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4. GRAVITY WAVES AND TURBULENCE IN THE MIDDLE ATMOSPHERE PROGRAM (GRATMAP)

4.1 AN OVERVIEW OF GRAVITY WAVE STUDIES DURING MAP/MAC

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Considerable progress has been made in understanding gravity waves and their effects in the middle atmosphere during the MAP and MAC periods. During this time, gravity waves have been recognized to play a central role in controlling the large-scale circulation and the thermal and constituent structure of this region through wave transports of energy and momentum, a significant induced meridional circulation, and through the action of wave-induced turbulence. Both theoretical and observational studies also have contributed to our understanding of the gravity wave spectrum, its temporal and spatial variability, and the processes responsible for wave saturation. As a result, we are beginning to understand the propagation, interactions, and detailed effects of such motions in the middle atmosphere. This talk will provide an overview of this work and a lead-in to the review talks that follow.

Gravity Wave Overview

- Advances in observational capabilities

- Understanding of gravity wave propagation, saturation, and effects

- Large-scale middle atmosphere effects of gravity waves and turbulence

- Gravity wave variability

- Future directions

Gravity wave scales, fluxes and saturation	I. M. Reid
Turbulence, evolution and varaibility	W. K. Hocking
Gravity wave spectral understanding	T. E. VanZandt

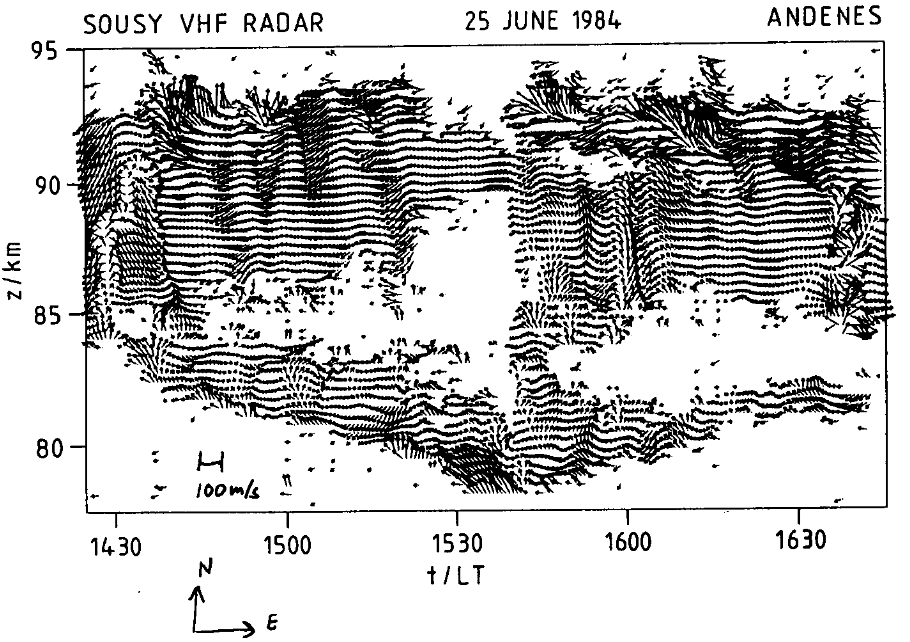


Figure 1. Time-height cross section of horizontal wind observed with the SOUSY radar during June 1984 exhibiting MAP/MAC remote sensing capabilities [Reid et al., submitted 1988].

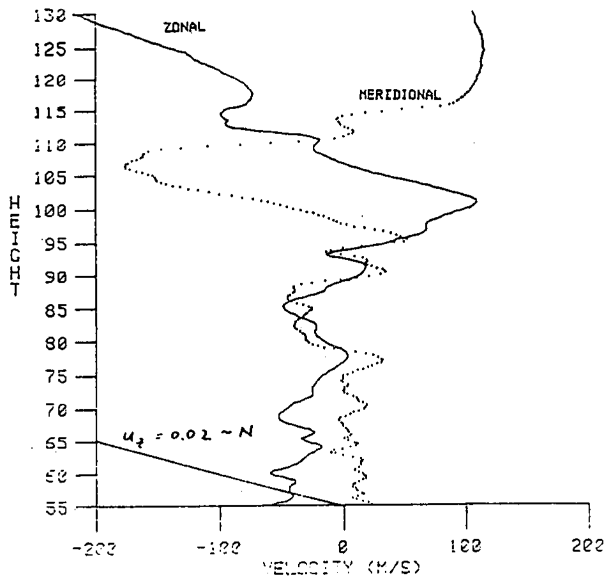


Figure 2. Vertical profiles of zonal and meridional winds from active falling sphere obtained during the STATE experiment [Fritts et al., *J. Geophys. Res.*, 1988].

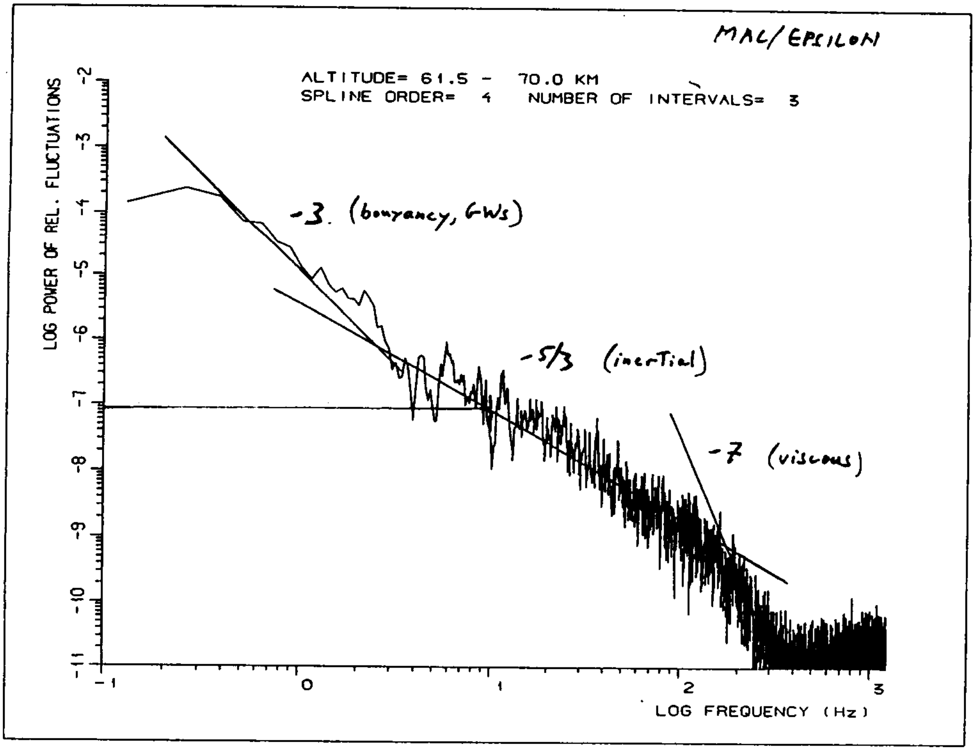


Figure 3. Frequency spectrum of ion fluctuations obtained by positive ion probe during MAC/Epsilon experiment showing in situ small-scale measurement capabilities [Thrane et al., 1988, in preparation].

Gravity Wave Saturation

Structure

$u' \sim m^{1/2}\, e^{z/2H}\, e^{i\phi}$

$\theta'_z/\theta = -\, u'/(c-\bar{u})$

Linear saturation theory

m or z increasing ⇒ wave growth and instability

1. Dynamical (KH or shear) instability

$$Ri = \frac{\frac{g}{\theta}\frac{\partial \theta}{\partial z}}{(u_z^2 + v_z^2)} < 1/4$$

2. Convective instability

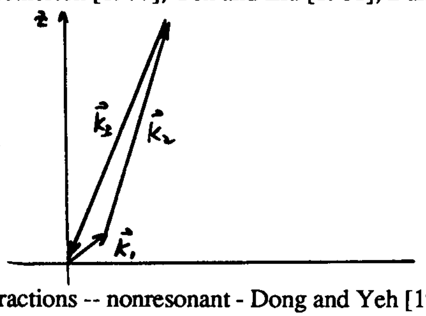
$$\frac{\partial \theta}{\partial z} < 0,\ \frac{u'}{(c-\bar{u})} > 1 \qquad \text{- vertical}$$

$$\frac{\partial \theta}{\partial z} < 0 \qquad \text{- slantwise}$$

⇒ amplitude limits $u' \sim c - \bar{u} \sim N/m$ or $u'_z \sim N$

Nonlinear theory

3. Wave-wave interactions -- resonant and nonresonant
   - Parametric subharmonic instability (PSI)
     McComas and Bretherton [1977], Yeh and Liu [1981], Dunkerton [1987].



4. Wave-vortical mode interactions -- nonresonant - Dong and Yeh [1987]

$$\frac{u'}{(c-\bar{u})} > \sqrt{2} \qquad \text{- less restrictive than linear instabilities}$$

Figure 4. Illustration of linear gravity wave structure and conditions from "linear" saturation; Schematic of nonlinear wave-wave interactions (PSI) and wave-vortical mode threshold for nonlinear wave saturation.

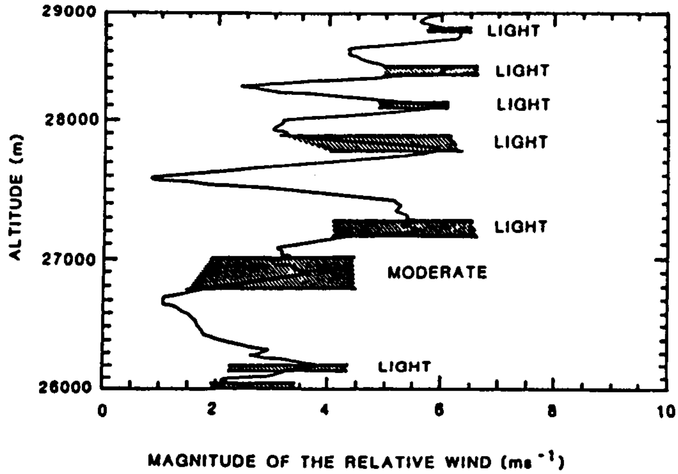


Figure 5. Correlation of turbulence occurrence with preferred sites within wave field suggesting linear rather than nonlinear saturation processes [Sidi and Barat, *J. Geophys. Res.*, 1986].

<u>Gravity Wave Fluxes</u>

Momentum flux: $\overline{u'w'} \sim \frac{\omega}{N}\,\overline{u'^2}$

Energy flux: $c_{gz}\,E \sim \frac{\omega}{N}(c - \bar{u})\,\overline{u'^2}$

$\Rightarrow$ dominant fluxes by gravity waves with large u' or λ_z.

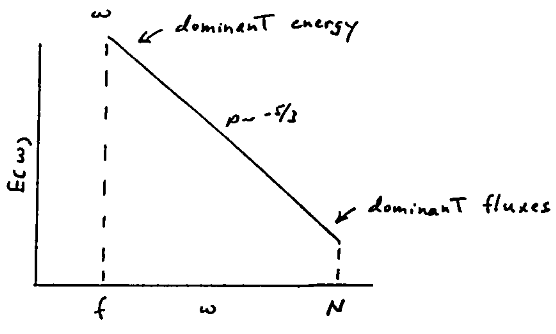


Figure 6. Schematic of gravity wave fluxes and their dominance by high frequency motions.

A Saturated Gravity Wave Spectrum: Saturation Conditions

Monochromatic wave: $\theta_z = 0 \Rightarrow \bar{\theta}^2/2 = \overline{\theta_z'^2}$

Gravity wave spectrum: $\bar{\theta}_z^2/2 = \int F_{\theta_z}(m)\,dm = \int \frac{m^2\bar{\theta}_z^2}{pN^2} F_u(m)\,dm$

$\Rightarrow$ saturated PSDs are

$F^s_{\theta'/\bar{\theta}}(m) \approx \frac{1}{10}\frac{N^4}{g^2m^2}$ for $\frac{\theta'}{\bar{\theta}}, \frac{T'}{\bar{T}}, \frac{e'}{\bar{e}}$

$F_u^s(m) \approx \frac{p}{10}\frac{N^2}{m^3}$ for u', v'

Variation of Wave Spectrum with N(z)

WKB scaling: $c_{gz} E \approx \frac{\omega}{m} E \sim$ constant (conservative, $\omega \sim$ constant)

$m_{GW} \sim N$

$\Rightarrow$ $E_{GW} \sim m$

Thus $E_{WKB}(m > m_*) \sim N^3$

$E_{SAT}(m > m_*) \sim N^2$

$\Rightarrow$ Increase in N(z) causes:

- enhanced wave dissipation and drag
- adjustment to new saturation spectrum

Consequences of a Saturated Gravity Wave Spectrum

Wave saturation and turbulence throughout atmosphere:

$u'_z, \theta'_z \sim$ bounded, $E(z) \sim e^{z/H_E}$, $H_E \sim 12 - 15$ km

No physical "breaking" level; smooth increase in drag and diffusion

Increases of $N^2(z)$ $\Rightarrow$ enhanced saturation and enhanced drag and diffusion

Figure 7. Derivation of saturated spectrum amplitude following arguments of monochromatic theory [Smith et al., *J. Atmos. Sci.*, 1987] and scaling of wave energy due to changes in $N^2(z)$ showing tendency towards enhanced saturation.

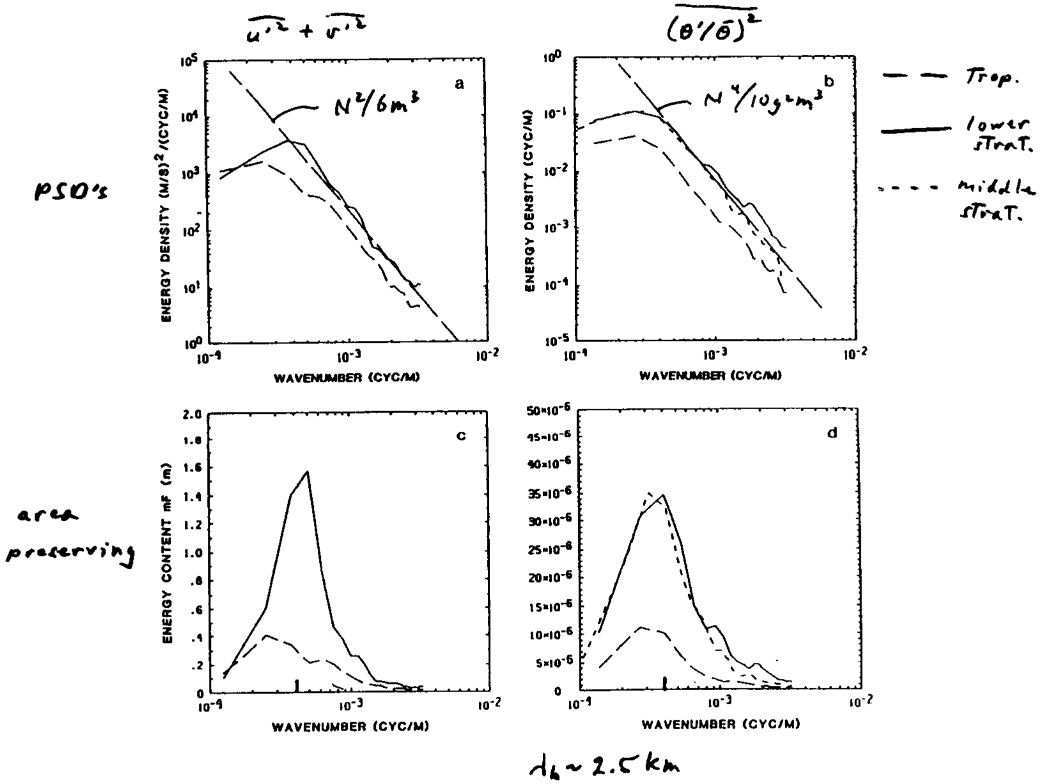


Figure 8. Predicted and observed saturated spectra of velocity and temperature using MU radar and balloon data [Fritts et al., *J. Atmos. Sci.*, 1988].

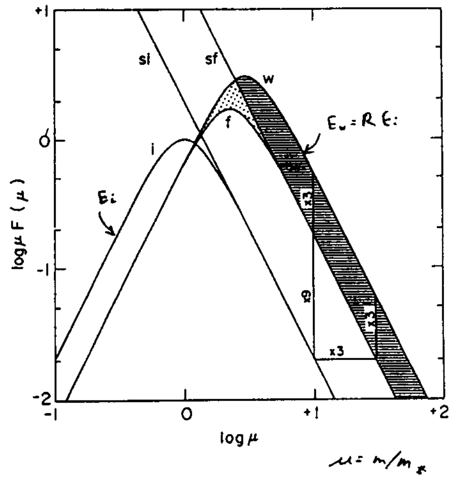


Figure 9. Illustration of the spectral change due to a change of 3 in N(z) and the portion lost (shaded) due to enhanced saturation.

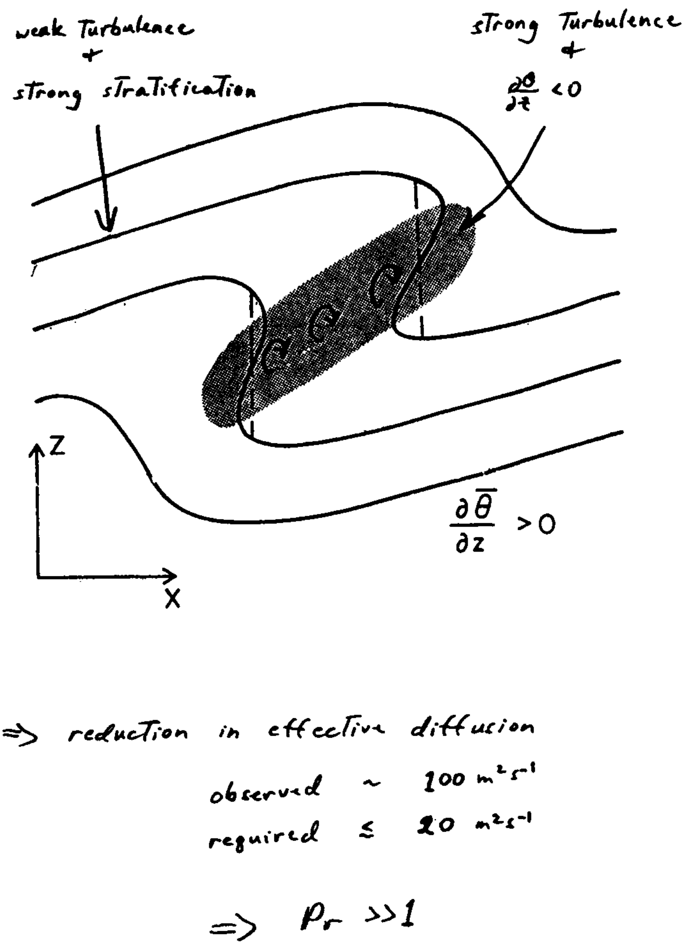


Figure 10. Schematic of localized turbulence leading to an effective Prandtl number greater than 1.

Influences on the Large-Scale Circulation and Structure Gravity Wave Saturation/Dissipation

a. Momentum flux divergence and mean flow acceleration:

$$\frac{\partial}{\partial t}\bar{u} = -\frac{1}{\rho_o}\frac{\partial}{\partial z}(\rho_o\,\overline{u'w'}\delta_-),\ \delta_- = 1 - f^2/\omega^2$$

$$\overline{u'w'},\ \overline{v'w'} \sim 1 - 5\ m^2/s^2$$

$$\bar{u}_t,\ \bar{v}_t \sim 10 - 100\ m/s/day$$

b. Turbulent diffusion:

$K \leq 20\ m^2/s$, seasonally varying

-plays some role, but appears less important now than thought previously.

Gravity Wave Variability

Geographic: Land/sea differences; Latitudinal source differences; Filtering by mean winds

Temporal: Seasonal and planetary wave modulation of sources and filtering; LF modulation of gravity wave energies and fluxes

Figure 11. Effects of wave saturation on the mean structure through momentum flux divergence and turbulent diffusion; Introduction to gravity wave variability.

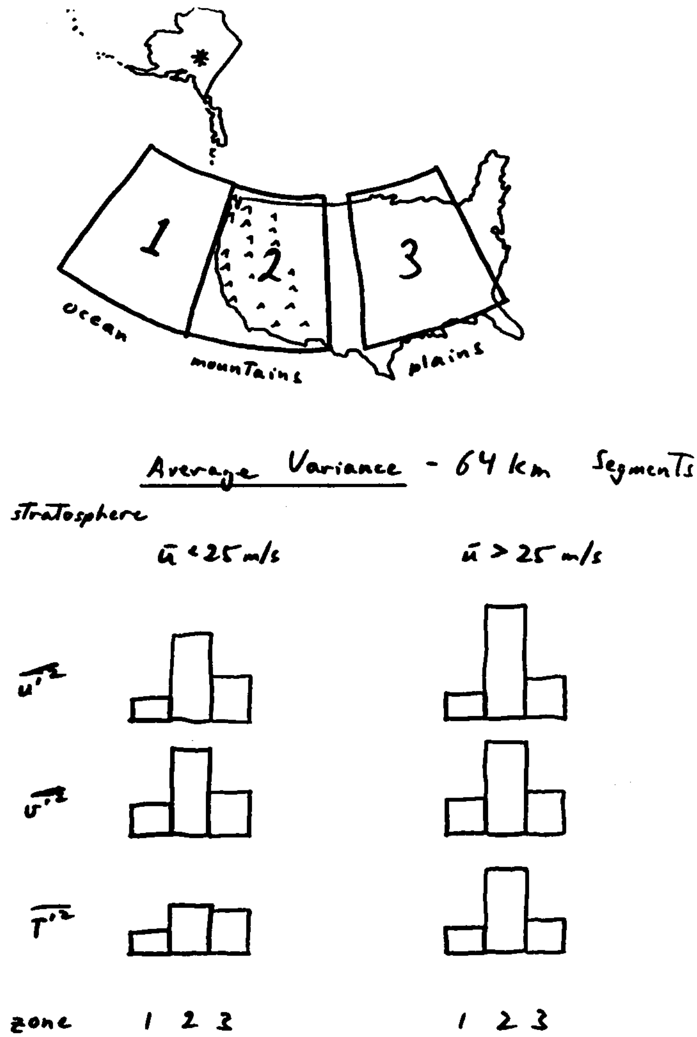


Figure 12. Geographic distribution of horizontal wind and temperature variance obtained with GASP data and suggesting strong topographic forcing [Nastrom et al., *J. Atmos. Sci.,* 1987].

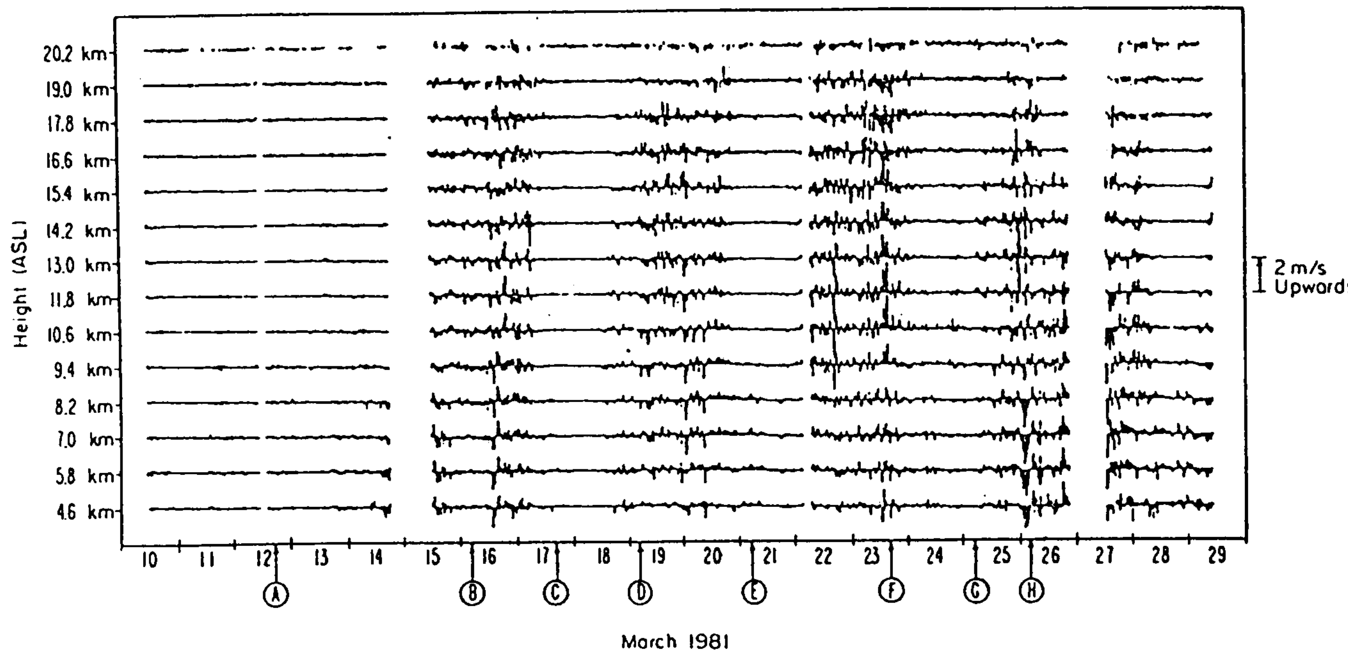


Figure 13. Vertical velocity variability from Platteville radar showing periods of enhanced activity correlating with strong topographic forcing [Ecklund et al, *Mon. Weather Rev.*, 1981].

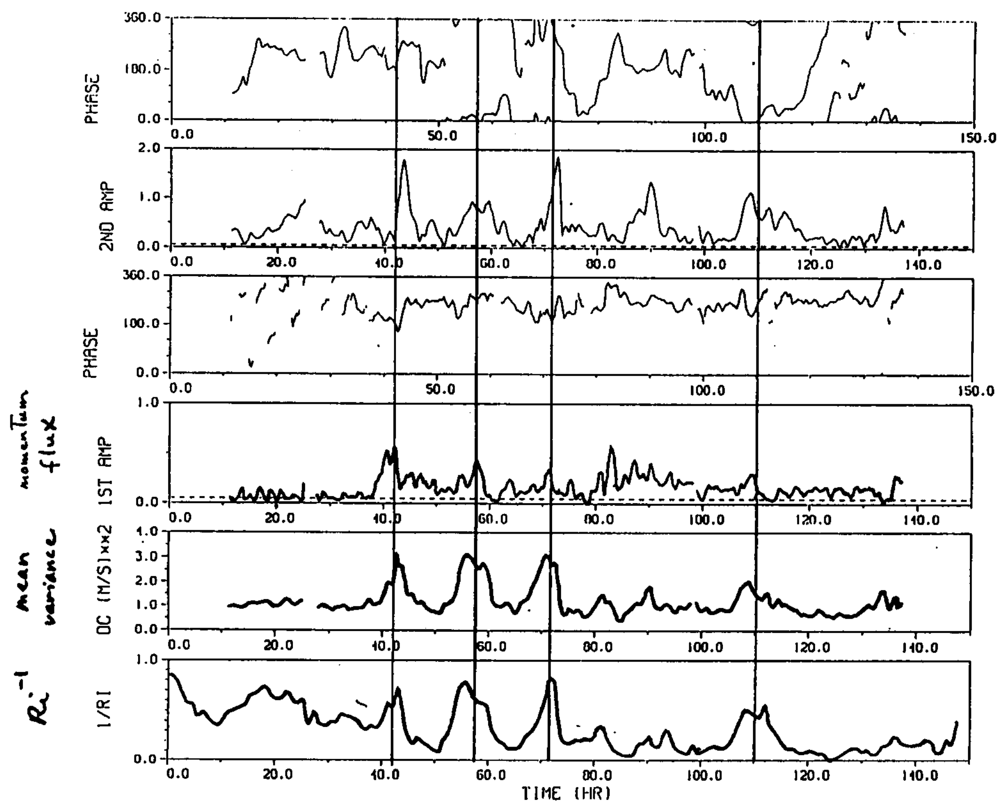


Figure 14. Correlation of inverse Richardson number Ri^{-1}, with mean variance and momentum flux suggesting shear-excited gravity waves [VanZandt et al., *J. Atmos. Sci.*, submitted, 1988].

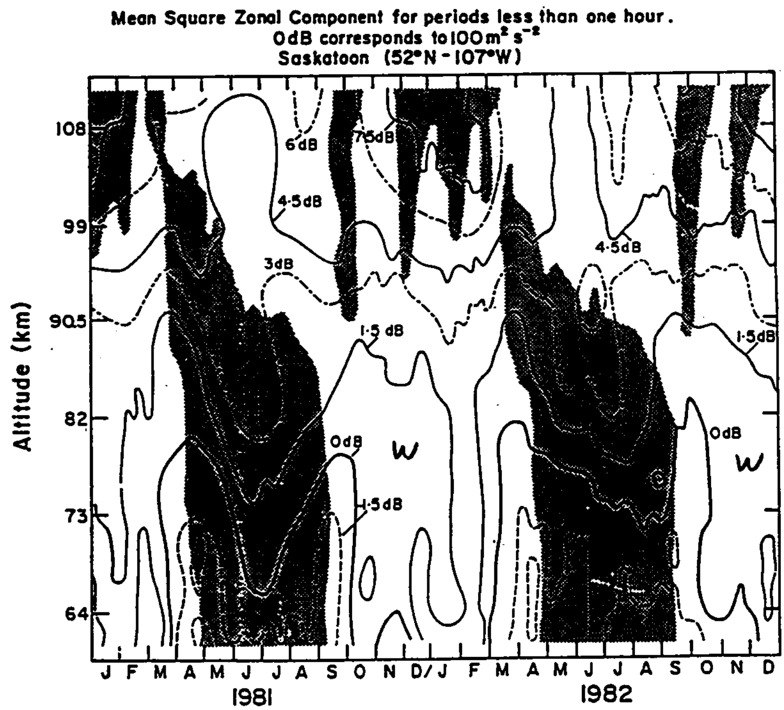


Figure 15. Time-height cross section of high frequency gravity wave zonal variance showing strong seasonal modulation and pronounced minima near equinoctial transitions [Meek et al., *Radio Sci.*, 1985].

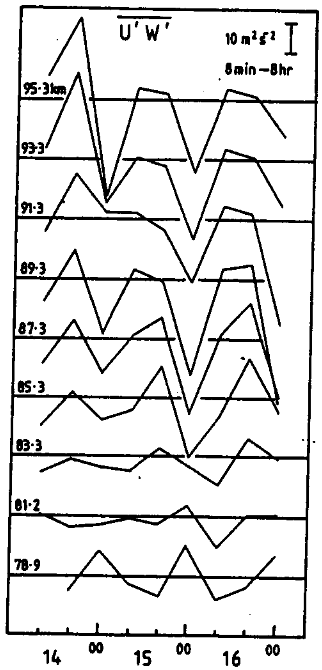


Figure 16. Eight-hour estimates of the momentum flux using the Adelaide HF radar which reveals a strong 24-h modulation and provides evidence of a strong modulation by the diurnal tides [Fritts and Vincent, *J. Atmos. Sci.*, 1987].

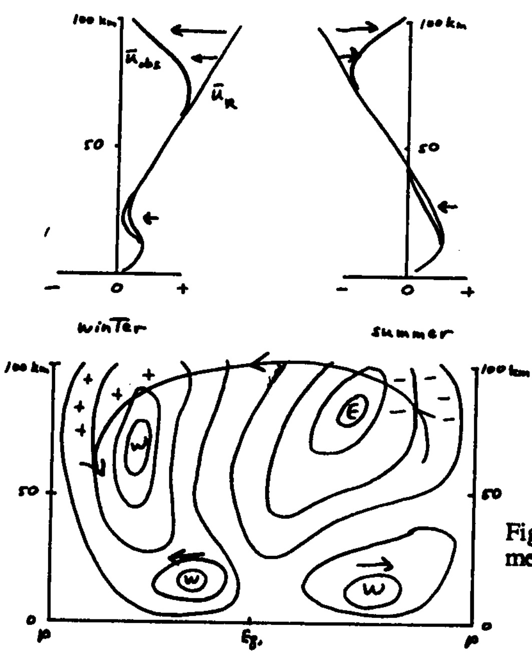


Figure 17. Schematic of gravity wave effects on mean wind profiles and the meridional circulation.

Unknowns and Future Needs

Causes and effects of gravity wave variability
- variable sources, source distributions and spectra
- filtering by/interactions with other motions
- forcing, wave excitation in middle atmosphere

Evolution of gravity wave/turbulence spectrum
- wave saturation
- effects of stratification

More complete, distributed gravity wave/turbulence climatology
- gravity wave sources
- wave parameters, amplitudes, fluxes
- wave drag and effective diffusion
- meridional propagation, fluxes

Parameterizations of
- wave and turbulence effects
- mechanisms of large-scale variability

Figure 18. Statement of unknowns and future needs for gravity wave and turbulence studies in the middle atmosphere.