NCAR Manuscript No. 68-205

PLANETARY WAVES AND LARGE-SCALE DISTURBANCES IN THE STRATOSPHERE AND MESOSPHERE*

Robert E. Dickinson

National Center for Atmospheric Research

Boulder, Colorado

September 1968

*Paper presented at Third Illinois Aeronomy Conference, "Meteorological and Chemical Factors in D-Region Aeronomy," September 1968.

1. Introduction

It has become increasingly clear from statistical studies that there exist connections between stratospheric and ionospheric processes (Bossolasco and Elena,[1] Shapley and Beynon,[2] Gregory,[3] and Belrose[4]). It is now necessary to develop physical models of this interaction not only to explain the present body of data but also to provide a theoretical structure for more systematic observational investigation. Ionospheric fluctuations are generally ascribed to anomalous composition changes at the same level. These in turn can be due either to irregular transport processes or to temperature fluctuations affecting photochemical rates. I shall discuss here some aspects of the connection by planetary waves of wind and temperature oscillations between the lower stratosphere and the upper mesosphere.

I shall consider three points: (1) the definition and observational basis for planetary waves; (2) the objectives of planetary wave theory; (3) interpretation of mesospheric motions according to the present theory.

2. Definition and Observational Basis for Planetary Waves

Let us refer to the fields of horizontal winds, vertical motion and accompanying perturbations in the pressure, temperature, and density fields altogether as "atmospheric motions." The term "planetary wave," as coined by Rossby, refers to the deviations from symmetric motions occurring in middle and high latitudes with a time scale long compared to a day.

Historically, the recognition that such motions correspond to a separate degree of freedom in a rotating fluid goes back to Hough's[5] development of tidal theory. This work was all but forgotten when Rossby[6] rediscovered these motions in a very simple context. The resulting interpretations proved so fertile that they essentially resulted in the birth of modern dynamic meteorology and numerical weather forecasting.

Theory and observation both indicate that only planetary wave components of global horizontal extent can propagate upward out of the troposphere, so the adjective "planetary" seems especially appropriate for those global-scale meteorological eddy motions that extend upward from the troposphere into the stratosphere and mesosphere. For the remainder of this paper, I shall consider planetary waves defined in this more limited sense. Discussion is restricted to middle and high latitudes because the theoretical distinction between planetary waves and gravity waves becomes blurred in the vicinity of the equator.

In order to distinguish observationally planetary waves from other motions, one needs not only data with sufficient resolution in space to separate the eddies from the zonal flow, but also sufficient resolution in time to permit separation of the long period disturbances from the tides and gravity waves.

The troposphere is dominated by long period motions generated by the baroclinic release of potential energy. The global network of meteorological observations, taken once or twice a day, can provide a description of planetary waves in the lower atmosphere limited primarily by our capacity to reduce and evaluate large amounts of data. As we progress upward to the mesosphere, where tidal and gravity wave amplitudes are as large as planetary wave amplitudes, we need more frequent observations to resolve planetary waves, but unfortunately, as a result of increased expense and few users, the available data are much more limited in their space and time coverage.

The Free University of Berlin and the Upper Air Branch of the Weather Bureau's National Meteorological Center have for several years now prepared a continuous series of stratospheric maps up to 10 mb (roughly 30 km) and have recently begun analyses at higher levels[7,8] using meteorological rocket data. In the next two figures I would like to show 0.4 mb (essentially stratopause level) Weather Bureau maps typical of summer and winter conditions in the upper stratosphere. Figure 1 indicates that at least up to the stratopause the easterly summer circulation is a symmetric vortex about a high pressure cell over the pole. The cross isobaric flow indicated by the wind arrows is interpreted as a tidal contribution to the motion which has been filtered out in the map analysis. Figure 2, representative of late fall or early winter circulation, indicates the westerly winter circulation is typically oval shaped and displaced somewhat from the winter pole. Mathematical description of these departures from symmetry is in terms of Fourier wave components. Fourier decomposition is only possible at the 5 mb level or below, where hemispheric maps are available. Most of the variance of these departures is found to reside in longitudinal wave numbers one and two.

The wave number one component represents much of the displacement of the vortex from the pole, while the departure from spherical shape of the stream lines is largely given by wave number two. Figure 3, from Muench,[10] shows the monthly mean amplitude and phase angle for wave number one during January 1958. This wave tilts westward with increasing height. The phase increases by almost a full cycle, and the amplitude by an order of magnitude going from the surface to 10 mb. I have been emphasizing the typical winter stratospheric motions. There are occasionally spectacular departures from these typical conditions during periods of "midwinter breakdowns" of the vortex. These are also known as "sudden warmings" because of the accompanying introduction into high latitudes of large pools of warm air. Figure 4, taken from a recent synoptic analysis of Williams,[11] shows the February 1966 breakdown of the upper stratosphere in progress. The main synoptic feature accompanying wave number one, the Aleutian high, is amplified and pushed poleward, splitting the polar vortex in two.

To summarize the observational status of planetary waves, we note that the present ceiling for detailed observational information on planetary waves is about 30-35 km. The limited observations at higher levels are not really sufficient to resolve planetary waves, but do indicate an upward extension into the mesosphere of the gross features of planetary waves in the middle stratosphere. Large amplitudes are indicated for the winter season, and amplitudes too small to be detected against the background noise of tides and gravity waves in the summer.

3. Objectives of Planetary Wave Theory

Planetary wave theory as I have defined it involves slowly evolving global scale eddies propagating upward from sources in the troposphere. We seek to identify the governing equations, including relevant approximations, and to develop integration procedures for these equations. In developing planetary wave theory, however, we must recognize the peculiarities distinguishing these motions from motions of the troposphere, that is:

a. Inadequate observations for the calculation of time-dependent planetary waves as functions of initial conditions;

b. The apparent dependence of the excitation of planetary waves on conditions in the lower troposphere.

These two considerations provide a rationale for the hypothesis that planetary wave motions can, to a first approximation, be defined entirely by the past history of some open lower boundary, say the 10 mb (30 km) surface. Thus I propose as a goal of planetary wave theory the development of dynamic models giving long period eddy motions in the mesosphere as functions of prescribed conditions at some lower boundary. These models could then be coupled to the elaborate numerical models of the lower atmosphere to construct upper atmosphere motions and possibly, as a by-product, improve the upper boundary condition of the lower atmosphere models. A first effort along these lines has been made by Byron-Scott.[12]

4. Interpretation of Mesospheric Motions

It may be possible, as I have just suggested, for dynamic meteorologists to provide aeronomers with useful predictions of the time-dependent long period motions at D-layer heights, considering these motions to be forced by a "radiating top" of the lower atmosphere. The available upper level wind observations should, of course, whenever possible, be incorporated in such a prediction model. A first necessary step for such a program is to get a good qualitative understanding of the importance of various dynamical processes.

My interest has been in the development of linear analytic models to provide such an understanding. Assume motions of a single spectral component - that is, a single wave number and phase speed in longitude. We may then, without further loss of generality, consider only motions in a coordinate system moving with the phase speed of the wave to eliminate dependence on time. Anyway, the almost time-independent waves excited by orography and ocean-continent heating contrasts are of special interest. The following effects are then revealed by linear theory as developed by Charney and Drazin,[13] Lindzen,[14] myself,[15, 16, 17, 18] and others.

a. Dependence of disturbance structure on the horizontal wave number of disturbances. High wave number disturbances conserve local potential vorticity and are essentially advected with the mean flow, while planetary-scale disturbances interact with the vorticity of the earth's rotation and can propagate through the atmosphere as waves, that is, planetary waves.

b. The easterly wind filter - planetary waves are everywhere strongly evanescent[13] in the presence of an easterly zonal wind. This prediction is strikingly born out by the almost complete zonal symmetry of long period motions of the upper stratosphere in summer and the large amplitude asymmetries observed in winter.

c. The trapping of vertically-propagating planetary-scale waves by strong westerly winds.[13]

d. Absence of such trapping locally near the equator.[14] This vanishing of the trapping near the equator diminishes the trapping of normal modes in a spherical geometry from that indicated by mid-latitude zonal strip models.[15] If we assume the atmosphere to be in constant angular rotation, the appropriate planetary wave normal modes for a spherical geometry are the Hough functions of tidal theory. Table I indicates the strength of westerly winds at 45N necessary for the lowest normal modes to be evanescent. Here m is the longitudinal wave number; j-m is the modal number. While the model considered here is rather unrealistic, it is at least as acceptable as that of Charney-Drazin[2] and suggests that for typical winter winds not exceeding 100 m/sec there will always be some modes that can leak up through strong westerly winds.

e. The guiding of planetary waves by horizontal shears.[16]

f. The absorption of planetary waves at singular lines where the wave phase speed equals the zonal velocity.[15,16] Figure 5 shows a schematic drawing of the winter-summer zonal winds and the trajectories of planetary wave rays in the presence of these winds. The maximum westerly jet in middle latitudes at the stratopause acts as a reflecting barrier as indicated by the earlier Charney-Drazin study,[13] but now the inclusion of latitudinal variation of winds suggests the formation of polar and equatorial wave guides where the winds are weaker. Rays in the polar wave guide undergo multiple reflections between the pole and the westerly jet, setting up a standing wave normal mode in latitude. I would like to suggest that this description applies to the Alaskan high planetary wave observed in the stratosphere. Perhaps of more interest is the deflection of rays in the equatorial wave guide onto the zero wind line where they are absorbed. This internal absorption should result in rapid attenuation with height of disturbances in tropical latitudes, and may provide the drive for the semi-annual wind oscillation over the equator in the mesosphere (cf. Reed[19]). Leakage of planetary waves from the polar wave guide may, however, maintain a flux of planetary waves into the zero wind line at higher levels. Figure 6, taken from Webb,[20] indicates the presence of large amplitude planetary waves along the winter-summer zero wind line (which he denotes the "interhemispheric front").

g. Strong damping of planetary waves by radiative processes for weak zonal winds.[18] Figure 7 shows the fractional damping in one scale height for wave numbers one (a) and two (b) using typical parameters and Newtonian cooling ranging in time from 1 to 100 days. The shaded region of parameter space shows where the damping is severe enough to give wave amplitudes decreasing with height.

h. Potential vorticity transport and hence transfer of momentum and heat from the planetary waves to the zonal flow consequent to singular line absorption or dissipation.[17] Because of the strong interaction between planetary waves and the zonal wind it will probably also be necessary to calculate zonal motions as responding to the influx of solar radiation and coupling with the planetary waves.

The other processes that determine to a large extent the structure of zonal winds are the temperature-dependent heat losses[21, 22, 23] including possible coupling with the ozone photochemistry. This coupling is, however, negligible, if the joint losses of oxygen and ozone are determined primarily by hydrogen compound reactions.[24,25]

Recently numerical general circulation calculations have been made by Hunt and Manabe,[26] modeling the planetary horizontal and vertical transports of ozone and radioactive dust in the lower stratosphere. Figure 8, taken from this study, shows the rate of change of a trace substance due to large scale atmospheric transport. The change by eddies is shown on the left, the change by meridional circulation on the right. These calculations suggest the level of information on trace substance transport processes that meteorologists may eventually be able to provide.

To summarize, planetary waves can influence D-layer processes:

a. by direct transport

b. by forcing zonal winds and meridional circulations

c. by modulating upward propagating gravity waves and other small-scale structures.

The last two possibilities will be important for D-layer processes if the consequent motions are important for trace substance transports.

References

[1] Bossolasco, M. and A. Elena, Compt. Rend. 256, 4491-4493, 1963.

[2] Shapley, A. and W. Beynon, Nature 206, 1242-1243, 1965.

[3] Gregory, J., J. Atmos. Sci. 22, 18-23, 1965.

[4] Belrose, J., Nature 214, 660-664, 1967.

[5] Hough, S., Phil. Trans. Roy. Soc. A 191, 139-185, 1898.

[6] Rossby, C., J. Mar. Res. 2, 38-55, 1939.

[7] Kriester, B., K. Labitzke, R. Sherhag, and K. Sieland, Meteorologische Abhandlungen 88, 1, 1-23, 1967.

[8] Finger, F., H. Woolf, and C. Anderson, Mon. Wea. Rev. 94, 651-661, 1966.

[9] Staff, Upper Air Branch, N.M.C., ESSA Technical Report, WB-3, 1-73, 1967.

[10] Muench, S., Seventh Stanstead Seminar on the Middle Atmosphere, McGill Publication in Meteorology No. 90, 1-7, 1968.

[11] Williams, B., Mon. Wea. Rev. 96, 549-558, 1968.

[12] Byron-Scott, R., Doctoral Thesis, McGill Publication in Meteorology No. 87, 201 pp, 1967.

[13] Charney, J. and P. Drazin, J. Geophys. Res. 66, 83-109, 1961.

[14] Lindzen, R., Mon. Wea. Rev. 95, 441-451, 1967.

[15] Dickinson, R., Mon. Wea. Rev. 96, 405-415, 1968.

[16] __________, J. Atmos. Sci. 25, Nov. 1968.

[17] __________, J. Atmos. Sci. 26, Jan. 1969 (in press).

[18] __________, J. Geophys. Res. 74, in press, 1969.

[19] Reed, R., J. Geophys. Res. 71, 4223-4234, 1966.

[20] Webb, W., Met. Mono. 9, 31, 158-169, 1968.

[21] Leovy, C., J. Atmos. Sci. 21, 327-341, 1964.

[22] Dickinson, R., J. Atmos. Sci. 25, 269-279, 1968.

[23] Lindzen, R., Met. Mono. 9, 31, 37-46, 1968.

[24] Hunt, B., J. Geophys. Res. 71, 1385-1398, 1966.

[25] Leovy, C., Rand Memo. RM-5643-PR, 28 pp, 1968.

[26] Hunt, B. and S. Manabe, Mon. Wea. Rev. 96, 503-539, 1968.

Figure Legends

Figure 1. Height contour map of the 0.4 mb surface for July 14, 1965[9] - and typical of summertime circulation in the upper stratosphere.

Figure 2. Height contour map of the 0.4 mb surface for November 17, 1965[9] - and typical of the wintertime circulation in the upper stratosphere.

Figure 3. Wave number one for January 1958[10] - showing the longitude of the high pressure center (above) and the amplitude in meters (below).

Figure 4. Height contour map of the 1 mb surface for February 7, 1966[11] - showing a stratospheric breakdown in progress.

Figure 5. Schematic sketch of the winter and summer zonal wind systems indicating planetary wave ray paths for the winter hemisphere.[17]

Figure 6. Sketch of deformation of the zero wind line in the upper stratosphere during the "winter storm period."[20]

Figure 7. Planetary wave transmissivity as a function of Newtonian cooling coefficient and zonal wind. The relative damping of energy density in one scale height is shown for latitudinal scale of 5.10^8 cm and longitudinal scales of (a) 5.10^8 cm and (b) 2.10^8 cm.

Figure 8. Total rate of change of trace substance by combined vertical and horizontal motions according to Hunt and Manabe.[26] Eddies are on the left, meridional circulation on the right.

TABLE 1.—*The westerly zonal wind in m./sec. at 45° N. beyond which, according to the theory of this paper, the Rossby wave modes are trapped (assuming trapping for* $\gamma < 10$*).*

m	j	The exact model	The approximate model
1	1	1583.0	400.6
1	2	77.2	83.2
1	3	43.2	44.8
1	4	27.0	28.8
2	2	144.9	125.0
2	3	49.2	50.2
2	4	29.6	30.0
3	3	62.4	59.3
3	4	31.9	
4	4	35.5	
5	5	23.1	

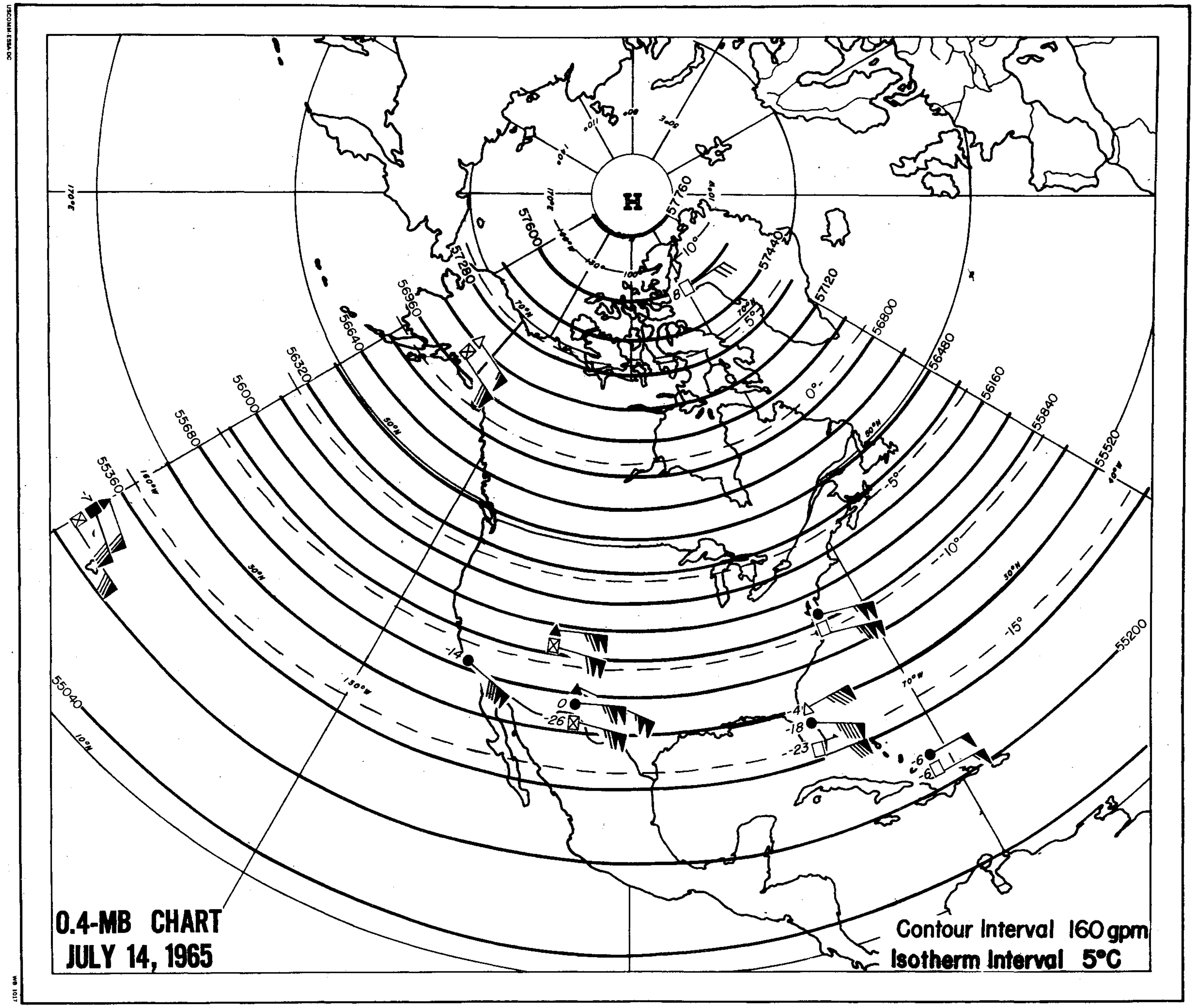

0.4-MB CHART
JULY 14, 1965
Contour Interval 160 gpm
Isotherm Interval 5°C
H
57760
57600
57440
57280
57120
56960
56800
56640
56480
56320
56160
56000
55840
55680
55520
55360
55200
55040
10°
5°
0°
-5°
-10°
-15°

Fig. 1

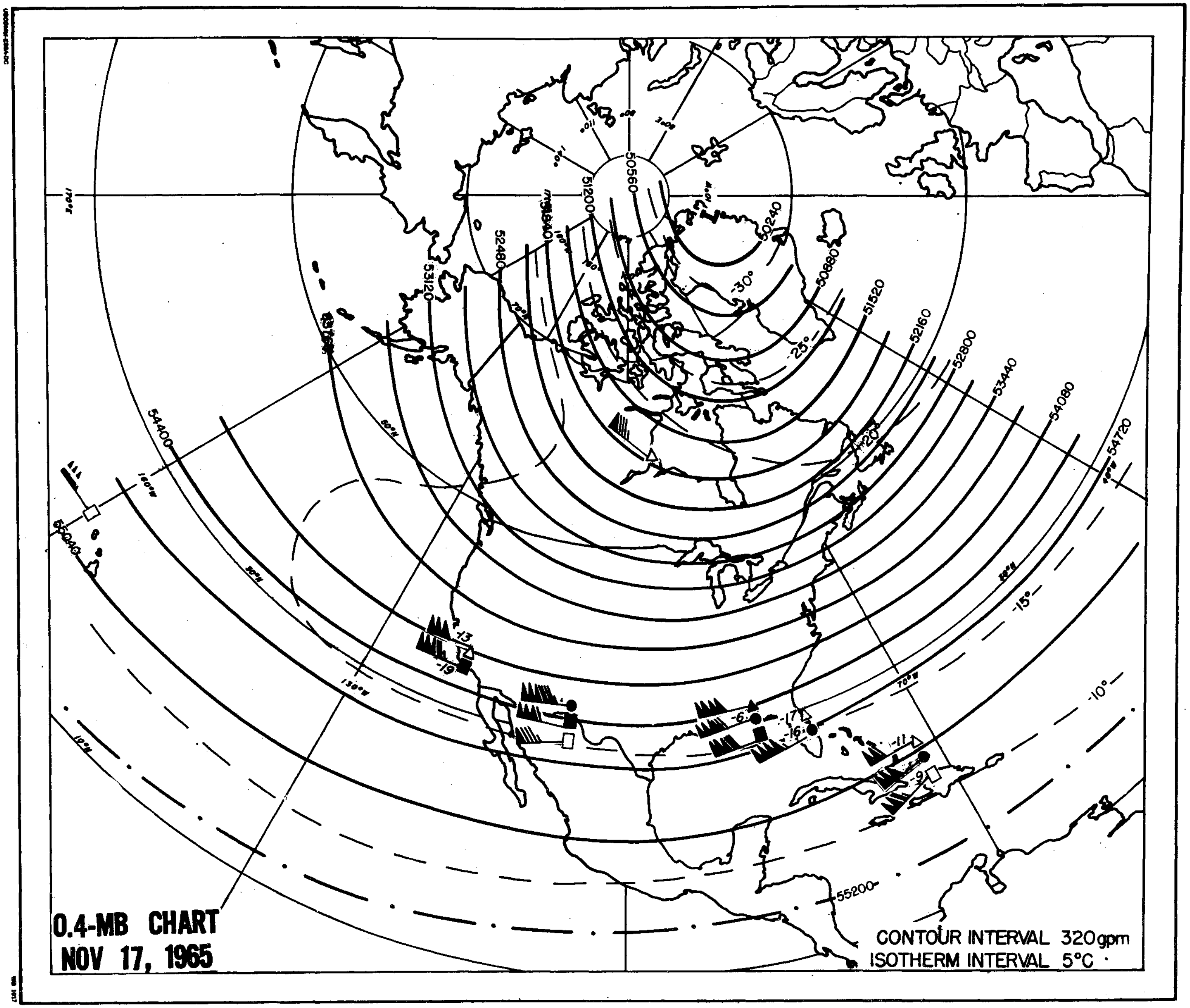
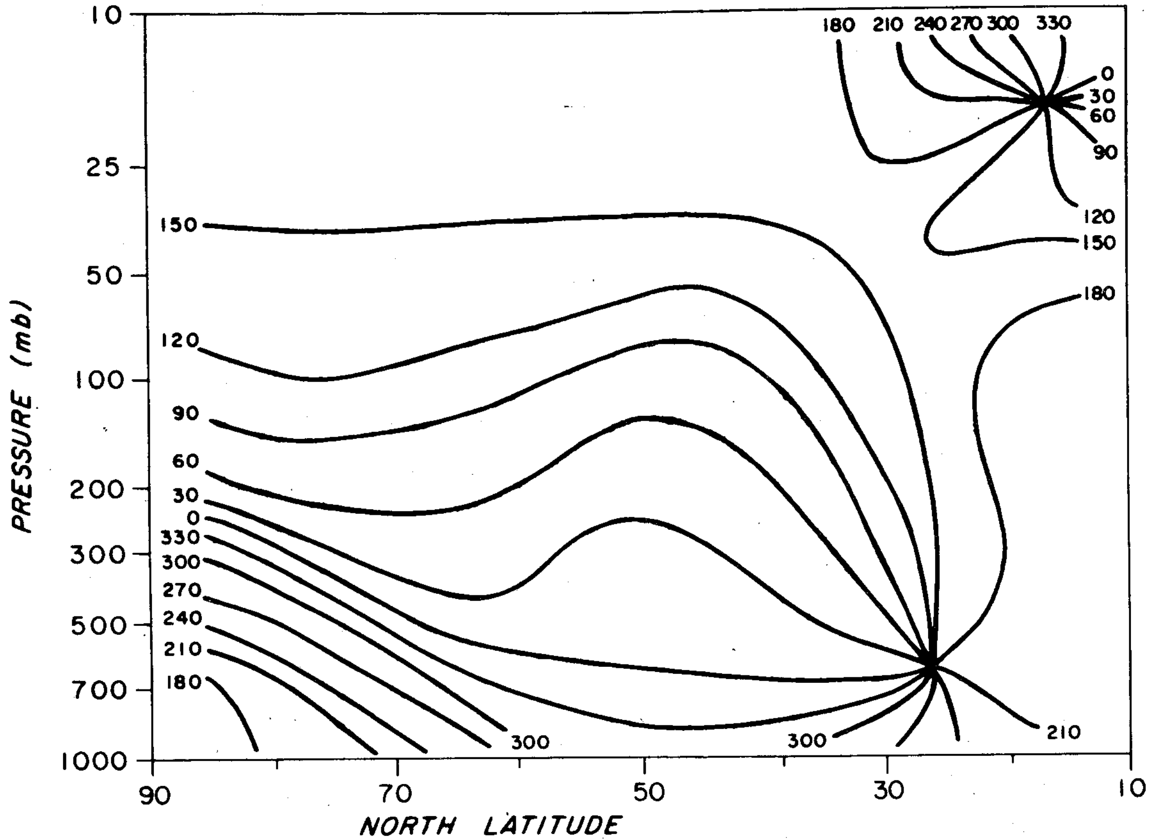
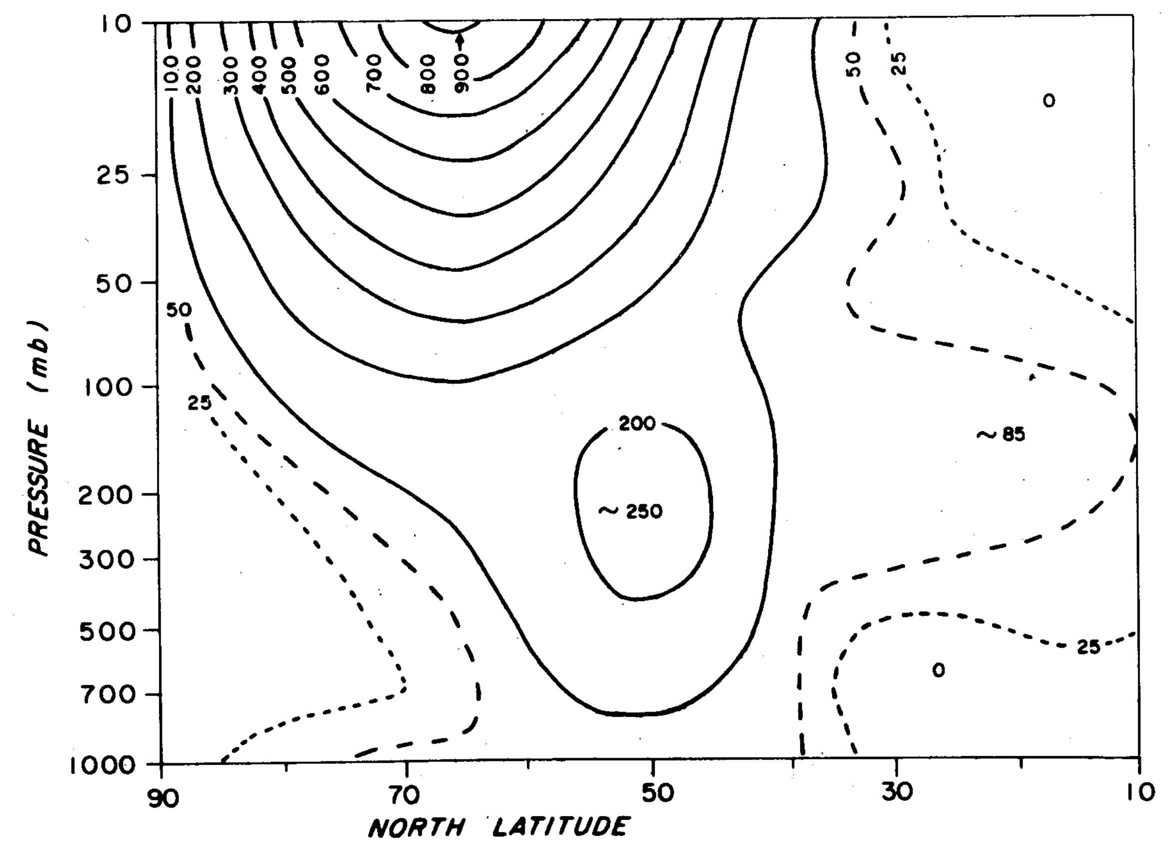

0.4-MB CHART
NOV 17, 1965
CONTOUR INTERVAL 320gpm
ISOTHERM INTERVAL 5°C
50560
50240
50880
51200
51520
52160
52480
52800
53120
53440
54080
54400
54720
55040
55200
-30°
-25°
-20°
-15°
-10°
-13
-19
-6
-17
-16
-11
-9

Fig. 2



LONGITUDE OF RIDGE, WAVE NO. 1, JAN. 1958



AMPLITUDE OF WAVE NO. 1, JAN. 1958, METERS

Fig. 3

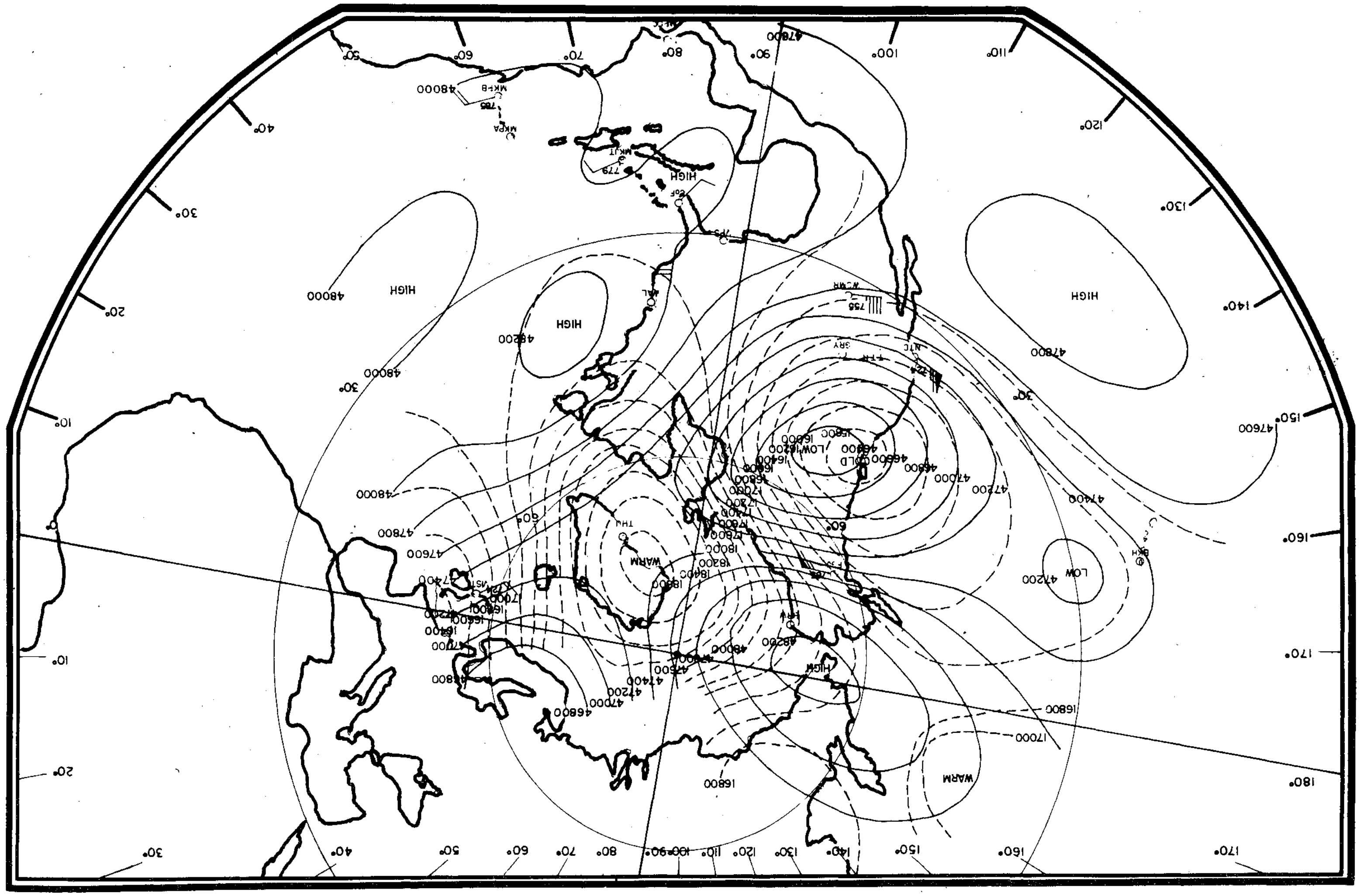
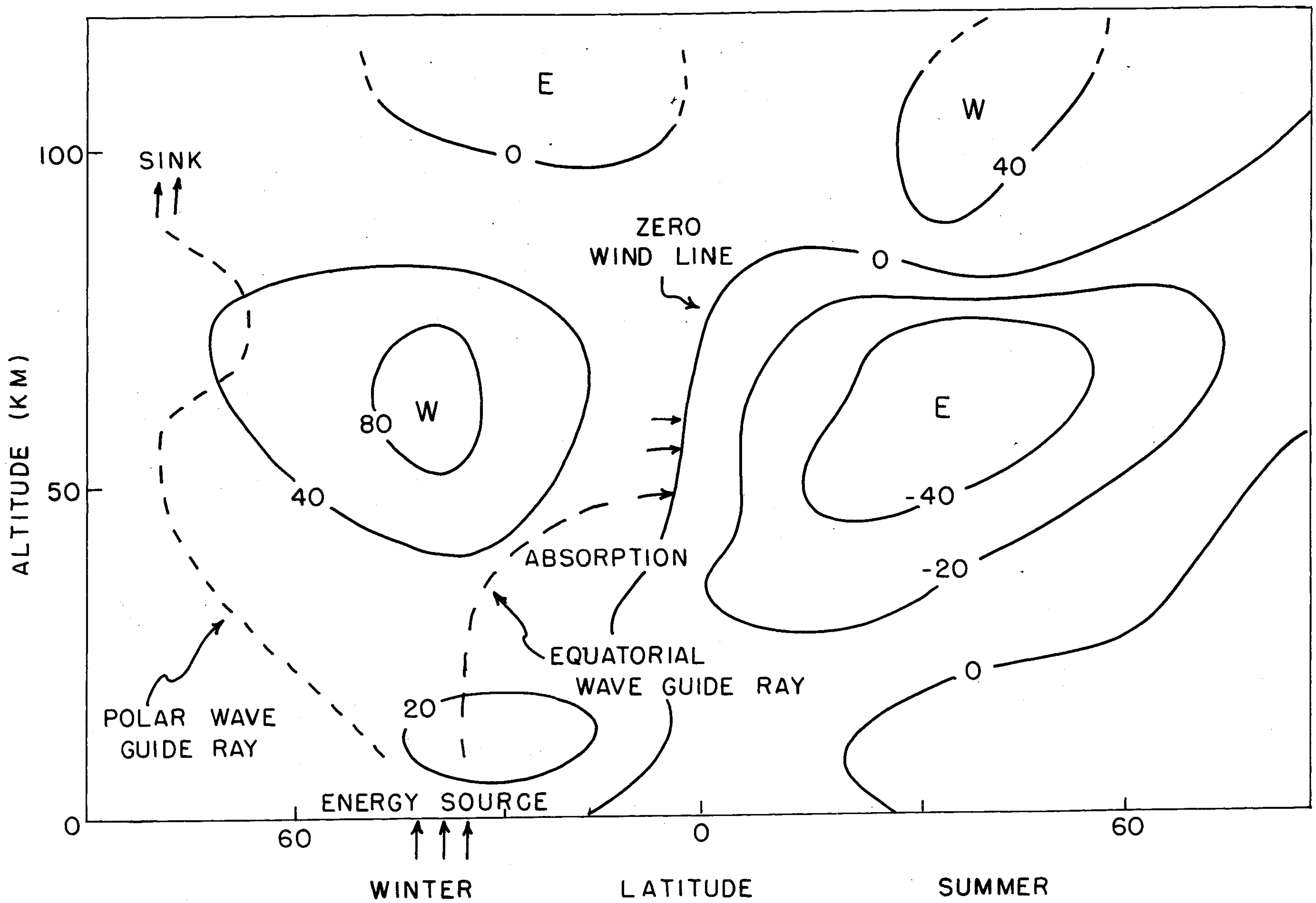


Fig. 4



E
W
100
SINK
0
40
ZERO
WIND LINE
0
W
80
E
50
40
-40
ABSORPTION
-20
EQUATORIAL
WAVE GUIDE RAY
0
20
POLAR WAVE
GUIDE RAY
ENERGY SOURCE
0
60
0
60
WINTER
LATITUDE
SUMMER
ALTITUDE (KM)

Fig. 5

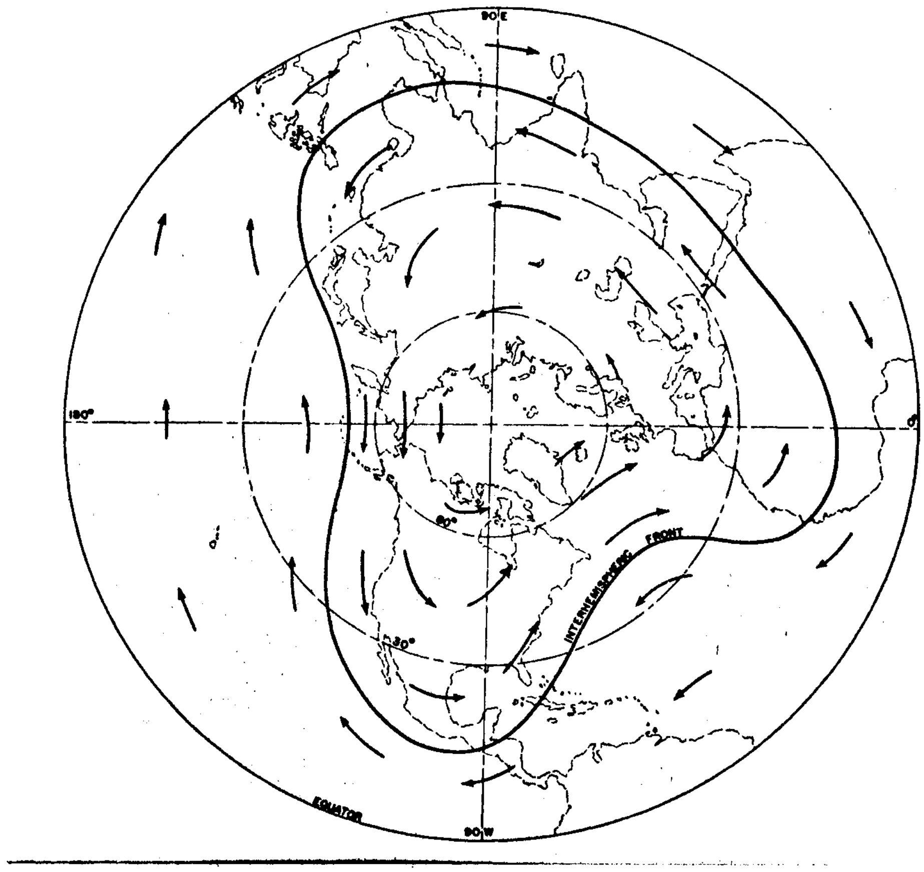


Fig. 6

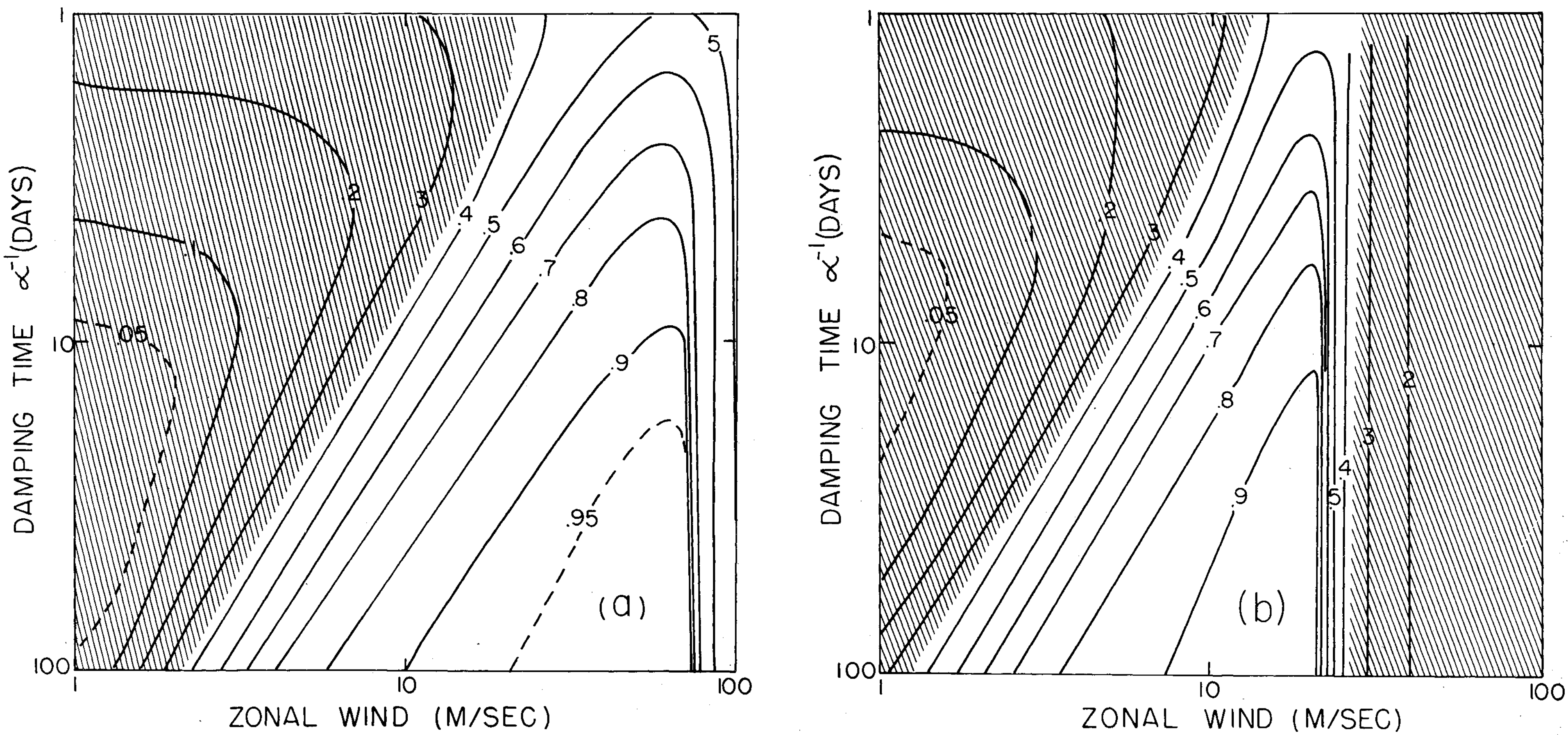

DAMPING TIME α^{-1}(DAYS)
ZONAL WIND (M/SEC)
1
10
100
.05
.1
.2
.3
.4
.5
.6
.7
.8
.9
.95
(a)
(b)

Fig. 7

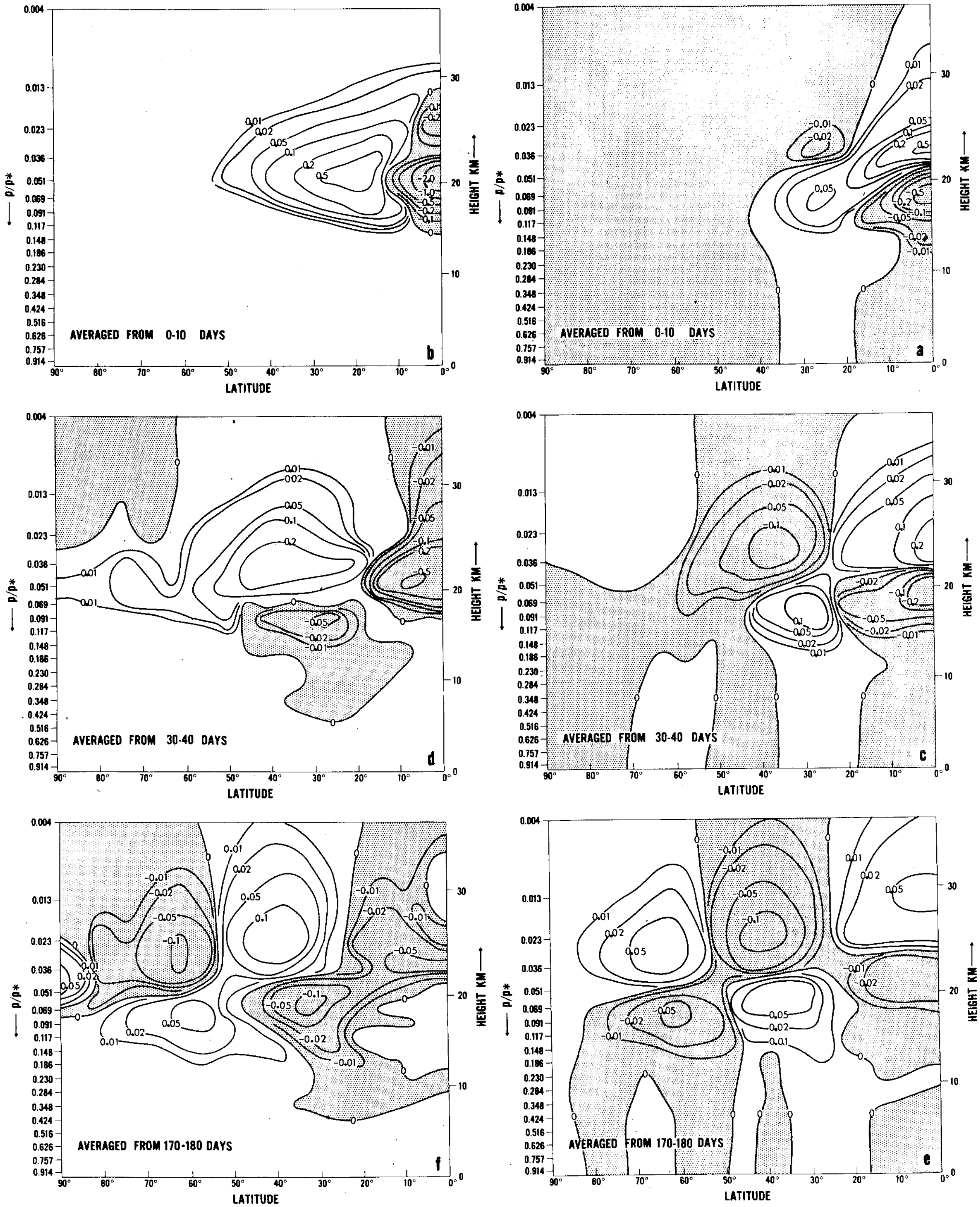

AVERAGED FROM 0-10 DAYS
b
a
AVERAGED FROM 30-40 DAYS
d
c
AVERAGED FROM 170-180 DAYS
f
e
LATITUDE
p/p*
HEIGHT KM

Fig. 8