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Energy Agency

**310/1749-9**

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**International Advanced School**
**on**
**Space Weather**
**2-19 May 2006**

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# *Introduction to Middle Atmospheric Dynamics*

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# Introduction to Middle Atmospheric Dynamics

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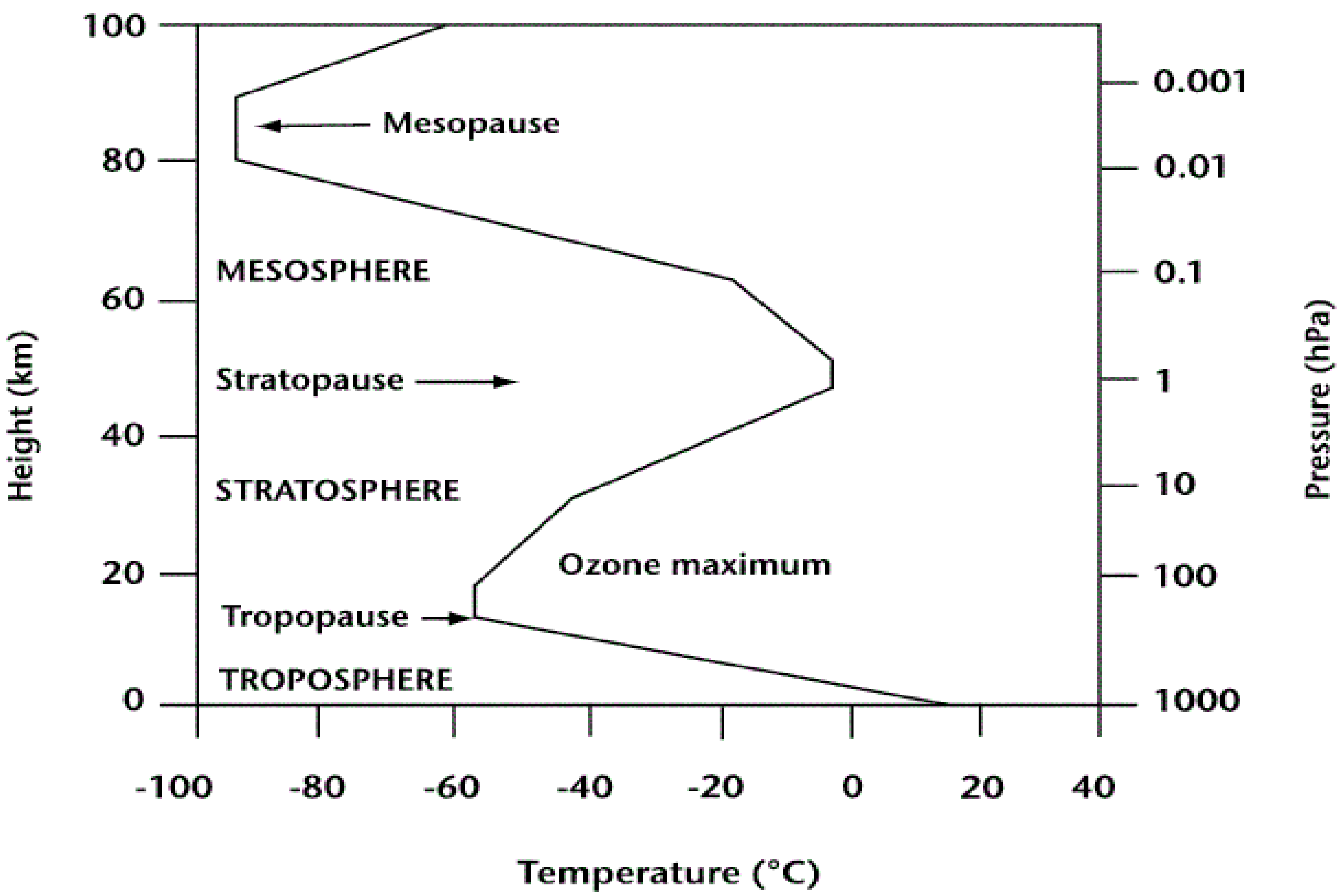
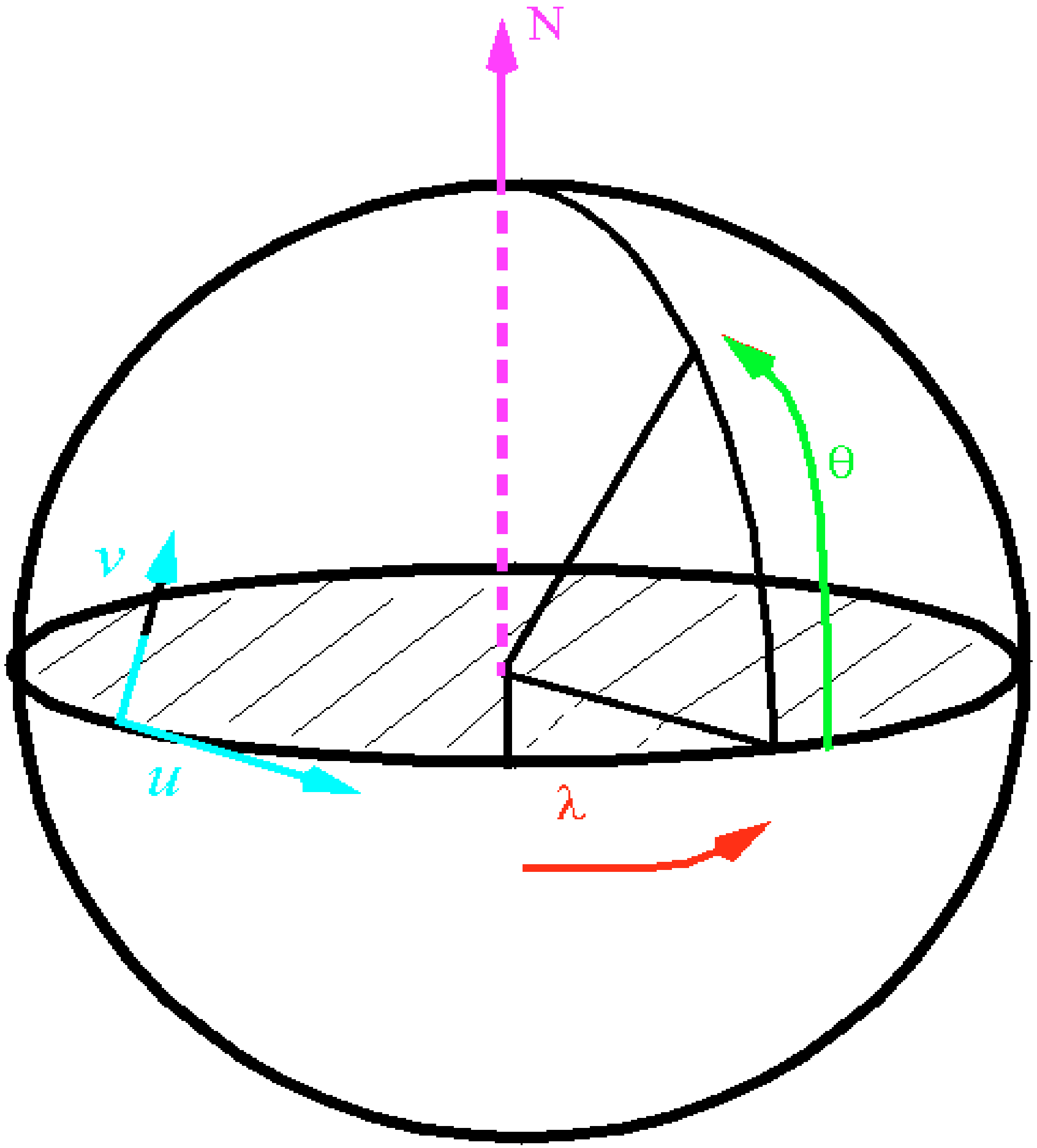
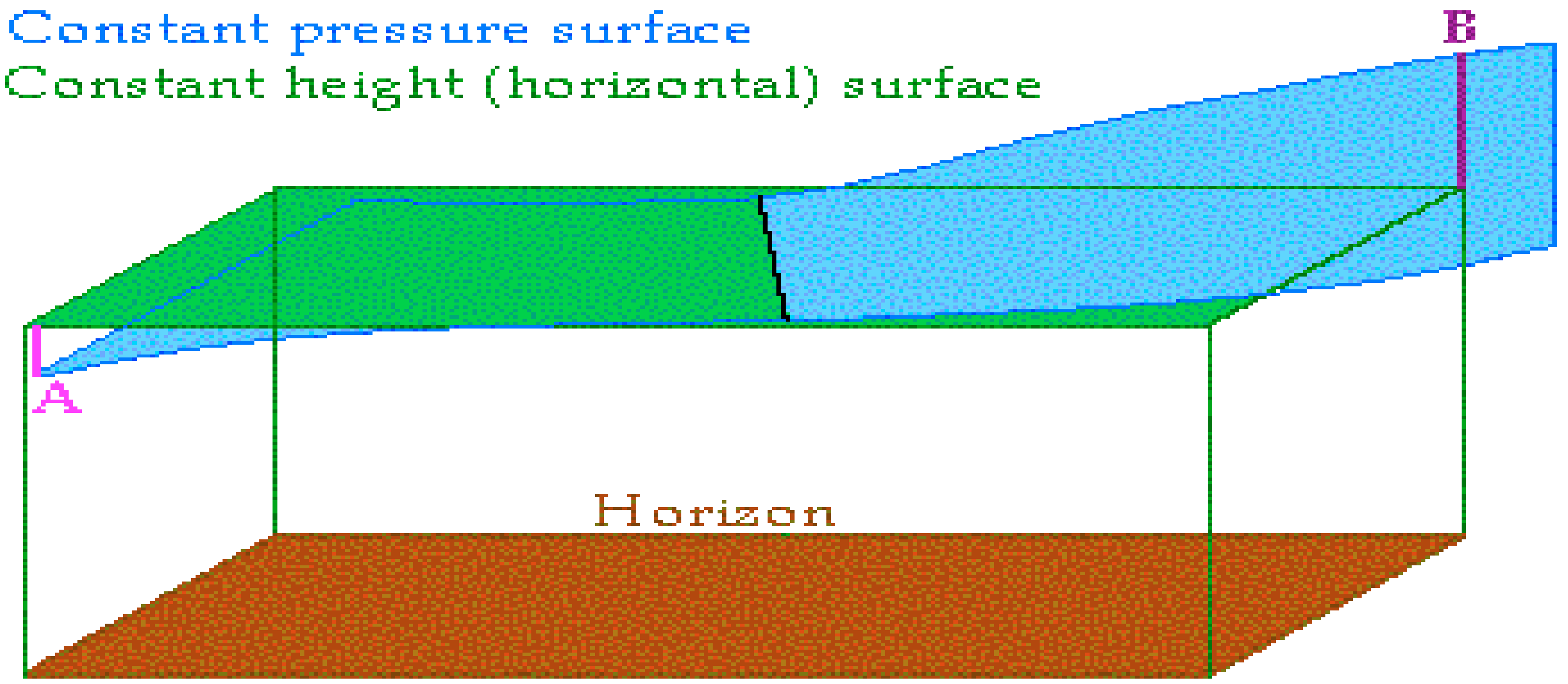



Typical mid-latitude temperature profile


N
θ
v
u
λ

## Pressure as a Vertical Coordinate

As illustrated below, **upper air analysis** is much more convenient using **pressure** rather than height as the reference **vertical coordinate.** Other than in violent atmospheric circulations with locally rapid accelerations such as tornadoes, pressure always decreases with increasing altitude (else an upward acceleration greater than gravity's downward acceleration is necessary). Thus for all practical purposes, pressure is a continuously and smoothly decreasing function with respect to elevation (height above mean sea level). Just as the horizontal direction defines a surface of constant elevation or height, a surface of constant pressure can also be defined. Just as our previous surface pressure analysis was for a constant height of mean sea level, upper air air analyses are done for constant pressures (surfaces) aloft.




Along A, pressure on the constant height surface is less than that on the constant pressure surface; similarly, height on the constant pressure surface is less than that on the constant height surface. Thus, A is the low pressure/height area of this region. Vice-versa, B is the high pressure/height area.

$$\omega = \frac{dp}{dt}$$

$$\omega \cong -g\rho w$$

# Zonal Mean and Eddy Components

- Overall the strongest gradients in circulation are north-south rather than east-west

So we describe circulation as *zonal-mean* (average around latitude circles) plus *eddy* (deviations form zonal-mean) components

Zonal-mean circulation consists of generally strong zonal flow and much weaker overturning circulation in the meridional plane (mean meridional circulation, MMC)

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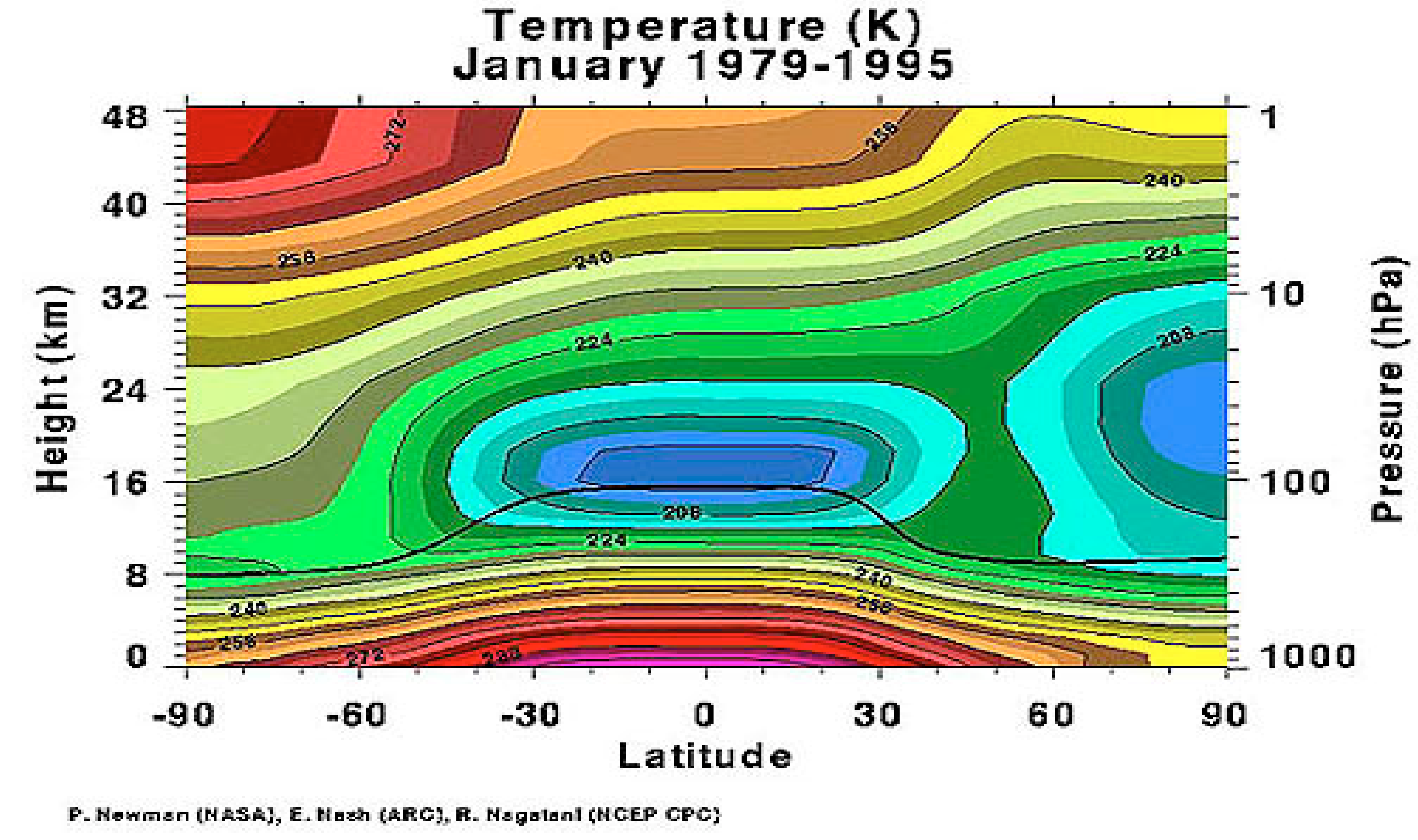
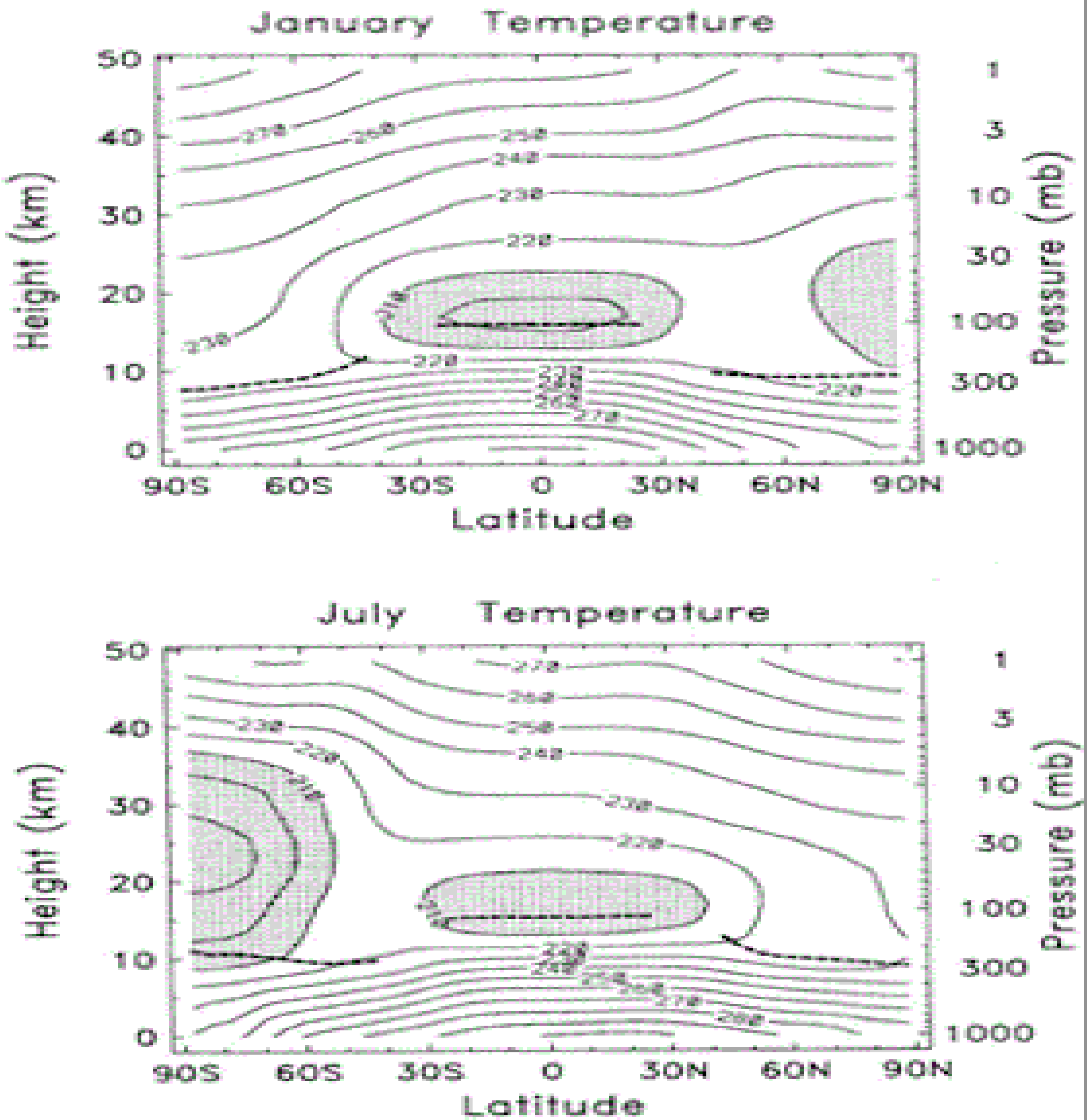
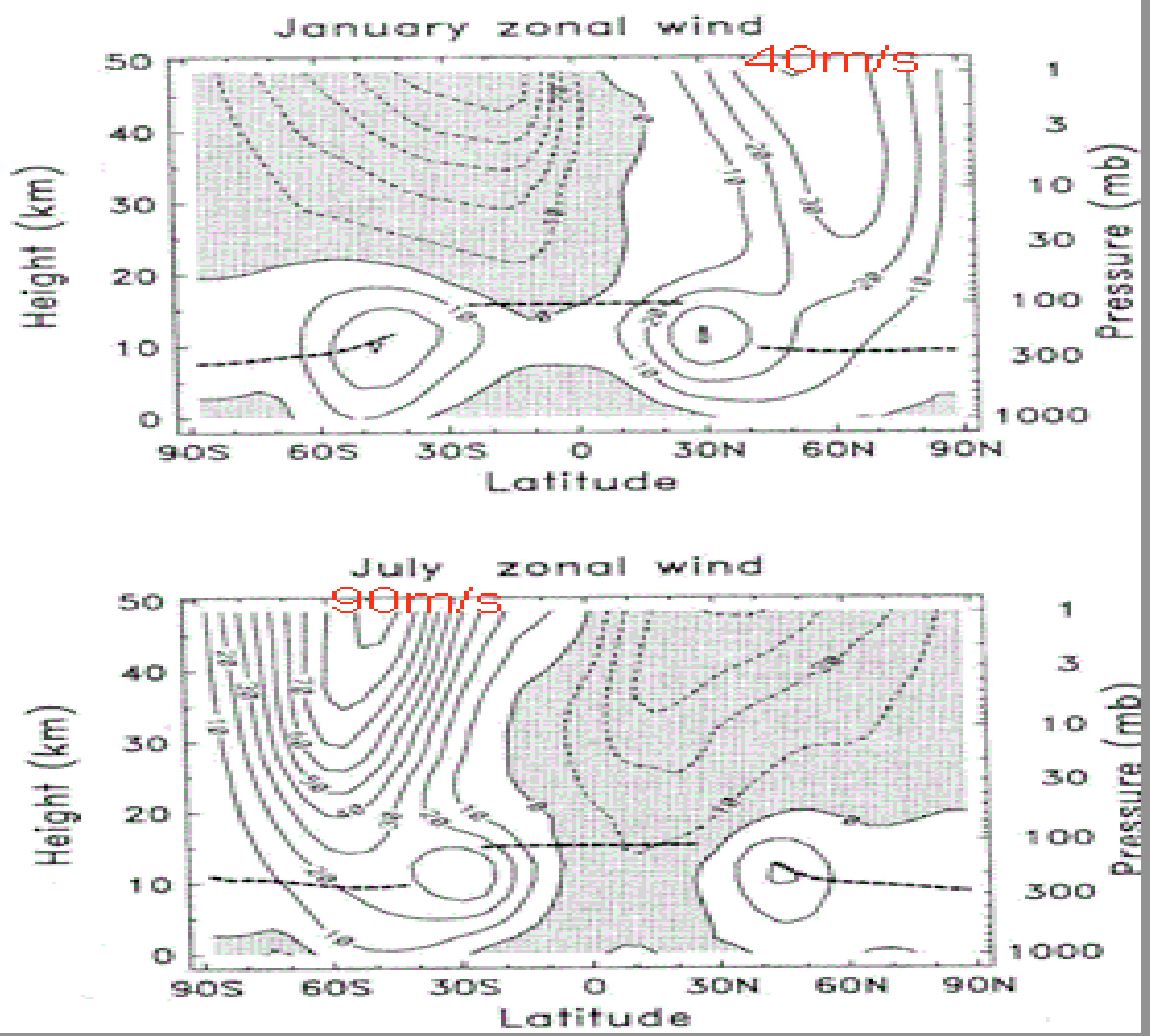


Temperature (K)
January 1979-1995
Height (km)
Pressure (hPa)
Latitude
48
40
32
24
16
8
0
1
10
100
1000
-90
-60
-30
0
30
60
90
P. Newman (NASA), E. Nash (ARC), R. Nagatani (NCEP CPC)

# • zonal-mean temperature



- **Zonal-mean zonal wind**



$$\frac{du}{dt} - fv + \frac{uv\tan\theta}{a} = \frac{-1}{a\cos\theta}\frac{\partial\Phi}{\partial\lambda}$$

$$\frac{d}{dt}v + fu + \frac{u^2}{a}\tan\theta = \frac{-1}{a}\frac{\partial\Phi}{\partial\theta}$$

$$\frac{\partial\Phi}{\partial p} = \frac{RT}{p}$$

$$C_p\frac{\partial T}{\partial t} - \frac{RT\omega}{p} = Q$$

$$\frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(v\cos\theta) + \frac{1}{a\cos\theta}\frac{\partial u}{\partial\lambda} + \frac{\partial\omega}{\partial p} = 0$$

**where d/dt is the material derivative:**

$$\frac{dA}{dt} = \frac{\partial A}{\partial t} + \frac{u}{a\cos\theta}\frac{\partial A}{\partial\lambda} + \frac{v}{a}\frac{\partial A}{\partial\theta} + \omega\frac{\partial A}{\partial p}$$

# Dominant Balances Determining the MMC

- Write nonlinear advection in terms of eddy flux convergences
- Look for steady state
- Consider only dominant terms for extratropical region

$$f\bar{v} = \frac{\partial}{\partial p}(\overline{u'\omega'}) + \frac{1}{\cos^2\theta}\frac{\partial}{\partial\theta}(\overline{u'v'}\cos^2\theta)$$

$$f\bar{u} + \frac{u^2}{a}\tan\theta = \frac{-1}{a}\frac{\partial}{\partial\theta}\bar{\Phi}$$

$$-S\bar{\omega} = \frac{\bar{Q}}{C_p} - \frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(\overline{T'v'}\cos\theta)$$

$$\frac{\bar{Q}}{C_p} \approx -\alpha(\bar{T} - \bar{T}_{rad})$$

$$\frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(\bar{v}\cos\theta) + \frac{\partial}{\partial p}\bar{\omega} = 0$$

# "Transformed-Eulerian" Equations

- Define a transformed MMC that is "forced" (mostly) by the diabatic heating
- Effects of eddy fluxes on the zonal mean takes the form of an "Eliassen-Palm (EP) flux divergence
- TE MMC is close to Lagrangian MMC

$$\bar{v}^* = \bar{v} - \frac{\partial}{\partial p}\left(\frac{c_p}{S}\overline{T'v'}\right)$$

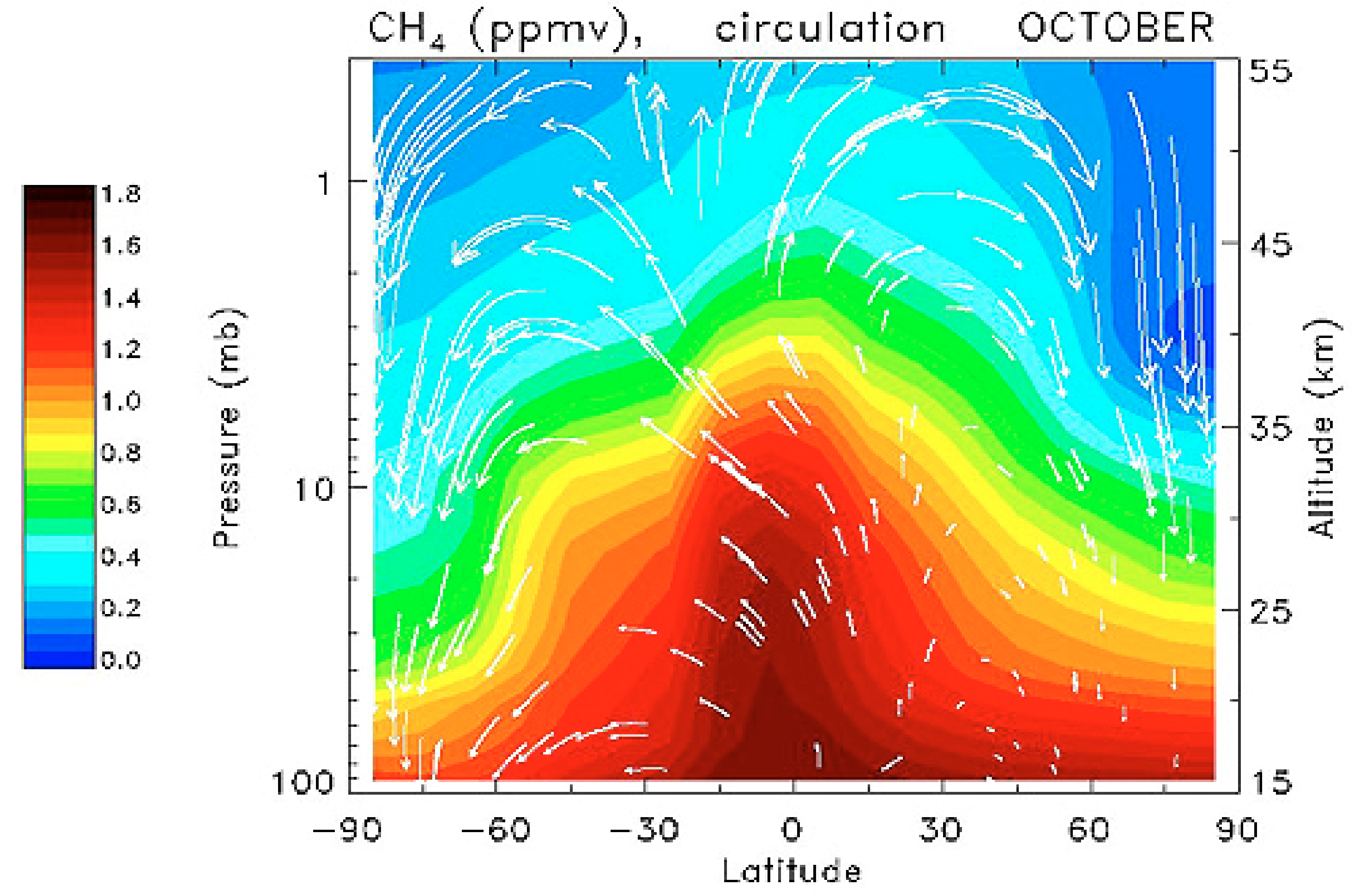
$$\bar{\omega}^* = \bar{\omega} - \frac{c_p}{S}\left(\frac{1}{a\cos\theta}\frac{\partial}{\partial\theta}(\overline{T'v'}\cos\theta)\right)$$

$$F^{\theta} = -a\overline{u'v'}\cos\theta$$

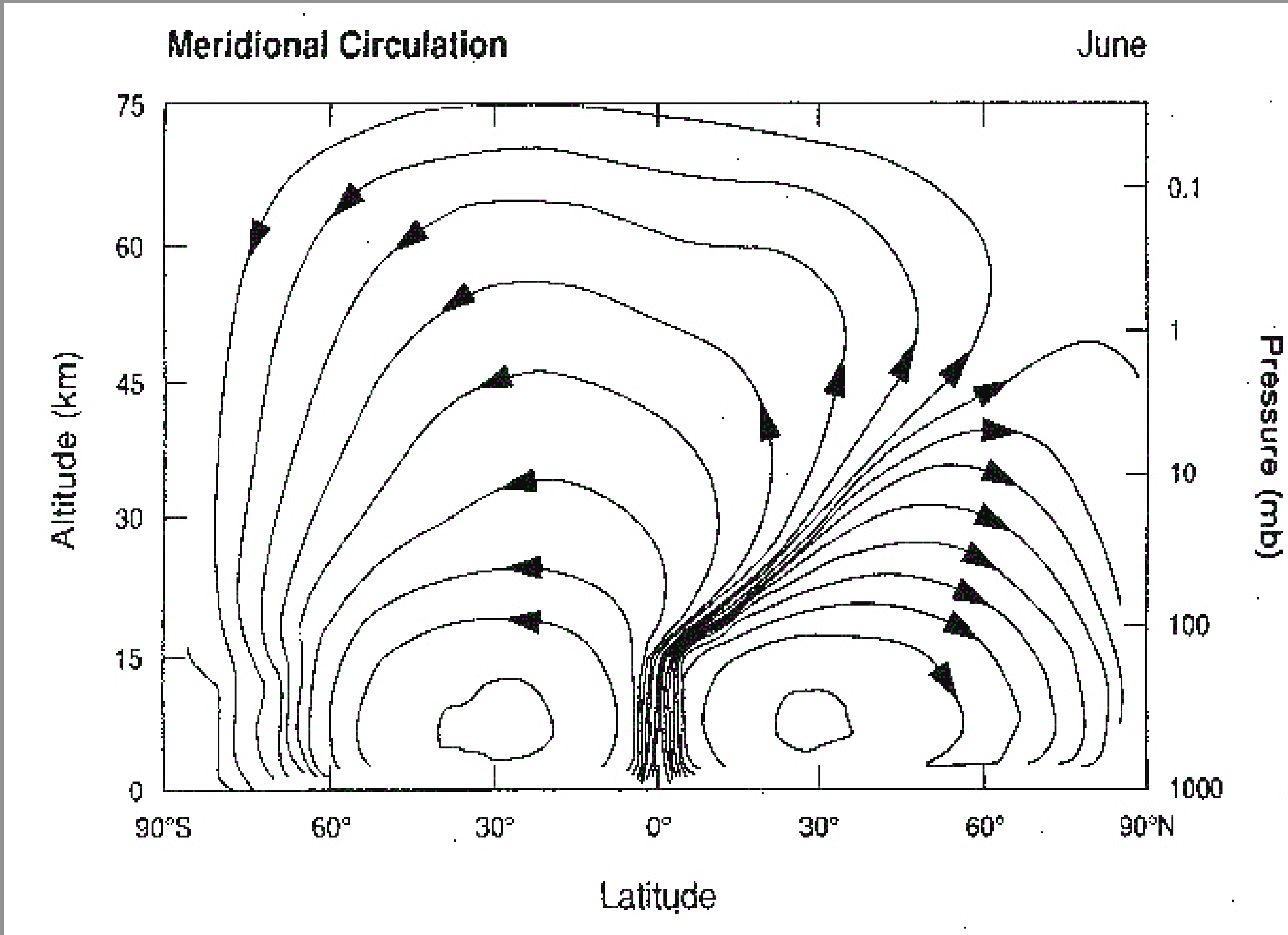
$$F^{p} = -a\cos\theta\left(\overline{u'\omega'} - \frac{fC_p}{S}\overline{T'v'}\right)$$

$$\left(-S\overline{\varpi^*}\right) \approx \frac{Q}{C_p}$$

$$-fv^* = \frac{1}{a\cos\theta}\left(\left(\frac{1}{a\cos\theta}\right)\frac{\partial}{\partial\theta}\left(F^{\theta}\cos\theta\right) + \frac{\partial F^{p}}{\partial p}\right)$$



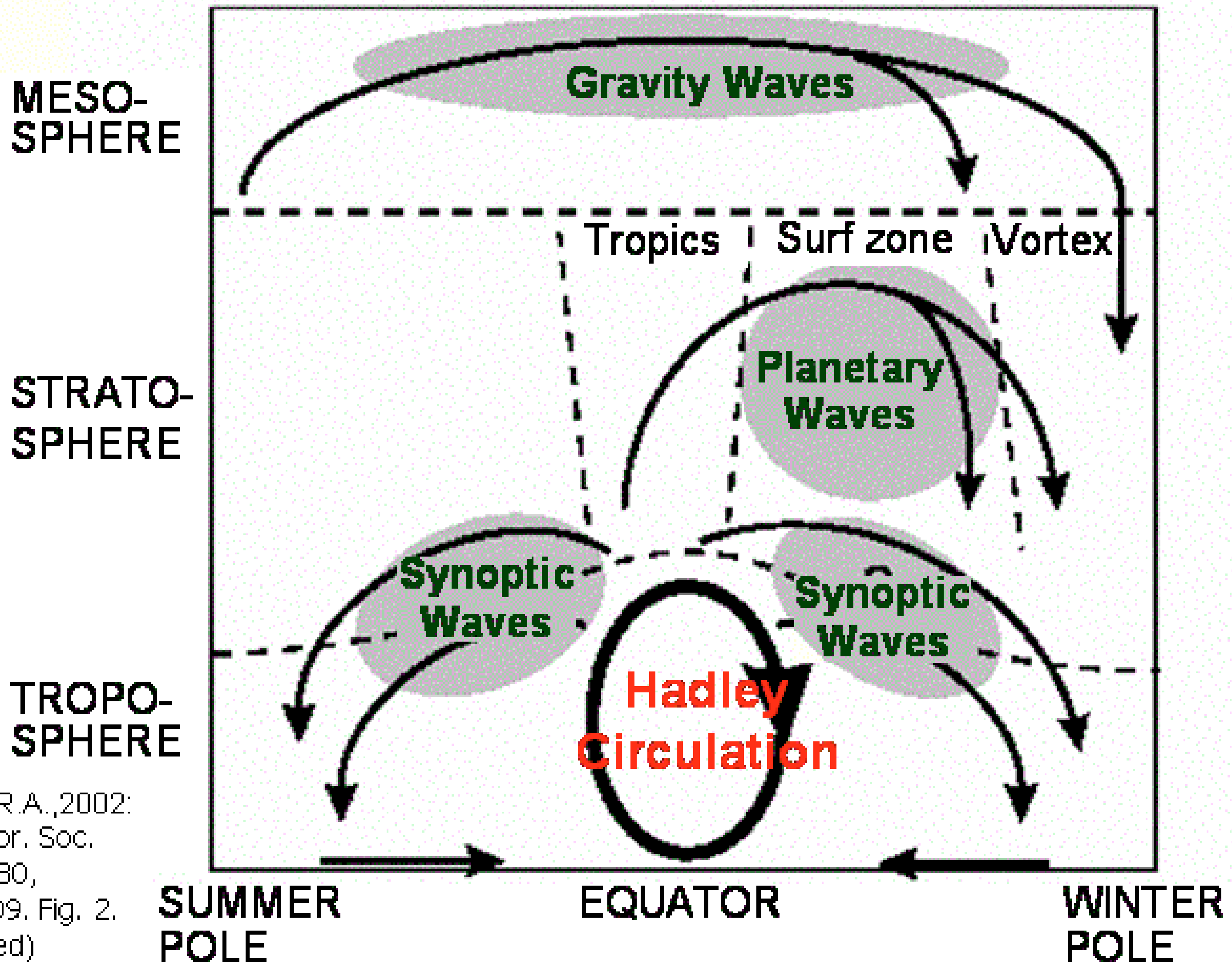
CH4 (ppmv), circulation OCTOBER
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Pressure (mb)
1
10
100
Altitude (km)
55
45
35
25
15
−90
−60
−30
0
30
60
90
Latitude



Meridional Circulation
June
Altitude (km)
75
60
45
30
15
0
Pressure (mb)
0.1
1
10
100
1000
90°S
60°
30°
0°
30°
60°
90°N
Latitude

## ❖ Mean Meridional Circulation

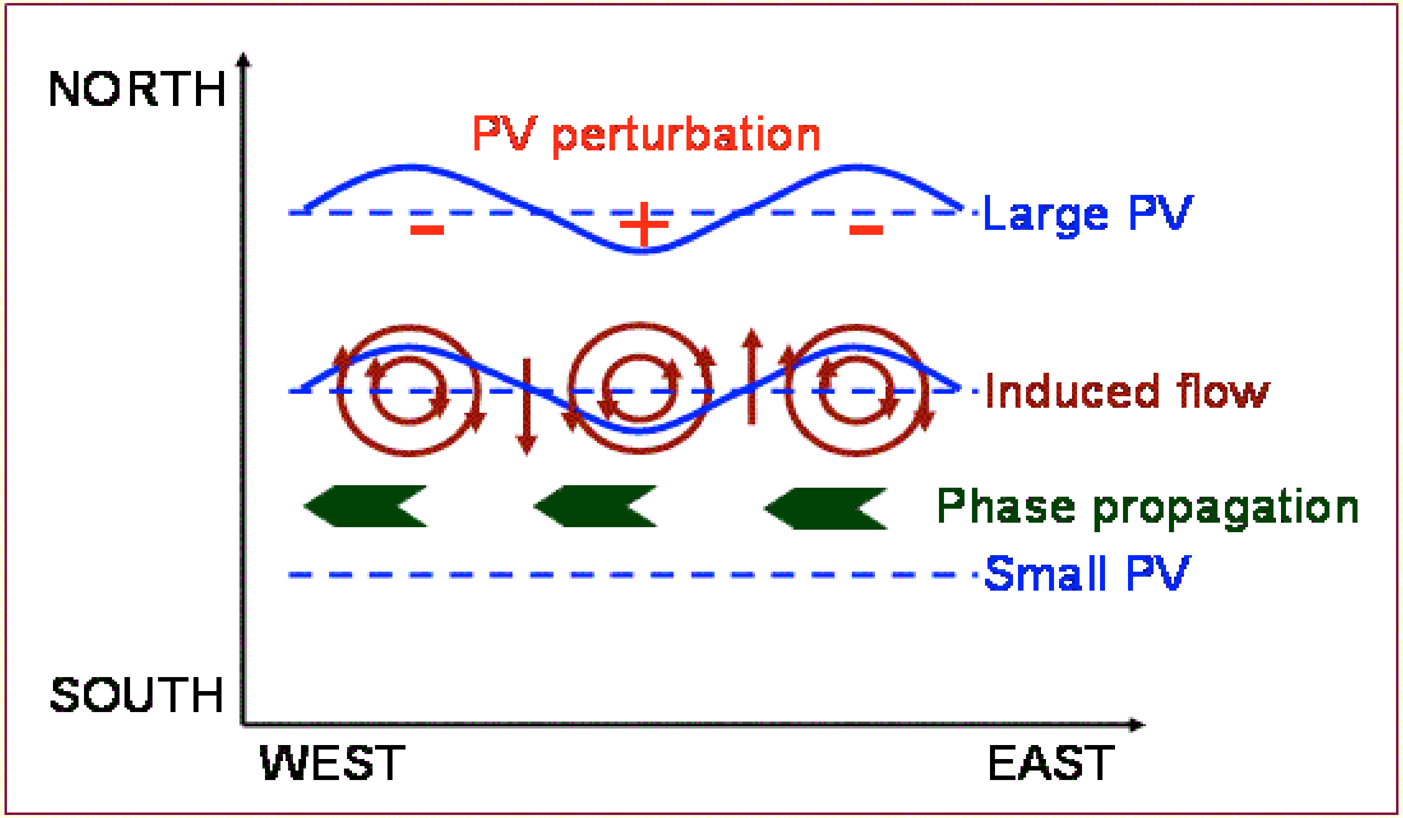
thermally or wave driven

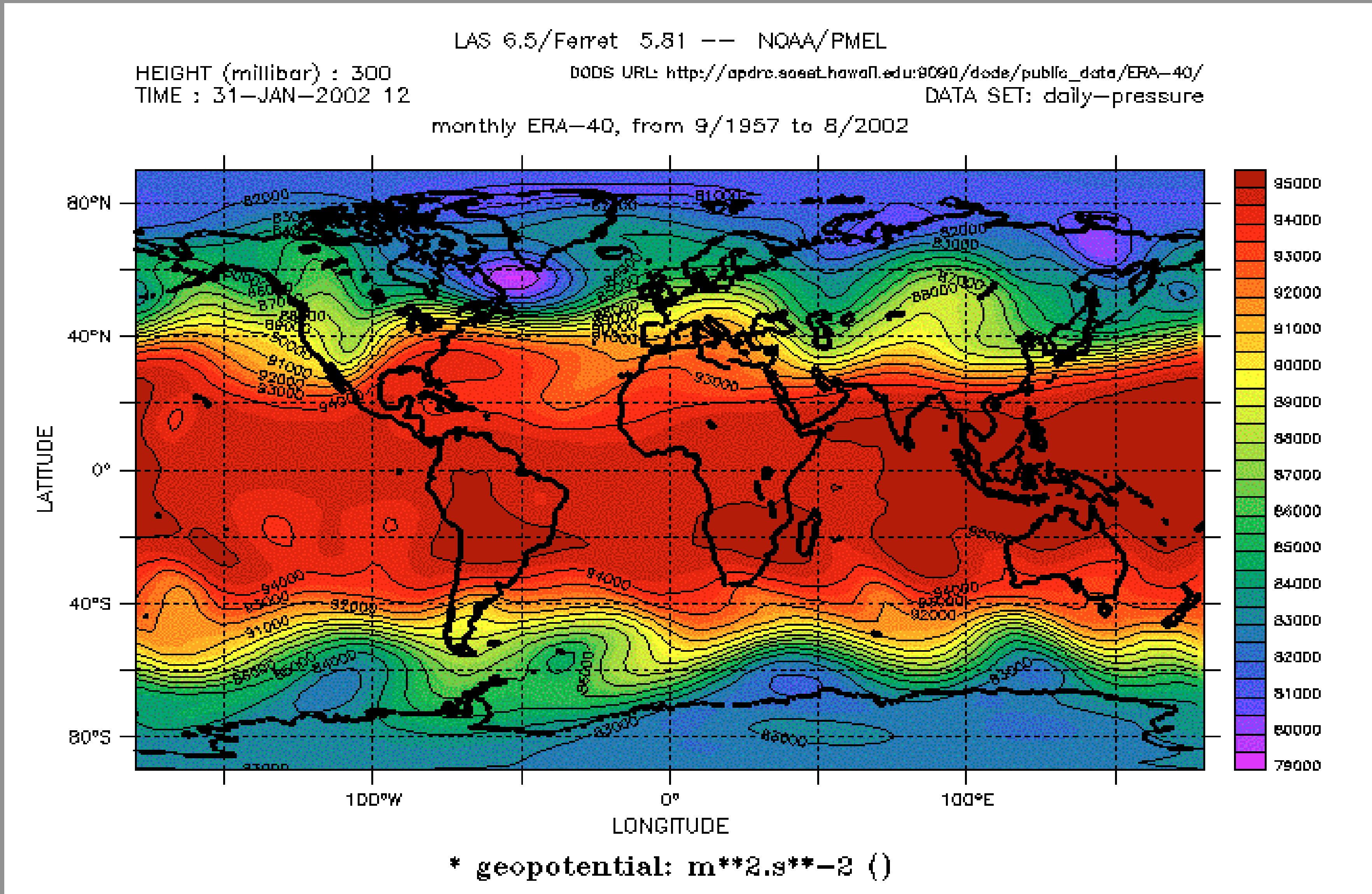



Plumb,R.A.,2002: J. Meteor. Soc. Japan, 80, 793--809. Fig. 2. (modified)

# Propagation of Rossby Waves

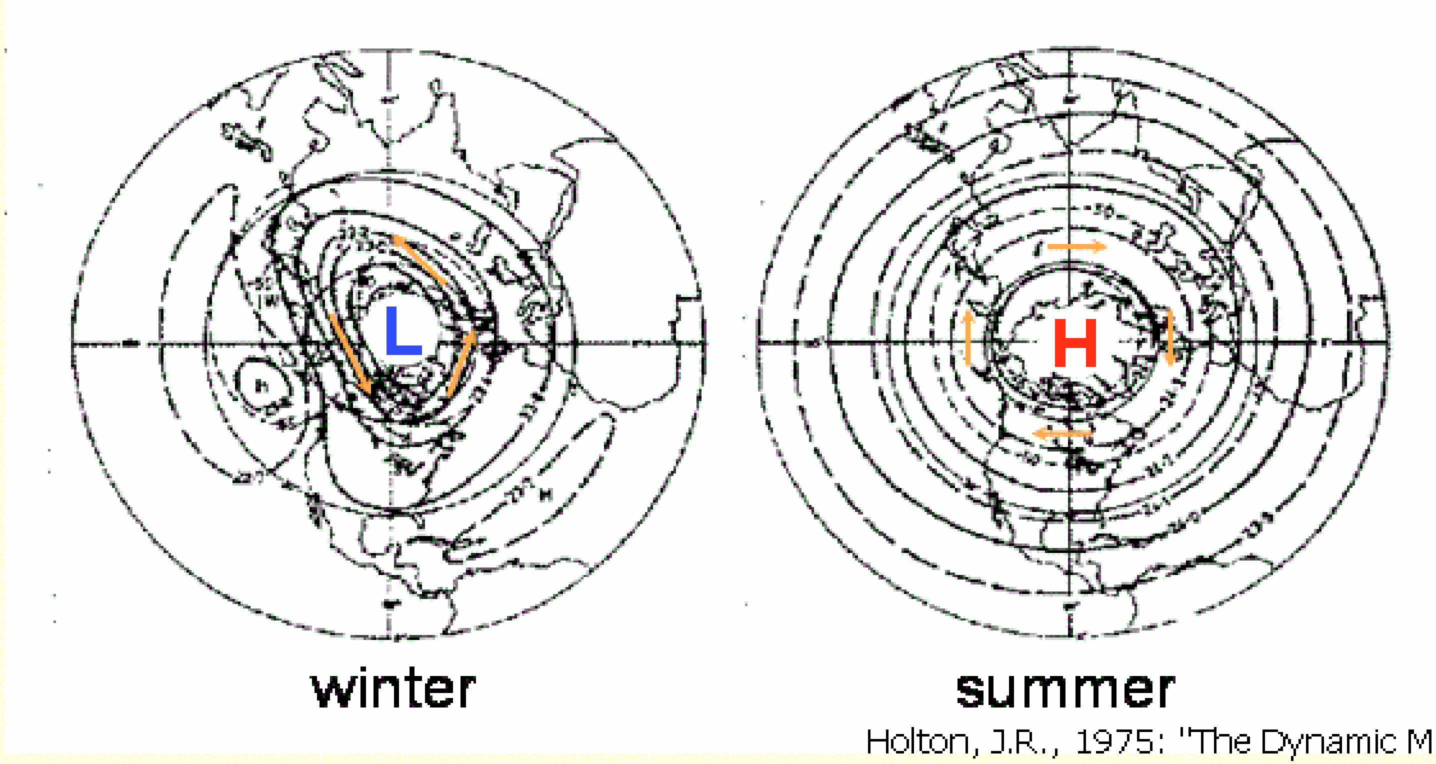
- basic state: monotonic increase of potential vorticity (PV)
- perturbation: wave-like meridional displacement




LAS 6.5/Ferret 5.81 -- NOAA/PMEL
HEIGHT (millibar) : 300
TIME : 31-JAN-2002 12
DODS URL: http://apdrc.soest.hawaii.edu:9090/dods/public_data/ERA-40/
DATA SET: daily-pressure
monthly ERA-40, from 9/1957 to 8/2002
80°N
40°N
0°
40°S
80°S
LATITUDE
100°W
0°
100°E
LONGITUDE
95000
94000
93000
92000
91000
90000
89000
88000
87000
86000
85000
84000
83000
82000
81000
80000
79000
* geopotential: m**2.s**-2 ()

# Polar vortex and stationary planetary waves

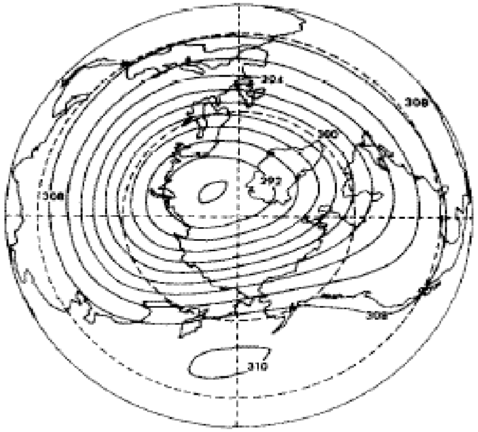
- Seasonal-mean geopotential height at 30 hPa



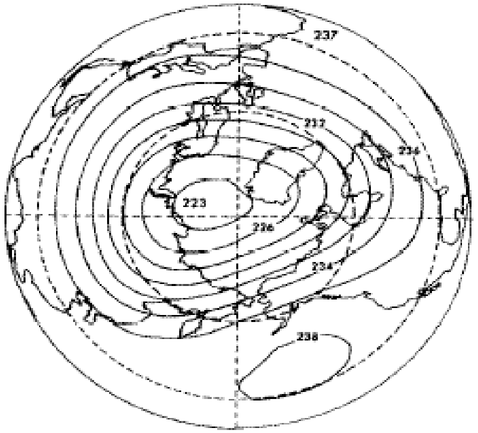

Holton, J.R., 1975: "The Dynamic Meteorology of the Stratosphere and Mesosphere", Meteorological Monographs, Vol.15, Number 37, American Meteorological Society, 216pp. Fig.1.9

- Charney-Drazin theory (1961)
  - vertical propagation of planetary waves: $U - c_p > 0$
  - a stationary wave ($c_p = 0$) may exist only for westerly wind ($U > 0$)

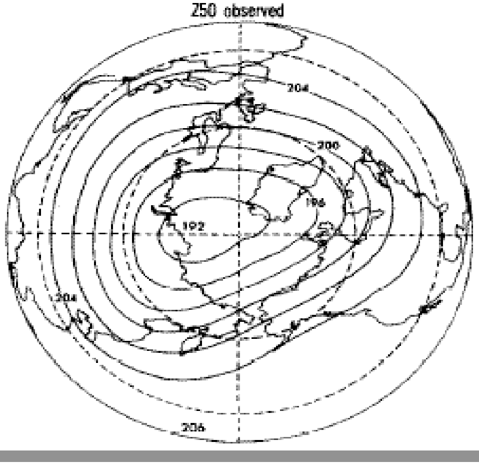
Z10 observed



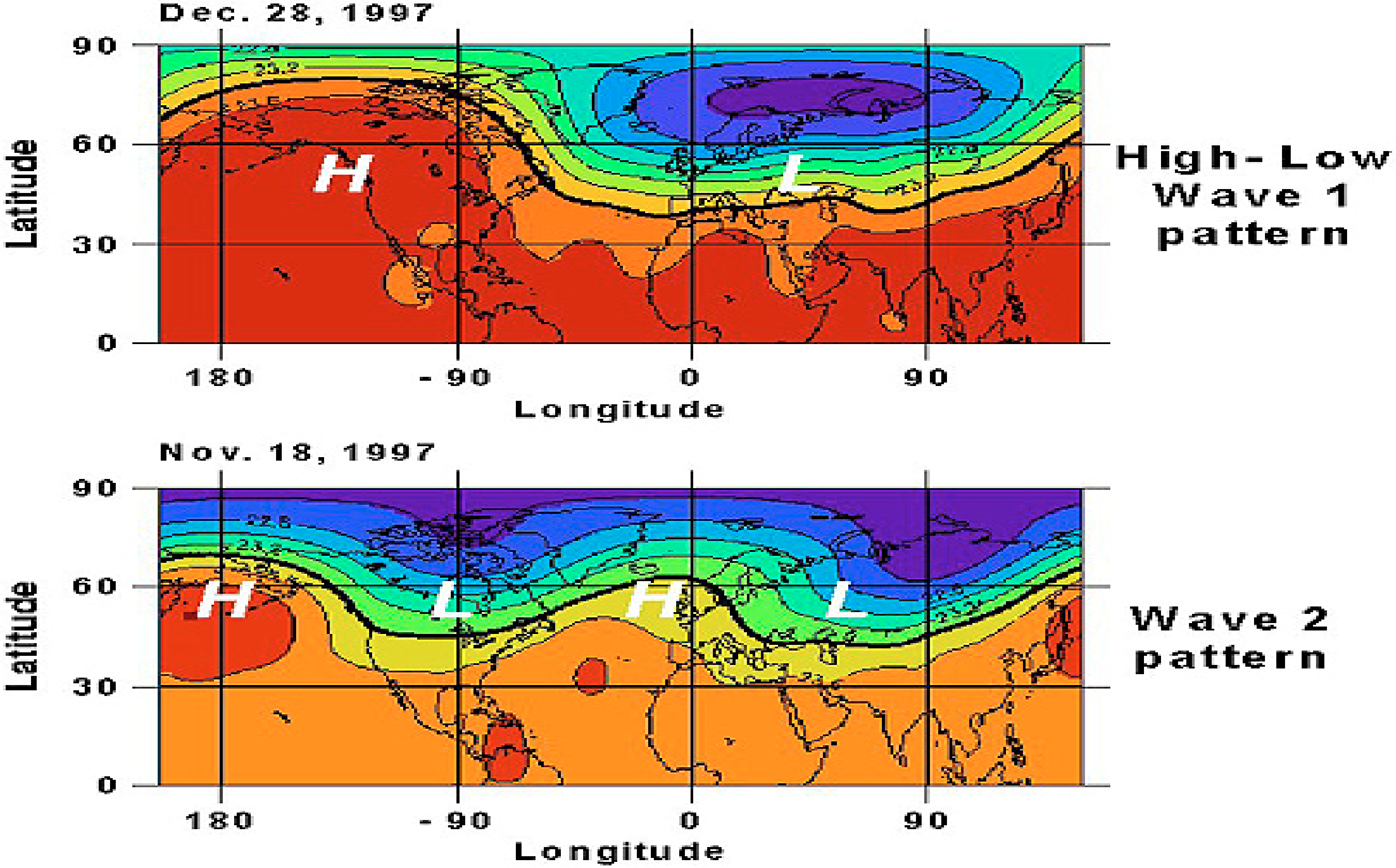

Z30 observed




Z50 observed



# 30 mb Geopotential Height




As we move from east to west, we observe high-low structures, A single high-low structure is a wave 1 pattern, while 2 high-low structures is a wave 2 pattern. Winds tend to follow along a line of constant geopotential. The units used here are geopotential kilometers.

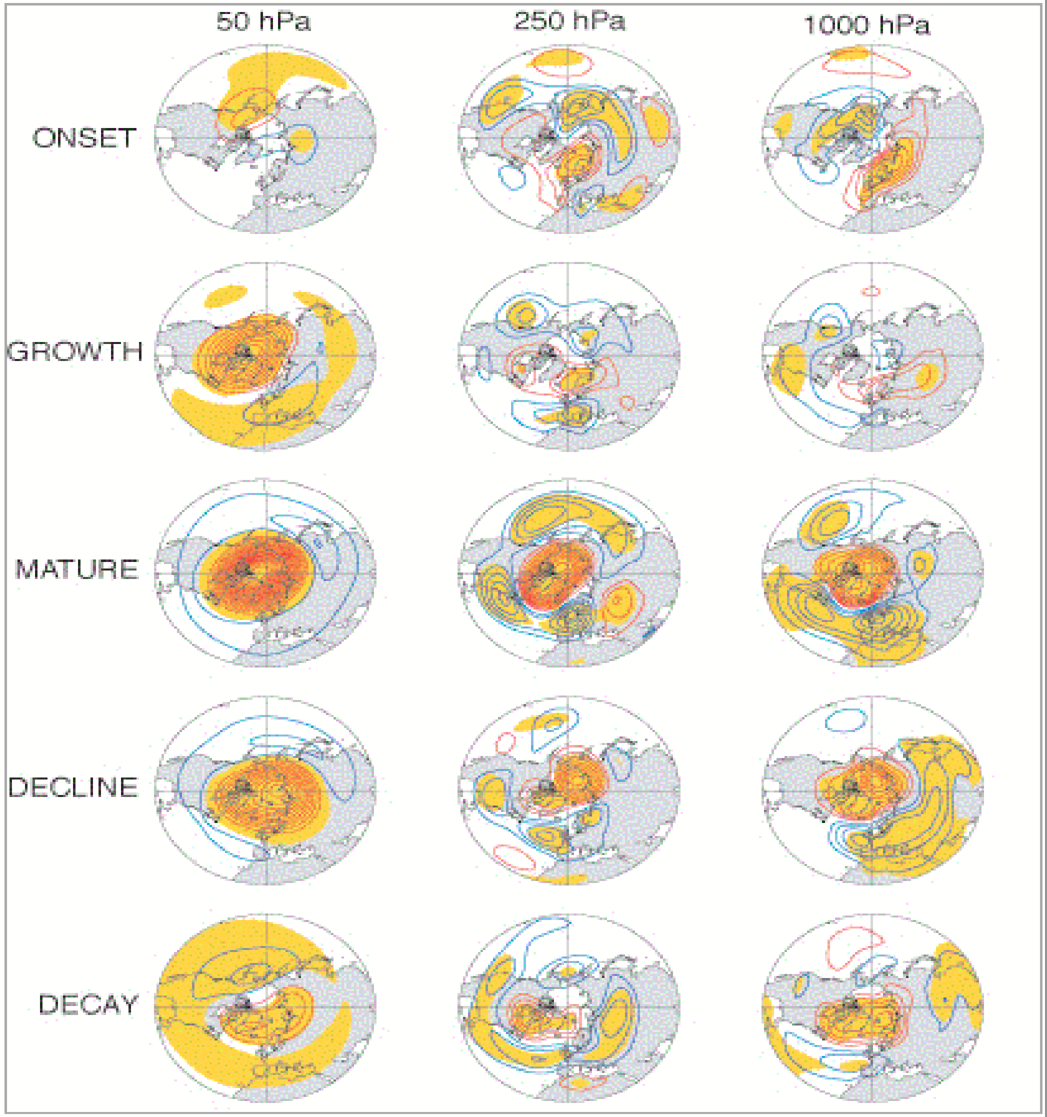
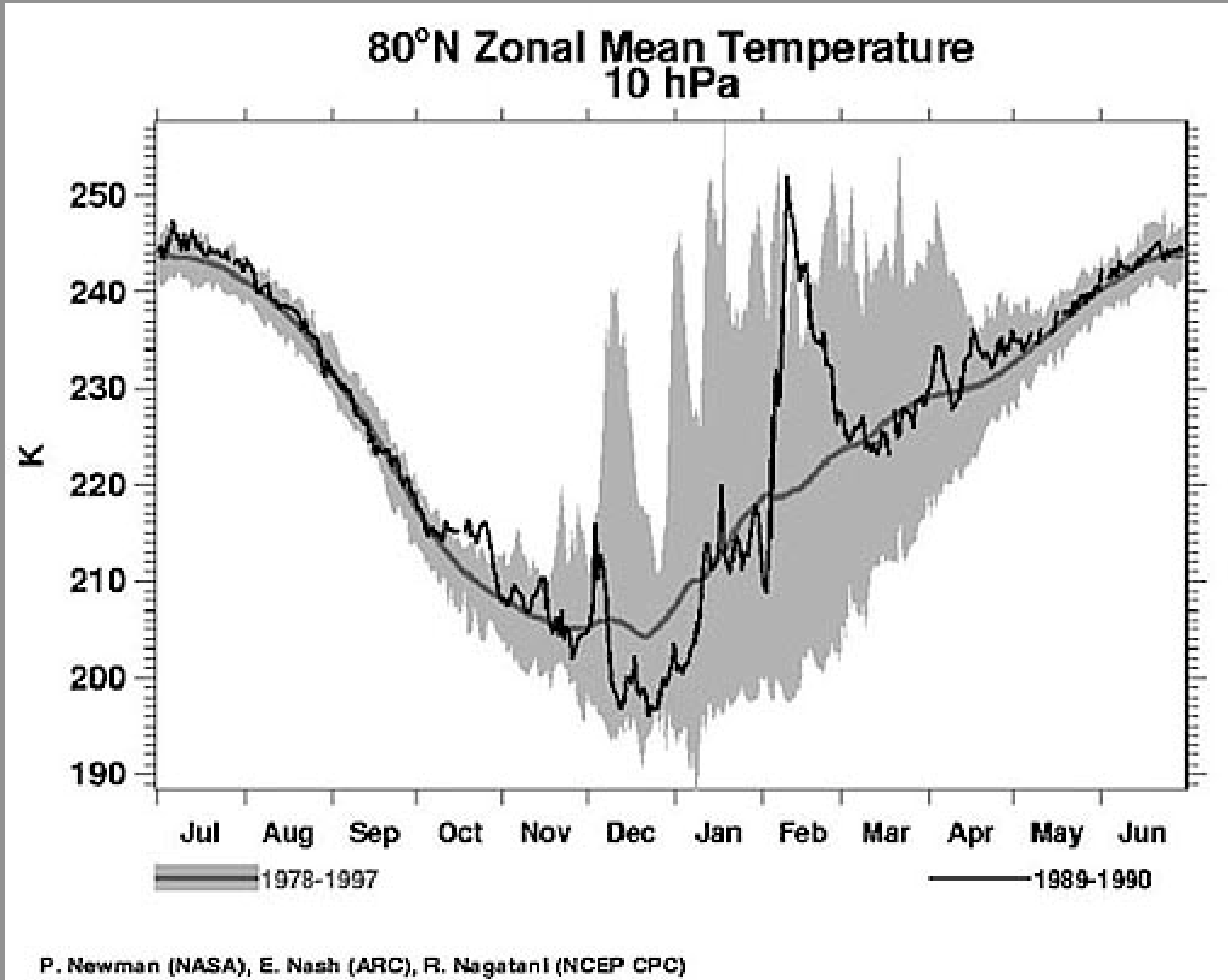
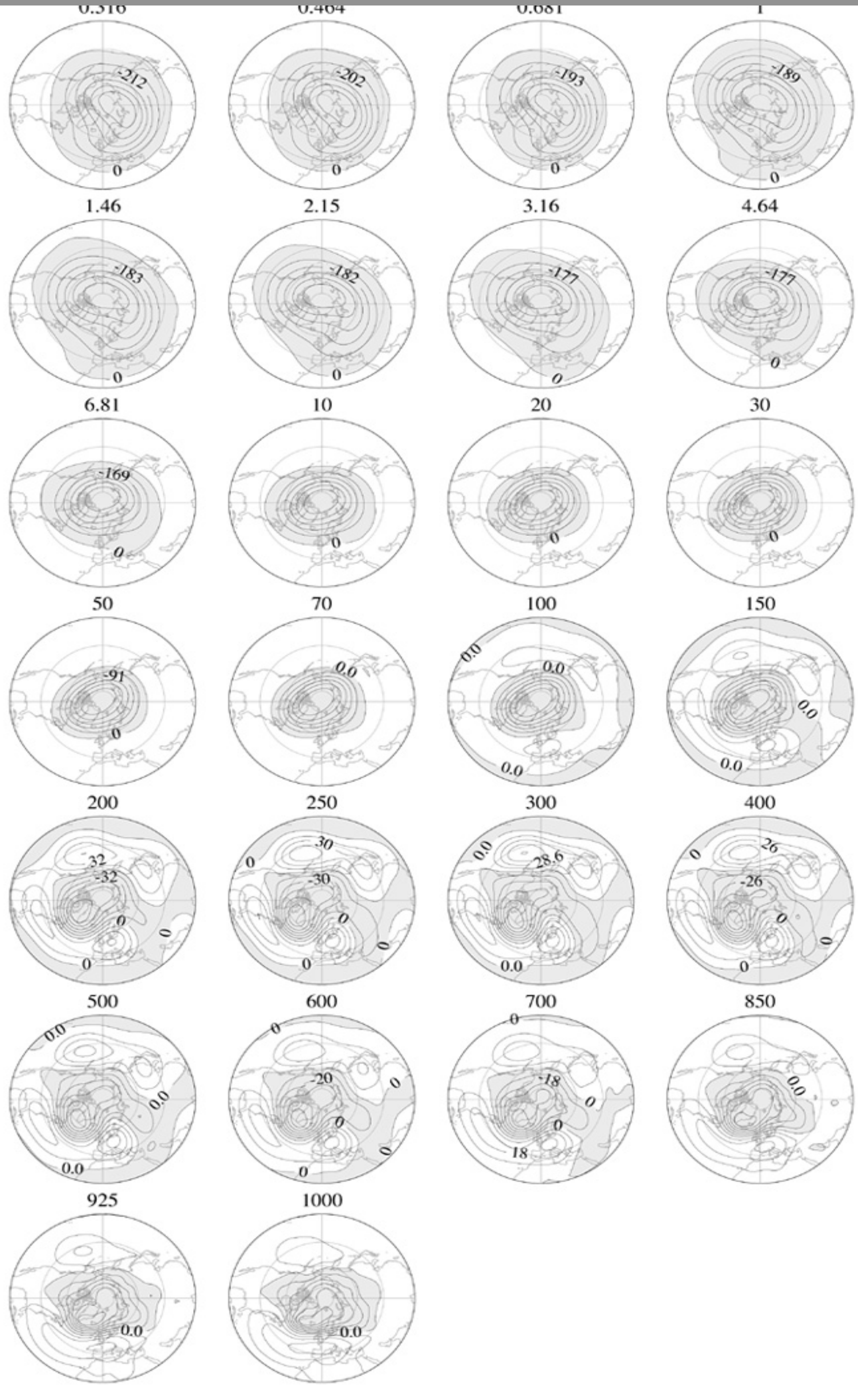


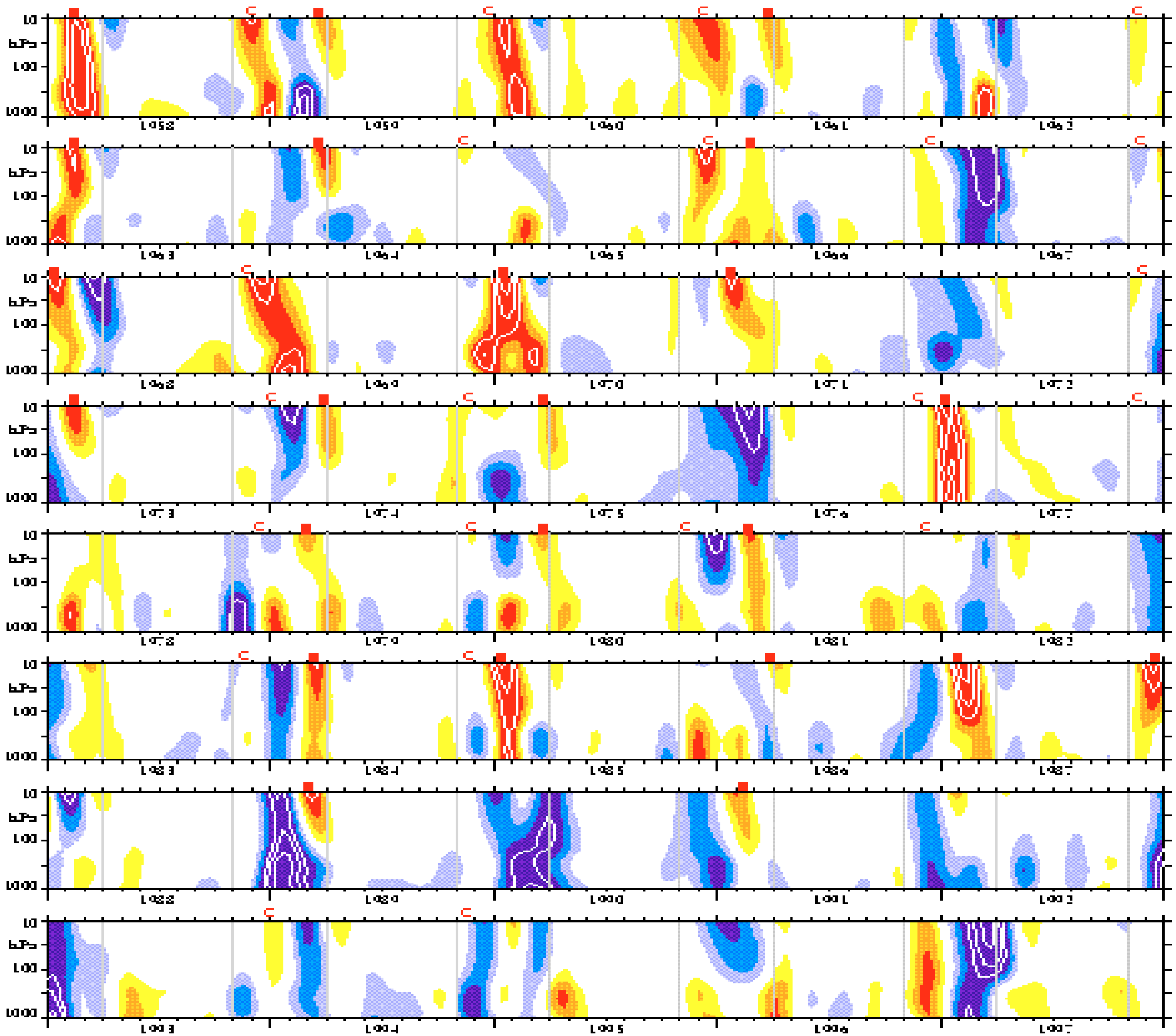

**Figure 1.** Composite geopotential height anomalies at 50, 250 and 1000 hPa for five phases of stratospheric warmings for 39 warming events from NCEP/NCAR Reanalysis during the period 1958–2001. Contour intervals are 3, 1 and 0.5 decameters. Negative contours are blue, positive red. Zero contours are omitted for clarity and 95% confidence limits are shown as yellow shading.

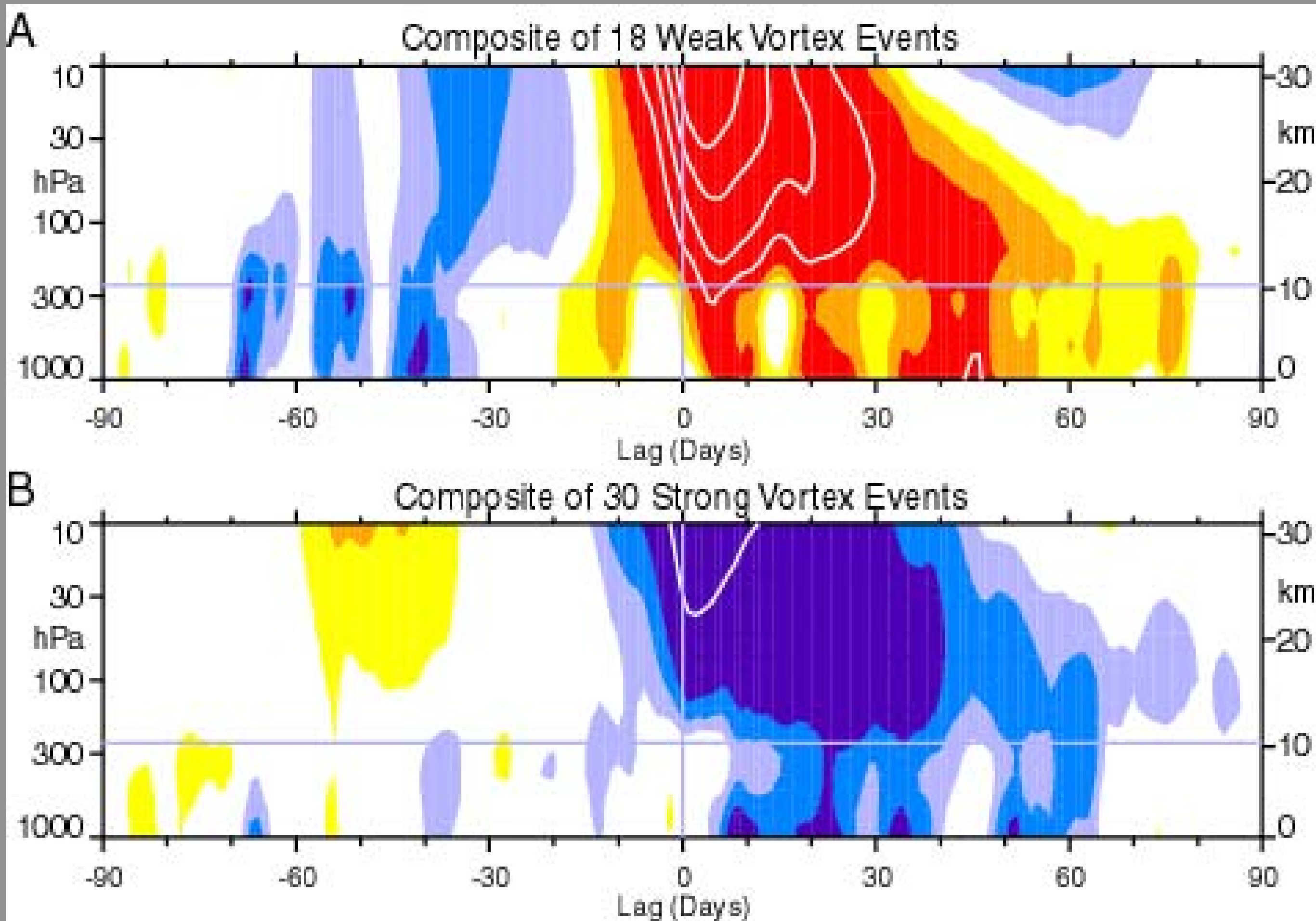


80°N Zonal Mean Temperature
10 hPa
250
240
230
220
210
200
190
K
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1978-1997
1989-1990
P. Newman (NASA), E. Nash (ARC), R. Nagatani (NCEP CPC)



0.316
-212
0.464
-202
0.681
-193
1
-189
1.46
-183
2.15
-182
3.16
-177
4.64
-177
6.81
-169
10
20
30
50
-91
70
0.0
100
0.0
150
0.0
200
32
-32
250
30
-30
300
28.6
400
26
-26
500
0.0
600
-20
700
-18
18
850
0.0
925
0.0
1000
0.0


10
hPa
100
1000

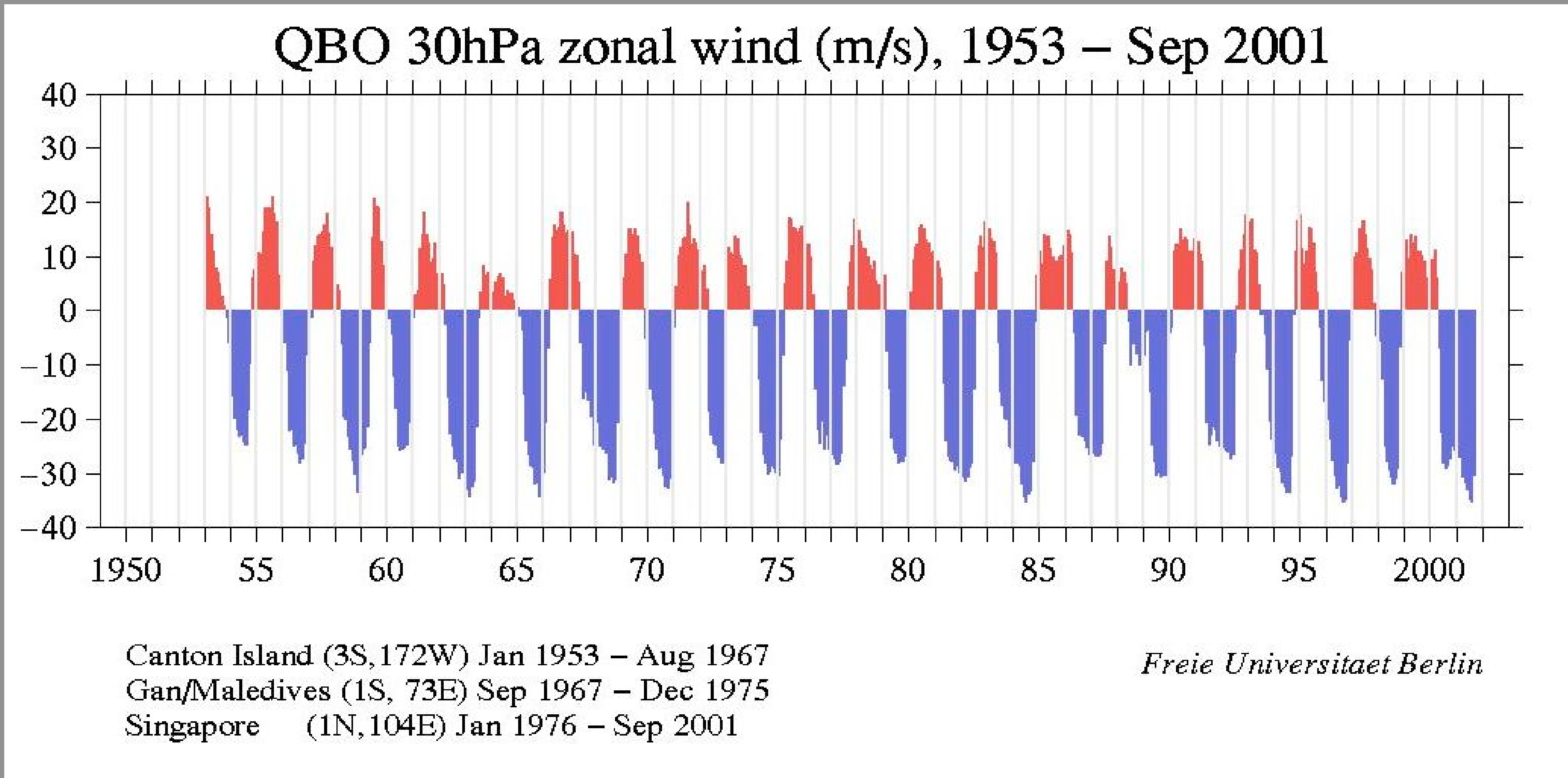

A
Composite of 18 Weak Vortex Events
10
30
hPa
100
300
1000
30
km
20
10
0
-90
-60
-30
0
30
60
90
Lag (Days)
B
Composite of 30 Strong Vortex Events
10
30
hPa
100
300
1000
30
km
20
10
0
-90
-60
-30
0
30
60
90
Lag (Days)

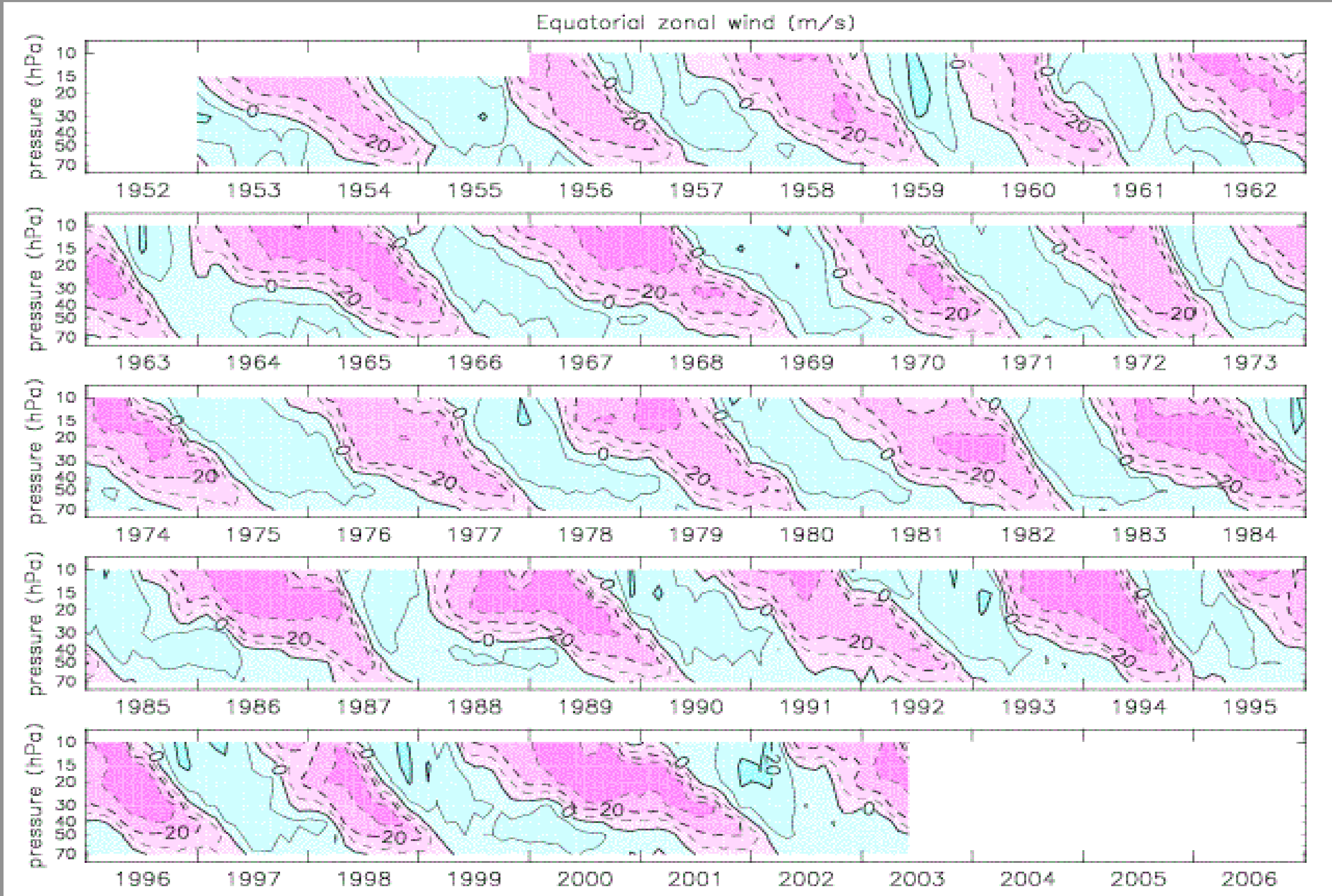
# Tropical Middle Atmosphere

Quasi-biennial Oscillation

Semiannual Oscillation

Tropical Effects on Extratropics


QBO 30hPa zonal wind (m/s), 1953 – Sep 2001
40
30
20
10
0
−10
−20
−30
−40
1950
55
60
65
70
75
80
85
90
95
2000
Canton Island (3S,172W) Jan 1953 – Aug 1967
Gan/Maledives (1S, 73E) Sep 1967 – Dec 1975
Singapore (1N,104E) Jan 1976 – Sep 2001
Freie Universitaet Berlin



Equatorial zonal wind (m/s)
pressure (hPa)
10
15
20
30
40
50
70
0
20
1952
1953
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
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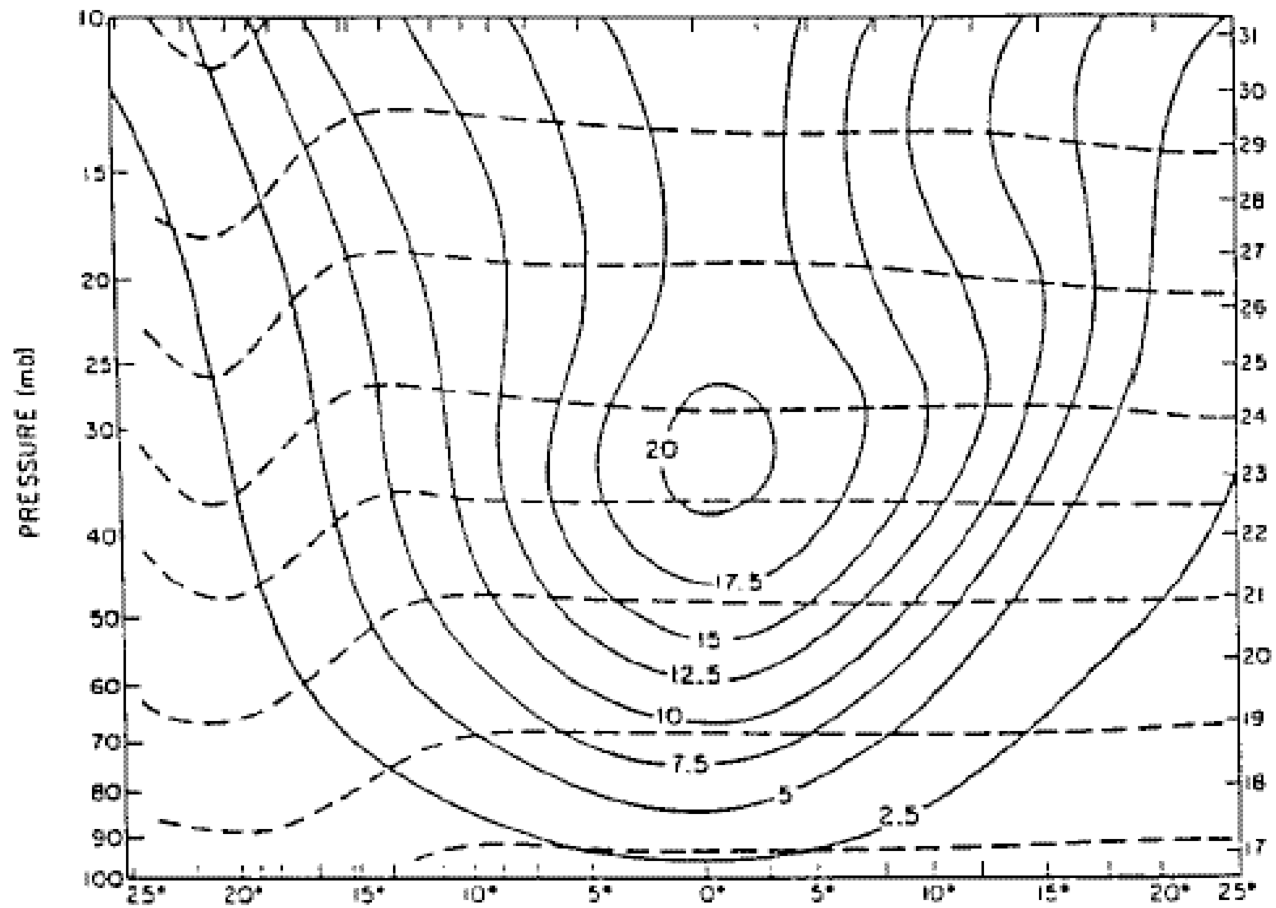
2002
2003
2004
2005
2006




Latitude-height section of the amplitude and phase of the QBO in zonal wind determined from radiosonde observations. Amplitude contours are solid and the contour interval is 2.5 m $s^{-1}$. The Northern Hemisphere is shown on the left. Phase contours are dashed and the contour interval is 1 month. The thin tick marks on the axis show the latitude of each of the stations used in the analysis. The scale on the right is a standard height (in km). Adapted from Reed (1965b).

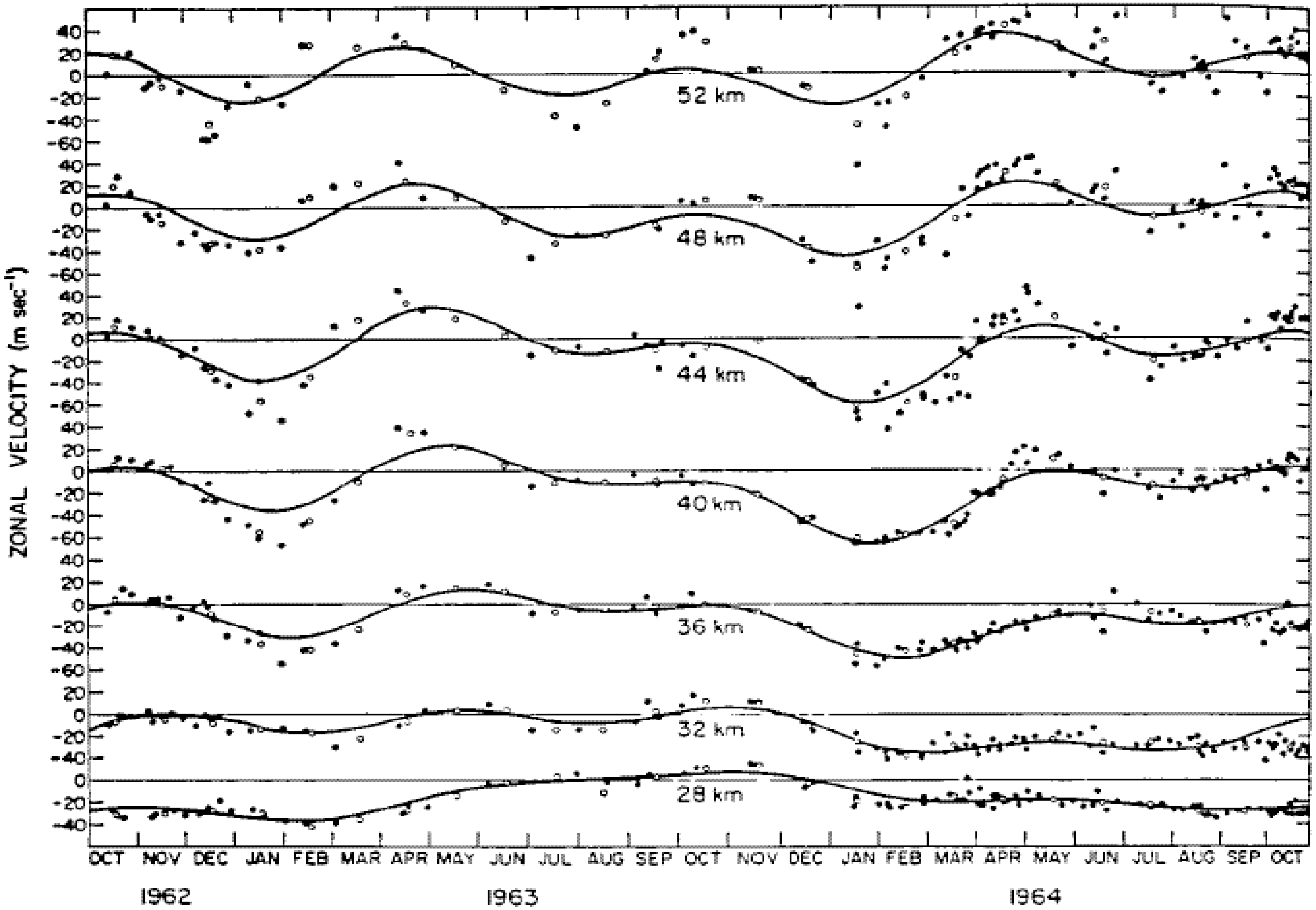



Fig. 6 Zonal wind measurements taken at Ascension island (7.9°S) during the period October 1962 through October 1964. The solid circles show individual measurements and the open circles are monthly means for months when there was more than one measurement available. Reproduced from Reed (1965a).

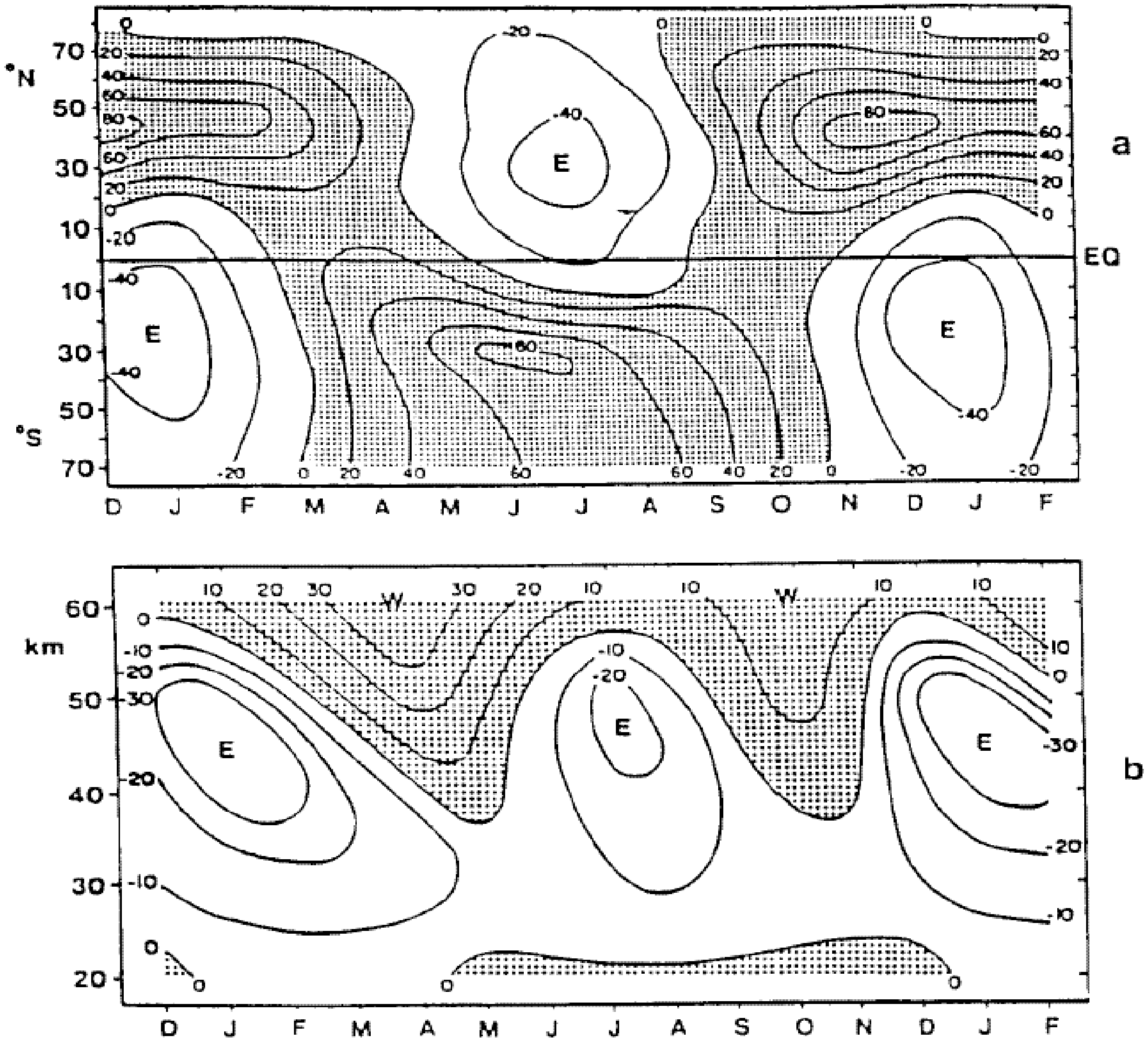



Fig. 7 (top) Latitude-time section of the climatological annual march of zonal-mean zonal winds at 50-km height determined from rocketsonde observations at several stations. Contour interval is 20 m $s^{-1}$ and regions of westerlies are shaded. (bottom) Altitude-time section of the annual march of equatorial zonal wind determined from interpolation of observations at Kwajalein (8.7°N) and Ascension Island (7.9°S). Contour interval is 10 m $s^{-1}$ and regions of westerlies are shaded. Reproduced from Delisi and Dunkerton (1988b) and based on an earlier figure from Belmont et al. (1975).

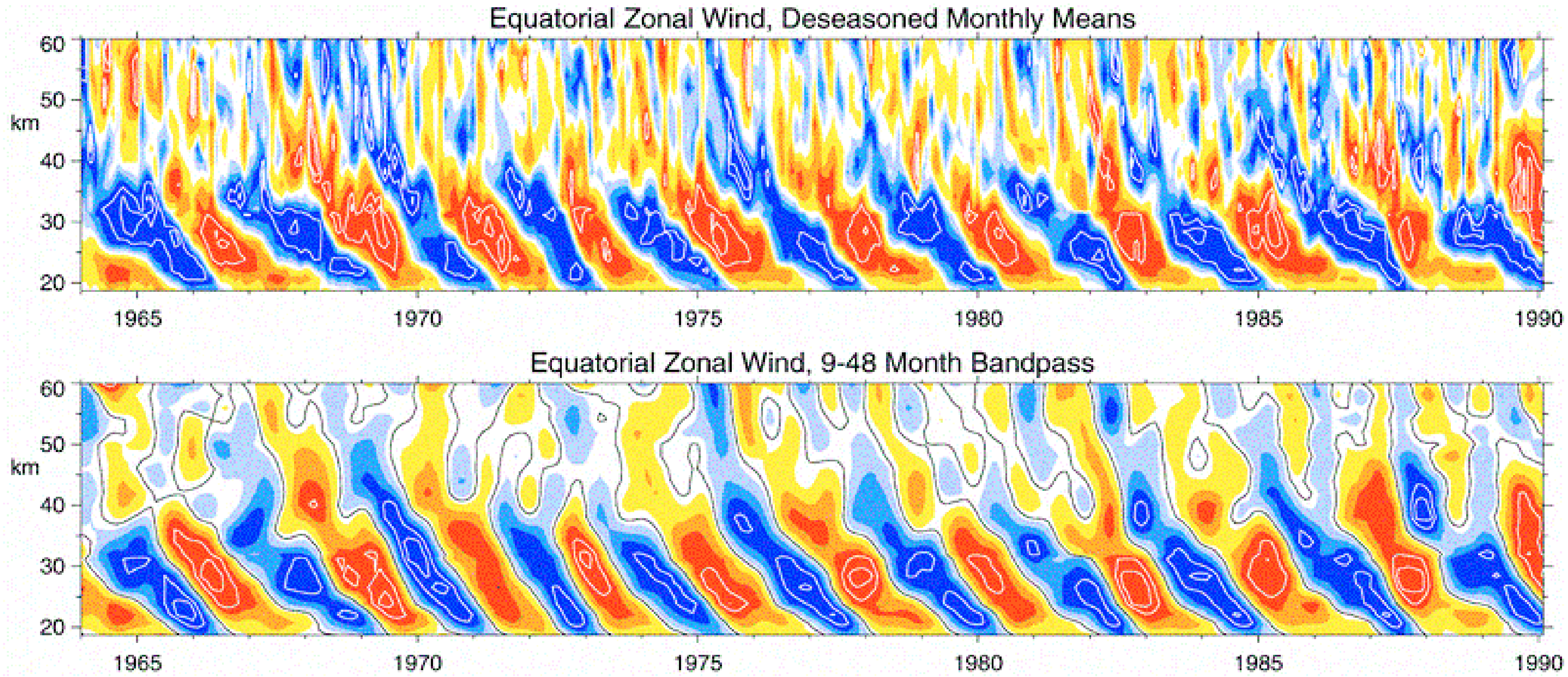



**Plate 1.** (top) Time–height section of the monthly-mean zonal wind component (m $s^{-1}$), with the seasonal cycle removed, for 1964–1990. Below 31 km, equatorial radiosonde data are used from Canton Island (2.8°N, January 1964 to August 1967), Gan/Maledive Islands (0.7°S, September 1967 to December 1975), and Singapore (1.4°N, January 1976 to February 1990). Above 31 km, rocketsonde data from Kwajalein (8.7°N) and Ascension Island (8.0°S) are shown. The contour interval is 6 m $s^{-1}$, with the band between –3 and +3 unshaded. Red represents positive (westerly) winds. After *Gray et al. [2001]*. In the bottom panel the data are band-pass filtered to retain periods between 9 and 48 months.

# Tropical Mean Flow Dynamics

Near the equator the eddy forcing of zonal-mean momentum (EP flux divergence) is not balanced by Coriolis torques, but directly forces mean flow accelerations

Sustained, but self-limiting eddy driven mean flow forcing comes from upward-propagating gravity waves (and related equatorial-planetary waves)

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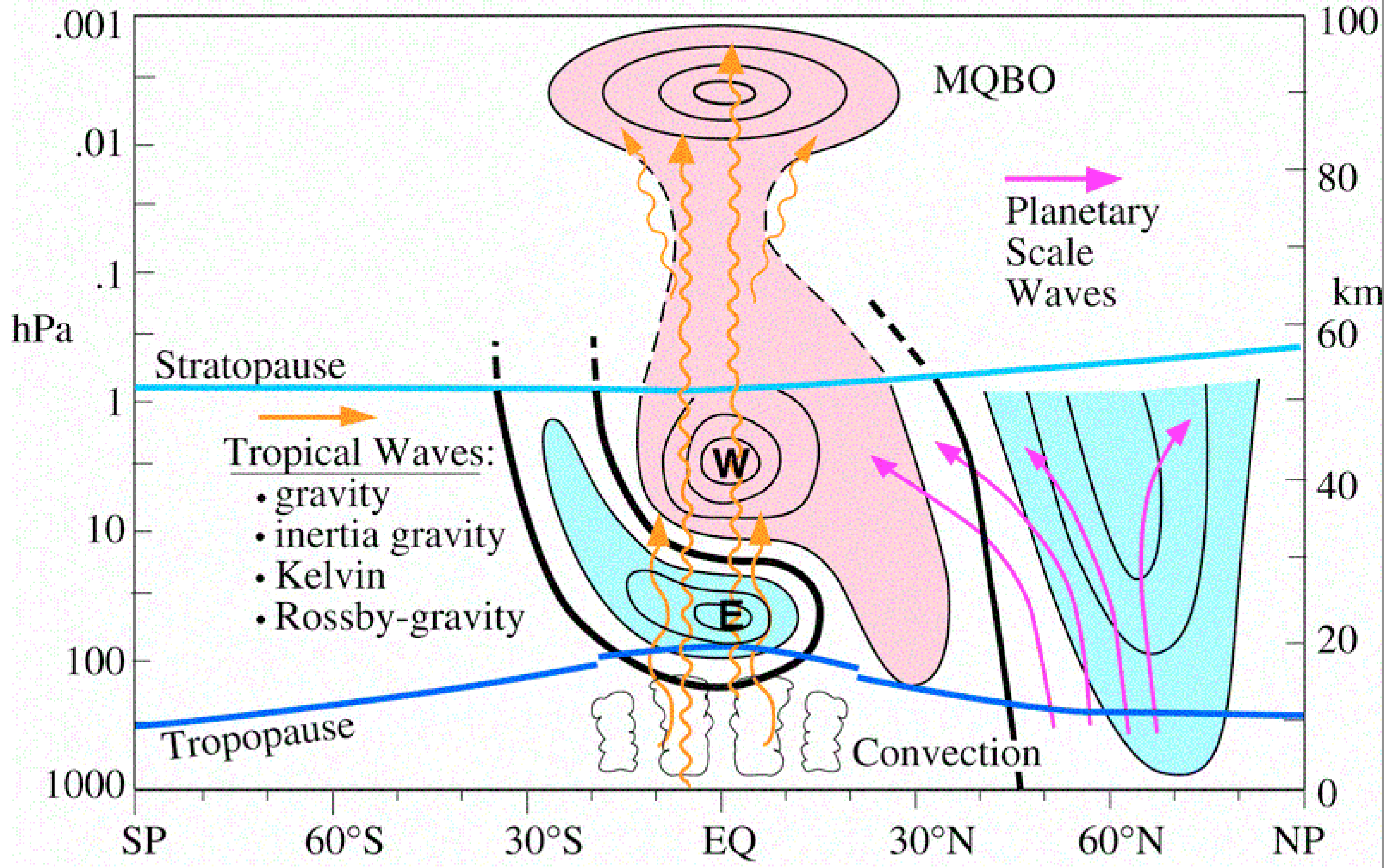
- Sustained, but self-limiting eddy driven mean flow forcing comes from upward-propagating gravity waves (and related equatorial-planetary waves)



.001
.01
.1
hPa
1
10
100
1000
100
80
km
60
40
20
0
MQBO
Planetary
Scale
Waves
Stratopause
Tropical Waves:
• gravity
• inertia gravity
• Kelvin
• Rossby-gravity
W
E
Tropopause
Convection
SP
60°S
30°S
EQ
30°N
60°N
NP

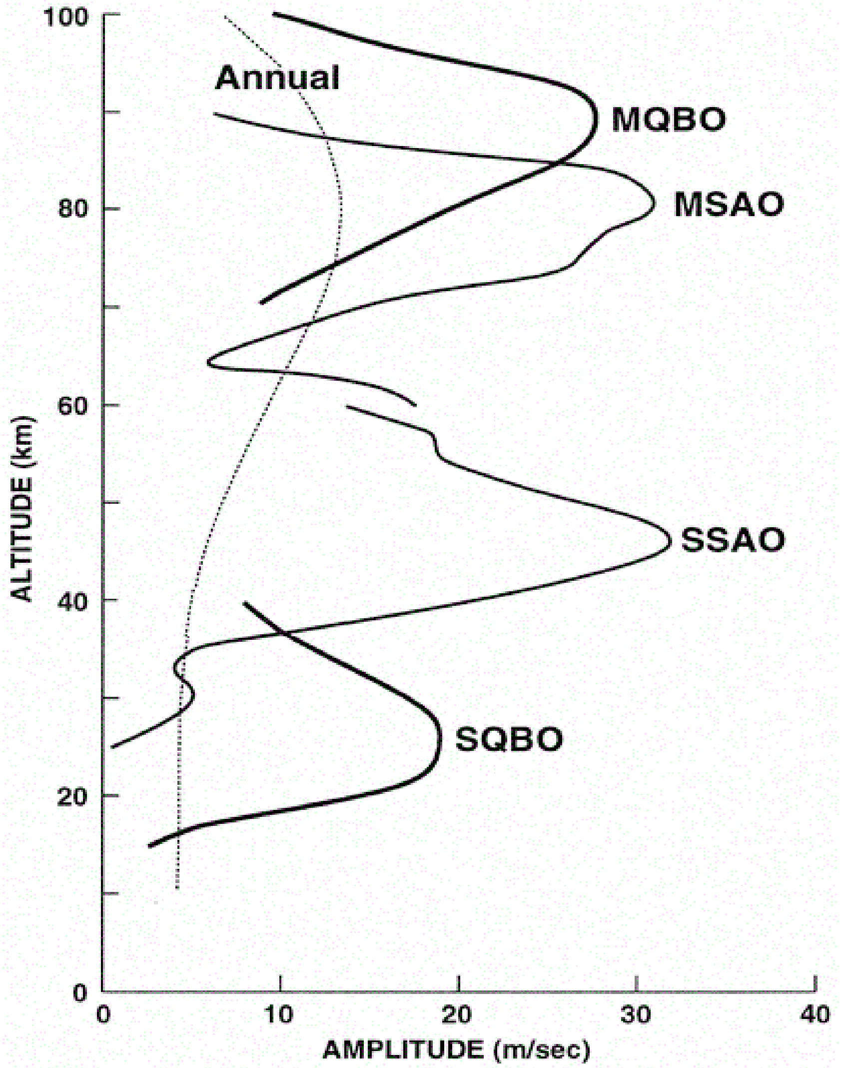
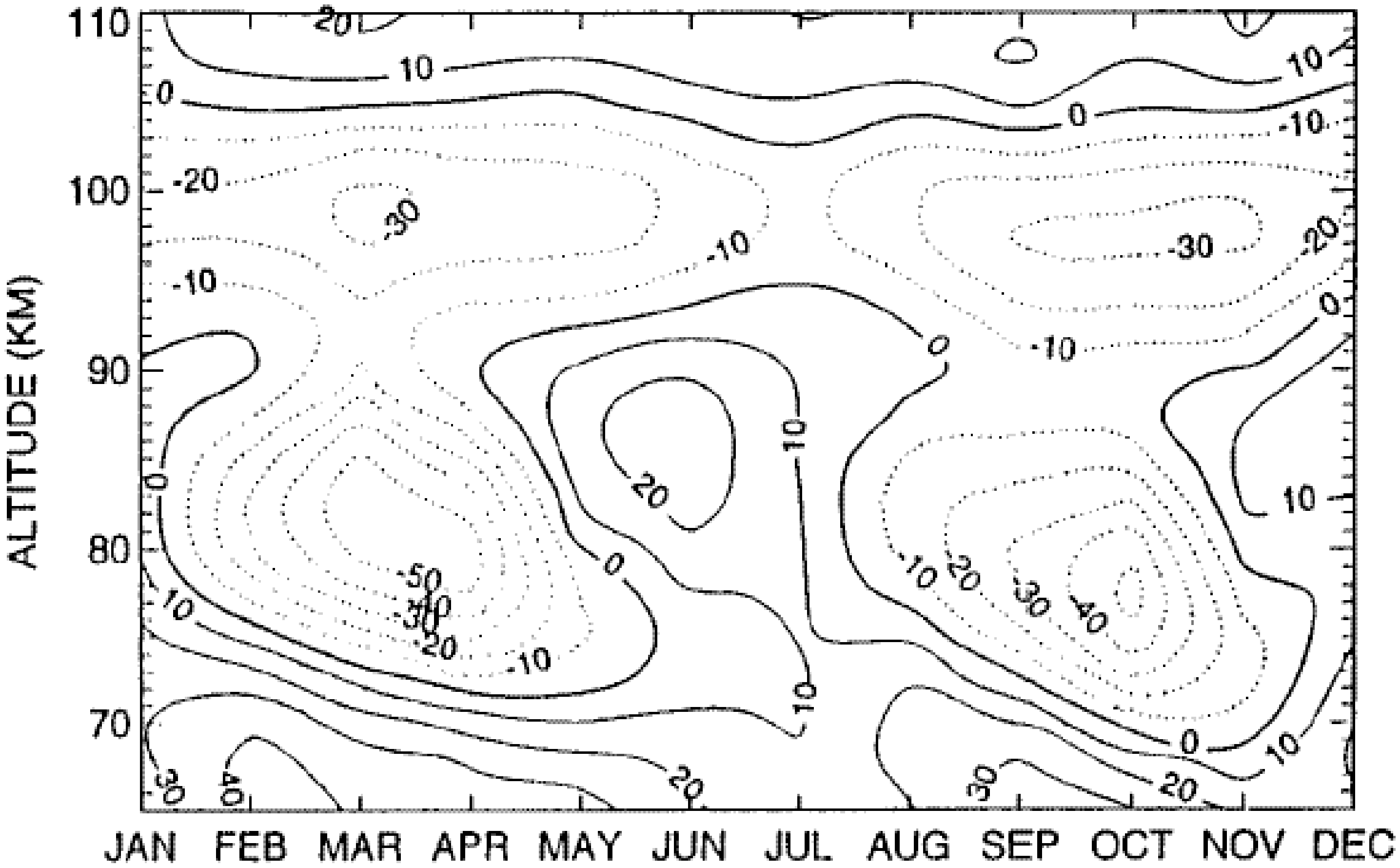



**Figure 30. Vertical distribution of the amplitude of the MQBO, MSAO, SSAO, SQBO, and annual component at the equator. The MQBO is based on UARS/HRDI observations [*Burrage et al., 1996*]. The SAO is based on rocket observations at Ascension Island [*Hirota, 1978*], and the annual component is after COSPAR International Reference Atmosphere (1986).**




Annual march of the zonally-averaged equatorial zonal wind measured by the HRDI Doppler radiometer. The contour intervals is 10 m $s^{-1}$ and dashed contours denote easterly winds.

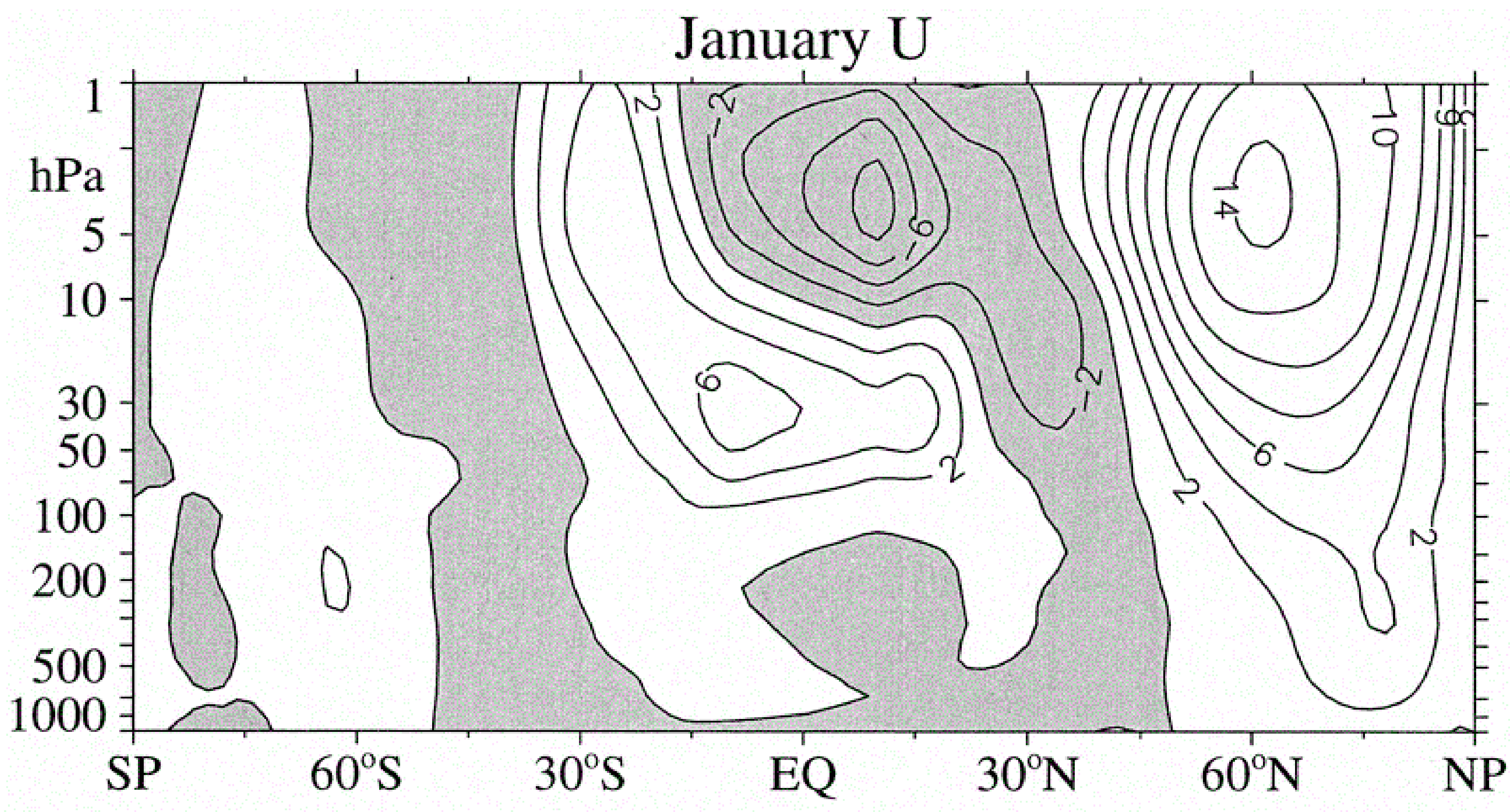
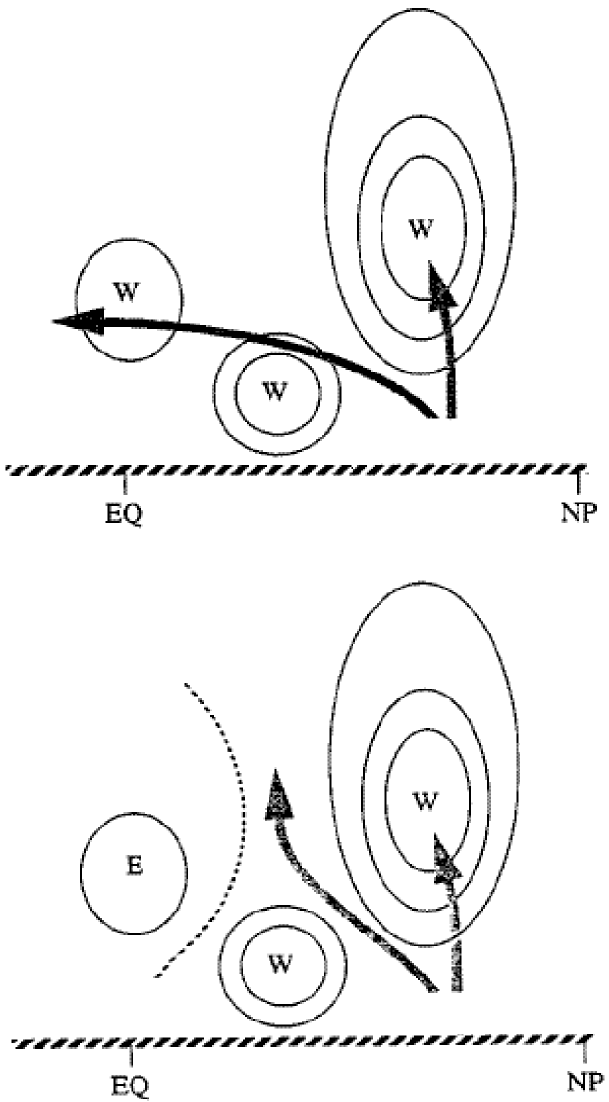



**Figure 14.** January latitude–height zonal–mean wind difference between the average of all years with westerly QBO and those with easterly QBO, during 1964–1996. The phase of the QBO is optimized for the Northern Hemisphere (NH) and is defined using the empirical orthogonal function technique of *Baldwin and Dunkerton* [1998b]; it is nearly equivalent to using 40–hPa equatorial winds. The contour interval is 2 m $s^{-1}$, and negative values are shaded. From *Baldwin and Dunkerton* [1998b].




A schematic diagram showing the zonal wind structure in the winter hemisphere in the westerly phase of the QBO in the lower stratosphere (top) and in the easterly phase (bottom). The dashed line in the bottom panel shows the location of the zero wind line. The thick arrows denote the dominant paths of wave activity propagation for quasi-stationary planetary waves forced near the surface in the extratropics.

# W-E QBO Composite of 1964-96 1000-hPa Z

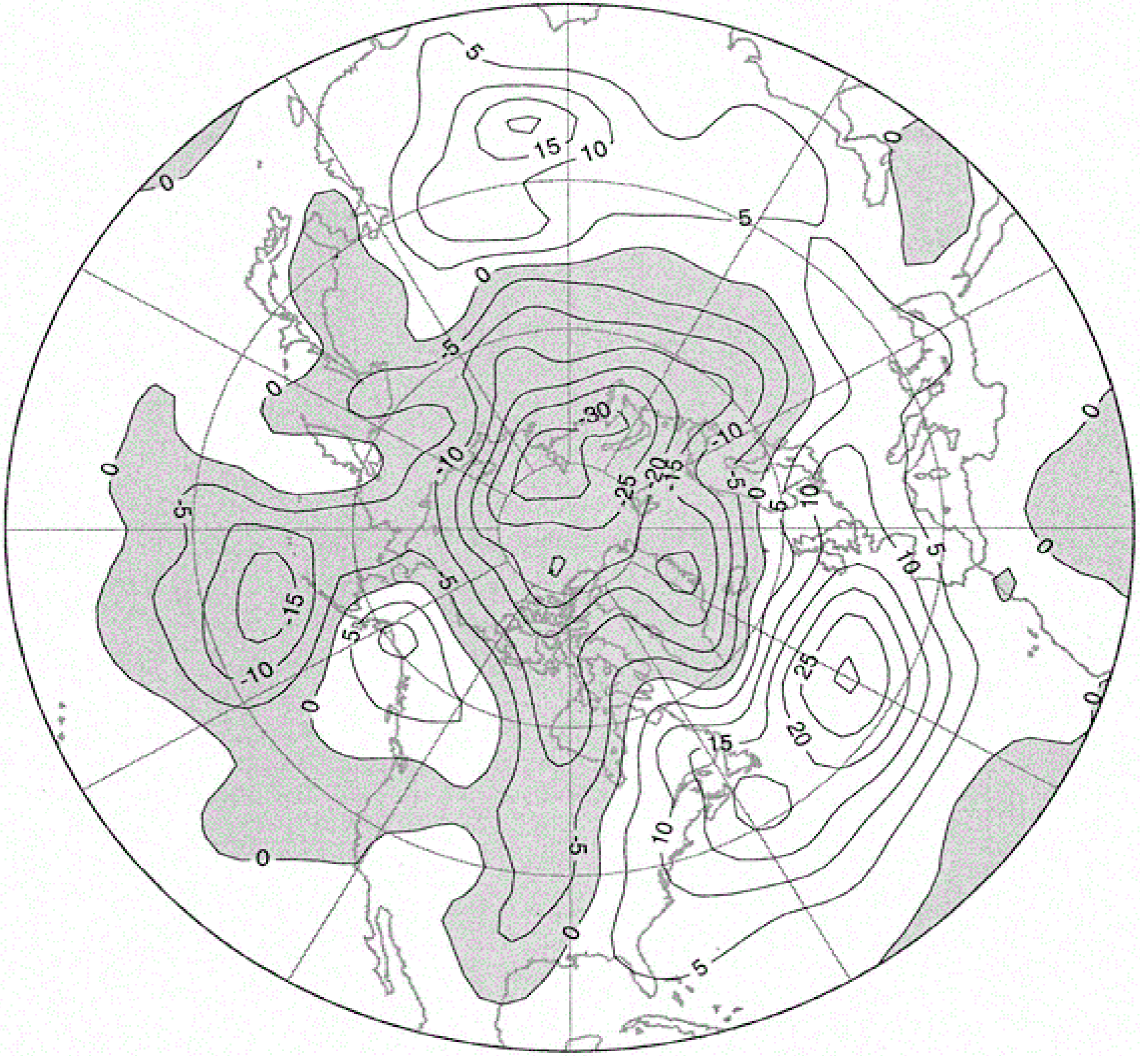
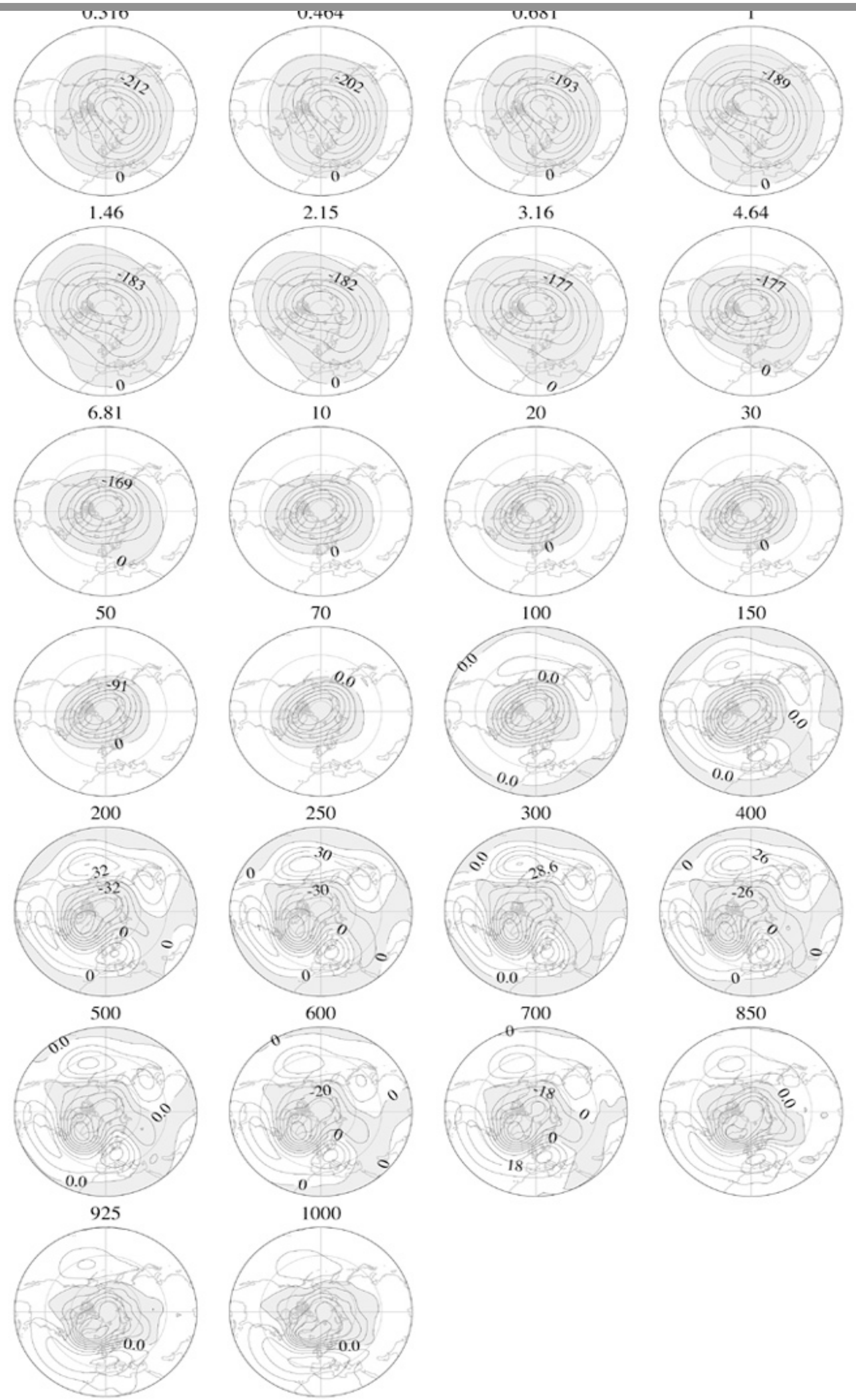
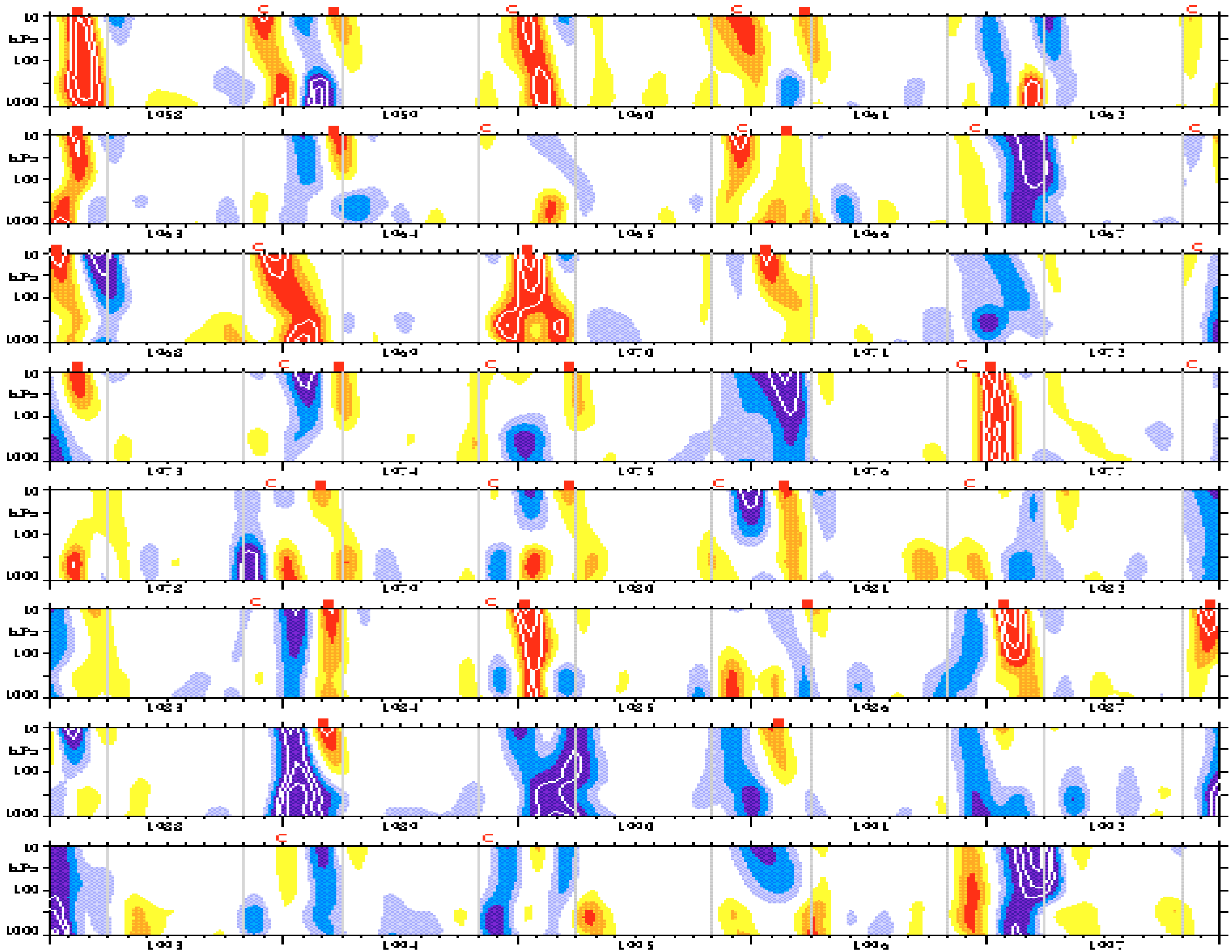
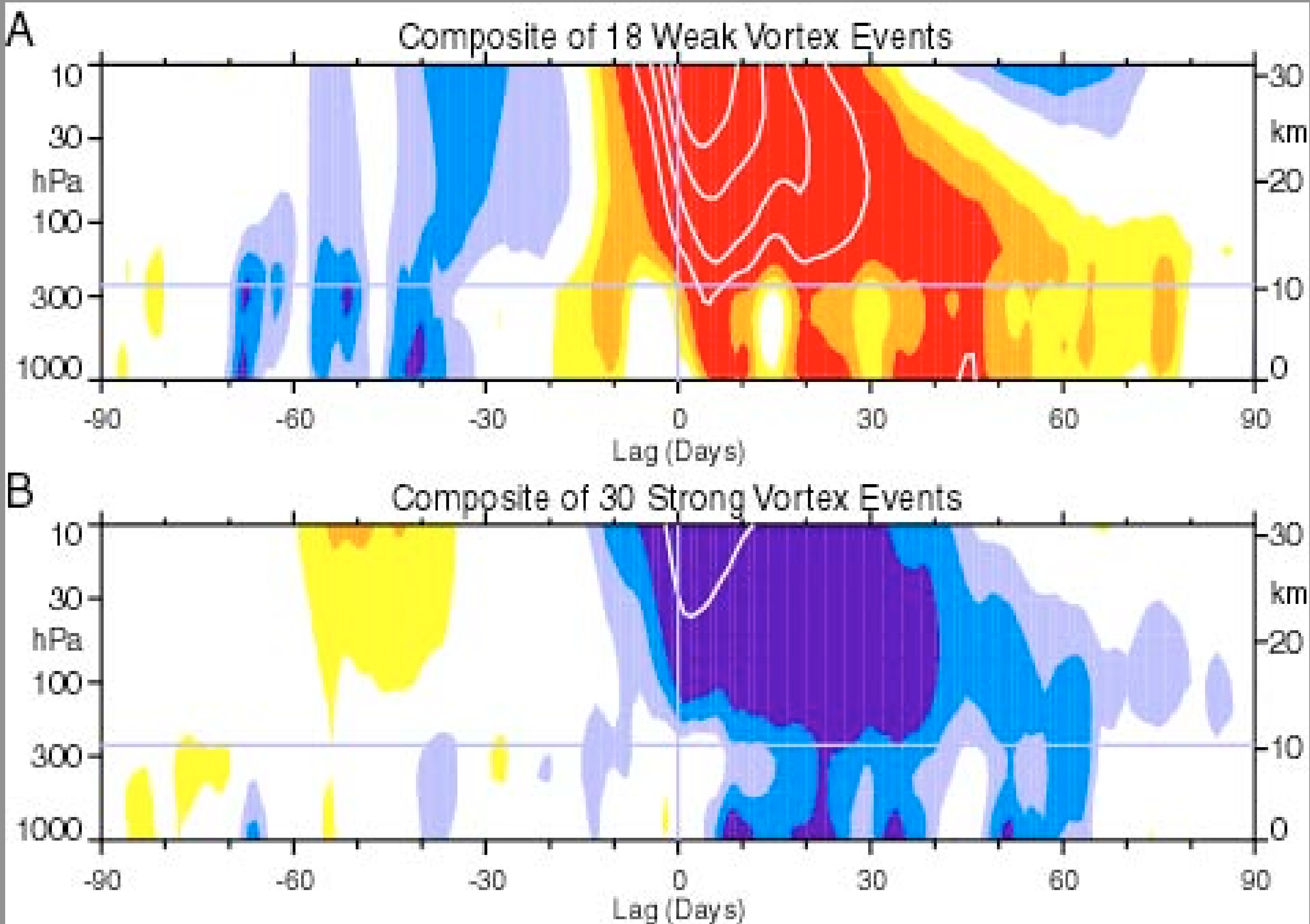


**Figure 31. Difference in 1000–hPa geopotential height composites (meters) between westerly and easterly QBO composites. December–February monthly–mean National Centers for Environmental Prediction data for 1964–1996 were used.**


0.316
0.464
0.681
1
1.46
2.15
3.16
4.64
6.81
10
20
30
50
70
100
150
200
250
300
400
500
600
700
850
925
1000




A
Composite of 18 Weak Vortex Events
10
30
hPa
100
300
1000
30
km
20
10
0
-90
-60
-30
0
30
60
90
Lag (Days)
B
Composite of 30 Strong Vortex Events
10
30
hPa
100
300
1000
30
km
20
10
0
-90
-60
-30
0
30
60
90
Lag (Days)