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School on the Physics of Equatorial Atmosphere

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The Role of Equatorial Waves in the Semiannual Oscillation of the Tropical Atmosphere

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Introduction

The semiannual oscillation (SAO) of mean zonal winds in the tropical stratosphere and mesosphere was first documented by *Reed* [1962, 1965, 1966]. The SAO is actually two linked oscillations approximately out of phase with each other, one peaking near the stratopause and the other near the mesopause, as shown by *Hirota* [1978]. Recent measurements made by the High-Resolution Doppler Imager (HRDI) onboard the Upper Atmosphere Research Satellite (UARS) have extended the range of observations into the lower thermosphere and documented an apparent coupling between the stratospheric quasibiennial oscillation (QBO) and the mesopause SAO [*Burrage et al*, 1996]. *Garcia et al* [1997] have summarized existing observations and discussed the behavior of the mesopause SAO, including its possible link to the stratospheric QBO.

Even though the mean structure of the SAO is well documented and there is a growing body of data on its variability, the physical mechanism that gives rise to the oscillation is not completely understood. It is generally agreed that the easterly phase in the stratosphere is due to advection of zonal mean easterly momentum by the meridional circulation, with a contribution from planetary Rossby waves propagating into the tropics from the winter hemisphere. (The fact that both advection and Rossby wave forcing are tied to the seasonal cycle, producing easterly accelerations at the solstices, explains the semiannual periodicity of the oscillation). The stratospheric westerly phase is known to be driven, at least in part, by planetary-scale Kelvin waves [*Hirota*, 1980; *Hitchman and Leovy*, 1988]. However, *Hitchman and Leovy* have also shown that large-scale Kelvin waves alone cannot account for the observed westerly acceleration (they estimate their contribution to be between 30 and 70%). This conclusion is consistent with the results of General Circulation Models (GCMs) [e.g., *Sassi et al*, 1993], which do not produce a completely realistic stratospheric SAO, although the computed planetary-scale Kelvin wave amplitudes are comparable or even larger than those observed.

Less is known about the mechanism of the mesospheric SAO, except that both the westerly and easterly phases appear to be wave-driven since mean advection at mesopause altitudes cannot account for the observed easterly accelerations. A number of hypotheses have been put forward to explain the mesospheric oscillation; these have generally relied on momentum transport by a spectrum of waves propagating from the lower atmosphere and filtered by the wind system of the stratospheric oscillation. That is, zonal mean westerlies in the stratosphere suppress waves that transport westerly momentum but allow propagation of those that transport easterly momentum, and vice-versa. The result is a mesospheric oscillation out of phase with the stratospheric one, as observed. Although this aspect of the mechanism is almost certainly correct, the nature of the waves involved continues to be the subject of speculation. In *Dunkerton's* [1982] pioneering study of the mesopause SAO it was assumed that momentum was transported by planetary-scale Kelvin waves and small-scale gravity waves (zonal wavelength $<$ 1000 km). A similar scheme was used in a model of the zonally-averaged circulation of middle atmosphere by *Garcia et al* [1992], who dispensed with the planetary-scale Kelvin waves. More recently, *Mengel et al* [1995] have used a parameterization of small-scale gravity waves to model both the quasi-biennial and the semiannual oscillations. Although these mechanistic models have succeeded in producing more or less realistic oscillations in both the stratosphere and mesosphere, the mesospheric oscillation has never been simulated with a GCM [e.g., *Sassi et al*, 1993; *Hamilton et al*, 1995].

The state of theoretical understanding of the SAO can thus be described as mixed. On the one hand, there is little doubt that the westerly phase in the stratosphere, and both phases in the mesosphere, are wave-driven; and that filtering of vertically propagating waves gives rise to the out-of-phase relationship between the stratospheric and mesospheric winds. On the other hand, there is scant evidence about the nature of the waves that drive the SAO, aside from the fact that planetary-scale Kelvin waves are responsible for a substantial fraction of the westerly forcing in the stratosphere.

In this lecture, we review certain observational and modeling studies that shed light on the waves that force the SAO. The studies have been motivated by the work of *Bergman and Salby* [1994], who have analyzed the behavior of tropical deep convection using space-borne OLR observations. Bergman and Salby have argued that heat release by deep convection can force a broad spectrum of equatorial waves, both in wavenumber and frequency. The role of these waves in driving the observed SAO is explored.

OUTLINE

1. The observed SAO

2. Theory and modeling: Current status

3. Excitation of equatorial waves by convection

4. Modeling the effect of convectively excited waves

5. Conclusions

1. Observations of the SAO

- SAO first documented by Reed (1962, 1965, 1966)

- SAO extends into the upper mesosphere; the stratospheric and mesospheric oscillations are linked (Hirota, 1978, 1980)

- Recent satellite observations (SAMS, LIMS, HRDI) give a picture of the 3D structure of the SAO

- HRDI and radar data docuemnt inetrannual variability (Garcia et al, 1997)

- Mesospheric oscillation appears to be influenced by QBO (Burrage et al, 1996)

- However, the mechanism of the SAO remains incompletely understood

The following figures show

- Seasonal march of zonal-mean zonal wind from Ascension Island rocketsonde data (Reed, 1966)

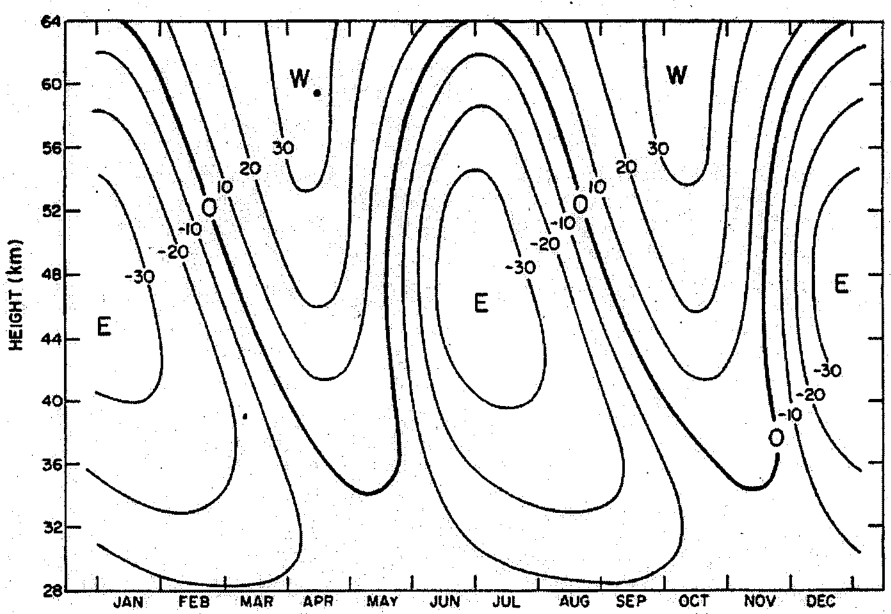
- Seasonal march of zonal-mean zonal wind to 80 km, from Ascension and Kwajalein islands rocketsonde data (Hirota, 1978, 1980)

- Semiannual harmonic of the zonal wind at the equator (Hirota, 1978)

- Seasonal march of zonal-mean zonal wind at 40 and 80 km, as function of latitude from HRDI observations (Garcia et al, 1997)

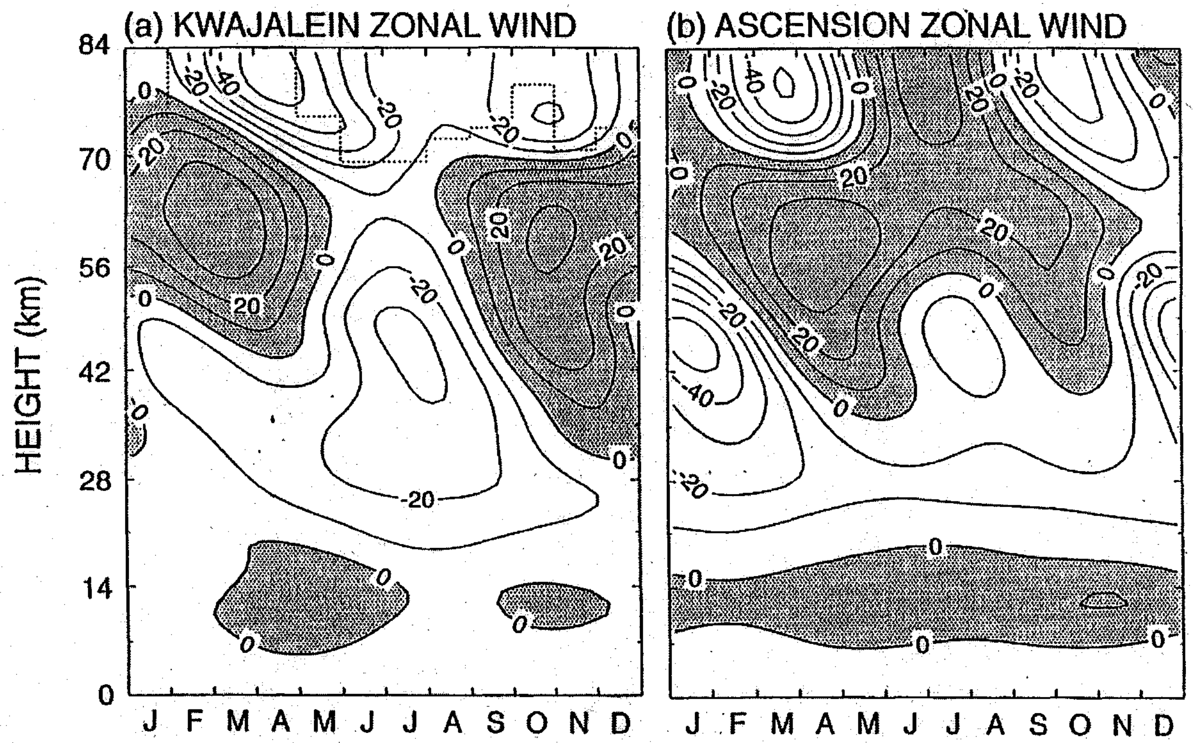
- Seasonal march of zonal-mean zonal wind in the stratosphere and mesosphere from HRDI observations (Garcia et al, 1997). Note the apparent relationship between the QBO phase in the stratosphere and the strength of the SAO easterly phase in the mesosphere (Burrage et al, 1996)

 (JGR, 1966)



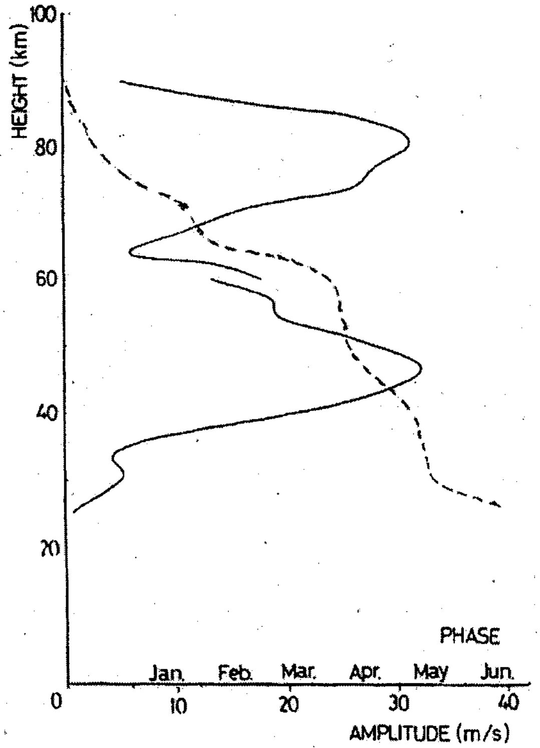
Estimated variation of zonal wind (in m sec^{-1}) with month and altitude at the equator.

(Ascension I. rocketsondes)

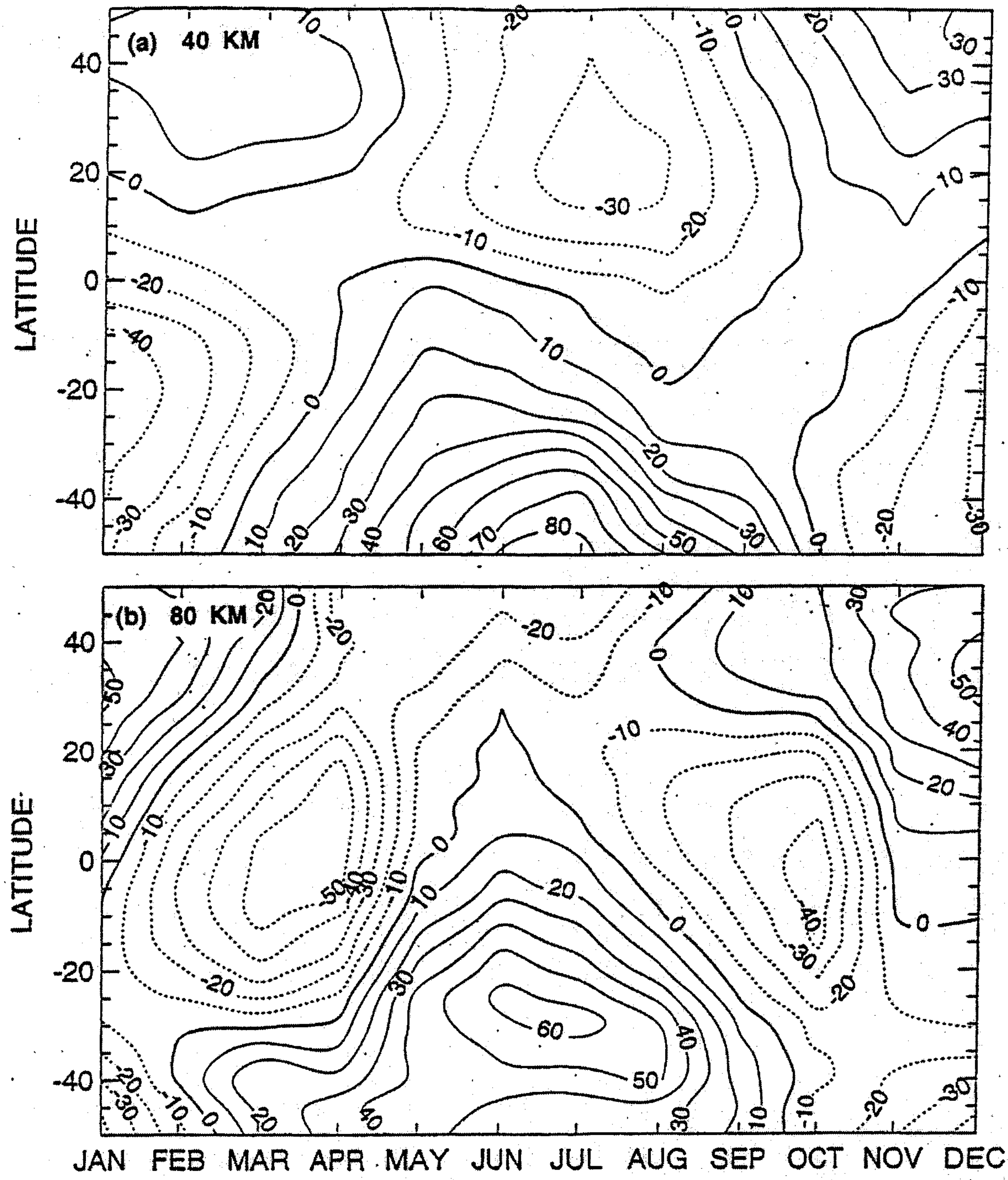


(Ascension + Kwajalein Rocketsondes) Annual Composite

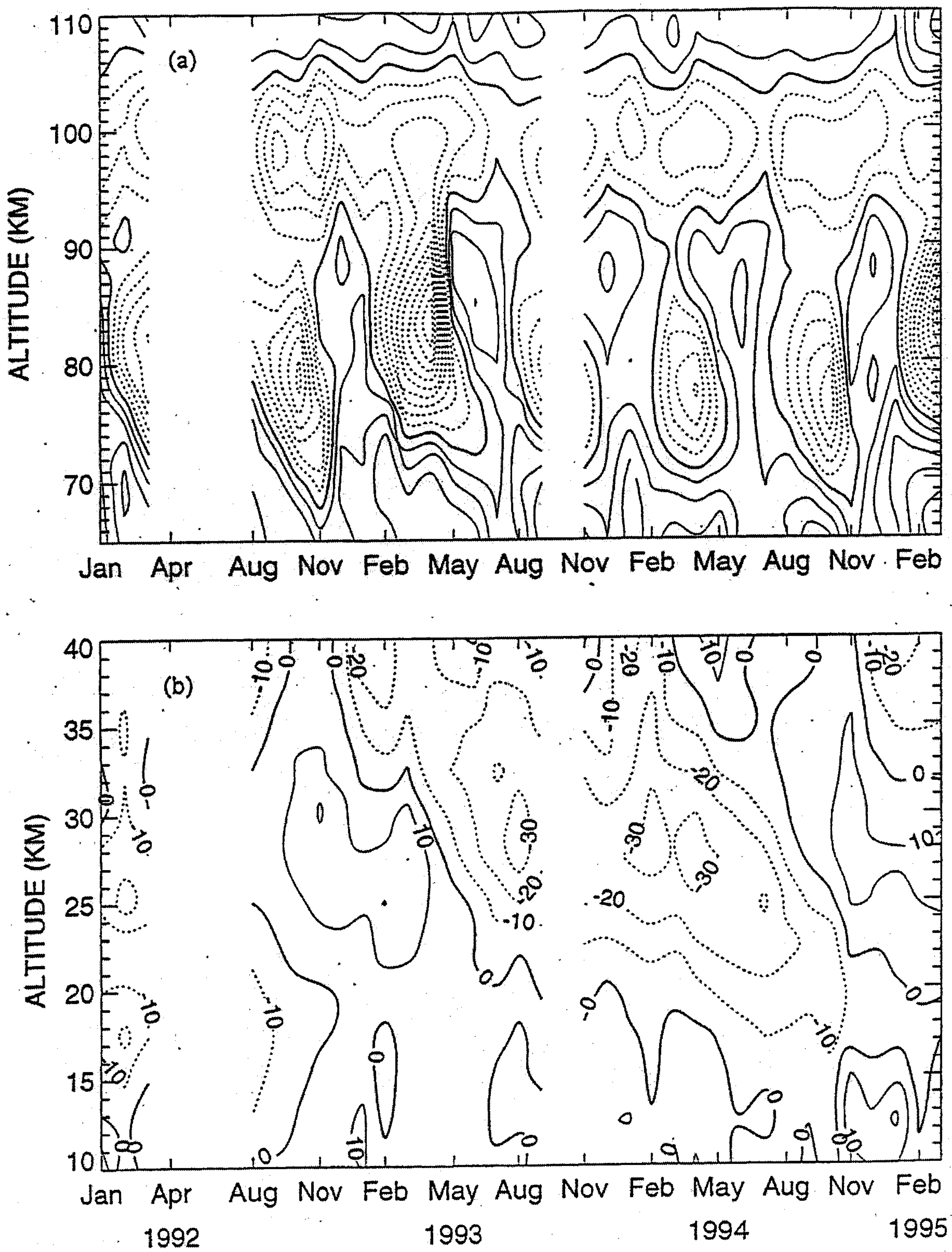
– Semiannual Harmonic –



The SAO at Ascension Island (8°S); amplitude (solid lines), phase (dashed line).


(a) 40 KM
(b) 80 KM
LATITUDE
LATITUDE
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

(HRDI wind)



ALTITUDE (KM)
(a)
(b)
Jan Apr Aug Nov Feb May Aug Nov Feb May Aug Nov Feb
1992
1993
1994
1995

(HRDI wind)

2. Theory and Modeling of the SAO

We know that...

- Easterly phase at stratopause is linked to the seasonal cycle (nonlinear mean advection; direct planetay wave driving); it sets the *clock* for the oscillation

- Westerly phases, and easterly phase at the mesopause, are wave-driven; planetary-scale Kelvin waves play a role in the stratopause westerly phase

- Planetary Kelvin waves alone do not supply all the wave driving for the stratopause westerly phase (Hitchman and Leovy, 1986)

- Current GCMs do not produce realistic SAOs

We do not know...

- What are the waves that drive the mesopause SAO, or provide the missing forcing for the stratopause westerly phase

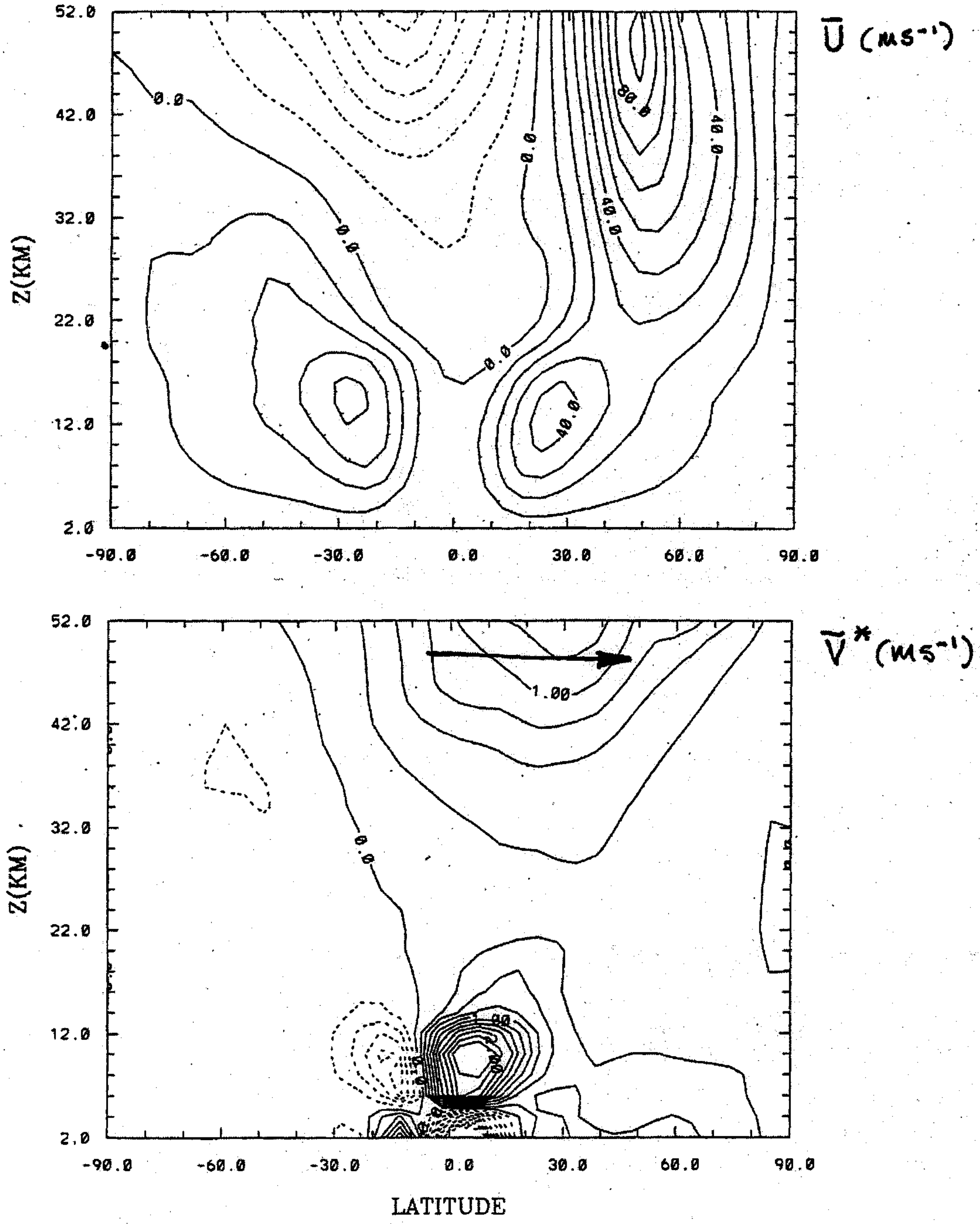
- Details of the excitation mechanisms for the waves

The following figures show:

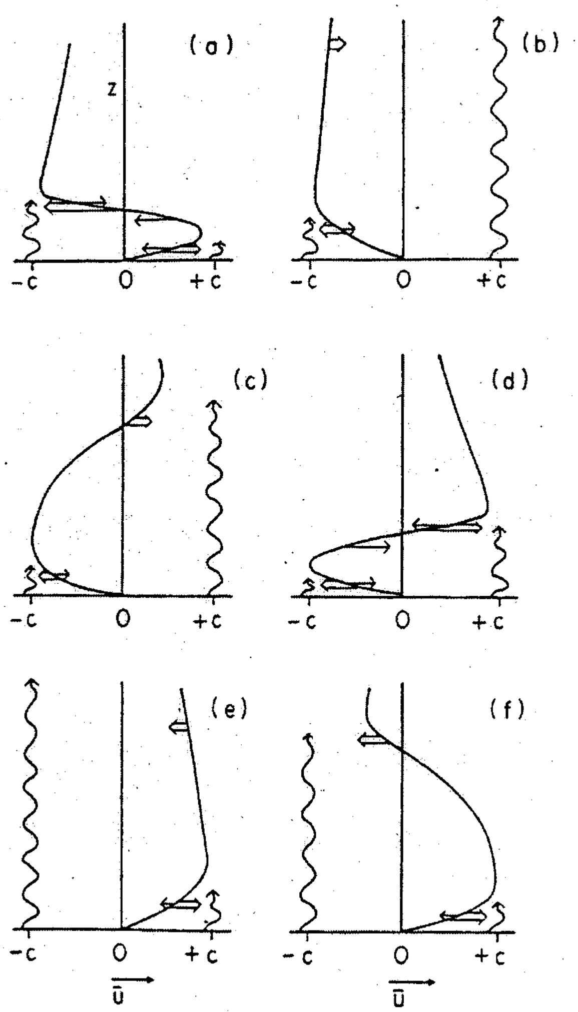
- Zonal mean zonal (U) and meridional (V) wind during northern hemisphere winter (from the model of Garcia and Solomon, 1992). The strong meridional circulation from the summer to the winter hemisphere advects zonal mean easterlies across the equator at stratopause level

- Mechanism for the forcing of tropical oscillations in zonal mean zonal wind (after Plumb, 1984)

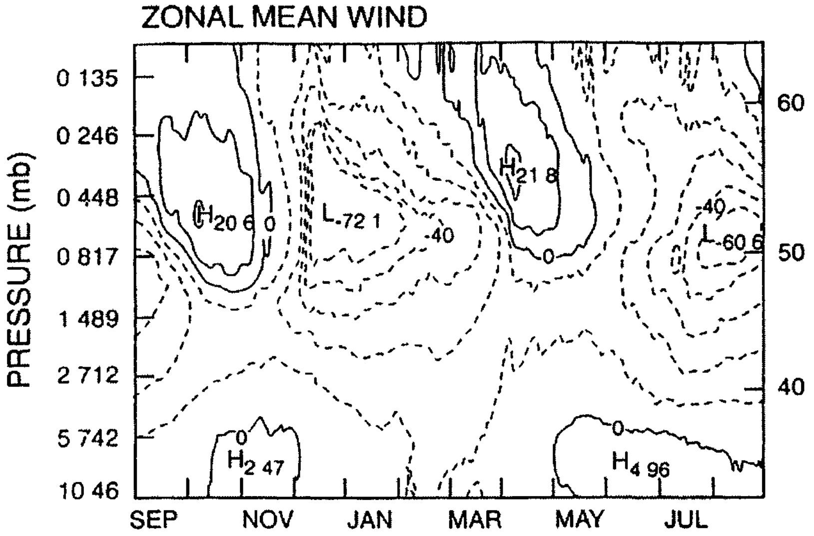
- The SAO simulated by two GCMs: the NCAR CCM2 and the GFDL SKYHI model. Although both models produce a stratopause SAO, neither is completely realistic, and neither model is able to simulate the mesopause SAO



Ū (ms⁻¹)
52.0
42.0
32.0
22.0
12.0
2.0
Z(KM)
-90.0
-60.0
-30.0
0.0
30.0
60.0
90.0
V̄* (ms⁻¹)
1.00
LATITUDE

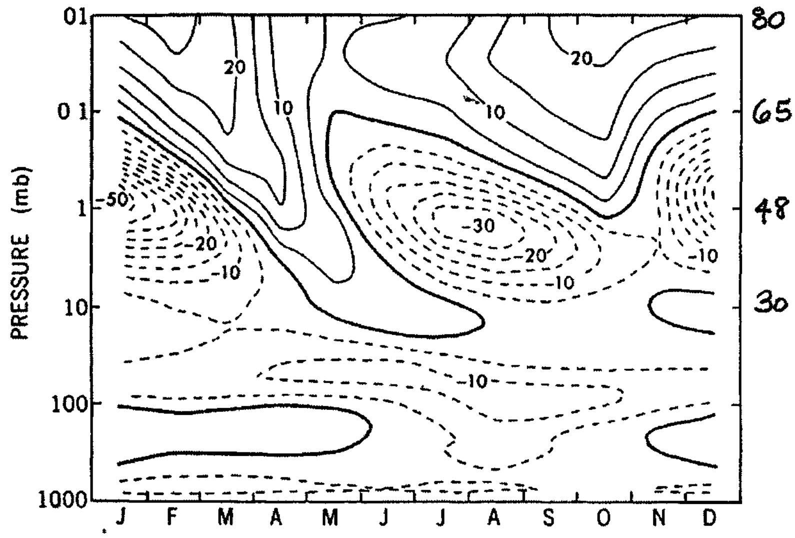


Schematic representation of the evolution of the mean flow in Plumb's analog of the QBO. Six stages of a complete cycle are shown. Double arrows show wave-driven accelerations and single arrows show viscously driven accelerations. Wavy lines indicate relative penetration of easterly and westerly waves. See text for details. [After Plumb (1984).]



Time-height profile of equatorial mean winds, from 1 September through 31 August. Contour interval is 10 m s^{-1}

NCAR CCM2
(Sassi et al, '93)



Time-height section for the long-term mean annual cycle of equatorial zonally averaged zonal wind from the $N30$ SKYHI integration Contours are based on the 12 monthly means The contour interval is 5 m s^{-1} and dashed contours denote easterly winds

GFDL SKYHI
(Hamilton et al. '95)

3. Excitation of Equatorial Waves by Deep Convection

- OLR observations from satellites can be used as proxy for deep convection in Tropics (Bergman and Salby, 1994)

- Convection can force equatorial waves over a wide range of spatial and temporal scales

- Waves with fast phase velocities may play a role in the SAO

- These include Kelvin waves and inertia-gravity waves (broad range of zonal wavenumber)

The following figures show

- Mean and standard deviation of latent heat release by convection as estimated by Ricciardulli and Garcia (2000) from OLR data using the method of Bergman and Salby (1994)

- Zonal wavenumber/frequency spectrum of convective heating deduced from OLR data (Ricciardulli and Garcia, 2000)

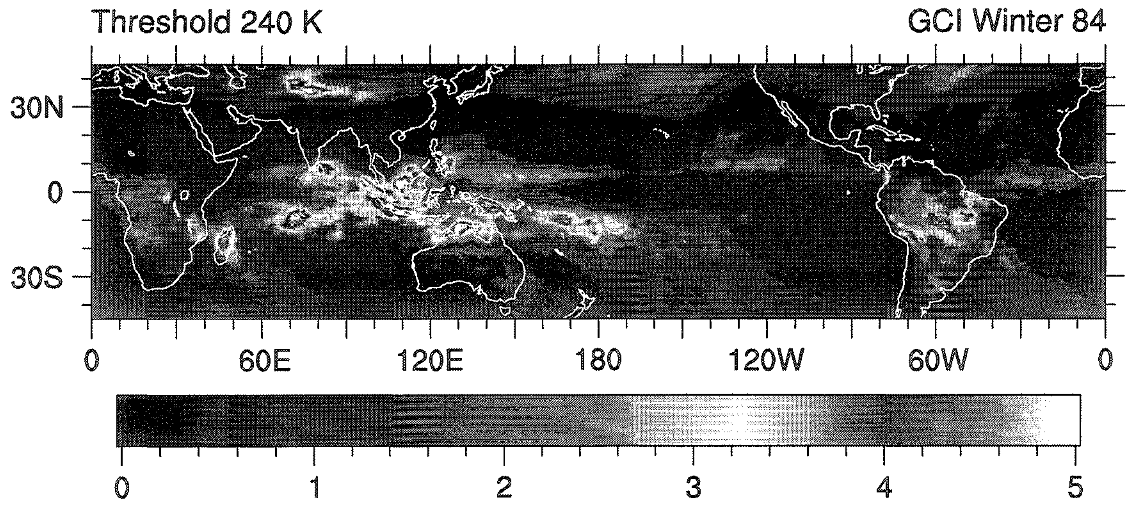
- Zonal wavenumber/frequency distribution of vertical component of EP Flux, estimated from OLR data by Ricciardulli and Garcia (2000)

- Schematic representation of the mechanism for vertical scale selection (after Salby and Garcia, 1987). The first maximum in the vertical projection response occurs at $\lambda_z \simeq 2D$, where D is the effective depth of the convective heating distribution. The second vertical projection maximum occurs at $\lambda_z \simeq 2D/3$

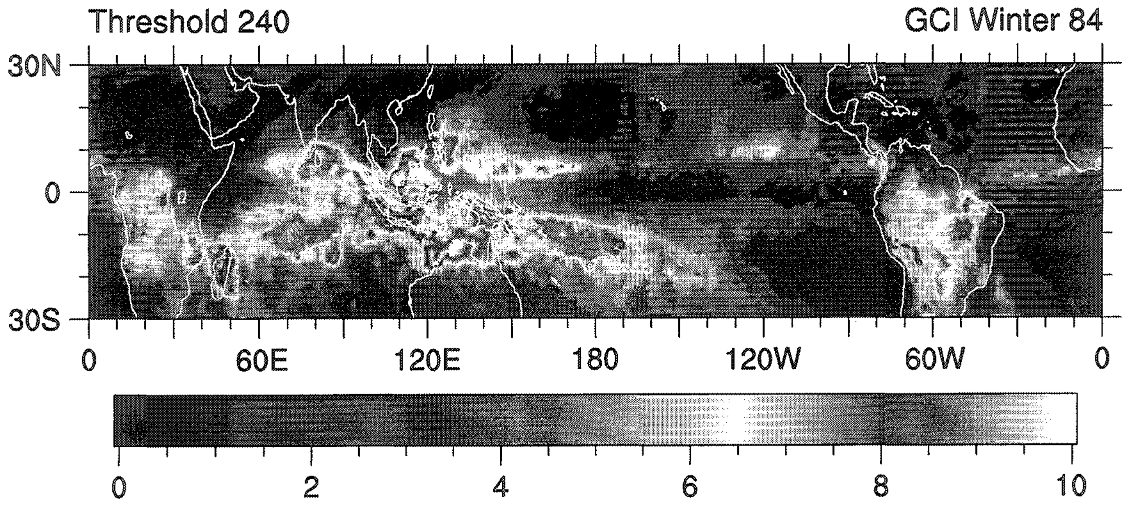
- Frequency distribution of vertical component of EP Flux estimated from OLR data and from CCM3 output (Ricciardulli and Garcia, 2000). The CCM3 run in this case uses the Hack (1994) convection parameterization. Note the small values of F_z due to gravity waves in CCM3

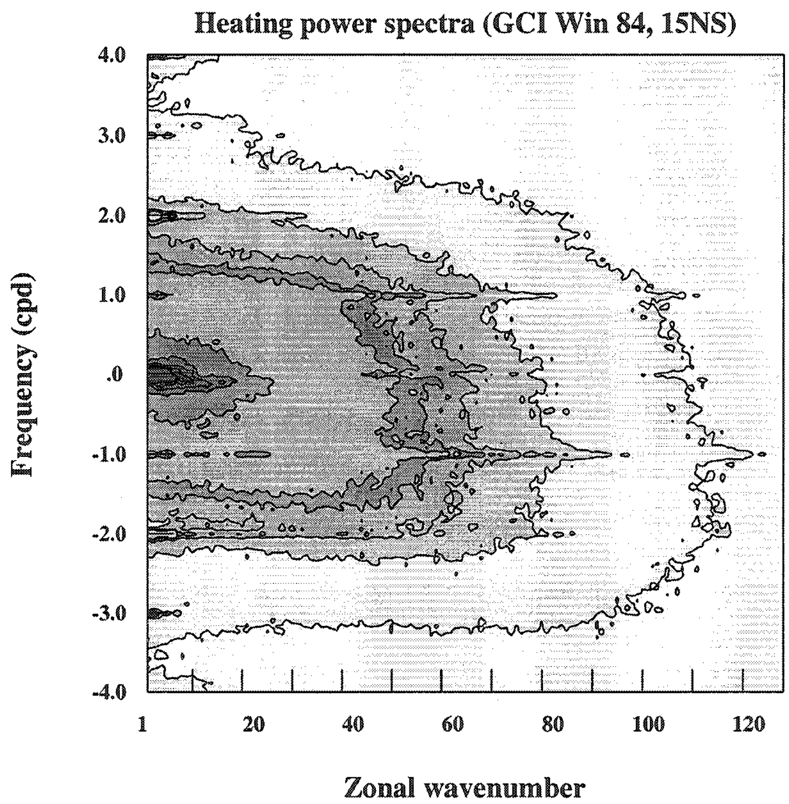
- Numerical estimates of the vertical component of EP flux near the tropopause from OLR data (Ricciardulli and Garcia, 2000), and from rawinsonde data (Sato and Dunkerton, 1997)

Mean DCH (K/day)



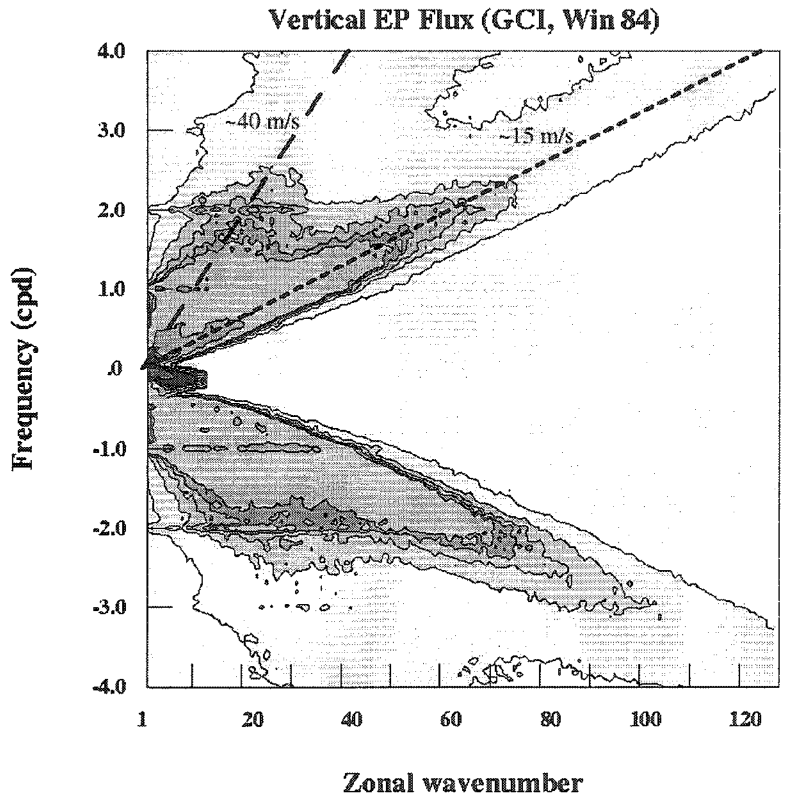
Standard deviation of DCH



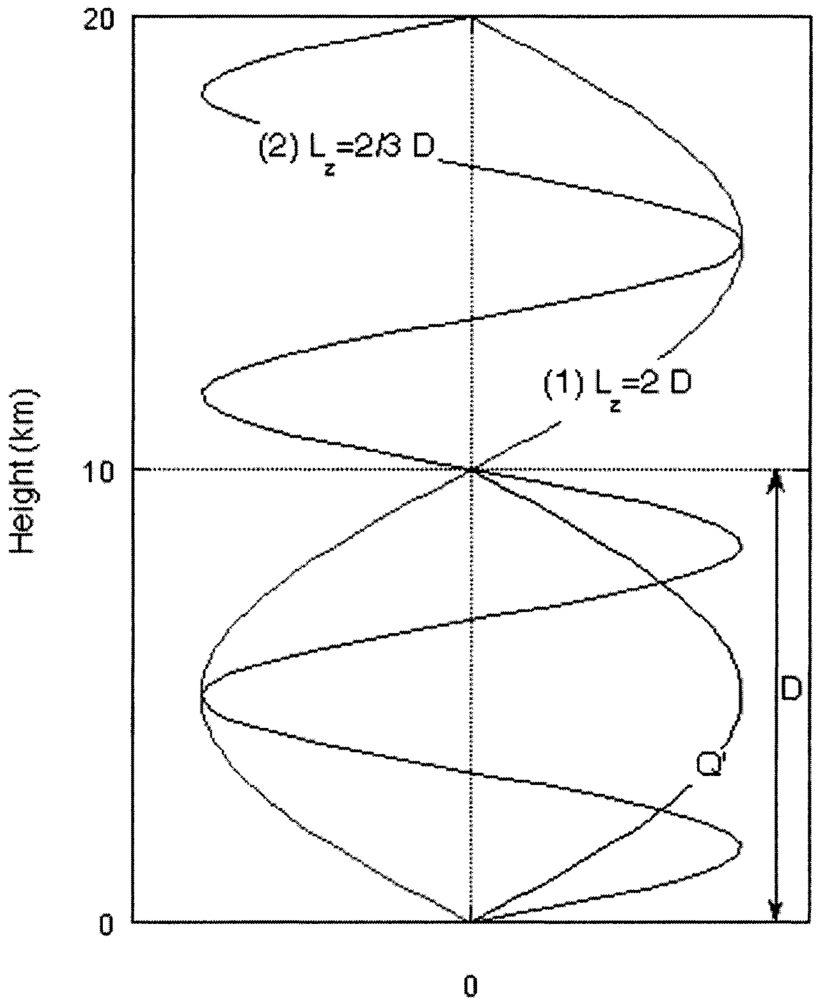


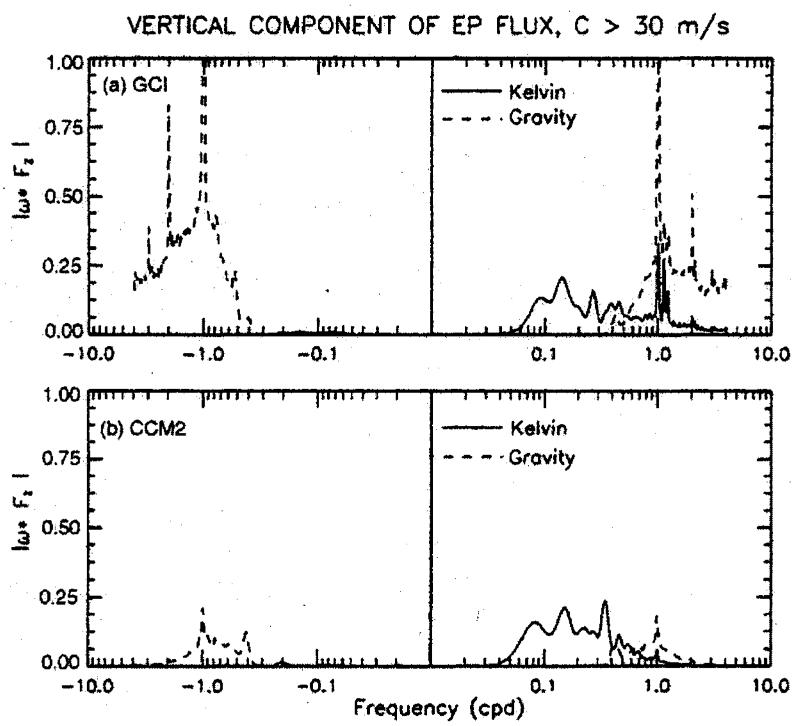
Heating power spectra (GCI Win 84, 15NS)
4.0
3.0
2.0
1.0
.0
-1.0
-2.0
-3.0
-4.0
Frequency (cpd)
1
20
40
60
80
100
120
Zonal wavenumber

Fz deduced from OLR observations (Bergman and Salby, 1994)



Vertical Scale Selection



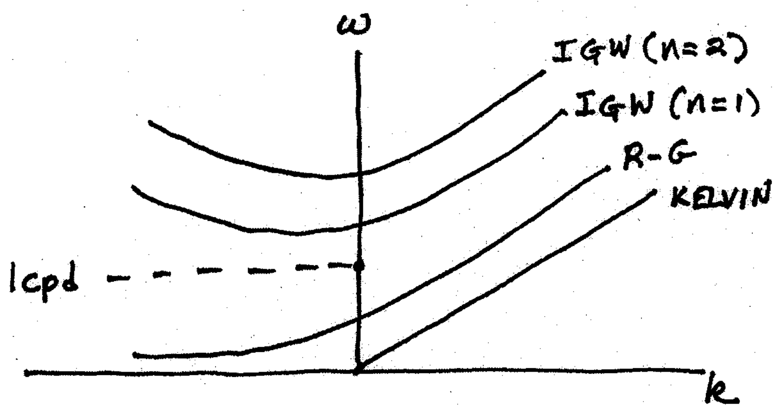


VERTICAL COMPONENT OF EP FLUX, C > 30 m/s
(a) GCI
Kelvin
Gravity
(b) CCM2
Kelvin
Gravity
Frequency (cpd)

ESTIMATES OF F_z IN TROPICS

	GCI[1]	SATO & DUNKERTON[2]
WESTWARD		
GRAVITY	1.08	0.35 to 3.0
EASTWARD		
GRAVITY	−0.58	
ROSSBY-GRAVITY	−0.18	
KELVIN	−0.56	
TOTAL EASTWARD	−1.32	−0.35 to −3.0

(1) GCI estimate @ 100mb
(2) SATO & DUNKERTON @ 95mb
All numbers $\times 10^{-2}\ m^2 s^{-2}$



4. Modeling the Effect of Equatorial Waves

- Equatorial beta-plane model

- Specify heating distribution consistent with OLR observations

- Model calculations
  - Nominal case
  - Planetary-scale waves only
  - No diurnal forcing
  - No seasonal "clock"
  - Interaction with the QBO

Beta-Plane Model of the SAO

(Sassi and Garcia, 1997)

- Quasi-linear (only wave-mean flow interactions)

- 15 zonal wavenumbers

- Vertical resolution 1 km; meridional resolution 300 km

- Model domain 0-120 km, $\pm 30^{\circ}$

- Semiannually-varying drag produces equatorial easterlies at the solstices (SAO "clock")

- Forcing by latent heat release Q'

The following figures show

- Schematic representation of the model domain and imposed equatorial seasonal easterlies in the model of Sassi and Garcia (1997)

- Simulation of the SAO with the model of Sassi and Garcia (1997). Shown are the zonal and EP flux divergence as fuc-ntions of time and height

- Semiannual harmonic from the model of Sassi and Garcia (1997) compared to Hirota's (1978) observations

- EP Flux divergence as a function of wavenumber and time at the stratopause and mesopause

- Contributions to the toal EP flux divergence by planetary-scale ($k = 1-3$) waves and intermediate-scale waves ($k = 4-15$)

- Wave structure at $k=1$. This is dominated by Kelvin waves (eastward propagating) as evidenced by the very small v' field

- Wave structure at $k=11$. Inertia-gravity waves make a major contribution here: v' is large for both eastward and westward propagating waves

- Spectra of T' at 30 and 60 km. Note the shift of the spectrum to higher frequency (faster phase velocity) at 60 km compared to 30 km

- The SAO in the model of Sassi and Garcia (1997) when the simulation is truncated at $k=3$

- The SAO in the model of Sassi and Garcia (1997) when the diurnal cycle of convective forcing is suppressed

- The SAO in the model of Sassi and Garcia (1997) when effect of nonlinear advection of easterly winds at the solstices is ignored

- Interaction between the QBO and the SAO in the model of Sassi and Garcia (1997)

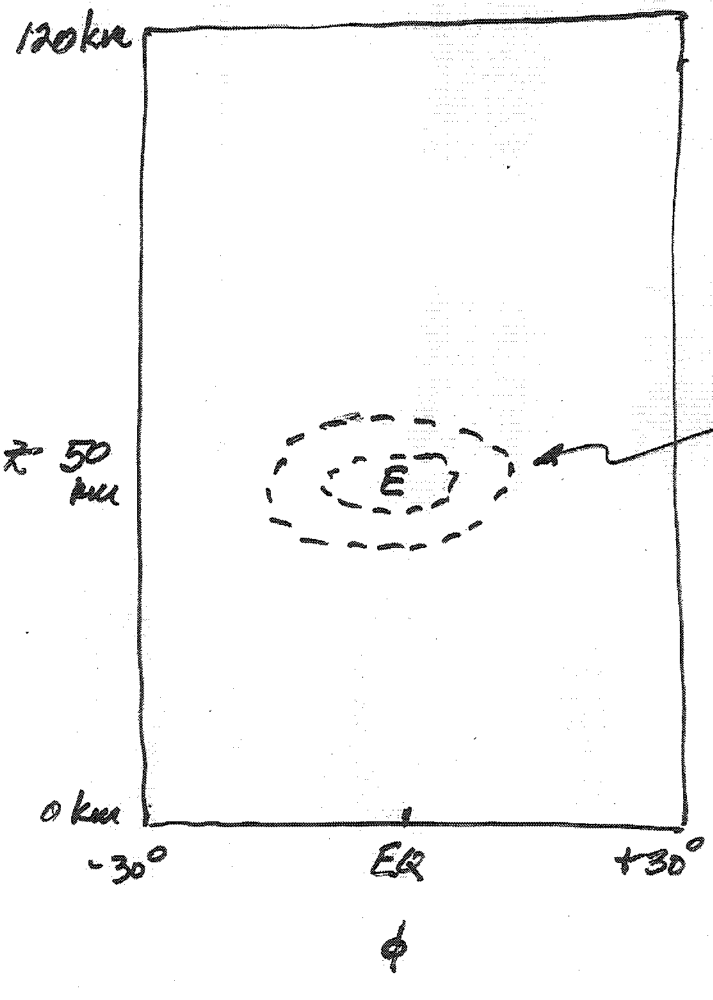
- Spectra of T' at 60 km during the westerly and easterly phases of the stratospheric QBO

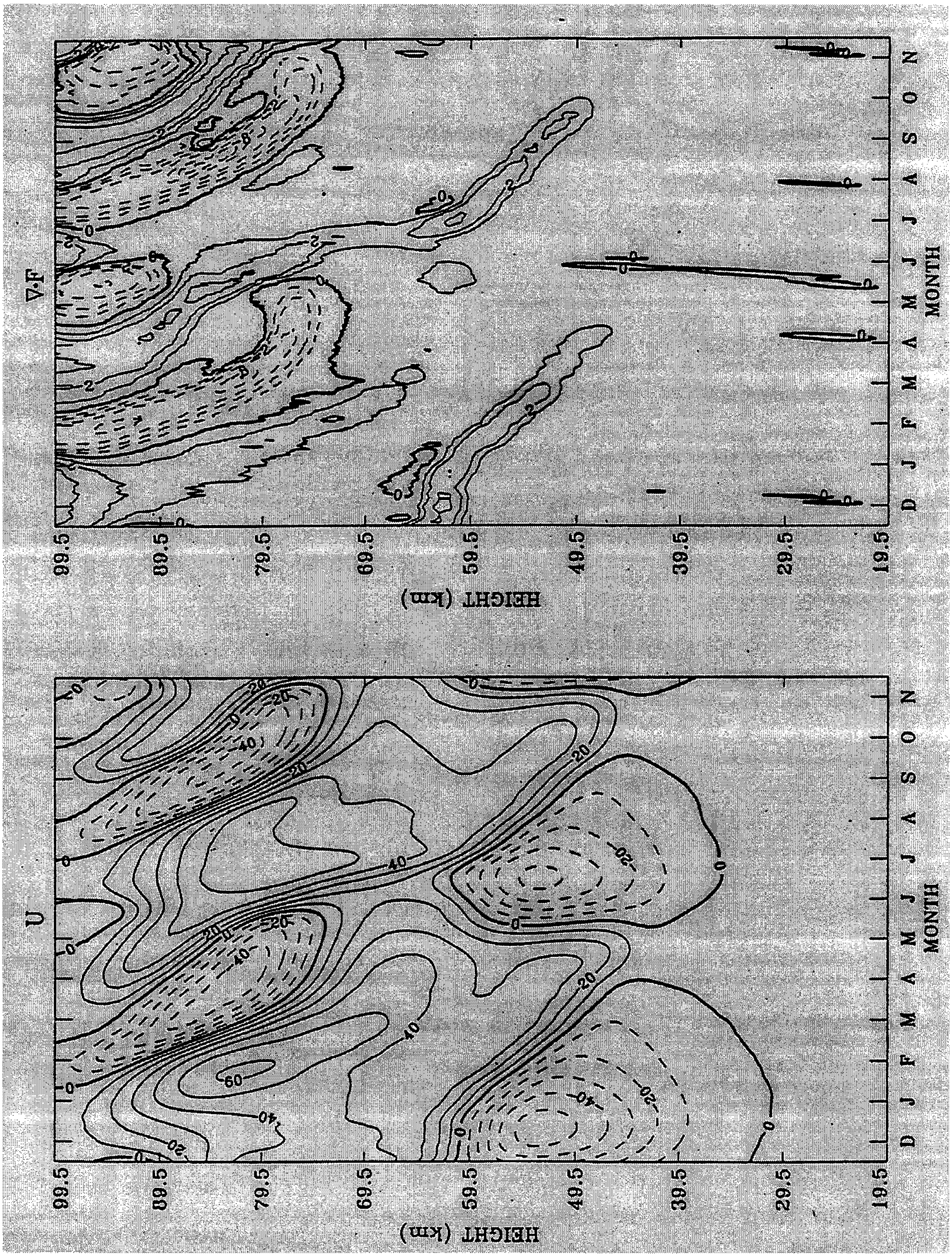
MODEL DOMAIN

0–120 km VERTICAL

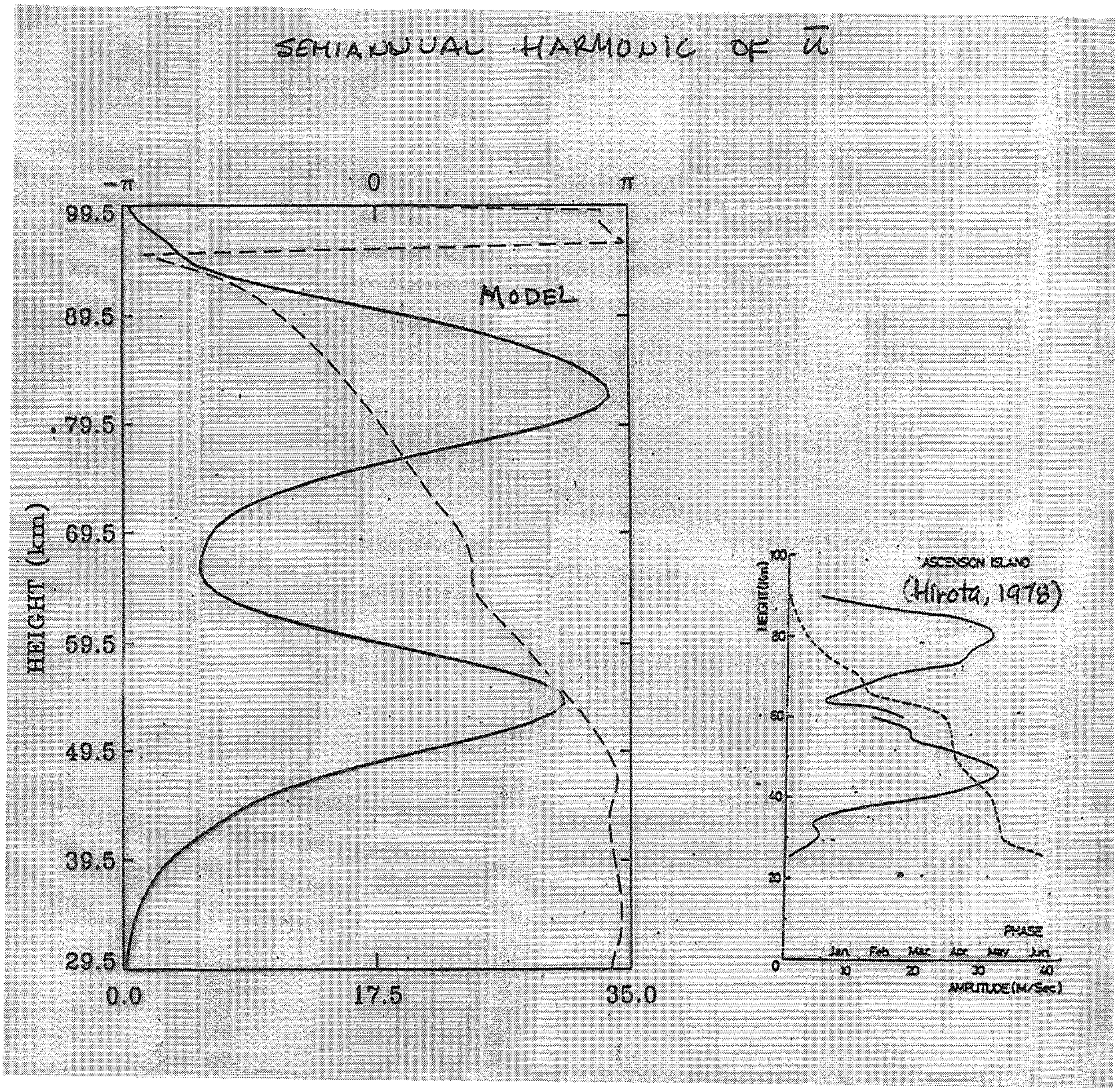
−30°, 30° LATITUDE

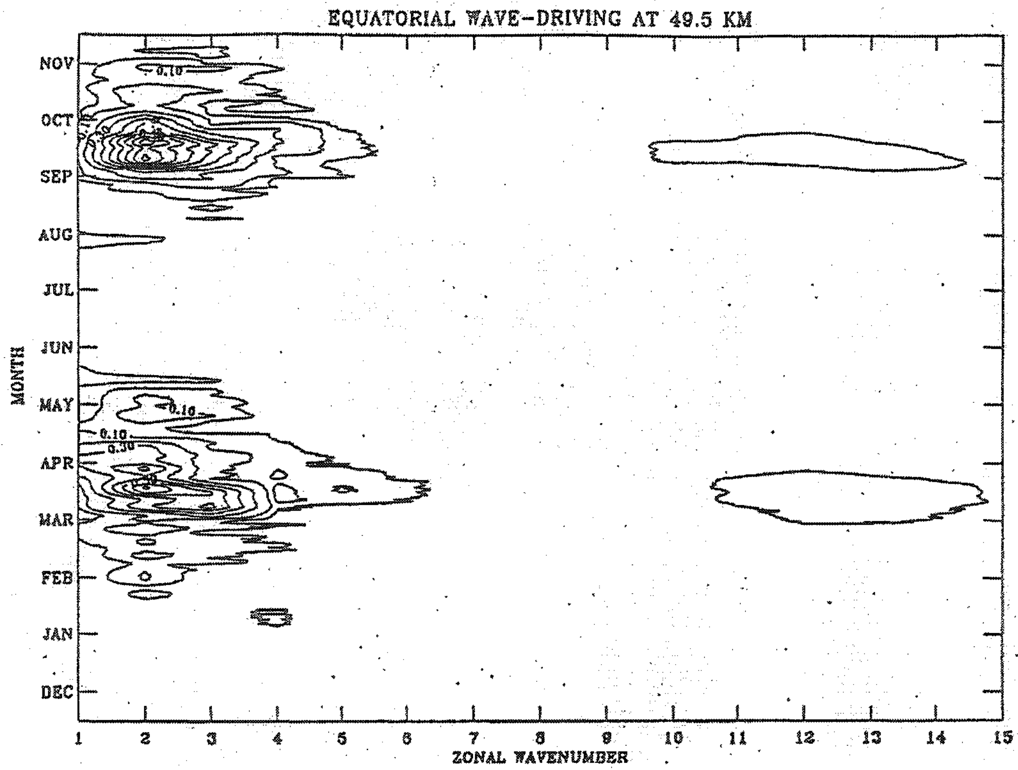
k = 0, 15 ZONAL

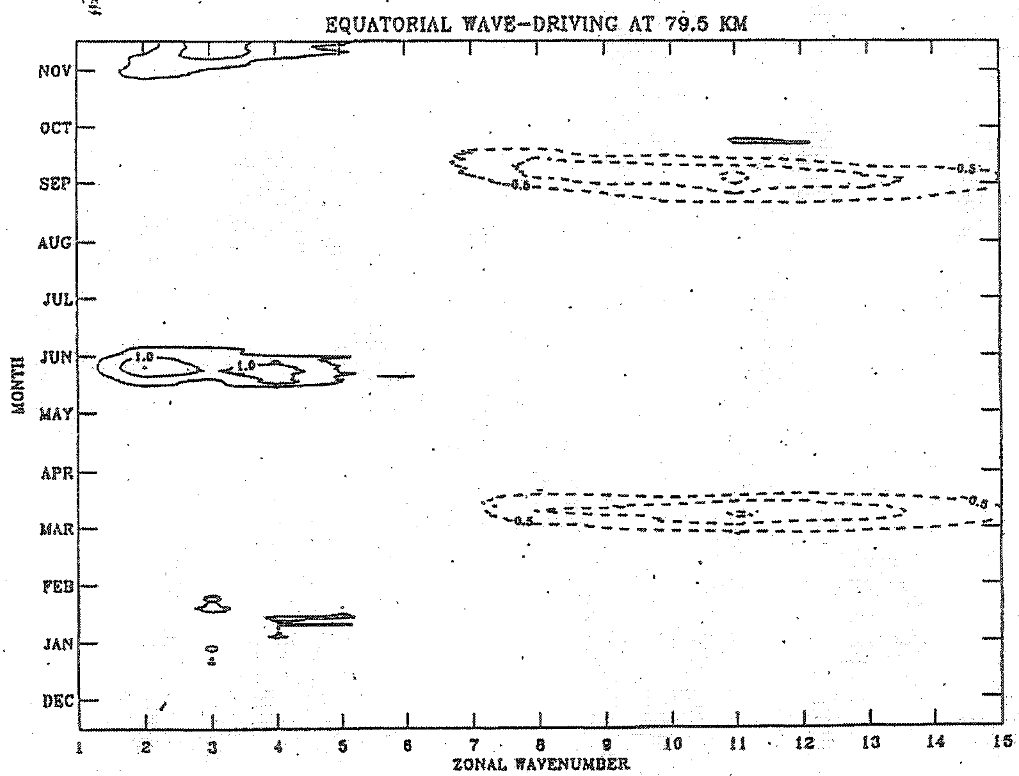


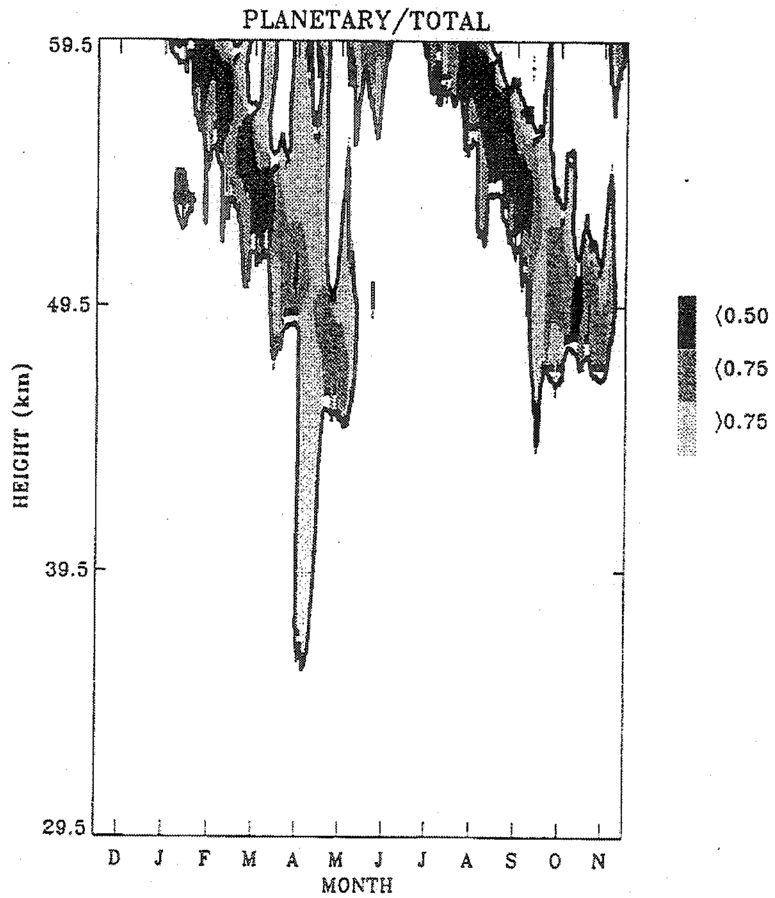


U
∇·F
HEIGHT (km)
MONTH
99.5
89.5
79.5
69.5
59.5
49.5
39.5
29.5
19.5
D J F M A M J J A S O N

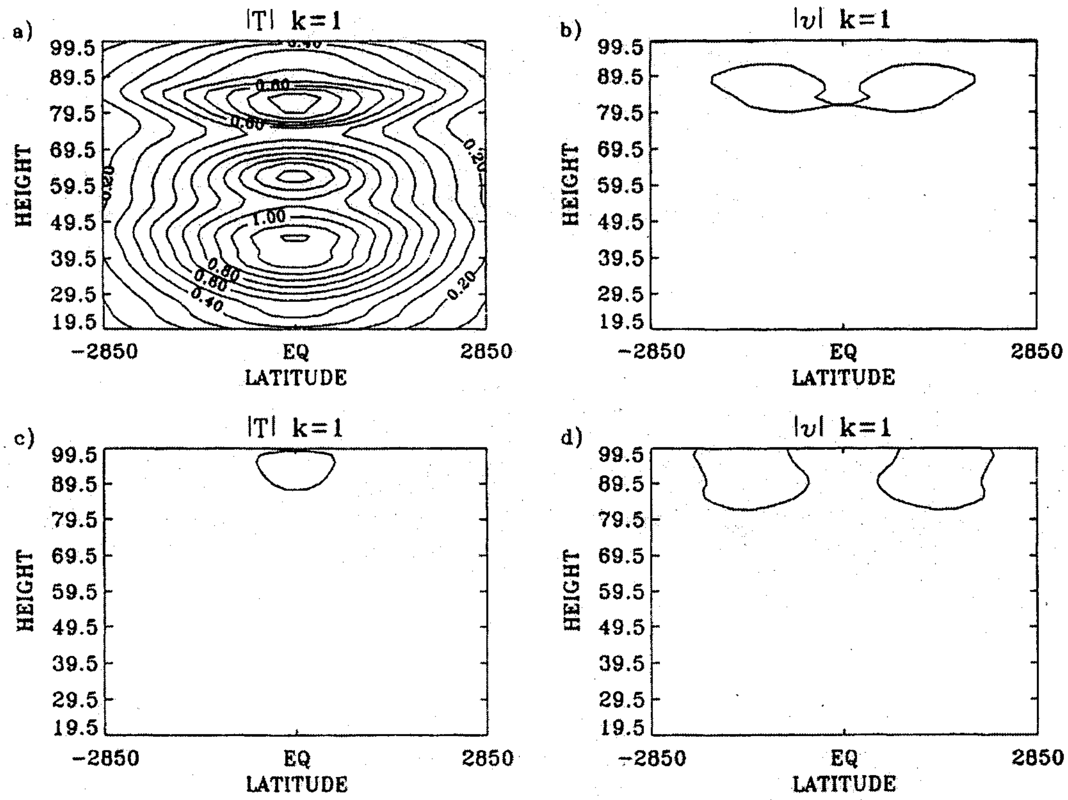

SEMIANNUAL HARMONIC OF $\bar{u}$
MODEL
HEIGHT (km)
$-\pi$
0
π
99.5
89.5
79.5
69.5
59.5
49.5
39.5
29.5
0.0
17.5
35.0
ASCENSION ISLAND
(Hirota, 1978)
HEIGHT (Km)
PHASE
Jan Feb Mar Apr May Jun
AMPLITUDE (M/Sec)


EQUATORIAL WAVE-DRIVING AT 49.5 KM
MONTH
NOV
OCT
SEP
AUG
JUL
JUN
MAY
APR
MAR
FEB
JAN
DEC
0.10
0.10
0.10
0.30
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
ZONAL WAVENUMBER


EQUATORIAL WAVE-DRIVING AT 79.5 KM
MONTH
NOV
OCT
SEP
AUG
JUL
JUN
MAY
APR
MAR
FEB
JAN
DEC
1.0
1.0
-0.5
-0.5
-0.5
-0.5
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
ZONAL WAVENUMBER



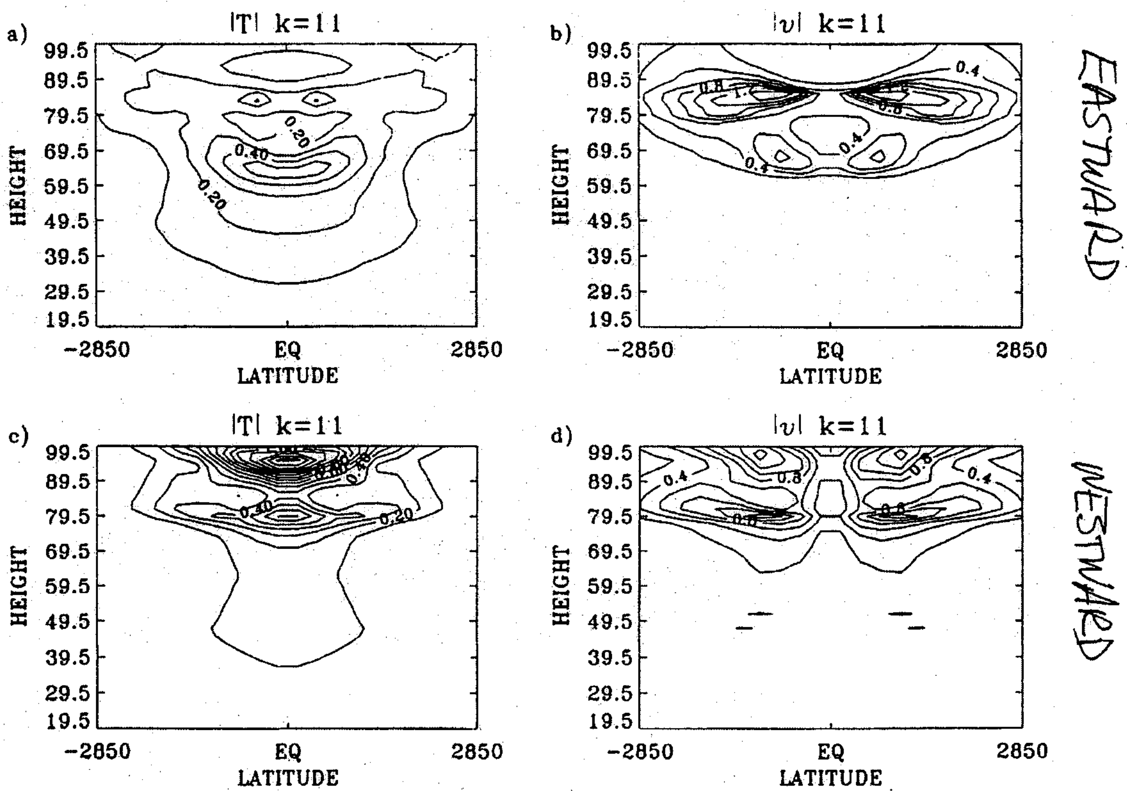
Ratio of the force exerted by planetary-scale waves to force exerted by all waves. Three shadings are marked: less than 0.5 (the darkest), between 0.5 and 0.75 (medium dark), and more than 0.75 (light shade). The bold line encloses the region where the total force is larger than 0.25 m s^{-1} day^{-1}.



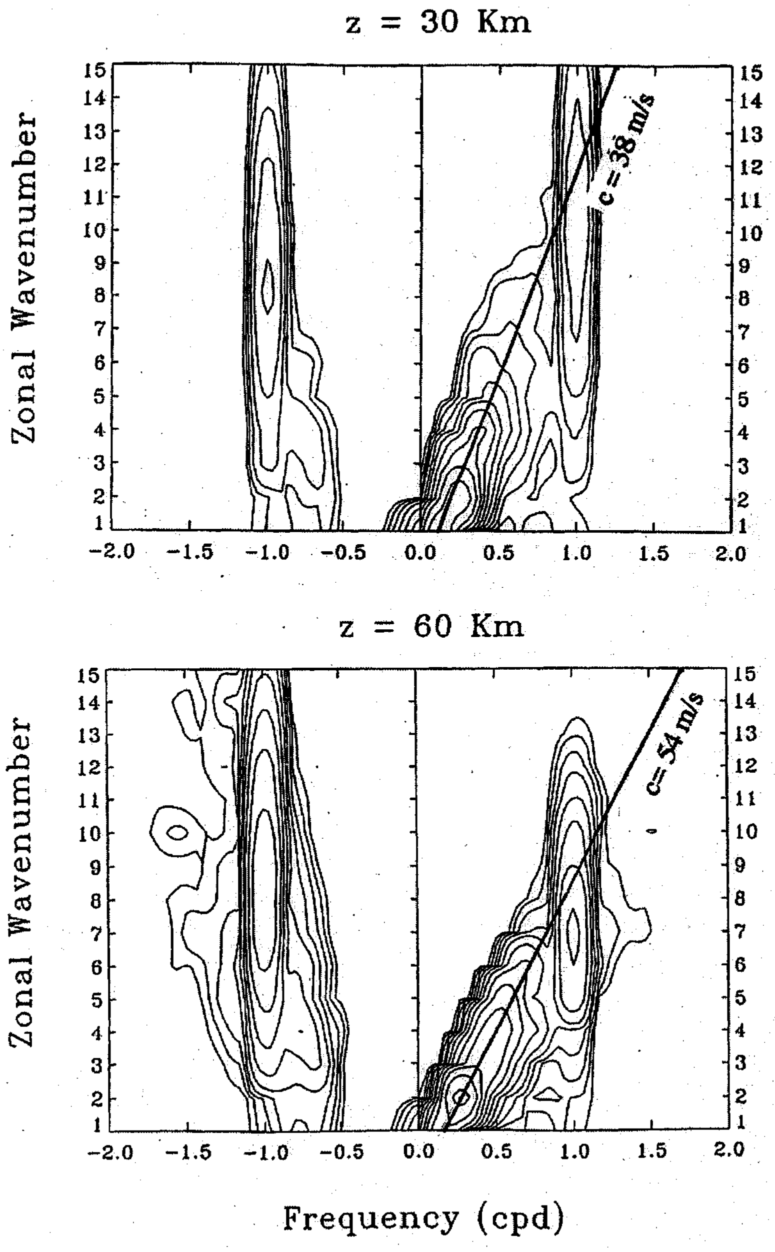
EASTWARD

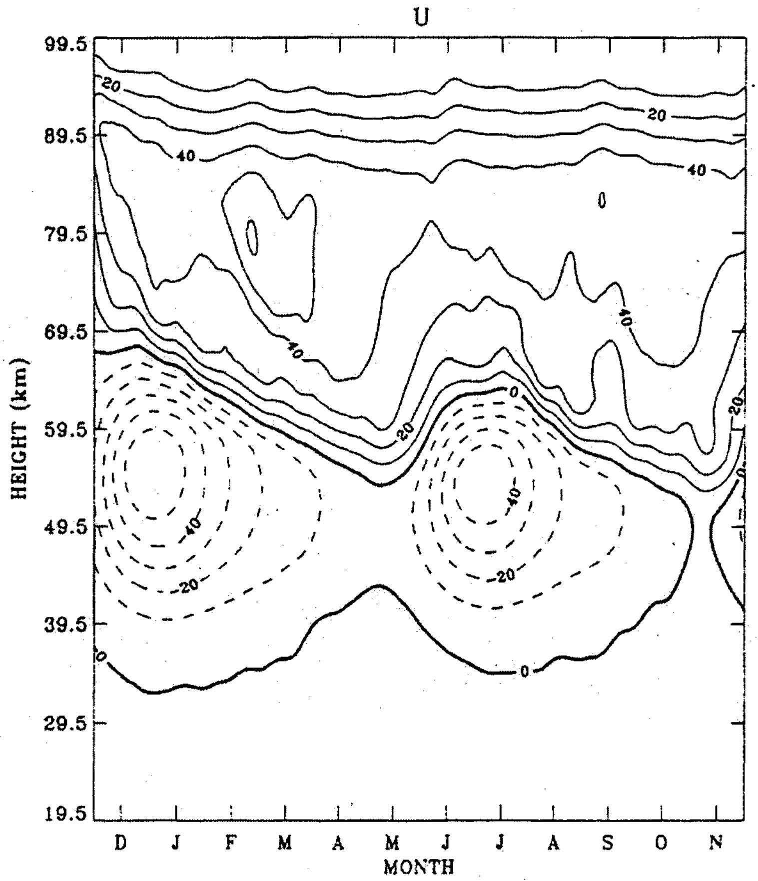
WESTWARD

Symmetric temperature amplitude at zonal wavenumber 1 for eastward (a) and westward (c) propagating waves, as a function of height and latitude (in km). Contour interval is 0.1 K. Antisymmetric meridional velocity at zonal wavenumber 1 for eastward (b) and westward (d) propagating waves; contour interval is 0.2 m s^{-1}.

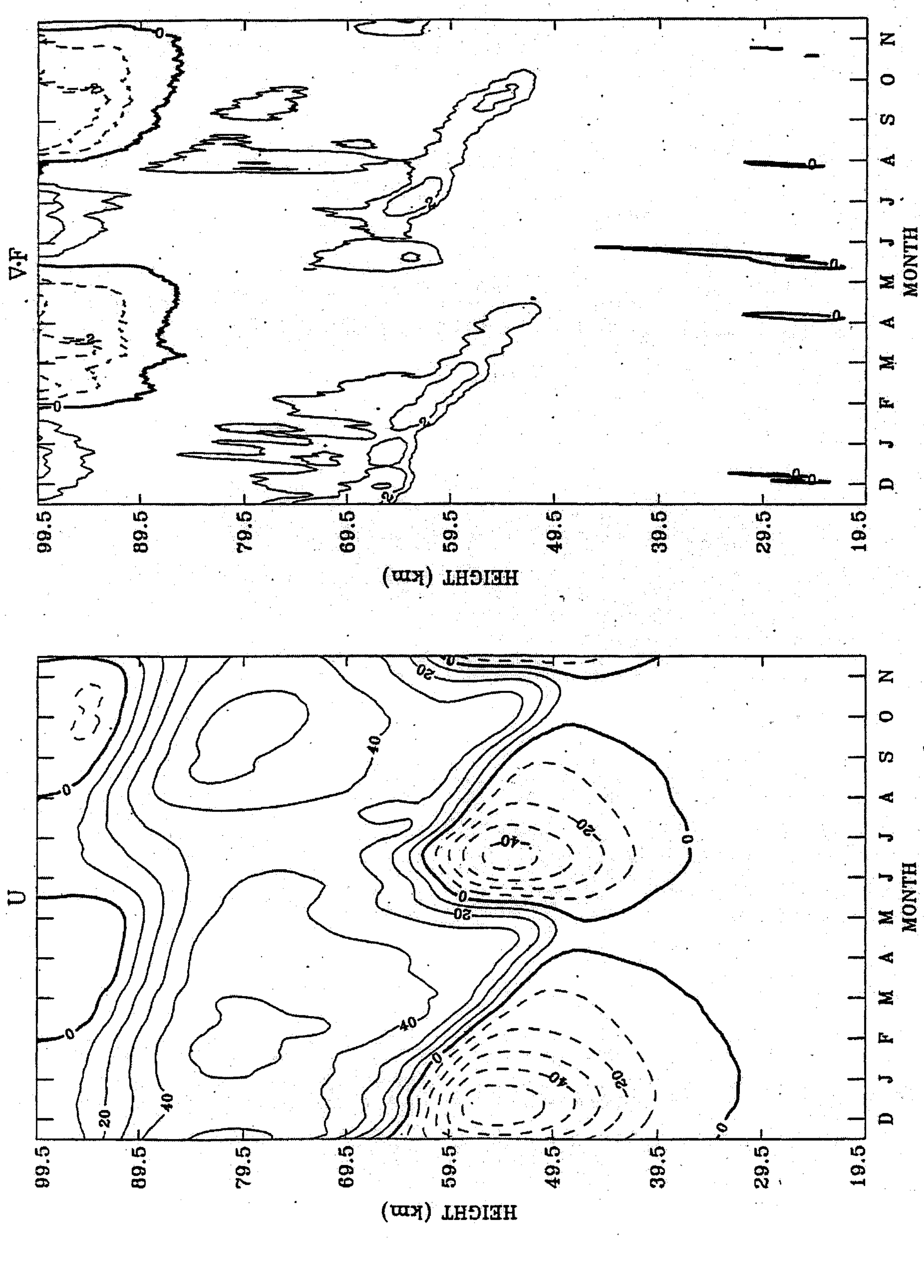


As in Fig. 8, but for zonal wavenumber 11.

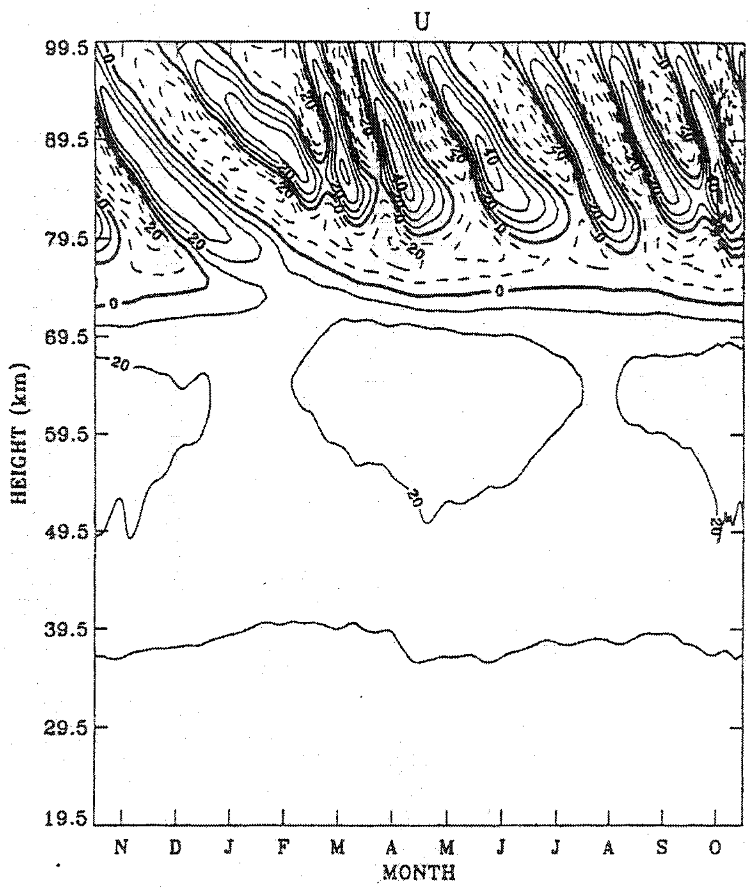

z = 30 Km
c = 38 m/s
z = 60 Km
c= 54 m/s
Zonal Wavenumber
Frequency (cpd)



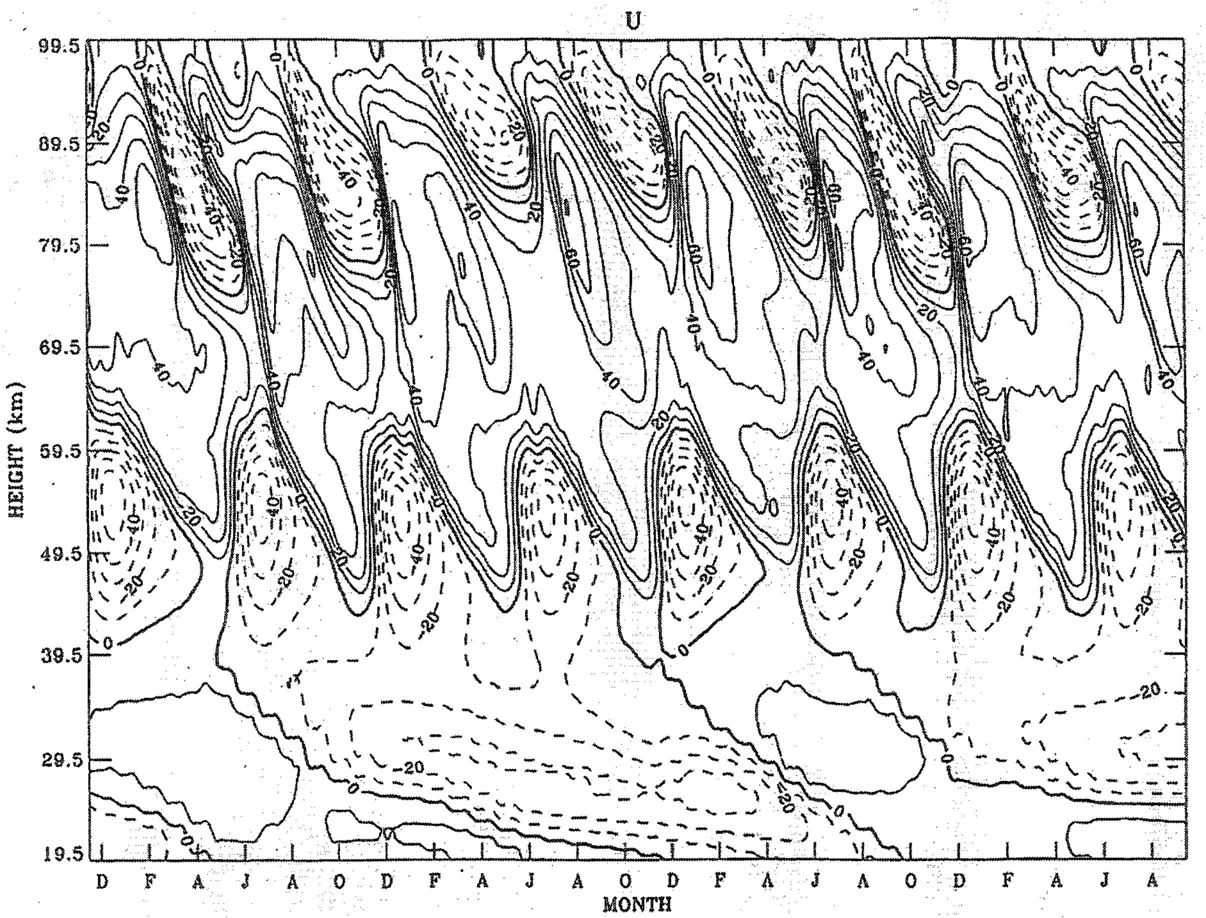
As in Fig. 2a. but for Case 2. (k= 1-3 only)



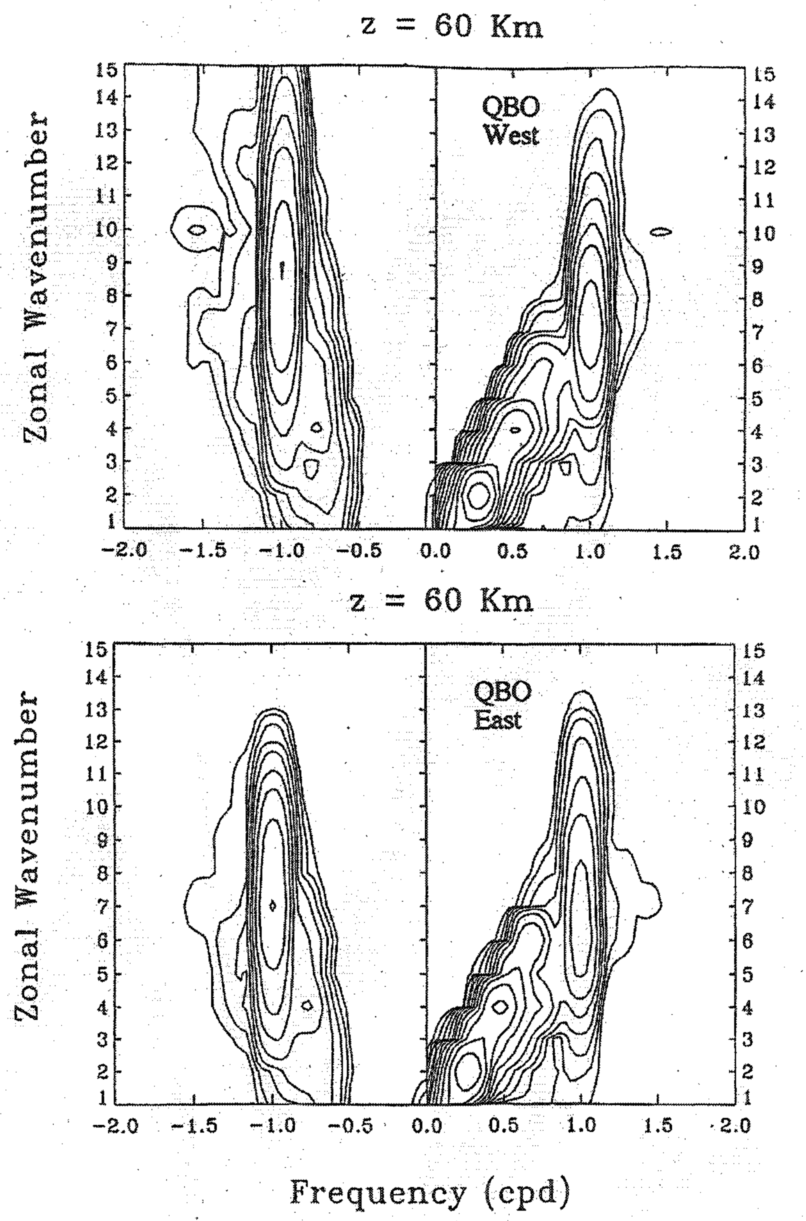
(No Diurnal Heating)



Equatorial zonal-mean zonal wind during the second year of a simulation with no seasonal cycle at the stratopause. Contour interval is 10 m s^{-1}.



YEAR 1 YEAR 2 YEAR 3 YEAR 4


z = 60 Km
QBO
West
Zonal Wavenumber
z = 60 Km
QBO
East
Zonal Wavenumber
Frequency (cpd)

5. CONCLUSIONS

- Evidence form OLR observations suggests that equatorial waves excited by convective heating may play important role in SAO

- Waves include: Planetary and intermediate-scale Kelvin waves; intermediate-scale inertia-gravity waves; $k = 1 - 20, 25$?

- Periods between ~ 5 and 1 d are impoprtant; diurnal forcing crucial for IGW

- Kelvin waves most important for westerly phase (stratopause and mesopause); forcing not limited to planetary scales

- Kelvin wave forcing produces westerly layer in mid-mesosphere (60-70 km)

- Mesopause easterly phase driven by intermediate-scale IGW of periods near diurnal

- Role of small-scale gravity waves?

- More observational evidence is needed

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