1993 CEDAR Workshop Tutorial

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Atmospheric Gravity Wave Effects on the Climate, Dynamics and Composition of The Upper Mesosphere and Lower Thermosphere (MLT)

Richard Walterscheid

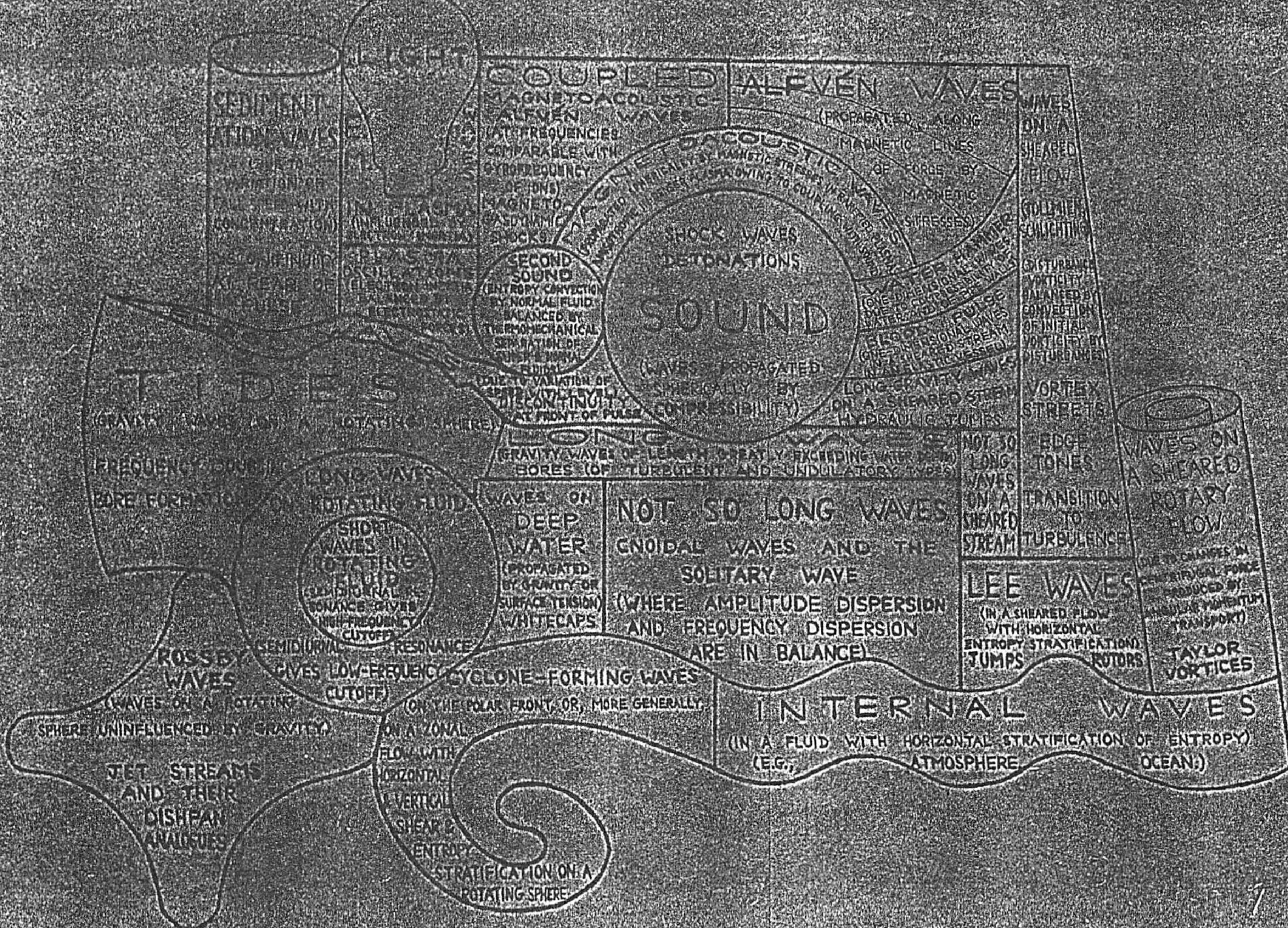
The Aerospace Corporation

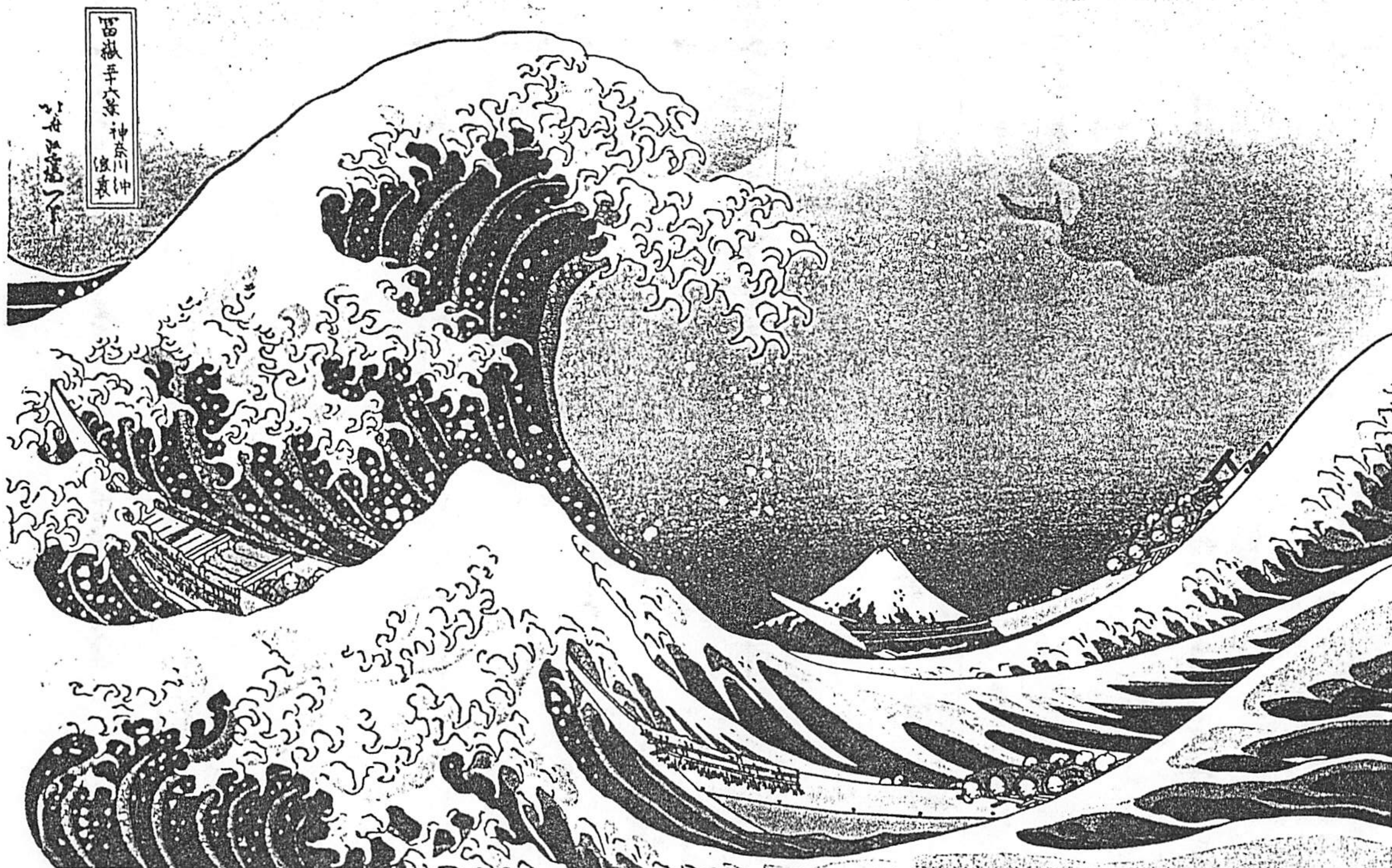
Topics

Review of Gravity Waves

Wave-mean-flow interactions

- Theory
  - Wave transports
  - Nonacceleration theorem
  - Chemically induced interactions
- Phenomena
  - Cold Summer Mesopause
  - Pseudotides
  - Compositional changes


LIGHT
COUPLED
MAGNETOACOUSTIC
ALFVÉN WAVES
AT FREQUENCIES COMPARABLE WITH GYROFREQUENCY OF IONS)
MAGNETO-GASDYNAMIC SHOCKS
ALFVÉN WAVES
(PROPAGATED ALONG MAGNETIC LINES OF FORCE BY MAGNETIC STRESSES)
MAGNETOACOUSTIC WAVES
WAVES ON A SHEARED FLOW
SECOND SOUND
SHOCK WAVES
DETONATIONS
SOUND
(WAVES PROPAGATED SPHERICALLY BY COMPRESSIBILITY)
WATER HAMMER
BLOOD PULSE
LONG GRAVITY WAVES ON A SHEARED STREAM
HYDRAULIC JUMPS
VORTEX STREETS
EDGE TONES
TRANSITION TO TURBULENCE
TIDES
(GRAVITY WAVES ON A ROTATING SPHERE)
FREQUENCY DOUBLING
BORE FORMATION
LONG WAVES
(GRAVITY WAVES OF LENGTH GREATLY EXCEEDING WATER DEPTH)
BORES (OF TURBULENT AND UNDULATORY TYPES)
NOT SO LONG WAVES ON A SHEARED STREAM
WAVES ON A SHEARED ROTARY FLOW
LONG WAVES ON ROTATING FLUID
SHORT WAVES IN ROTATING FLUID
WAVES ON DEEP WATER
(PROPAGATED BY GRAVITY OR SURFACE TENSION)
WHITECAPS
NOT SO LONG WAVES
CNOIDAL WAVES AND THE SOLITARY WAVE
(WHERE AMPLITUDE DISPERSION AND FREQUENCY DISPERSION ARE IN BALANCE)
LEE WAVES
(IN A SHEARED FLOW WITH HORIZONTAL ENTROPY STRATIFICATION)
JUMPS
ROTORS
TAYLOR VORTICES
ROSSBY WAVES
(WAVES ON A ROTATING SPHERE UNINFLUENCED BY GRAVITY)
SEMIDIURNAL RESONANCE GIVES LOW-FREQUENCY CUTOFF)
CYCLONE-FORMING WAVES
(ON THE POLAR FRONT, OR, MORE GENERALLY, ON A ZONAL FLOW WITH HORIZONTAL & VERTICAL SHEAR & ENTROPY STRATIFICATION ON A ROTATING SPHERE)
INTERNAL WAVES
(IN A FLUID WITH HORIZONTAL STRATIFICATION OF ENTROPY)
(E.G., ATMOSPHERE OCEAN.)
JET STREAMS AND THEIR DISHPAN ANALOGUES


冨嶽三十六景
神奈川沖
浪裏

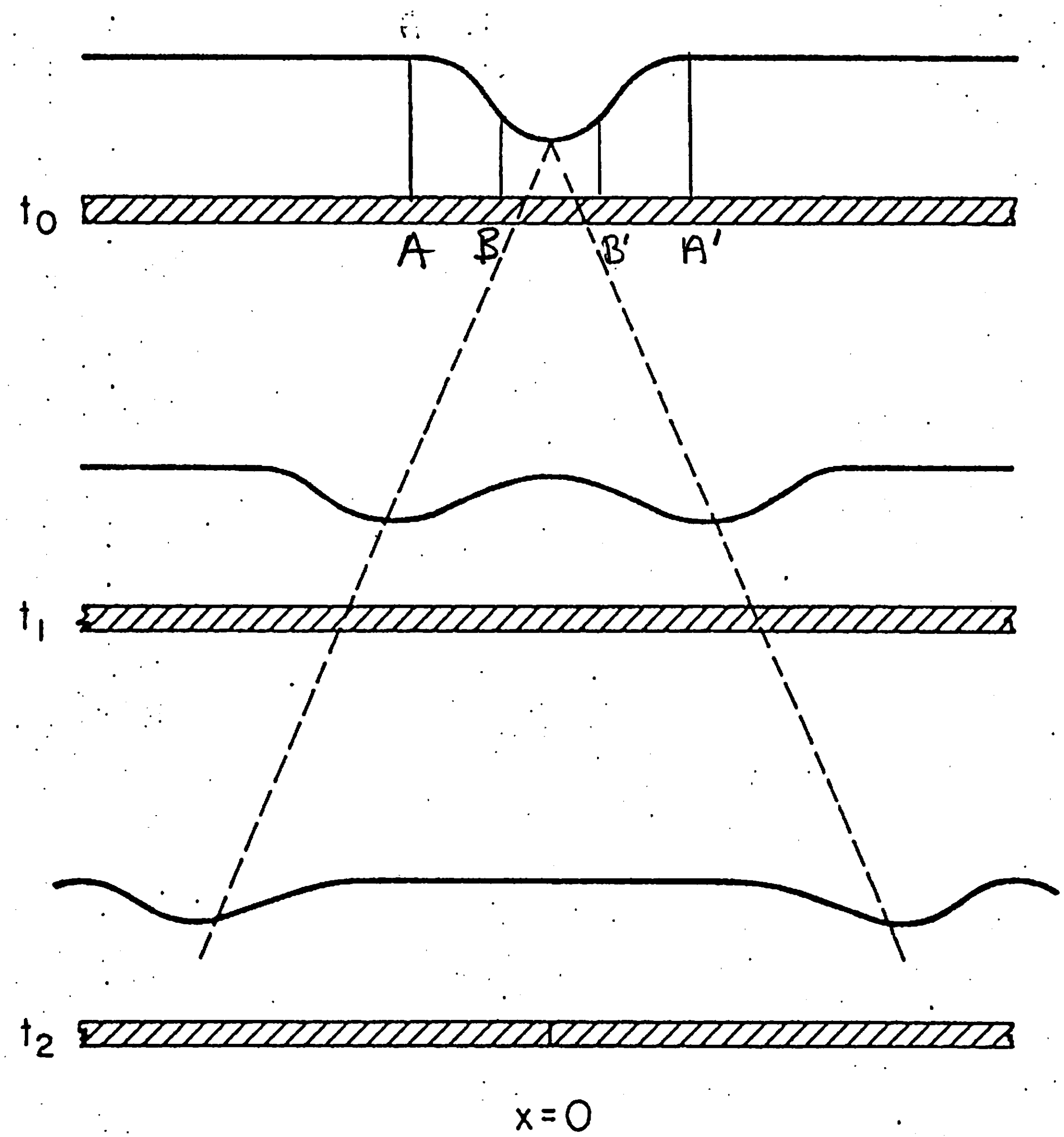
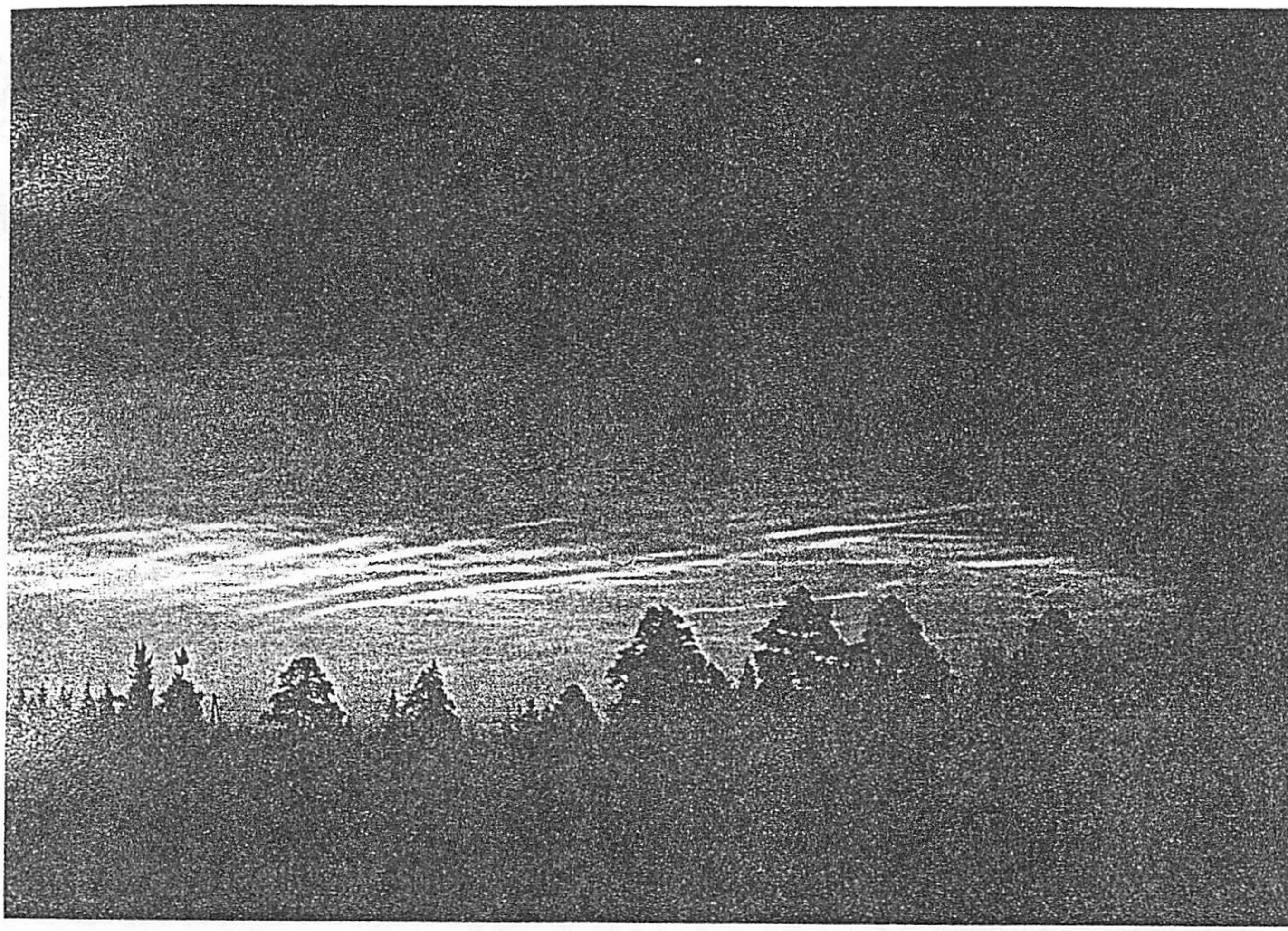


Fig. 8.2 The propagation of a surface gravity wave initiated by a depression at time t_0.

Pl.199 A stratiform deck of clouds affected by a strong wind that is producing waves similar to those often seen on water. A band of higher clouds shows that the wind effects are widespread.



Believed to consist of ice particles of dimensions less than 0.1 μm, noctilucent clouds offer a splendid summertime light show to northern inhabitants. During the long summer twilights these high-altitude (85 km) clouds are visible by direct solar illumination, while the lower atmosphere is in shadow. The cloud color is generally silvery-blue, primarily due to the Rayleighlike scattering properties of the tiny particles, and secondarily due to partial removal of red light from absorption in the Chappuis bands of ozone. The characteristic wave forms are probably a result of viewing perspective, a geometrical consequence of the wave undulation of a thin homogeneous cloud layer. However, at times, clouds can sometimes be viewed directly overhead where this effect should not be present, indicating that divergence/convergence of ice particle concentrations may also be partially responsible. This photograph was taken by Pekka Parviainen at Kustavi, Finland (latitude 60.7°N, longitude 21.3°E). It was taken on the night of July 13, 1983, at 2140 UT (about 2300 local time). Camera details: *f*/2 50-mm lens, Kodachrome K64 film, exposure time unknown.

Atmospheric Internal Gravity Waves

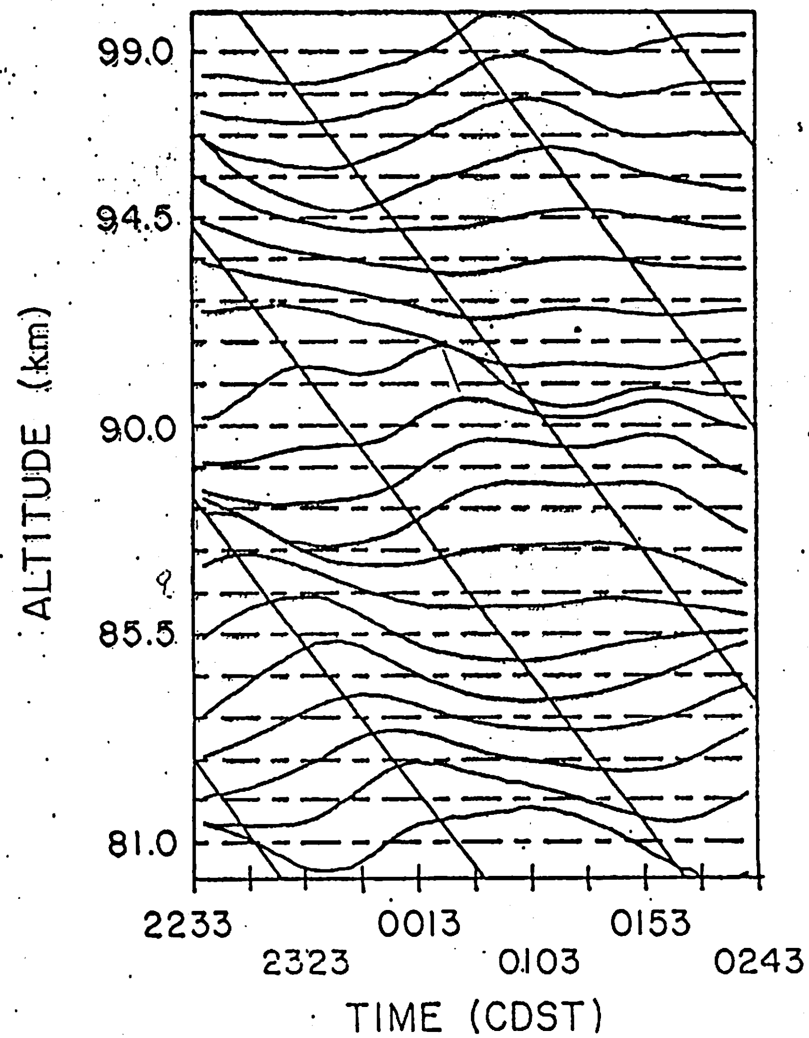
Recall: Tilted surface in a stratified fluid $\rightarrow$ horizontal pressure gradient

In a continuously stratified fluid a wave disturbance in one layer tilts adjacent layers and excites traveling disturbances which tilt layers adjacent to them and so on

Waves may be external or internal

- External: Maximum energy density at a boundary
  - Evanescent
- Internal: Maximum energy density within the fluid
  - Vertically propagating (usually)
  - Phase propagation is opposite to vertical group (i.e. energy) propagation
  - Amplitude $\propto \overline{\rho}^{-1/2}$ for steady conservative waves

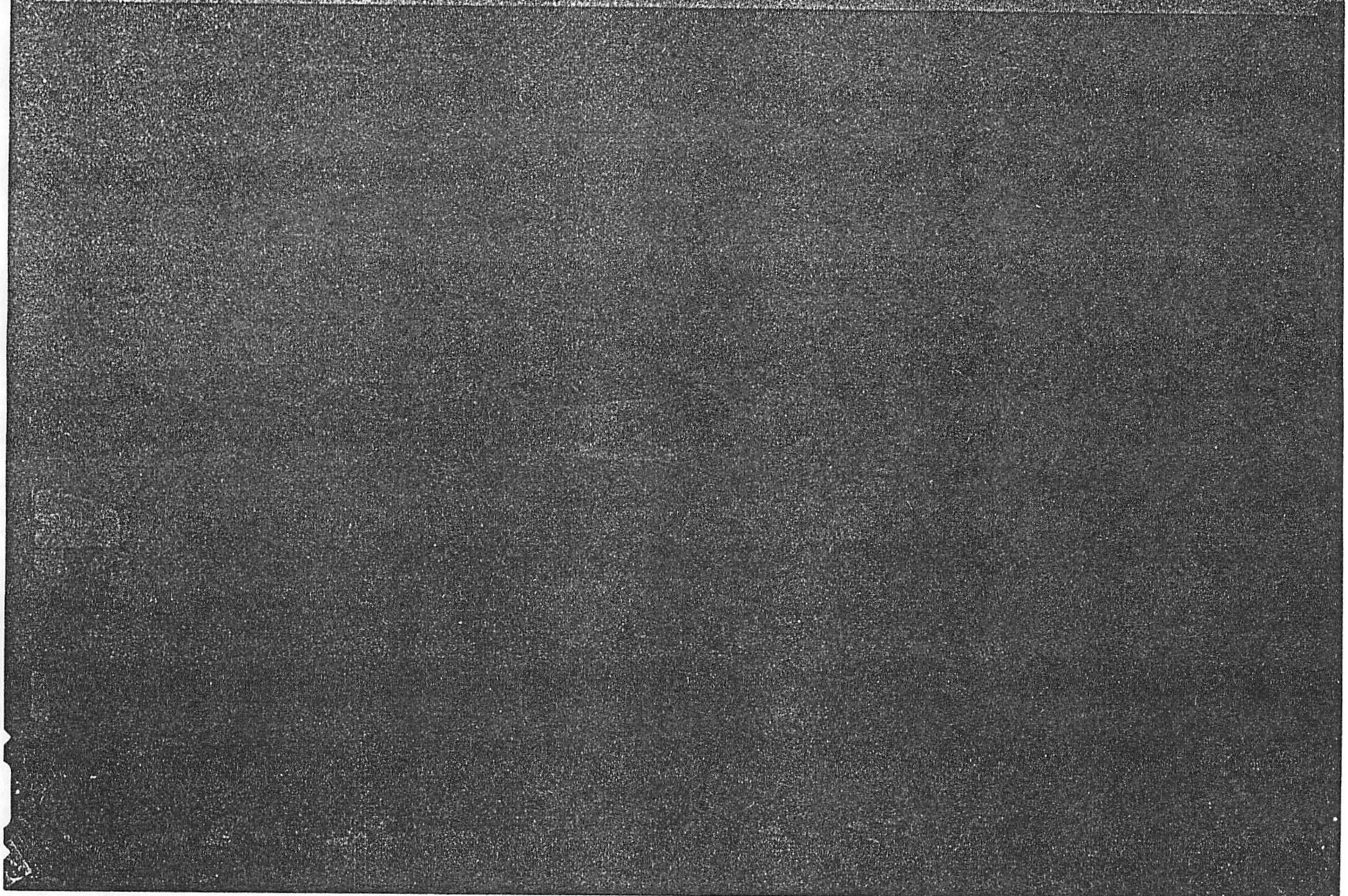
Internal waves dominant in MLT because they are vertically propagating and grow in amplitude



Shelton et al (1980)

5

C Pl.24 Track of a Minuteman Missile launched from Vandenberg A.F.B. as seen from Pasadena, Calif. Such condensation trails show the types of air velocity, shear, and turbulence in the high atmosphere.



Wave Mean State Interactions

Wave Fluxes

Wave Forcing of the Mean State

Nonacceleration theorem

Chemically induced forcing

Wave Mean State Interaction Phenomena in the Upper Mesosphere and Lower Thermosphere

Cold summer mesopause

Pseudotides

Compositional changes

Nonacceleration Conditions

Waves

Linear

Conservative

Steady

No critical level ($\bar{u} \neq c$)

Wave Fluxes

Mean state changes induced by wave fluxes

$$\frac{\partial \overline{\psi}}{\partial t} = \ldots - \frac{1}{\overline{\rho}} \frac{\partial F_z(\psi)}{\partial z}$$

$$F_z(\psi) = \overline{\rho}\,\overline{w'\psi'}$$

Wave stress

$$\psi = u$$

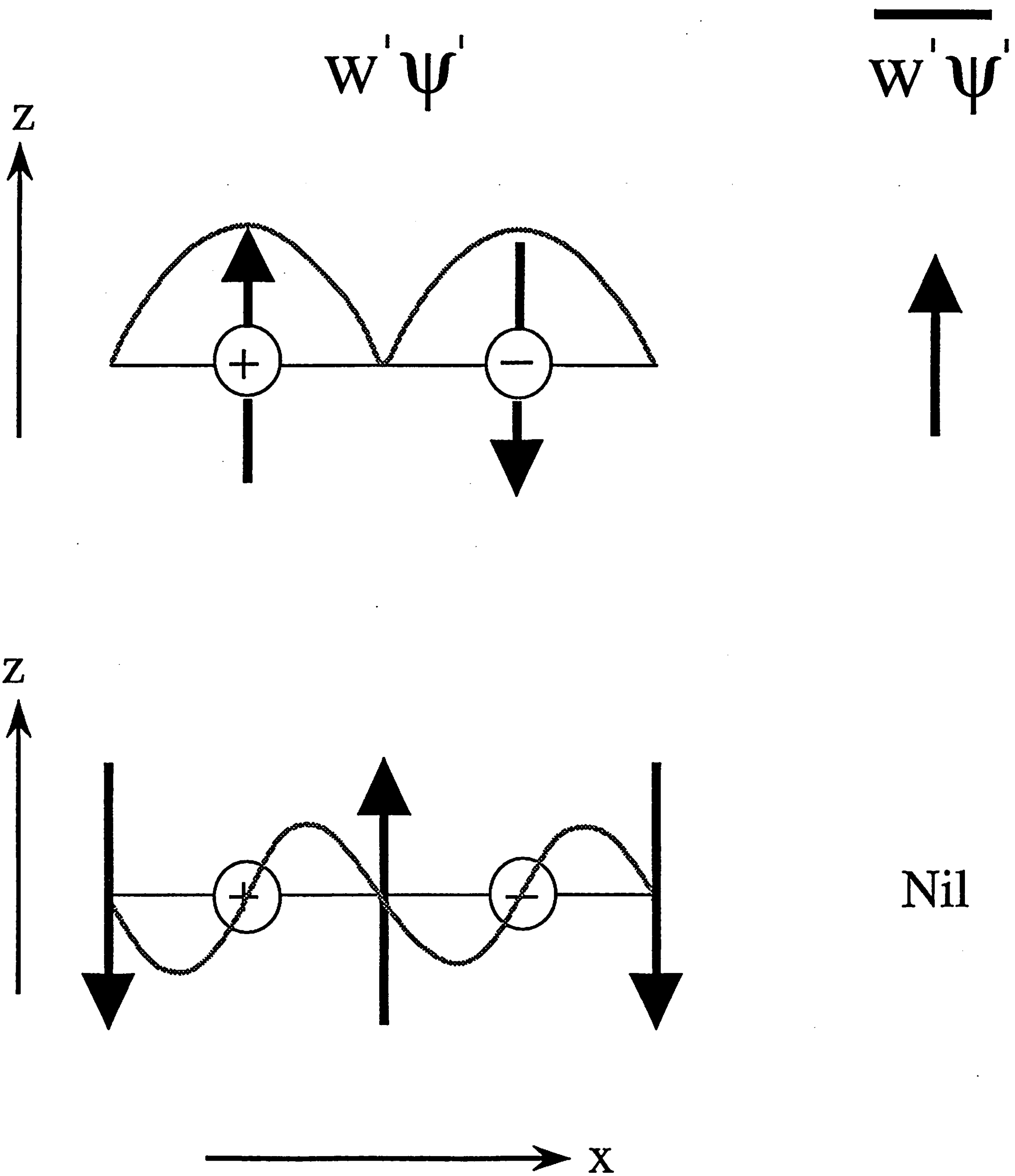
Sensible heat flux

$$\psi = c_p T$$

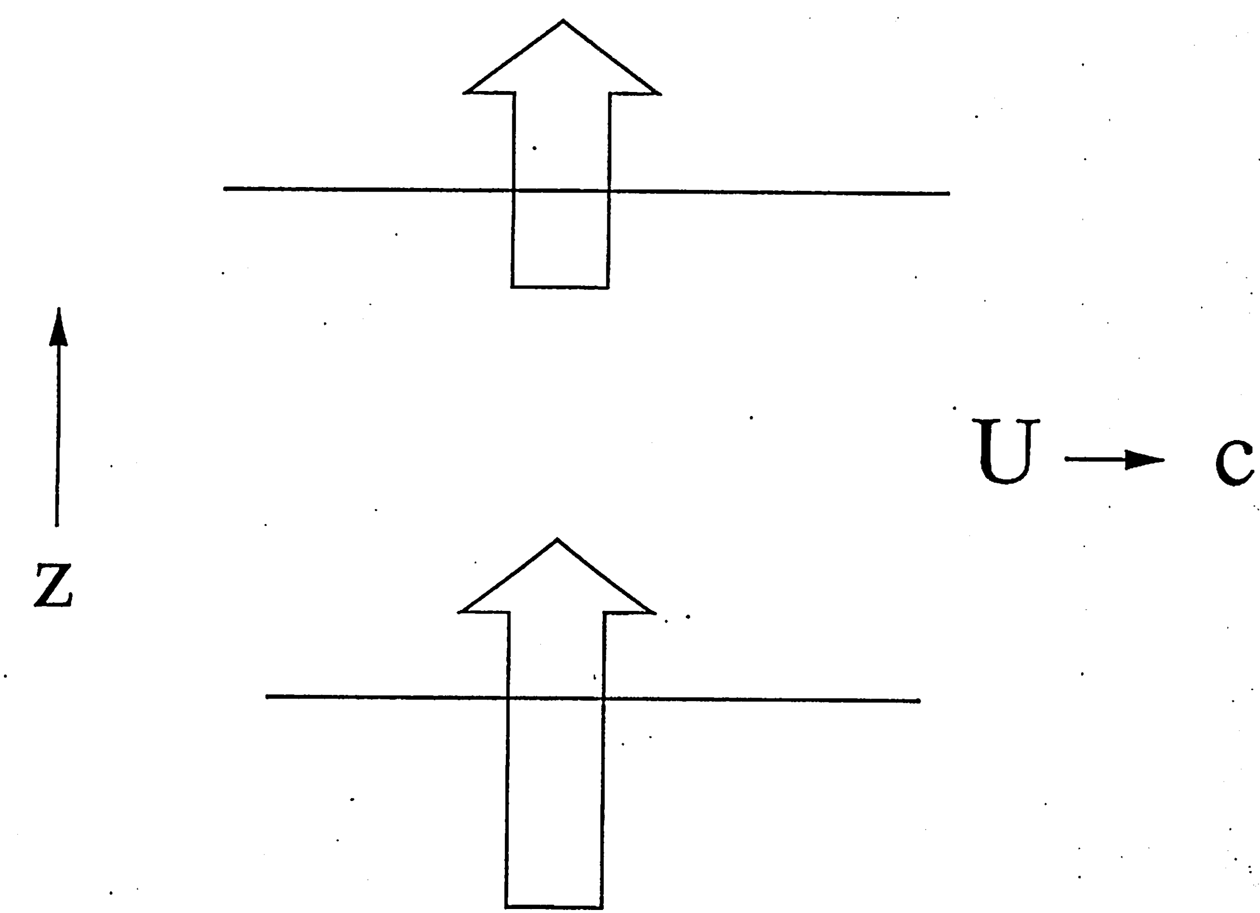
Species flux

$$\psi = r,\ \psi = n$$

Vertical Wave Fluxes



Forcing of Mean Wind by Momentum Flux



Wave Drag Effects on the Mesospheric General Circulation

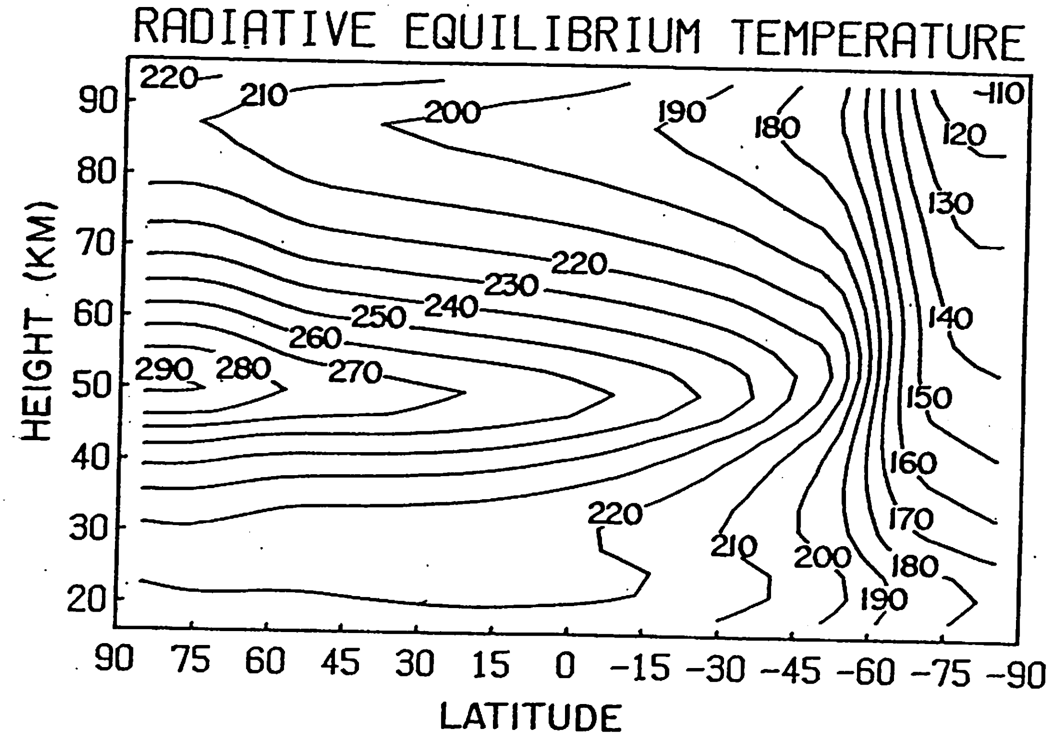


FIG. 3. Derived radiative equilibrium temperature distribution at solstice. Winter hemisphere on right.

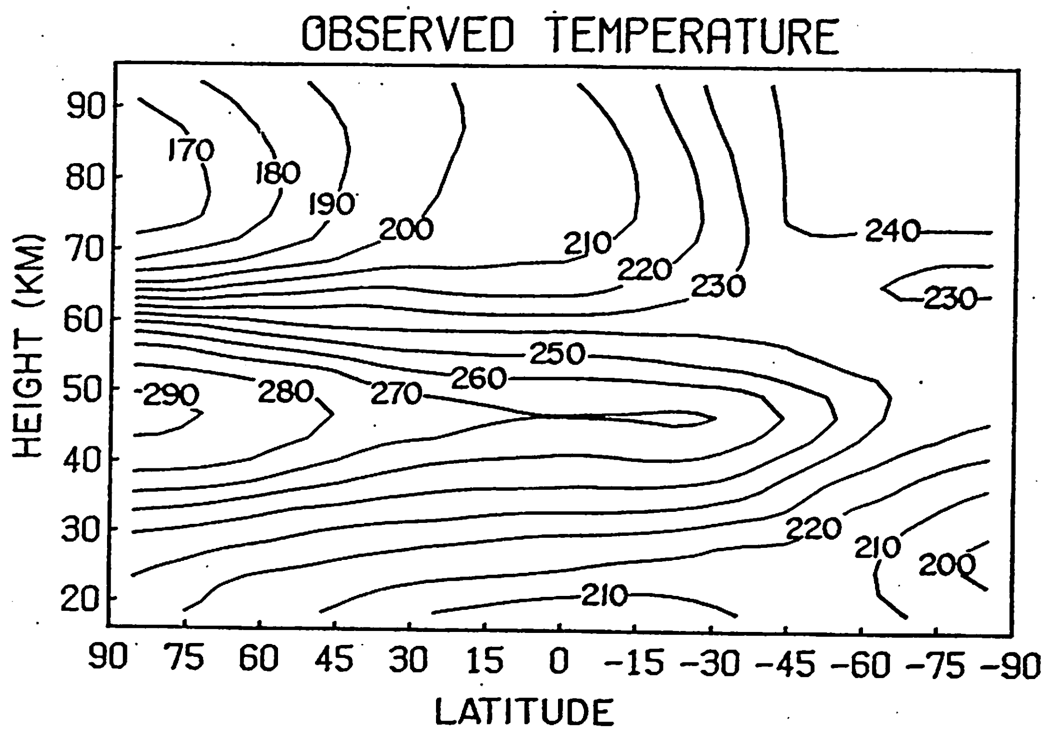


FIG. 4. Observed zonal mean temperature distribution at solstice (after Murgatroyd, 1969). Winter hemisphere on right.

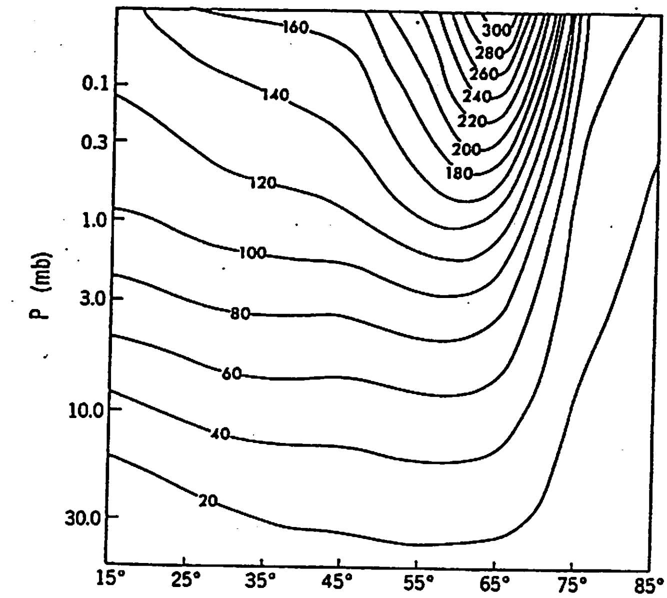
Thermal Wind Relation

In geostrophic balance

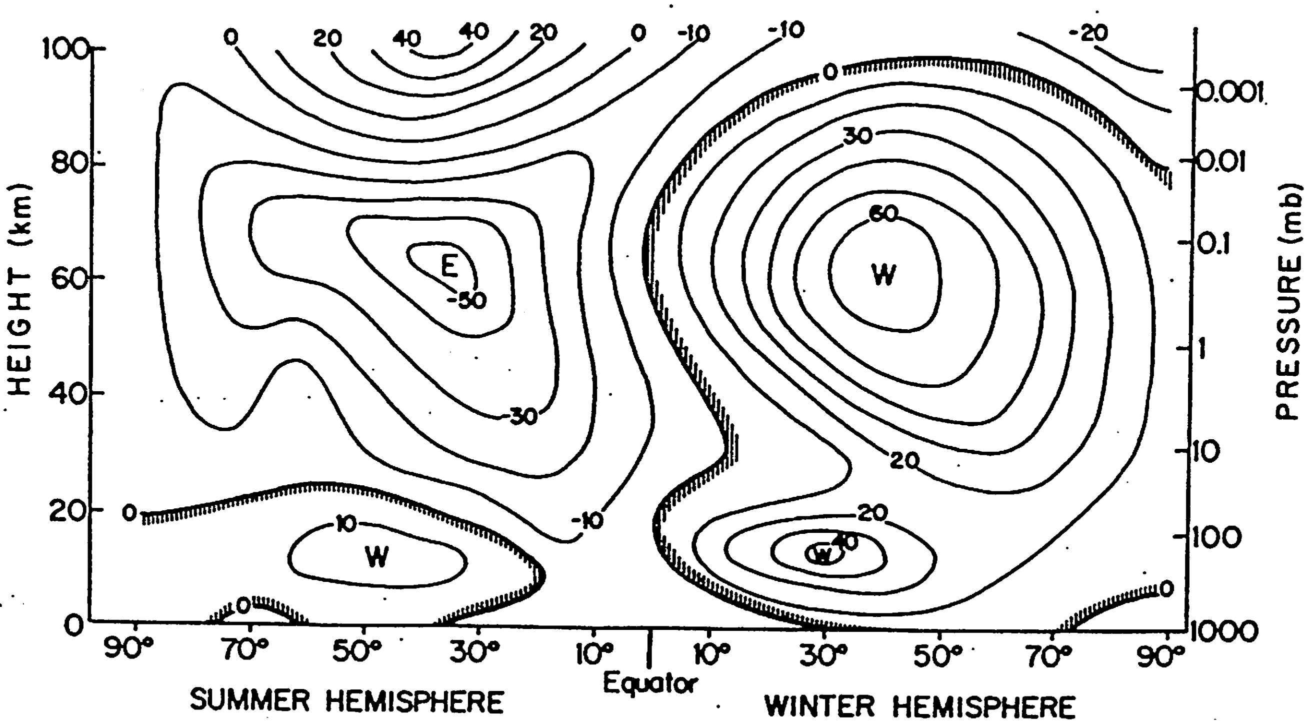
$$f\frac{\partial \overline{u}}{\partial p} = \frac{R}{p}\left(\frac{\partial \overline{T}}{\partial y}\right)_p$$

In words:

Westerly shear $\Rightarrow$ temperature decreases poleward


P (mb)
0.1
0.3
1.0
3.0
10.0
30.0
160
140
120
100
80
60
40
20
300
280
260
240
220
200
180
15°
25°
35°
45°
55°
65°
75°
85°
LATITUDE

(a)


HEIGHT (km)
PRESSURE (mb)
100
80
60
40
20
0
0.001
0.01
0.1
1
10
100
1000
E
W
-50
-30
-10
30
60
20
40
90°
70°
50°
30°
10°
Equator
SUMMER HEMISPHERE
WINTER HEMISPHERE

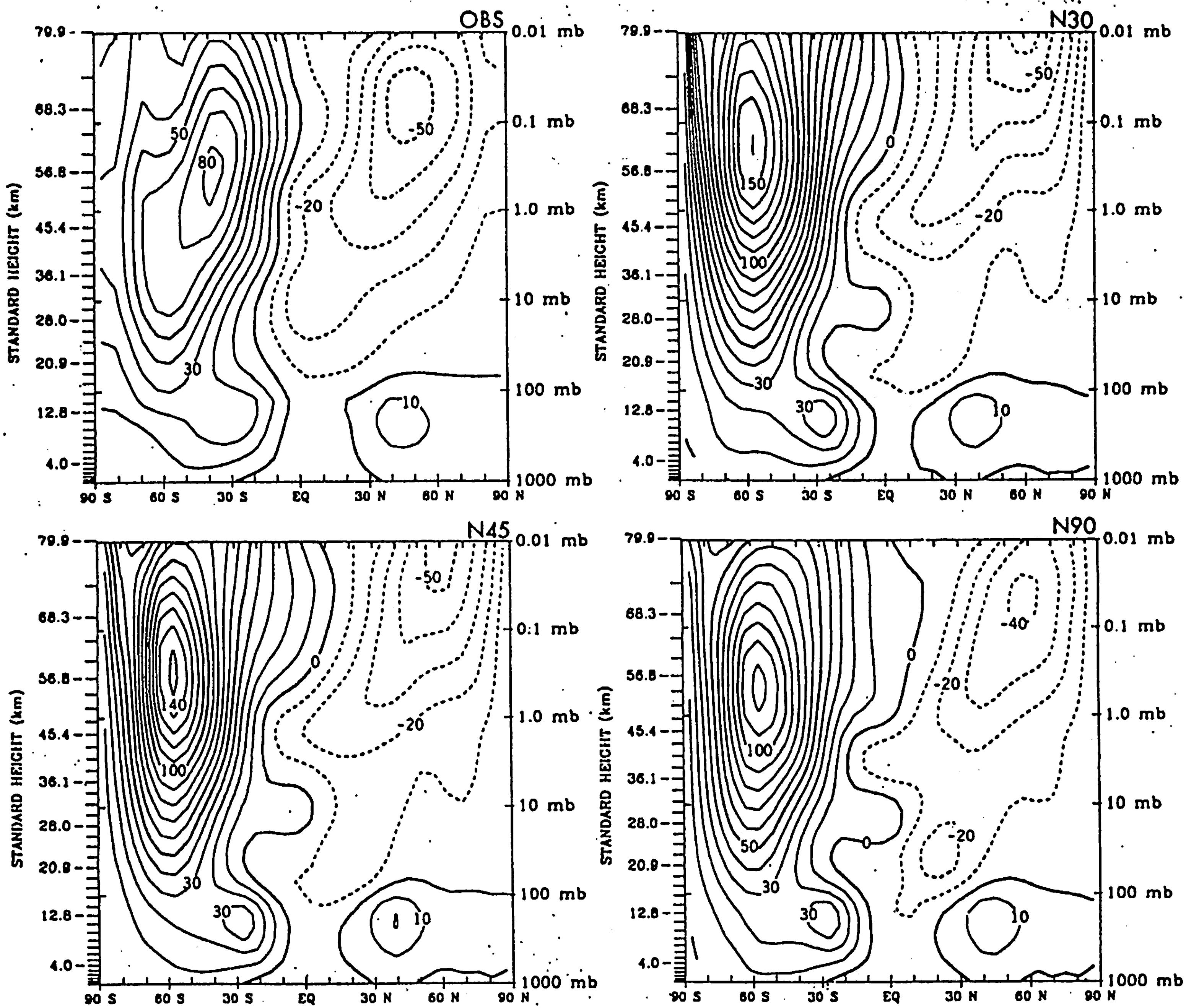


Fig. 4. As in Fig. 1, but for the June-August period.

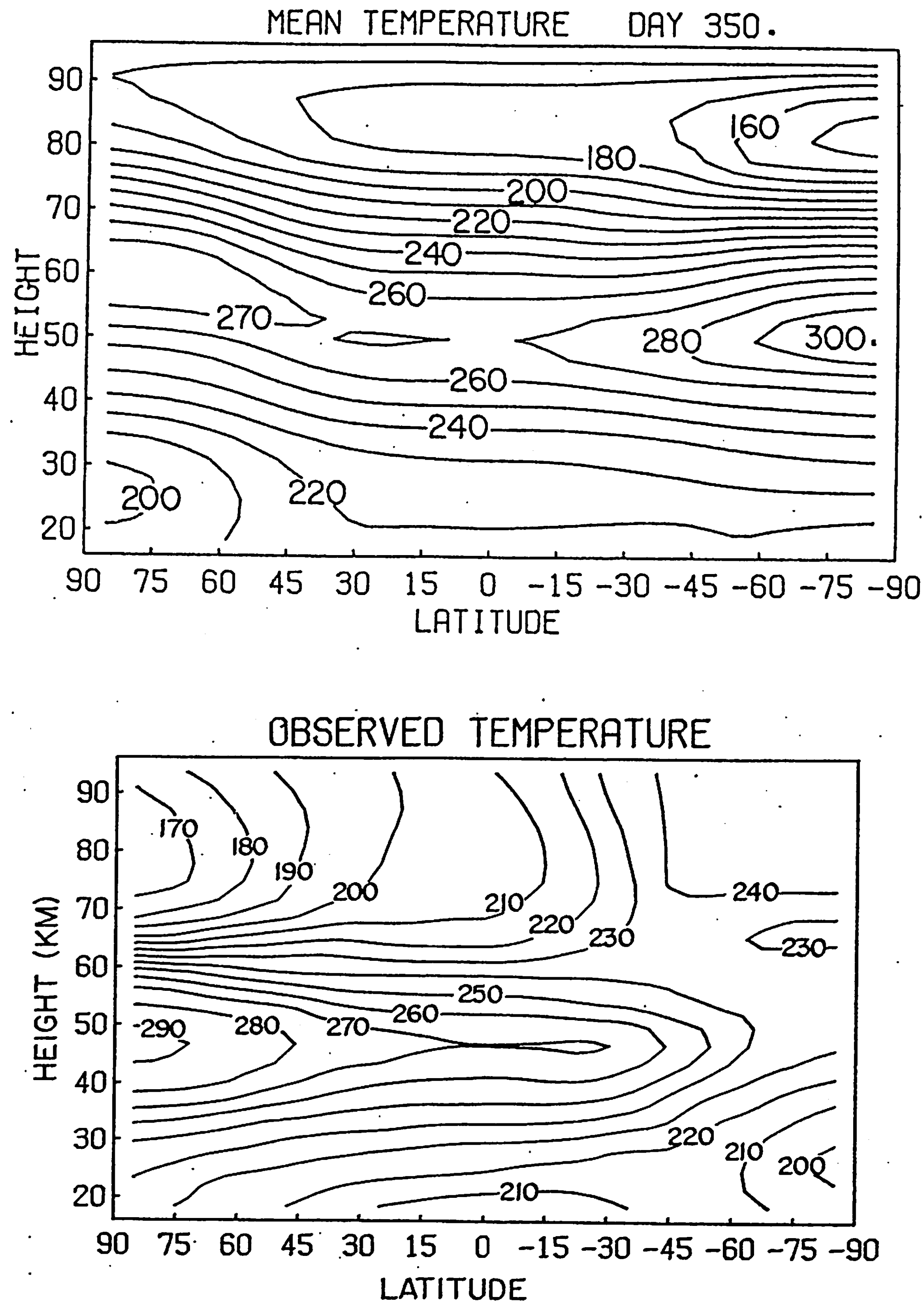


FIG. 4. Observed zonal mean temperature distribution at solstice (after Murgatroyd, 1969). Winter hemisphere on right.

Cold Summer Mesopause

Cold summer mesopause is caused by deceleration of summertime easterlies due to wave drag

Drag Mechanisms

Wave breakdown

Viscous dissipation

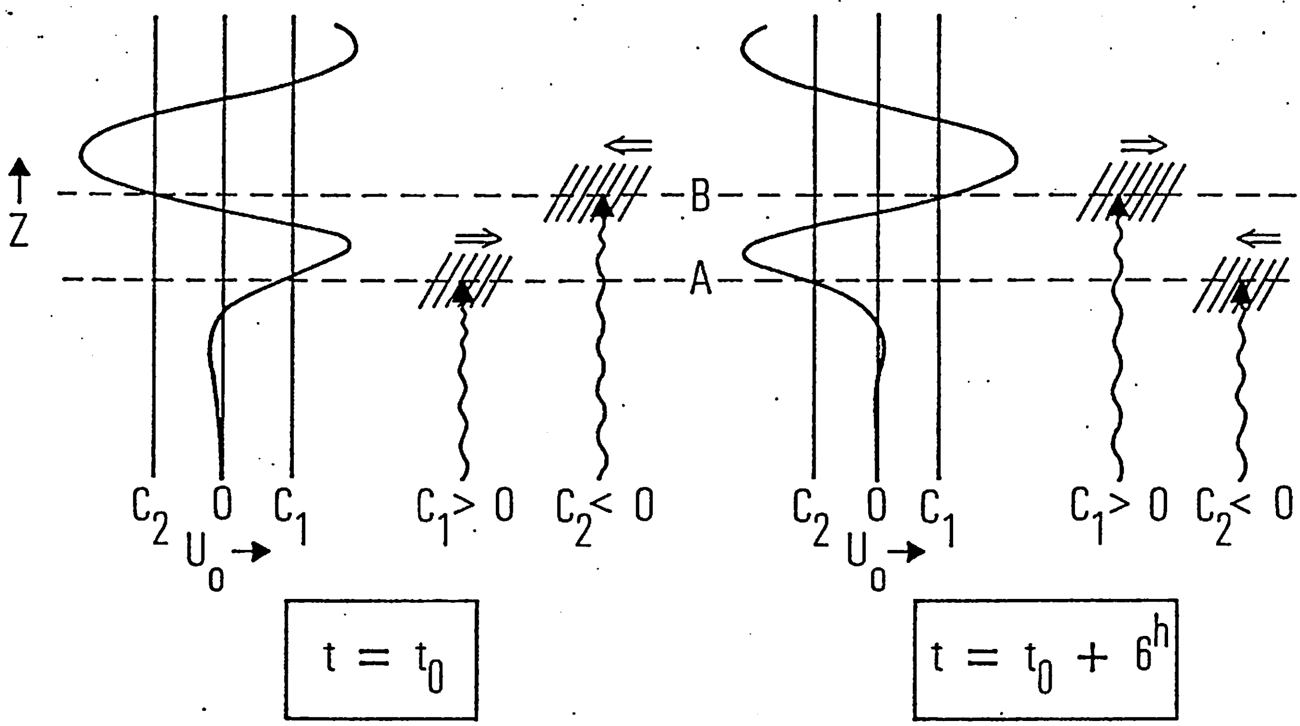
Wave transience

Pseudotides

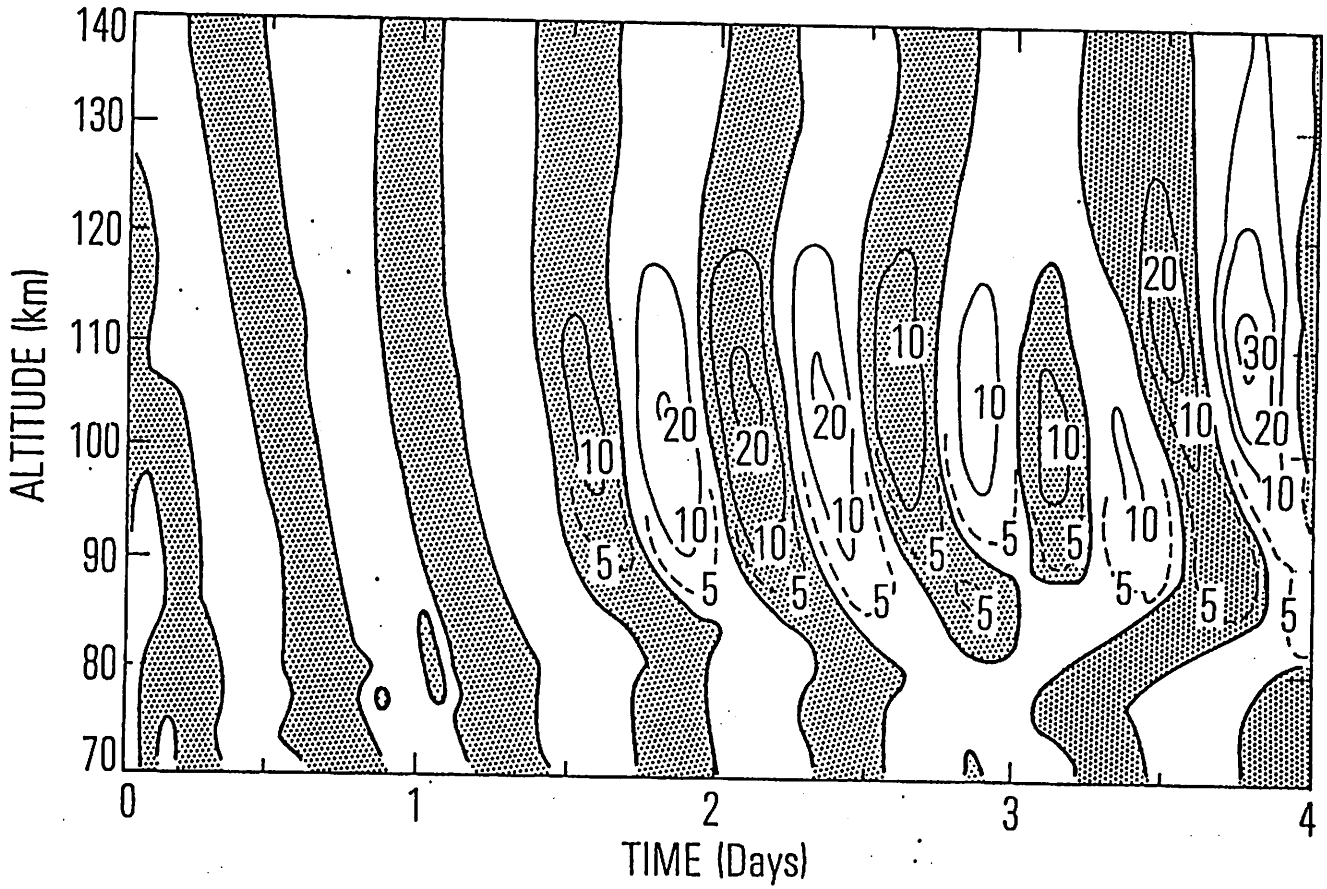
Tides: Periodic response to periodic external forcing by astronomical agency

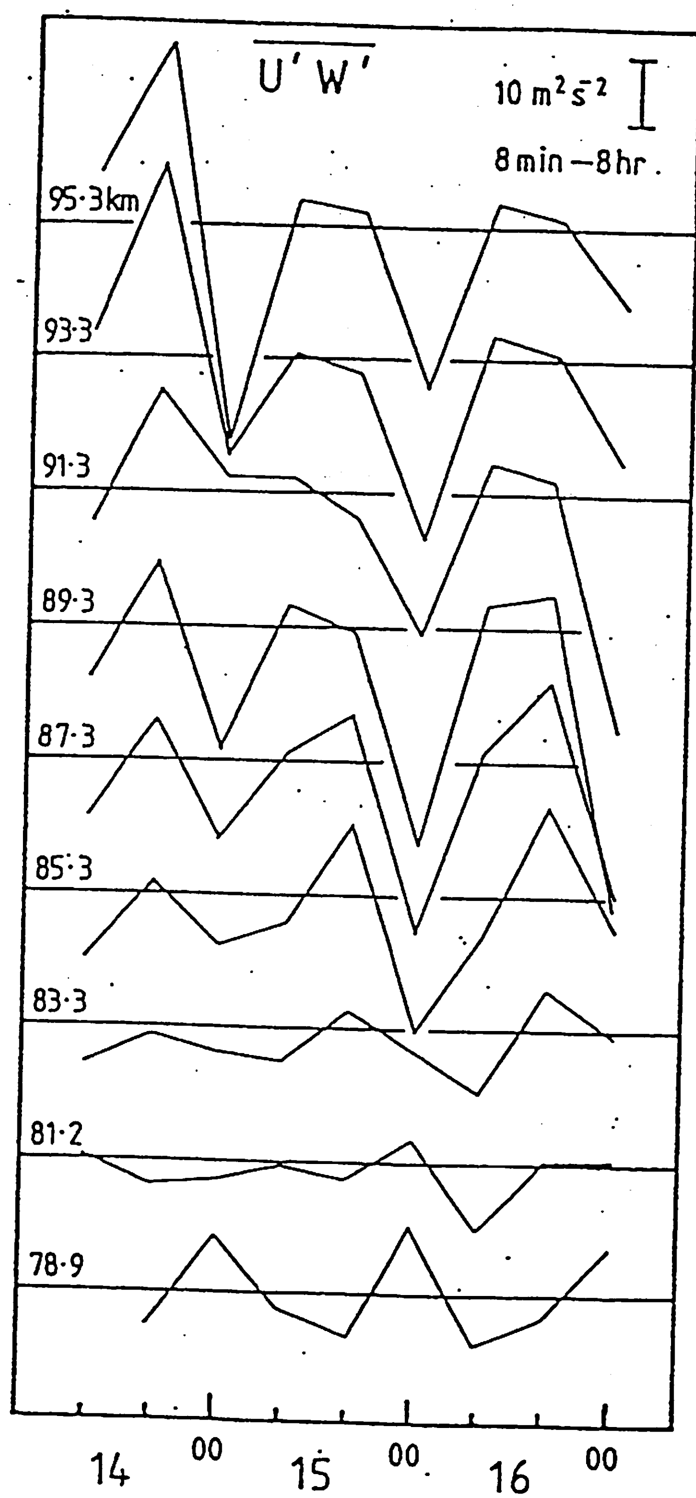
Pseudotides: Tidal frequency oscillations forced internally by tidally modulated gravity wave mean flow interactions

> Viscous absorption near critical levels (Walterscheid, 1981)
>
> Wave breakdown (Fritts and Vincent, 1987)



Z
B
A
C_2 0 C_1
U_0
$C_1 > 0$ $C_2 < 0$
$t = t_0$
C_2 0 C_1
U_0
$C_1 > 0$ $C_2 < 0$
$t = t_0 + 6^h$


ALTITUDE (km)
140
130
120
110
100
90
80
70
TIME (Days)
0
1
2
3
4
5
10
20
30


$\overline{U'W'}$
10 m^{2}s^{-2}
8 min — 8 hr.
95·3km
93·3
91·3
89·3
87·3
85·3
83·3
81·2
78·9
14
00
15
00
16
00

Tidally Modulated Gravity Wave Mean Flow Interactions

Fritts and Vincent (1987)

Observed correlation between momentum fluxes and tidal winds

Proposed that gravity waves dissipate via wave breakdown

Lu and Fritts (1992)

Used momentum flux parameterization based on linear saturation theory

Simulated large wave-induced tidal period oscillation

Forbes et al. (1991)

Examined nonlocal effects

Used saturation parameterization in tidal model and inferred deceleration of global tidal modes

Chemical Forcing of Mean-State Minor Constituent Profiles

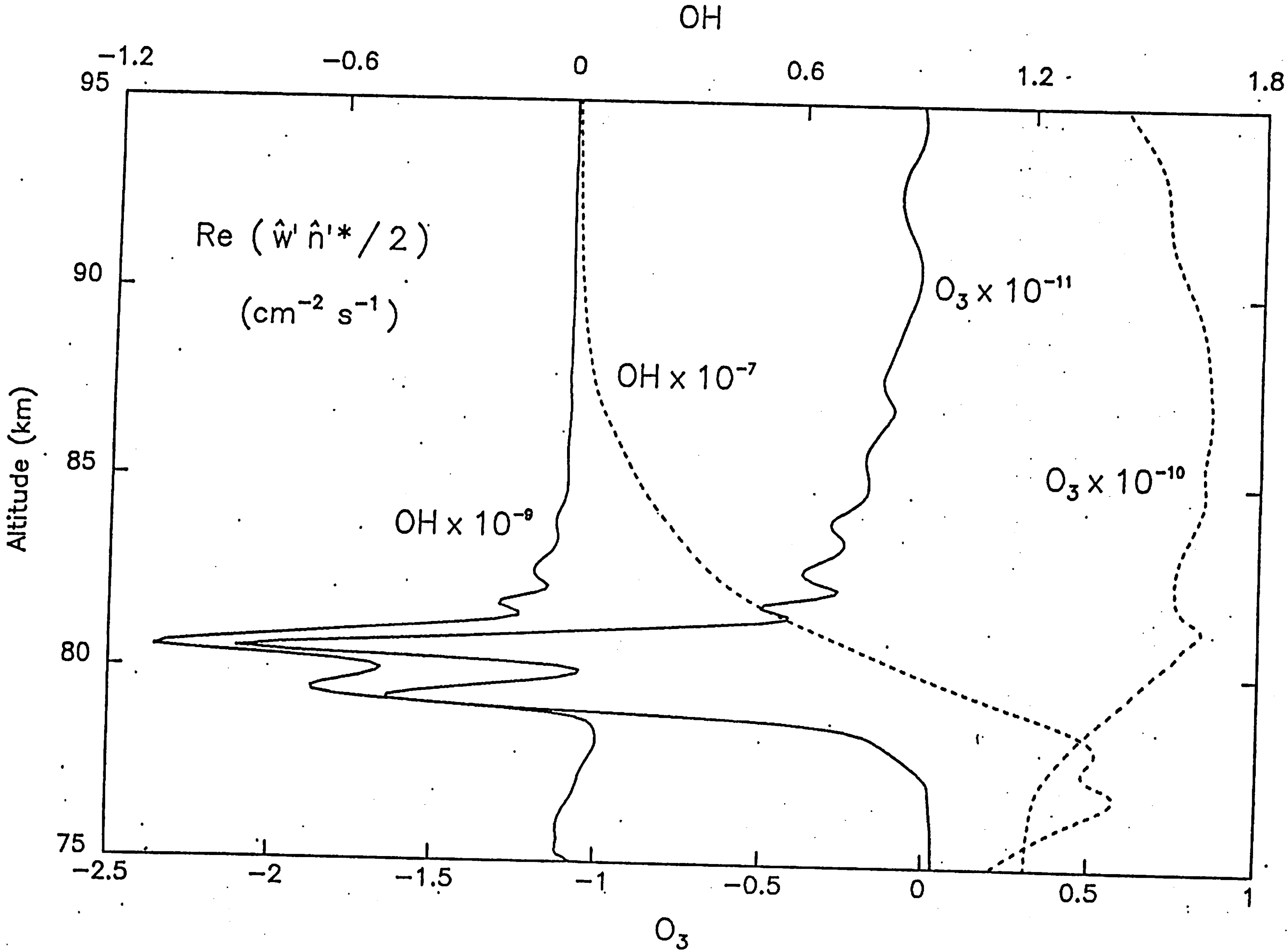
Vertical flux of constituent mixing ratio is zero when nonacceleration conditions apply and chemical production and loss are nil

Vertical flux can be induced by chemistry even when nonacceleration conditions apply

Strobel (1981) parameterized effects of chemistry in terms of eddy diffusion coefficient

Schoeberl et al. (1983) modified Strobel's parametization to incorporate turbulent mixing (Lindzen, 1981; Garcia and Solomon, 1985, Bjarnason et al., 1987; LeTexier et al., 1987)

Walterscheid and Schubert (1989) used five-reaction model of wave-perturbed O_3 chemistry near the mesopause to calculate chemically induced wave fluxes of minor constituents



OH
−1.2
−0.6
0
0.6
1.2
1.8
95
90
85
80
75
Altitude (km)
Re (ŵ' n̂'* / 2)
(cm⁻² s⁻¹)
$O_3 \times 10^{-11}$
$OH \times 10^{-7}$
$OH \times 10^{-9}$
$O_3 \times 10^{-10}$
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
O_3

Conclusions

Gravity wave drag is the probable cause of the cold summer mesopause

Tidal modulation of gravity wave induced winds may generate strong mean winds with tidal frequency in the upper mesosphere and lower thermosphere

Gravity wave induced fluxes of chemically reacting species can alter concentrations on time scales comparable to chemical lifetimes in the mesopause region, and can be comparable to fluxes attributed to small-scale turbulence