EXPLORATORY STUDY ON THE PHYSICAL NATURE OF CERTAIN MESOSTRUCTURAL DETAILS IN VERTICAL WIND PROFILES

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Atmospheric Science Department
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ABSTRACT

A series of 18 balloon soundings made at approximately 45-minute intervals on 3 January 1963 from Cape Canaveral, using FPS-16 radar for tracking, revealed certain structural details in the vertical wind profiles which --- due to their persistence in time and space -- have to be considered as atmospheric perturbations and not as instrument noise.

This report contains a brief and exploratory study on the possible nature of these perturbations. Some of the mesostructure in the vertical wind profiles shows a certain correlation with changes in the temperature lapse rate. There is also a possiblity that secondary wind speed maxima and minima may be induced by phase differences of internal waves within adjacent atmospheric layers.

Recommendations for future measurements and research efforts are made.

1. Purpose and Scope of Study:

From a close scrutiny of upper-wind data obtained with standard rawinsonde equipment, as for instance the GMD-1A, it becomes obvious that these systems are subject to relatively large errors in measurements, especially in the vicinity of, and above, jet streams. In order to reduce these errors to a limit tolerable for routine weather analysis a drastic smoothing over at least two-minute intervals is applied to the wind data (Reiter, 1957, 1958; for extensive literature references see Reiter, 1961a, 1963a).

For missile design and operation it became imperative to know more about small-scale details of vertical wind shear. Serial ascents of rawinsondes revealed that certain features in vertical wind profiles may remain in existence for several hours (Barbé, 1957). Due to instrumental errors and the necessary smoothing operations these measurements did not permit valid conclusions as to the size and persistence of meso- and microscale perturbations in the atmospheric field of flow.

Aircraft measurements, especially those of Project Jet Stream Endlich, 1963; Reiter, 1961b, c, d, 1962a; Reiter, Lang, et al., 1961) substantiated the existence of mesoscale disturbances along horizontal flight legs. Positive and negative "anomalies" in wind speeds -- as compared with a smoothed basic field of flow -- seem to be oriented along isentropic channels parallel to the direction of flow. Some of these mesoscale features could be identified over several hundreds of miles downstream, and over several hours of flight time.

Although flight measurements usually give a poor indication of vertical distributions of meteorological parameters, the existence of a non-random but well-organized mesostructure of wind and temperature fields along quasi-horizontal coordinates necessarily leads to the conclusion that some of the "irregularities" encountered in vertical wind profiles obtained with classical equipment actually reflected atmospheric disturbances rather than instrument errors.

More advanced wind sounding systems like the FPS-16 radar and the smoke trail photographic technique have to a large extent overcome the barrier in instrumental accuracy, which limited the use of the GMD series (Scoggins, 1963a; Scoggins and Vaughan, 1963). A new barrier is set by the not yet fully explored aerodynamic behavior of rising balloons in the FPS-16 measurements and by small-scale diffusion processes affecting the smoke trails from rockets used in the above-mentioned photographic technique.

Nevertheless, a large number of wind measurements carried out so far indicates the existence of meso- and microscale stratifications in vertical wind profiles, which are well above noise level of instrumental errors and erratic balloon behavior. Some of these detailed features seem to be highly transient in nature; others, however, may persist for several hours.

From the point of view of missile design the mere existence of a mesostructure along vertical wind profiles is of sufficient interest to warrant its study. A logical approach has been taken by Scoggins (1963b) who performed power-spectrum analyses of such detailed profiles. While the results of such studies give valuable information on atmospheric input into missile response along trajectories under various adverse wind conditions, the question of response during any one <u>specific</u> mission is still left open -- even with given pre-launch wind information -- as long as the <u>representativeness</u> in time and space of the wind profiles measured is not known. Optimum information on winds aloft for a launching operation should contain not only the spectral distribution of gusts derived from detailed vertical wind profiles at the time of measurement, but at the time of launching. This necessitates the following:

1. Distinction between the transient and the quasi-stable meso-structural features in vertical wind profiles.

2. Short-range forecasts of mesostructural details in the wind field within the layers affecting the first stage of the missile.

In order to arrive at a solution to these two problems, the physical properties of the atmospheric mesostructure will have to be known. The present study -- only preliminary in scope and nature -- has been set up in order to establish possible causes of structural details in vertical wind profiles. Larger samples of data and modified collection techniques will be needed in order to specify more clearly the physical processes leading to the formation of these structural details and hence to methods of forecasting them.

2. Data Sample:

The sample of data used in this study consists of 18 balloon runs, measured over Cape Canaveral on 3 January 1963 with an FPS-16 radar. The balloons were released at approximately 45-minute intervals (Scoggins, and Vaughan, 1963). Wind readings were obtained every 0.1 seconds and averaged over 25 m or 3 second periods. The values thus obtained are plotted as series of dots in Figure 1.

Four rawinsonde runs were made during the time interval covered by this experiment: one each at 11 GCT, 17 GCT, 20 GCT, and 23 GCT.

The wind profiles obtained from these ascents by standard rawinsonde tracking equipment are entered as solid lines in Figure 1 and are superimposed upon the appropriate FPS-16 soundings.

As a whole, the agreement between FPS and rawinsonde data is reasonably good, especially as far as the representation of a smoothed vertical profile of the basic flow from which mesostructural details have been eliminated is concerned (see Figure 3). There are, however, several regions in which small-scale mesostructural details detected by the two sounding systems do not agree. This is particularly evident from wind data obtained above 10 km at 17 GCT. Apparently in this case the rawinsonde data of Cape Canaveral do not describe adequately the detailed wind structure in the lower stratosphere. The sounding made at Tampa on 3 January, 12 GCT, on the other hand indicates three wind maxima: one each at 10, 12, and 14 km (Figure 2) corresponding closely to what the FPS-16 measures one to two hours later over Cape Canaveral. Because of the slight discrepancies between radar and rawinsonde measurements over the Cape, we may not attach too much significance to the Tampa measurements; however, they tend to support the conclusion that some of the mesostructure is rather persistent in space as well as in time.

Superficial inspection of Figure 1 reveals several rather conspicuous mesostructural wind maxima and minima above the 9 km level, which seem to persist over several hours. The persistence of such features should only be viewed in connection with the thermal structure of the atmosphere, however. One should estimate the behavior of these mesostructural details along isentropic surfaces and in connection with the larger-scale weather situation.

3. The Macroscale Weather Situation:

From the 300 mb maps as obtained through the U.S. Weather Bureau facsimile transmission, it becomes evident that a marked trough was passing the Cape Canaveral area shortly before 12 GCT on 3 January. This is the time in which pronounced mesostructural details start to appear in the wind profiles above 9 km in Figure 1.

It is noteworthy that larger amplitudes of mesostructural anomalies from smoothed wind profiles first appear at higher levels (ca. 12 GCT at 13 km) and subsequently work their way down to lower heights (ca. 13 GCT at 10 km, ca. 14 GCT at 8 km). In previous investigations (Fleagle, 1947; Palmén, 1958; Reiter, 1963b) it has been found that the region to the rear of troughs associated with jet streams usually is characterized by sinking motion in the lower stratosphere. The temperature distribution along stream lines at the 200-mb surface corroborates this for the present case: Cape Canaveral, Fla., reports -54°C at 200 mb on 3 January 1963, 12 GCT; Jacksonville, Fla., -56°C; Charleston, S.C., -56°C; Tampa, Fla., -59°C; Montgomery, Ala. (almost straight upstream from Cape Canaveral), -61°C; Atlanta, Ga., -60°C. (These values, again, are taken from the U.S. Weather Bureau facsimile charts). The strong cold advection at this level (approximately 12 km) would indicate sinking motion.

The 300 mb charts indicate that there are two jet fingers merging into the jet maximum downstream from the trough. The passage of these two fingers is also evident from the time section of wind speeds in Figure 3. This diagram shows the isotachs of the basic flow, from which mesostructural anomalies have been removed.* The first "jet

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* The smoothing has been done graphically by equalizing the areas of positive and negative anomalies as which the mesostructural details of the profiles in Figure 1 may be considered. A numerical approach for this smoothing could easily be devised, using original measurements as input, and filtering oscillations with wave lengths up to 2 vertical km by an overlapping averaging process.

finger" passes shortly before 17 GCT on 3 January; the second one after 00 GCT, on 4 January. The second jet finger has its core about $1\frac{1}{2}$ km higher than the first finger, which also agrees with previous findings (Reiter and Nania, 1963).

4. The Mesostructure in Its Relation to the Large-Scale Weather Pattern:

From Figure 4a it may be seen, that in the layer between 8,500 and 12,500 m the wind veers to a northwesterly direction. This layer apparently outlines the influence region of the northernmost of the two jet fingers. It also contains the most prominent mesostructural features shown in Figure 1.

By 3 January, 17 GCT the winds in the upper troposphere are from NW (Figure 4b). They back to a more westerly direction above 12,000 m, indicating the influence of the southern jet finger overlying the northern one. Similar conditions hold for the 20 GCT sounding.

With the passage of the first jet finger before 17 GCT on 3 January, the upper troposphere undergoes a marked warming trend. The lower stratosphere cools considerably up to about $15\frac{1}{2}$ km as the cold region upstream from the trough, which was mentioned earlier, moves over Cape Canaveral. At the same time the tropopause height rises by about 1,300 m.

Unfortunately no radiosonde ascents were made over the Cape between 11 GCT and 17 GCT of 3 January when the mesostructure in the wind profiles reached its maximum amplitudes. The question, whether these structural details are quasi-geostrophic phenomena which are reflected in the temperature field, can therefore not be resolved with certainty.

The sharp positive vertical shear which appears in sounding No. 31 between 7 and 8 km may coincide with the passage of a baroclinic zone as indicated in the potential-temperature analysis of Figure 5. For the correctness of interpolation details between successive soundings in this diagram there is, of course, no conclusive proof.

We may, however, draw some indirect conclusions as to possible geostrophic relationships between detailed temperature and wind structure by comparing the FPS-16 sounding with the rawinsonde of 3 January, 17 GCT (figures 1 and 4b). Figure 6 shows a simplified outline of the vertical wind profile measured at this time together with the position of relatively stable layers as evident from Figure 4b. As may be seen from this diagram, the absolute wind maximum along the vertical profile corresponds very closely to tropopause height (T). The secondary wind maximum at approximately 11.8 km coincides with a "secondary tropopause" (T') in which the vertical lapse rate again experiences a marked change. The third wind maximum at 13 km falls into the level of a less conspicuous but nevertheless existing discontinuity in lapse rate.

Let us now consider vertical shear and stability in a qualitative manner.* Below the level of maximum wind underneath jet streams with well-defined vertical wind shears, positive baroclinicity (as indicated by an increase of wind with height) is concentrated in relatively stable layers. Above the level of maximum wind relatively stable layers contain a concentration of negative baroclinicity. Figure 6 is in excellent agreement with this statement: Stable layers below the tropopause are

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* A quantitative study would necessitate the availability of soundings at neighboring stations for the same map time.

marked by a sharp increase of wind with height, above the tropopause by a sharp decrease of wind with height. Figure 7 containing a time section of stability $(\Gamma + \partial T/\partial z)$ shows a similar correspondence between stable layers and mesostructural wind shears (Figure 8).

In order to arrive at a somewhat more quantitative conclusion we may apply the following consideration: Let us assume that the average vertical wind shear over a relatively deep laper follows geostrophic conditions given by

$$\frac{\partial u}{\partial z} = -\frac{g}{fT}\frac{\partial T}{\partial y} + \frac{u}{T}\frac{\partial T}{\partial z} \tag{1}$$

where $\partial T/\partial y$ stands for the horizontal temperature gradient normal to the direction of flow. We may apply the transformation

$$\left(\frac{\partial T}{\partial z}\right)_\theta = \left(\frac{\partial T}{\partial y}\right)_z \left(\frac{\partial y}{\partial z}\right)_\theta + \frac{\partial T}{\partial z} \tag{2}$$

Using the standard meteorological notation, this becomes

$$-\left(\frac{\partial T}{\partial y}\right)_z = \left(\Gamma + \frac{\partial T}{\partial z}\right)\left(\frac{\partial z}{\partial y}\right)_\theta \tag{3}$$

Assuming now that the slope of isentropic surfaces, $\left(\frac{\partial z}{\partial y}\right)_\theta$, is controlled by macrometeorological conditions, and is not influenced by the mesostructure we may write

$$\frac{\partial u}{\partial z} = + \frac{A}{T}\left(\Gamma + \frac{\partial T}{\partial z}\right) + \frac{u}{T}\frac{\partial T}{\partial z} \tag{4}$$

where $A = (g/f)(\partial z/\partial y)_\theta$ is taken to be constant over a relatively deep atmospheric layer that does not intersect the jet stream level. Even under extreme conditions the second term on the right-hand side of this equation will be at least one order of magnitude smaller than the first term. It may therefore be neglected.

For the case under consideration some of the values are summarized for the 17 GCT sounding in the following table: $\Gamma \cong 1°C/100\,m$, $\overline{\partial u/\partial z}$ indicates the mean shear over a deep layer and $A/\overline{T}$ has been evaluated from $\overline{\partial u/\partial z}$ and $(\Gamma + \overline{\partial T/\partial z})$.

Layer (m) from	to	$\overline{\partial u/\partial z}$ (mps/100m)	Observed $\partial u/\partial z$ (mps/100m)	$A/\overline{T}$	$\overline{T}$ (°K)	Observed $\Delta T/\Delta z$ °C/100m
7,000	8,000	0.42	+1.5	1.45	241	-0.70
8,000	9,000	0.42	-1.0	1.45	234	-0.76
9,000	10,300	0.42	+1.23	1.45	226	-0.66
10,300	11,200	-0.53	-1.67	-8.83	219	-0.39
11,200	11,800	-0.53	+1.17	-8.83	216	-0.52
11,800	12,600	-0.53	-2.0	-8.83	216	+0.17
12,600	13,000	-0.53	+2.5	-8.83	217	+0.12
13,000	14,000	-0.53	-1.2	-8.83	216	-0.28

Layer (m) from	to	$\Gamma + \Delta T/\Delta z$	Computed $\Delta u/\Delta z$ (mps/100m)	$\Delta u/\Delta z$ obs. $-\Delta u/\Delta z$ comp.
7,000	8,000	0.30	0.46	1.04
8,000	9,000	0.24	0.38	-1.38
9,000	10,300	0.34	0.57	0.66
10,300	11,200	0.61	-5.30	3.63
11,200	11,800	0.48	-4.23	5.40
11,800	12,600	1.17	-10.32	8.32
12,600	13,000	1.12	-9.83	12.33
13,000	14,000	0.72	-6.35	5.15

As may be seen from the last column in this table, the quantitative agreement between observed and computed shears is not nearly as good as suggested by the qualitative deductions made from Figure 6. This may largely be due to the assumption $(\partial z/\partial y)_{\bar{\theta}} =$ const. throughout a deep layer. On the other hand, we should expect that there exists a real discrepancy between the two shear values due to ageostrophic motions present. The systematic increase in the last column of the above table between 8 and 13 km might be taken as an indication of this. A definite decision cannot be reached with only this small a sample of data available.

As has been pointed out earlier, the large-scale upper flow pattern showed significant changes during the period of observation. This, again, prevents us from making any valid statement about the "life expectancy" of mesostructural details in the vertical wind profiles. From the foregoing it appears that details in wind profiles, which are reflected in the vertical temperature profiles as well, are quite stable in space and time. As may be seen from Figure 2, some of the same mesostructure in the winds of the lower stratosphere also shows up over Tampa, which is approximately 100 miles from Cape Canaveral. Therefore, under weather situations which do not call for a rapid change of the macroscale flow pattern, short-range forecasts of these detailed shears seem feasible. A study of more measurement sequences will be necessary, though, before generally valid recommendations can be made.

5. Possible Ageostrophic Effects in the Generation of Mesostructure:

As may be inferred from a comparison of Figure 8, which contains a time-section of the mesostructure of the wind field*, with the potential temperature analysis of Figure 5. some of the detailed features in the vertical wind profiles do not follow isentropic surfaces. This may be due to large-scale changes in the flow pattern. On the other hand it might indicate the passing of individual mesostructural systems oriented side by side on an isentropic surface. Evidence for the latter possibility could be gathered from the analyses of flight data (Reiter, 1961d, 1962a). Due to the limited data available at this time, no definite explanation of this apparent shift of mesostructural anomalies to different isentropic surfaces can be given as yet.

Because of the drastic macrometeorological changes inherent in the present data sample and the relative brevity of the period of measurement, it cannot be decided whether or not pure inertia oscillations might have a bearing on the behavior of the structural details in the vertical wind profiles. (Inertia period for 25° latitude is 28.3 hours). This possibility should be explored by measurements taken during more stable weather situations. Blackadar (1957) and others have found inertia oscillations to be the cause of wind maxima near low-tropospheric inversions (for literature see Reiter, 1961a, 1963a).

Another possible source of transient mesostructural features in vertical wind profiles might be phase differences in gravity-type wave disturbances contained within adjacent layers (Figure 9). The group velocity with which such phase differences travel over the station may determine the sequence of wind speed-anomaly maxima and minima in a layer contained between two specific isentropic surfaces.

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* The mesostructure in this diagram is analyzed in terms of anomalies from the smoothed wind field presented in Figure 3. The values at any given point in these two diagrams, added with the proper sign, should give the original wind speeds as reported in Figure 1.

At the present our knowledge on possible wave spectra and their behavior in the free atmosphere is rather limited. As a first estimate of possible effects Lyra's wave number

$$\ell^2 = \frac{g}{\theta}\frac{\partial\theta}{\partial z} \Big/ V^2 \qquad (5)$$

has been computed for 250 m intervals for the four radiosonde ascents in sequence on 3 January 1963 over Cape Canaveral (Figure 10) (Lyra, 1940, 1943; Scorer, 1949; for further literature see Reiter, 1960, 1961a, 1962b, 1963a). It should be realized, of course, that this wave number gives only a very limited account of possible atmospheric perturbations, specifically derived for standing wave formation. It takes into consideration, however, both the vertical changes in lapse rate and in wind speed. For the computations presented here the wind speeds reported from the rawinsondes have been used rather than the ones obtained with the FPS-16 radar.

Only the 17 GCT and the 20 GCT soundings show a more or less continuous decress of ℓ^2 in the lower and middle troposphere, which is necessary for an upward transport of perturbation energy and for the formation of waves near tropopause level. Especially the 11 GCT, but also the 23 GCT soundings show a much more irregular distribution of ℓ^2 in the lower troposphere. In agreement with this, the mesostructural details in the vertical wind profiles are more pronounced at 17 and 20 GCT than at 11 and 23 GCT. This leaves the question to be answered by future research whether or not some of the observed mesostructure may be caused by internal waves within more or less deep atmospheric layers.

Richardson's number, commonly used for turbulence research, has not been evaluated in this study for the following two reasons:

(1) From the persistence of some of the mesostructural details in the wind soundings, it is evident that these disturbances do not represent "turbulence" in the classical sense.

(2) Actual turbulence may influence the aerodynamic behavior of ascending balloons, and with this the quality of the wind measurements. More detailed data should be awaited, however, before the application of any turbulence criterion could provide a useful input.

6. Conclusions and Recommendations for Future Research:

The foregoing investigation is based on a very small sample of data. This, naturally, will limit the conclusions that may be drawn from this study.

The fact that some of the observed mesostructure in the wind field may last for several hours, and thus is rather stable in space and time, seems to be fairly well established. The first impression of "turbulence", which one might get in inspecting the various secondary maxima and minima in an accurately measured vertical wind profile, therefore does not conform to the classical concept of turbulence. Physical causes other than random mixing processes must be sought to explain this phenomenon.

A certain correlation between vertical wind shears and temperature lapse rates, which seems to exist with the long lived mesostructure, might eventually be used in separating the stable from the unstable, short lived features in vertical wind profiles. The limitations of the data sample available do not permit any further conclusions at this point. The possible interaction of wave phenomena in adjacent atmospheric layers also deserves closer study.

For this purpose a number of serial measurements of vertical wind profiles should be made, similar to the ones investigated in this report. These ascents should cover a variety of weather situations with preference to such periods where no drastic changes in the upper flow patterns are to be expected.

If at all feasible, simultaneous measurements from two or more sites should be carried out on a synoptic basis. This would enable the study of the orientation in space of mesostructural features and their advective and dynamic properties. A knowledge of these will be essential for the development of effective forecasting techniques.

Last, but not least, attempst should be made to space simultaneous radiosonde observations even more closely than has been the case in the present measurement series. This would help to establish closer correlations between changes in the wind and temperature fields. From such correlations, again, inferences on the dynamics of mesostructural features may be made.

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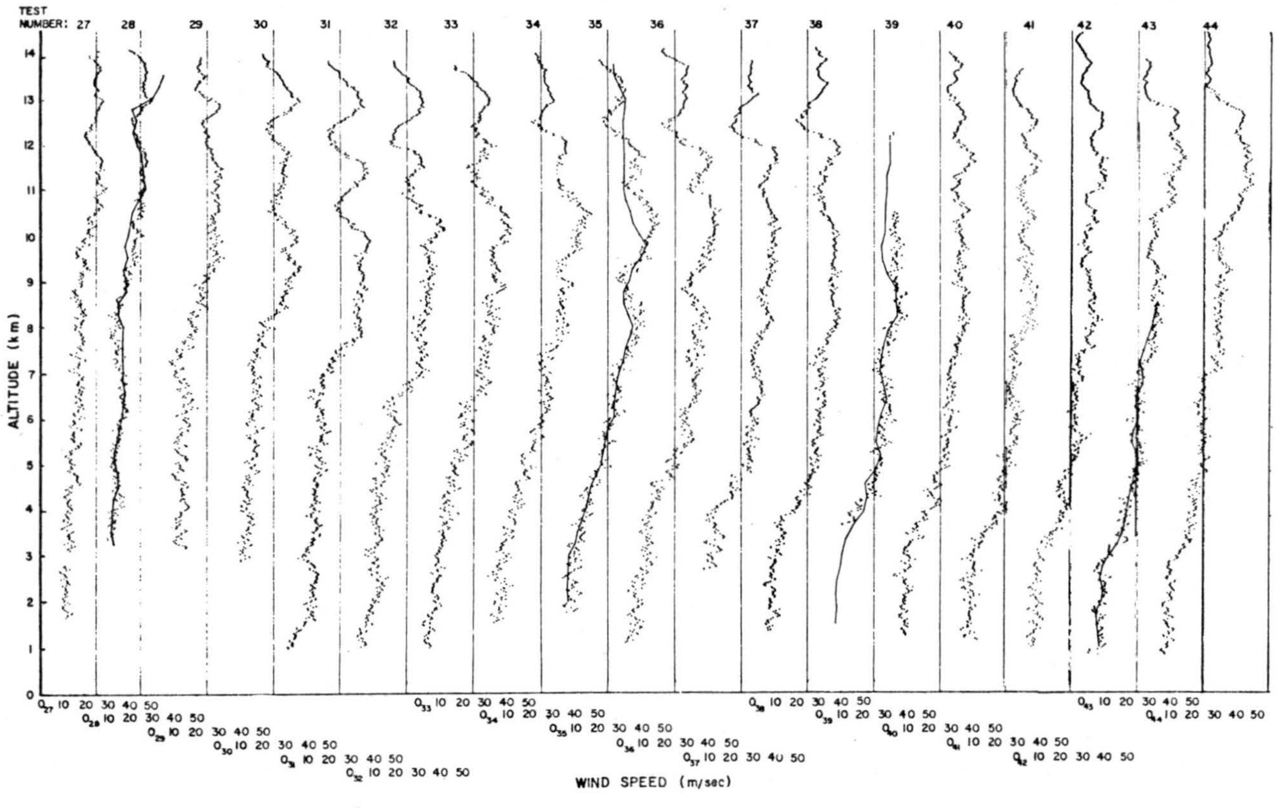

Fig. 1 Vertical wind profiles measured at approximately 45-minute intervals by FPS-16 radar over Cape Canaveral on 3 January 1963. The solid curves indicate wind measurements by standard rawinsonde equipment at 11, 17, 20, and 23 GCT, 3 January 1963. A shifting scale has been used for the indication of wind speeds (mps) along the abscissa. (Scoggins and Vaughan, 1963).

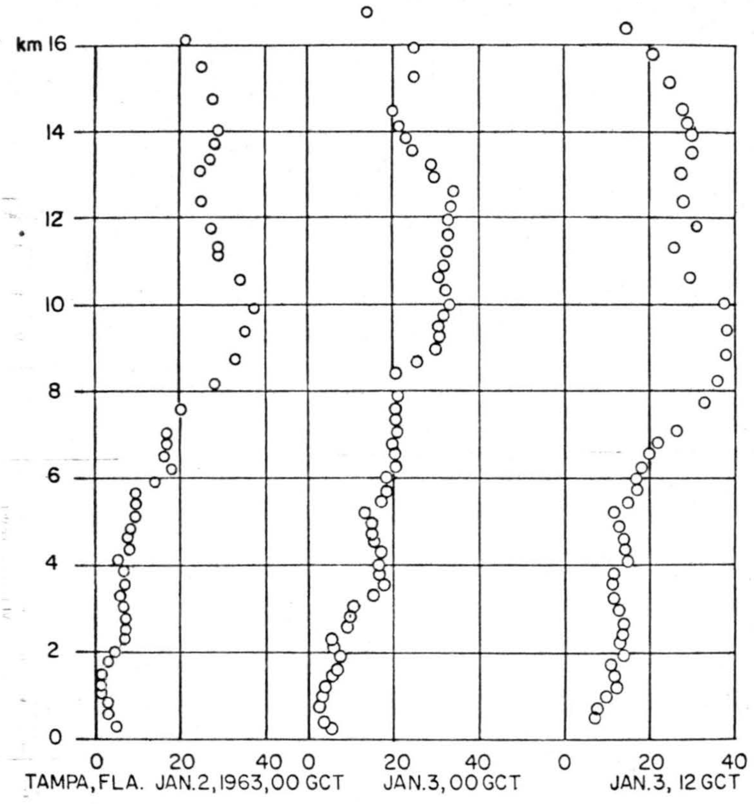

Fig. 2 Vertical wind profiles from rawinsonde observations over Tampa, Florida, 2 January 1963. 00 and 3 January 1963, 00 and 12 GCT.

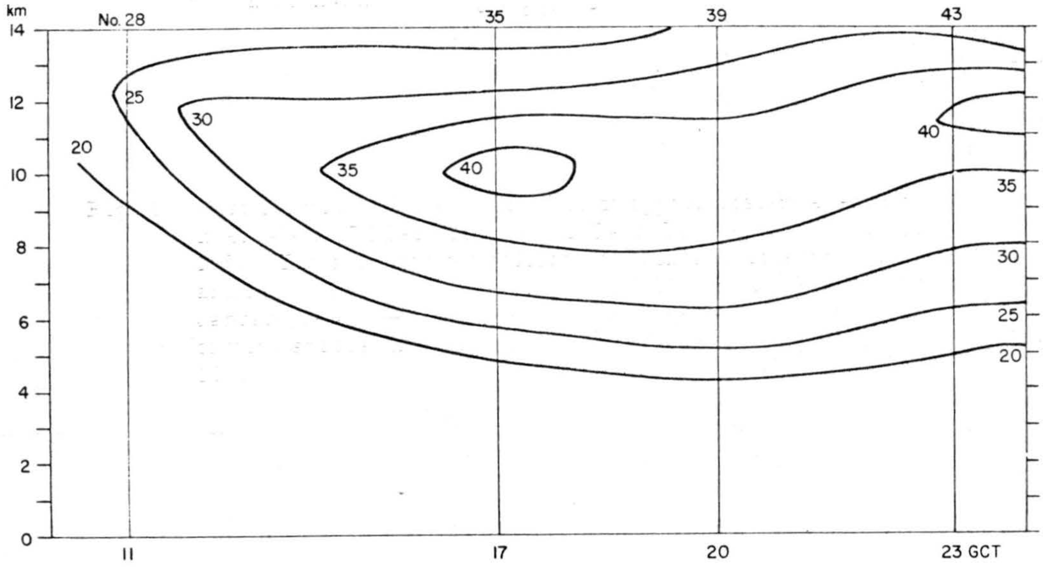

Fig. 3 Time section of wind speed (mps) of "basic flow" over Cape Canaveral, for the same time period as in Figure 1.

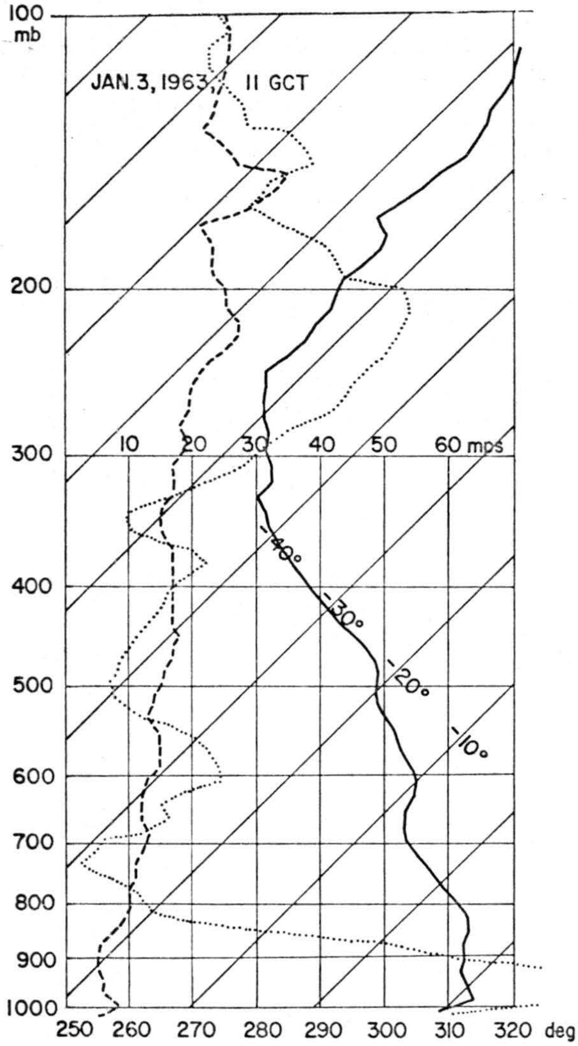

Fig. 4a Soundings of wind direction (dotted), wind speed (dashed) and temperature (solid curve) over Cape Canaveral for observation times as indicated.

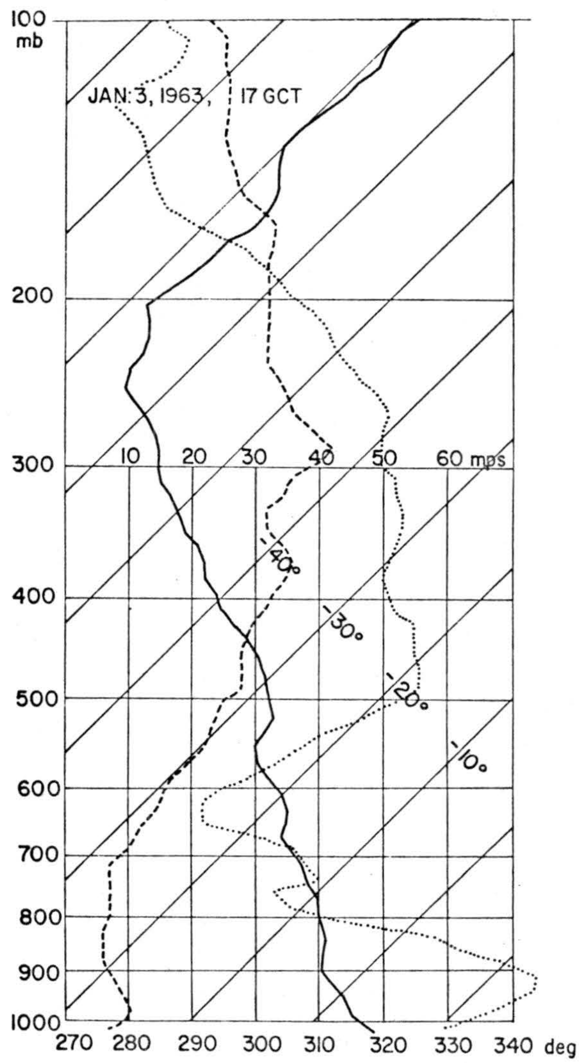

Fig. 4b

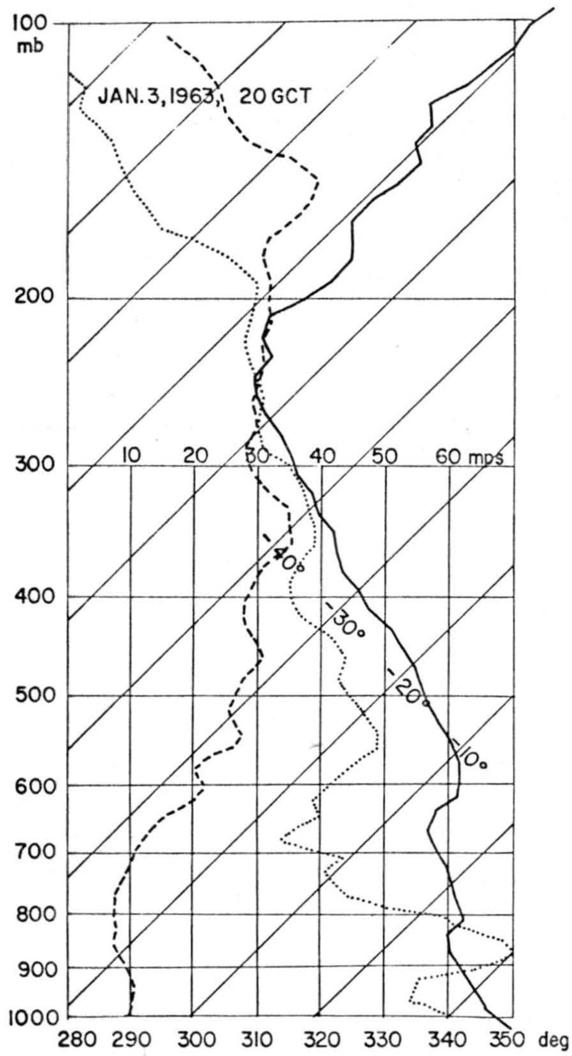
100 mb
JAN. 3, 1963, 20 GCT
200
300
400
500
600
700
800
900
1000
10 20 30 40 50 60 mps
40°
30°
20°
10°
280 290 300 310 320 330 340 350 deg

Fig. 4c

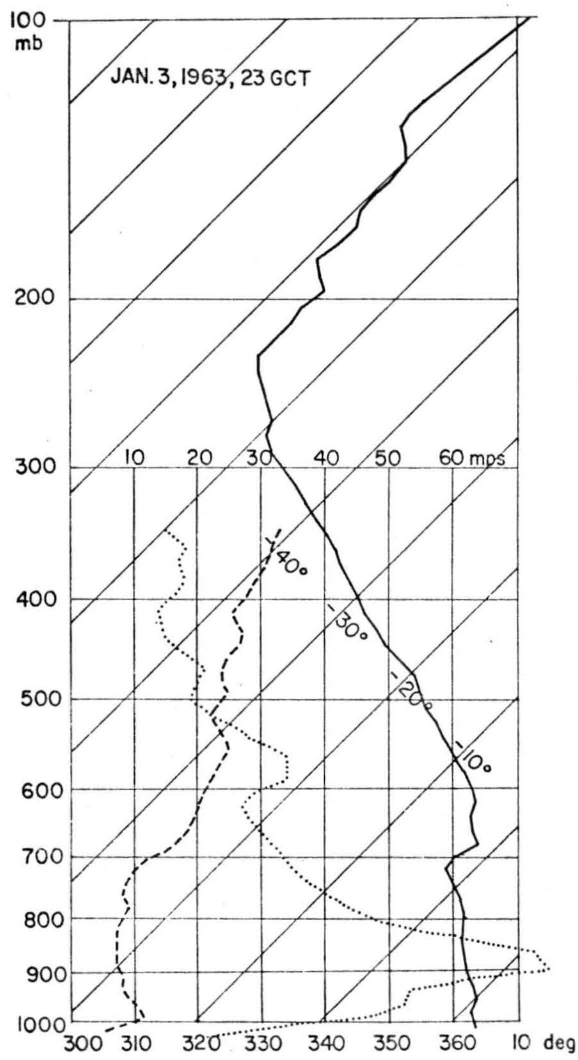
100 mb
JAN. 3, 1963, 23 GCT
200
300
400
500
600
700
800
900
1000
10 20 30 40 50 60 mps
40°
30°
20°
10°
300 310 320 330 340 350 360 10 deg

Fig. 4d

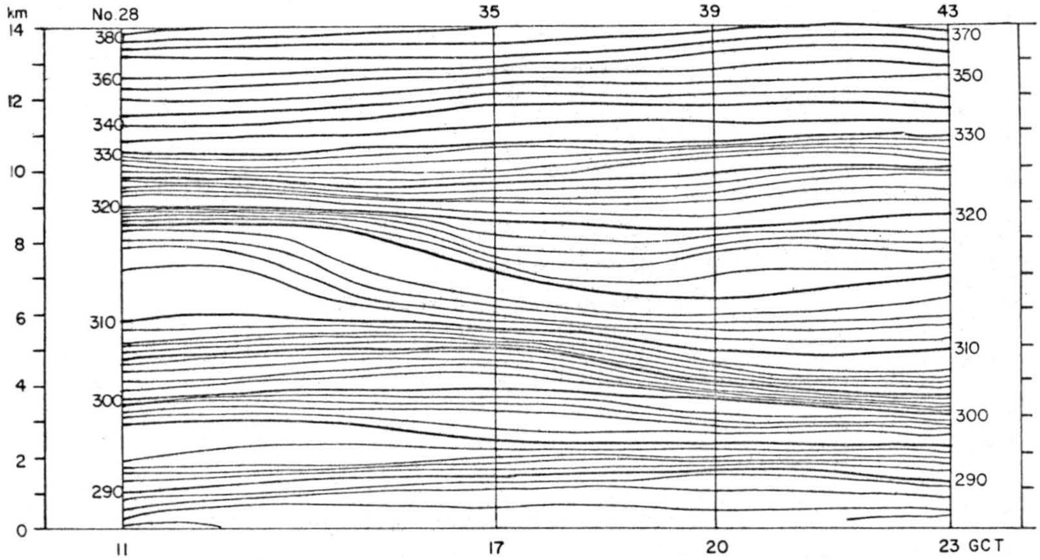

Fig. 5 Time section of potential temperature (°K), Cape Canaveral for the same time period as in Figure 1.

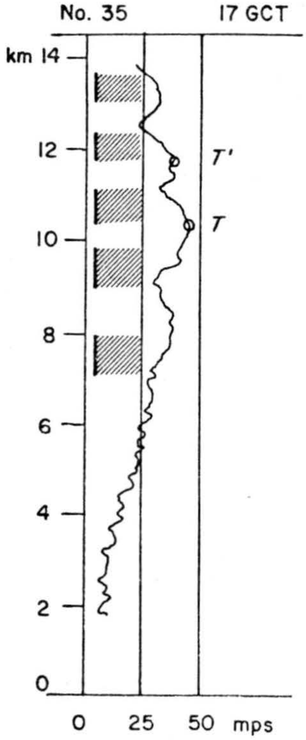

Fig. 6 FPS-16 sounding No. 35 of 3 January 1963, 17 GCT, Cape Canaveral, and position of relatively stable layers (shaded) according to the 17 GCT radiosonde ascent. T = tropopause. T' = secondary tropopause.

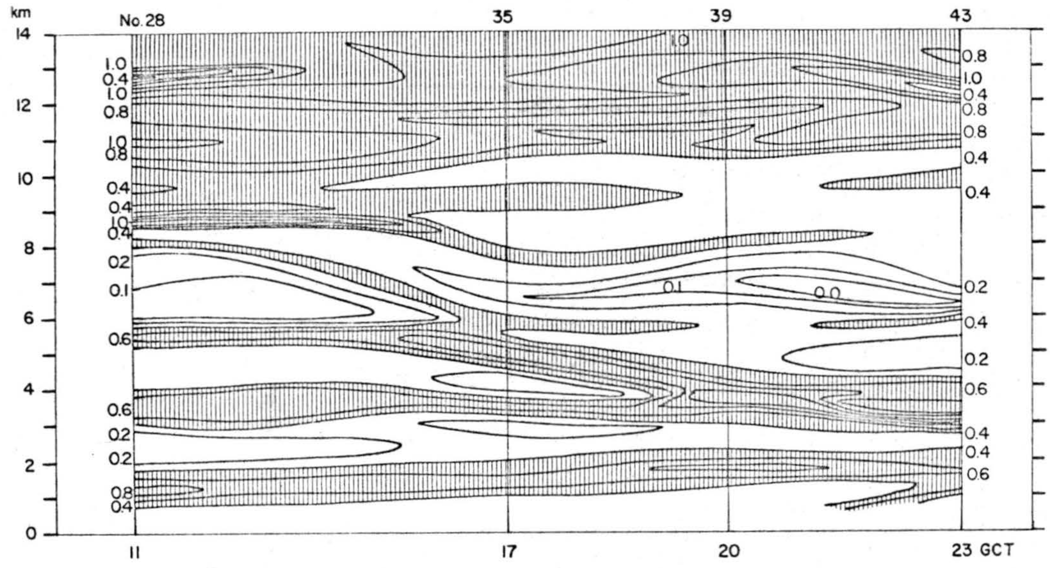

Fig. 7 Time section of stability $(\Gamma + \frac{\partial T}{\partial z})$, Cape Canaveral, 3 January 1963, same time period as in Figure 1. Layers with stability >0.4 °C/100 m are shaded.

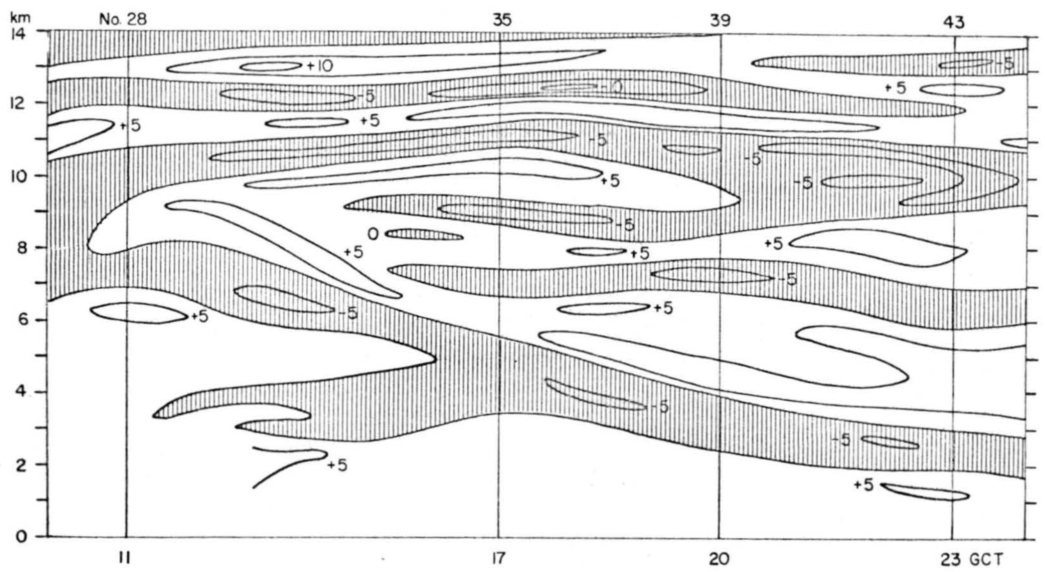

Fig. 8 Time section of mesostructure of wind speeds, Cape Canaveral, 3 January 1963, expressed in terms of anomalies (mps) from the analysis presented in Figure 4. Time scale in this diagram is the same as in Figure 1. Negative anomalies are shaded.

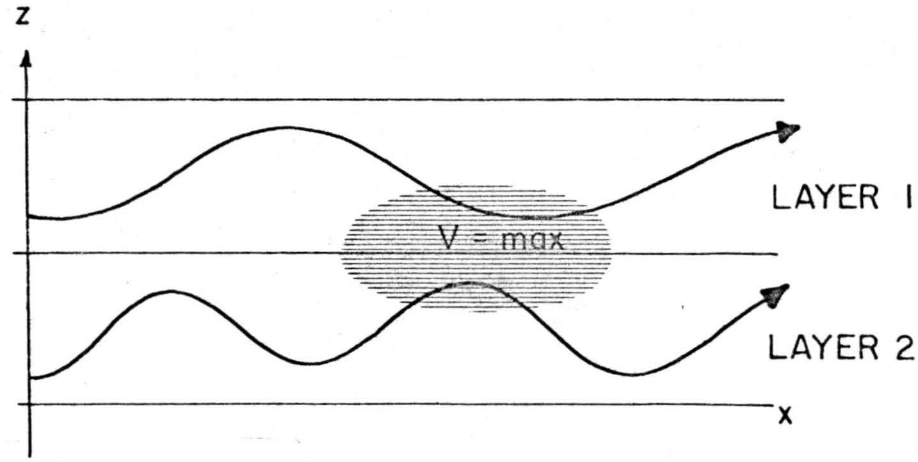

Fig. 9 Schematic diagram showing a possible mechanism of formation of local mesoscalar secondary wind maxima by superposition of internal waves within adjacent atmospheric layers.

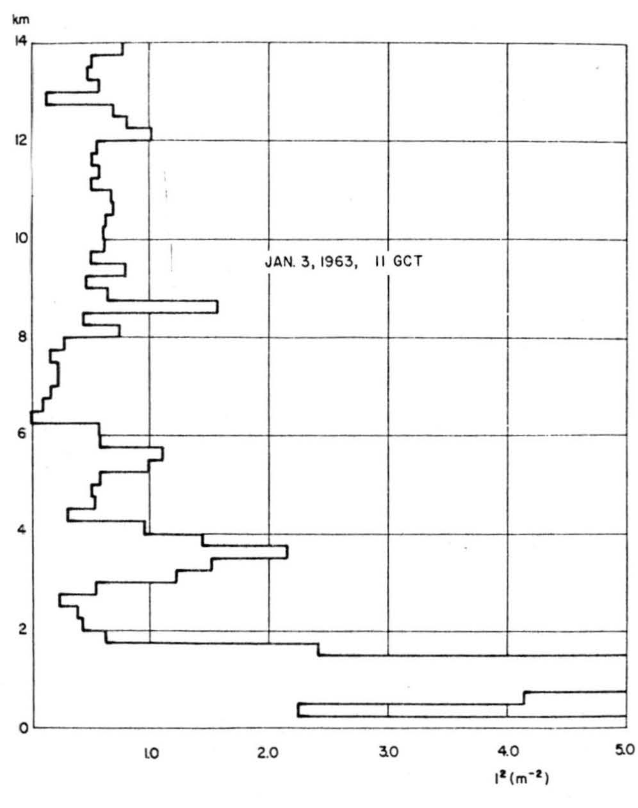

Fig. 10 Lyra's wave number $\ell^2 = \dfrac{\frac{g}{\theta} \frac{\partial \theta}{\partial z}}{V^2}$ (m^{-2}) computed for Cape Canaveral soundings shown in Figure 5.

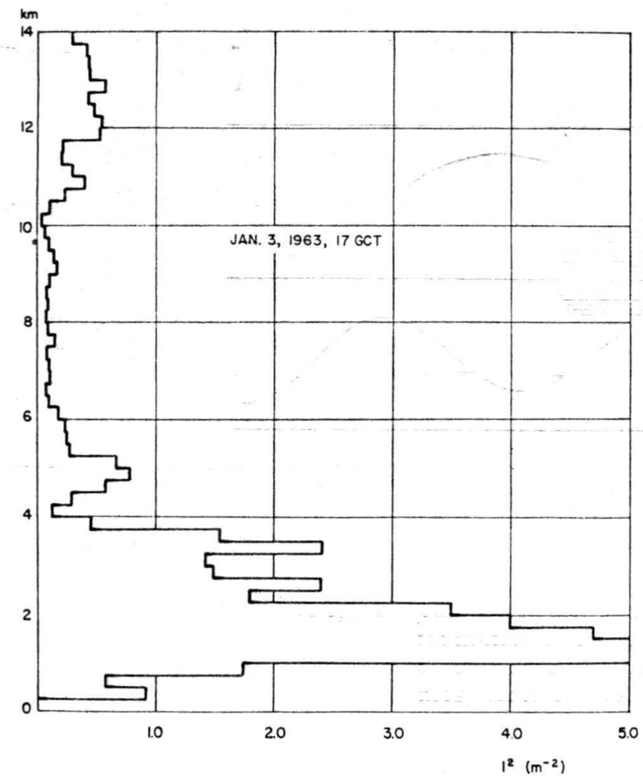

Fig. 10b

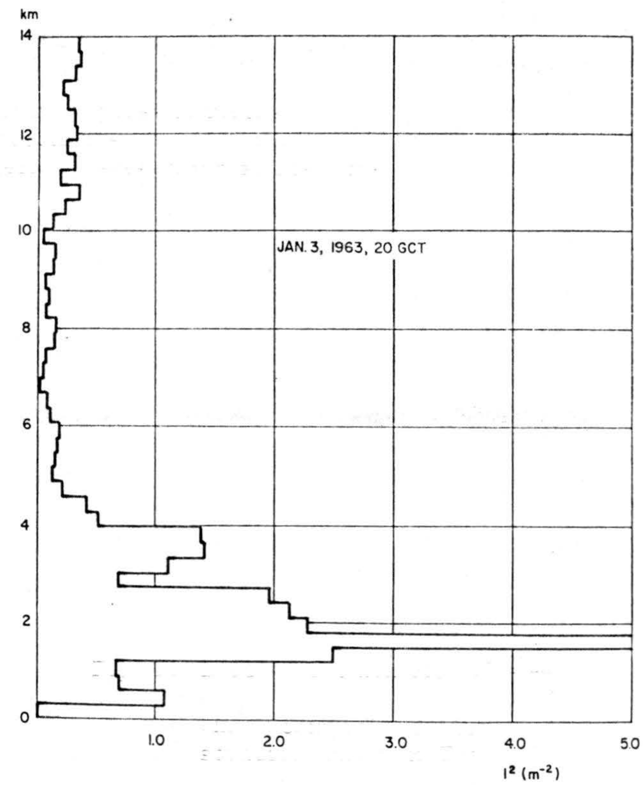

Fig. 10c

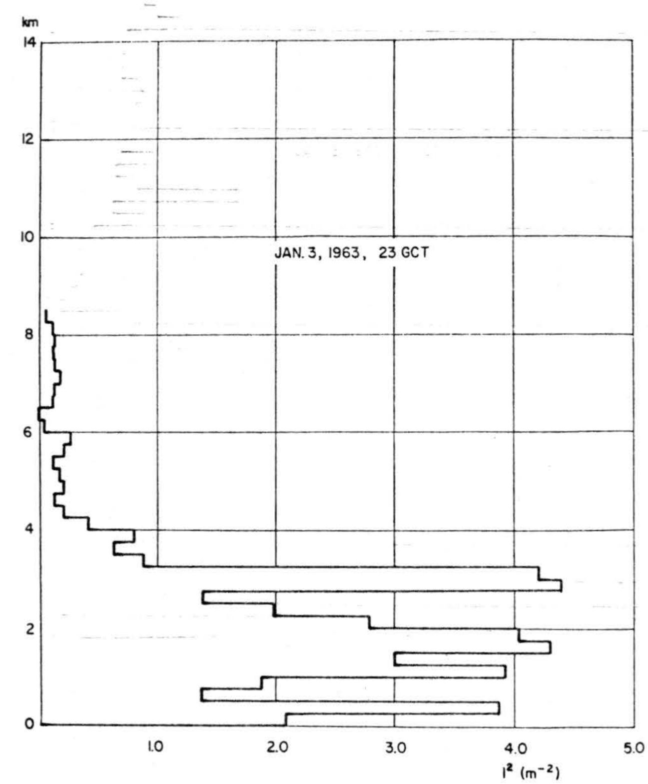

Fig. 10d