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Modeling Wave Driven Non-linear Flow Oscillations: The Terrestrial QBO, and a Solar Analog

Modeling Wave Driven Non-linear Flow Oscillations: The Terrestrial QBO, and a Solar Analog

Hans G. Mayr
in Collaboration with
John Mengel, Hayden Porter, for QBO
Richard Hartle, Charles Wolff, for Solar Analog

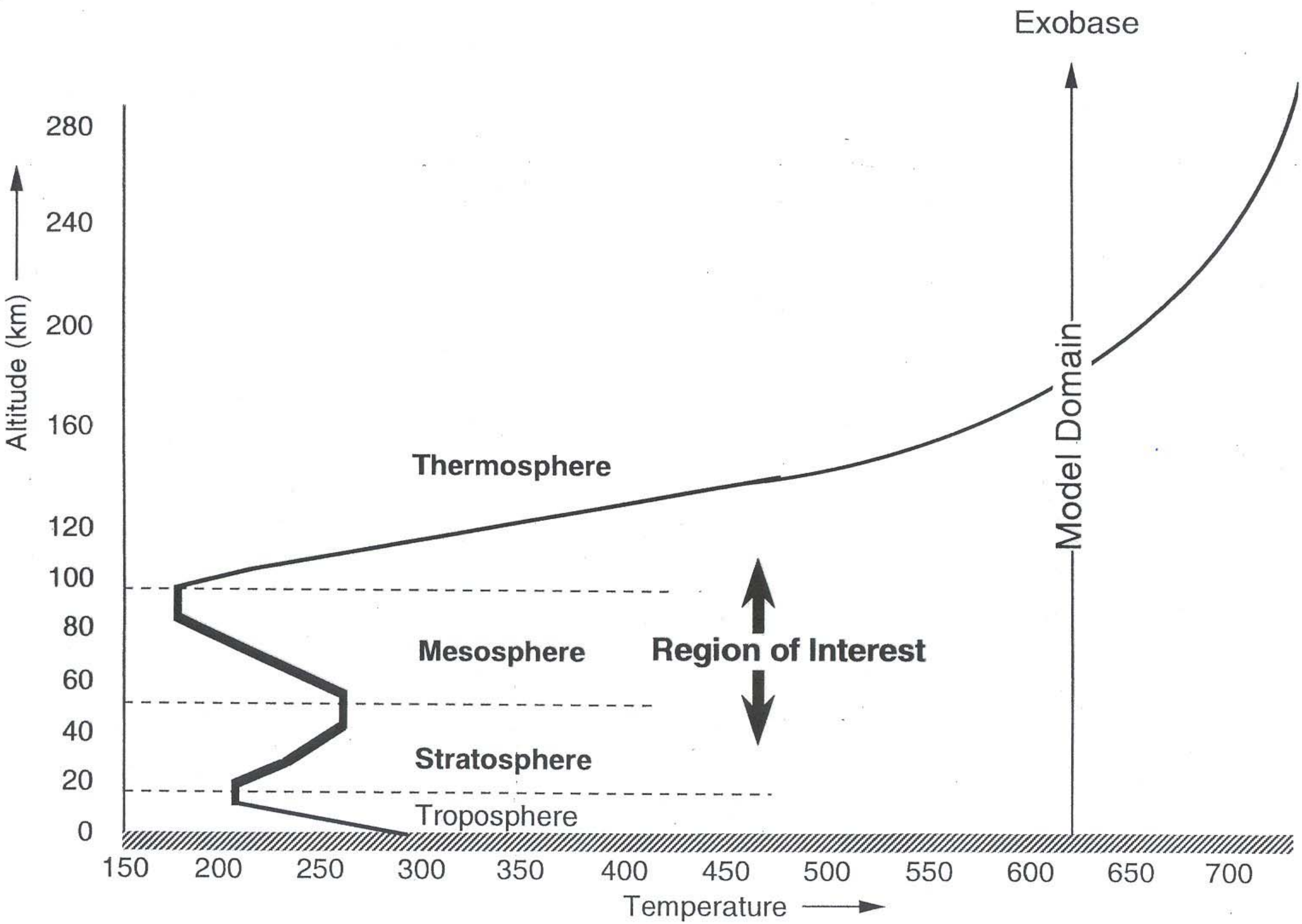
Terrestrial Quasi-Biennial Oscillation (QBO):

- Lindzen and Holton mechanism, planetary wave forcing
- Gravity wave forcing
- Our numerical model
- QBO & decadal oscillations
- Of non-linear oscillators (QBO, clock)

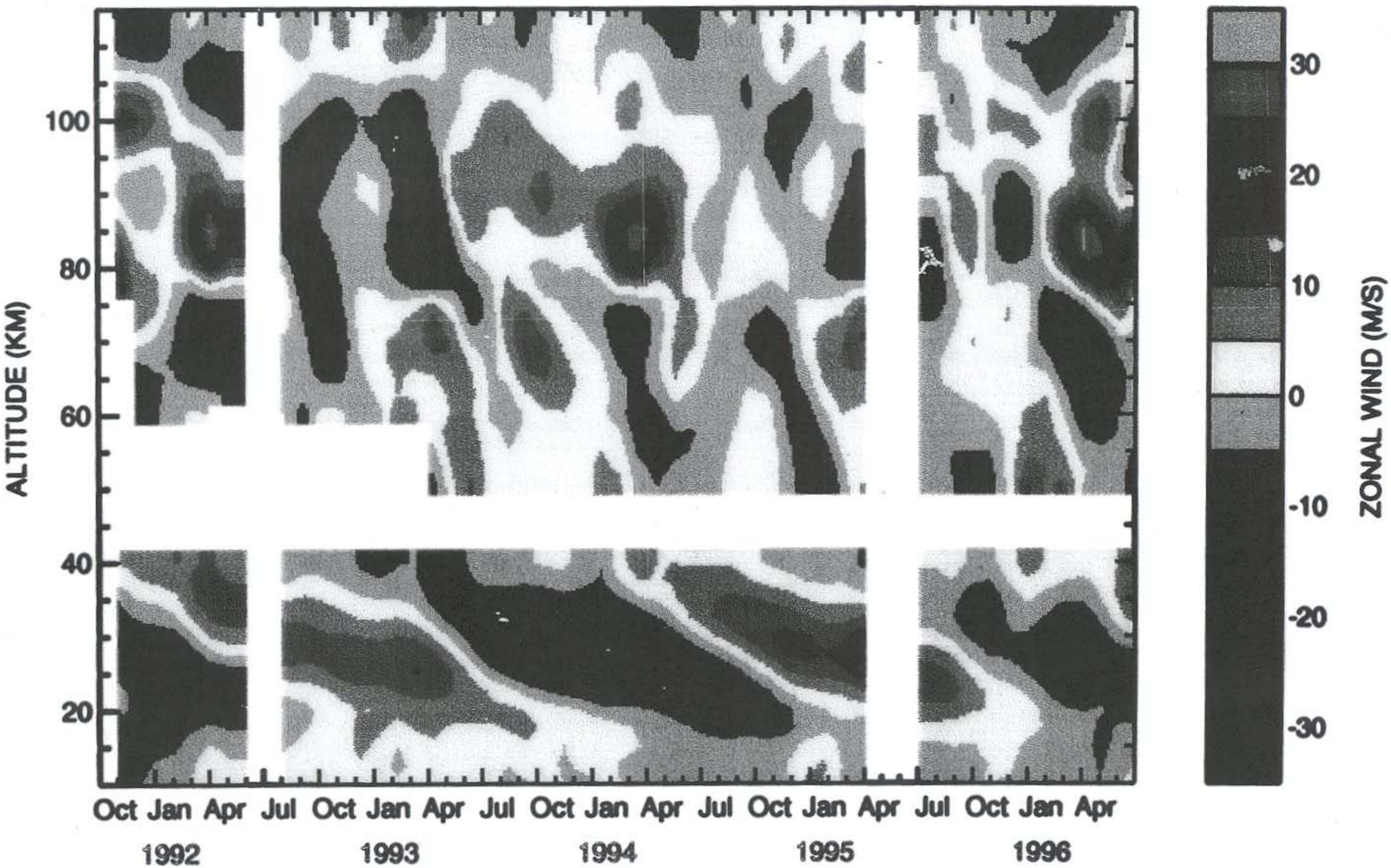
What we may learn for the Sun from the QBO mechanism:

- Analytic model extracted from terrestrial experience
- Proposed 22-year flow oscillation
- Related dynamo magnetic fields

Conclusions

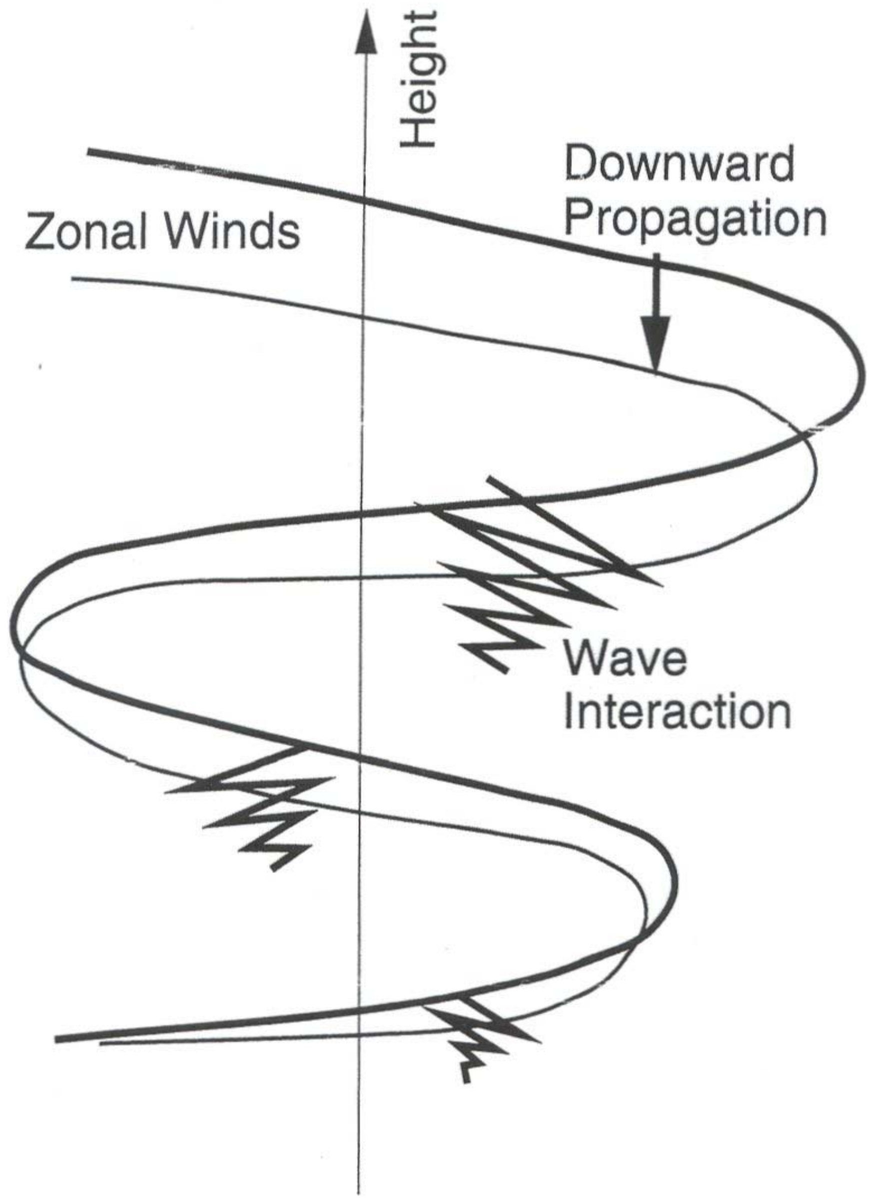

Exobase
Altitude (km)
280
240
200
160
120
100
80
60
40
20
0
Thermosphere
Mesosphere
Region of Interest
Stratosphere
Troposphere
Model Domain
150
200
250
300
350
400
450
500
550
600
650
700
Temperature

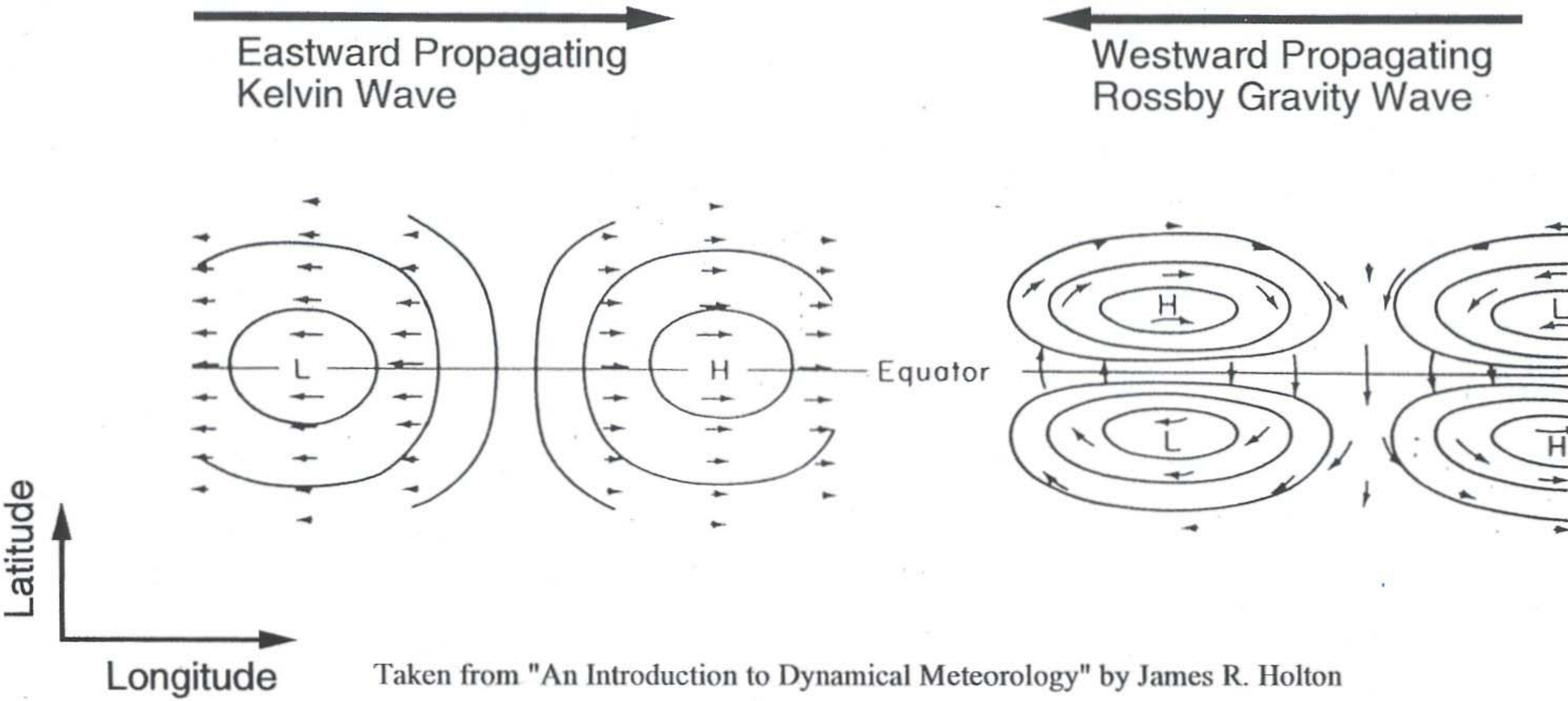
HRDI zonal winds at the equator (AO and SAO removed)



M D Burrage 3-Jul-1996

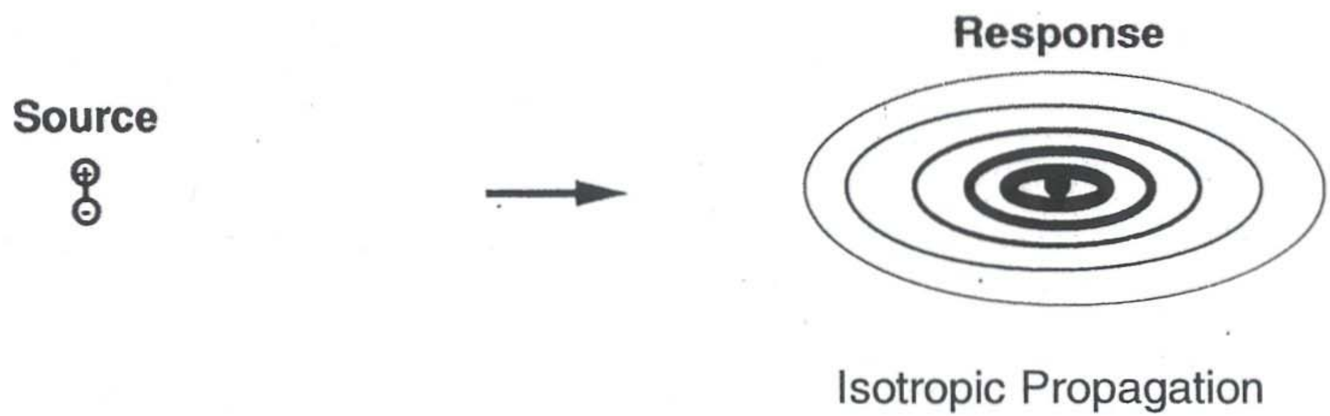
Quasi-biennial Oscillation (QBO)

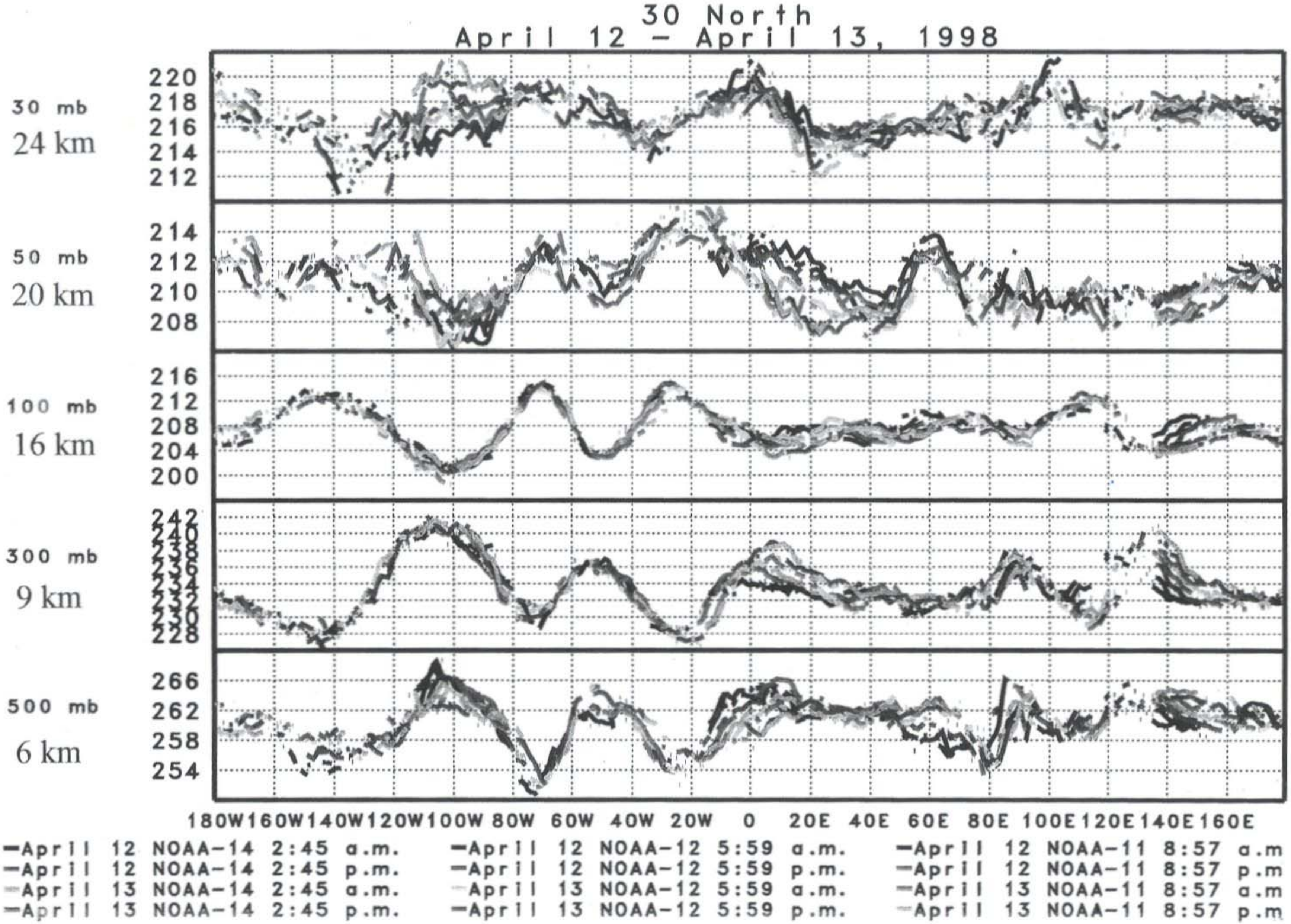




Taken from "An Introduction to Dynamical Meteorology" by James R. Holton

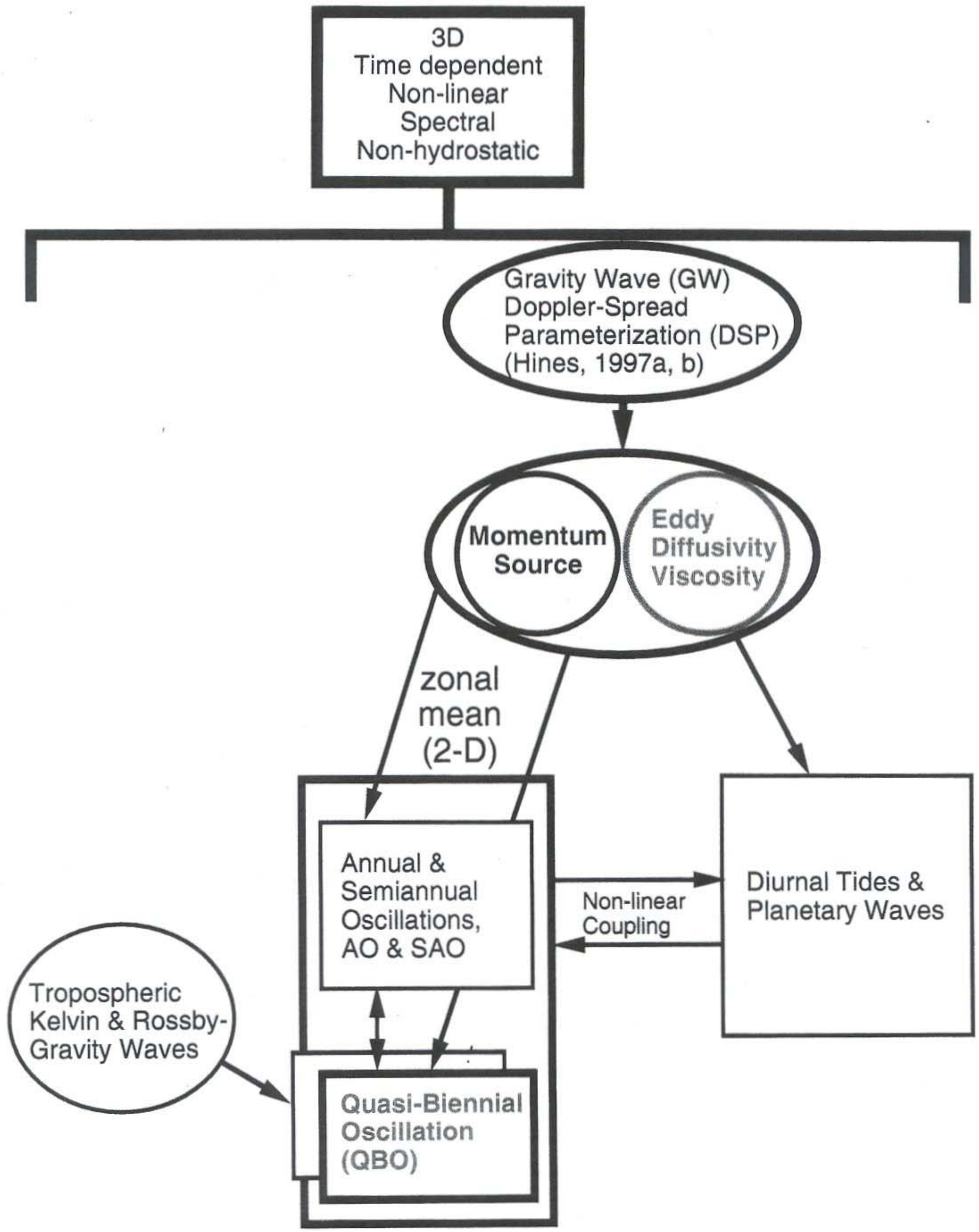
Gravity Waves



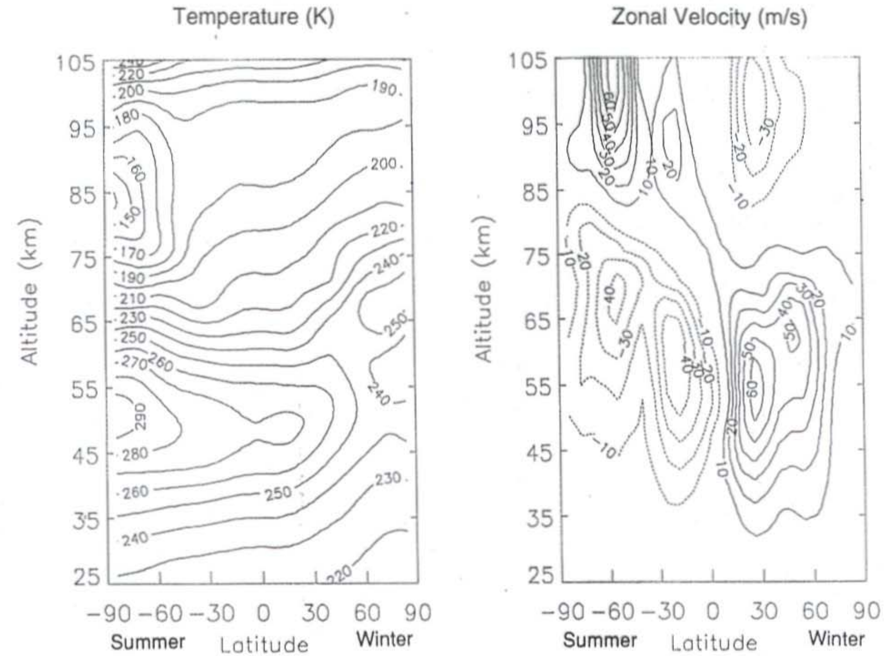


Temperature variations from NOAA satellite measurements, taken from a paper in preparation (Reddy, Susskind, Mayr).

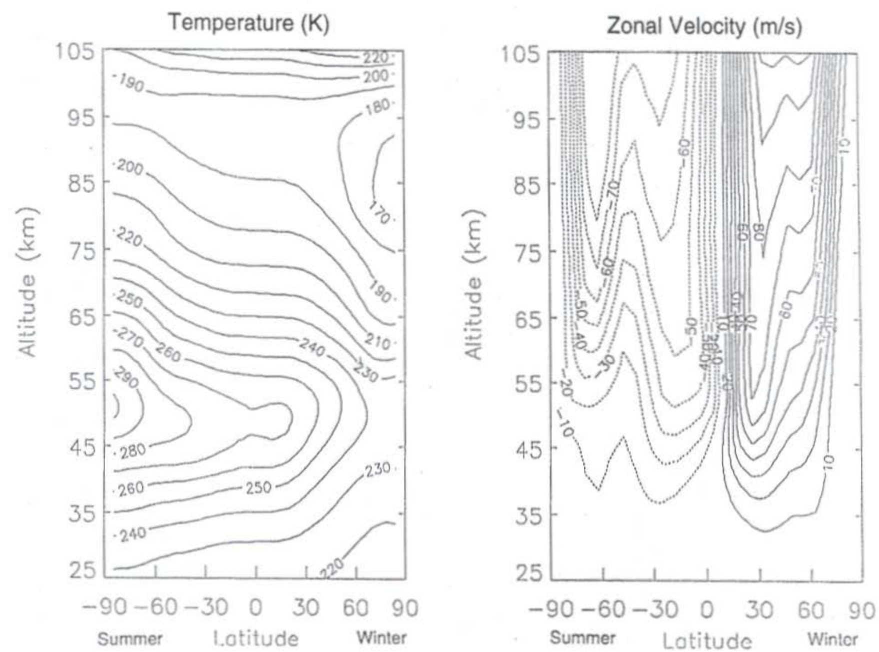
Numerical Spectral Model (NSM)

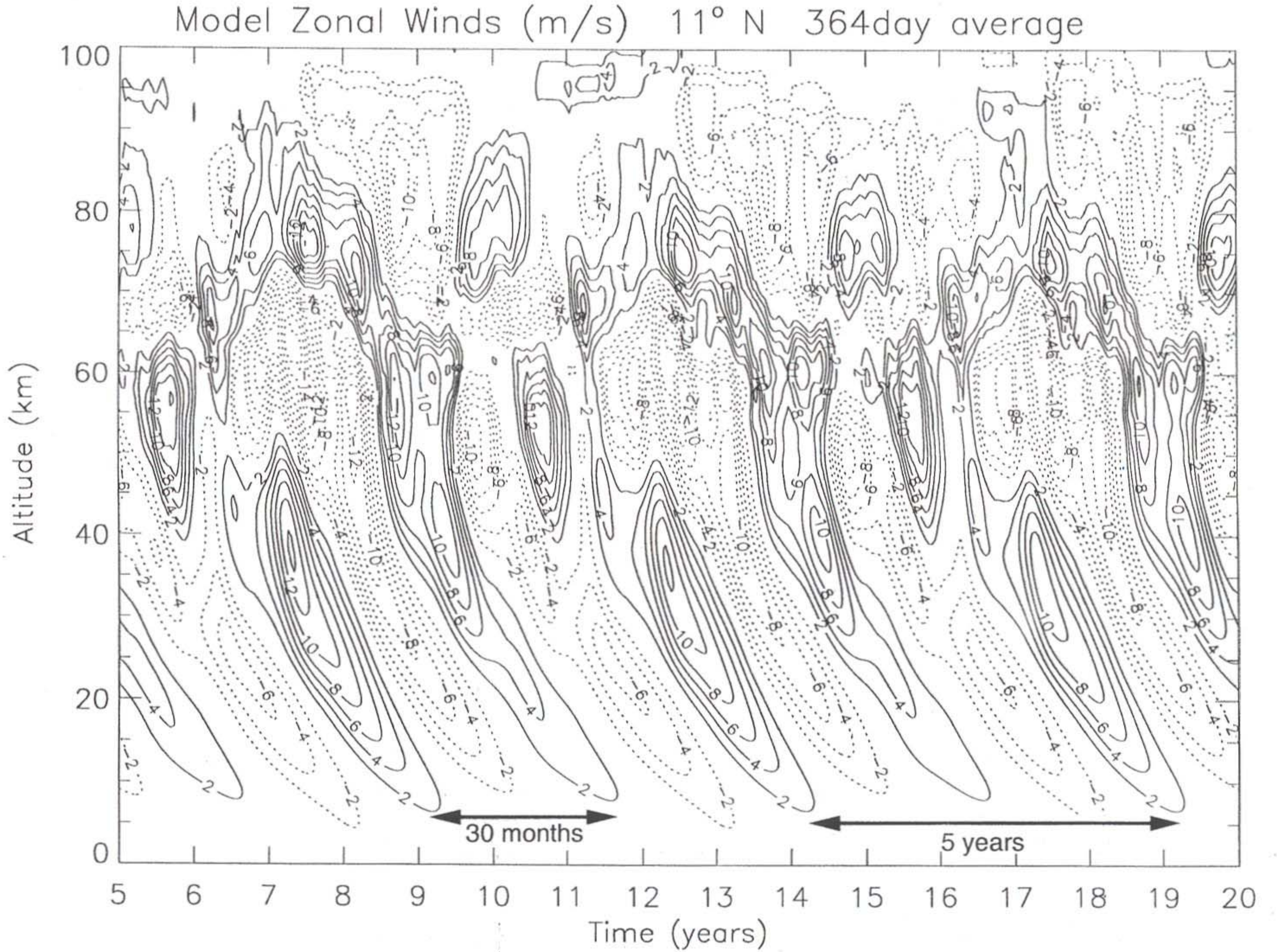


with GW Momentum Source



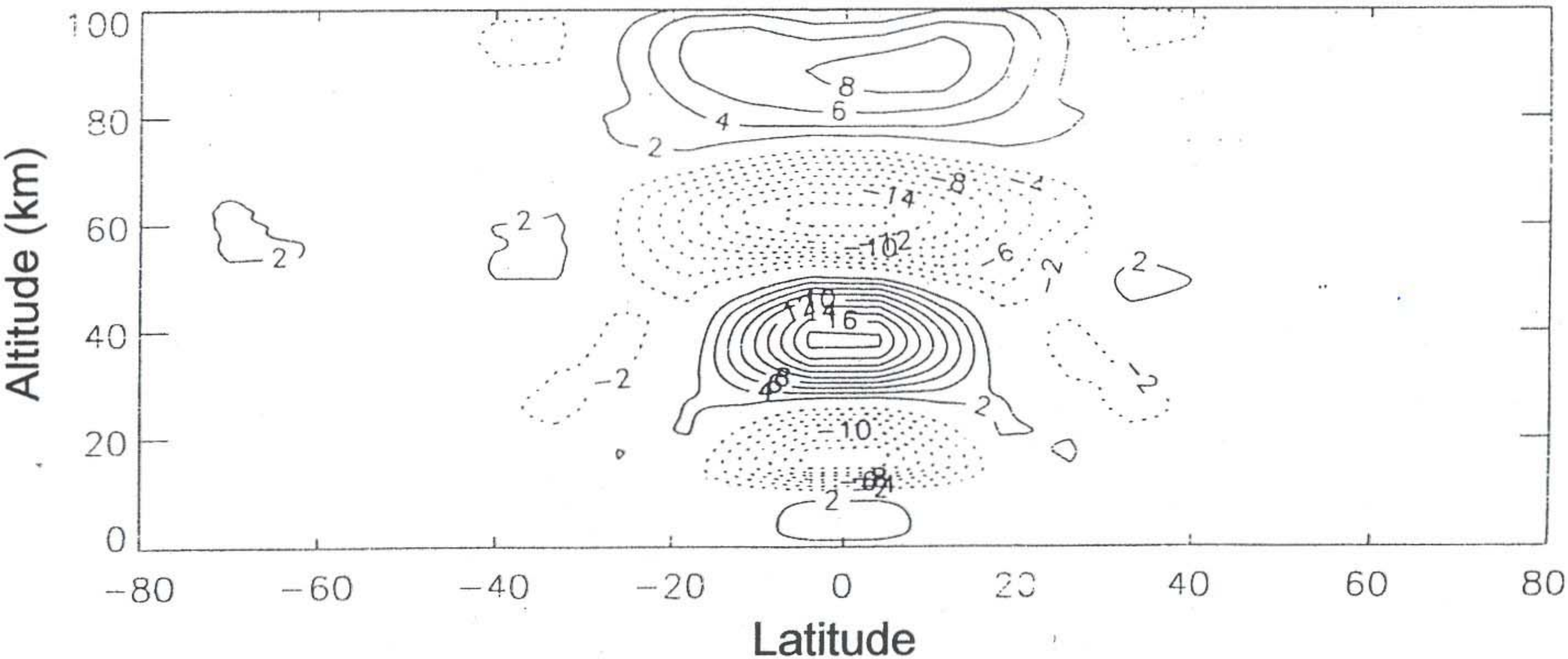
without GW Momentum Source



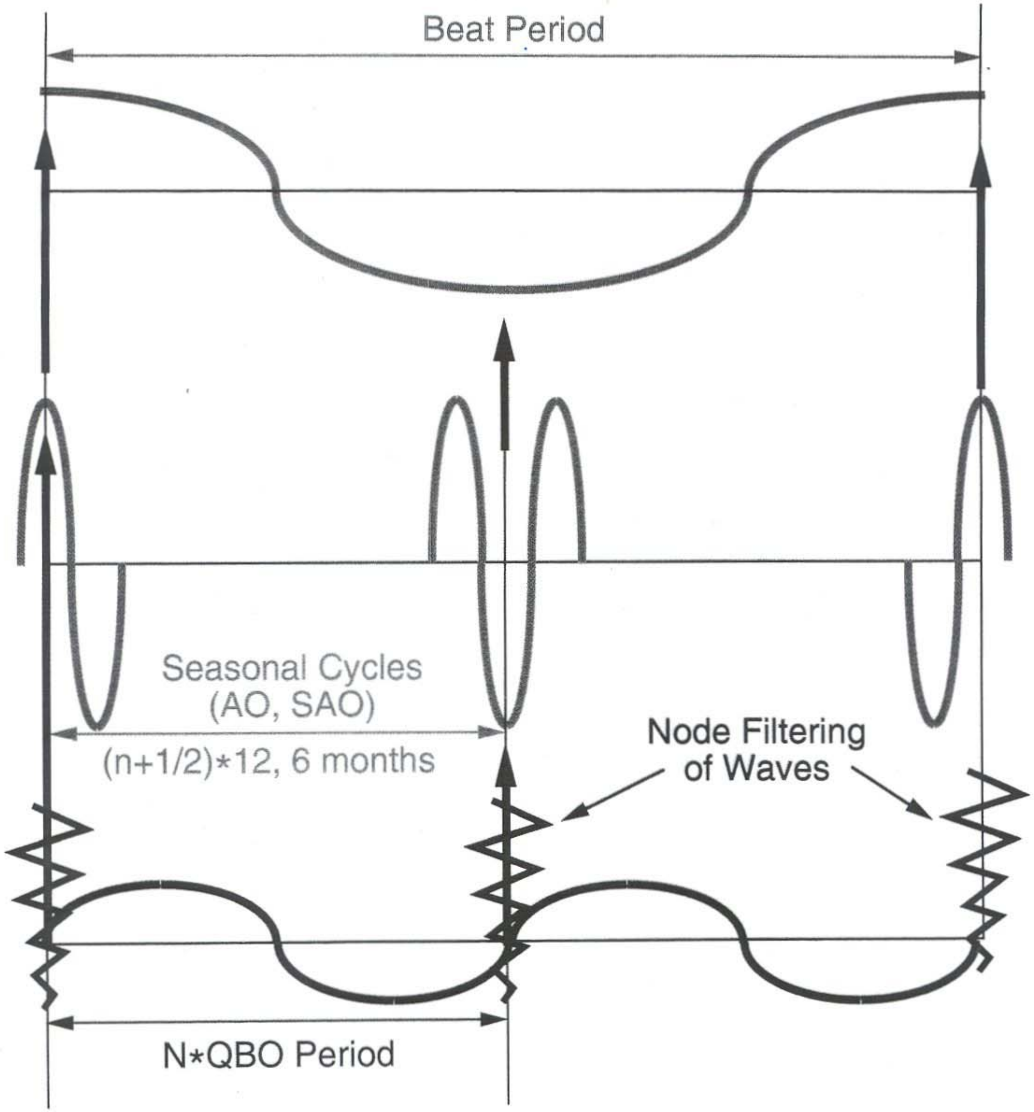


Model Zonal Winds (m/s) 11° N 364day average
Altitude (km)
Time (years)
30 months
5 years

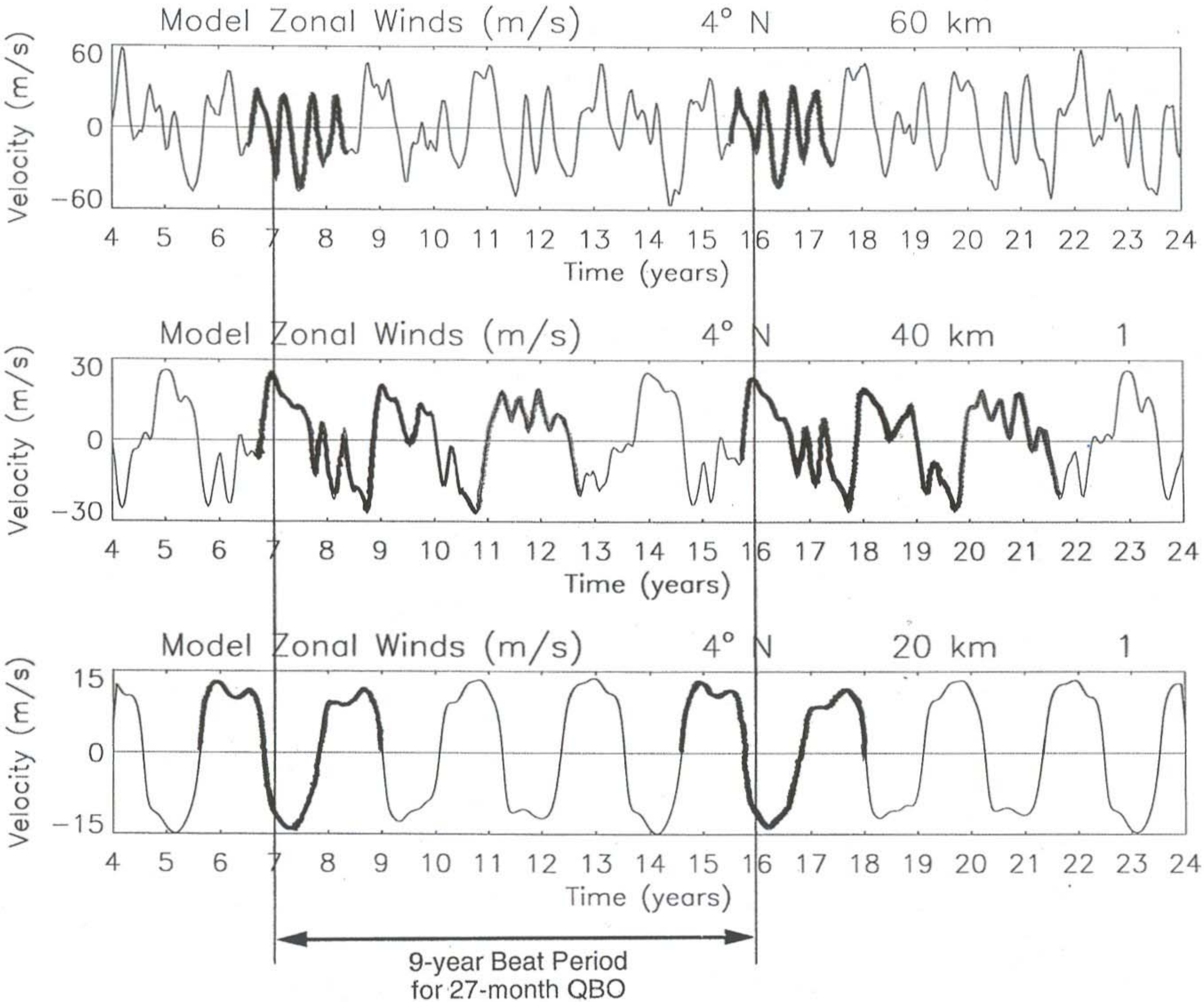
Zonal Winds (m/s) of 30 Month Period

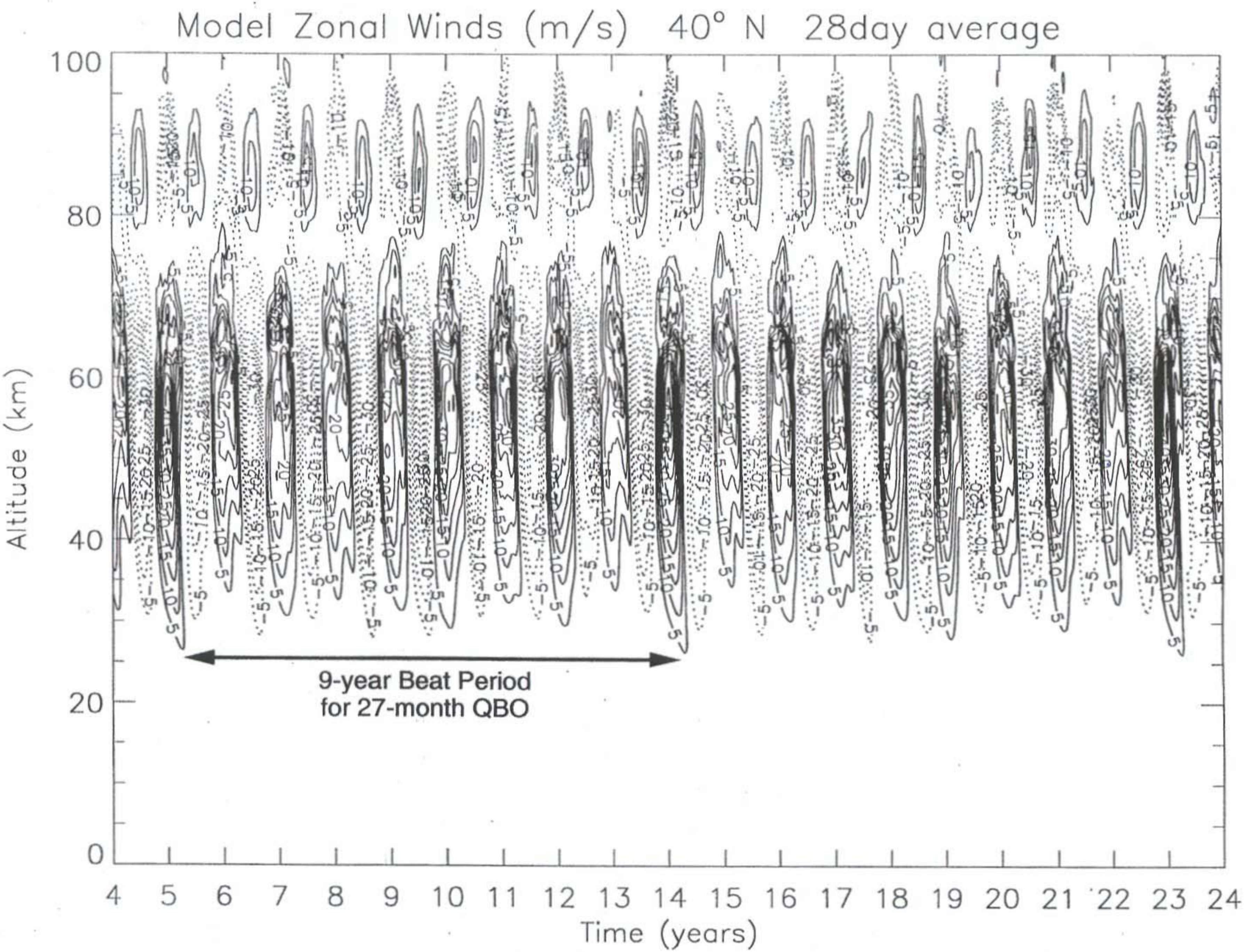


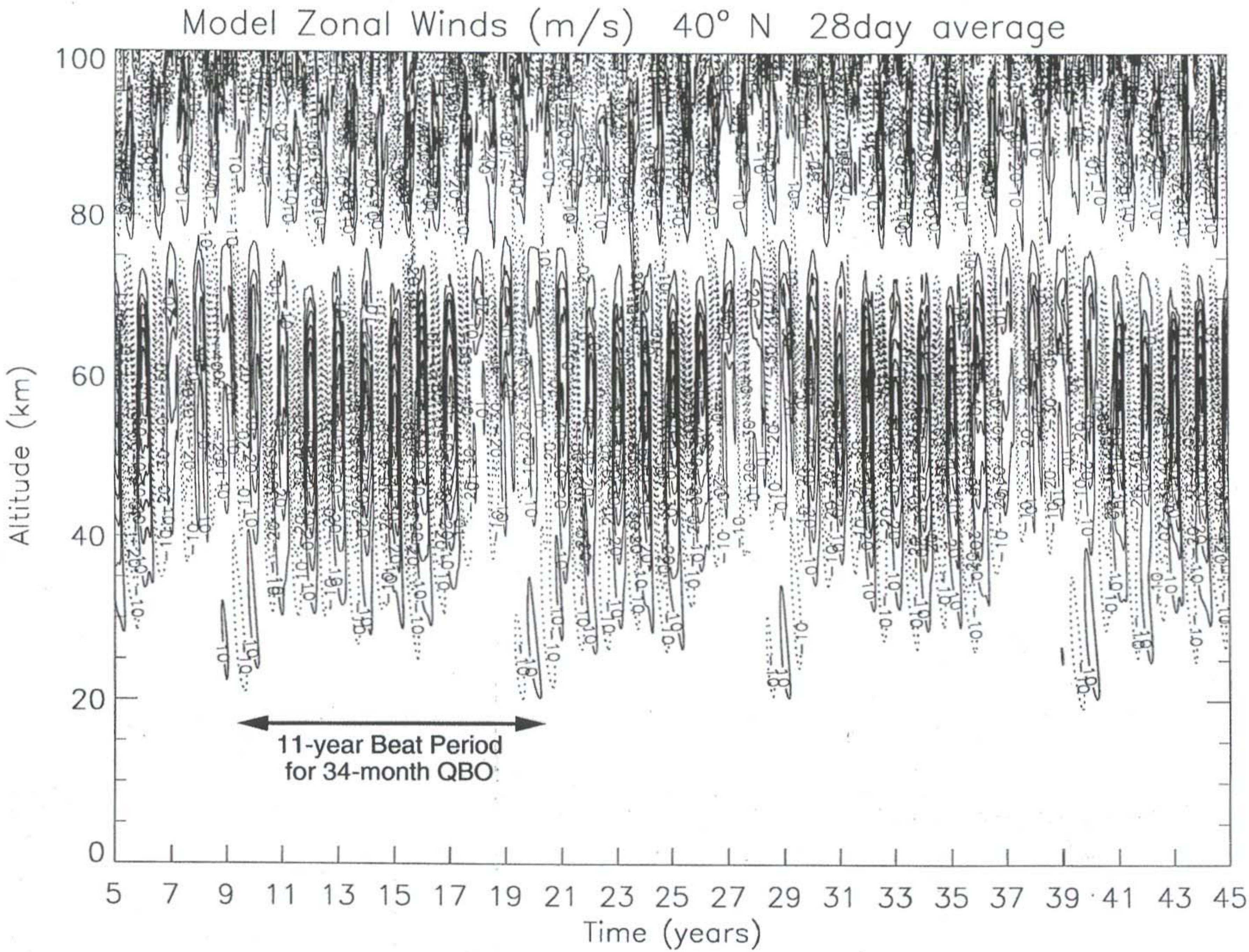
Beat Periods Between QBO and Seasonal Cycles Generated by Gravity Wave Node Filtering



QBO (30 mo) x AO --> 5-year Beat
QBO (27 mo) x AO --> 9-year Beat
QBO (34.5 mo) x SAO --> 11.5-year Beat

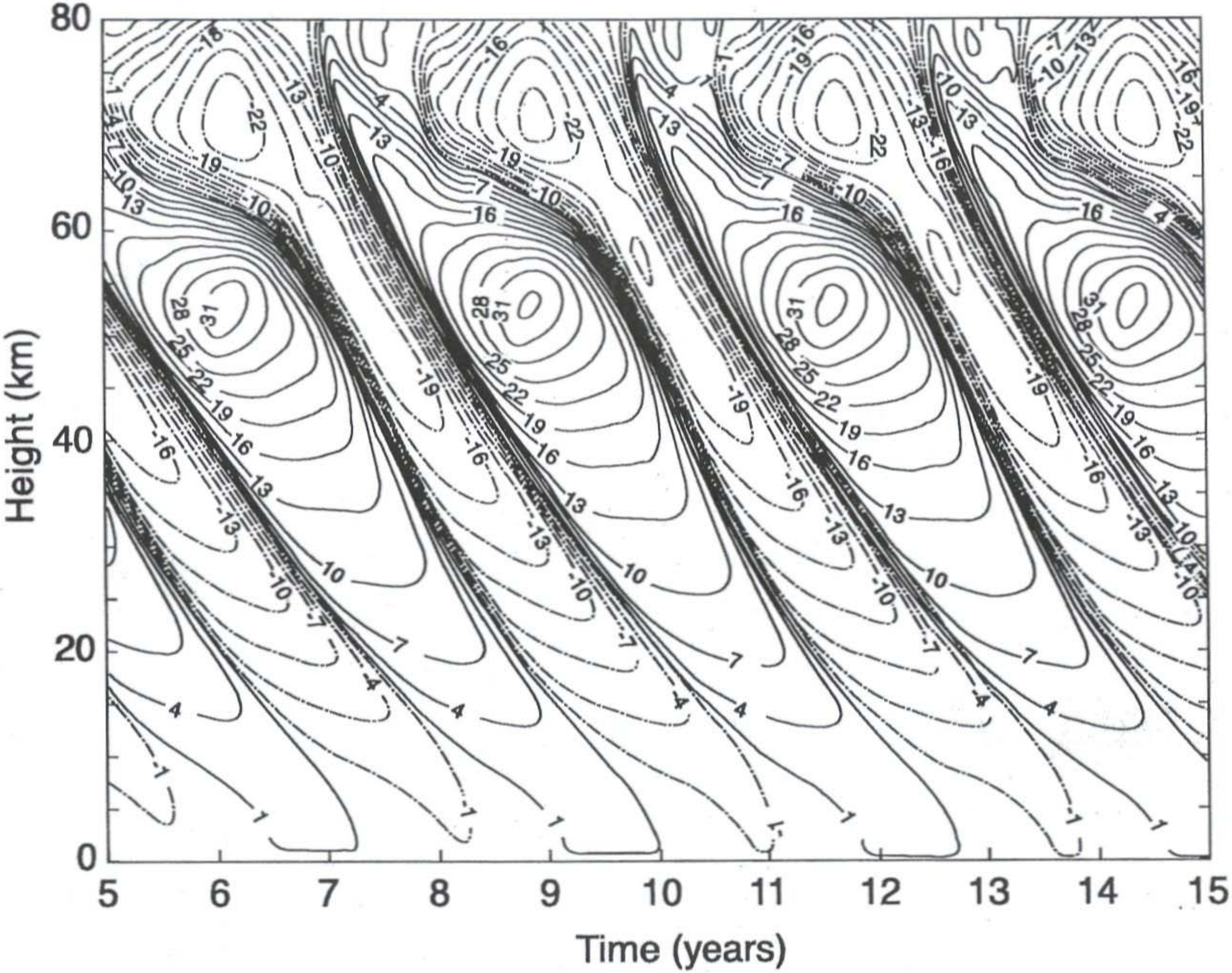

Model Zonal Winds (m/s) 4° N 60 km
Velocity (m/s)
60
0
−60
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (years)
Model Zonal Winds (m/s) 4° N 40 km 1
Velocity (m/s)
30
0
−30
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (years)
Model Zonal Winds (m/s) 4° N 20 km 1
Velocity (m/s)
15
0
−15
4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (years)
9-year Beat Period
for 27-month QBO


Model Zonal Winds (m/s) 40° N 28day average
Altitude (km)
Time (years)
9-year Beat Period
for 27-month QBO

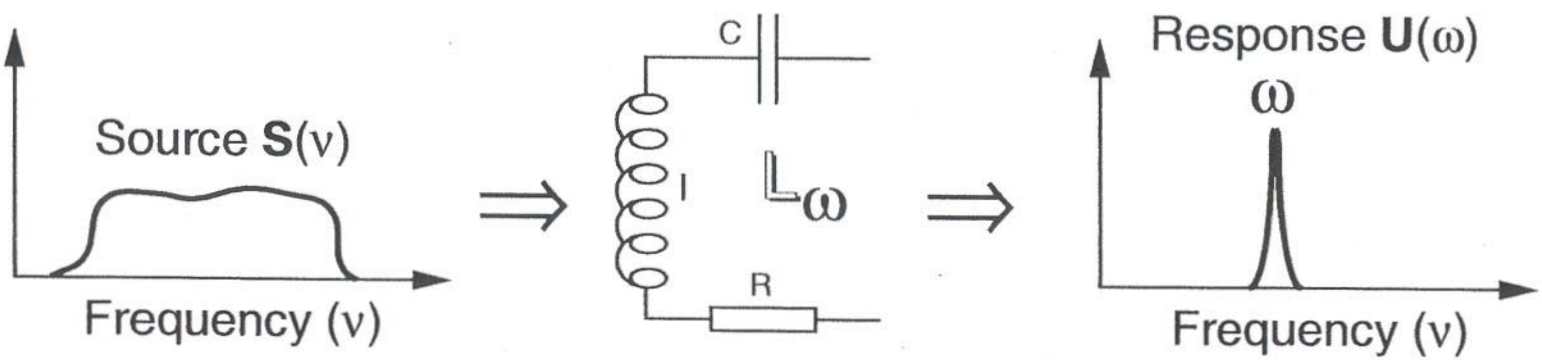


Model Zonal Winds (m/s) 40° N 28day average
Altitude (km)
Time (years)
11-year Beat Period
for 34-month QBO

Perpetual Equinox
Zonal Winds



Linear Oscillators (e.g., circuit, waves):

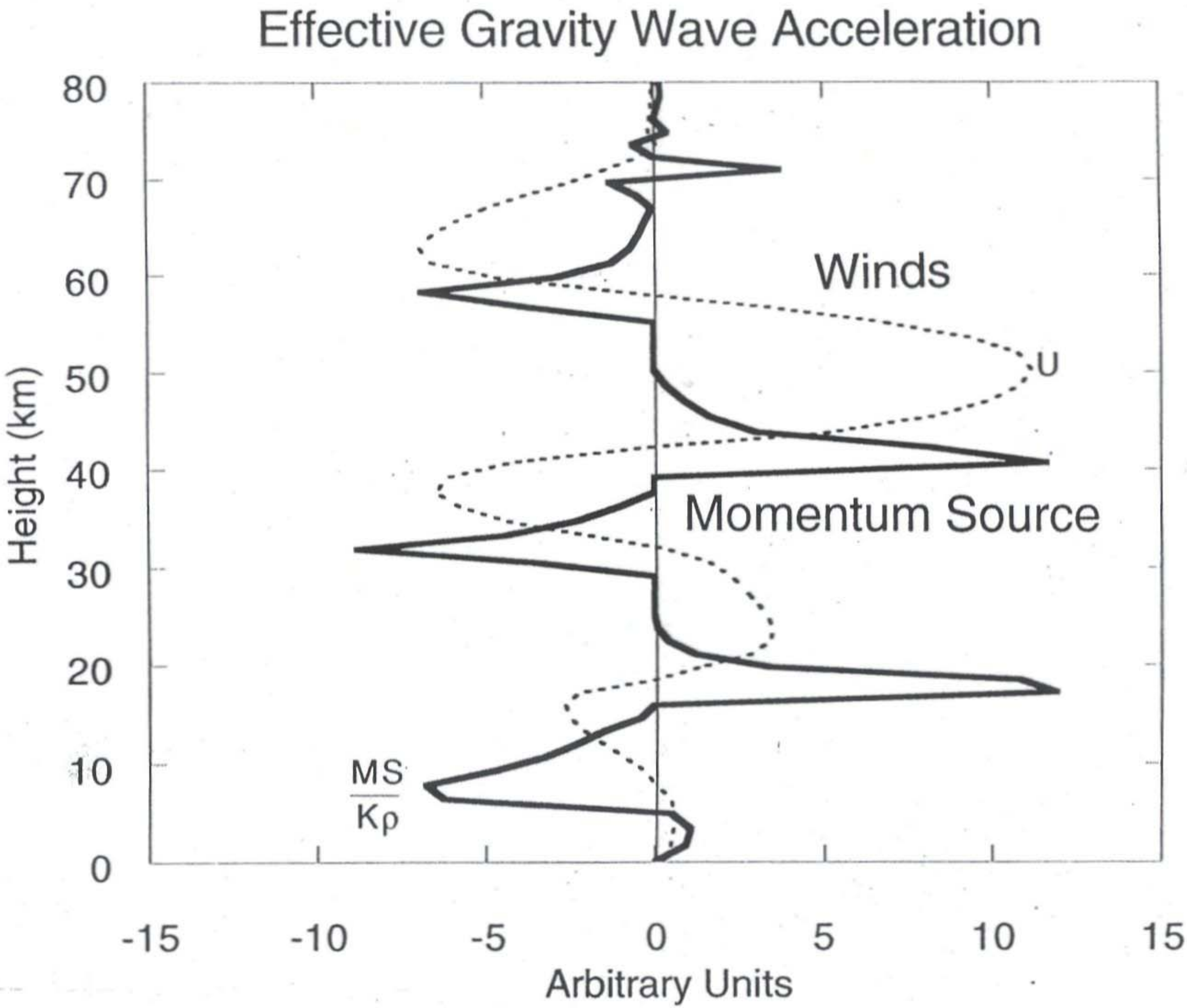


$$\mathbb{L}_{\omega} \times \mathbf{U}(\omega) = \mathbf{S}(\nu)$$

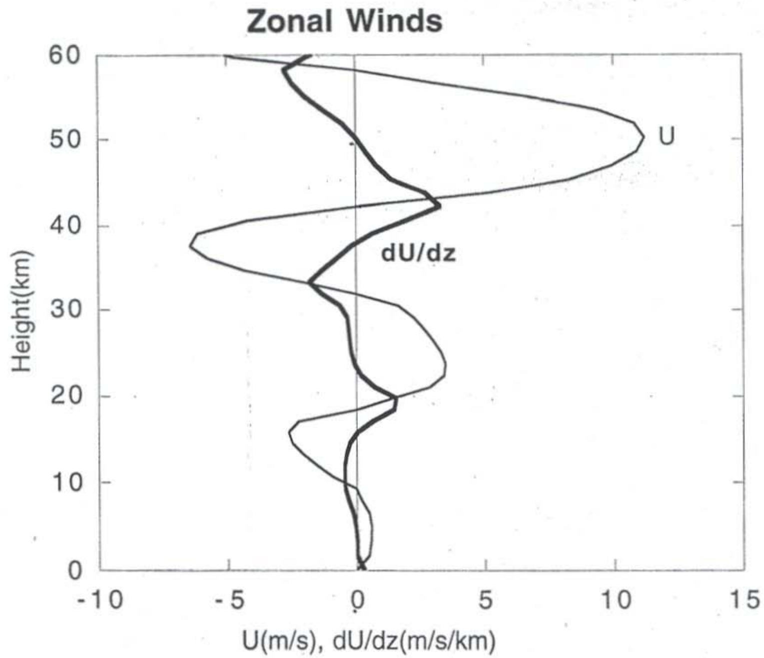
Non-linear Oscillators (e.g., QBO, clock):

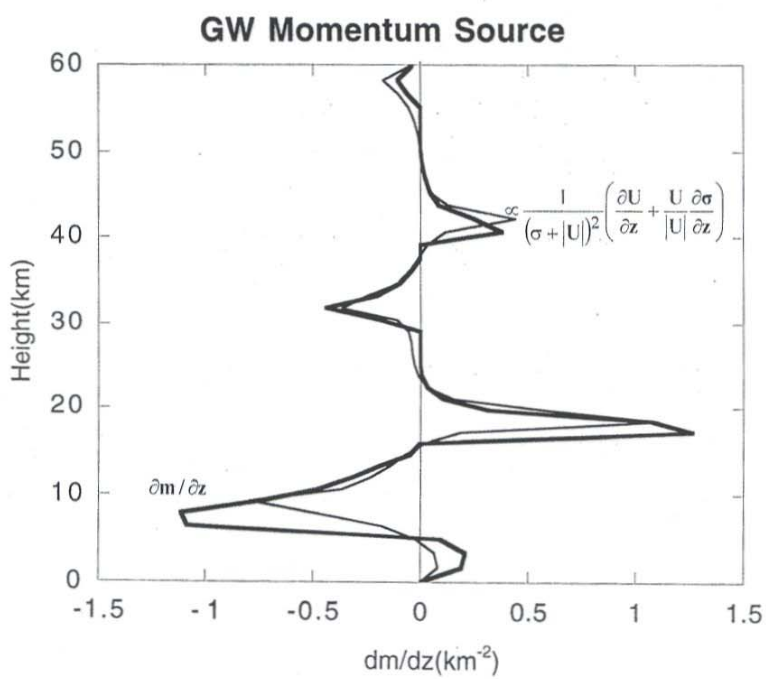
$$\mathbb{N}_{\omega} \times \mathbf{U}(\omega) = \mathbf{S}(\mathbf{U}(\omega)) \propto \mathbf{U}(\omega)^{3}$$

$$\Rightarrow \mathbf{U}(\omega) = \mathbf{U}_{1}(\omega) + \mathbf{U}_{3}(3\omega)$$



Effective Gravity Wave Acceleration
Height (km)
80
70
60
50
40
30
20
10
0
-15
-10
-5
0
5
10
15
Arbitrary Units
Winds
U
Momentum Source
MS
Kρ


Zonal Winds
U
dU/dz
Height(km)
U(m/s), dU/dz(m/s/km)
0
10
20
30
40
50
60
-10
-5
0
5
10
15


GW Momentum Source
$\propto \frac{1}{(\sigma+|U|)^2}\left(\frac{\partial U}{\partial z}+\frac{U}{|U|}\frac{\partial \sigma}{\partial z}\right)$
$\partial m/\partial z$
Height(km)
dm/dz(km^{-2})
0
10
20
30
40
50
60
-1.5
-1
-0.5
0
0.5
1
1.5

Conclusions

<u>Terrestrial Quasi-Biennial Oscillation (QBO):</u>

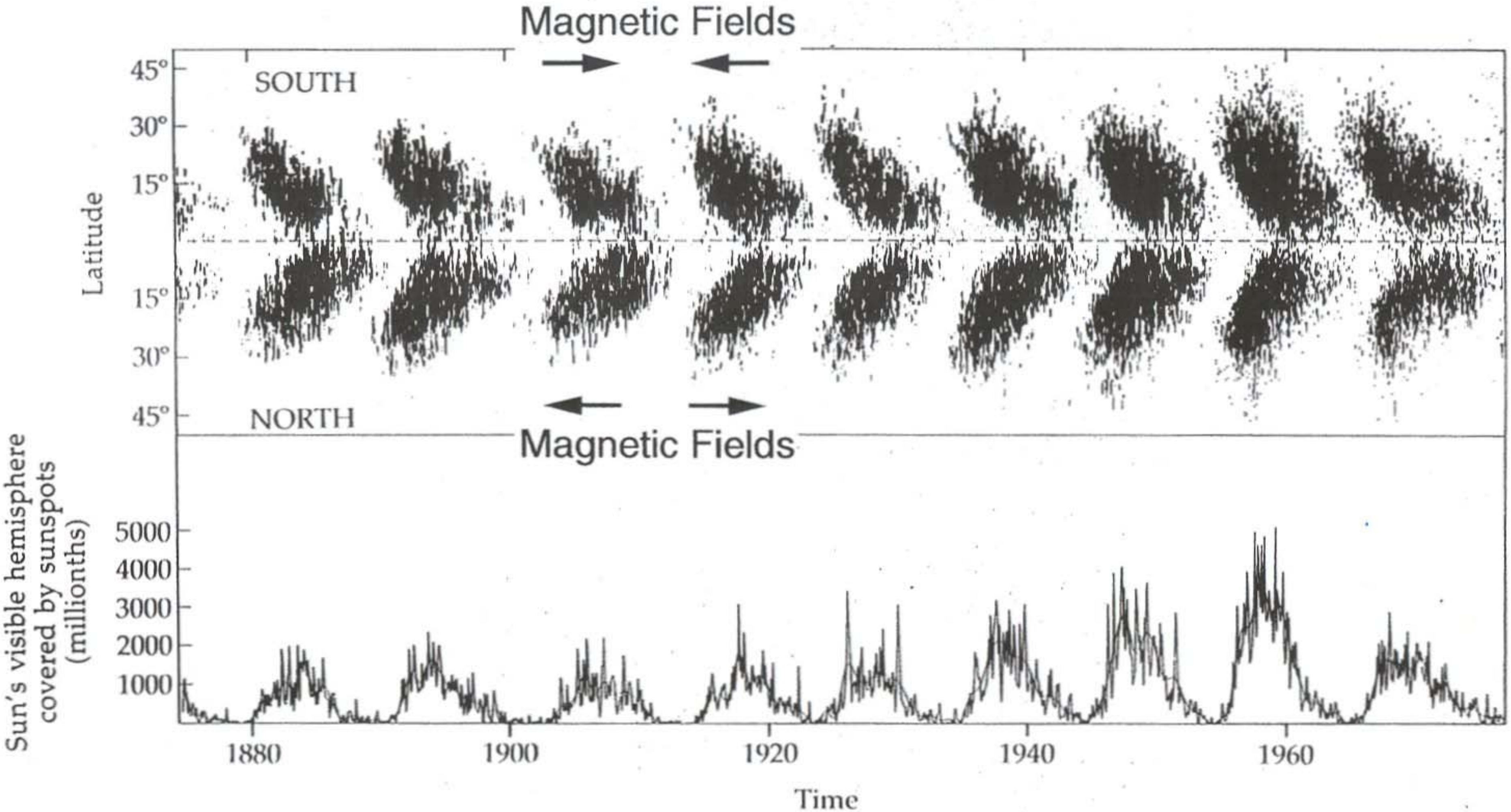
1) At low latitudes, generated by globally uniform wave source.

2) Extends into the upper mesosphere.

3) Interaction with seasonal cycles generates periods around 10 years.

4) Wave driven non-linear flow oscillation -- a fluid chronometer.

A Solar Analog for the QBO?



Solar Activity Cycle = 11 years

Solar Magnetic Cycle = 22 years
the cause of sunspot activity

Chiueh, T., in the *Astrophysical Journal*, 2000, asks:

"why the solar dynamo should appear periodic, what makes the polarity of magnetic fields change in a half cycle, and why a new half cycle always starts below the 40° latitude?"

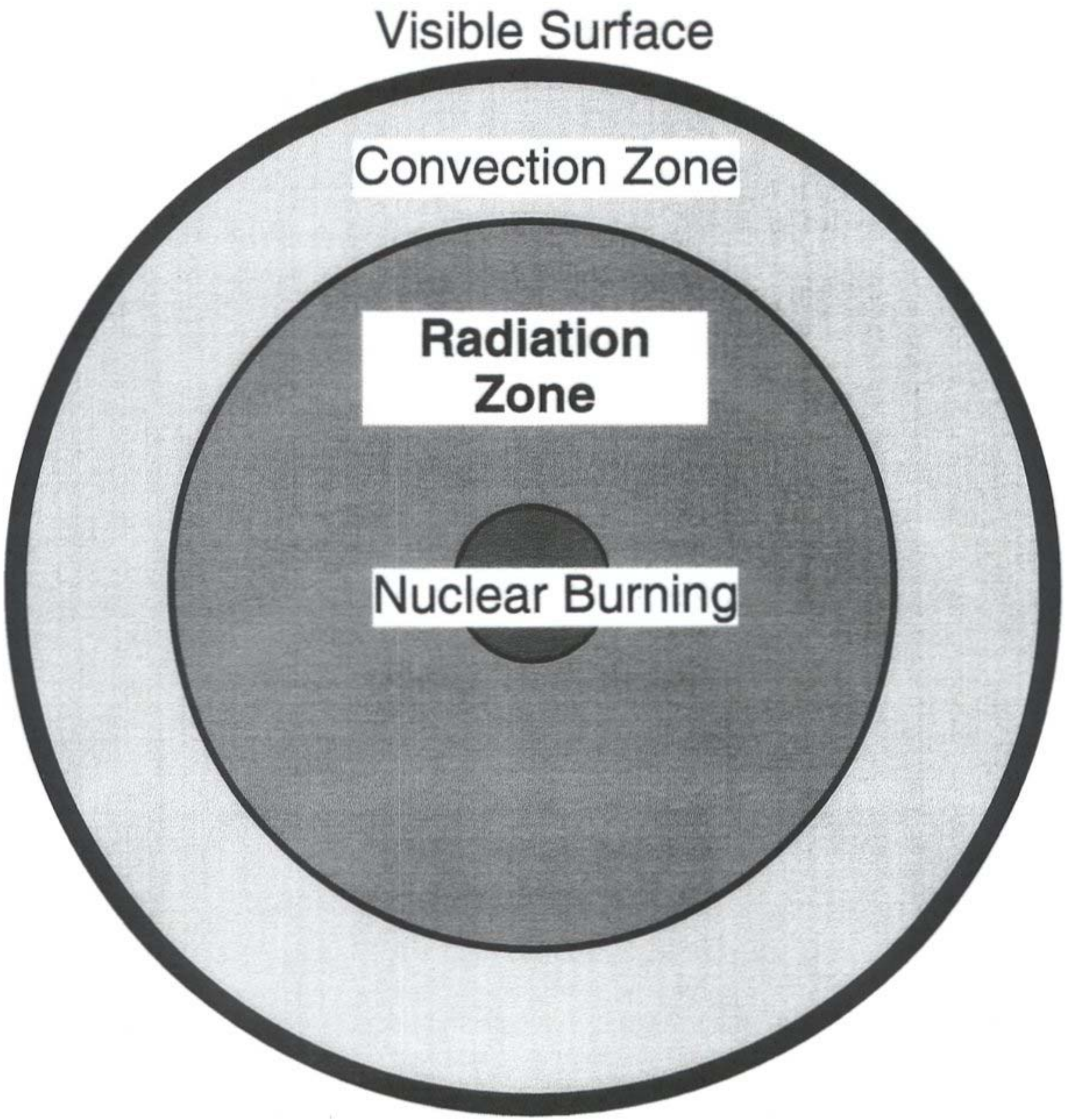
Is there a chronometer hidden deep in the Sun?

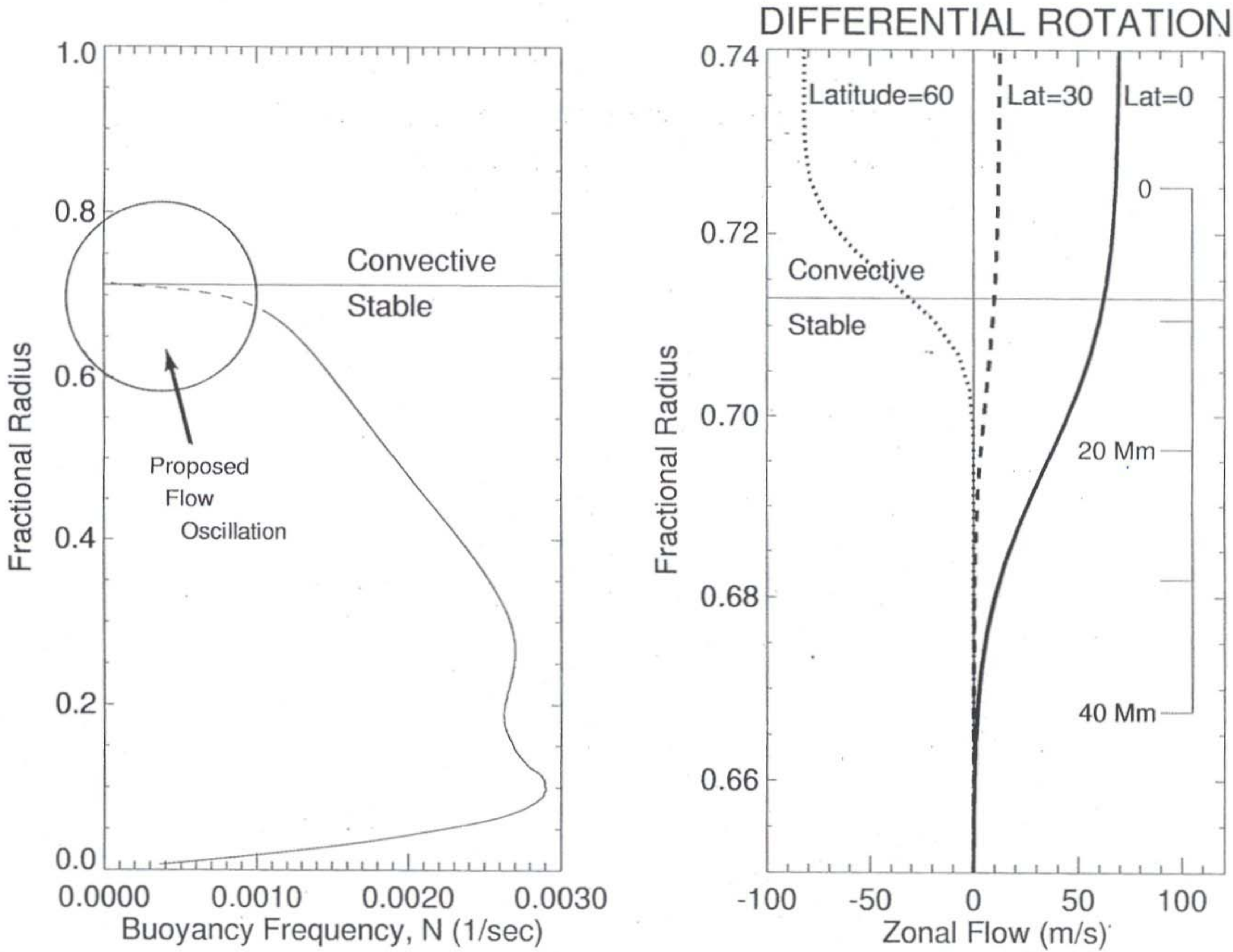
R. H. Dicke (*Nature*, 1978)

Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, New Jersey 08540

No support is found for the conventional view of the sunspot cycle, that there exists a large random walk in the phase of the cycle. Instead, both sunspots and the [D/H] solar/terrestrial weather indicator seem to be paced by an accurate clock inside the Sun.

Solar Structure





1.0
0.8
0.6
0.4
0.2
0.0
Fractional Radius
Convective
Stable
Proposed
Flow
Oscillation
0.0000
0.0010
0.0020
0.0030
Buoyancy Frequency, N (1/sec)
DIFFERENTIAL ROTATION
0.74
0.72
0.70
0.68
0.66
Fractional Radius
Latitude=60
Lat=30
Lat=0
Convective
Stable
0
20 Mm
40 Mm
-100
-50
0
50
100
Zonal Flow (m/s)

Analytic Model

Zonal momentum balance at the equator:

$$\rho\frac{\partial \mathbf{U}}{\partial \mathbf{t}}-\frac{\partial}{\partial \mathbf{z}}\rho\mathbf{K}\frac{\partial \mathbf{U}}{\partial \mathbf{z}}=\rho\left[\frac{\Phi^2\sigma_h{}^4}{2\lambda_h\mathbf{N}\left(\Phi\sigma_h+|\mathbf{U}|\right)^2}\right]\left(\frac{\partial \mathbf{U}}{\partial \mathbf{z}}+\frac{\mathbf{U}\Phi}{|\mathbf{U}|}\frac{\partial\sigma_h}{\partial \mathbf{z}}\right)$$

U, zonal wind velocity;
N, buoyancy frequency;
$0.95 < \Phi = 1.3 < 1.74$ GW parameter;
$\sigma_h \propto \approx \rho^{-1/3}$, GW horizontal wind amplitude; ρ, density;
λ_h, characteristic horizontal wave length of GW's;
K, the vertical eddy diffusivity provided by the DSP.

For $\mathbf{U} = \mathbf{U}_o \exp\left(i\, 2\pi\left(\frac{\mathbf{t}}{\tau}+\frac{\mathbf{z}}{\lambda_O}\right)\right)$;

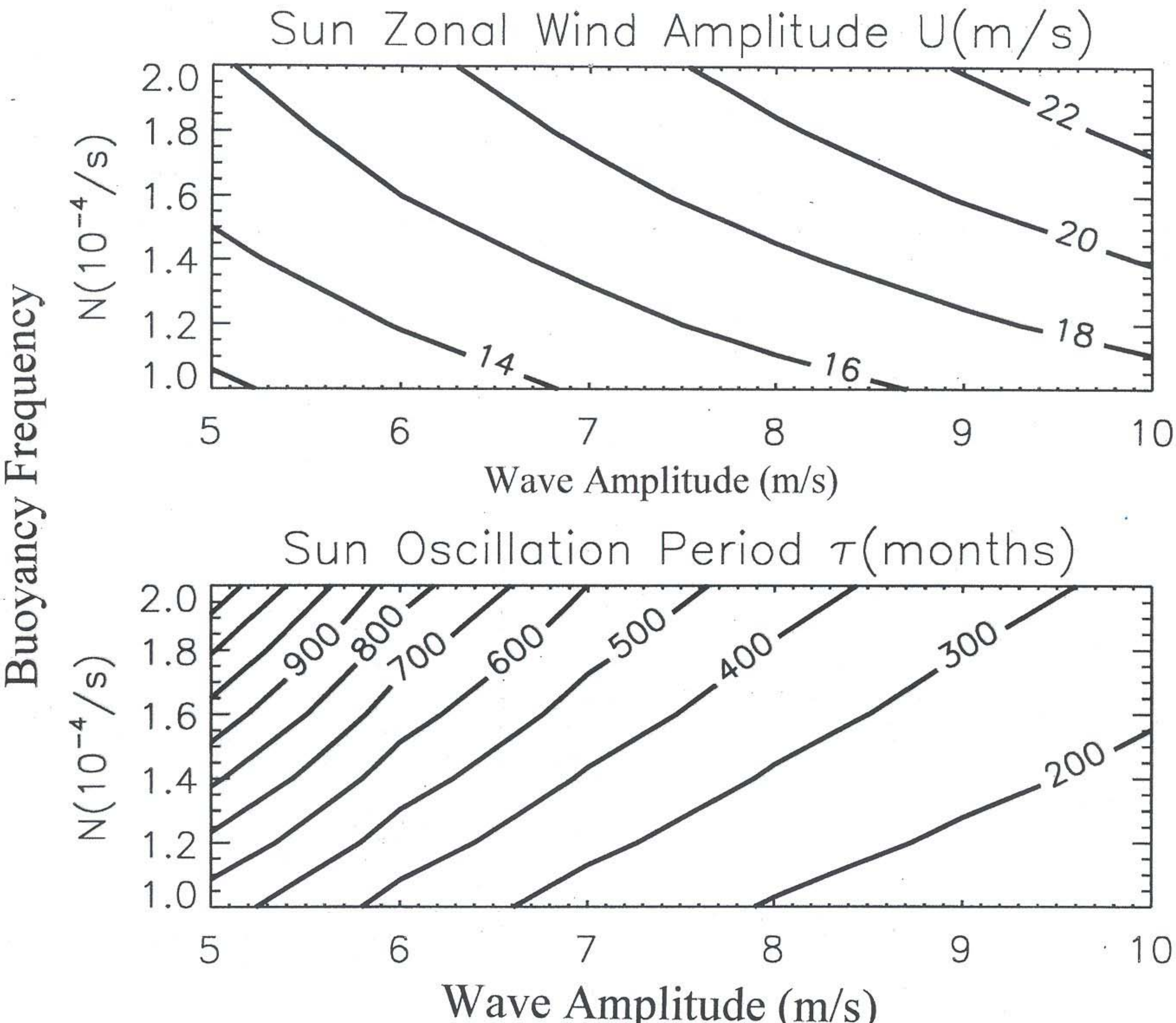
λ_O, τ, vertical wavelength & period of flow oscillation:

$$|\mathbf{U}| \propto \left(\frac{\sigma_h^5\,\lambda_O^2}{\lambda_h\,\mathbf{N}\,\mathbf{K}}\right)^{1/3}; \qquad \tau \propto \frac{\mathbf{N}\,\lambda_h\,\lambda_O}{\sigma_h^4}|\mathbf{U}|^2$$

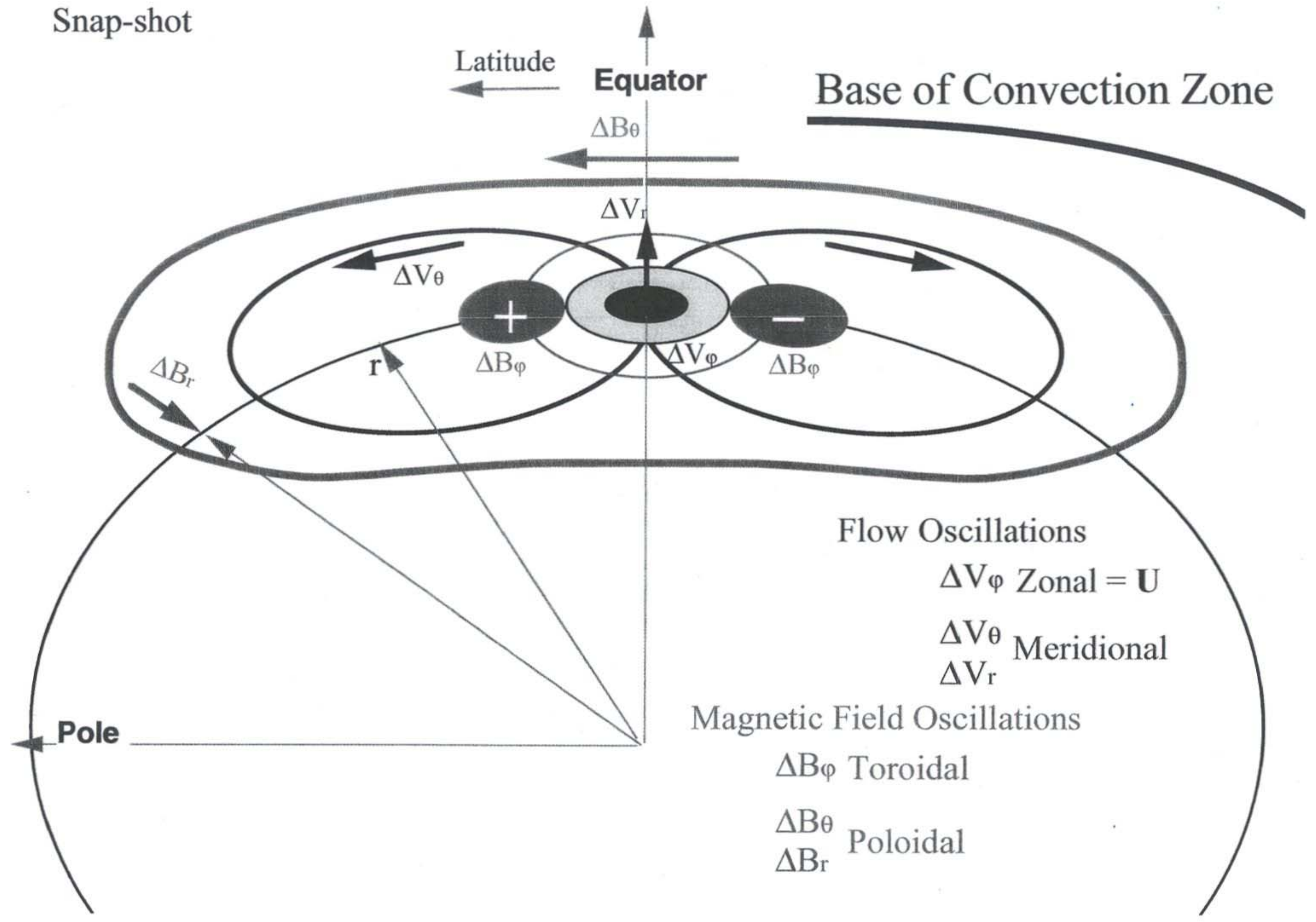
With larger length scales in the Sun:

λ_O, λ_h (sun) >> λ_O, λ_h (earth) → τ (sun) >> τ (earth).

Low N near base of convection zone → τ (sun) ≈ 22 years.


Sun Zonal Wind Amplitude U(m/s)
22
20
18
16
14
Sun Oscillation Period τ(months)
900
800
700
600
500
400
300
200
Buoyancy Frequency
N(10⁻⁴/s)
2.0
1.8
1.6
1.4
1.2
1.0
5
6
7
8
9
10
Wave Amplitude (m/s)

Bi-decadal Oscillations (BDO) of Flows and Magnetic Fields



Conclusions

Solar Analog of QBO:

1) Wave-driven flow oscillation generates 22-year magnetic (11-year activity) cycle.

2) Below convection region. Low convective stability like upper mesosphere.

3) Strong toroidal field, generated by zonal flow, peaks at low latitudes.

4) Weaker poloidal field, generated by meridional circulation, peaks when toroidal field changes direction.