1997 CEDAR Workshop

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Tutorial Lecture

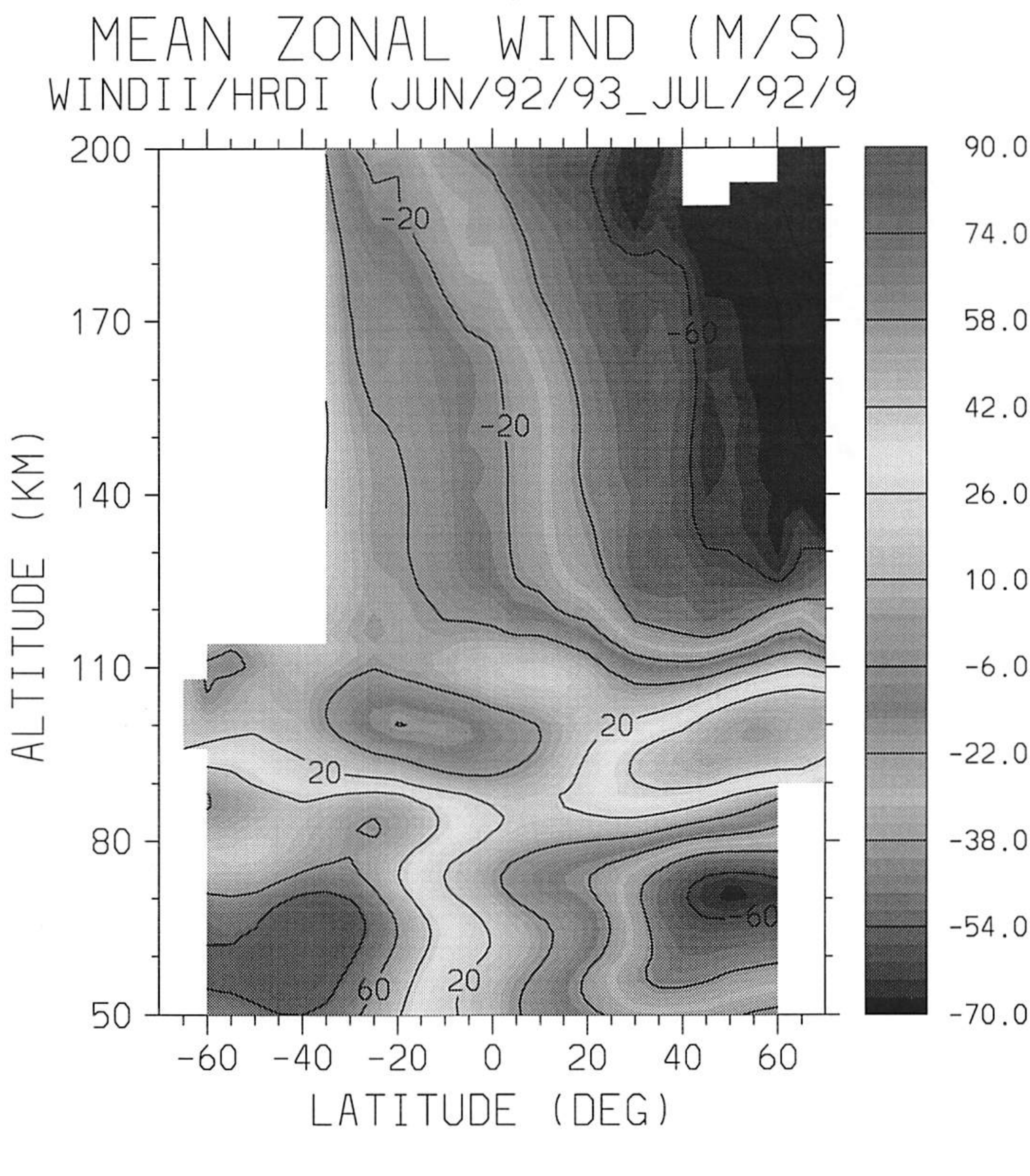
by Charles McLandress
University of Washington
and ISTS/York University

Gravity Waves: Their Importance in the Middle Atmosphere and Parameterization in General Circulation Models

GRAVITY WAVES: THEIR IMPORTANCE IN THE MIDDLE ATMOSPHERE AND PARAMETERIZATION IN GENERAL CIRCULATION MODELS

Charles McLandress
University of Washington and ISTS/York University

1. **zonal mean circulation**
2. **linear gravity wave theory**
3. **gravity wave drag parameterizations:**
   - Lindzen (1981)
   - Fritts and Lu (1993)
   - Hines (1997)
   - Medvedev and Klaassen (1997)
4. **modelling results - impact of different parameterization schemes on:**
   - extra-tropical circulation
   - equatorial oscillations (SAO and diurnal tide)
5. **improvement of parameterizations:**
   - observational constraints


MEAN ZONAL WIND (M/S)
WINDII/HRDI (JUN/92/93_JUL/92/9
ALTITUDE (KM)
LATITUDE (DEG)
200
170
140
110
80
50
-60
-40
-20
0
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20
-60
90.0
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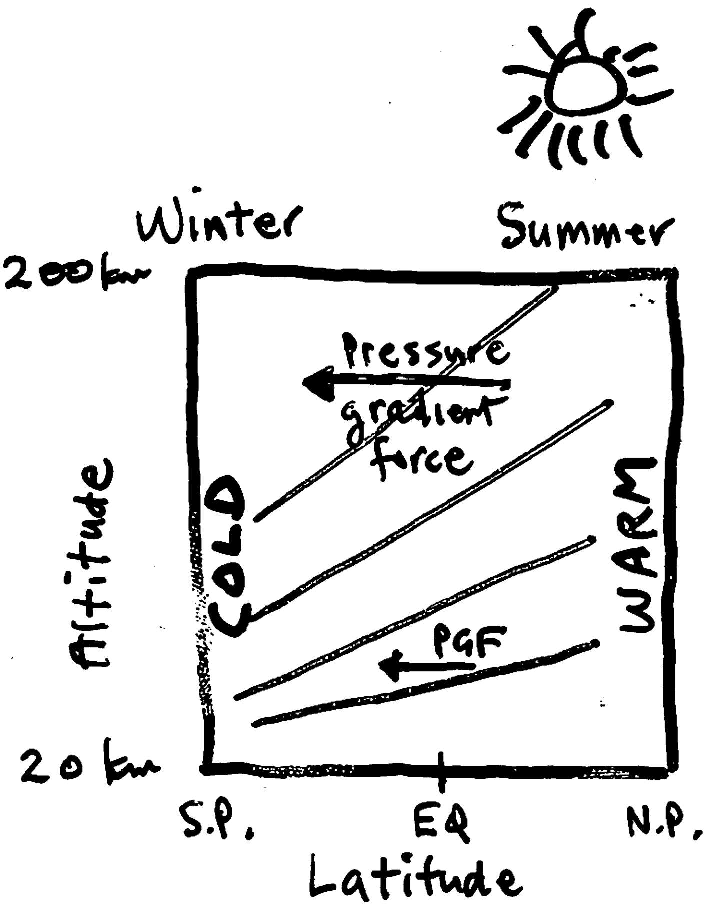
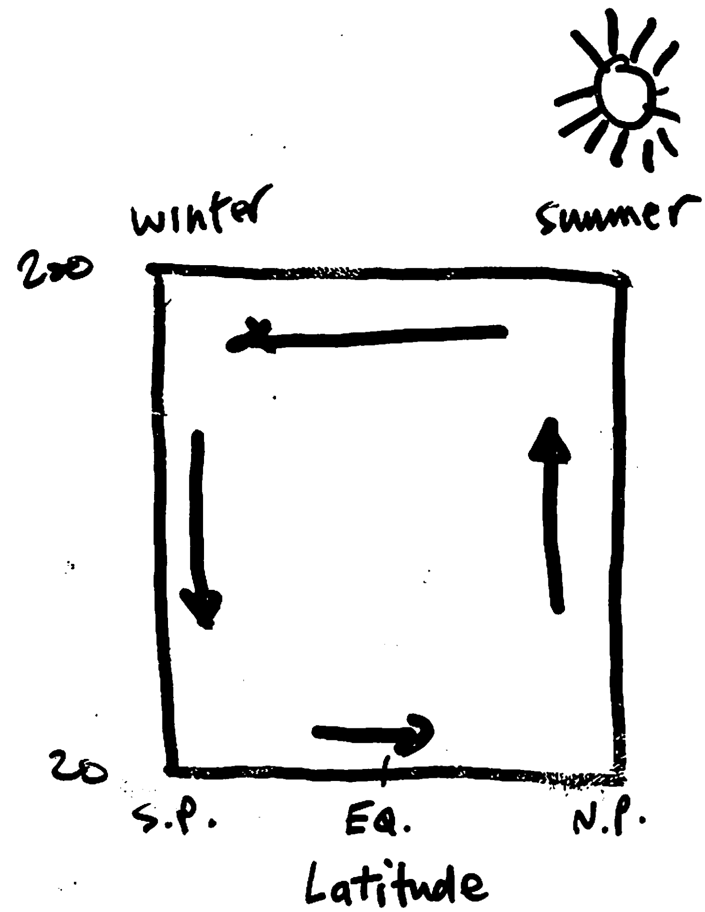
-70.0


Winter
Summer
200 km
20 km
Pressure gradient force
COLD
WARM
PGF
Altitude
S.P.
EQ
N.P.
Latitude


winter
summer
200
20
S.P.
EQ.
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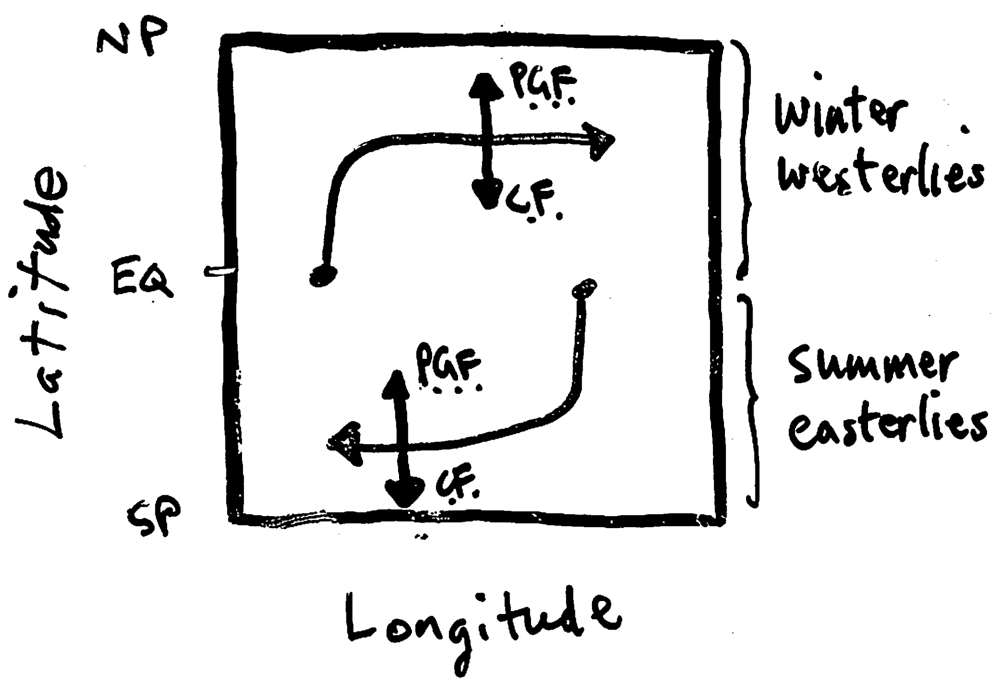
Latitude


NP
EQ
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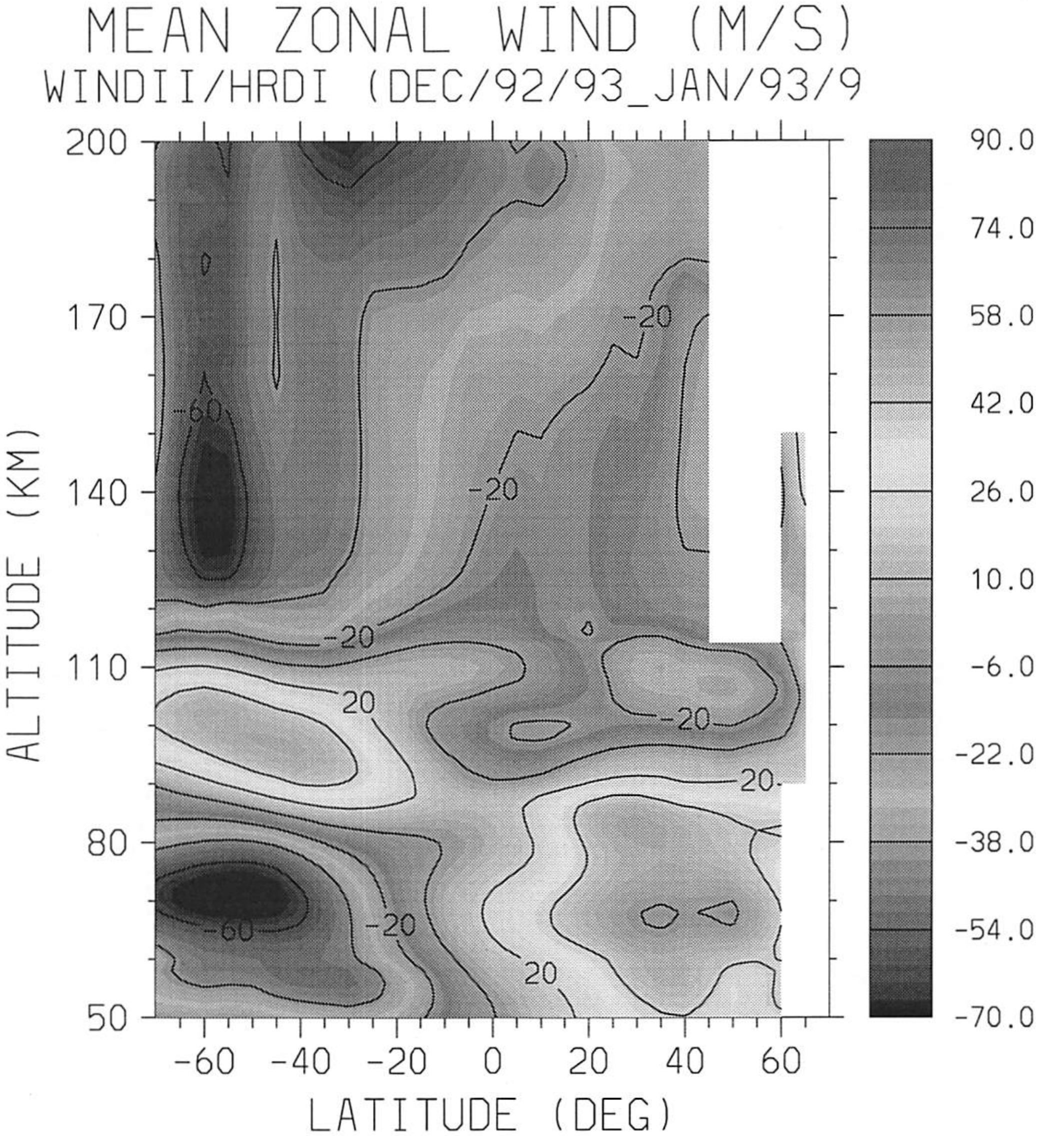
Latitude
PGF.
C.F.
PGF.
C.F.
winter westerlies
summer easterlies
Longitude



MEAN ZONAL WIND (M/S)
WINDII/HRDI (DEC/92/93_JAN/93/9
ALTITUDE (KM)
LATITUDE (DEG)
200
170
140
110
80
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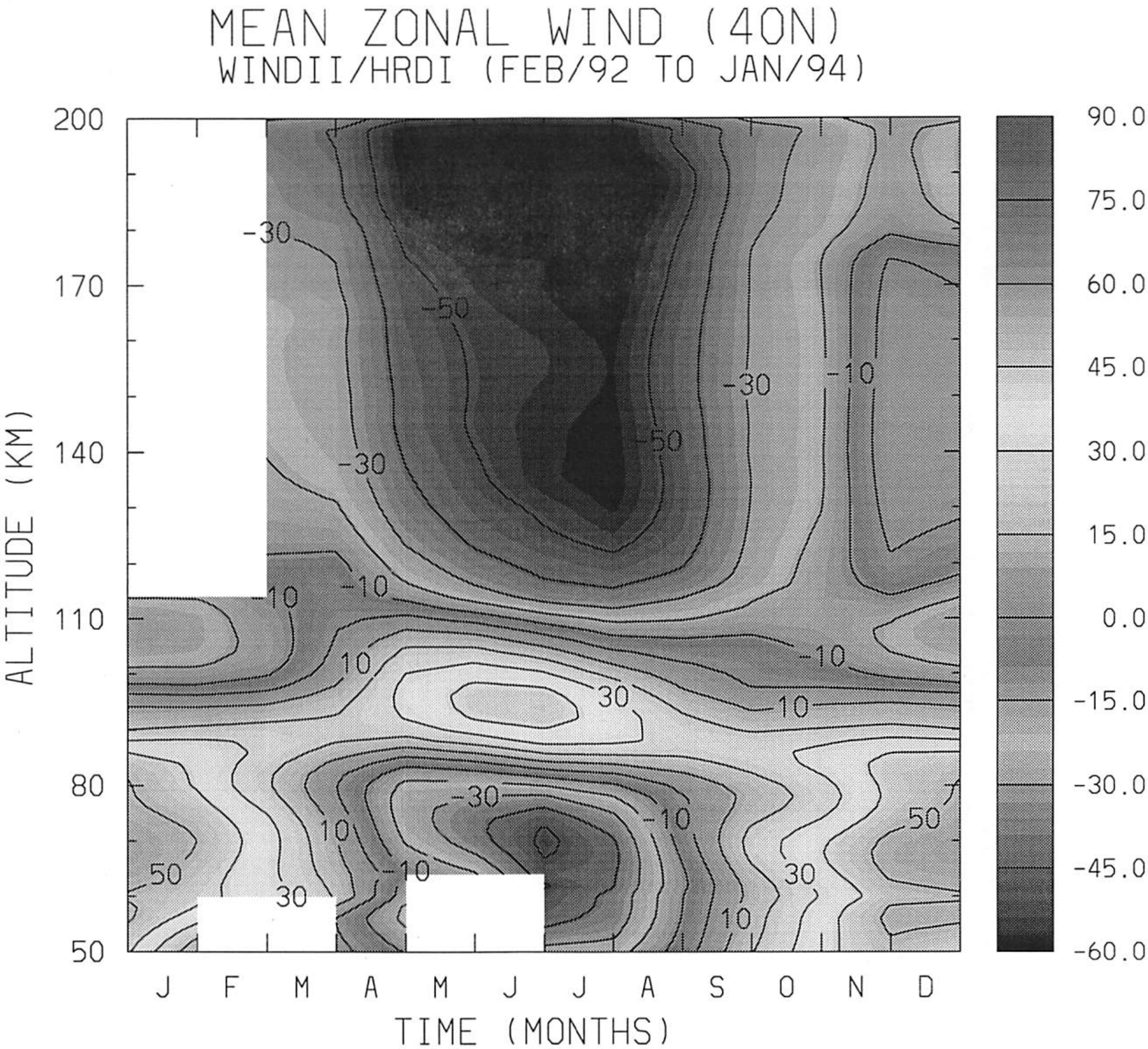
MEAN ZONAL WIND (40N)
WINDII/HRDI (FEB/92 TO JAN/94)
ALTITUDE (KM)
TIME (MONTHS)
200
170
140
110
80
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J F M A M J J A S O N D
90.0
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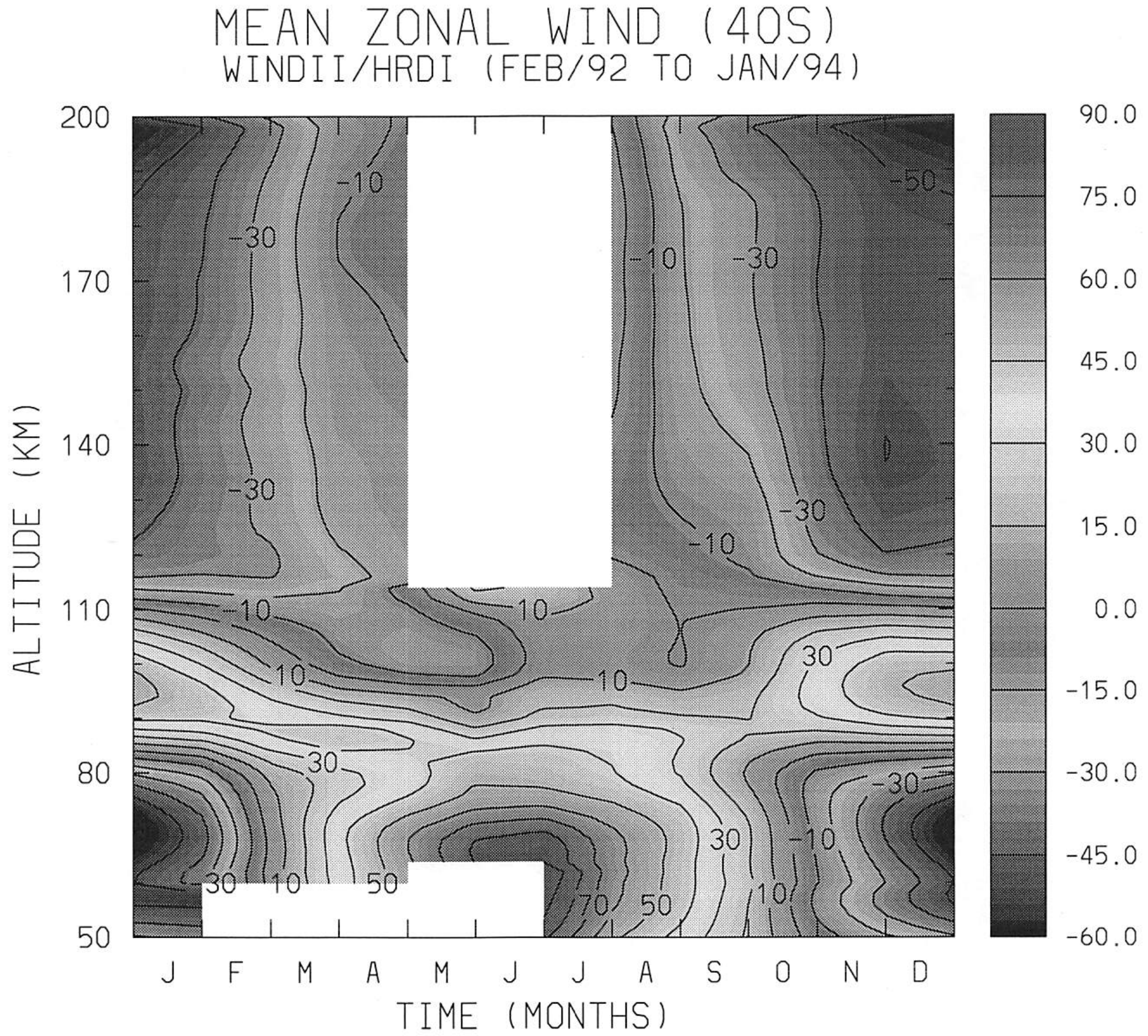
MEAN ZONAL WIND (40S)
WINDII/HRDI (FEB/92 TO JAN/94)
ALTITUDE (KM)
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J F M A M J J A S O N D
TIME (MONTHS)
90.0
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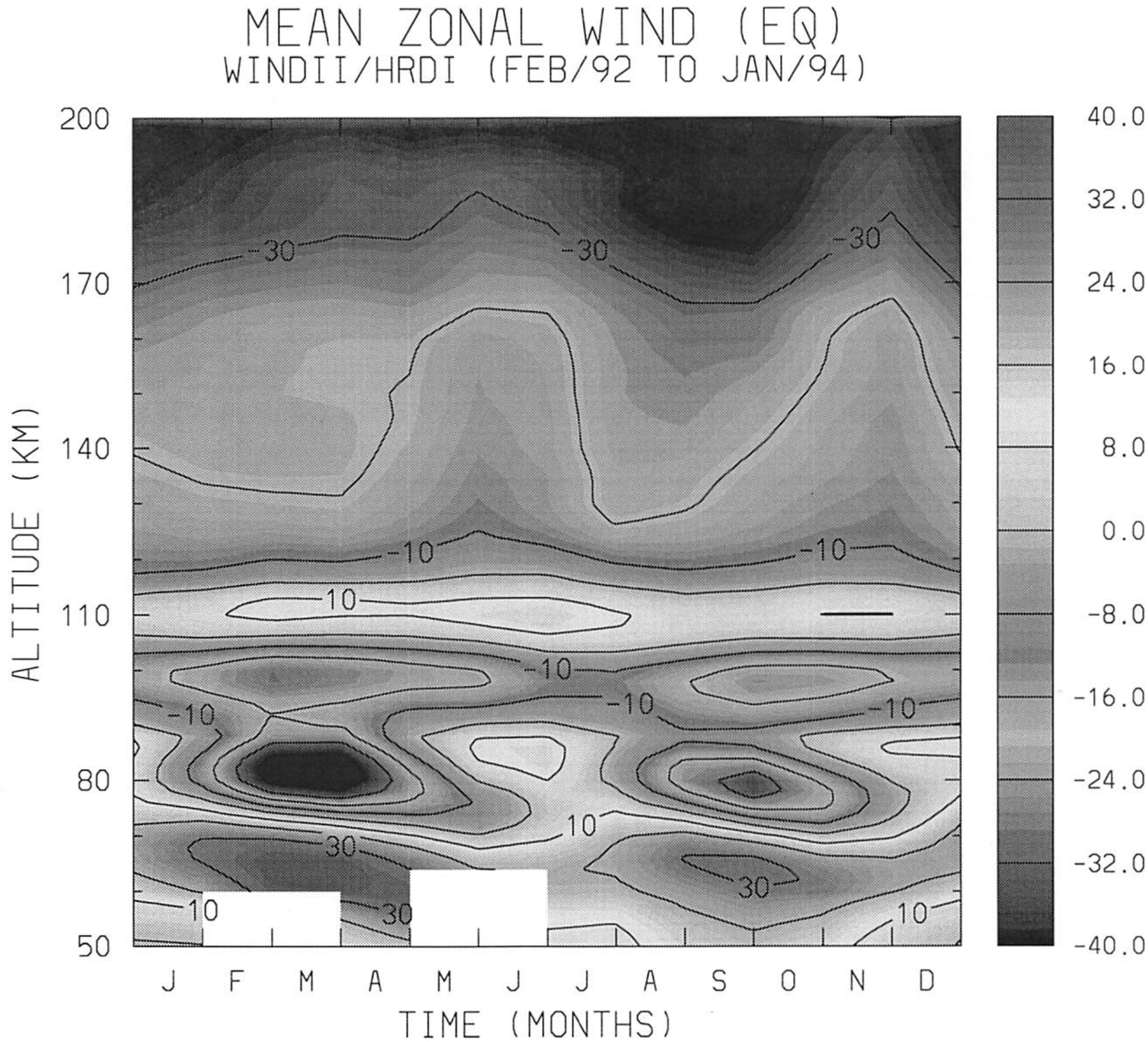
-45.0
-60.0


MEAN ZONAL WIND (EQ)
WINDII/HRDI (FEB/92 TO JAN/94)
ALTITUDE (KM)
200
170
140
110
80
50
TIME (MONTHS)
J F M A M J J A S O N D
-30
-10
10
30
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8.0
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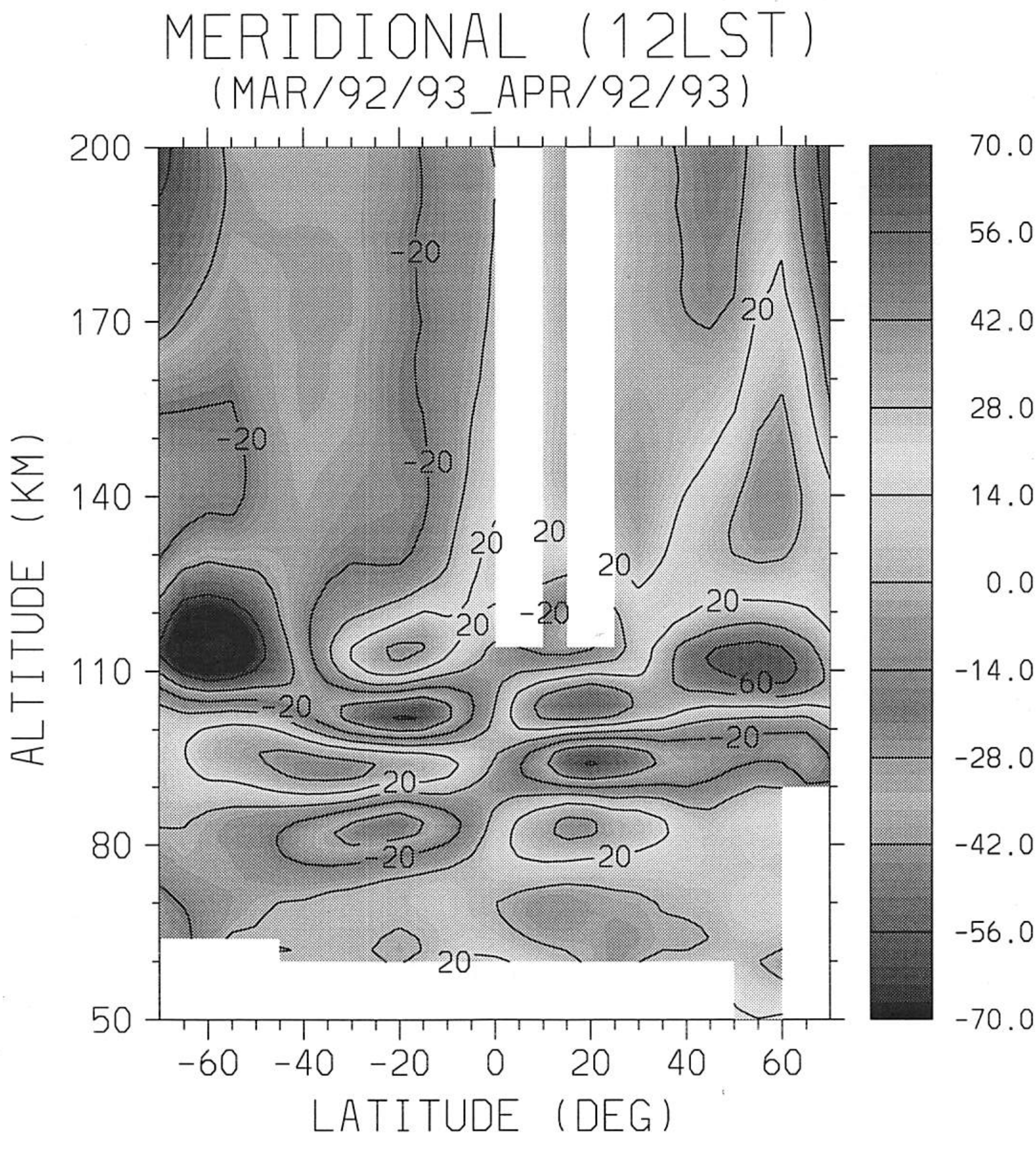
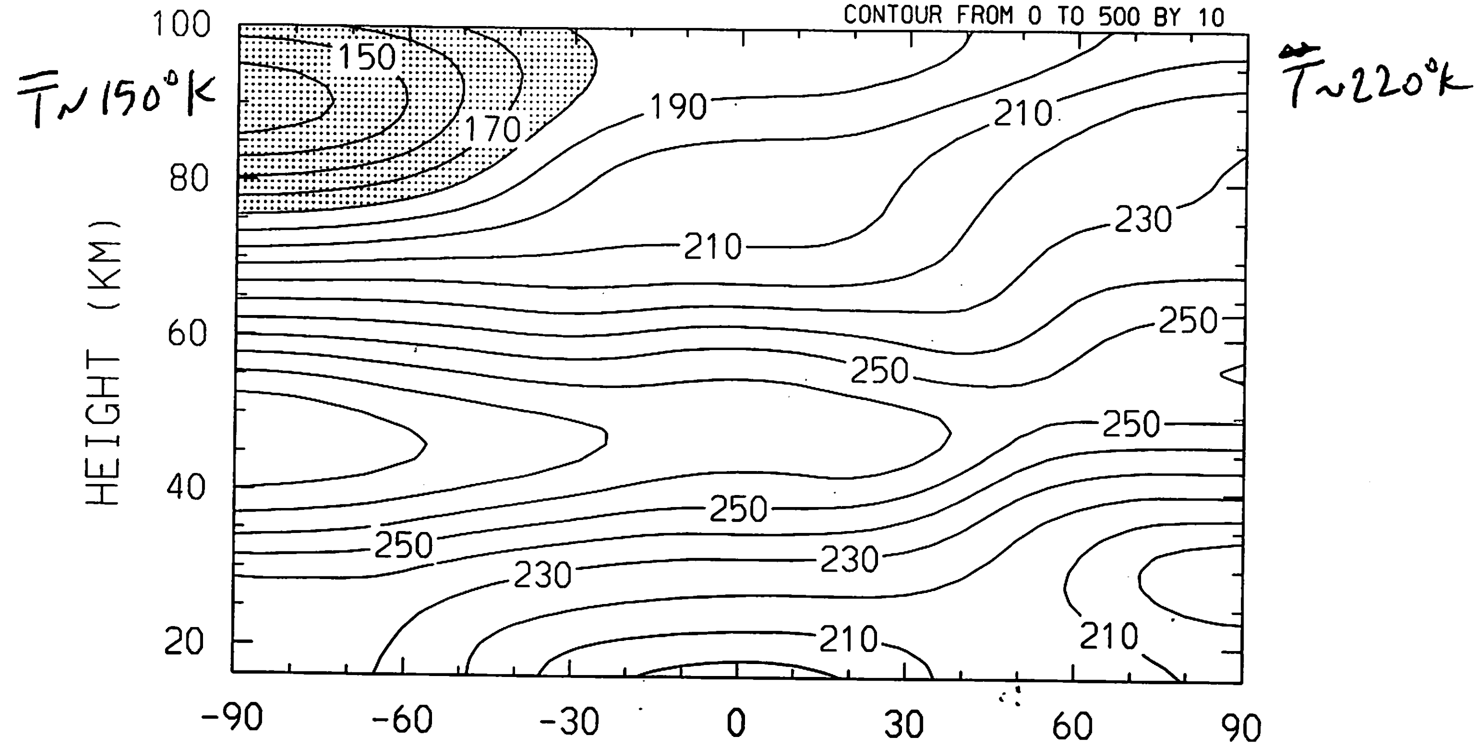
7.


MERIDIONAL (12LST)
(MAR/92/93_APR/92/93)
ALTITUDE (KM)
200
170
140
110
80
50
LATITUDE (DEG)
-60
-40
-20
0
20
40
60
70.0
56.0
42.0
28.0
14.0
0.0
-14.0
-28.0
-42.0
-56.0
-70.0
-20
20
-60

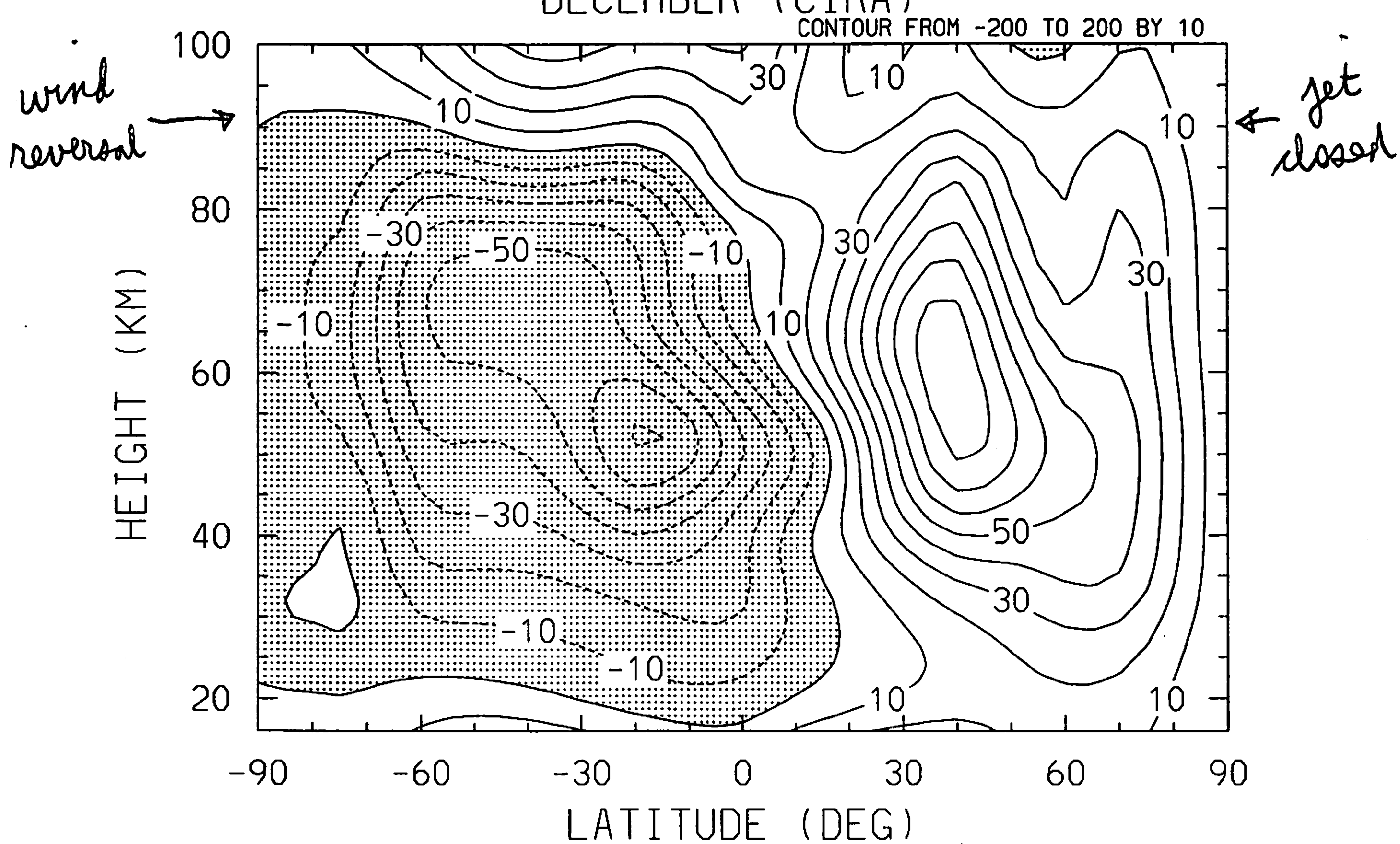
ZONAL MEAN TEMPERATURE (K)

DECEMBER (CIRA)



ZONAL MEAN WIND (M/S)

DECEMBER (CIRA)



(1) ZONAL MEAN CIRCULATION

- the extra-tropical middle atmosphere is approximately in geostrophic balance (i.e., Coriolis force equals pressure gradient force).
- the quasi-geostrophic system of equations governing the zonally averaged circulation is given by:

momentum eqn: $$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = \bar{F}$$

thermodyn. eqn: $$\frac{\partial \bar{T}}{\partial t} + \frac{N^2 H}{R}\bar{w} = \bar{Q}$$

thermal wind eqn: $$f\frac{\partial \bar{u}}{\partial z} + \frac{R}{aH}\frac{\partial \bar{T}}{\partial \theta} = 0$$

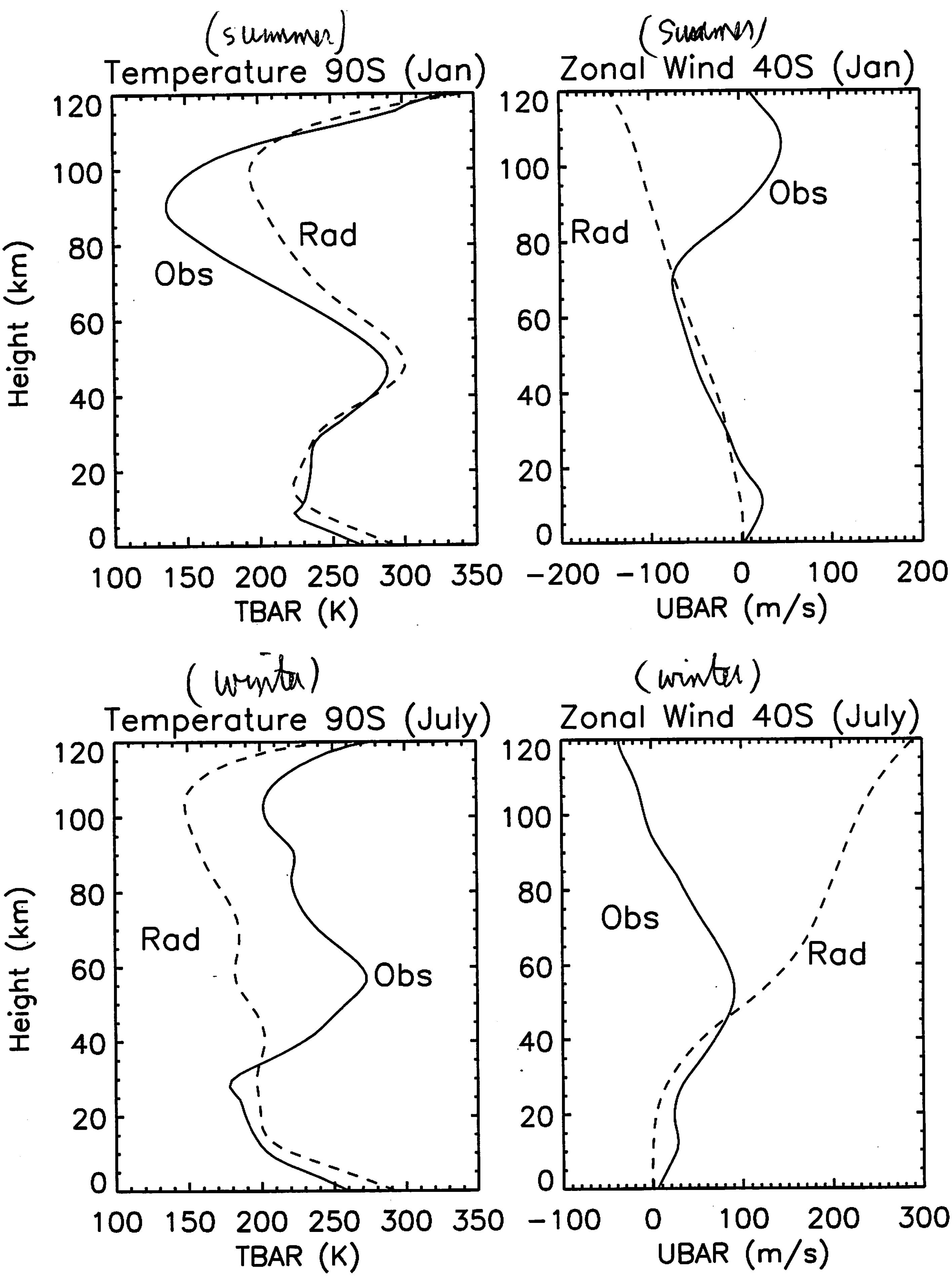
continuity eqn: $$\frac{1}{a\cos\theta}\frac{\partial}{\partial \theta}(\bar{v}\cos\theta) + \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\bar{w}) = 0$$

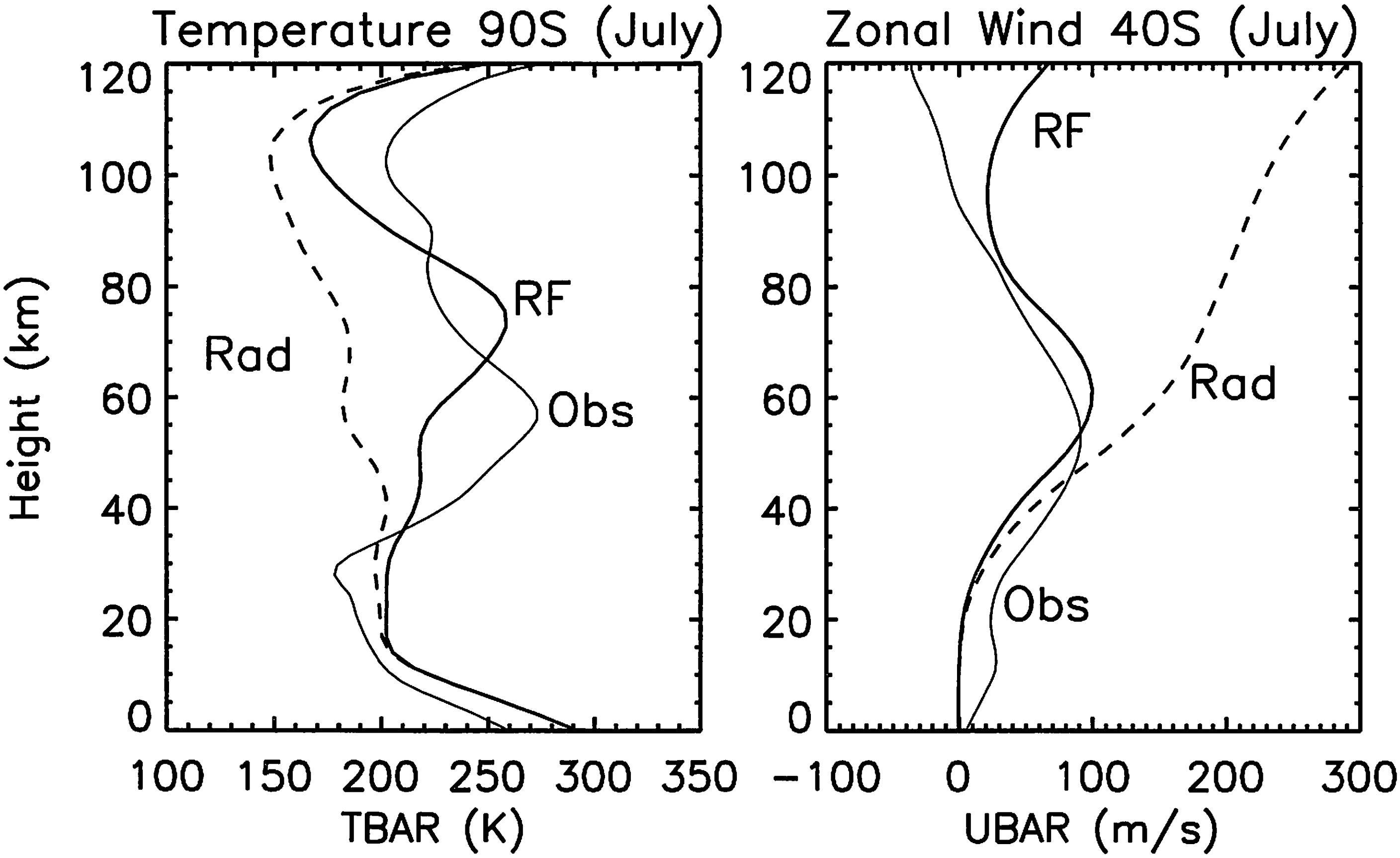
- set the forcing term $\bar{F}$ to zero and get steady-state solution with no vertical or meridional motion (i.e., $\bar{v} = \bar{w} = 0$).
- atmosphere is in radiative equilibrium since heating term $\bar{Q} = 0$.
- consider a numerical model based on QG equations.
- compute the net heating rate as follows:
  - short wave (solar) radiation using the parameterization of Strobel (1978) for O_3 and O_2.
  - long wave (terrestrial) radiation using the parameterization of Fomichev et al (1993) which includes nonlocal thermodynamic equilibrium in the 15 μm CO_2 band.

- compute the steady-state solution in the absence of the zonal force ($\bar{F} = 0$) to yield the radiative-equilibrium temperature $\bar{T}_{rad}$ and wind $\bar{u}_{rad}$:
  - in summer polar mesosphere: $\bar{T}_{rad} \gg \bar{T}_{obs}$.
  - in winter polar mesosphere: $\bar{T}_{rad} \ll \bar{T}_{obs}$.
  - by thermal wind relation have $|\bar{u}_{rad}| \gg |\bar{u}_{obs}|$.
- require a zonal force (i.e., $\bar{F} \neq 0$) in the upper mesosphere to keep the zonal mean temperature away from radiative equilibrium.
- early modelling studies [e.g., Holton and Wehrbein, 1980] employed strong Rayleigh friction in the mesosphere:

$$\bar{F} = -K(z)\,\bar{u} \,.$$

- problems with Rayleigh friction:
  - cannot produce the observed wind reversal of the zonal mean zonal winds in the upper mesosphere.
  - drag depends only on wind speed and not on vertical shear and cannot result in downward propagation of the equatorial semiannual oscillation (SAO).


(summer)
Temperature 90S (Jan)
Height (km)
TBAR (K)
Obs
Rad
(Summer)
Zonal Wind 40S (Jan)
UBAR (m/s)
Obs
Rad
(winter)
Temperature 90S (July)
Height (km)
TBAR (K)
Rad
Obs
(winter)
Zonal Wind 40S (July)
UBAR (m/s)
Obs
Rad



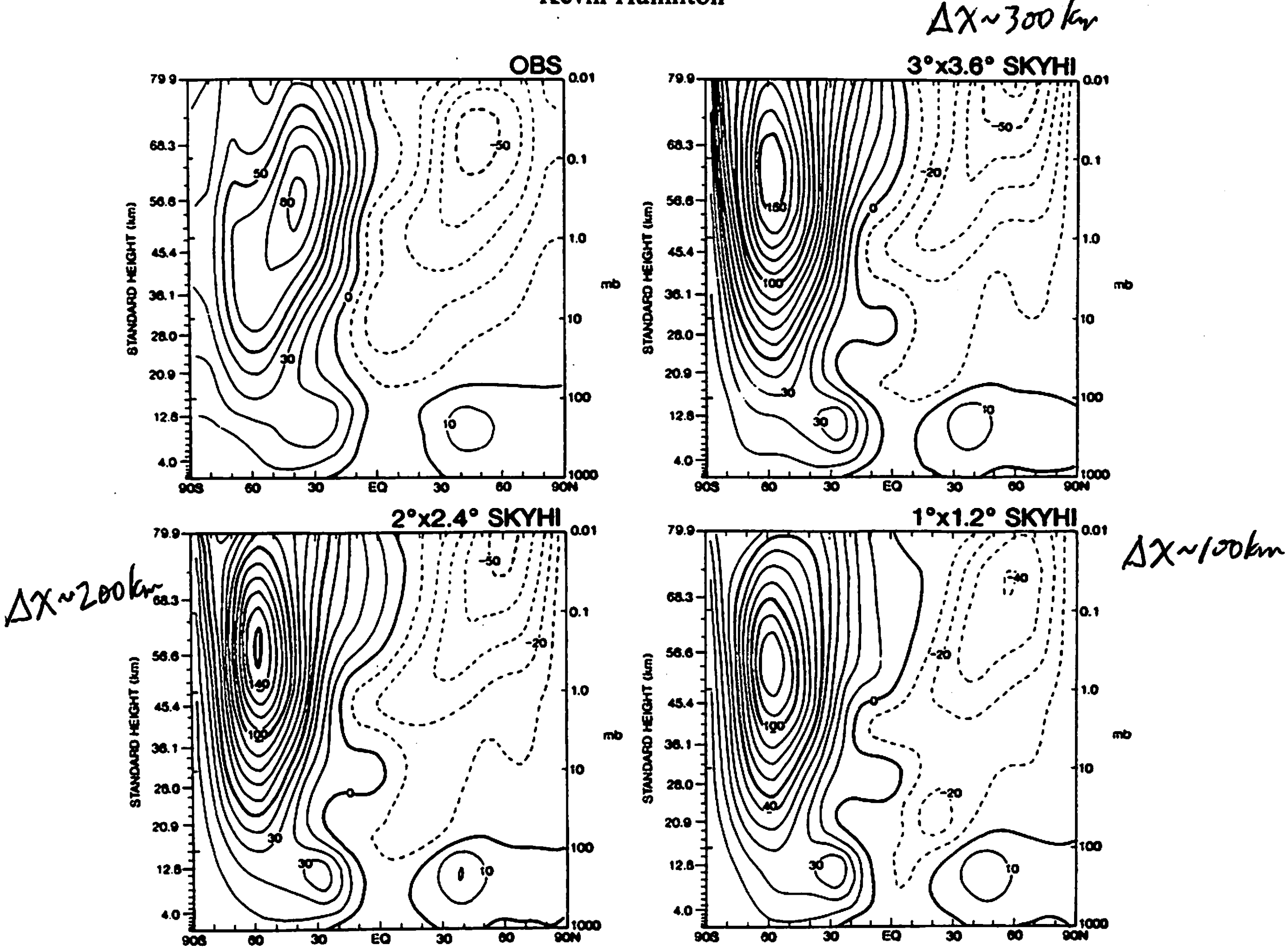
"RF" = using Rayleigh friction ($\bar{F} = -K\bar{u}$)

"Rad" = no forcing ($\bar{F} = 0$) ⇒ radiative equilibrium

"Obs" = CIRA observations

Comprehensive meteorological modelling of the middle atmosphere: a tutorial review*

Kevin Hamilton



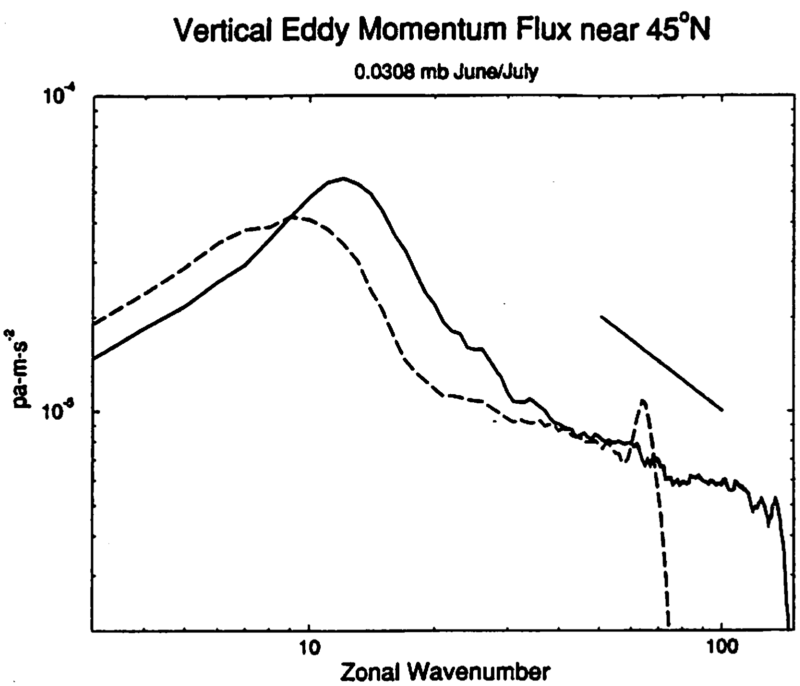


Fig. 18. Zonal wavenumber cospectrum of u'and ω' near 45°N in simulations in June and early July for the 1 × 1.2° SKYHI model (solid) and the 2 × 2.4° model (dashed). Results in each case represent averages over a large number of instantaneous spectra and have been smoothed somewhat in zonal wavenumber.

(2) LINEAR GRAVITY WAVE THEORY

- internal gravity waves exist in a compressible stably stratified atmosphere as a consequence of the restoring force of buoyancy.
- consider the following wavelike disturbance:

$$u' = \hat{u}(z)\, e^{z/2H} \cos[k(x-ct)+mz+\phi]\,.$$

From the governing equations (i.e., momentum, thermodynamic, continuity, etc.) a dispersion relation can be derived that relates the horizontal and vertical wavenumbers k and m to the phase speed c.

- e.g., for a non-rotating atmosphere with a constant background wind $\bar{u}$ the dispersion relation is:

$$m^2 \approx \frac{N^2}{(c-\bar{u})^2} = \frac{N^2\, k^2}{\omega^2}$$

where ω is called the intrinsic frequency.

- gravity waves transport momentum and heat upwards. Consider the vertical flux of horizontal momentum τ:

$$\tau = \rho < u'w' >$$

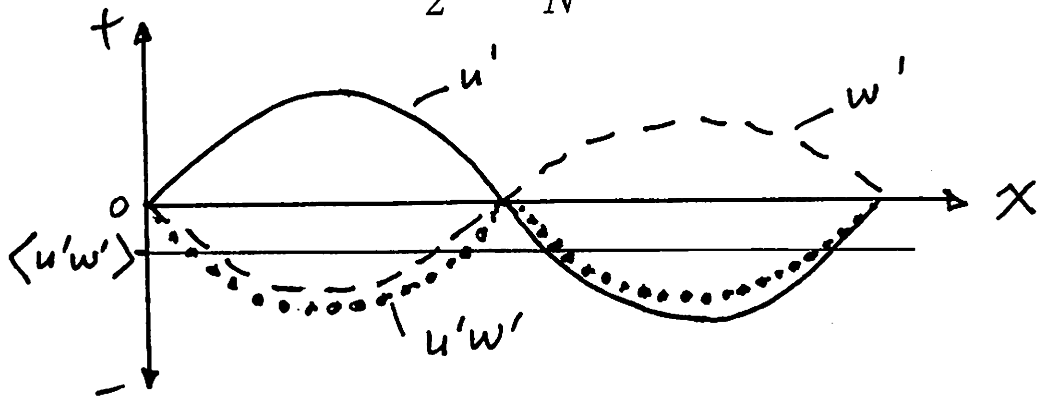
where the $<>$ denote an average over the horizontal wavelength and $\rho(z) = \rho_s e^{-z/H}$.

- from the continuity equation get

$$w' \approx -\frac{k}{m}\hat{u}\, e^{z/2H} \cos[k(x-ct)+mz+\phi]$$

which after use of trigonometric identities and the dispersion relation yields the momentum flux

$$\tau = -\frac{1}{2}\rho_s \frac{k(c-\bar{u})}{N}\hat{u}^2 \, .$$



- mean state changes only if there is a vertical variation in the momentum flux or flux divergence:

$$\frac{\partial \bar{u}}{\partial t} + \ldots = -\frac{1}{\rho}\frac{\partial \tau}{\partial z} = \bar{F} \, .$$

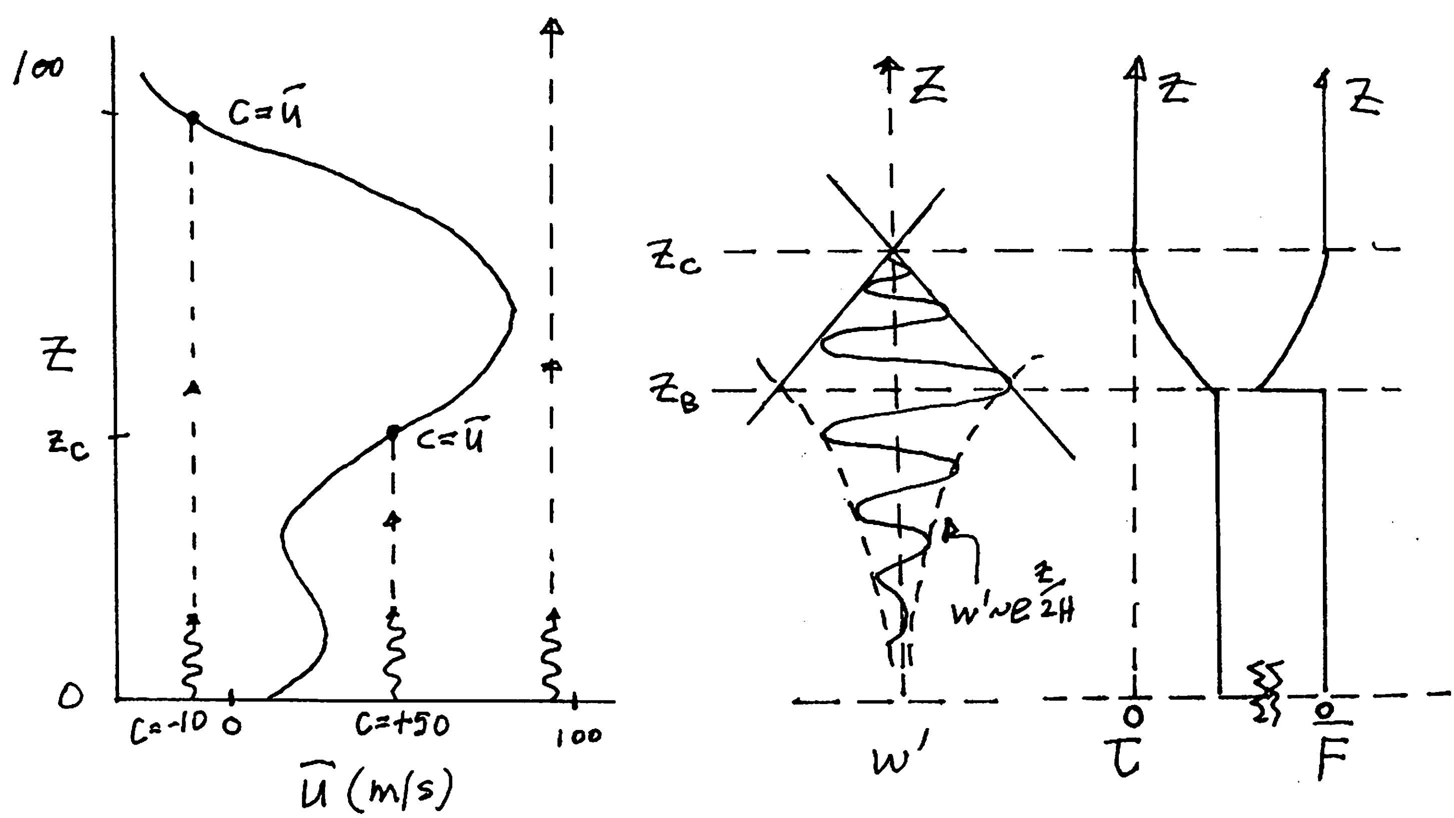
- for steady, non-dissipative waves the momentum flux is independent of height and so no mean force is generated ($\bar{F}=0$).

- dissipation of gravity waves causes a flux divergence and a nonzero mean force, i.e., gravity wave drag (GWD).

- a gravity wave propagating upwards in a height-dependent basic state can reach a critical level where its phase speed c matches the mean wind speed $\bar{F}$. Vertical propagation no longer possible and gravity waves are dissipated ⇒ mean wind filtering.

(3) GWD PARAMETERIZATIONS

- **Lindzen (1981) parameterization**:
  - linear monochromatic gravity waves propagating vertically on a height-dependent background wind.
  - growth of amplitude with height due to decreasing density.
  - gravity wave breaks when the total temperature lapse rate becomes convectively unstable.
  - turbulent diffusion is introduced above the breaking height to maintain neutral stability (i.e., saturation).
  - damped wave results in momentum flux divergence and a force on the zonal wind wind.
  - force drives the zonal wind to the phase speed of the gravity wave (i.e., $\bar{u} \rightarrow c$).
  - Lindzen parameterization appears in a modified form in orographic GWD schemes used in GCMs [e.g., McFarlane, 1987].



Smith et al (JAS, 87)

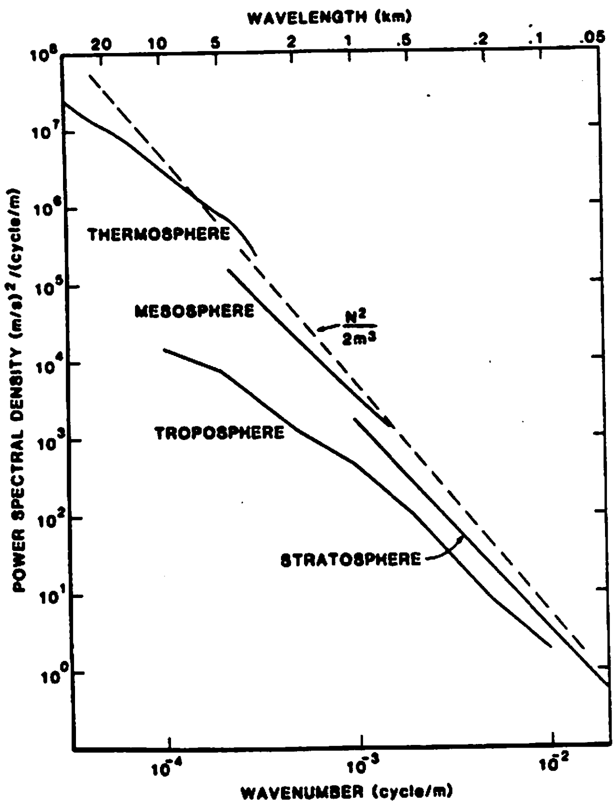


FIG. 1. Spectra of horizontal velocity versus vertical wavenumber as a function of altitude.

THE UNIVERSAL SPECTRUM

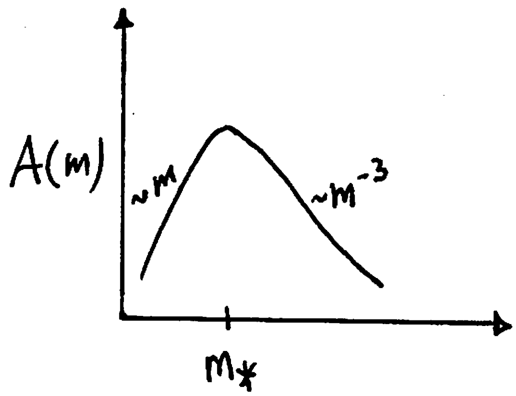
- **Fritts and Lu (1993) parameterization:**

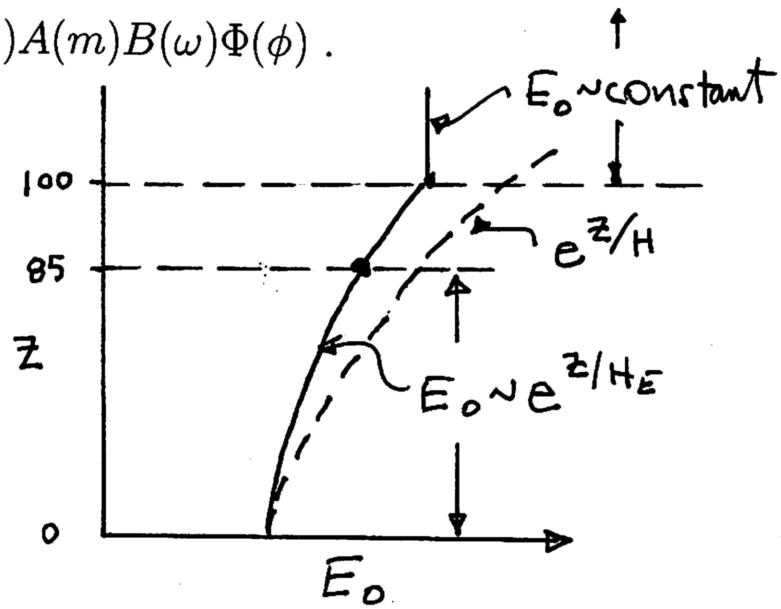
  – total gravity wave energy expressed as:

$$E_o(z) = \int_0^{2\pi} d\phi \int_0^{\infty} dm \int_f^N d\omega E(m, \omega, \phi, z) .$$

  – assume separable spectrum whose form is specified:

$$E = E_o(z) A(m) B(\omega) \Phi(\phi) .$$





  – divide energy into 4 quadrants each with same spectral form:

$$E_o(z) = E_e + E_w + E_n + E_s .$$

  – apply constraints to energy based on observation and theory:

$$E_o(z) \propto N^{1/2} e^{z/H_E}$$

$$E_j(z) \propto \frac{1}{40} \frac{N^2}{m_{*j}^2} \leq e^{z/H}$$

  where m_{*j} is the characteristic vertical wavenumber.

  – calculate momentum fluxes τ_j in each direction from E_j and then compute GWD.

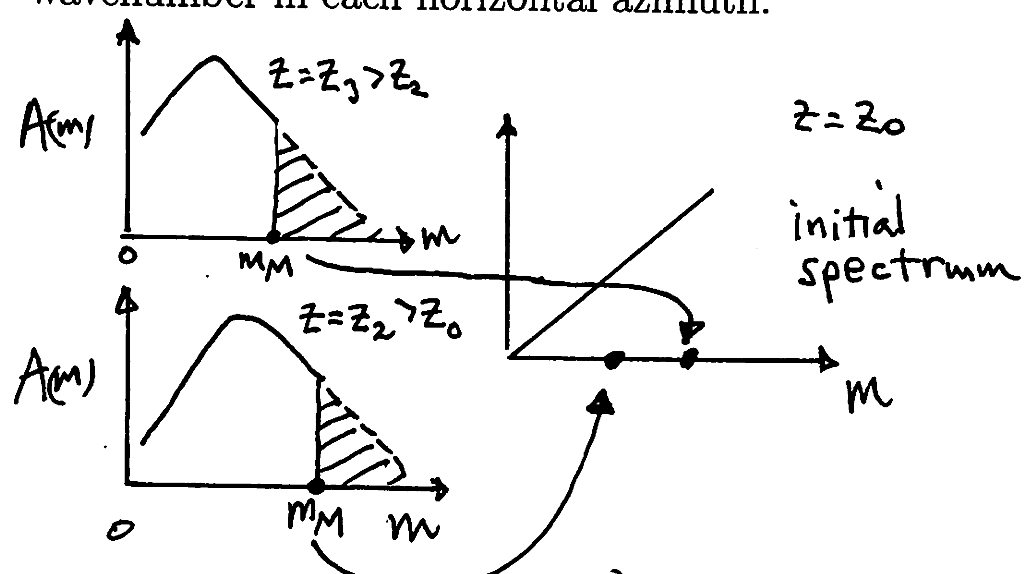
- **Hines (1997) parameterization**:

  - Hines postulates that fluctuating winds of induced by the spectrum of gravity waves acts as an additional background wind which Doppler spreads spectral harmonics from the low wavenumber portion of the spectrum to high wavenumbers where they are dissipated.
  - assumes a maximum allowable vertical wavenumber m_M called the cutoff wavenumber such that all waves with $m > m_M$ are obliterated as a result of Doppler spreading to critical levels.
  - specify the form the low wavenumber portion of the m spectrum at an initial height in lower atmosphere
  - calculate cutoff wavenumber in region above using the dispersion relation and assuming conservative propagation for unobliterated waves, i.e.,

$$(m_c)_j = \frac{N_\circ}{V_j - V_{j\circ} + \Phi_1 \sigma_j + \Phi_2 \sigma_h}$$

  where V_j is mean wind in jth direction, σ variance of gravity wave horizontal winds, Φ_1 and Φ_2 are constants.

  - momentum flux then depends on vertical variation of the cutoff wavenumber in each horizontal azimuth.



- **Medvedev and Klaassen (1997) parameterization:**

  – combines aspects of Doppler spread theory of Hines and non-linear enhanced diffusion of Weinstock [1990].

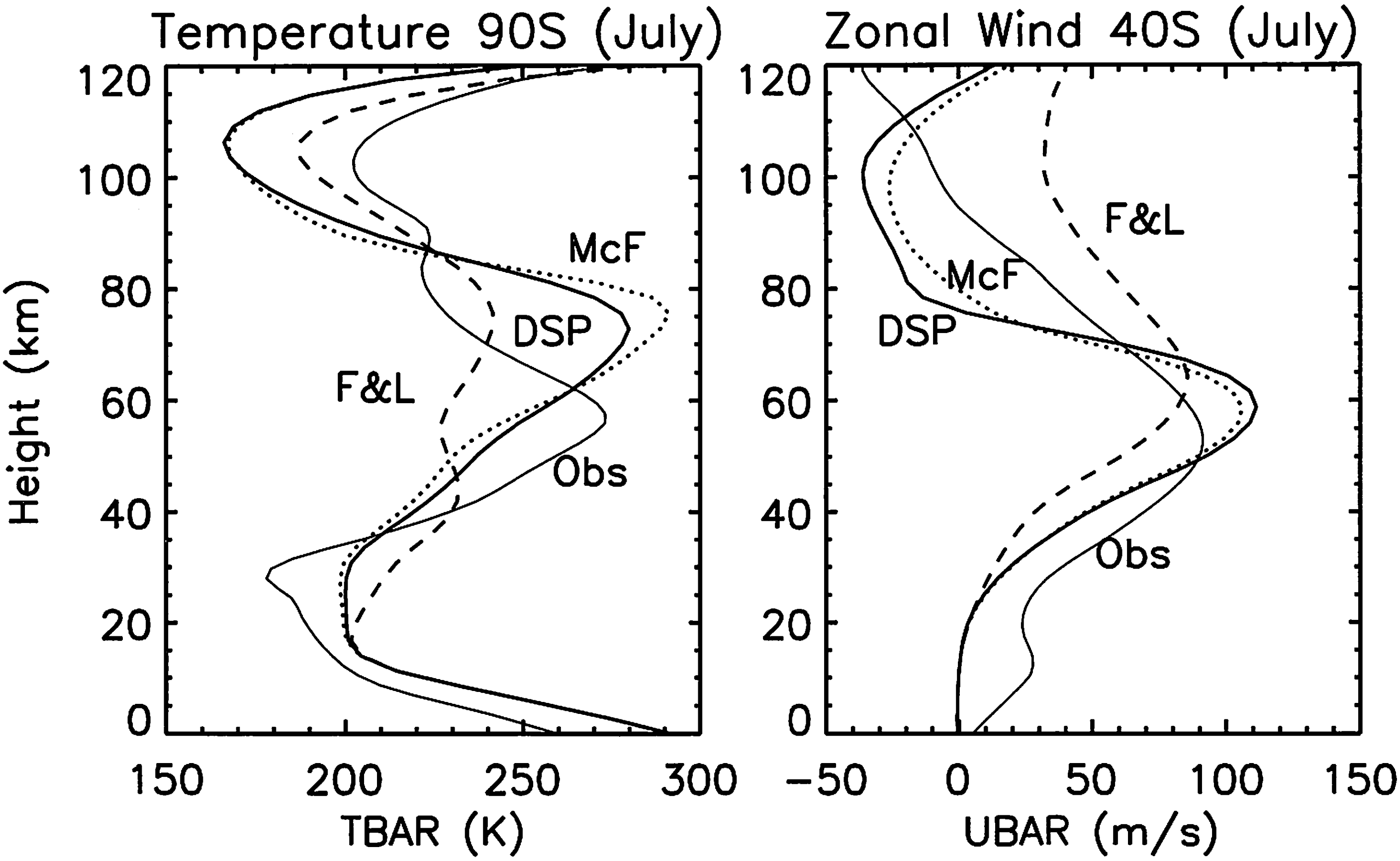
  – power spectral density of horizontal winds given by

$$\frac{dS(m)}{dz} = \left(-\frac{1}{\rho}\frac{d\rho}{dz} + \frac{1}{m_R}\frac{dm}{dz} - \beta\right) S(m)$$

  where β is the nonlinear damping coefficient.

  – nonlinear diffusion coefficient arise from supposition that gravity waves of small vertical scales act to diffuse longer vertical wavelengths.

  – vertical wavenumber m depends on background mean winds and rms winds from low frequency portion of the spectrum.



"McF" = using McFarlane (JAS, 1987) modified to include non-zero phase speeds $c = \pm 30, \pm 20, \pm 10$ and 0 m/s

"DSP" = Doppler spread parameterization (Hines, 97) using isotropic source at bottom level.

"F&L" = Fritts and Lu (93) parameterization using isotropic source at bottom level.

(4) MODELLING RESULTS

- Canadian Middle Atmosphere Model (CMAM):
  - global general circulation model that extends from earth's surface to 100 km.
  - 3-dimensional using spherical harmonic representation in horizontal (T32 $\Rightarrow$ grid spacing $\approx$ 5 degrees).
  - contains many physical processes
- two simple mechanistic models:
  - zonally averaged model with radiative transfer code.
  - linear tidal model that neglects zonal mean wind effects.
- examine effects of GWD on:
  - zonal mean circulation in the extratropics.
  - zonal mean winds in the tropics (semiannual oscillation).
  - migrating diurnal tide.

from McFarlane (JAS, 1987)
GCM results

(without orographic GWD param.)

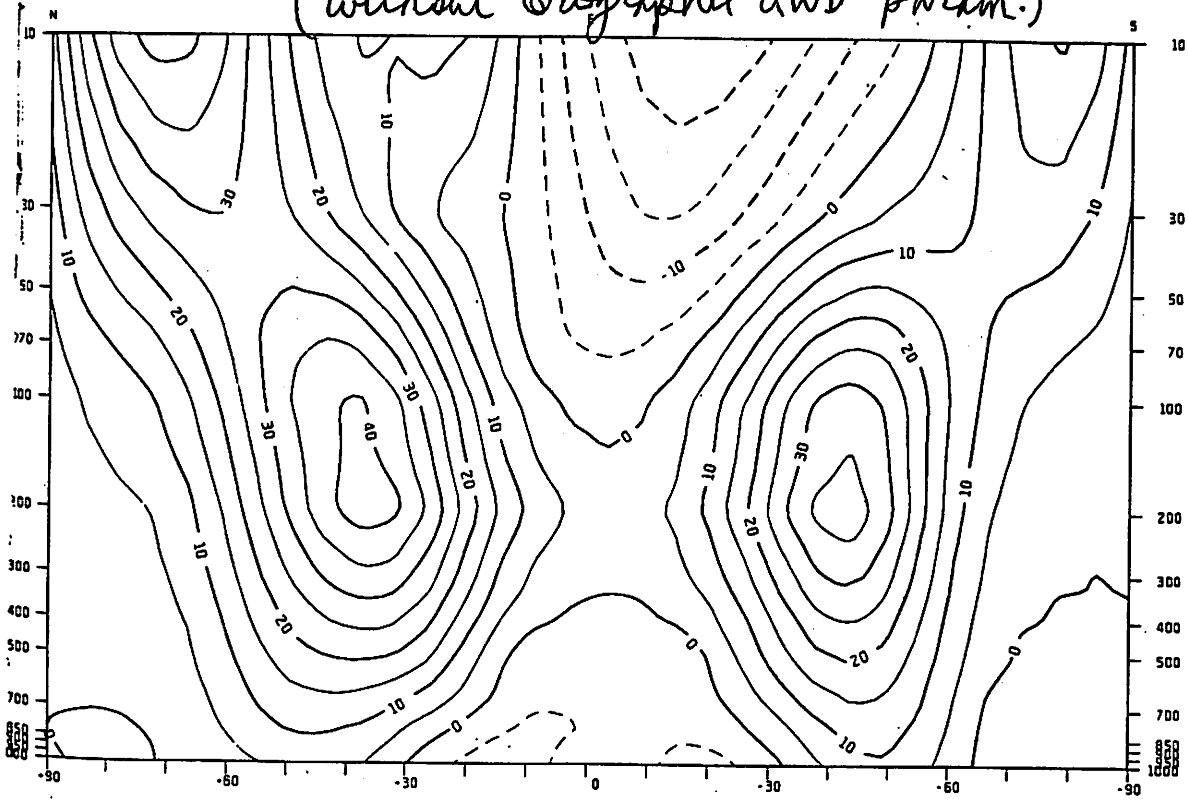


FIG. 6. Mean zonal winds for the control simulation.

(with orographic GWD)

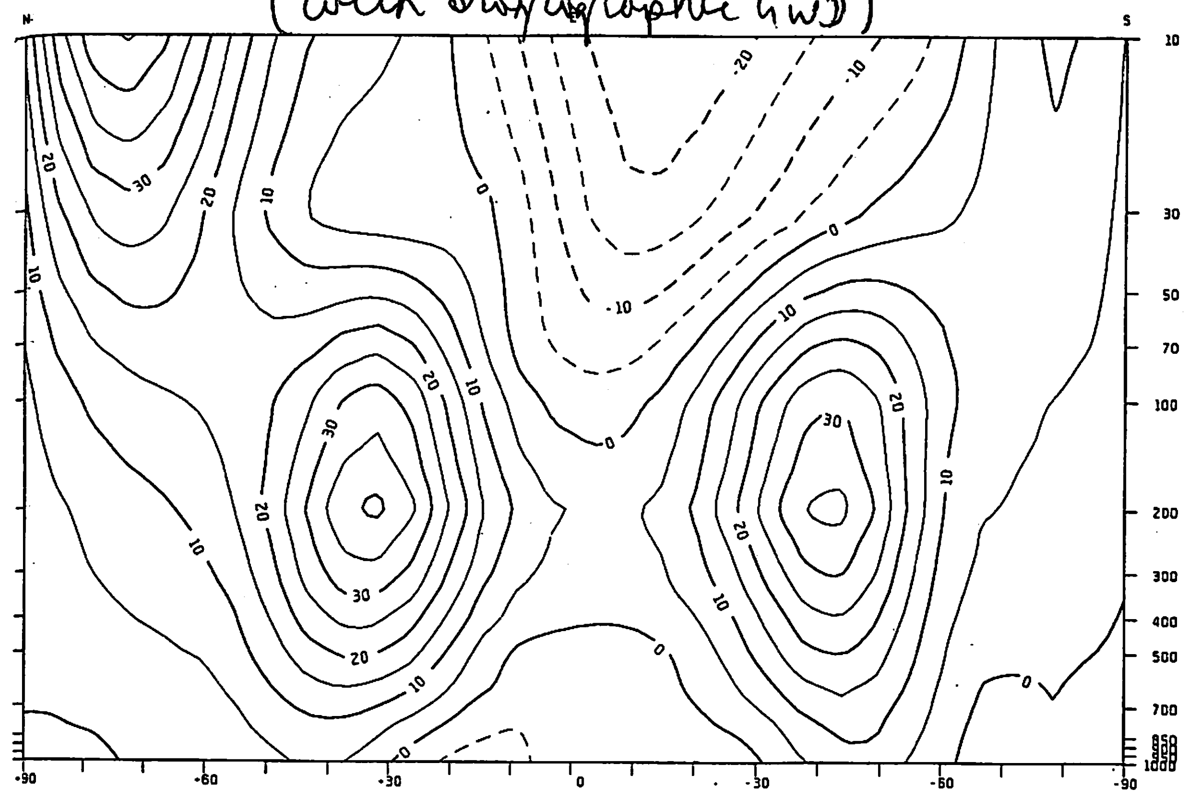
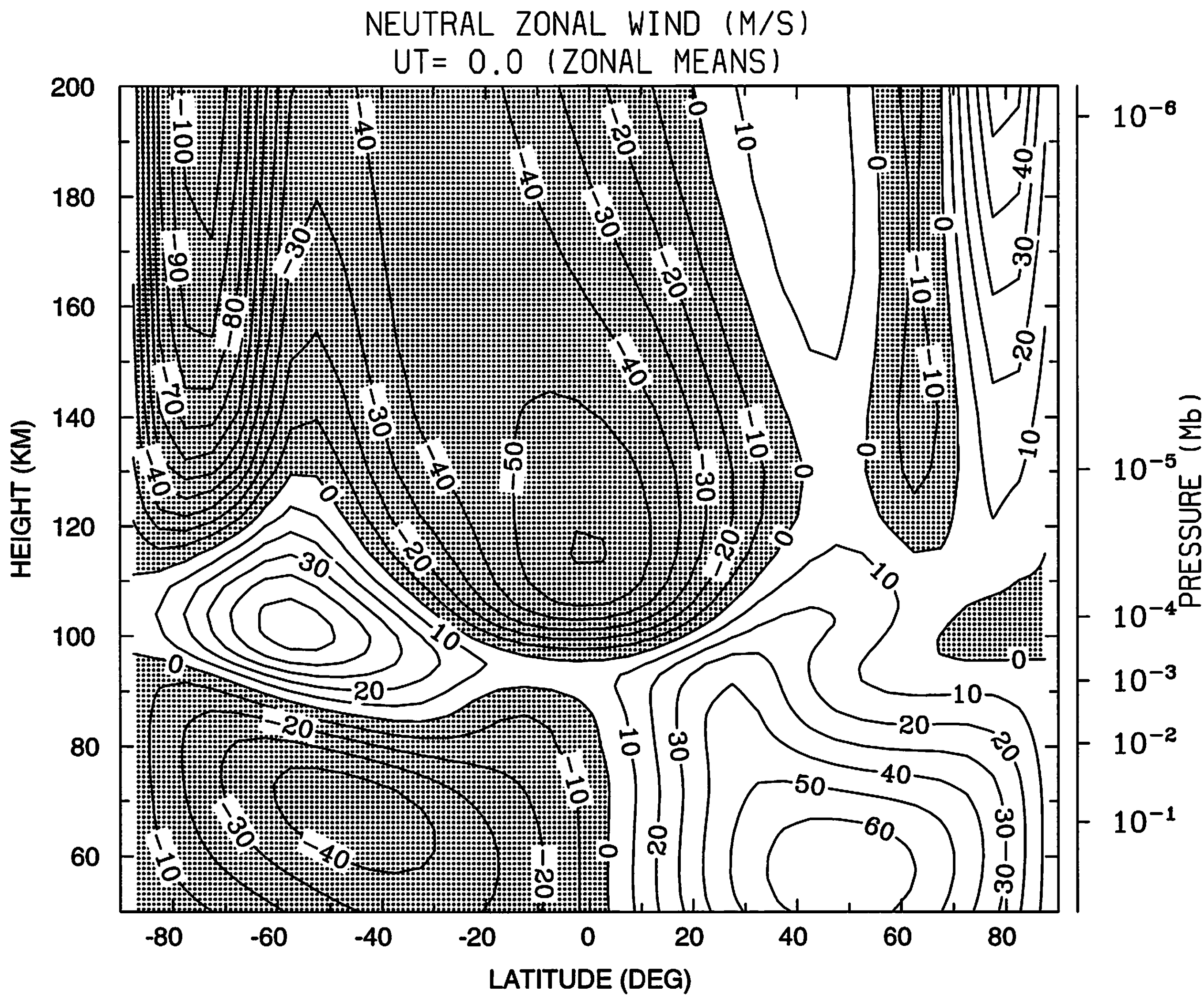


FIG. 8. As in Fig. 6, except for WD.

TIME-GCM results courtesy of Ray Roble
(using Fritts and Lu(93) GWD parameterization)

(December solstice)



MIN,MAX= -1.0832E+02 6.7890E+01 INTERVAL= 1.0000E+01
TIME-GCM /ROBLE/RGR97/TSDNZB2 (DAY,HR,MIN= 56, 0, 0)

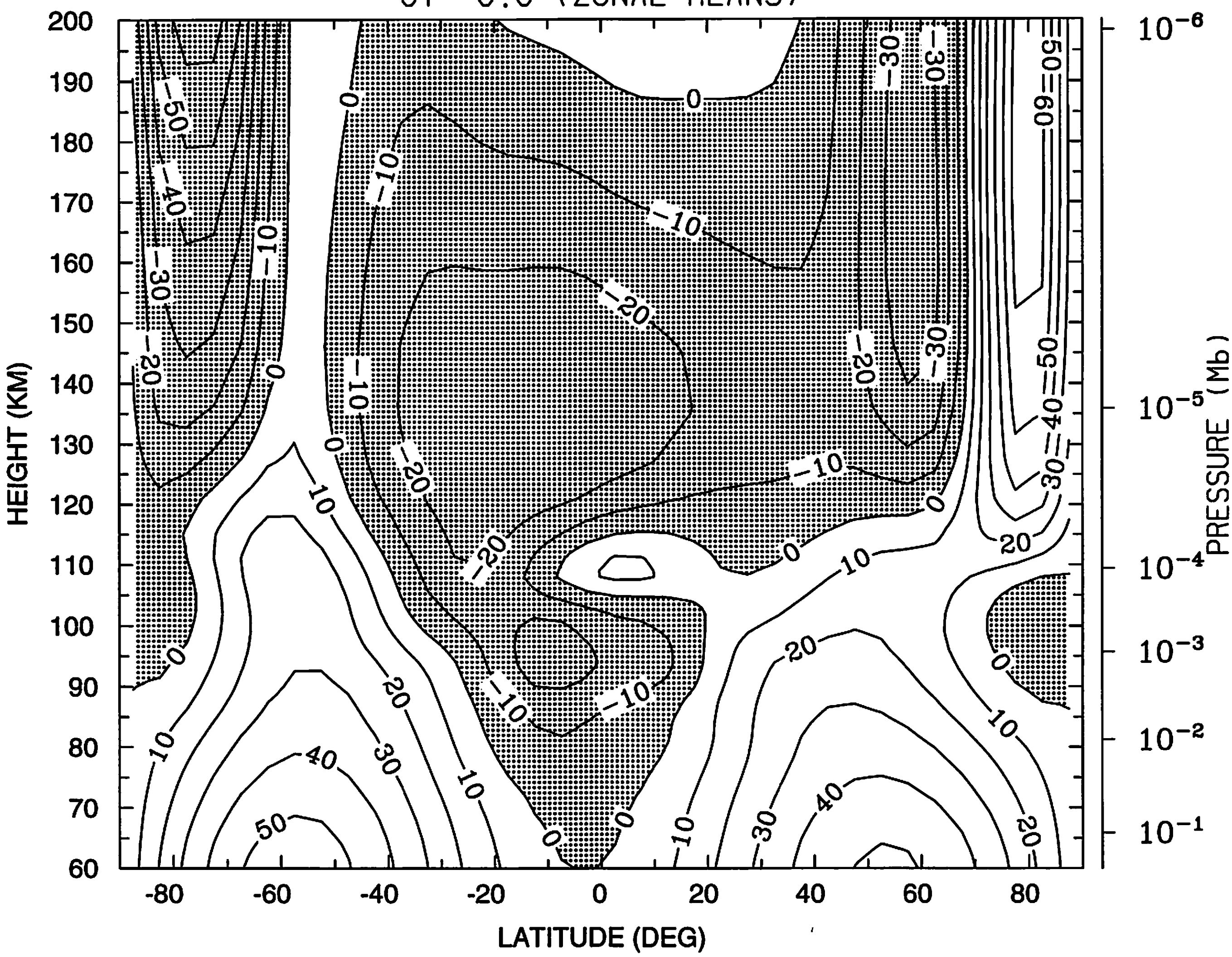
TIME-GCM results

using F & L (93) GWD

(Equinox)

NEUTRAL ZONAL WIND (M/S)

UT= 0.0 (ZONAL MEANS)

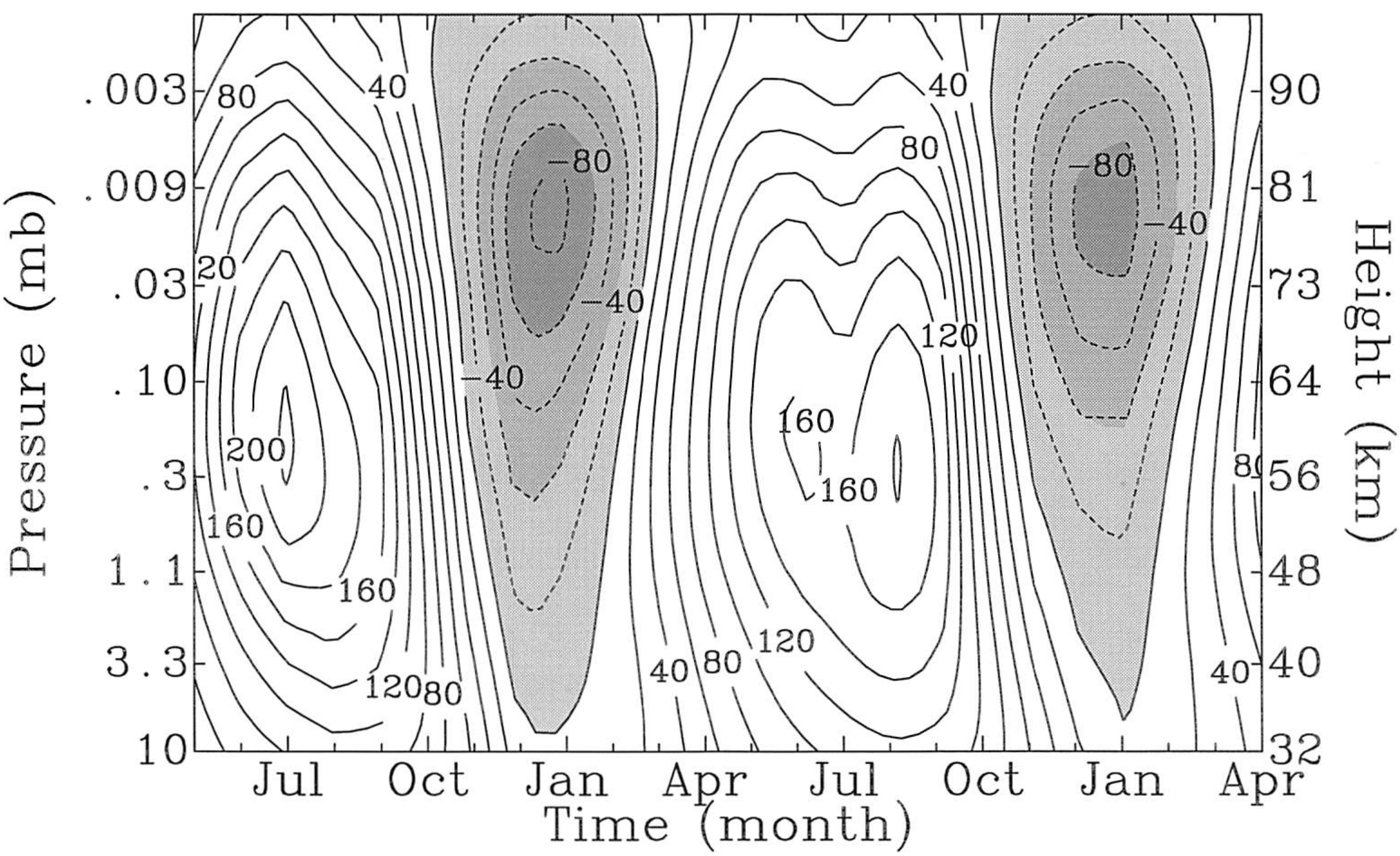


MIN,MAX= -6.5482E+01 6.3893E+01 INTERVAL= 1.0000E+01

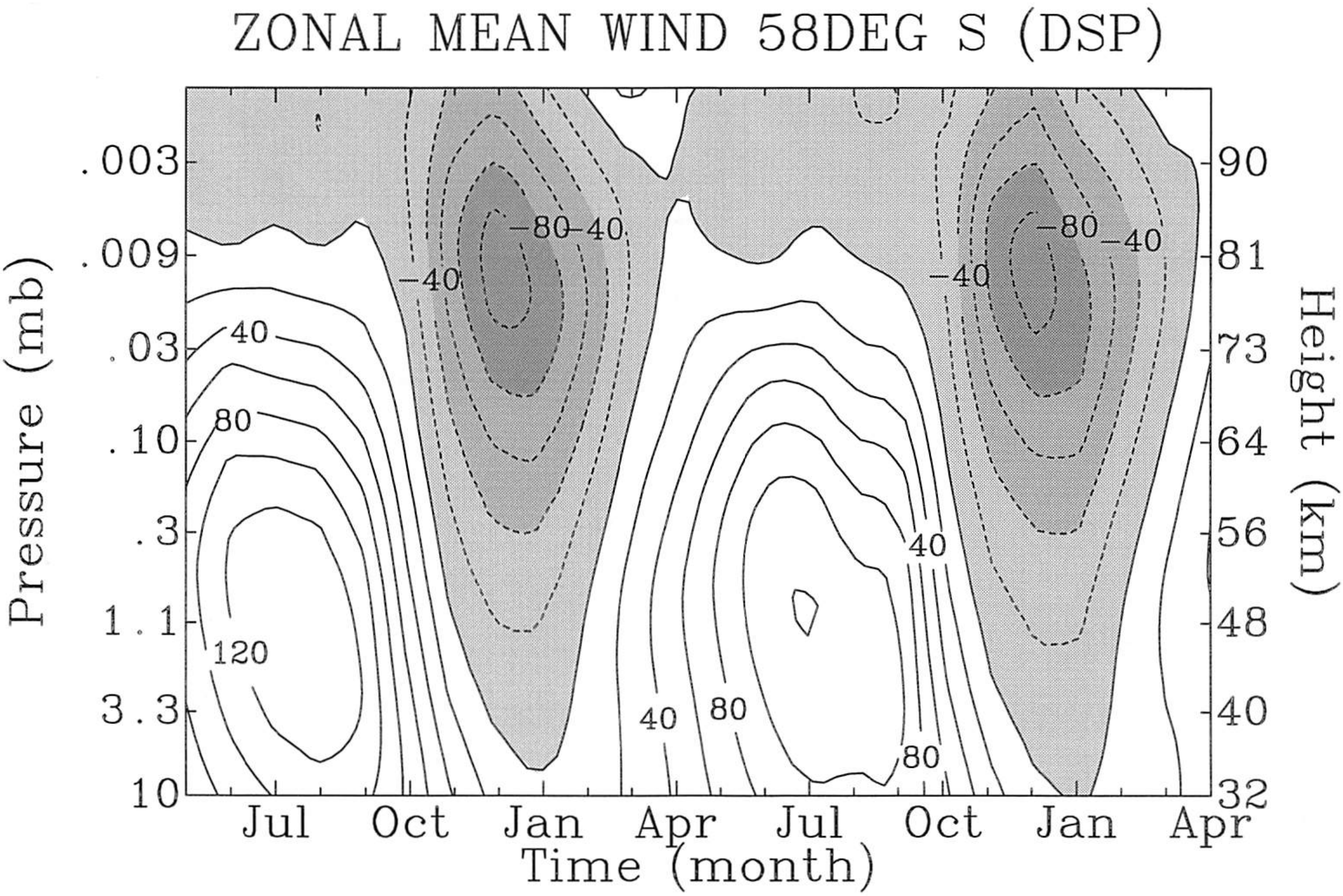
TIME-GCM /ROBLE/RGR96/TSEQUJ8 (DAY,HR,MIN= 32, 0, 0)

CMAM results (without DSP GWD)

ZONAL MEAN WIND 58DEG S (NO DSP)

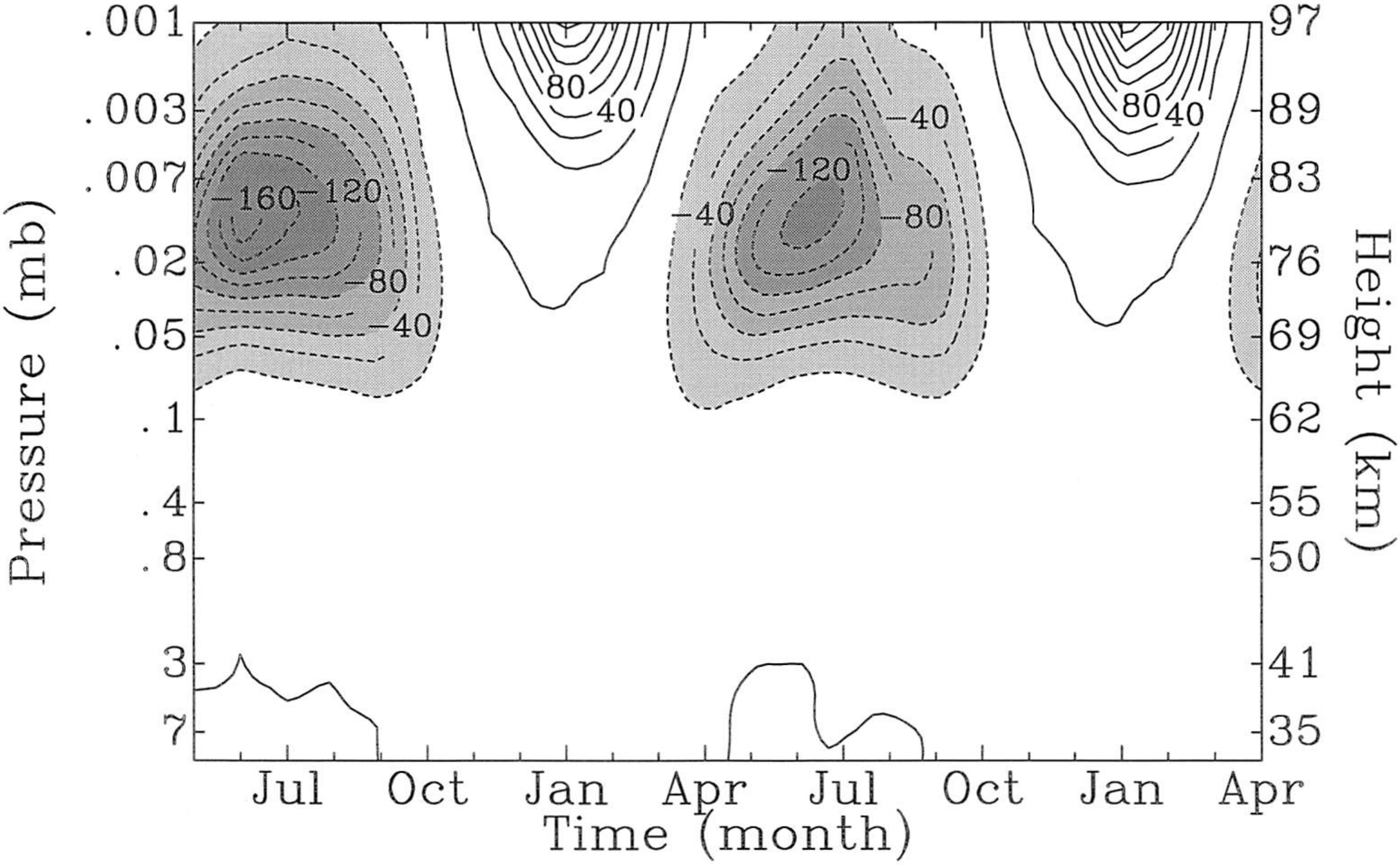


CMAM results using DSP GWD



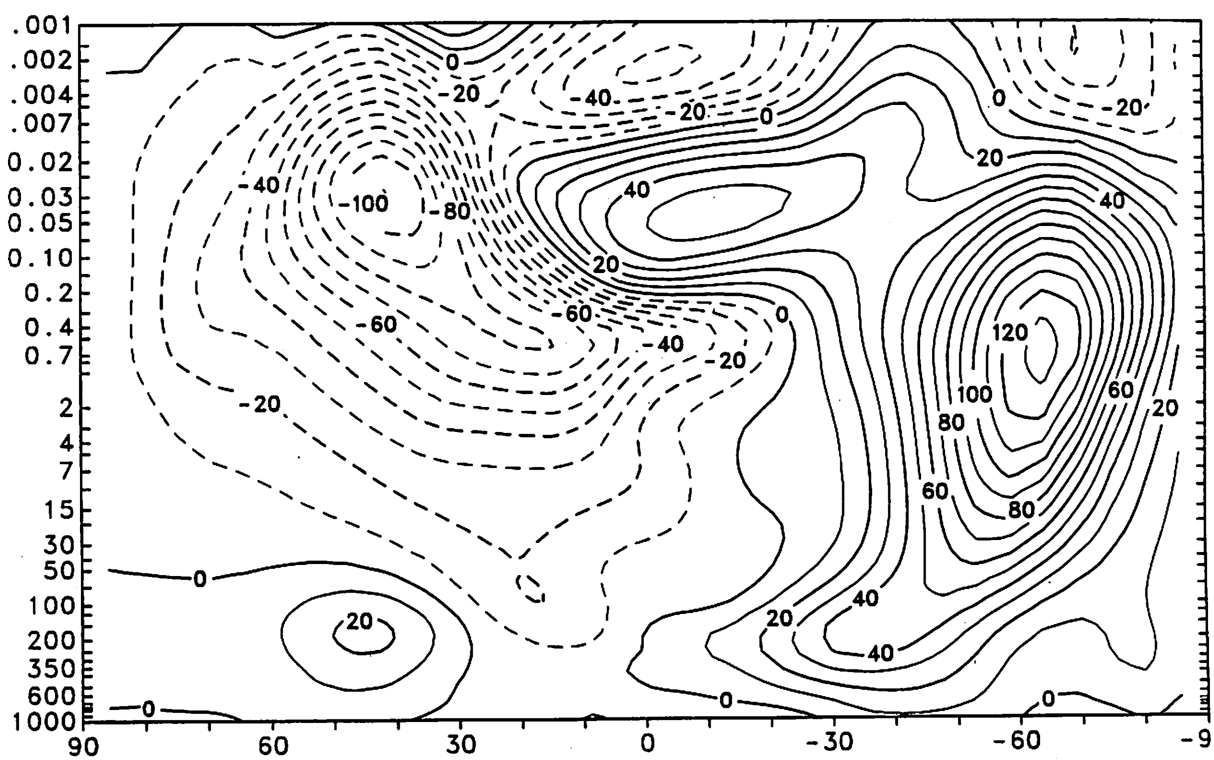
CMAM Results (DSP GWD)

ZONAL MEAN GWD 58DEG S (DSP)



CMAM results using DSP GWD

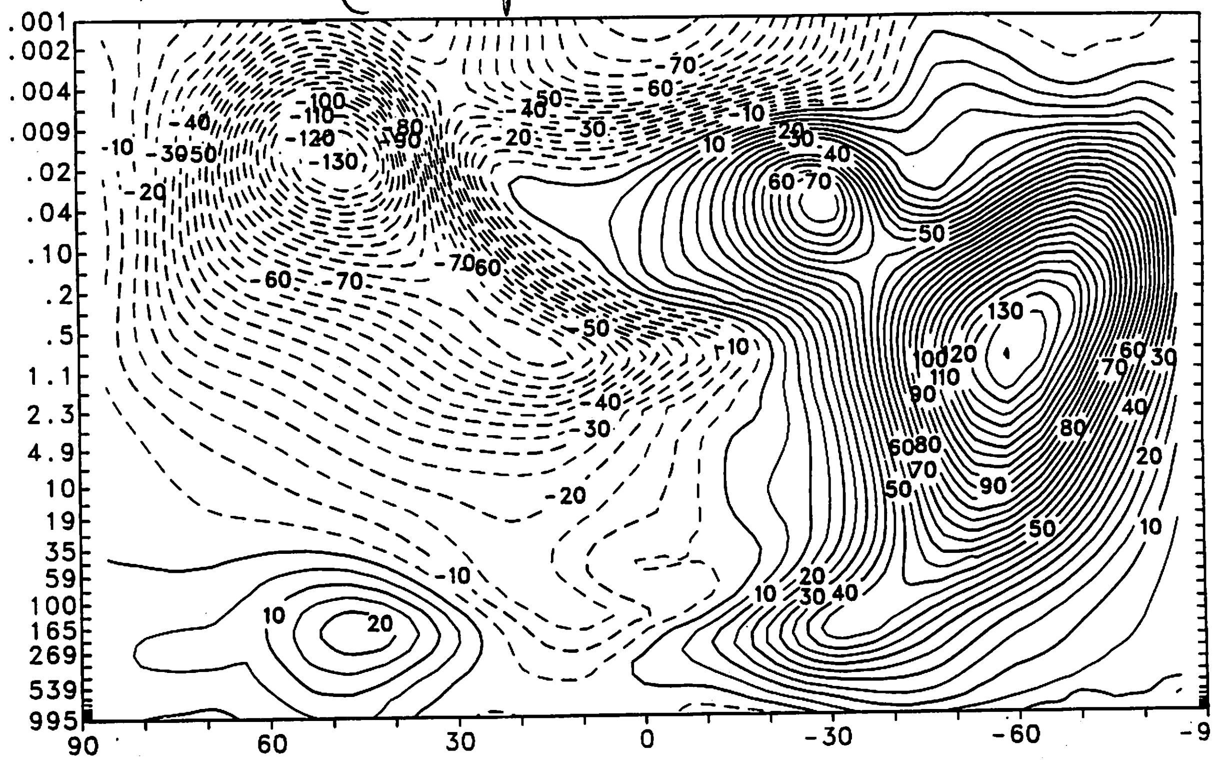
RUN MAM3C JUL(II) ZONAL-TIME AVG ZONAL WIND (M/S)



CMAM (results using Medvedev-Klaassen GWD param)

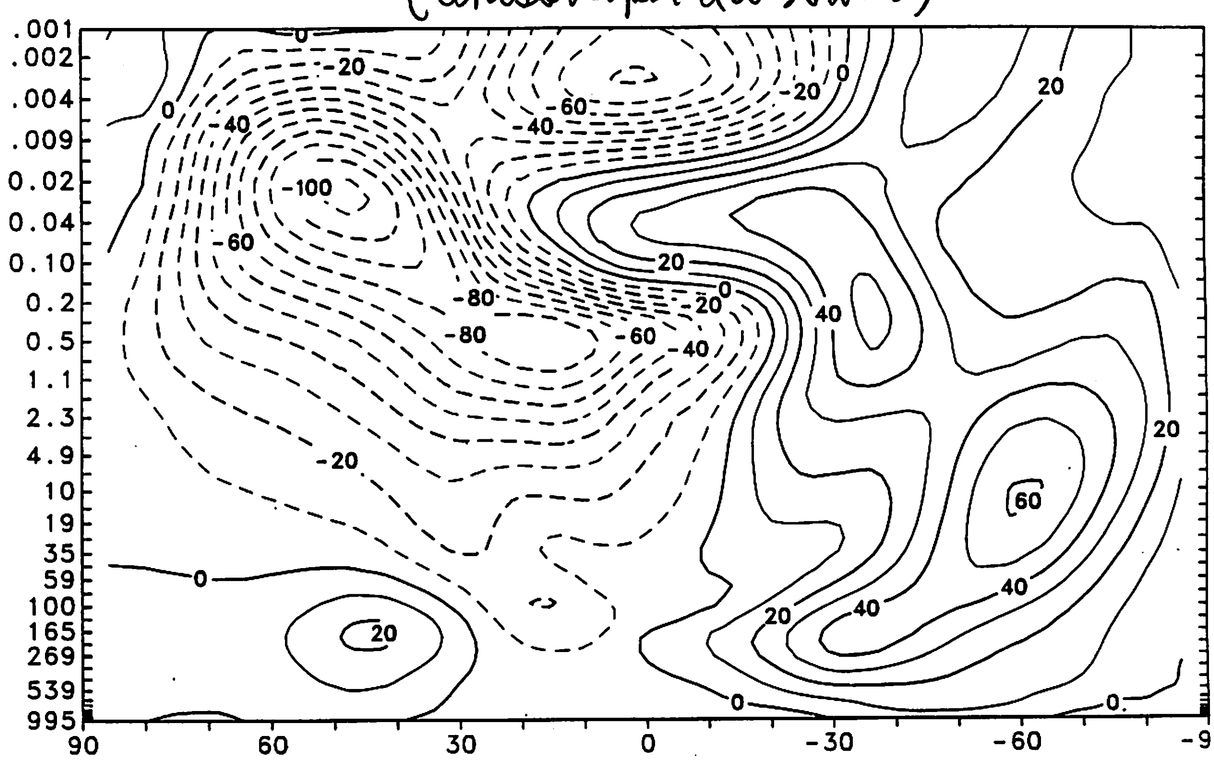
RUN YBOF. JUL(I). ZONAL VELOCITY U UNITS M/SEC.

(isotropic GW source)



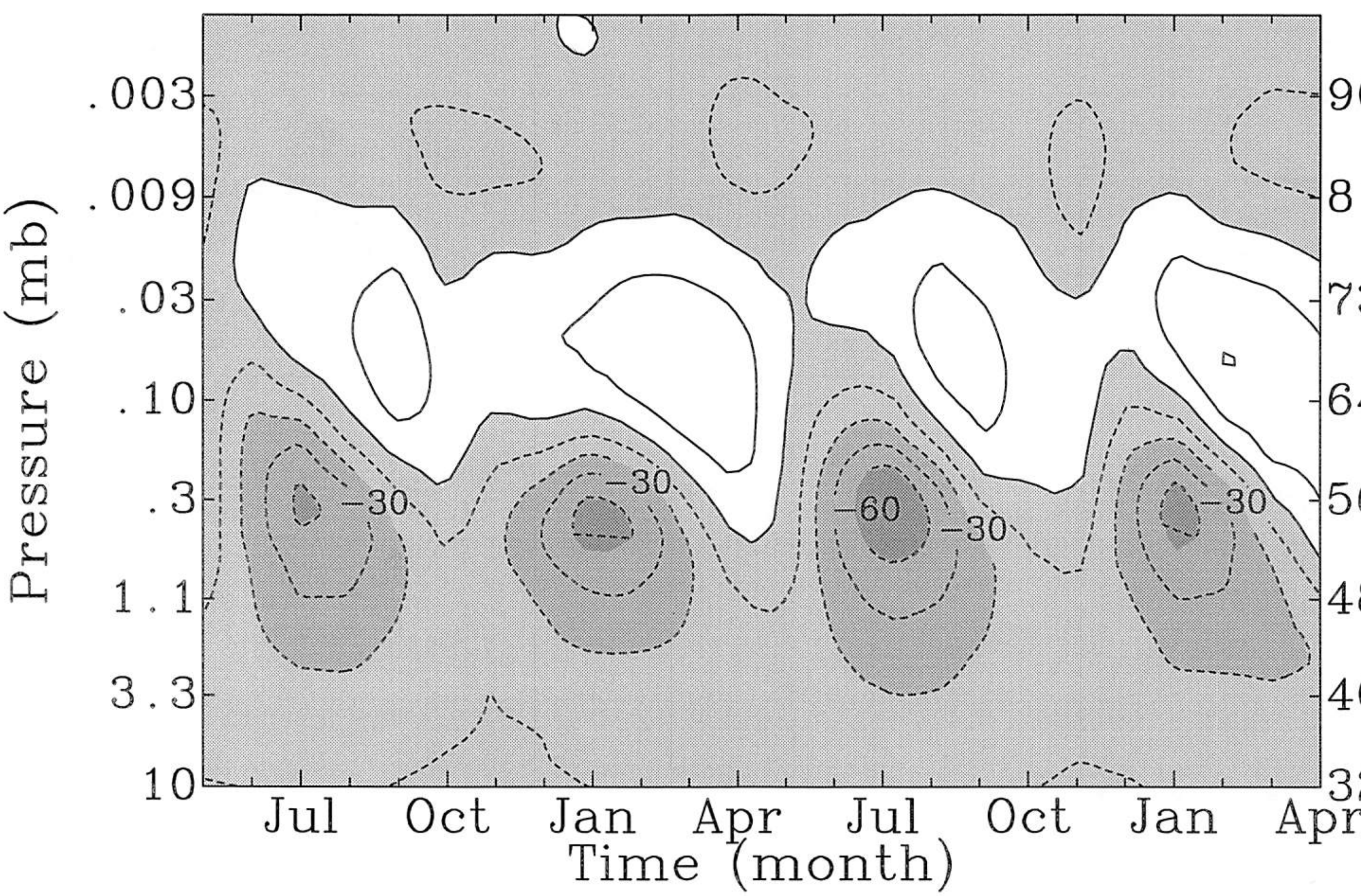
RUN MAM3F. JUL(II). ZONAL MEAN WIND (TIME AVG) UNITS M/S.

(anisotropic GW source)



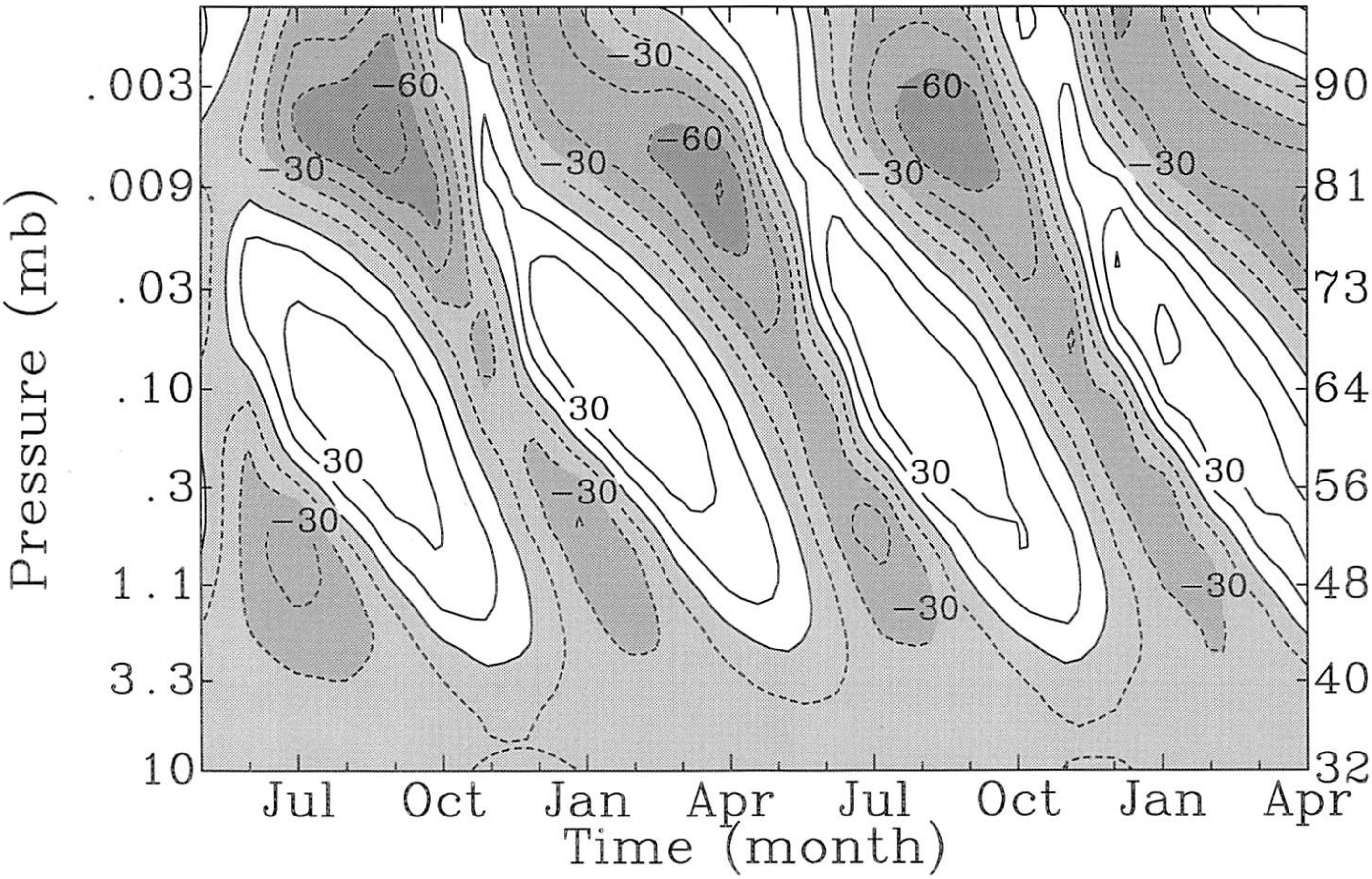
CMAM results without DSP GWD

ZONAL MEAN WIND 3DEG N (NO DSP)

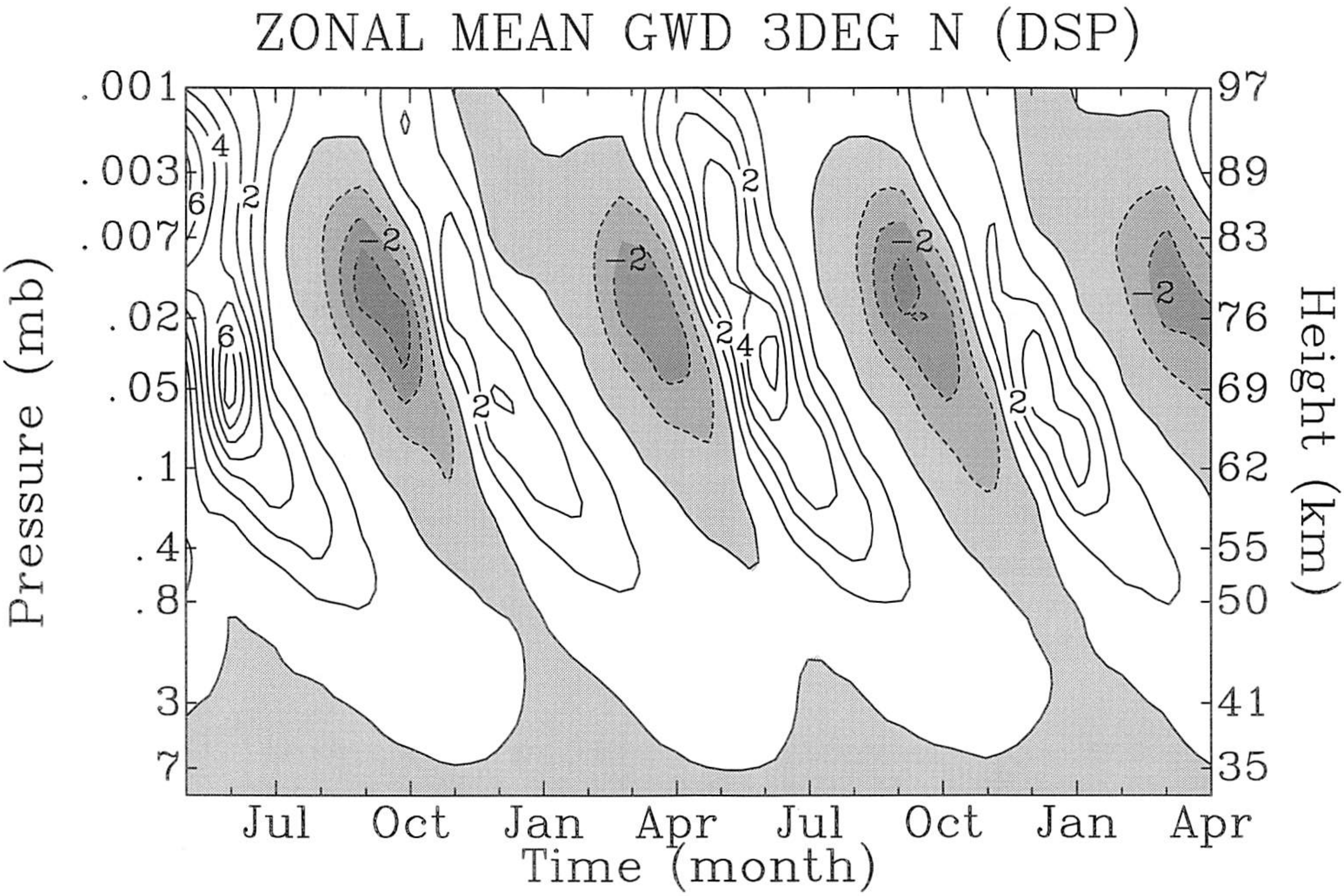


CMAM results using DSP GWD

ZONAL MEAN WIND 3DEG N (DSP)



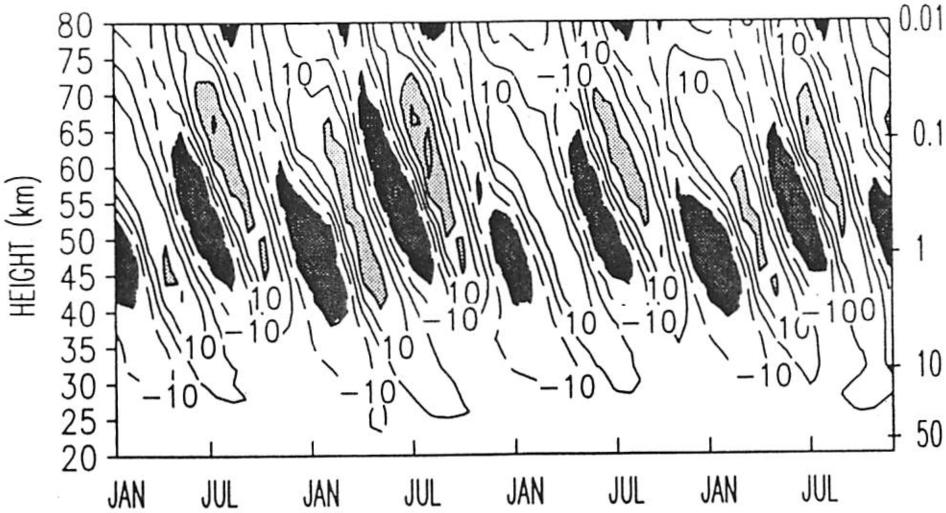
CMAM (DSP GWD)



ZONAL MEAN GWD 3DEG N (DSP)
Pressure (mb)
.001
.003
.007
.02
.05
.1
.4
.8
3
7
Height (km)
97
89
83
76
69
62
55
50
41
35
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Time (month)

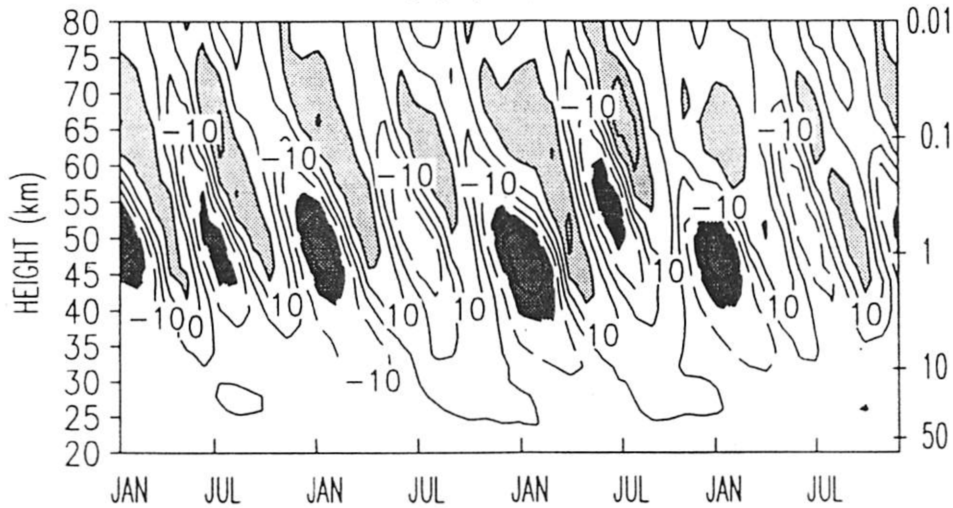
ECHAM4 GCM results using DSP GWD
(Manzini et al, JGR 97)

DSP U (m/s) Equator



isotropic source

DSP.II U (m/s) Equator



anisotropic source.

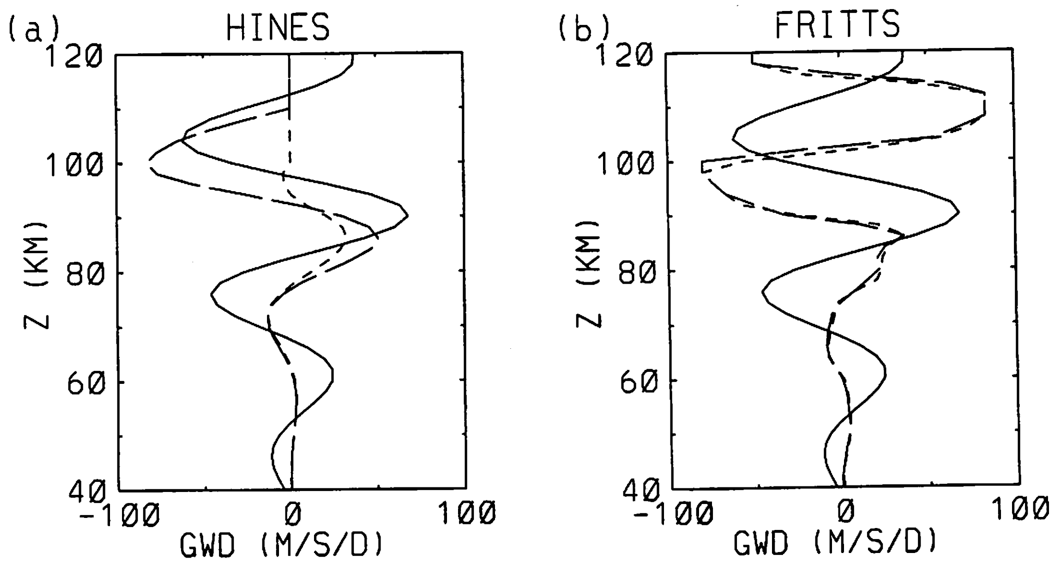


Figure 5. GWD using idealized tidal wind profile: (a) Hines GWD for tidal wind amplitudes of 70 m/s (short dashes) and 35 m/s (long dashes) ($\sigma_{h0} = 2$ m/s, $s = 1$, $m_{min} = 1/(3\text{km})$); and (b) same but for Fritts GWD ($E_0 = 0.5$ m^{2}s^{-2}). Zonal wind component for 70 m/s tide in m/s (solid).

mechanistic tidal model results
(without GWD)

McLandress (97) in Gravity Wave Processes and their parameterization in global climate models

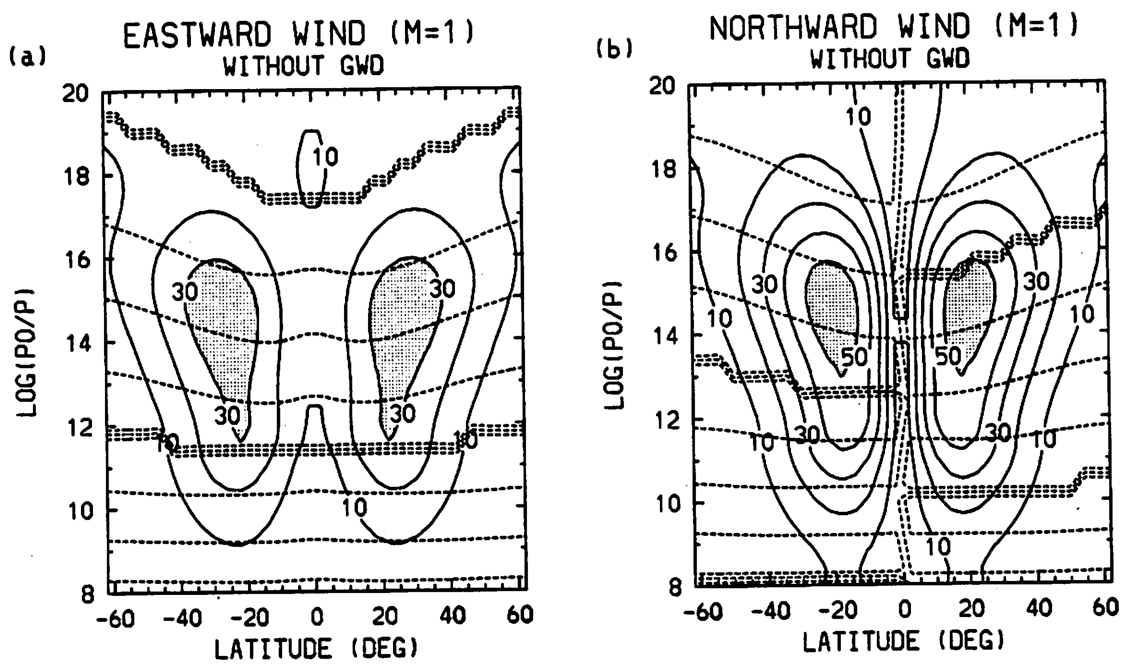


Figure 5. Diurnal tide at 0h UT without GWD: (a) zonal and (b) meridional wind components. Amplitude in m/s (solid) and phase defined as longitude of maximum (dashes). Vertical wavelength given by distance between two sets of the 3 closely-spaced phase lines where the phase jumps from 360° to 0°.

mechanistic tidal model with GWD

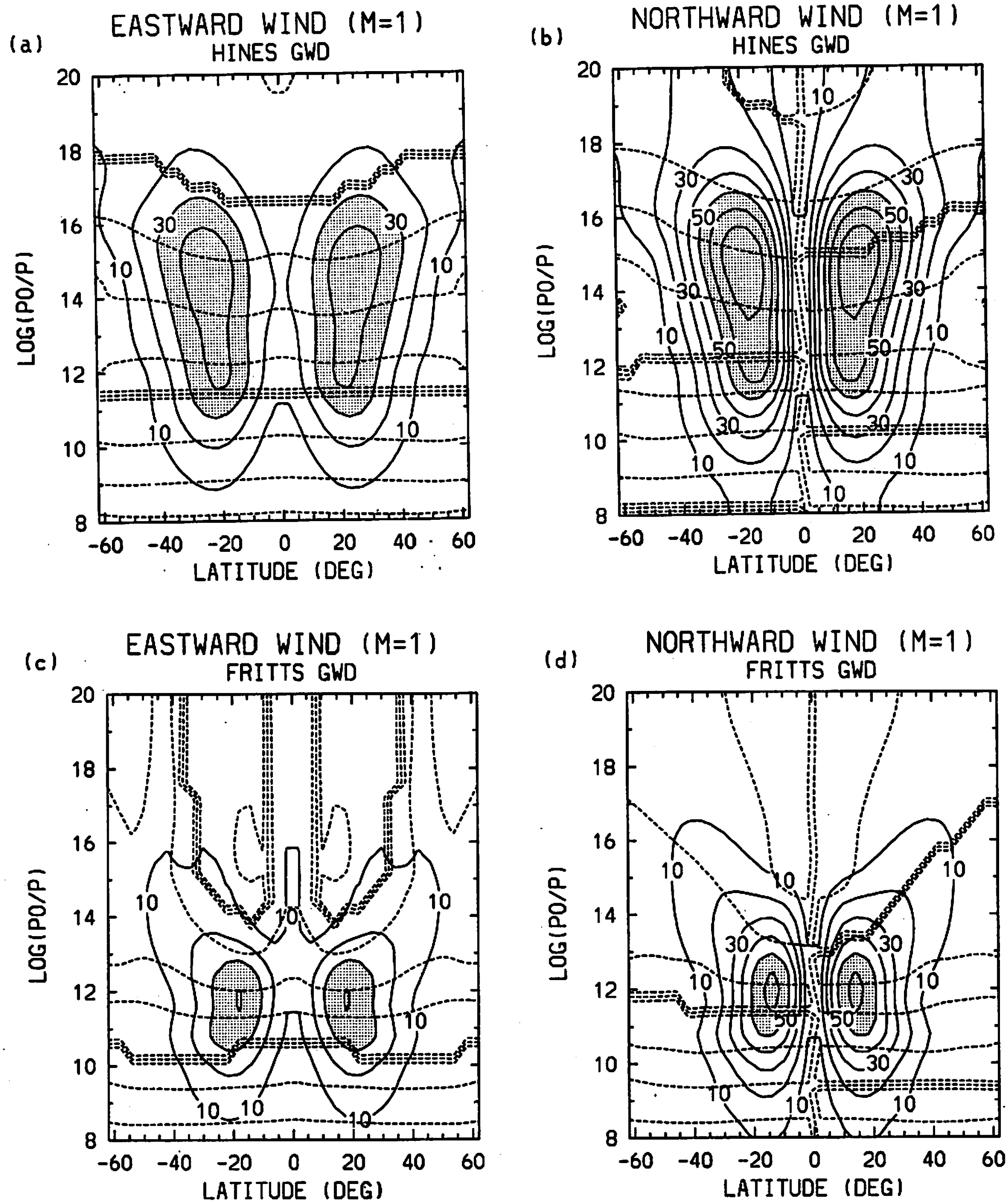
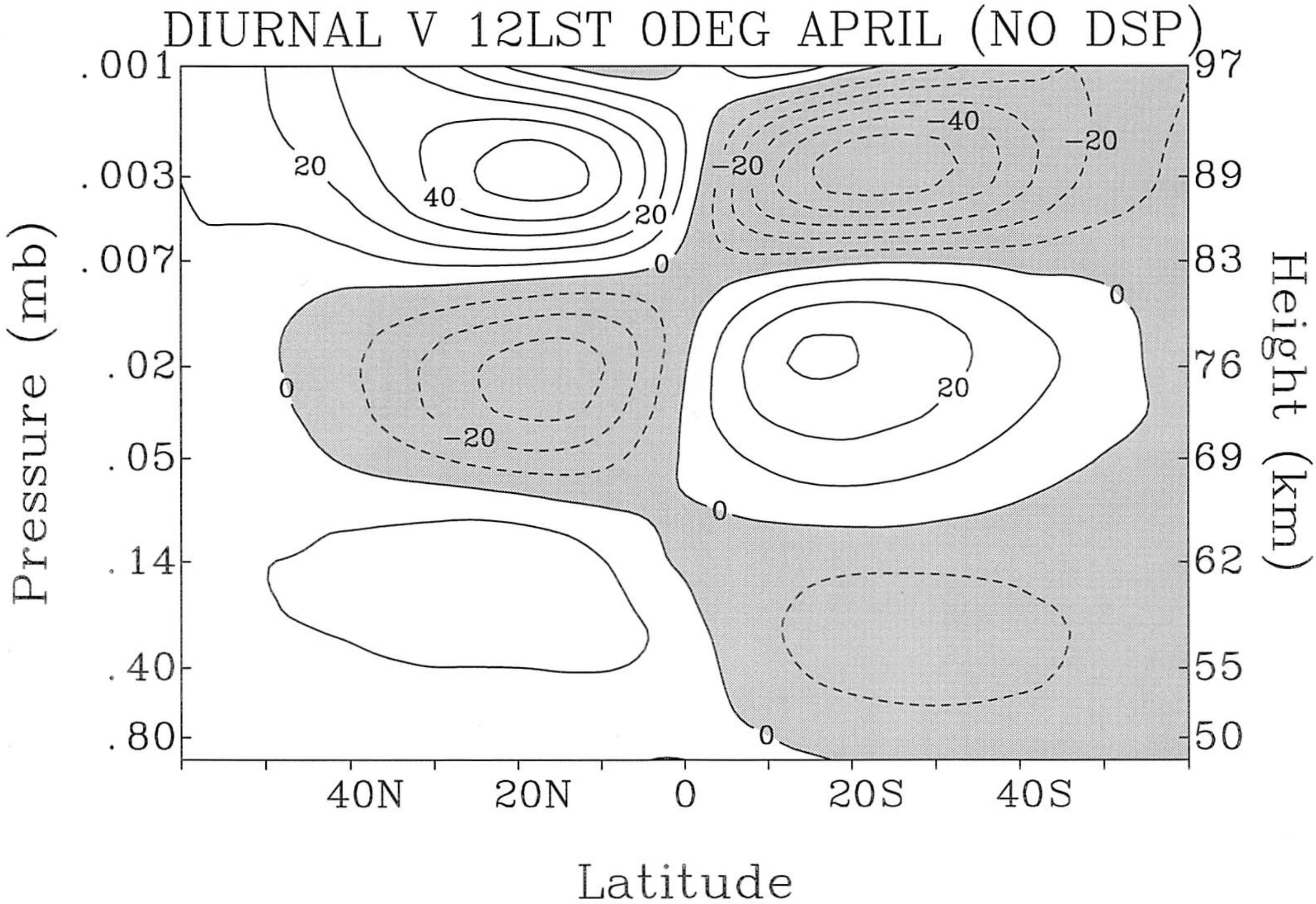


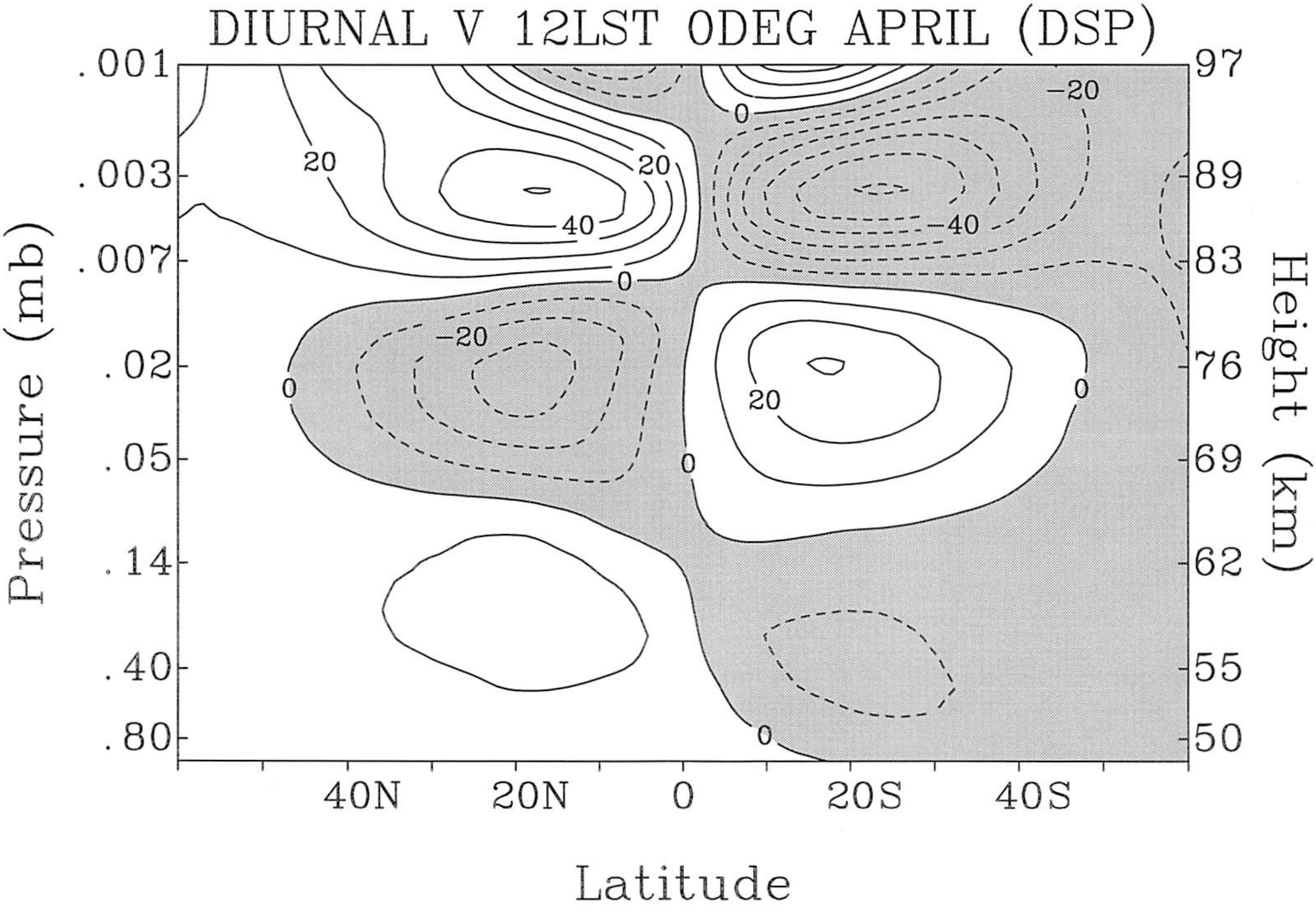
Figure 6. Diurnal tide **amplitude and** phase at 0h UT. Using Hines GWD ("control" parameters): (a) zonal and (b) meridional wind components. Using Fritts GWD ("control" parameters): (c) zonal and (d) meridional wind components. Refer to Figure 5 caption **for more explanation.**

CMAM results (without DSP GWD)

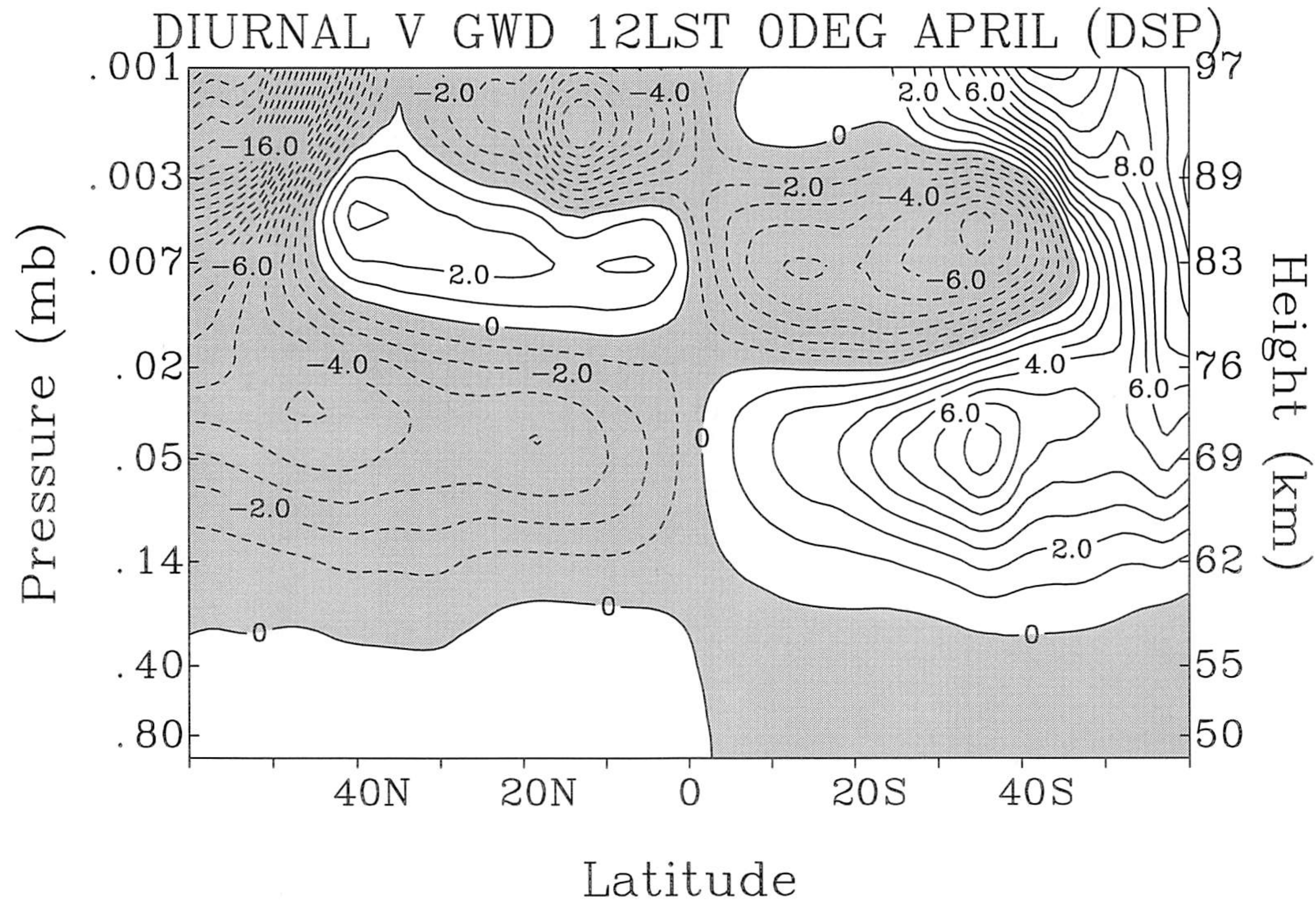
migrating diurnal tide meridional wind at 12h LST and 0° longitude



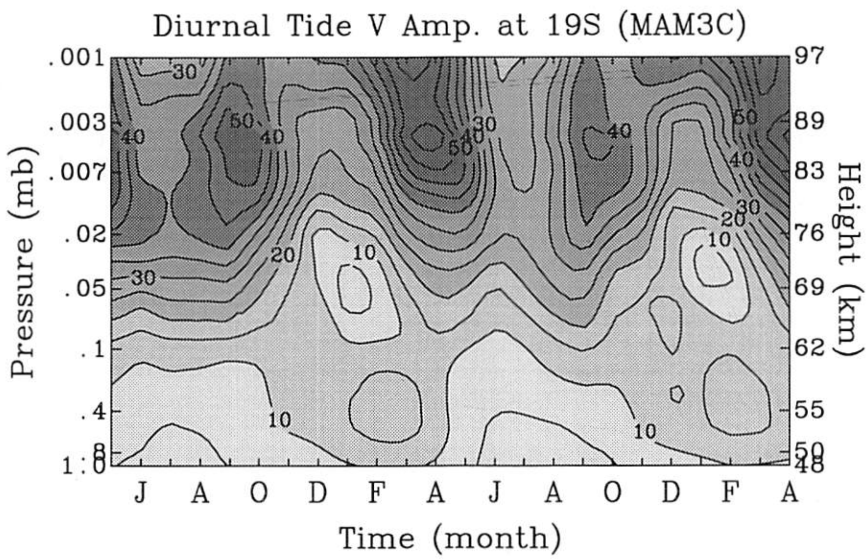
CMAM results (with DSP GWD)



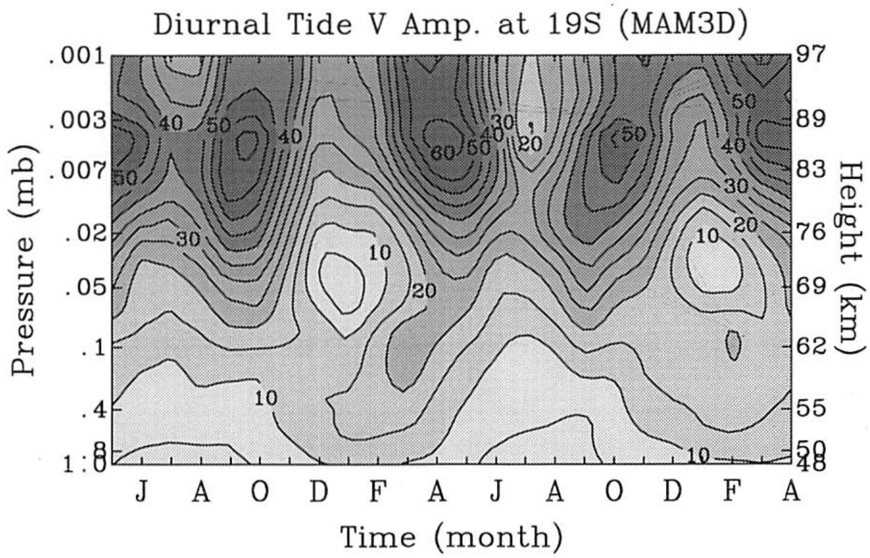
CMAM (DSP GWD)


DIURNAL V GWD 12LST 0DEG APRIL (DSP)
Pressure (mb)
Height (km)
Latitude
.001
.003
.007
.02
.05
.14
.40
.80
97
89
83
76
69
62
55
50
40N
20N
0
20S
40S
-16.0
-2.0
-4.0
-6.0
2.0
0
8.0
6.0
4.0

CMAM (with DSP GWD)
(amplitude (m/s) of meridional wind component (m/s) of migrating diurnal tide)



CMAM (without DSP GWD)



GRAVITY WAVE SOURCES

(1) mountains

(2) convection

(3) jet streams / fronts

- problem is how to quantify these sources in GWD parameterizations!
- need measurements!

McFarlane (JAS 87)

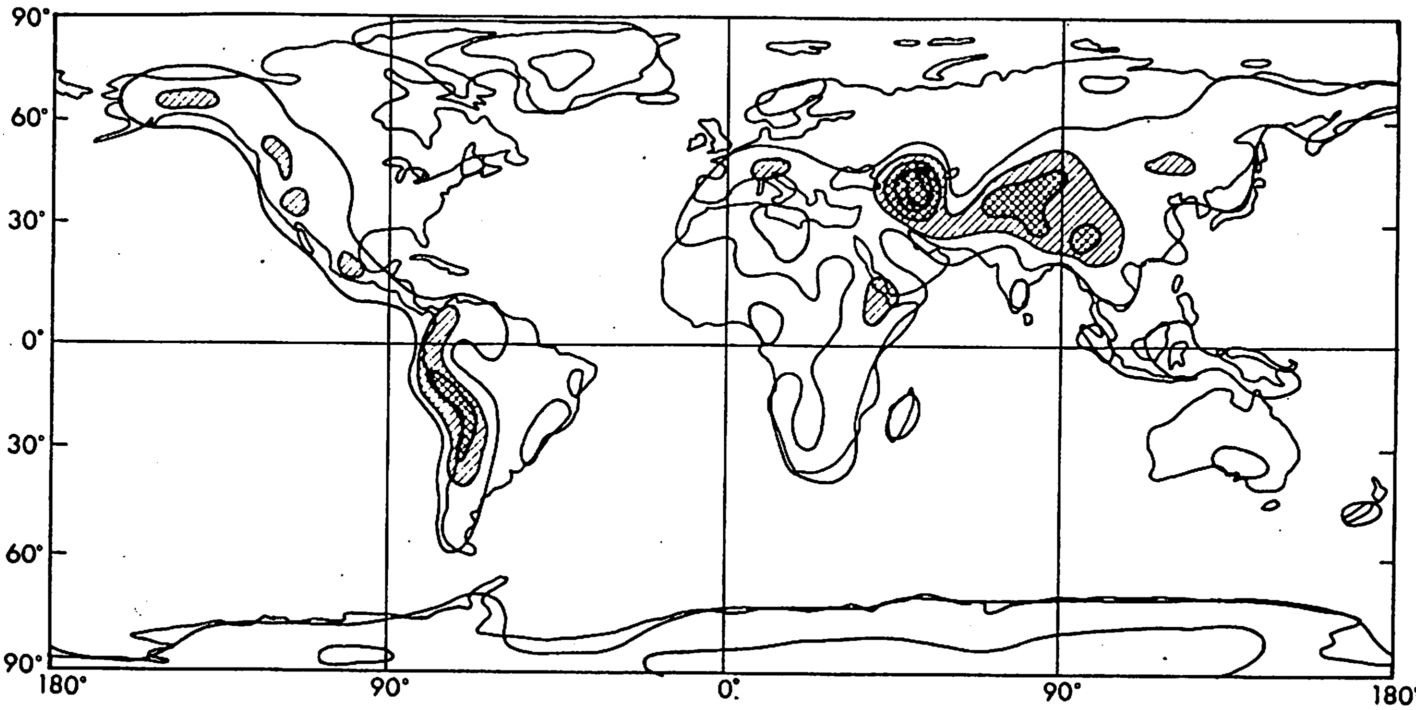


FIG. 3. Smoothed subgrid-scale orographic standard deviation field. Contours are of twice the standard deviation. The lowest value contoured is 250 m and the contour interval is 50 m. Regions with values in excess of 750 m are hatched; cross-hatched regions exceed 1250 m.

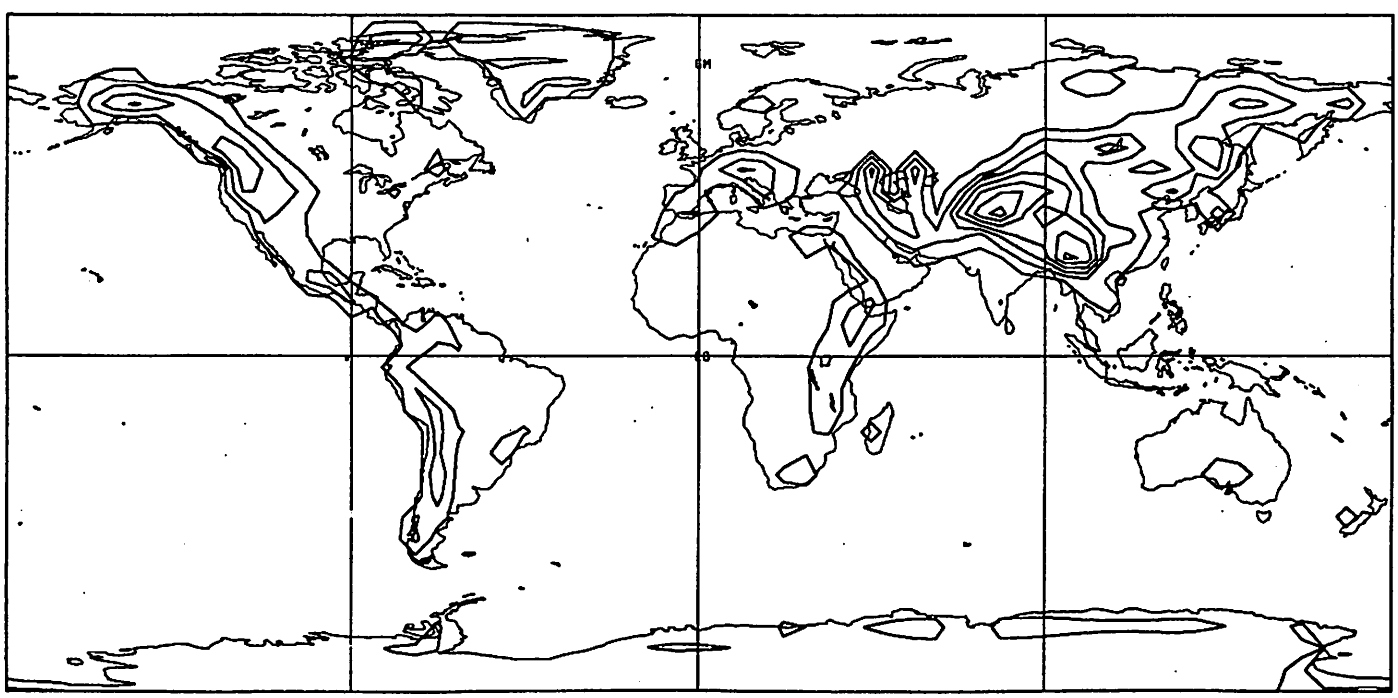
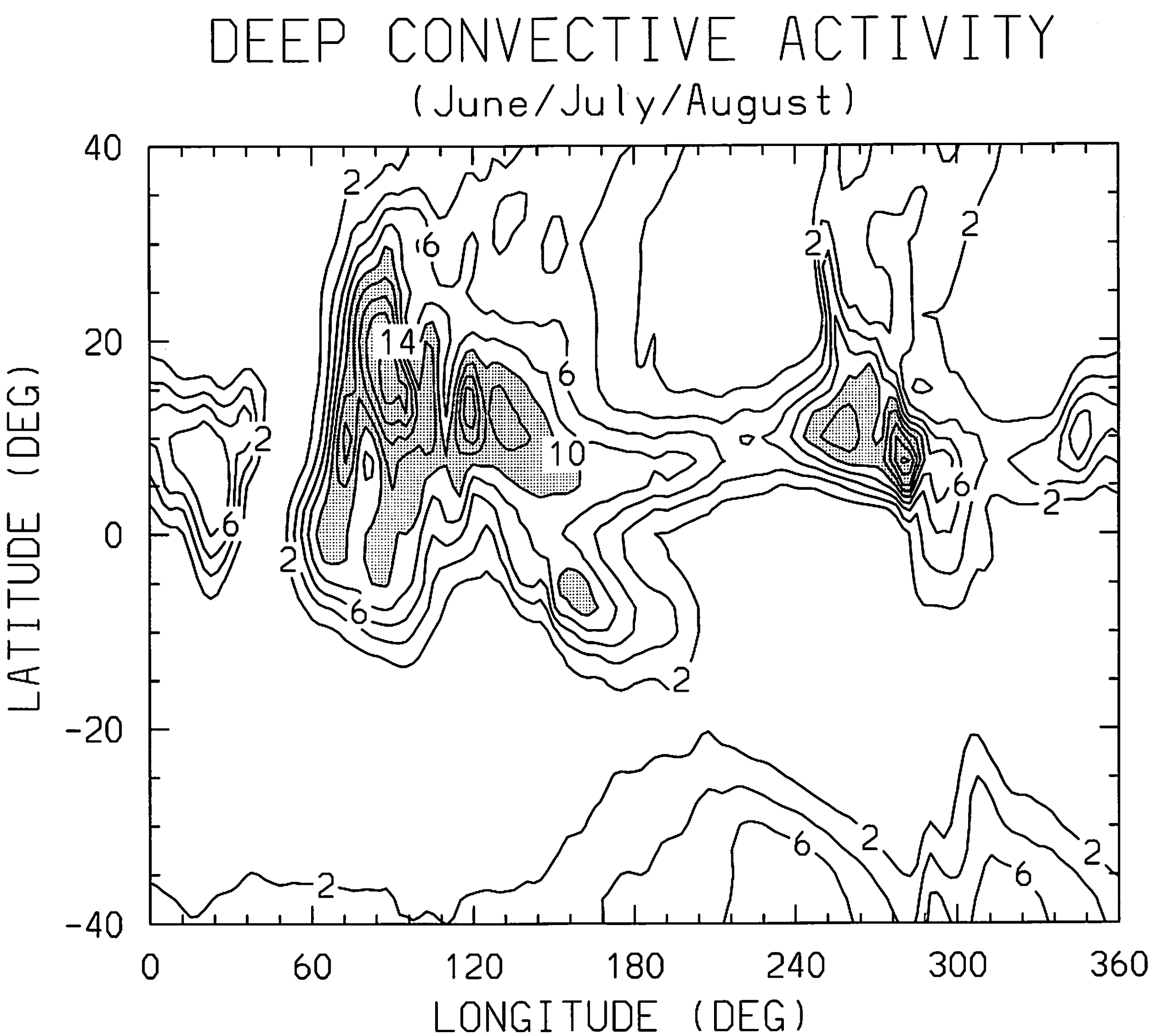


FIG. 21. Net stress drop over the vertical model domain due to the wave drag force. Contours are for 0.05 Pa and larger with an interval of 0.1 Pa.

Forbes et al (Annal Geophys. , 97)



improvement of parameterizations

- better understanding of processes causing universal spectrum
  - linear instability
  - Doppler spreading
- test assumptions used in parameterizations:
  - separable spectrum (ALL)

    i.e., $E \propto A(m)\, B(\omega) \ldots$
  - form of spectrum in different directions (Fritts assumes same)

  - is spectrum broad and interacting? (Hines).