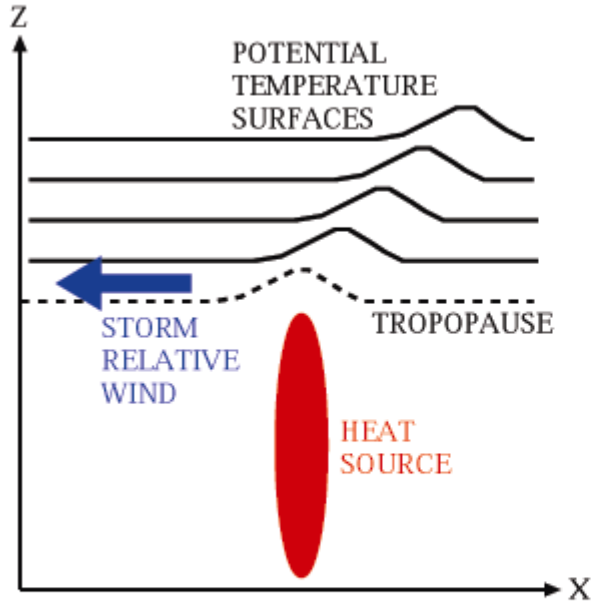
McLandress et al. [2000]

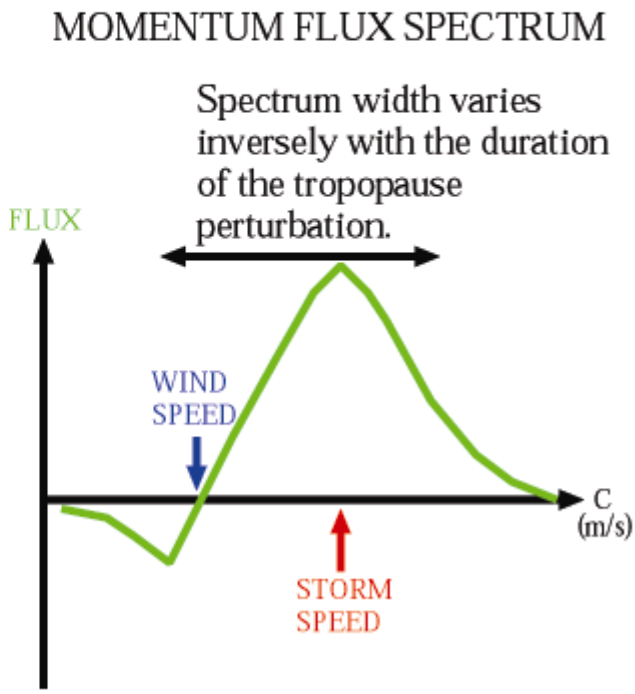
NH SH



"Transient Mountain" Mechanism for Convectively Generated Waves

Pfister et al., JGR, 1993; Pfister et al., JAS, 1993





Steady heating assumption --> moving mountain

Chun and Baik [1998; 2002] Parameterization

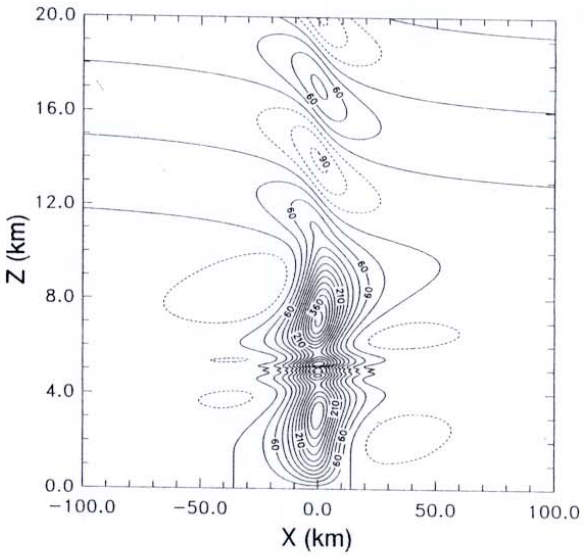


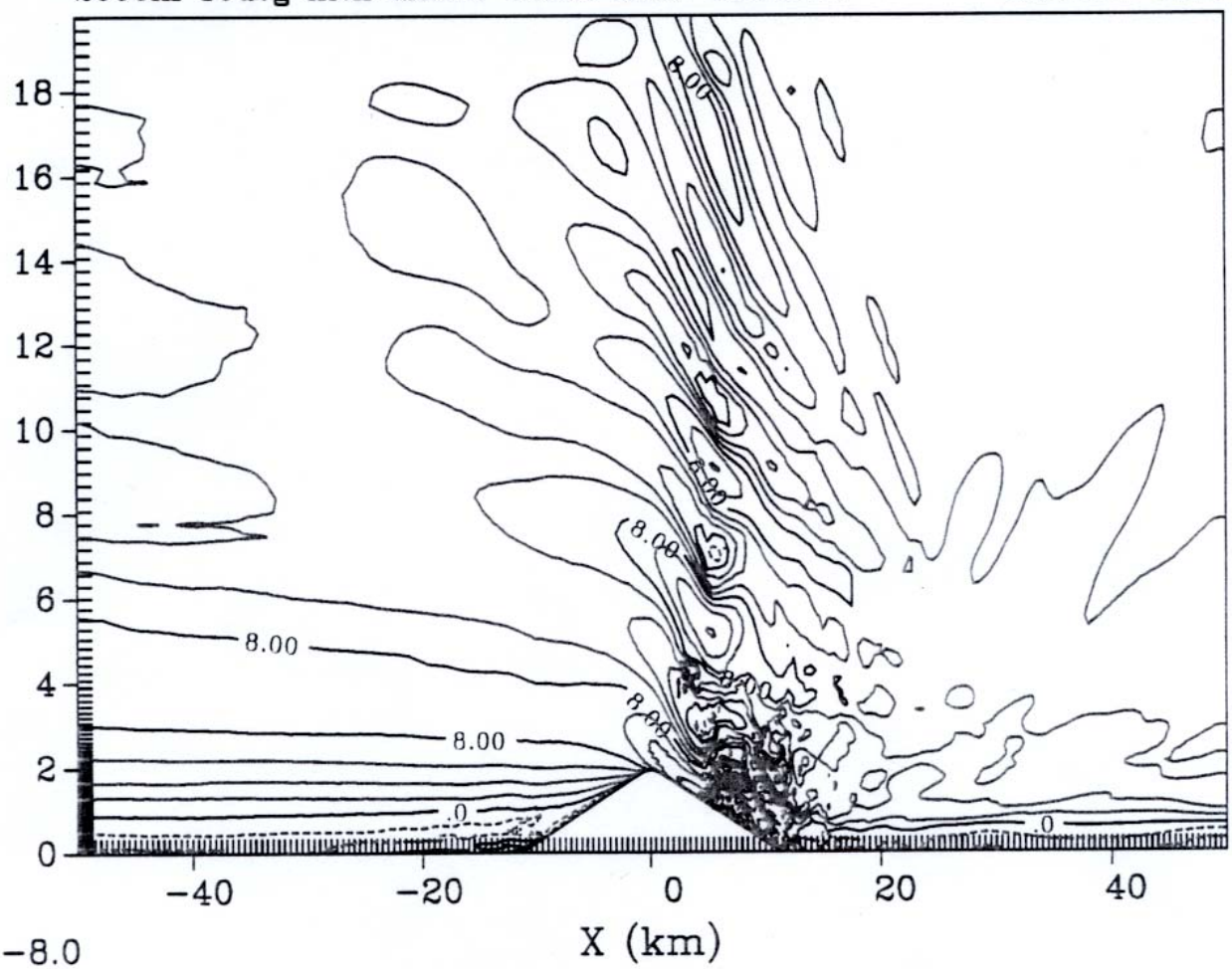
FIG. 2. Perturbation vertical velocity field by (9). The parameters used are $z_1 = 1.5$ km, $z_t = 11$ km, $z_c = 5$ km, $N_1 = 0.01$ s^{-1}, $N_2 = 0.02$ s^{-1}, $U_t = 20$ m s^{-1}, $Q_0 = 1$ J kg^{-1} s^{-1}, $a_1 = 10$ km, $a_2 = 5$ a_1, and $T_0 = 273$ K. The Richardson number associated with the basic flow is 9. The contour interval is 0.03 m s^{-1}.

- Assumes convective heating Q is steady, dQ/dt=0
- Waves are generated when there is a topside wind relative to the heating
- Response looks like mountain wave with c=storm propagation speed
- Models show this can be important for long-lived storms
- Observations suggest this as a viable mechansism for large-scale waves

12/01/95
Grid 1
050000 UTC

Kat + and Mountain Wave only

2000m 10deg mtn dX500-125m dZ20-5m nest



From -8.0
to 16.0
by 2.0

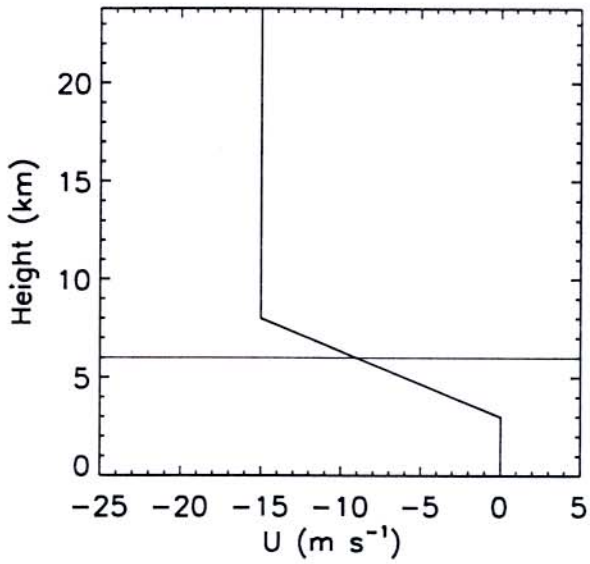
U-component wind (ms^{-1})

Model start 12/01/95 0300 UTC Y= .00 km

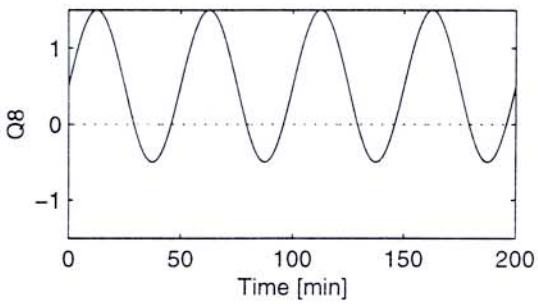
Simulations of Wave Generation by Convective Heating [Beres et al., 2002]

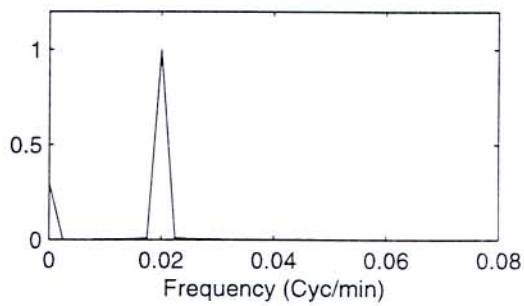
Isolated heat source
$0 < z < 6$ km

Two cases:
w/ and w/out upper-level wind shear



Heating has both an oscillating and a stationary component

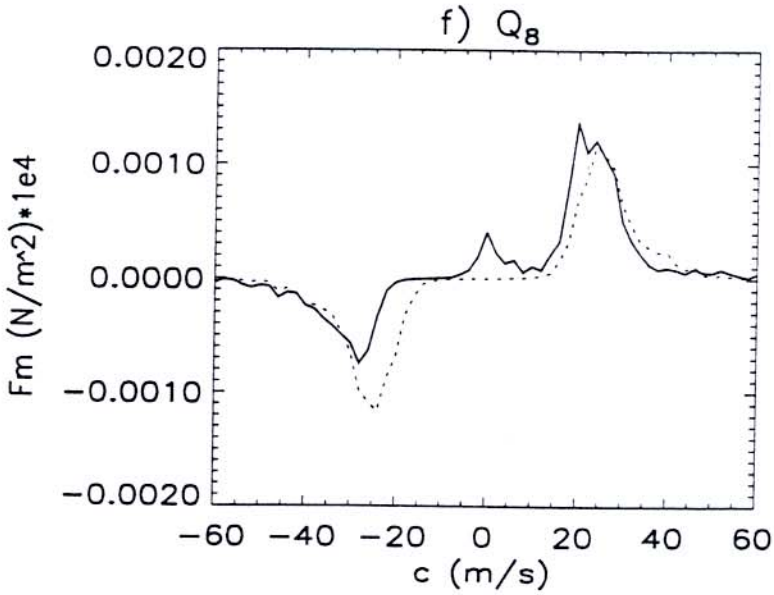




The response changes with the shear:

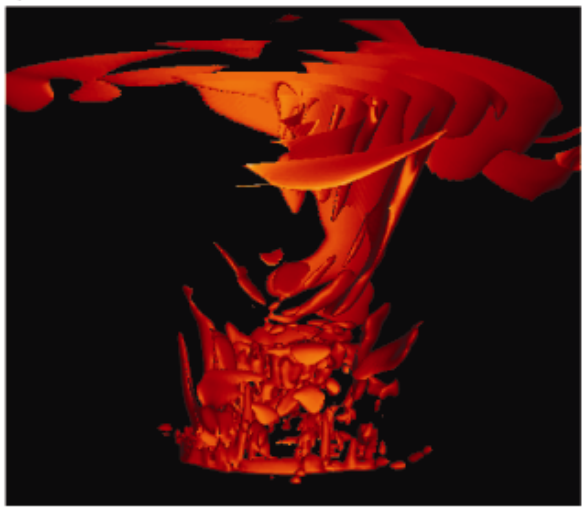
1. filtering of westward waves

2. generation of stationary waves

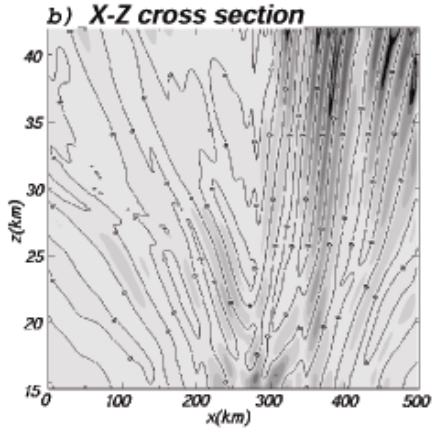


Gravity Waves above a Storm in a Numerical Model (Piani et al., 2000)

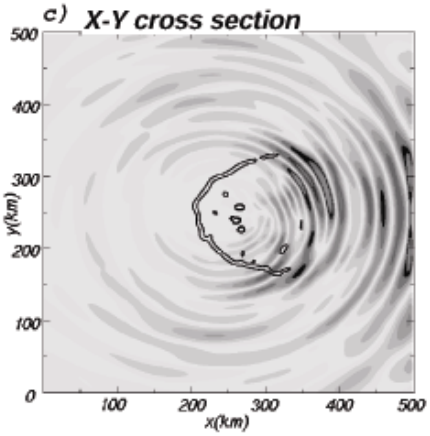
a) View from the SW of the w'=0.1 m/s isosurface.



b) X-Z cross section

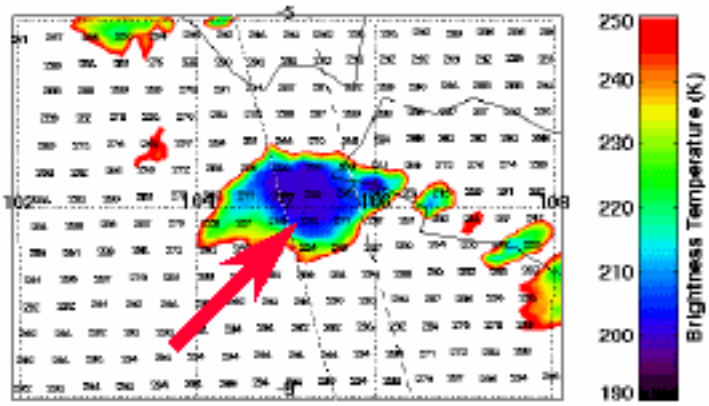


c) X-Y cross section

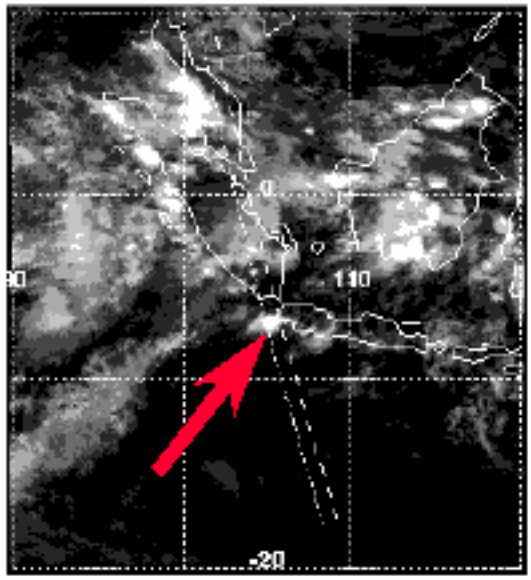


Dewan *et. al.* (1998)

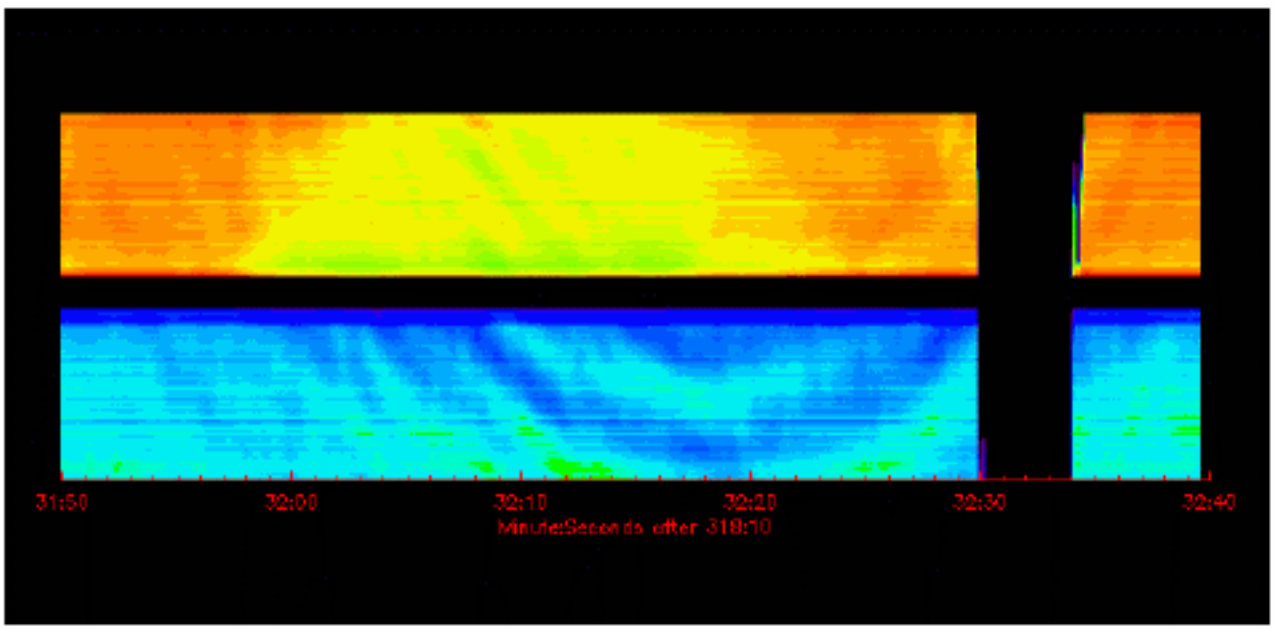
Geophysical
Research
Letters



Track of MSX image, 40 km altitude
..... Bottom edge --- Top edge



GMS 5 IR1 band (11μm): 09:32 UT November 13, 1996



MSX SPIRIT III (4.3 μm) : 10:32 UT November 13, 1996

APRIL 1, 1998 Volume 25 Number 7

AMERICAN GEOPHYSICAL UNION

Ongoing Research and Anticipated Future Directions

- Numerous spectral gravity wave parameterizations available that are being tested in different global models

- New satellite observation analysis techniques to detect small-scale perturbations

- New space-based observation techniques

- Availability of other new global data sets

- Several recent and planned campaigns will provide insight into gravity wave generation mechanisms and vertical propagation into the middle atmosphere