Motivation

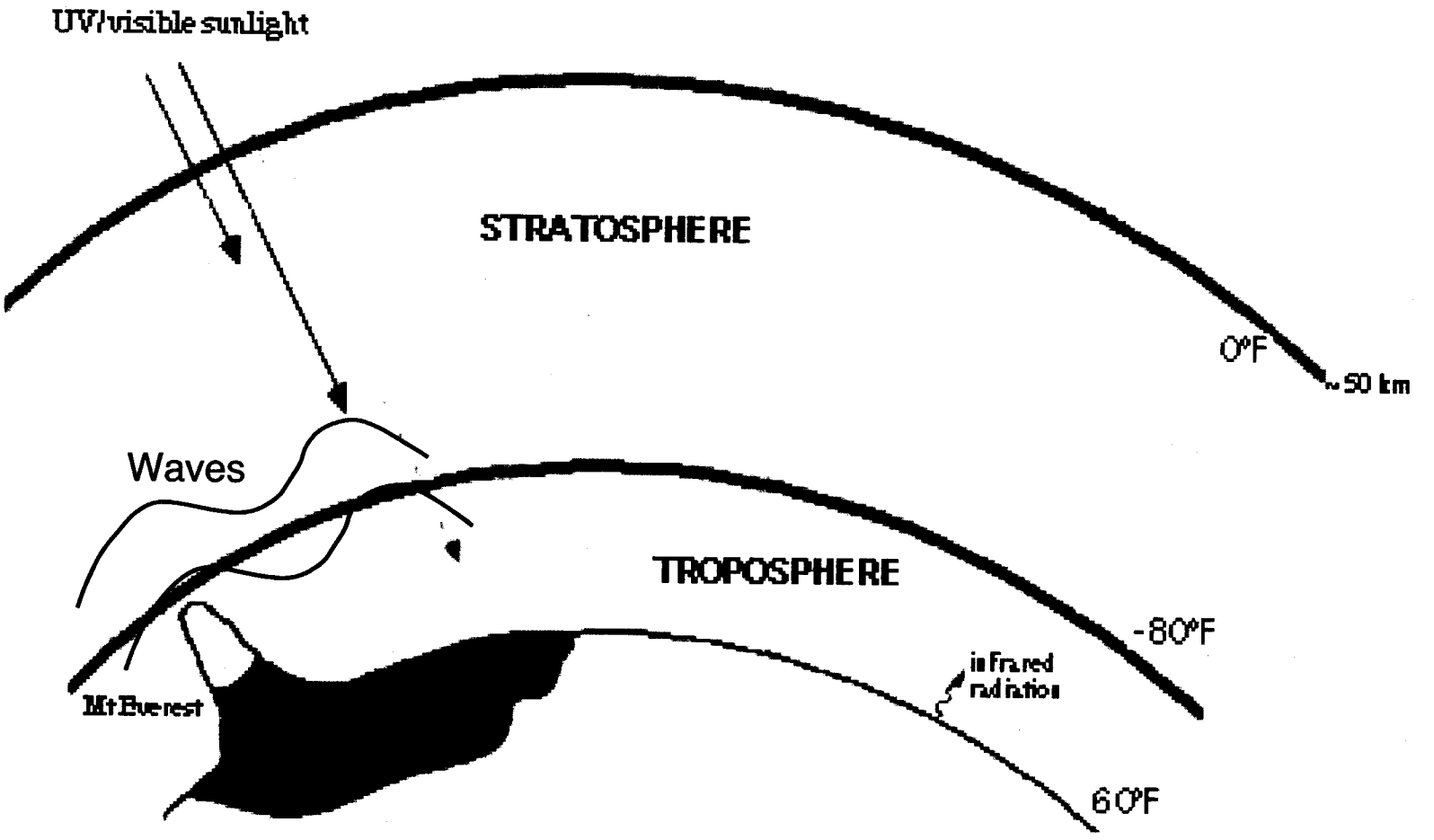
- Mechanisms of natural influences on climate

  --solar UV variability ⇒ ozone, temperature ⇒ dynamics

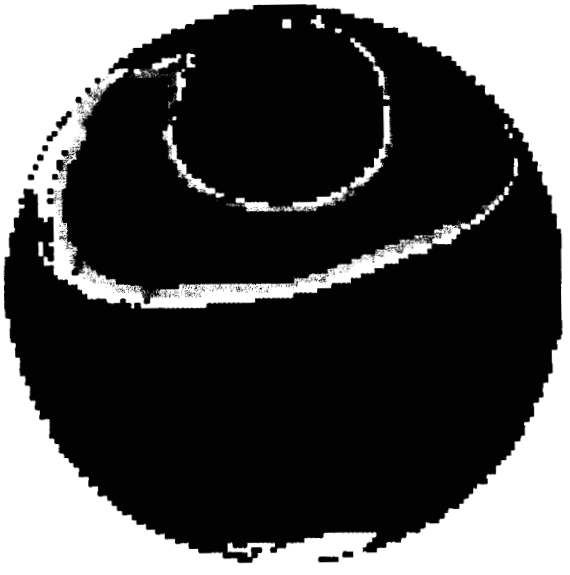
- Low-dimensional modes in the atmosphere

  -- flow patterns

  -- North Annular Mode


UV/visible sunlight
STRATOSPHERE
0°F
~50 km
Waves
TROPOSPHERE
-80°F
infrared radiation
Mt Everest
60°F

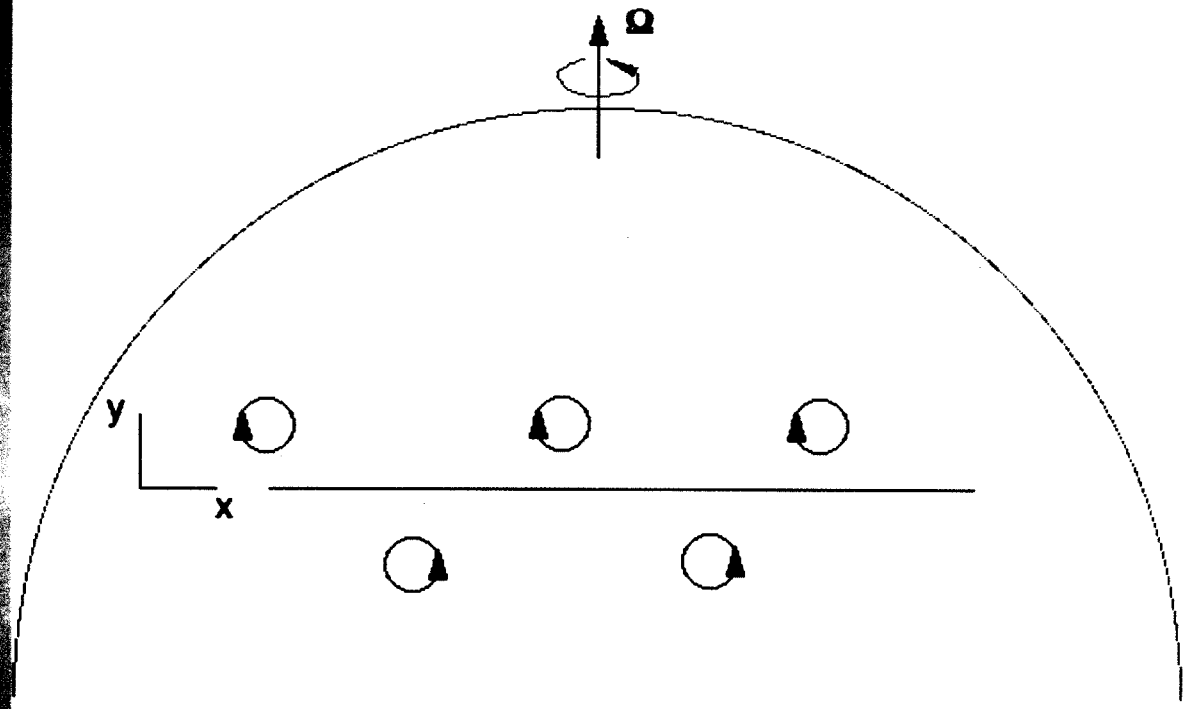
North Annular Mode



- A recurrent pattern of wintertime climate anomalies with two major states:
  - + polar jet displaced poleward
  - - polar jet displaced equatorward
- Account for 23% of variability
- Expands from sea-level to the stratosphere top
- Associated with modulation of PWs propagating into stratosphere

Thompson and Wallace, 1998

Planetary (Rossby) Waves



$$(\partial_t + \mathbf{V}\nabla)q = 0$$

$$q = f + \mathrm{rot}\mathbf{V}$$

$$f = 2\Omega\sin\phi$$

$$u = -\partial_y\psi,\ v = \partial_x\psi$$

$$\partial_t \nabla^2\psi + \beta\partial_x\psi = 0, \qquad \beta = 2\Omega\cos\phi$$

$$\psi = \exp(ikx + ly - \omega t), \quad c = \omega/k = -\beta/(k^2 + l^2) < 0$$

Two Standard Approximations

1. Given Zonal Wind (U):

$$\psi = \Psi(z)\, e^{z/2H + ikx} \sin ly,$$

$$\partial_{zz}{}^2 \Psi + n^2 \Psi = 0, \qquad n^2 = (N/f)^2[\beta/U - (k^2 + l^2)] - 1/4H^2$$

$$0 < U < U_{cr} = \beta\, [k^2 + l^2 + (f/2NH)^2]^{-1}$$

Charney & Drazin,

2. Given Wave (ψ):

$$\partial_t U = fv + \nabla F, \quad F = (0, -\langle u'v' \rangle, (f/N)^2 \langle v' \partial_z \psi' \rangle)$$

-EP flux

Coupled Wind and Wave

$u = U(z,t) \sin ly$ -zonal wind

$\psi = \mathrm{Re}[\Psi(z,t)\, e^{z/2H+ikx} \sin ly]$, $\Psi = X + iY$ - the wave

$$\partial\Psi/\partial t = F(\Psi, U, h, \Lambda),$$

$$\partial U/\partial t = G(\Psi, U, h, \Lambda)$$

h - wave amplitude at source

$\Lambda = \partial U_R/\partial z$ - equilibrium gradient ($U_R = U_B + \Lambda z$)

Holton&Mass (74), Yoden (90)

The Dynamical System

$$dX/dt = - X/\tau_1 - pY + qUY,$$

$$dY/dt = - Y/\tau_1 + pX - qUX - \zeta hU,$$

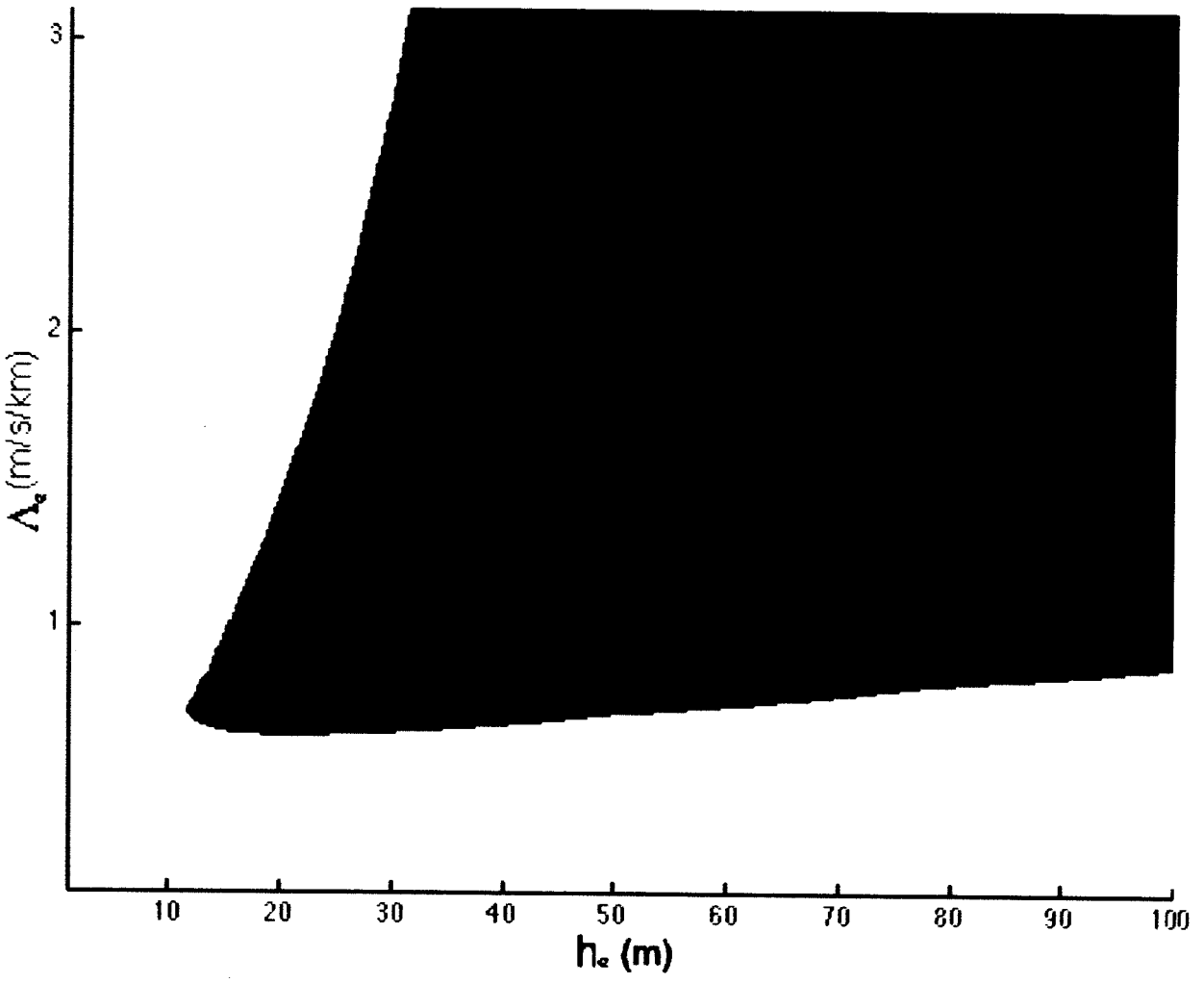
$$dU/dt = - (U - U_R(0) - \Lambda z_T)/\tau_2 - \eta hY.$$

$\tau_1 = 122.63$ T, $\tau_2 = 30.37$ T, X,Y = [L^2/T]; T= day, L = a (Earth's radius).

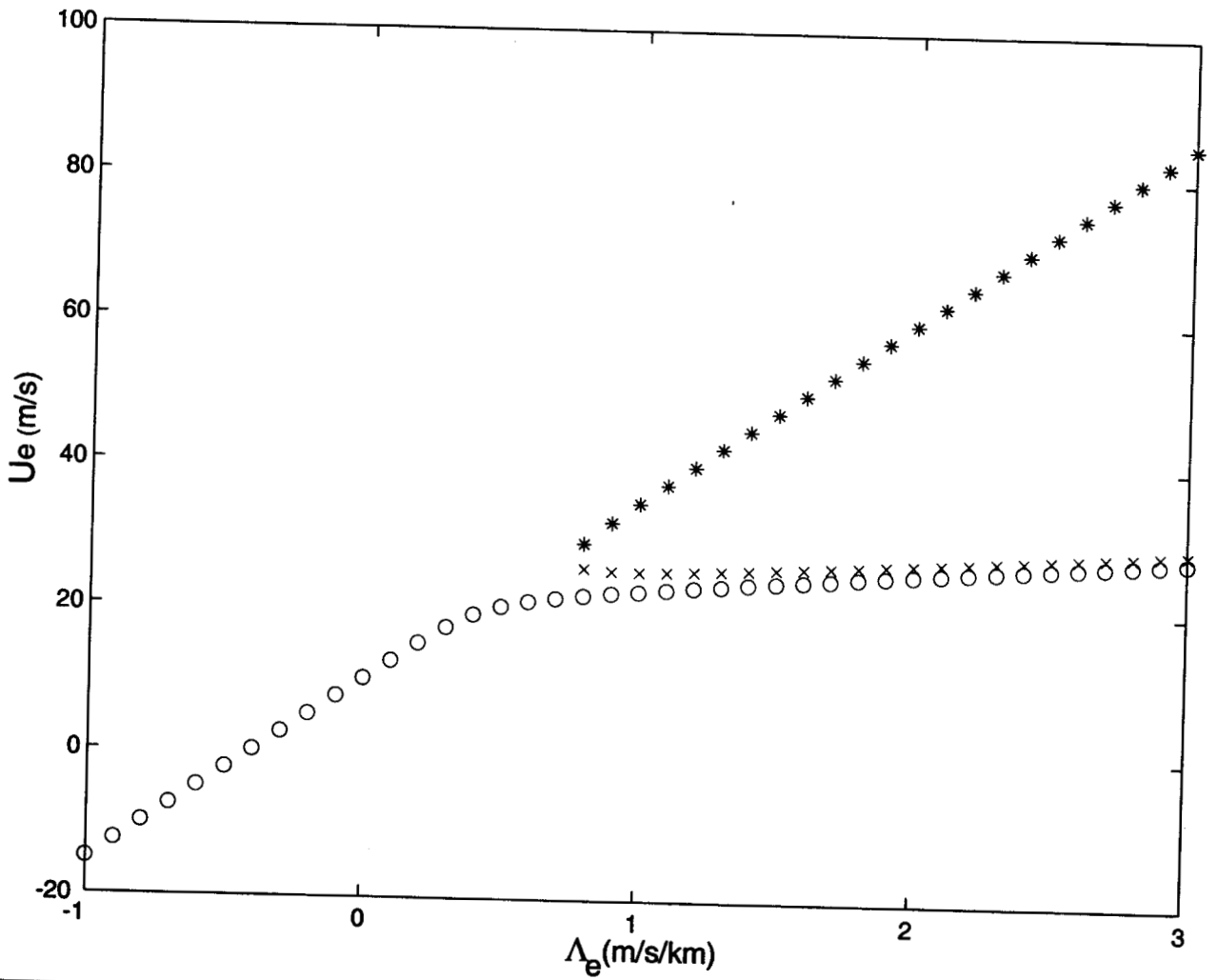
p, q, ζ, η = 0.63, 1.97, 0.23, 86.90 [1/T, 1/L, L/T^2, 1/T ,1/(L^2T), L/T, L].

(Ruzmaikin, Lawrence&Cadavid, 2002)

Stationary Points



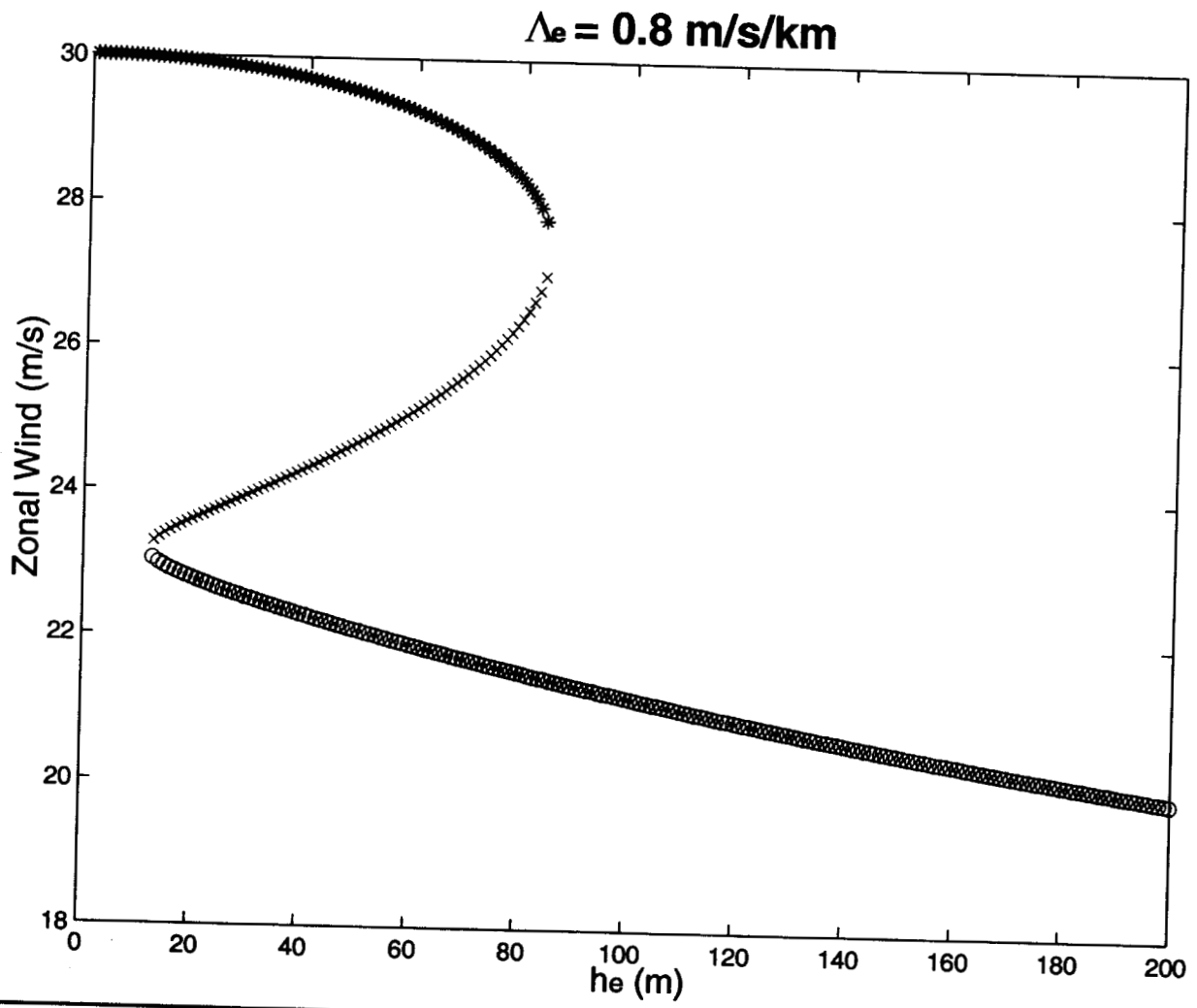
Three Equilibrium Solutions



h = 68 m

* o stable
X unstable

Three Equilibrium Solutions



* o stable
X unstable

Annual and Solar Variability

$$\Lambda = \Lambda_0 + \delta\Lambda_a \sin(2\pi t/1\text{year}) + \delta\Lambda_s \sin^2(\pi t/11\text{years})$$

$\Lambda_0 = 0.75$ m/s/km, $\delta\Lambda_a = 2.25$ m/s/km --standard

$$\delta\Lambda_s = \varepsilon\Lambda_0$$

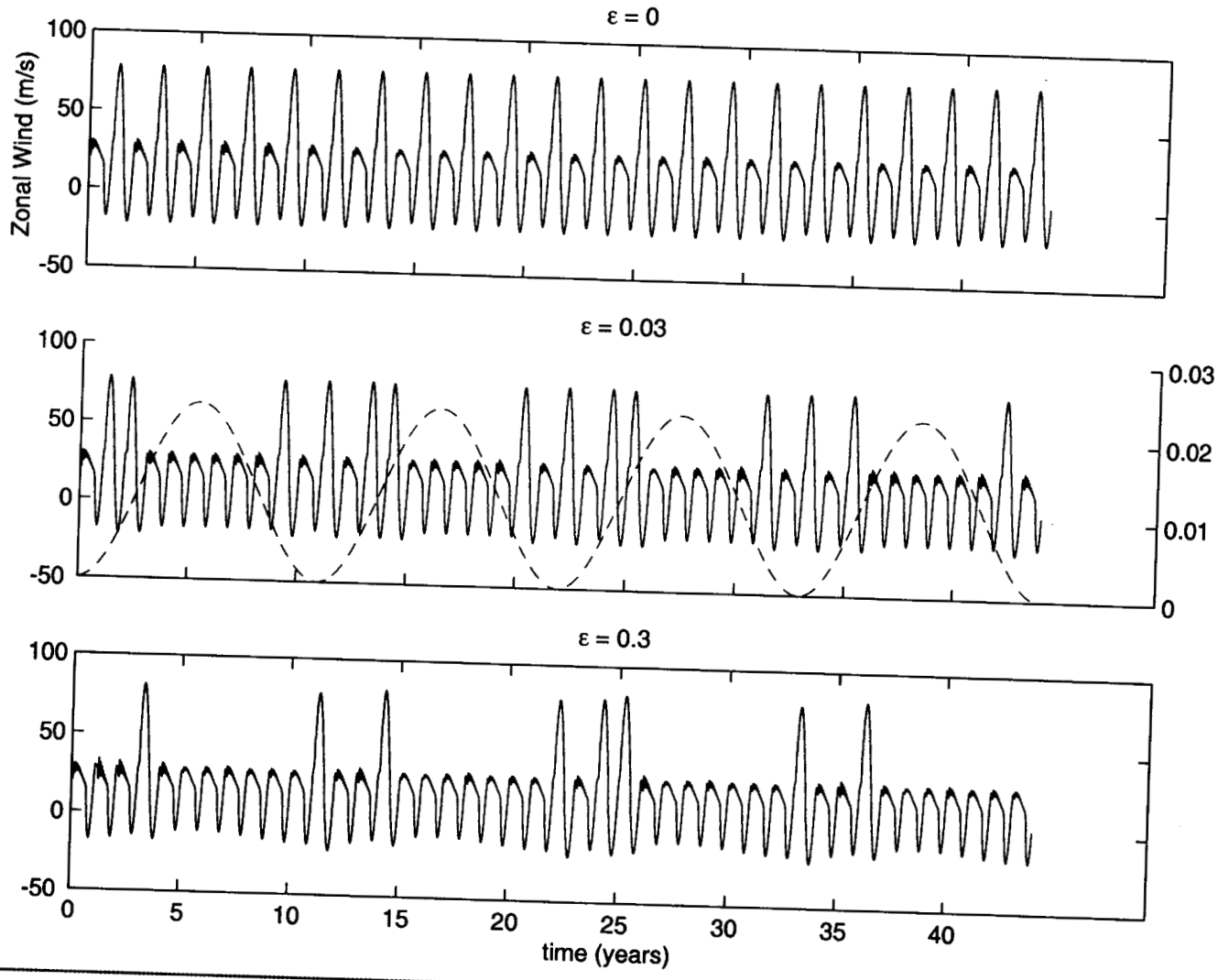
From theremal wind equation $dU/dz = -(R/fH)dT/dy$

$\delta\Lambda_s \approx 4\text{x}10^4\, \delta T/\delta y \approx 0.1$ m/s/km -estimate

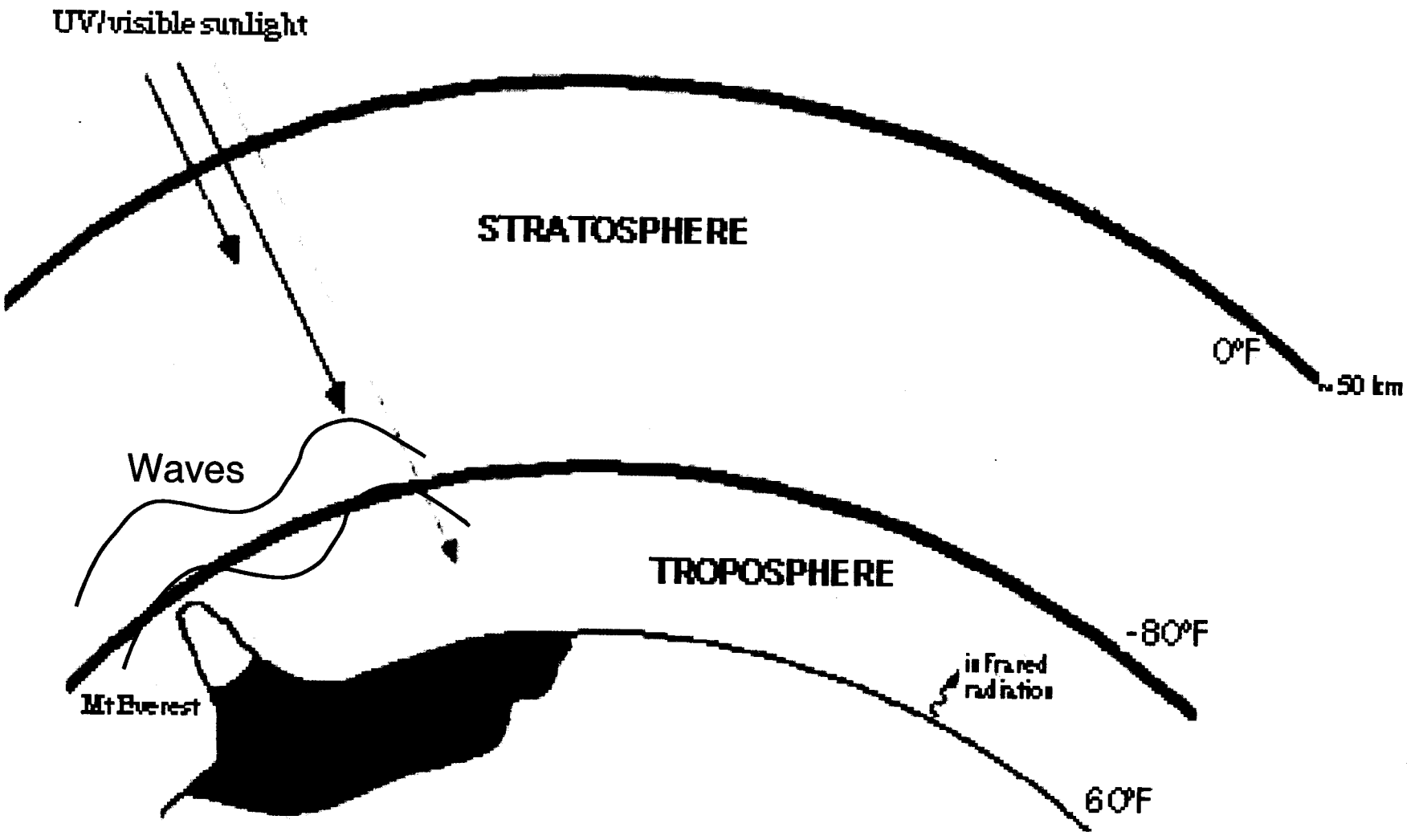
$R = 3\text{x}10^6\ \text{cm}^2\text{s}^{-2}$, $H = 7$ km, $f = 10^{-4}\text{s}^{-1}$, $\delta y \approx a$,

$\delta T \approx 2K$ (Hood et al.,93)

Zonal Wind Modulations



Discussion/Conclusions

- Two stable equilibria = two basic states of NAM?
- Seasonal variability can generate bi-annual oscillations
- Solar variability leads to modulation of warm and cold winters

A Possible Mechanism