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CLEAR-AIR TURBULENCE AND ITS ANALYSIS
BY USE OF RAWINSONDE DATA

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ABSTRACT

This investigation of clear-air turbulence has several parts. The first section reviews selected aspects of turbulence, and emphasizes the large size and persistent nature of certain areas of moderate or severe turbulence. The next section is an investigation of turbulence in pronounced jet stream flow over mountains. Turbulent layers in these cases appear to have the same meso-scale structure found elsewhere; however, the turbulence appears to be more intense and the areas larger than one would expect with the same flow over level or rolling terrain. Next a turbulence index (TI) is defined on empirical grounds as the product of wind speed, turning of the wind with height, and change of lapse rate. When applied to several detailed cross-sections through turbulent flow, this number has maximum values that correspond well to the turbulent areas. In order to test the utility of standard upper-air data in turbulence analysis, values of Richardson's number and the turbulence index were determined by electronic computer in eight layers between 500 and 150 mb at all rawinsonde stations in the United States during the period 12-24 March 1962. These values are compared with turbulence reports made by pilots of jet aircraft and collected by the Clear-Air Turbulence Project. Several maps are presented that illustrate substantial agreement of computed quantities with the turbulence reports. Standard statistical tests show that both the Ri and TI numbers have definite skill in turbulence analysis, and that combined use of the two numbers is more accurate than use of either one separately. Suggestions are given for further improvement of criteria for analyzing turbulence. Experiments in grid-point analysis of turbulence and in objective turbulence forecasting are recommended.

CONTENTS

ILLUSTRATIONS

I INTRODUCTION

Turbulence that affects subsonic aircraft consists of eddies having sizes in the range from 25-300m, approximately. It is reasonable to suppose that such eddies are produced by the breakdown of larger eddies, as normally happens in turbulent flow. In clear-air turbulence, large eddies probably originate in unstable gravity-inertia waves. As discussed in Sec. III, perturbation analysis of stratified fluids in the presence of wind shear indicates that disturbances with wave lengths on the order of a few kilometers will be unstable under typical conditions. Instability will give rise to turbulent mixing, with the consequent production of progressively smaller eddies (including the sizes that affect aircraft) until sizes are so small that molecular viscosity becomes effective in destroying the motion. On the other hand, in turbulence associated with convective clouds, the original large eddies are the upward and downward currents of the convective cells, rather than gravity-inertia waves. In mountain waves, parcels lifted in passing over a mountain barrier tend to oscillate in a thermally stable environment downstream. Certain portions of the waves (primarily the surface layer and certain upper-tropospheric layers) contain small eddies that constitute turbulence to an aircraft.

Clear-air turbulence is not a prevalent condition of flight in the upper troposphere and lower stratosphere. In winter over the United States, moderate or severe turbulence occurs less than 5 percent of the flight time, and light turbulence (which is not of operational importance) occurs 10 to 15 percent of the time. Thus the analysis of moderate or severe turbulence requires that restricted regions, altogether comprising about 5 percent of the volume of atmosphere between 300 and 150 mb, be identified. These special regions are invisible, and are not detected directly by ravinsonde measurements. Although the problem of turbulence analysis is difficult, it has been found that many turbulent regions can be identified by their association with

certain meso-scale features of the upper flow. For example, turbulent layers often lie within or along the boundaries of upper fronts (Anderson, 1957) or the tropopause, particularly on the cyclonic side of jet streams. Well-developed turbulence is more likely in troughs or ridges than in straight portions of the flow. Turbulence is also correlated with small values of Richardson's number (e.g., Reiter, 1961; McLean and Panofsky, 1964) and with layers in which wind direction and speed change rapidly (Endlich, 1963).

On certain occasions, turbulence is reported over large areas by the majority of aircraft that traverse the region. For example, the airline reports collected by Colson (1963) for 15 March 1962 indicate that a turbulent region extended from approximately St. Louis, Missouri to New York for a period of 18 hours. A pronounced upper front and jet stream were present in this area (see Sec. V). Colson's (1964) analyses for 5-9 February 1963 show that turbulent regions were related to mean trough and ridge positions. In a 2-1/2 by 2-1/2 degree region lying just to the east of the mean trough, 37 percent of the flights during the five days reported moderate or severe turbulence. In contrast, less than 5 percent of the flights reported moderate or severe turbulence in large regions of the United States away from the mean trough, ridge, and jet stream. These data show that turbulent regions are sometimes large and persistent, and are associated with identifiable features of the upper flow. It appears that the meso-scale phenomena that contain turbulence are produced by the synoptic-scale flow in certain favorable regions of the flow patterns.

Experiments concerning the identification of such turbulent regions by computer processing of rawinsonde data are the principal subject of this report. Other subjects that are covered include case studies of turbulence measured by research aircraft over the western United States, definition of a new turbulence index (called the TI number), discussion of the significance of Richardson's number as a stability criterion, statistical comparisons of several turbulence criteria, and the writers' appraisal of the most fruitful avenues of further research. Typical

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graphs of turbulent intensity and temperature (from which one can compare temperature gradients and turbulent encounters) are given in the appendix.

II DETAILED INVESTIGATION OF TURBULENCE OVER THE WESTERN UNITED STATES

Laboratory models of flow downstream from barriers show that turbulence can exist at interfaces between layers of different density (Long, 1953). Such turbulence appears analogous to clear-air turbulence in the vicinity of large mountain ranges. In this portion of the investigation, we wish to learn whether atmospheric structure associated with turbulence over mountains is similar to that found over flat or hilly terrain. Ideally, one would wish to have aircraft observations over mountains in synoptic flow patterns similar to cases studied previously over the eastern United States so that comparisons of paired cases would reveal any mountain effects on the flow. Such data are not available. However, an interesting series of flights into strong jet flow over California and Nevada was made during February 1958 from Edwards Air Force Base, California, by the B-47 aircraft of the Air Force Cambridge Research Laboratories. The instrumentation used has been described by Endlich and Rados (1959).

The four flights, E-35 through E-38, were made on the successive days 24 through 27 February 1958 with take-off times near 1800 and landings near 2400 GCT. At the beginning of the period, an upper ridge containing a strong jet stream lay over California. On successive days the ridge moved south-eastward and was replaced by a weak trough on the last day. The high-level flow was not oriented perpendicular to the predominantly NNW-SSE mountain ranges, so that mountain effects were not at maximum intensity. Cross sections of wind, temperature and turbulence were analyzed for each flight; however, in the interest of brevity, figures for the first and last flights are omitted from this report.

The aircraft measurements made during Flight E-35 showed a wide region of moderate turbulence on two traverses at approximately 33,000 ft. On the first of these, severe turbulence (containing gusts to 31 ft sec^{-1}) was located immediately over the crest of the Sierra Nevada range and over Tonopah, Nevada; however, on the second traverse (two

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hours and forty minutes later) turbulence in the same region was slightly less than severe in intensity. No clue to the decrease in intensity of turbulence is apparent from the wind or thermal fields. At 35,000 ft, moderate turbulence existed both east of the Sierra (toward Tonopah) and west of the crest. At the higher elevations flown, turbulence was absent. Over-all, severe turbulence was encountered for eight minutes, moderate turbulence for fifty-five minutes, and light turbulence for forty-one minutes. Expressed as percentages of the flight duration, these values are 2.6 percent, 17 percent, and 12.5 percent, respectively. The percentages of moderate and severe turbulence are an order of magnitude larger than typical values (0.2 percent severe and 2.5 percent moderate) associated with jet streams over the eastern United States.

Temperature measurements at 33,000 ft indicate that the aircraft intersected the top of a thermally stable layer. This layer appears as an inversion between 27,000 and 29,000 ft at Oakland at 0000 GCT. The Oakland wind at the inversion base was 237 degrees, 104 knots. Unfortunately, this was the highest elevation reached in the wind sounding. The aircraft data show winds of 290 to 300 degrees and a core speed slightly over 150 knots. The Oakland sounding and aircraft data together indicate marked veering of the winds between 27,000 and 33,000 ft, i.e., through a layer containing the temperature inversion.

In summary, in Flight E-35 a wide area of moderate turbulence lay beneath a jet core that crossed the Sierra Nevada mountains. Turbulence was severe over the Sierra crest, even though typical mountain waves were not present. It is probable that the turbulence extended downward into an upper front that contained strongly veering winds. No turbulence was observed in a layer about 5000 ft thick that contained the jet core.

Flight E-36 was made the following day between Los Angeles and Bryce Canyon, Utah. Wind speeds in the jet core were approximately thirty knots higher than on the previous day; however, the flight was much less turbulent than E-35, perhaps because of the different route that was followed. The flight profile and turbulent gusts are shown

in Fig. 1. Moderate turbulence was encountered for 5 minutes (2.2 per-
cent of the flight duration) and light turbulence for 27 minutes (12
percent). These values are typical of jet streams studied previously.
Maximum gusts were 18 ft sec^{-1}. The temperature field measured by the
aircraft is shown in the lower portion of Fig. 1. The atmosphere was
quite barotropic except for a pronounced stable layer (upper or jet
front) at the left end of the cross section. This stable layer also
appeared clearly in the Las Vegas soundings before and after flight
time. The regions of moderate turbulence lay within and at the lower
boundary of this layer, and light turbulence extended upward into the
jet core. (The temperatures and turbulence are shown in Fig. A-7 of
the Appendix.) It is also of interest that the temperatures measured
by the aircraft show wave-like perturbations having amplitudes up to
1.5°C and wave lengths on the order of fifteen miles. Turbulence did
not have any noticeable relationship to these waves. The Doppler wind
measurements of the aircraft show that the concentrated jet core lay
immediately above the stable layer (Fig. 2). Strong vertical and
horizontal shear were associated with the stable layer and pronounced
veering of the winds was concentrated near its lower boundary [Fig.
2(b)]. The Richardson number $g\theta^{-1}(\Delta\theta/\Delta z)[(\Delta u/\Delta z)^2 + (\Delta v/\Delta z)^2]^{-1}$ had
minimum values of approximately 0.25 along the upper and lower boundaries
of the jet front (Fig. 3). The observed turbulence corresponds well
to the latter region. The quantity $V(\partial\alpha/\partial z)$, the product of wind speed
and vertical change of wind direction, had maximum positive values in
the turbulent region. Moderately large positive and negative values
also existed south of the jet core. The present case and previous studies
indicate that this quantity is related to turbulence when associated with
a discontinuity in lapse rate. These discontinuities are characterized
by large magnitudes of $\partial^2 T/\partial z^2$, as shown in Fig. 4. Therefore, the pro-
duct $V(\partial\alpha/\partial z)(\partial^2 T/\partial z^2)$ may be expected to have maximum values at the
upper or lower boundaries of upper fronts, or at the tropopause, when
wind speed is large and pronounced turning of the wind with height
exists, i.e., under conditions found to be especially favorable to clear-
air turbulence. This quantity is shown in Fig. 4(b).

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FIG. 1 VERTICAL CROSS SECTION THROUGH A JET STREAM OVER MOUNTAINOUS
TERRAIN, FLIGHT E-36, 25 FEBRUARY 1958. Low pressure to left.
(a) Aircraft path, time (GCT), and turbulent gust intensity (ft sec^{-1})
(b) Temperature measured by aircraft. Heavy solid lines are frontal boundaries or
the tropopause. Regions of moderate turbulence shaded.

FIG. 2 VERTICAL CROSS SECTION, FLIGHT E-36
(a) Wind speed (knots) measured by aircraft. J denotes jet stream core.
(b) Wind direction. Regions of moderate turbulence shaded.

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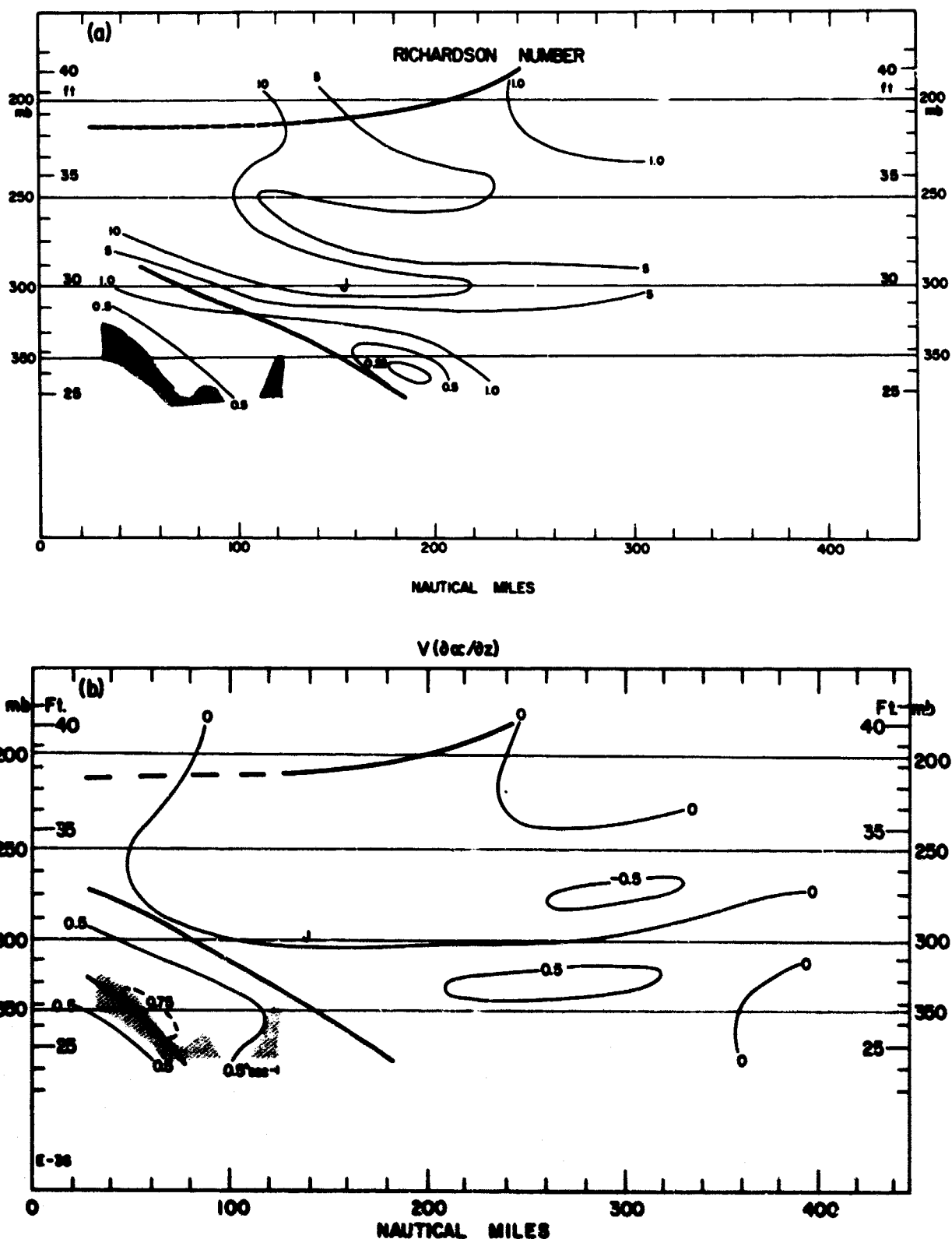
FIG. 3 VERTICAL CROSS SECTION, FLIGHT E-36

(a) Richardson number

(b) Product of wind speed (V, in m sec^{-1}) and vertical change of wind direction ($\partial\alpha/\partial z$, in deg m^{-1}).

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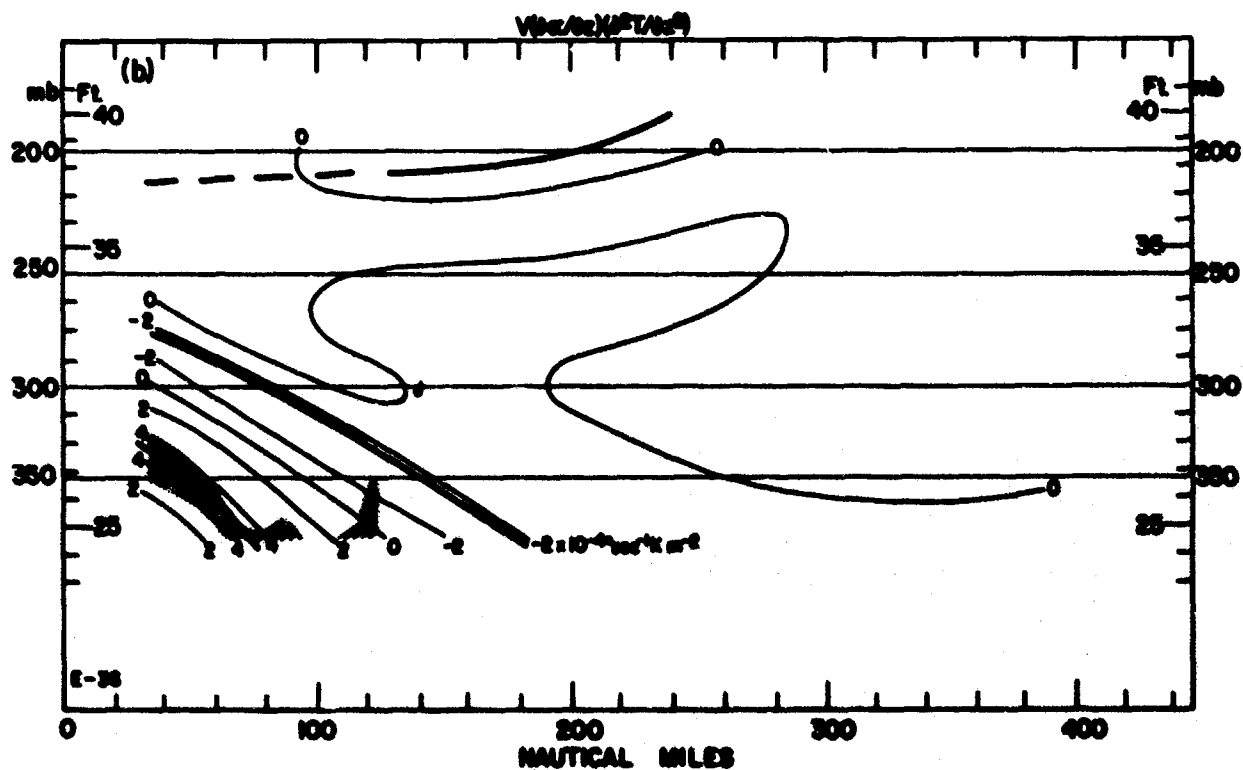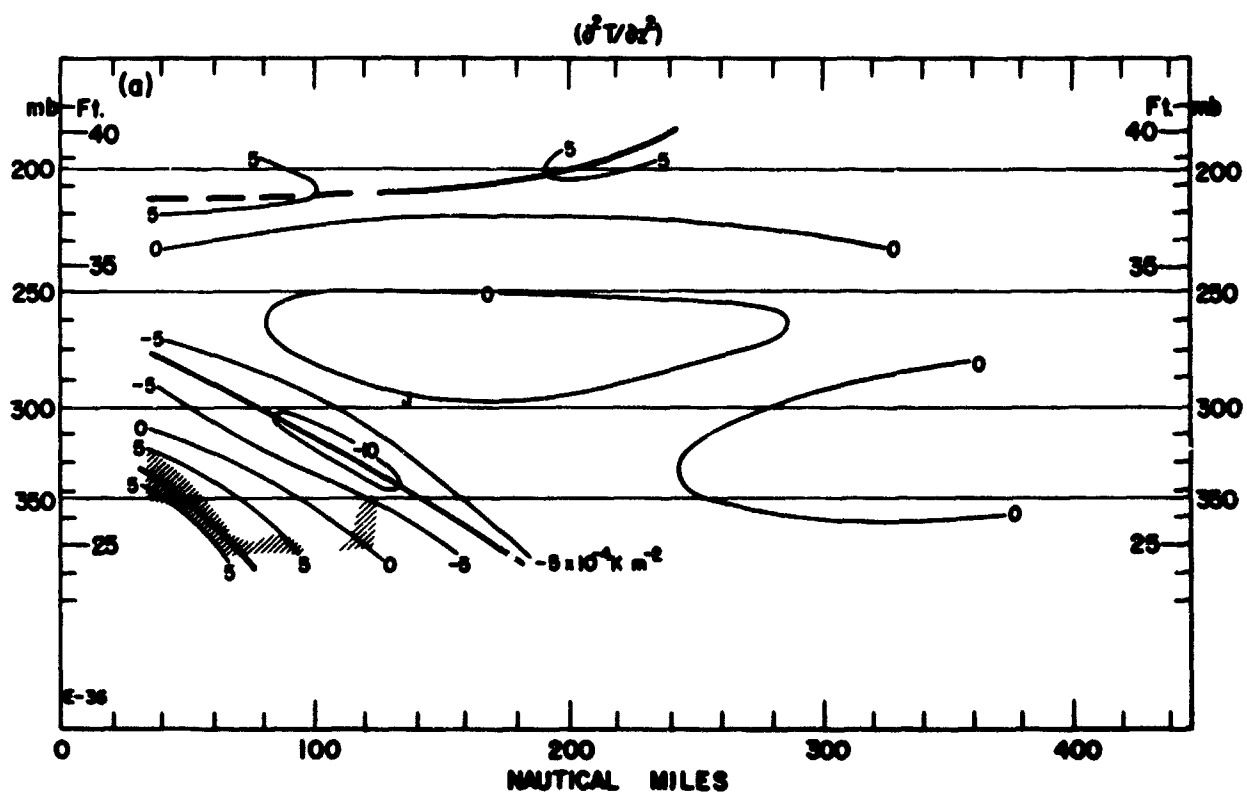
FIG. 4 VERTICAL CROSS SECTION, FLIGHT E-36
(a) Change of lapse rate ($\partial^2 T/\partial_z^2$, in K m^{-2})
(b) Product $V(\partial\alpha/\partial_z)(\partial^2 T/\partial_z^2)$ in deg sec^{-1} K m^{-2}, called turbulence index.

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The patterns of meso-scale vertical motions determined from aircraft measurements of true airspeed, pitch angle and altitude indicate downward motions of about 1 m sec^{-1} along the upper boundary of the stable layer and an upward current in excess of 1 m sec^{-1} in the turbulent region at the lower boundary of the stable layer. Elsewhere, vertical currents were smaller, with centers of rising or sinking motion separated by distances on the order of 50 to 150 miles. Such meso-scale vertical motions have been discussed previously by Kuettner and McLean (1961). With respect to the base and top of the upper stable layer, the motions are opposite to those found previously in Flights 27 and 29 (Endlich, 1963).

Flight E-37 explored the same jet stream system in the same general locality on the day following Flight E-36. Moderate turbulence was encountered for three minutes (slightly less than during the previous flight) and light turbulence for 54 minutes (18 percent of the flight duration). The latter value is 1-1/2 times that of Flight E-36. The distribution of turbulence is shown in Fig. 5. The region of light turbulence was quasi-horizontal and centered near 25,000 ft. The temperature field [Fig. 5(b)] shows that the upper stable layer found in the two previous flights was still present. The turbulent region was again associated with this phenomenon. At 20,000 ft, the temperature measurements indicate that the top of a second thermally stable layer was encountered at the left end of the cross section. The existence of this second layer is also shown by the soundings at Las Vegas and Santa Monica at 1200 GCT on 26 February. Wind speeds in the jet core (Fig. 6) were 183 knots--very close to the previous valu ; however, the core was located approximately 100 miles south of its position on the previous day. Vertical wind shear was approximately 10 knots per thousand feet in and above the stable layer. No turbulence was found in the immediate vicinity of the jet core. The field of wind direction shows that the wind backed with height and that largest directional changes occurred between 20,000 and 23,000 ft, i.e., in between stable layers. Thus the pattern was different than on the previous day when winds had veered sharply at the base of the upper front.
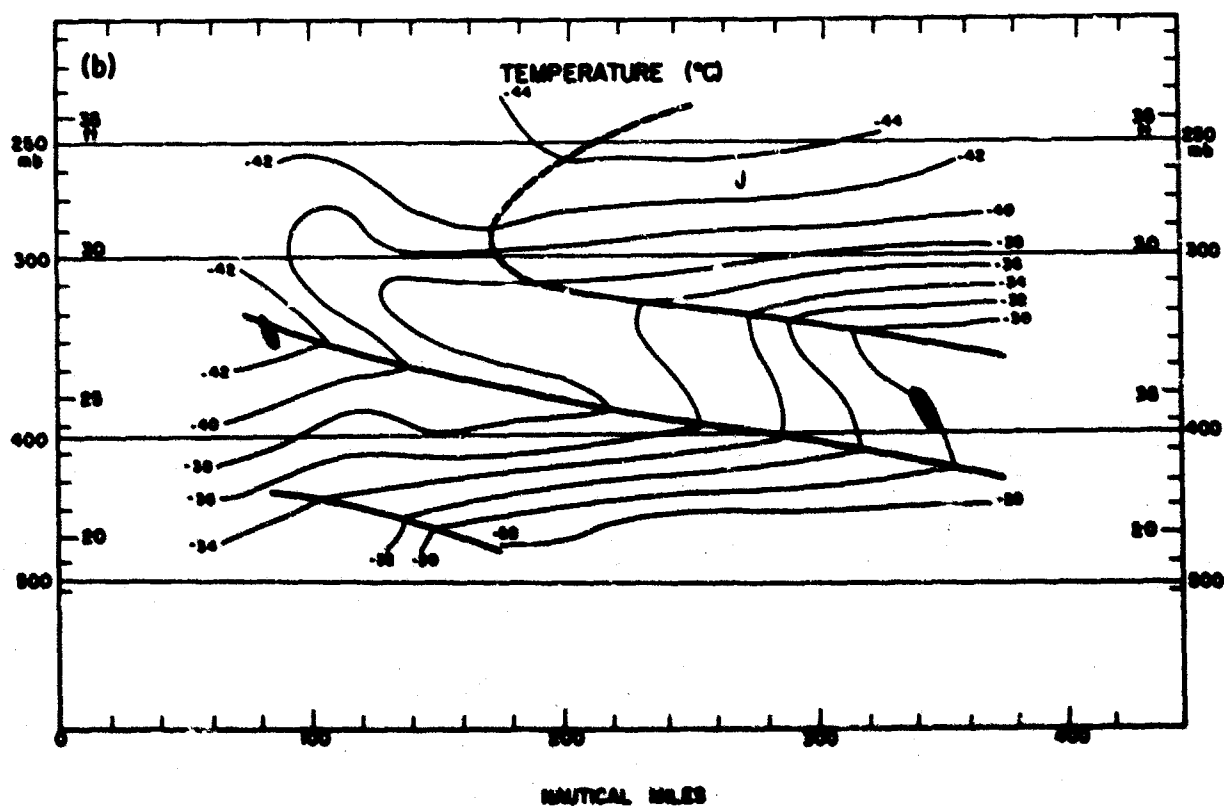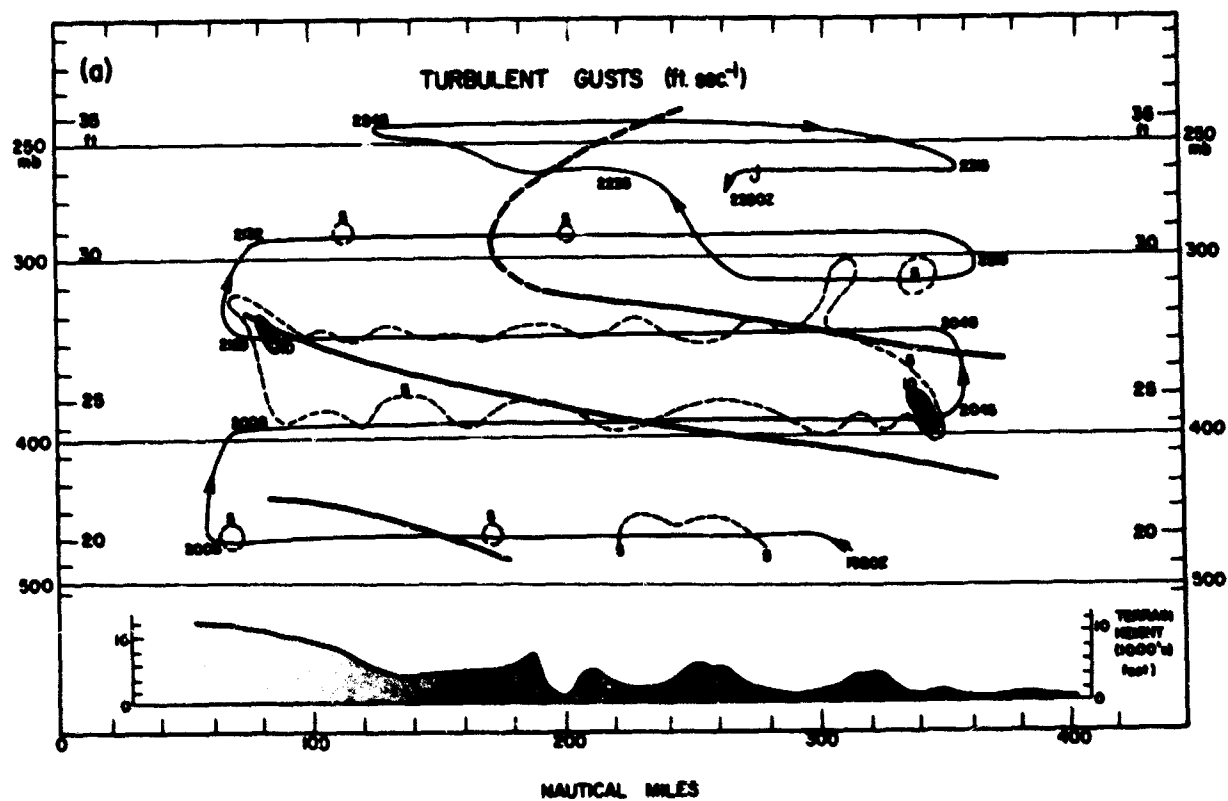
FIG. 5 **VERTICAL CROSS SECTION THROUGH A JET STREAM OVER MOUNTAINOUS TERRAIN, FLIGHT E-37, 26 FEBRUARY 1958. Low pressure to left.**
(a) Aircraft path, time (GCT), and turbulent gust intensity (ft sec^{-1})
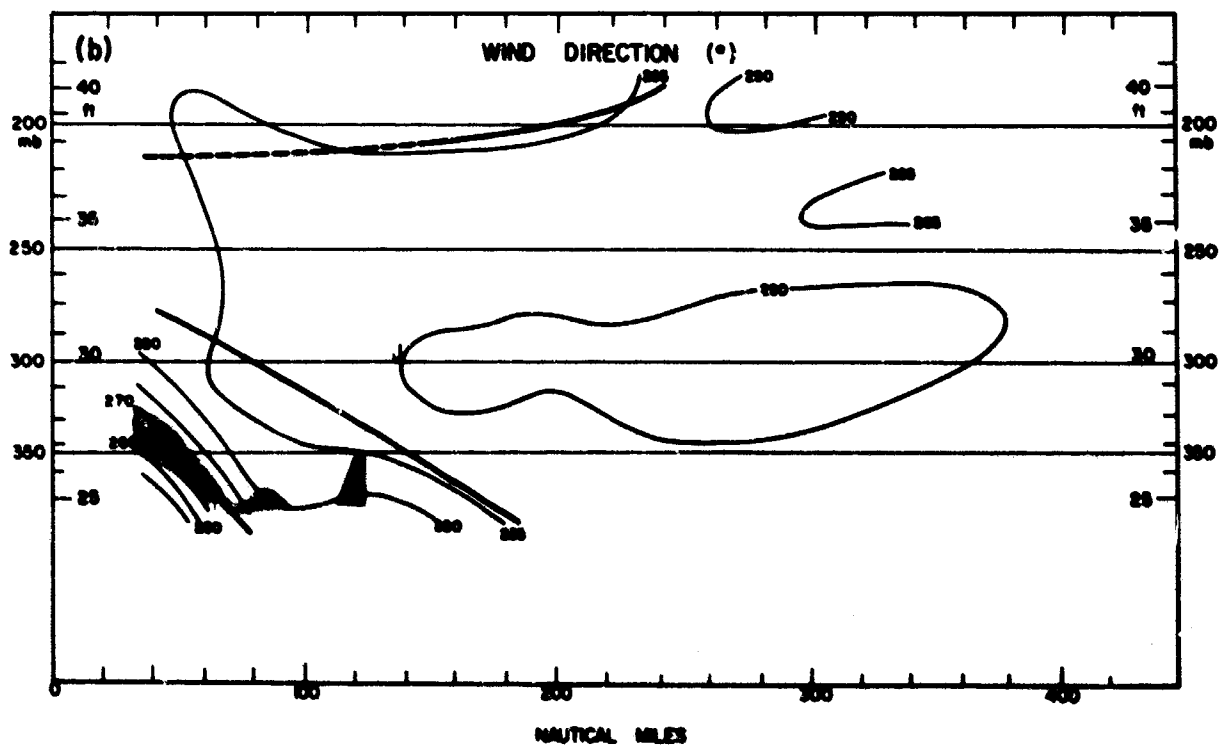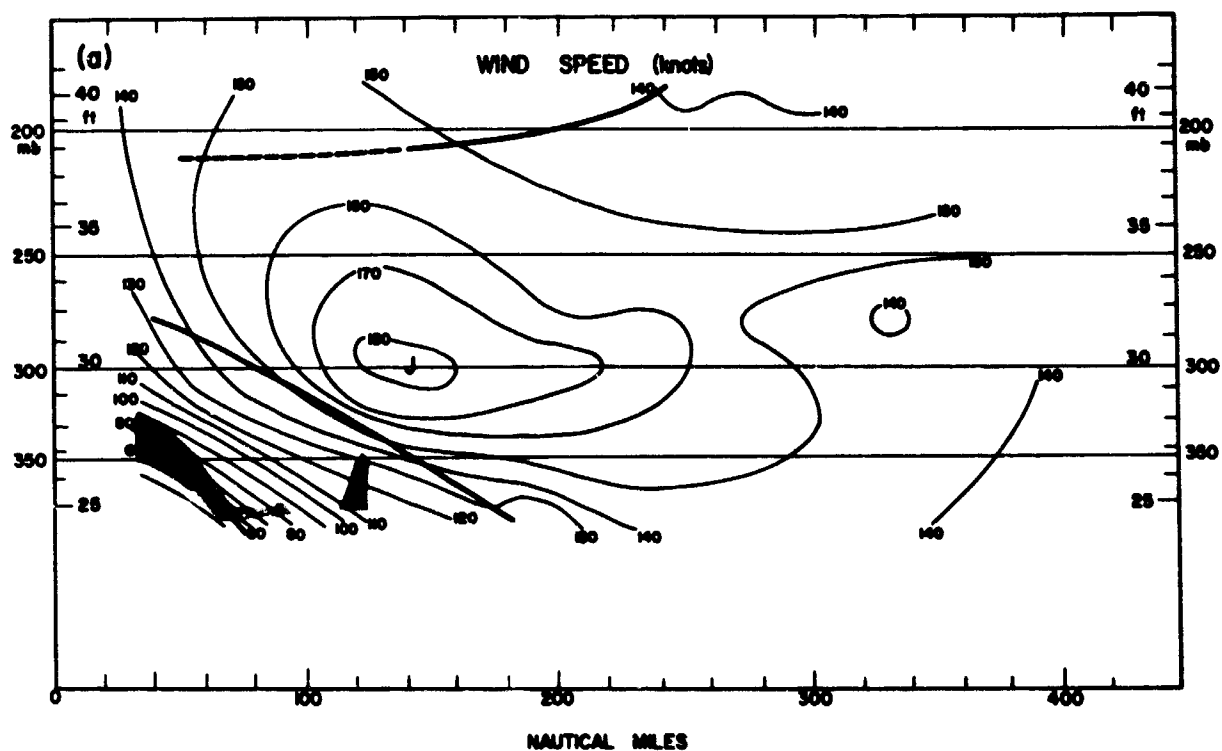(b) Temperature measured by aircraft. Heavy solid lines are frontal boundaries or the tropopause.

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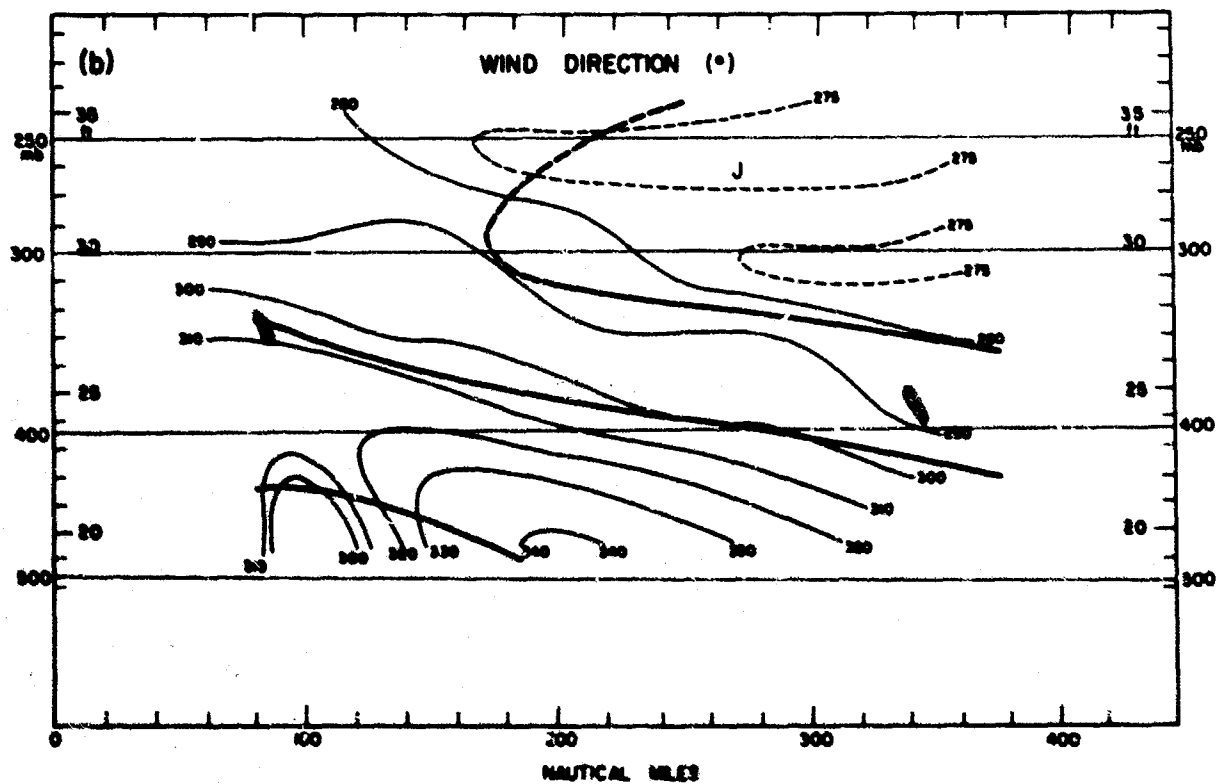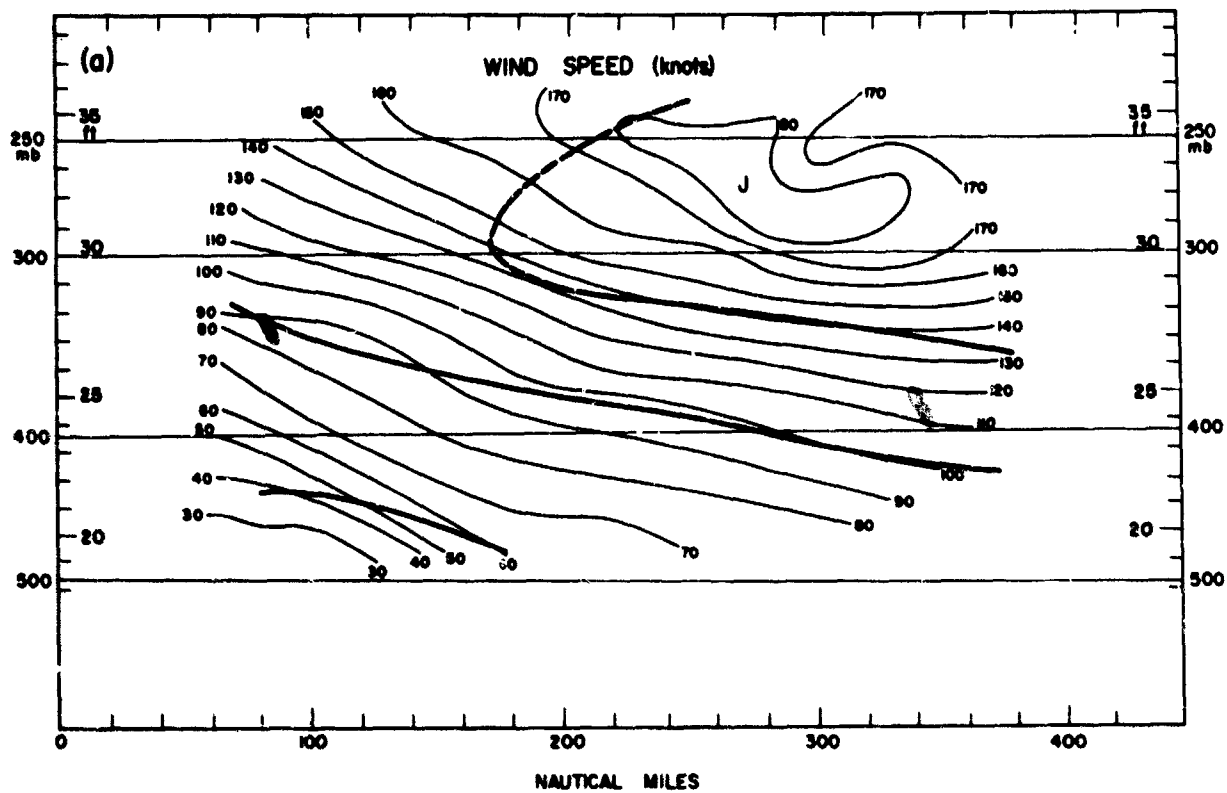
FIG. 6 VERTICAL CROSS SECTION, FLIGHT E-37
(a) Wind speed (knots) measured by aircraft.
(b) Wind direction. Regions of moderate turbulence shaded.

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Flight E-38 was made in the same region as E-37. During the twenty-four hours between flights, a weak trough replaced the ridge over Southern California and the region of strong winds moved rapidly eastsoutheastward. Thus, the maximum winds encountered during Flight E-38 (found east of San Diego) were 260 degrees at 109 knots. The aircraft traverses were made in cyclonic shear to the north of the jet core and a weakly defined upper stable layer and tropopause were intersected several times. The amount of turbulence found was very small-- less than three minutes of light turbulence were recorded by the VGH instrument. The turbulent patches showed an association with discontinuities in lapse rate and turning of the wind with height, and to a lesser extent, with the Richardson (Ri) number.

The reader should bear in mind that the four cases discussed above constitute only a small sample of turbulence over mountains. However, further detailed aircraft measurements of atmospheric quantities (and especially winds) in regions of moderate or severe turbulence over mountains apparently do not exist. In summarizing, we will only discuss those characteristics of the four cases that appear to be typical.

Since the Sierra wave studies of the 1950's, it has been known that the meso-scale wave motions induced by mountains are not necessarily turbulent. Moderate or severe turbulence was found universally in the low-level flow and occasionally at levels near the tropopause, while laminar flow normally occurred at intermediate levels. The present study of flow over mountains indicates that, in the upper troposphere, turbulence occurs in certain portions of stable layers that contain strong wind shear and marked turning of the wind direction with height. These are generally the same meso-conditions found in turbulent regions over flat terrain. Near mountain crests (such as the crest of the Sierra Nevada) turbulence is apparently more severe and more widespread than one would expect elsewhere with the same atmospheric structure, as suggested previously by Kuettner (1958). Probably the most severe clear-air turbulence to be found in the atmosphere should be expected as a combination of the effects of meso-phenomena associated with a sharp upper trough or ridge and mountain waves.

III DEFINITION AND DISCUSSION OF A TURBULENCE INDEX

In Sec. II, it was pointed out that favored regions for moderate
or severe clear-air turbulence include surfaces of discontinuity in
lapse rate (principally the upper or lower boundaries of upper fronts,
or the tropopause) when wind speeds are high and pronounced turning
of the wind occurs across the thermal discontinuity. Thus the quanti-
ties $\partial^2 T/\partial z^2$ and $V(\partial\alpha/\partial z)$ were important parameters for the occurrence
of clear-air turbulence. Patterns of $\partial^2 T/\partial z^2$ can be visualized quite
well by inspection of the temperature field itself (cf. Figs. 1 and 4).
Before defining a turbulence index, we wish to show the relationship
of an occurrence of <u>severe</u> turbulence with the quantity $V(\partial\alpha/\partial z)$. The
wind, temperature and turbulence fields for Flight 29 were described
in an earlier report (Endlich, 1963). The field of $V(\partial\alpha/\partial z)$ for this
flight through an anticyclonic jet stream is shown in Fig. 7. Regions
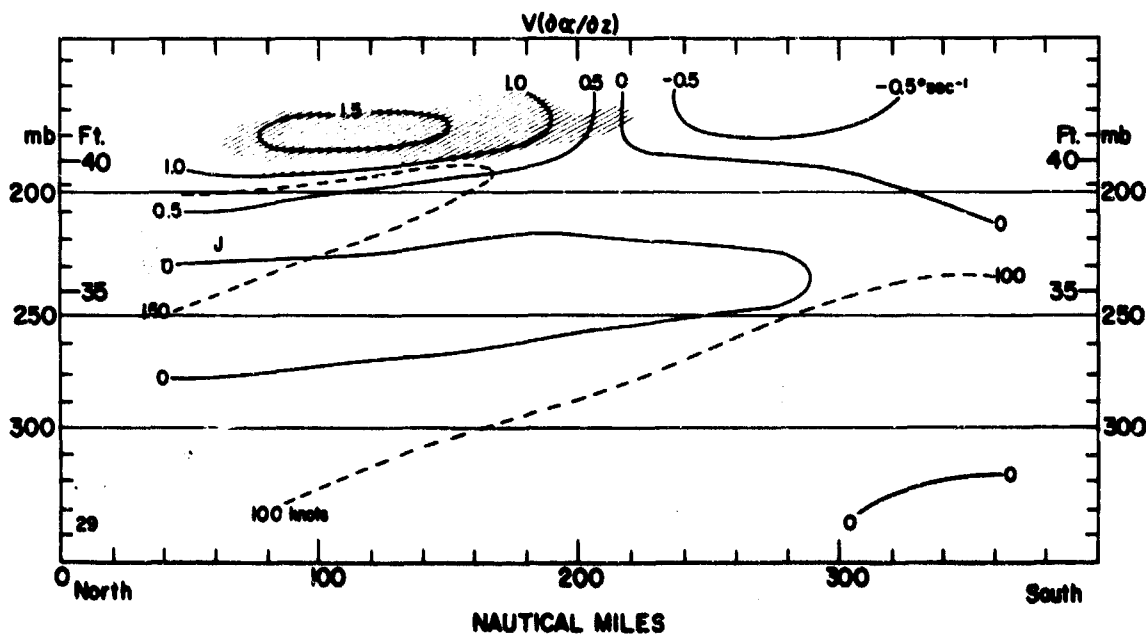
FIG. 7 VERTICAL CROSS SECTION, FLIGHT 29. The quantity $V(\partial\alpha/\partial z)$ is shown by solid
lines in units of deg sec^{-1}. Dashed lines are isotachs; J denotes jet core.

of moderate or severe turbulence are shaded, and the 100- and 150-knot
isotachs are also indicated. The maximum values of $V(\partial\alpha/\partial z)$ correlate

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well with the turbulent region. In Flight 27, a similar association existed between $V(\partial\alpha/\partial z)$ and a region of severe turbulence in an upper trough (Endlich, 1964).

On the basis of this empirical evidence, we have tentatively defined a turbulence index or "TI number" as $V(\partial\alpha/\partial z)(\partial^2 T/\partial z^2)$. This form is a convenient way of combining the wind and temperature terms discussed above. It will be shown in Secs. V and VI that this number has skill equivalent to that of Richardson's number in identifying regions of turbulence over the United States.

The Ri and TI numbers are not independent because of a relationship between $(\partial\underset{\sim}{V}/\partial z)^2$ (which is the denominator of Ri) and $V(\partial\alpha/\partial z)$ in TI. By a vector identity, $(\partial\underset{\sim}{V}/\partial z)^2 = (\partial V/\partial z)^2 + V^2(\partial\alpha/\partial z)^2$. So if $V(\partial\alpha/\partial z)$ is large, $(\partial\underset{\sim}{V}/\partial z)^2$ is large and Ri tends to be small, i.e., regions of directional shear and high speeds tend to have small Ri numbers. But the converse is not necessarily true, i.e., $(\partial\underset{\sim}{V}/\partial z)^2$ can be large if $\partial V/\partial z$ is large but $\partial\alpha/\partial z$ is zero. In other words, the shear can be large (and the Ri number small) if there is a large change in speed without a change in direction (TI = 0). These relationships are illustrated in Fig. 8. Another difference between the Ri and TI numbers is that the former depends on lapse rate and the latter upon the change in lapse rate. The correlation between Ri and TI, computed from values at all U.S. stations on 15 March 1962 at 0000 GCT, was -0.3, indicating a rather weak relationship.

The TI number is deficient from the dynamic standpoint since no existing theory indicates its importance. However, it is possible that the TI number has physical significance that can be determined by proper use of laboratory models, numerical integrations, or perturbation analysis. Aircraft observations show that regions of large TI number are usually regions where meso-scale vertical motions on the order of a m sec^{-1} exist. These vertical motions may be of opposite direction across a frontal boundary or tropopause. Strong horizontal divergence on the meso-scale is also present in these areas. These conditions of vertical motion and divergence may produce gravity-inertia waves in a

I. STRONG WINDS AND APPRECIABLE TURNING OF WIND WITH HEIGHT

UPPER WIND

SHEAR VECTOR

LOWER WIND

Ri	TI	TURBULENCE
SMALL	LARGE	USUALLY OBSERVED

2. STRONG SHEAR AND LITTLE TURNING OF WIND WITH HEIGHT

UPPER

LOWER

SHEAR VECTOR

Ri	TI	TURBULENCE
SMALL	SMALL	SOMETIMES OBSERVED

3. WEAK WINDS OR WEAK SHEAR

UPPER

SHEAR VECTOR

LOWER

Ri	TI	TURBULENCE
LARGE	SMALL	SELDOM OBSERVED

FIG. 8   COMPARISON OF Ri AND TI NUMBERS UNDER TYPICAL CONDITIONS

manner analogous to wave generation by vertical displacements over mountains. As mentioned in Sec. I, instability of such waves has been assumed to be a mechanism for the formation of turbulent eddies.

IV COMMENTS ON STABILITY CRITERIA AND CLEAR-AIR TURBULENCE

As mentioned earlier, one theoretical approach to turbulence is a perturbation analysis of instability beginning with prescribed initial conditions. In this section, reference will be made to stability criteria of Kuettner (1952), Sasaki (1958), Holmboe (1963), and Hildreth, et al. (1963) that have application to turbulence. Another method involving energy transformations by eddy processes (Clodman, Morgan, and Ball, 1960) is hampered in application by lack of observational data. The writers believe that there is a major deficiency in knowledge of conditions that produce turbulence. This aspect of the problem is usually neglected because of the difficulties involved. However, theory concerning the dissipation or growth of pre-existing turbulence is well established (cf. Ch. 4, Sutton, 1953). The theory states that turbulence will increase when Ri < 1 - a, where a is a small positive quantity. Although there has been dispute concerning the utility of Ri as a clear-air turbulence criterion, the statistical analysis of Sec. VI shows that it has appreciable skill.

Holmboe (1963) reviews an analysis by Goldstein (1931) showing that the Ri number is an important parameter concerning the instability of waves in a stratified fluid in which density and wind vary in the different layers. The stability diagram for a stratified shear layer of thickness d is shown in Fig. 9. The writers' interest in this model is due to its apparent analogy to an upper front in the atmosphere. The diagram shows that waves of an intermediate size are unstable. For a shear layer having a depth d = 600 m, a shear $2U = 10$ m sec^{-1}, and Ri = 1.0, a perturbation of wave length 1800 m doubles in amplitude in 8 minutes as long as the linear theory is valid. This rapid amplification is compatible with an application of the theory to clear-air turbulence. Figure 9 shows that instability can exist for values of Ri > 1.0. For example, for Ri = 2.0, wave lengths near (2/3)πd are unstable. Evidently, turbulence could exist at this value of Ri. However, in this situation, turbulence would tend to be short-lived (since dissipation by

buoyancy would be large) unless perturbations in the unstable range were
present continuously. Holmboe has extended the analysis to more realis-
tic initial conditions involving continuous variations of velocity and
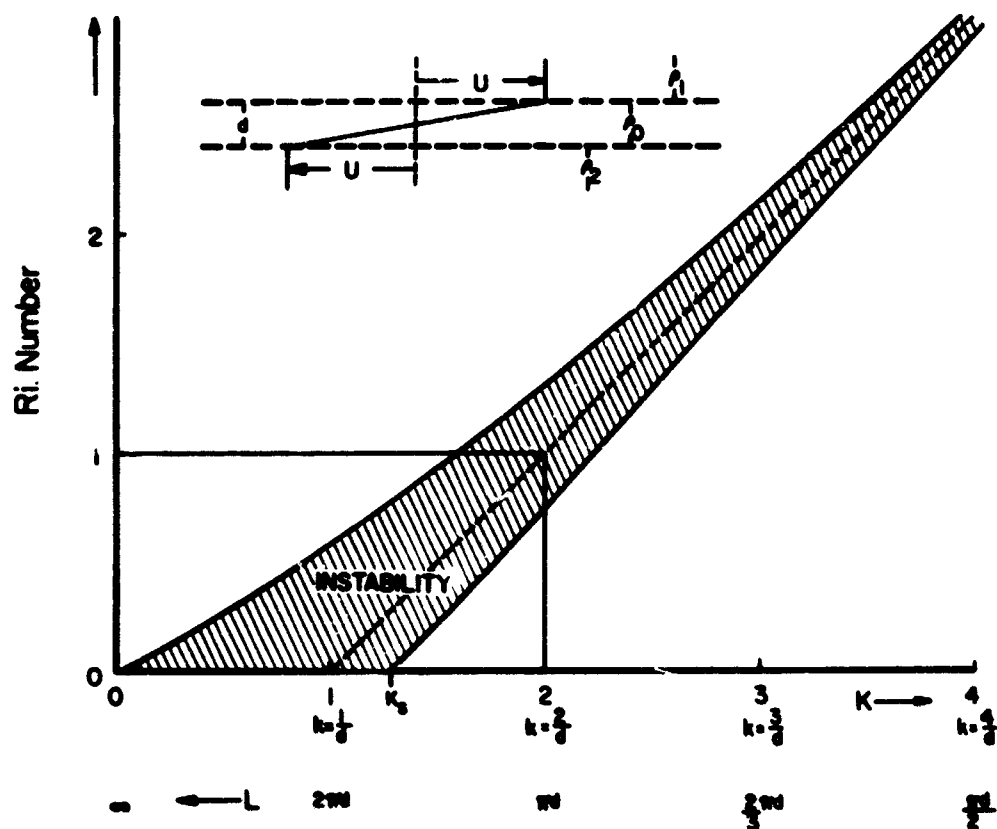
FIG. 9   STABILITY DIAGRAM FOR A STRATIFIED SHEAR LAYER OF DEPTH d
[after Goldstein (1931) as given by Holmboe (1963)]

density instead of the sharp discontinuities of Fig. 9, and found
similar stability properties for this more complex model.

Kuettner's analysis emphasized the importance of the curvature
term $\partial^2 V/\partial z^2$ (in addition to shear and lapse rate) in relation to in-
stability of wave motions. In addition, Sasaki's study indicated that
$\partial^2 T/\partial z^2$ entered into stability criteria. If one is concerned with the
stability of longer waves (lengths on the order of 100 km), the analysis
of Hildreth et al. (1963) indicates that horizontal wind shear is the
most important parameter. These analyses are all concerned with varia-
tions of wind speed, and do not consider changes in wind direction of
the type discussed in Secs. II and III.

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The present argument, offered to stimulate discussion of the production and dissipation of high-level turbulence, may be summarized as follows. Perturbation analyses of stratified shear layers that resemble upper fronts indicate that a certain range of relatively short waves is unstable. It has been assumed that instability of this sort in the atmosphere would produce eddies that transfer energy to smaller motions, including those eddy sizes that are turbulent to aircraft. Thus, it appears that instability and turbulence can exist for values of Ri > 1.0. However, when Ri < 1 - a, turbulence tends to increase rather than to dissipate. Therefore, correlations between high-level turbulence and Ri number should exist, but no clear-cut upper limit on Ri (above which turbulence is never observed) should be expected.

In the mathematical analyses described above, it is assumed that "perturbations" are present. In the atmosphere, perturbations may <u>not</u> be omnipresent since smooth flight has been reported by aircraft in areas where the Ri number appeared to be appreciably smaller than 1.0. Such areas are sometimes observed on the high-pressure side of jet streams below the maximum wind level (where lapse rates are rather unstable and vertical shear is moderately strong). Areas of appreciable perturbations (particularly meso-scale vertical motions) appear to be those regions of jet streams near upper fronts (especially in troughs or ridges), as well as mountain waves and areas immediately downstream from convective activity.

V TURBULENCE ANALYSIS FOR 12-24 MARCH 1962

We turn now to operational problems relating to the utility of
standard upper-air data in identifying turbulent regions, and to ob-
jective methods of utilizing the rawinsonde data for this purpose. In
this portion of the work, we have compared values of a number of
meteorological quantities to actual turbulence reports made by airline
pilots over the United States. The turbulence data are from a special
reporting period in March 1962 (Colson, 1963a) and were made available
to us in the form of plotted maps. Without data of this type, one
could not investigate these problems. By means of the comparisons, we
wished to discover quantities that have maximum or minimum values in
turbulent regions, and therefore potential utility in turbulence
analysis.

Past investigations have shown that several meteorological quan-
tities are related to turbulence, including wind speed, vertical and
horizontal shear, lapse rate, Ri number, horizontal curvature of flow,
etc. However, many conditions of interest occur concurrently. For
example, horizontal and vertical wind shear are correlated with wind
speed and with each other. Strongest shears usually occur in upper
fronts or at the tropopause, in both cases mainly in cyclonic horizontal
shear. Upper fronts are regions of large changes in lapse rate and
large horizontal temperature gradients. Sharp troughs are associated
with upper fronts. Consequently, the turbulence analyst could formulate
a number of criteria based on different combinations of factors. Ideally,
we wish to obtain criteria using the minimum number of factors that
correctly identify turbulent regions. At the same time, it is desirable
to minimize the volume of atmosphere identified as turbulent, i.e., to
pinpoint the analysis.

From previous experience, we expected the Ri and TI numbers to be
useful quantities that could be calculated easily from upper-air data.
These quantities (and their component terms such as wind shear and lapse

rate) were calculated by electronic computer from card deck 645, obtained from the National Weather Records Center. However, instead of computing the term $V(\partial\alpha/\partial z)$ in the TI number, we computed the quantity $(fT/g)(V^2\partial\alpha/\partial z)$, which has the units $K \; sec^{-1}$. By use of the thermal wind relation, this latter quantity is a form of the somewhat familiar term "thermal advection" that has been associated with turbulence by Keitz (1959) and Schwerdtfeger and Radok (1959). Although the patterns of $V(\partial\alpha/\partial z)$ and thermal advection are similar, it appears that the term V^2 in thermal advection over-emphasized high wind speeds. In the future we will use the TI number in the form discussed in Sec. III, with the expectation of achieving a slight improvement over the results given in this report.

In the range from 500 to 200 mb, the quantities were computed over 50-mb intervals, except for $\partial^2 T/\partial z^2$, which was computed over 100-mb intervals. From 200 to 100 mb data are twice as frequent so the corresponding computational intervals were 25 and 50 mb. The computed quantities were printed at station locations on the same base map for which the turbulence observations were plotted, thus permitting immediate comparison of the computer output and turbulence reports. An example of a map of the magnitude of wind shear $|\partial \underset{\sim}{V}/\partial z|$ is shown in Fig. 10 for 15 March 1962. Four numbers in a row are printed at each rawinsonde station, applying to four 50-mb intervals (500-450, 450-400, etc.). Dashes signify missing data. The shears have been scaled to arbitrary units so that the majority lie between 0 and 9, with 9 as an upper limit (to avoid printing two digits for a layer). The present units are $2 \times 10^{-3} \; sec^{-1}$ so that the printed number $\underline{4}$, for example, means a shear of $8 \times 10^{-3} \; sec^{-1}$ (4.75 knots per thousand feet). Isotachs and jet streams at the 400-mb level have also been indicated in Fig. 10. Most, but not all, of the layers of large shear are associated with high wind speeds. The letters $\underline{T}$ and $\underline{N}$ signify the presence or absence, respectively of moderate or severe turbulence as shown by Colson's data. The turbulence reports shown are for altitudes between 18,000 and 29,000 ft and fall within a six-hour period centered at the map time. In
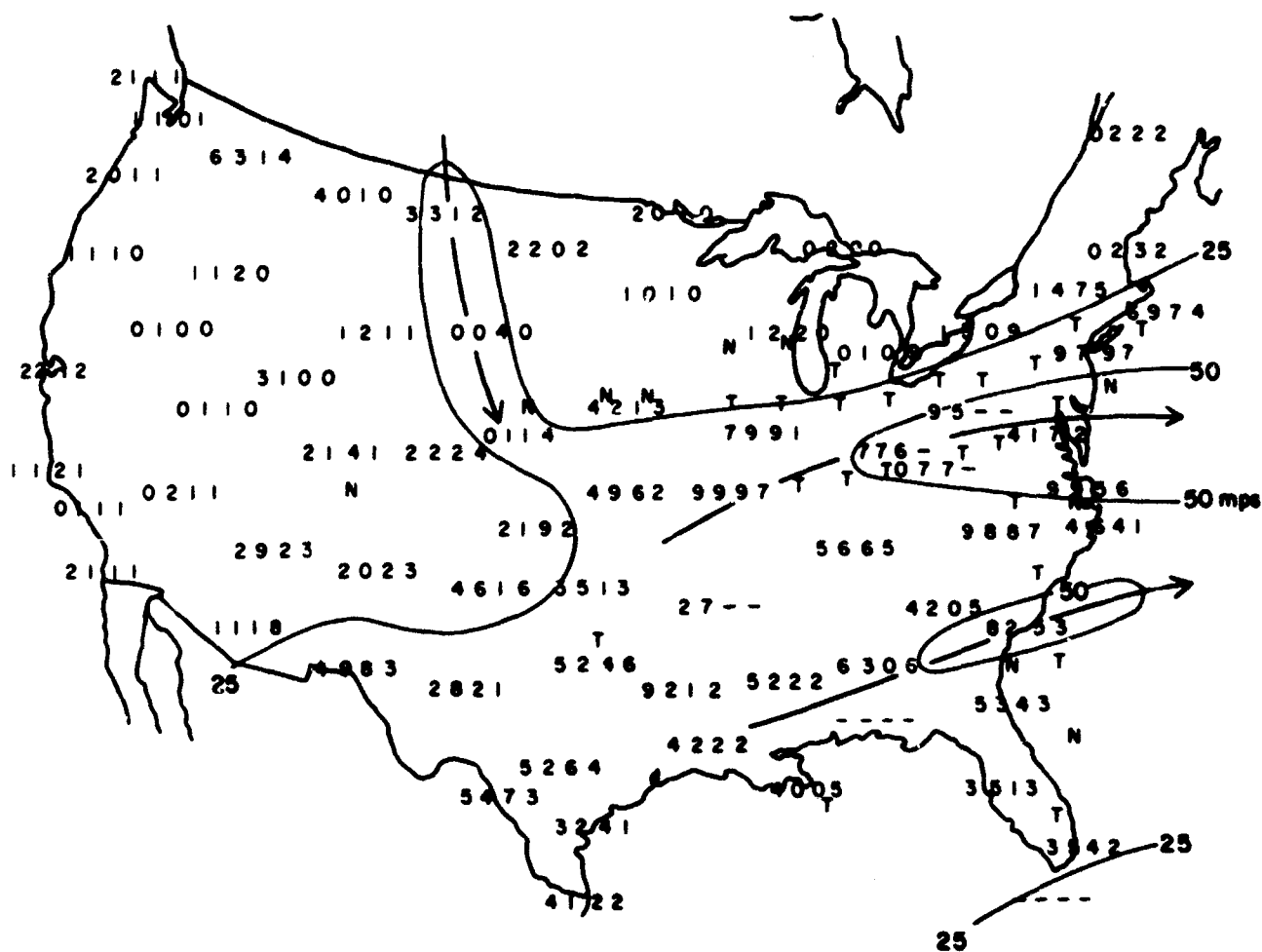
FIG. 10 VERTICAL WIND SHEAR OVER UNITED STATES, 00 GCT, 15 MARCH 1962.
Shear scaled in arbitrary units (see text) for intervals 500 – 450 mb, 450 – 400 mb,
400 – 350 mb, and 350 to 300 mb. T denotes moderate or severe turbulence reported
by aircraft; N denotes no turbulence reported.

order to make a reasonably clear differentiation between turbulent and
smooth conditions, it was decided arbitrarily to apply the letter N
only if three or more flights traversed a given region without en-
countering turbulence. One or more flights reporting turbulence is
assigned the letter T, regardless of non-turbulent flights in the same
area.

Computed values of the quantity $\partial^2 T/\partial z^2$ (units $10^{-4} K\ m^{-2}$) are
shown in Fig. 11 for 100-mb layers (500-400 mb etc.). Recalling that
large positive values indicate the base of stable layers and negative
values their upper surfaces, we can quickly scan the numbers to locate
such boundaries. For example, at Midland, Texas the sequence +6-3 0+1

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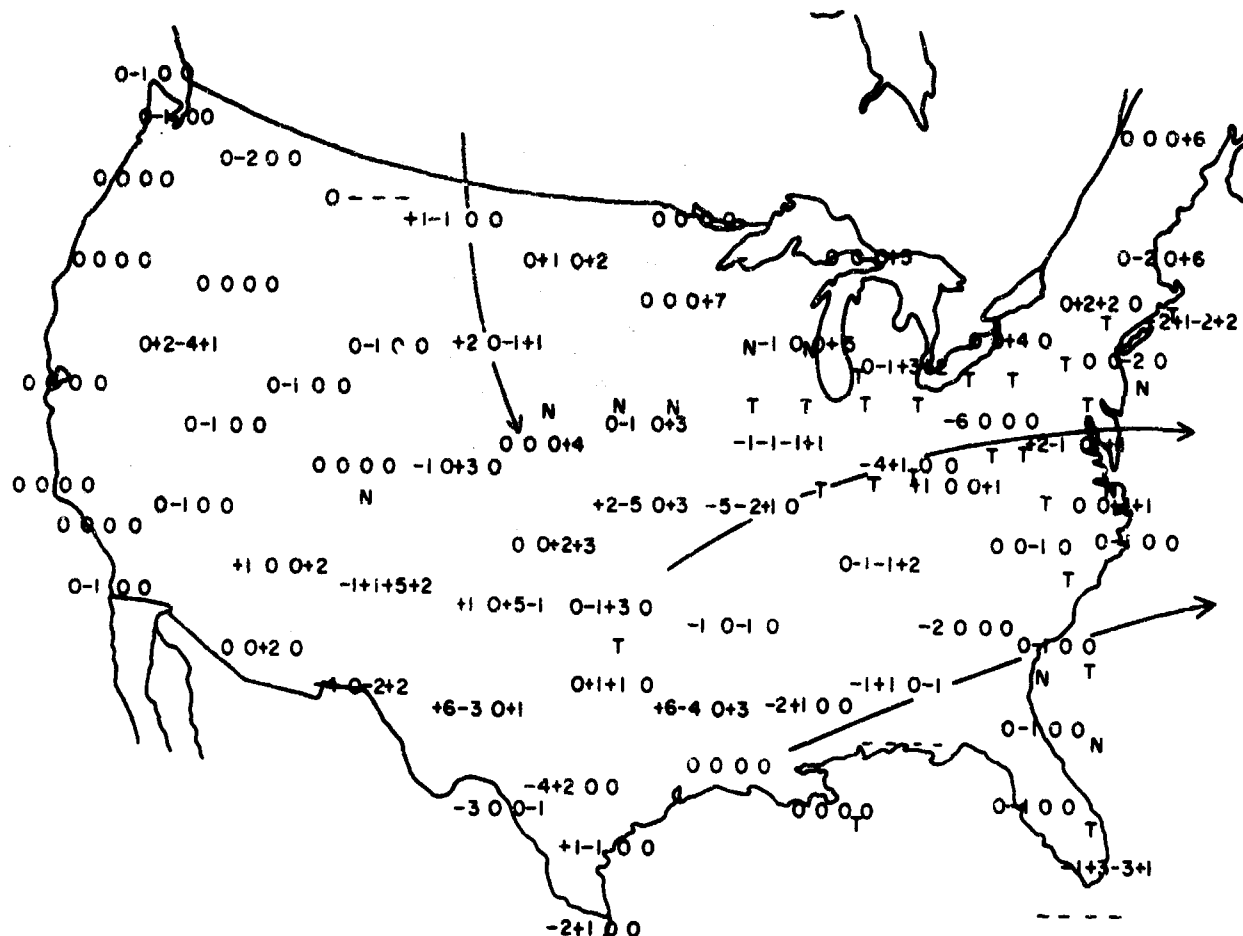
FIG. 11   THE QUANTITY $\partial T^2/\partial z^2$ OVER UNITED STATES, 00 GCT, 15 MARCH 1962.
Units of 10^{-4} K m^{-2} for intervals of 500 – 400 mb, 450 – 350 mb, 400 – 300 mb, and
350 – 250 mb. T denotes moderate or severe turbulence reported by aircraft;
N denotes no turbulence reported.

indicates the base and top of an inversion in the first two layers
followed by little change in lapse rate in the two higher layers. A
well-developed tropopause normally appears (in higher layers) as a
large positive value of $\partial^2 T/\partial z^2$.

The computed values of Ri number (top row at each station) and TI
number (bottom row) are shown in Fig. 12. It is interesting that the
T's occupy a large continuous area south of the Great Lakes, extending
from Illinois to New York. This turbulent region persisted for 18
hours. During this period, moderate turbulence was reported by approxi-
mately 50 percent of the flights made in each sector labelled by a T.
In Fig. 12, small values of Ri and large magnitudes of TI indicate

FIG. 12   VALUES OF Ri AND TI FOR 00 GCT, 15 MARCH 1962. Arbitrary units for intervals
500 – 450 mb, 450 – 400 mb, 400 – 350 mb, and 350 – 300 mb. T denotes moderate
or severe turbulence reported by aircraft; N denotes no turbulence reported

turbulence. Negative values of Ri (which have been noticed on a few
occasions) imply superadiabatic lapse rates. The TI number can be
positive or negative; however no utility has been found for the sign
so the magnitude is used as a criterion. Taking Peoria, Illinois (just
south of Lake Michigan) as an example, in the upper row the sequence
+9+2+4 n signifies Ri numbers of 0.9, 0.2, 0.4, and > 1.0 (no turbu-
lence expected). In the lower row, the sequence n+1+2 n signifies
TI numbers less than 1 (no turbulence expected), +1, +2, and no tur-
bulence.

At stations in the western United States, both Ri and TI numbers
generally indicate that no turbulence should be expected. East of the

Mississippi River, many layers are found having small values of Ri or large values of TI. The patterns of the two criteria match the turbulence reports quite well; however, in individual layers, the two criteria do not necessarily agree.

The Ri number, TI number, and turbulence reports above 29,000 ft on 15 March are shown in Fig. 13. The turbulent area south of the Great Lakes is similar to that at lower altitudes (Fig. 10). As frequently
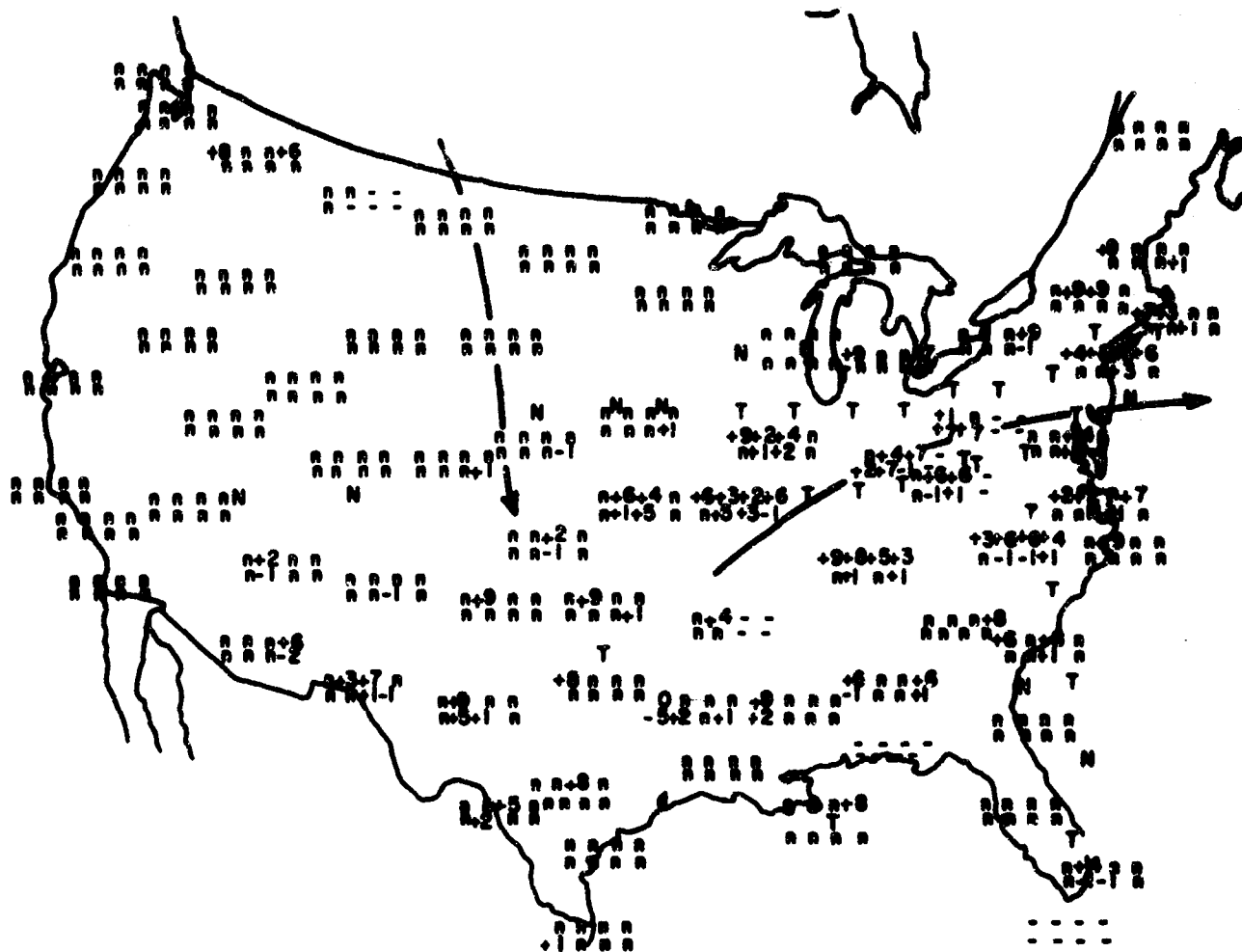

FIG. 13   VALUES OF Ri AND TI FOR 00 GCT, 15 MARCH 1962. Arbitrary units for intervals 300 – 250 mb, 250 – 200 mb, 200 – 175 mb, and 175 – 150 mb. T denotes moderate or severe turbulence reported by aircraft; N denotes no turbulence reported.

happens under conditions of strong flow, wind data were not obtained in or above the jet stream at several crucial stations. Thus the Ri and TI numbers could not be determined there.

The quantities mentioned above were computed and printed for 0000 and 1200 GCT during the period 12-24 March 1962. In the interest of brevity, only two additional charts of this series will be mentioned. On 21 March, the upper air pattern was quite different than on 15 March. In Fig. 14, the two turbulence criteria and turbulence reports above 29,000 ft are shown. An interesting feature is the region of turbulence
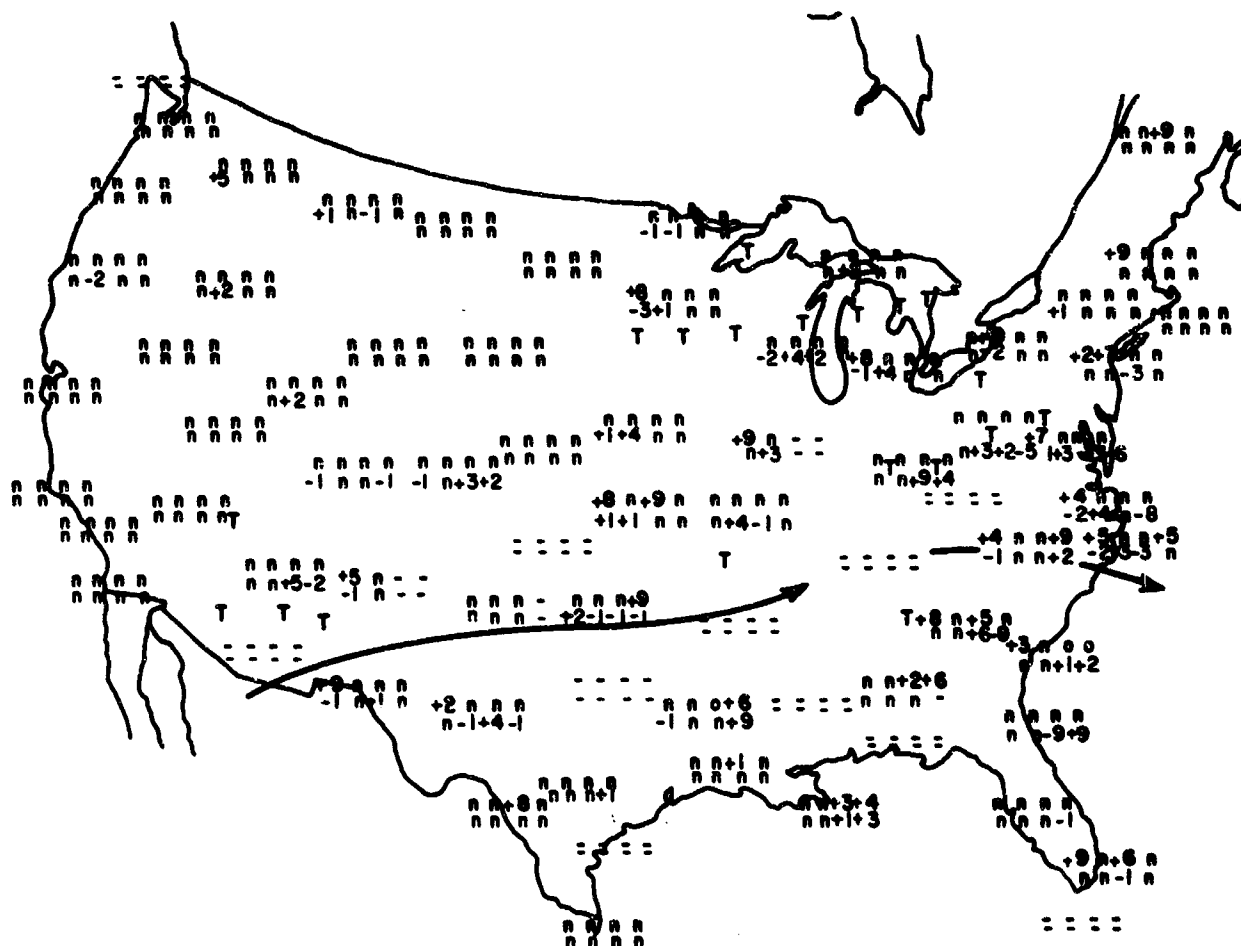
FIG. 14 VALUES OF Ri AND TI FOR 00 GCT, 21 MARCH 1962. Arbitrary units for intervals 300 – 250 mb, 250 – 200 mb, 200 – 175 mb, and 175 – 150 mb. T denotes moderate or severe turbulence reported by aircraft; N denotes no turbulence reported.

across the center of Lake Michigan, away from the jet stream. In this region, the TI number describes the turbulence more accurately than the Ri number. On 23 March (Fig. 15), a very strong jet in advance of a trough lay over the southeastern United States. Both turbulence
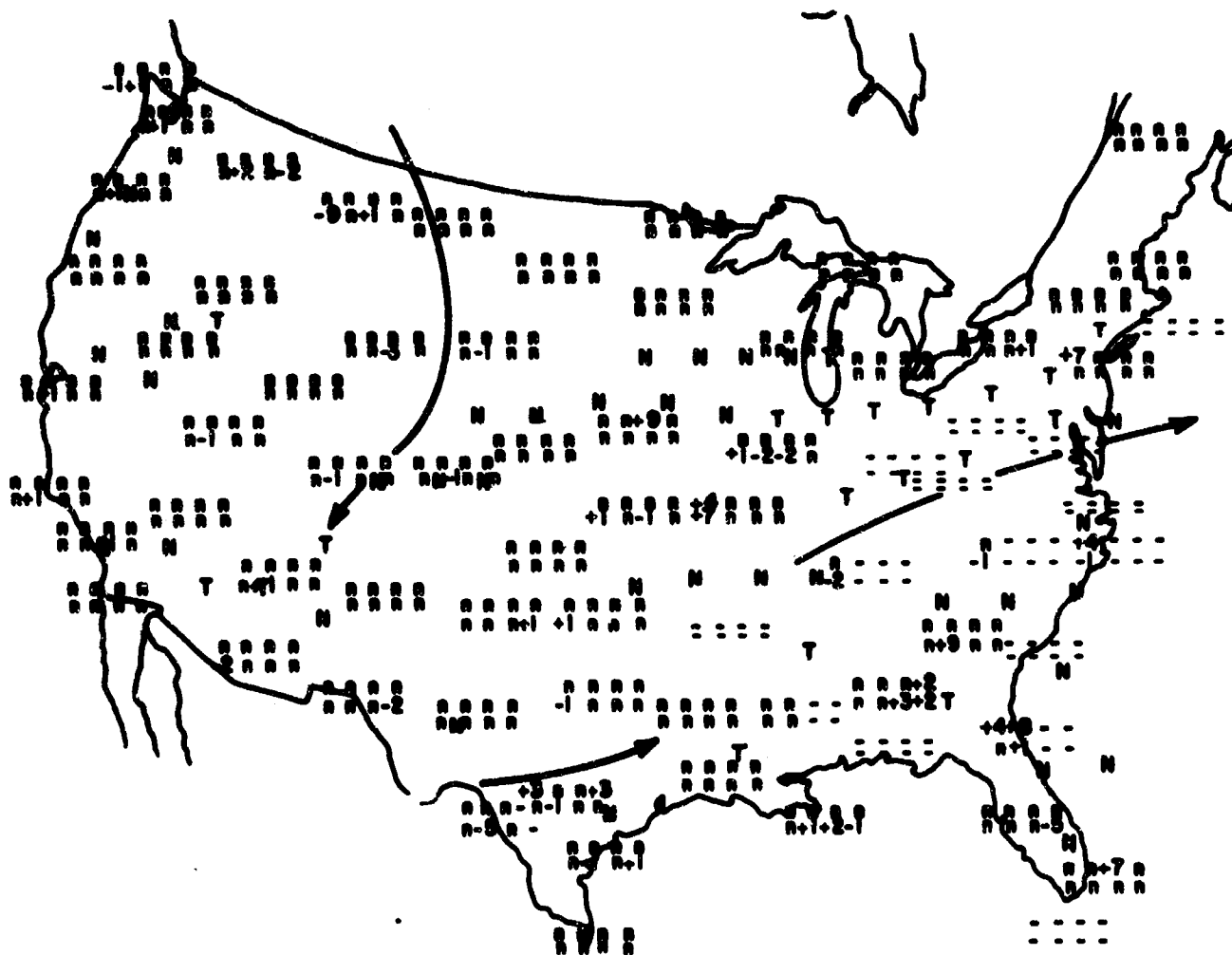
31
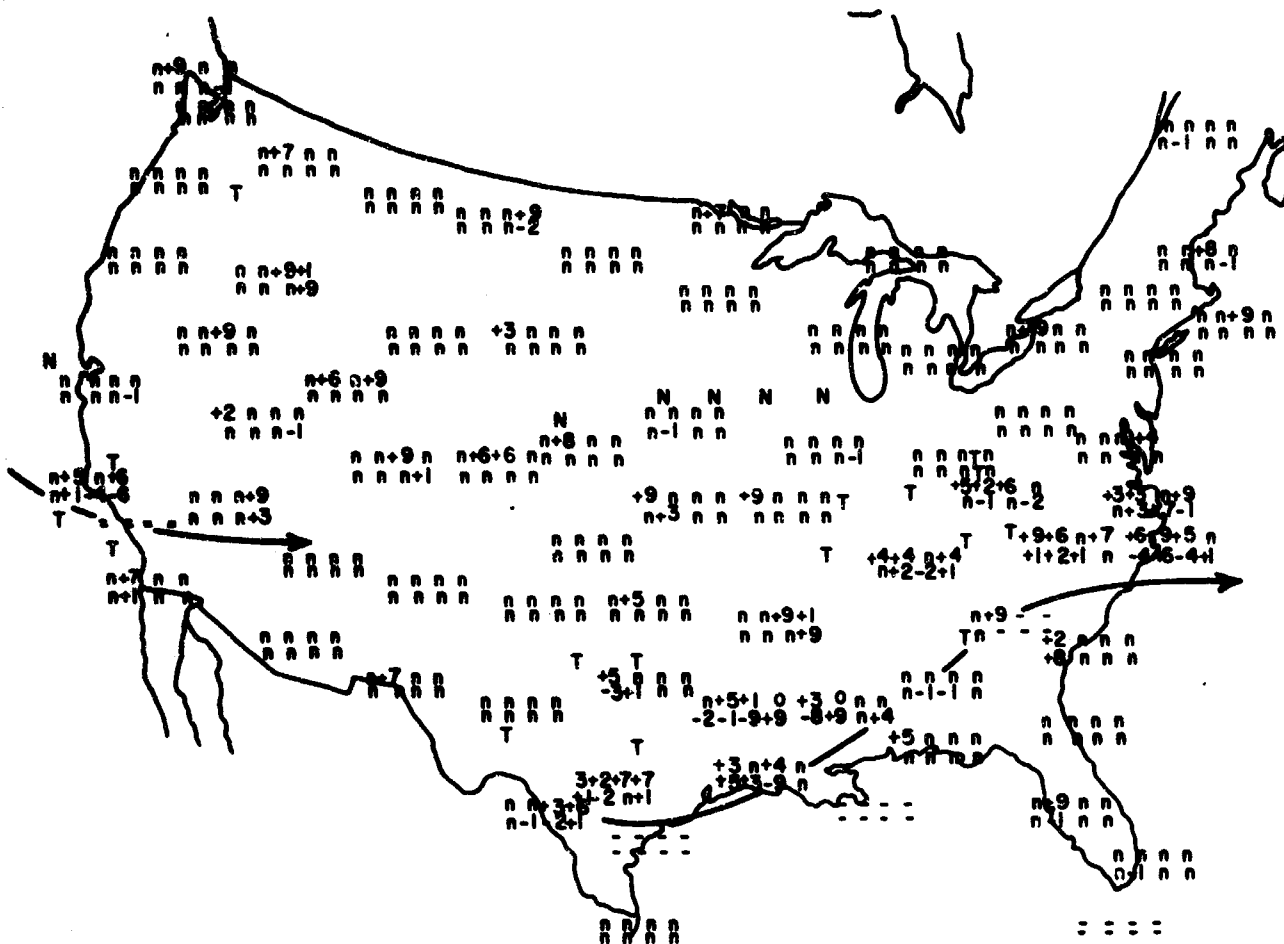
FIG. 15 VALUES OF Ri AND TI FOR 00 GCT, 23 MARCH 1962. Arbitrary units for intervals 500 – 450 mb, 450 – 400 mb, 400 – 350 mb, and 350 – 300 mb. T denotes moderate or severe turbulence reported by aircraft; N denotes no turbulence reported.

criteria indicate unusual values along the jet; however, no aircraft d· .a were available in this region. Further away from the jet, the aircraft reports compared favorably with the computations.

In evaluating the Ri and TI numbers (or any other criteria) for clear-air turbulence, it would be desirable to have a report of turbu-lent intensity in each layer at each station. In that case, one could determine whether the turbulent intensity is related quantitatively to the criteria. If so, the criteria would be useful in selecting alti-tudes for smoothest flight. Moreover, the amount of useful data would be tremendously enlarged. As matters stand, comparisons are confined mainly to major air routes.

In summary, it appears that the computed values of Ri and TI in Figs. 12-15 are in substantial agreement with turbulent intensity reported by aircraft. In regions where aircraft reports were not obtained the criteria indicate turbulent regions that are related to troughs, ridges and jet streams as one would expect.

VI STATISTICAL ANALYSIS OF TURBULENCE CRITERIA

The series of maps of Ri number, TI number, and turbulence reports for the period 12-24 March 1962 were used to prepare tables showing the accuracy of these two criteria in turbulence analysis. The plotted T's (turbulent flight) and N's (no turbulence) were compared with Ri and TI numbers at the nearest station in the region. For the first test, Ri < 0.6 and TI ≥ 3.0 were chosen as denoting turbulence. For the criteria within these ranges, a T constitutes a correct identification, and an N constitutes an error. Conversely, for Ri ≥ 0.6 and TI < 3.0, an N is correct identification, and a T is an error. The criteria were tested separately, and also on an alternative basis, as shown in Fig. 16.

Of the 327 cases that were available, 120 were turbulent and 207 were nonturbulent. Using Ri < 0.6 as a criterion, we correctly identify 34 (or 28 percent) of the turbulent cases and 191 (or 92 percent) of the nonturbulent cases. The numbers to be expected by chance are shown in the no-skill table. The value of χ^2 for the difference between the actual and no-skill tables is 26.2 which is significant at the 1 percent probability level. The skill score, S, (Panofsky and Brier, 1958) is 0.24 where 0 denotes no skill and 1.0 denotes perfect agreement between observations and analysis. The number of intervals found to have values of Ri < 0.6 was 4 percent of the total. The optimum analysis will maximize the number of correct identifications of turbulence while minimizing the portion of atmosphere involved.

Using TI ≥ 3.0 as a criterion (Part II of Fig. 16) gives 40 out of 120 (or 33 percent) correct identifications of turbulence and 186 out of 207 (or 90 percent) of the nonturbulent cases. Values of χ^2, S, and percentage of volume are similar to Part I of Fig. 16.

Since the Ri and TI numbers are not highly correlated, it is natural to consider the success that can be obtained by use of Ri < 0.6 and/or TI ≥ 3.0 as a turbulence criterion. From Part III of Fig. 16, we see that the number of correct identifications of turbulence is increased

I Ri NO. < 0.6

OBSERVED	ANALYZED			NO SKILL		
	NON-T	TURB				
NON-T	191	16	207	175	32	χ^2 = 26.2
TURB	86	34	120	102	18	S = 0.24
	277	50	327			VOL = 4%

II Ti NO. ≥ 3.0

OBSERVED	ANALYZED			NO SKILL		
	NON-T	TURB				
NON-T	186	21	207	168	39	χ^2 = 28.3
TURB	80	40	120	98	22	S = 0.26
	266	61	327			VOL = 3%

III Ri NO. < 0.6 AND I OR Ti NO. ≥ 3.0

OBSERVED	ANALYZED			NO SKILL		
	NON-T	TURB				
NON-T	175	32	207	151	56	χ^2 = 38.2
TURB	63	57	120	87	33	S = 0.34
	238	89	327			VOL = 6%

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FIG. 16 TABLE SHOWING ACCURACY OF ANALYSIS OF MODERATE OR SEVERE TURBULENCE USING Ri AND TI NUMBERS WITHIN SPECIFIED RANGES.
The No-Skill tables show the numbers to be expected by chance. The skill score is shown by S. VOL is the percentage of volume having the specified conditions of Ri or TI.

to 57 out of 120 (48 percent), while 175 out of 207 (85 percent) of the nonturbulent areas are identified. Thus, an increase in the first percentage is accompanied by a decrease in the second. Stated differently, a larger number of hits in specifying turbulence is obtained at the cost of incorrectly identifying more nonturbulent areas as being turbulent. Since there is some overlap in the regions specified by the two criteria, the volume in Part III is slightly less than the sum of the two separate volumes.

The accuracy in identifying turbulent regions shown in Fig. 16 is far less than we desire, even though positive skill has been demonstrated.

If the criteria are relaxed, more correct identifications of turbulence are made, more errors are made in specifying nonturbulent regions as turbulent, and volumes of atmosphere involved are increased (Fig. 17).

I Ri NO. < 1.0

ANALYZED
	NON-T	TURB	
NON-T	172	35	207
TURB	57	63	120
	229	98	327

(rows labeled OBSERVED)

NO SKILL
145	62
84	36

$\chi^2 = 45.7$
$S = 0.37$
VOL = 8%

II Ti NO. ≥ 2.0

ANALYZED
	NON-T	TURB	
NON-T	164	43	207
TURB	67	53	120
	231	96	327

NO SKILL
146	61
85	35

$\chi^2 = 20.6$
$S = 0.25$
VOL = 6%

III Ri NO. < 1.0 AND I OR Ti NO. ≥ 2.0

ANALYZED
	NON-T	TURB	
NON-T	141	66	207
TURB	35	85	120
	176	151	327

NO SKILL
111	96
65	55

$\chi^2 = 47.7$
$S = 0.37$
VOL = 13%

RB-4521-1

FIG. 17 TABLE SHOWING ACCURACY OF ANALYSIS OF MODERATE OR SEVERE TURBULENCE USING LARGER VALUES OF Ri AND SMALLER VALUES OF Ti THAN IN FIG. 16

Some of these errors may be due to a lack of flights at the altitude and place identified as turbulent, i.e., turbulence that existed may not have been detected by aircraft in the region. Skill scores and values of χ^2 in Fig. 17 are similar to those of the previous figure; however, the results of Fig. 17 may be of greater operational value. From the pilot's standpoint, the benefit of correctly identifying turbulent zones is probably considerably greater than the harm due to identification of nonturbulent zones as being turbulent (i.e., specifying too many turbulent regions). Therefore, the results shown in Part III of Fig. 17, where 85 out of 120 (71 percent) of the turbulent cases are correctly identified, are the best that we have obtained.

These encouraging results may be due in part to the exclusion of light turbulence (which frequently occurs in small patches not clearly related to identifiable phenomena) from the turbulent (T) category. At any rate, positive skill in analyzing moderate or severe turbulence has been demonstrated using two quantities calculated directly from standard upper-air observations. No plotting or analysis precedes the computation. A quantity (the TI number) has been found that has accuracy equivalent to Richardson's number as a turbulence criterion, judged on the basis of a reasonably large sample of data. Combined use of the Ri and TI numbers gives better analyses than sole use of either. These results have been obtained in spite of discrepancies due to the subjectivity of turbulence reports, and to upper air data not perfectly coincident in time and space with the turbulence observations.

VII FURTHER INVESTIGATIONS OF TURBULENCE

Further studies of turbulence criteria should be directed to increasing the percentage of correct identifications of turbulent areas, and to reducing the volume identified as turbulent toward the 5 percent value that is realistic. It is our qualitative impression that improvement could be accomplished, in part, by de-emphasizing the high-pressure side of jet streams (where turbulence is sometimes absent even when Ri is small and TI is large). Since vorticity has been shown to be related to turbulence (Colson, 1964), and because vorticity is large to the north of jets and small to the south, this quantity might be included in turbulence criteria. Or instead of vorticity $(\partial v/\partial x - \partial u/\partial y)$, the quantity $(\partial v/\partial x)(\partial u/\partial y)$ might be used. In a typical upper air pattern, this quantity will have largest magnitudes near troughs or ridges on the low-pressure side of jet streams, i.e., in regions that are often turbulent. This term is familiar as $\psi_{xx}\psi_{yy}$ in the balance equation. For the 15 March data, the Scorer number $g\theta^{-1}(\partial \theta/\partial z)[V(\partial^2 v/\partial z^2)]^{-1}$ was calculated. Although inaccuracies in wind data make the calculated second derivatives somewhat unreliable, this number appeared to identify some turbulent regions not indicated by the Ri or TI numbers. Therefore, the Scorer number may have practical application. If a convenient means were found for calculating vertical motion in the upper troposphere on a subsynoptic scale, this quantity might also be useful in turbulence analysis. This enumeration is not intended to be exhaustive, but rather to indicate types of parameters that have potential use in improving turbulence analysis.

Computation of quantities such as those mentioned above will require grid point analyses of wind (or stream function) that preserve features of jet streams, troughs, and ridges in as much detail as possible. Moreover, the analysis must rely on geostrophic or other balanced winds in regions of missing wind observations.

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In the future, objective analysis should be applied to turbulence criteria to obtain a turbulence analysis in layers at grid points. Within the United States, where upper-air data are relatively plentiful, we believe that such analysis is feasible. A weighting function that would emphasize stations upstream or downstream from a grid point, with lesser weighting to stations across the flow, would be required. It is expected that the resulting patterns of turbulence criteria would be elongated in the direction of flow, in agreement with actual observations (e.g., the turbulence patterns of 15 March 1962).

Investigation of methods of forecasting turbulent regions is a matter that has not received much attention up to the present time. It has been necessary to establish skill in analysis before hoping to achieve skill in forecasting. Grid-point analysis of turbulence criteria (mentioned above) is probably a necessary step toward objective turbulence forecasting. One approach to turbulence forecasting would be to use the output of multi-level baroclinic prediction models in direct computation of turbulence criteria. Another approach would be to determine future motions in the upper flow by tracing quantities such as vorticity provided by prediction models, and in advection of turbulent regions with the velocity of these quantities. A third alternative would be to determine the past motion of regions of turbulence by comparison of present and past analyses, and to carry the regions forward in accord with their past motion. This latter method would assume that upper-air patterns and associated turbulent regions tend to maintain their characteristic shapes and movements for periods up to a day. This assumption is believed reasonable as a first approximation. The third alternative is probably the easiest to formulate for the computer.

In addition to the meteorological aspects of clear-air turbulence, there are instrumental aspects that deserve attention. The writers believe that turbulence research and operational analysis would be more reliable and effective if turbulence observations were obtained concurrently with rawinsonde data. It would be desirable to obtain such

measurements by means of a sensor flown with the radiosonde system. Preliminary engineering estimates indicate that several possibilities exist for rather simple sensors, provided that one wants simple intensity measurements. This subject has not been considered in the present study, but is mentioned here in the interest of completeness.

VIII CONCLUDING REMARKS

The empirical studies that have been carried out indicate that
regions favorable to clear-air turbulence are associated with the boun-
daries of upper fronts or the tropopause, particularly when wind speeds
are high and pronounced turning of the wind with height exists. These
meso-scale conditions are apparently produced and maintained by synoptic-
scale processes in certain portions of the upper flow, and in particular,
on the cyclonic side of jet streams in sharp troughs or ridges. These
aspects of turbulent regions are in accord with the concept of wave
instability as a primary source of turbulence.

Other aspects of the study are the following:

(1) Clear-air turbulence in jet streams over mountainous
     terrain appears to be associated with the same meso-
     scale conditions found elsewhere; however, turbulent
     intensity and size of the region involved are greater
     than would be expected with the same flow over level
     terrain.

(2) An empirical index (the "TI number") has skill
     equivalent to that of Richardson's number as a
     criterion for clear-air turbulence.

(3) Combined use of the two numbers (Ri and/or TI with-
     in prescribed limits) gives appreciably better re-
     sults than separate use of a single number.

(4) Computations of Ri and TI from standard upper air
     data are definitely skillful in identifying regions
     of moderate or severe clear-air turbulence during
     six-hour periods centered on the synoptic hours.
     Such computations and convenient print-outs can be
     made in a matter of minutes after upper-air data
     are available for input into an electronic computer.

(5) Further improvement of criteria for turbulence
analysis should consider quantities such as
vorticity, the term $\psi_{xx}\psi_{yy}$, and vertical motion.

(6) Controlled tests of turbulence criteria suggested
by various investigators should be made utilizing
conventional upper-air data and standard sets of
turbulence reports (such as those collected by the
Clear Air Turbulence Project).

(7) Grid-point analyses of regions of moderate or
severe clear-air turbulence appear feasible
over the United States. Experiments in objective
forecasting of turbulence should be attempted in
the near future.

(8) The writers believe that a sensor having the
ability to measure turbulence in layers con-
currently with radiosonde observations would
be valuable for research and for operational
use. The feasibility of developing an appropriate
turbulence sensor is a matter that deserves in-
vestigation.

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APPENDIX

GRAPHS OF TURBULENT INTENSITY AND TEMPERATURE

During the analysis of turbulence data recorded by the B-47 air-
craft of the Air Force Cambridge Research Laboratories, turbulent in-
tensity was read from VGH records and compared with simultaneous wind
and temperature measurements. As detailed minute-by-minute tabulations
of the VGH data are not generally available, we present typical graphs
of turbulent intensity, temperature, and altitude in Figs. A-1 through
A-7. Turbulence in these figures is interpreted as follows: less than
5 ft sec^{-1} is regarded as nonturbulent; 5 to 9 ft sec^{-1} is light turbu-
lence; 10 to 19 ft sec^{-1} is moderate turbulence; and 20 ft sec^{-1} or more
is severe turbulence.

These traverses through jet streams were oriented approximately
perpendicular to the upper flow. Ten minutes of flight is equivalent
to a distance over ground of 50-60 miles. The temperature curves show
the complexities of the meso-scale structure of the atmosphere near jet
streams. The aircraft altitude trace for Fig. A-3 shows that the air-
craft was carried away from its original altitude by a vertical draft
that extended over approximately five minutes of flight. As the local
lapse rate was nearly isothermal, only minor adjustments for altitude
are needed in the temperature data for this traverse. Detailed analyses
of four of the five flights from which these data are taken have been
presented in a previous report (Endlich, 1963) or in Sec. II of the
present report.

It should be noted that time increases to the right in each graph.
Presumably, if the aircraft had flown over the path in the opposite
direction, the phenomena would have been encountered in the reverse
order. Thus, in determining temperature-turbulence relationships, the
diagrams can be read from left to right or right to left.

In the experience of the writers (cf. Sec. II), clear-air turbulence
is frequently associated with upper fronts or the tropopause, which often

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contain pronounced horizontal temperature gradients. Thus, correlations between turbulence and temperature gradients should be expected; however, additional factors favorable to turbulence appear to be high wind speeds combined with turning of the wind with height. These latter conditions exist only in certain portions of the upper flow, and are not always present at upper fronts or the tropopause.
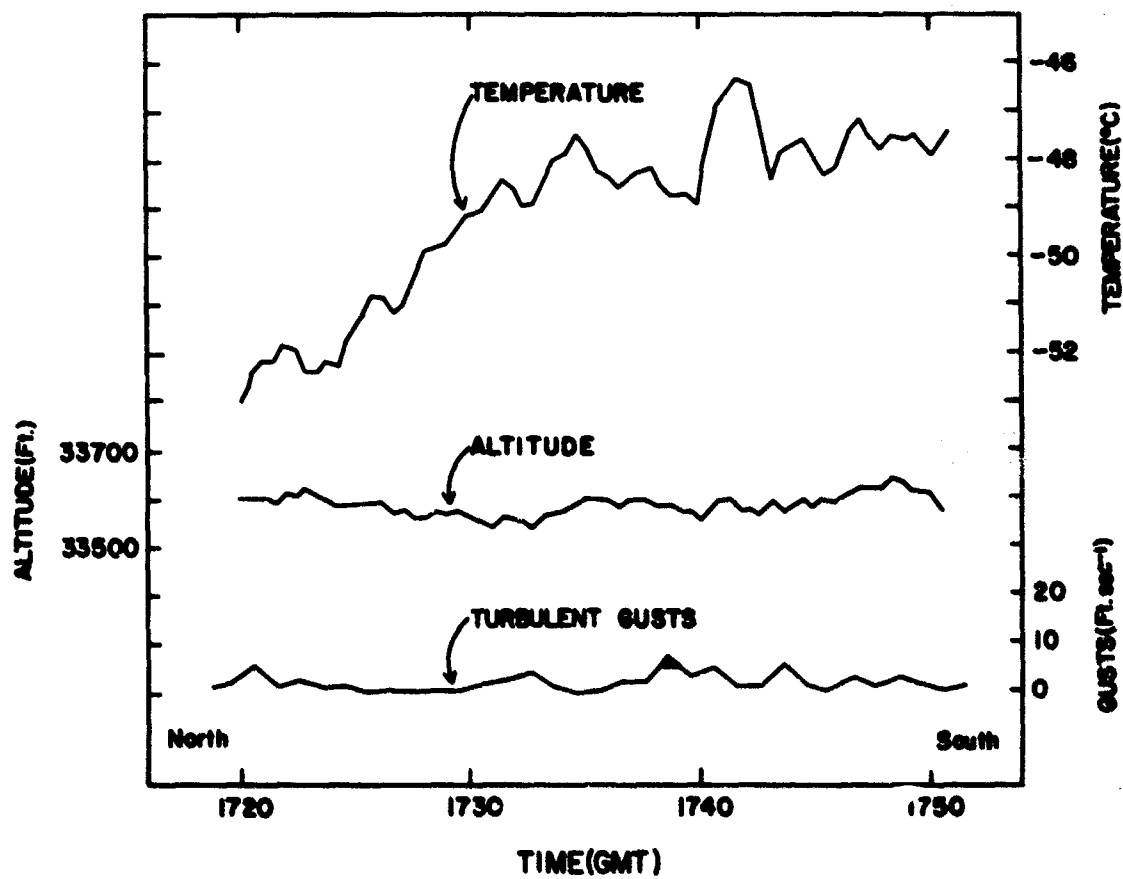
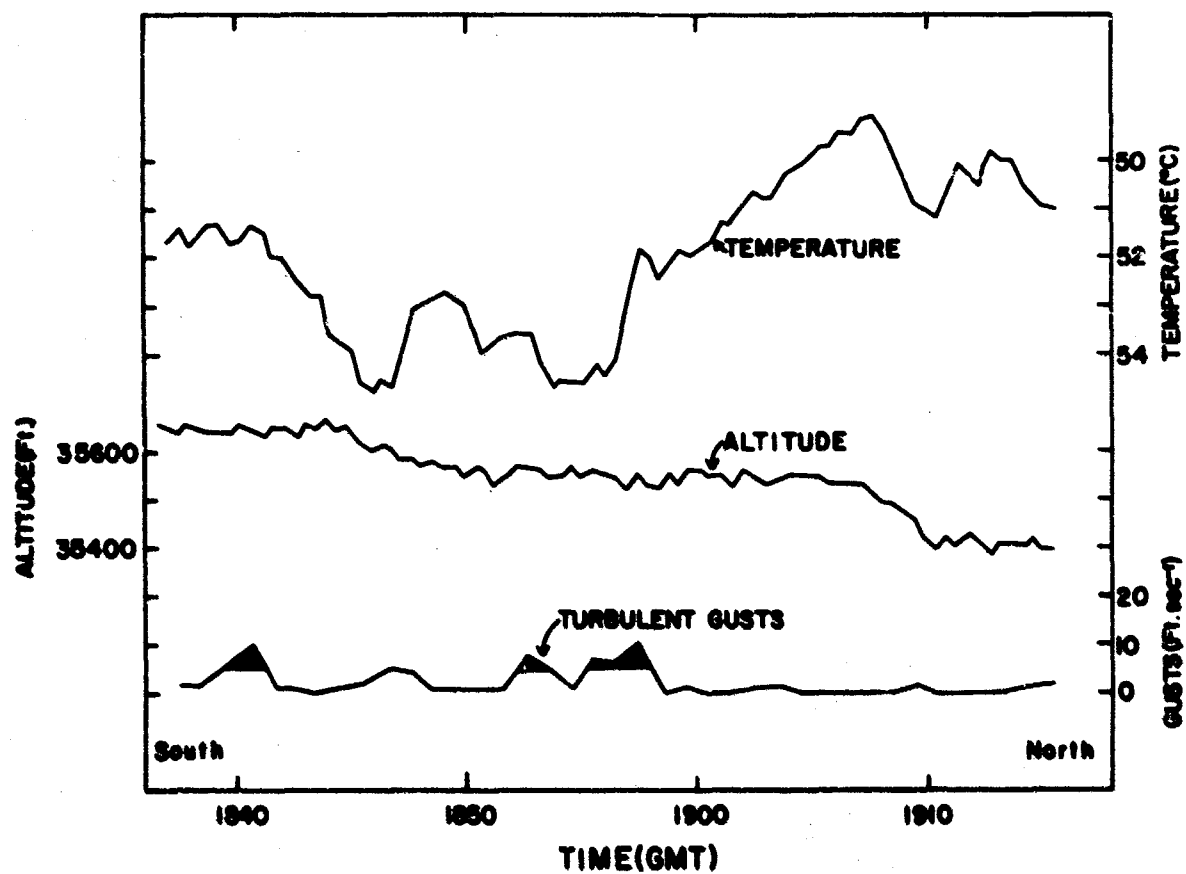FIG. A-1   TEMPERATURE, ALTITUDE, AND GUSTS, 1720 – 1750 GCT, FLIGHT 21

FIG. A-2 TEMPERATURE, ALTITUDE, AND GUSTS, 1840 – 1910 GCT, FLIGHT 21
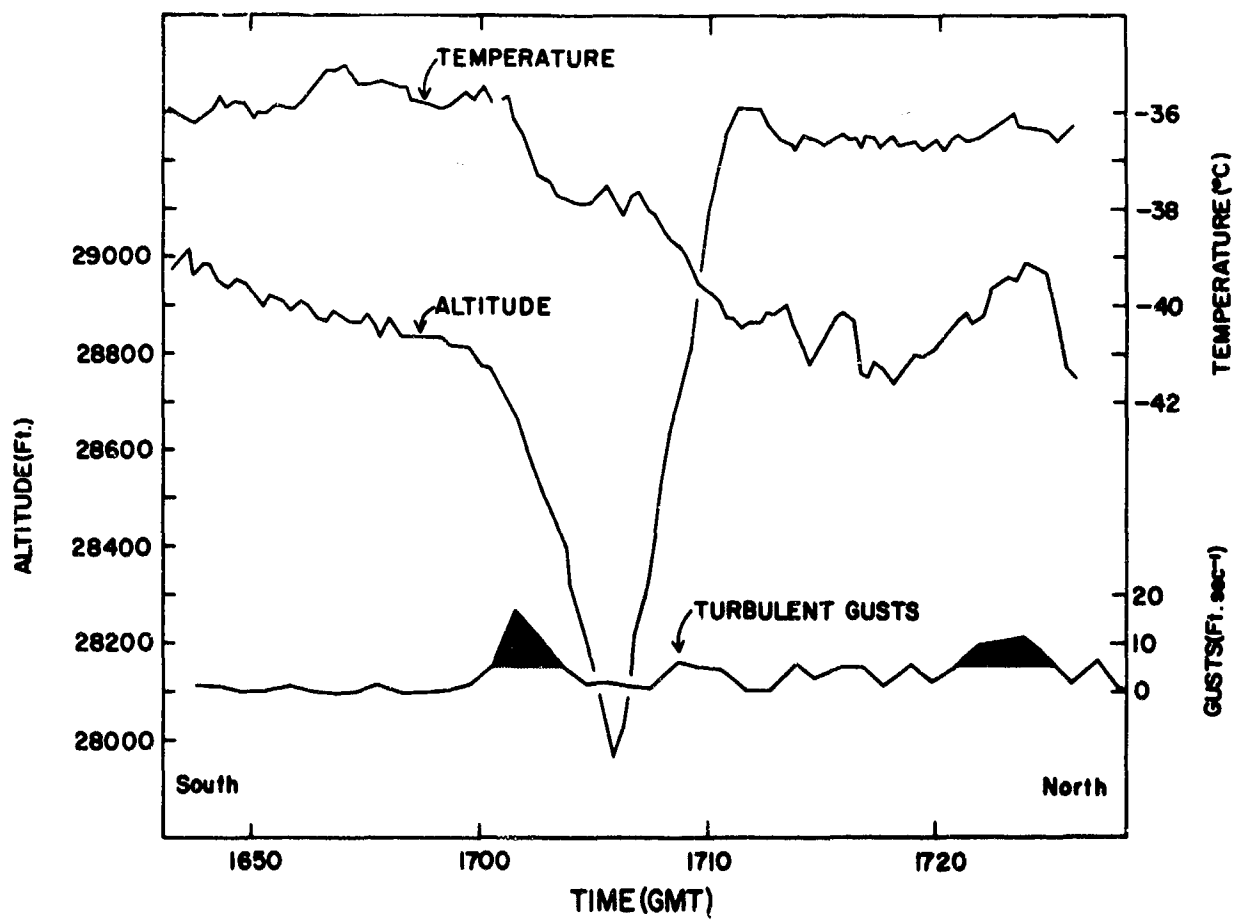
FIG. A-3 TEMPERATURE, ALTITUDE, AND GUSTS, 1650 – 1720 GCT, FLIGHT 26
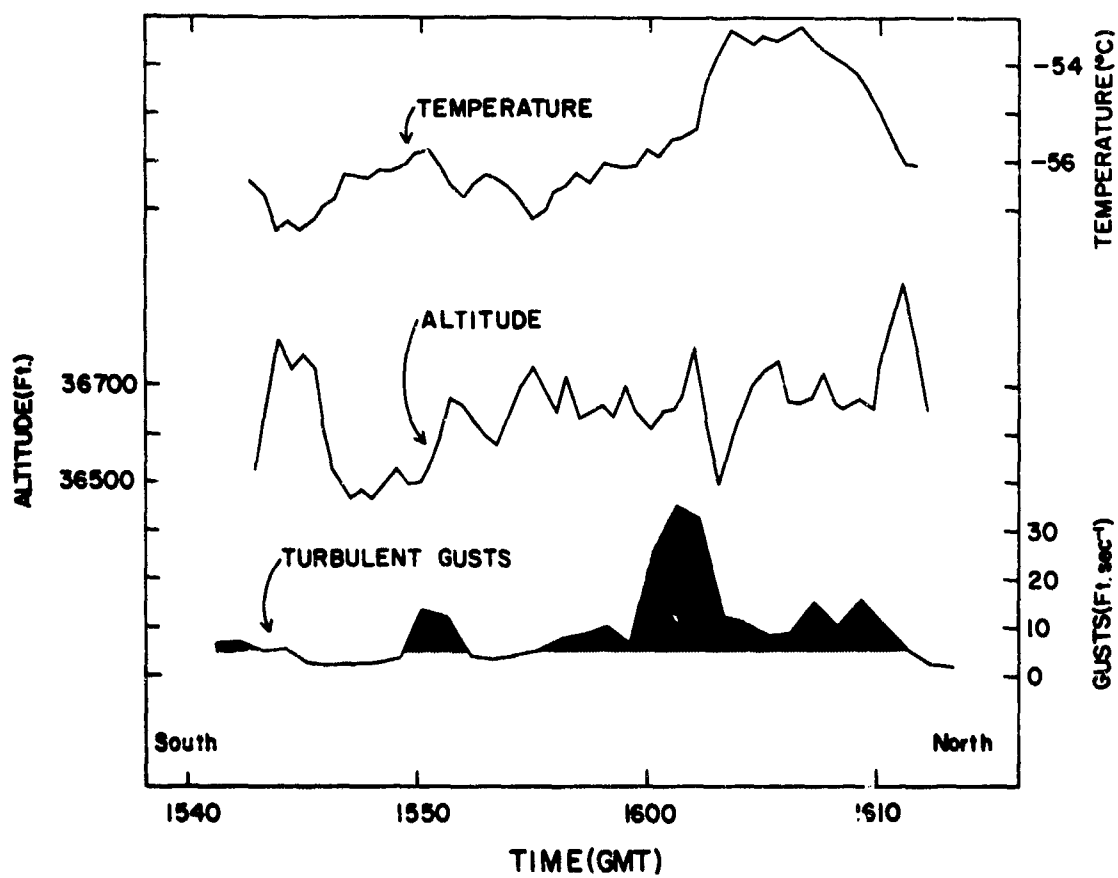
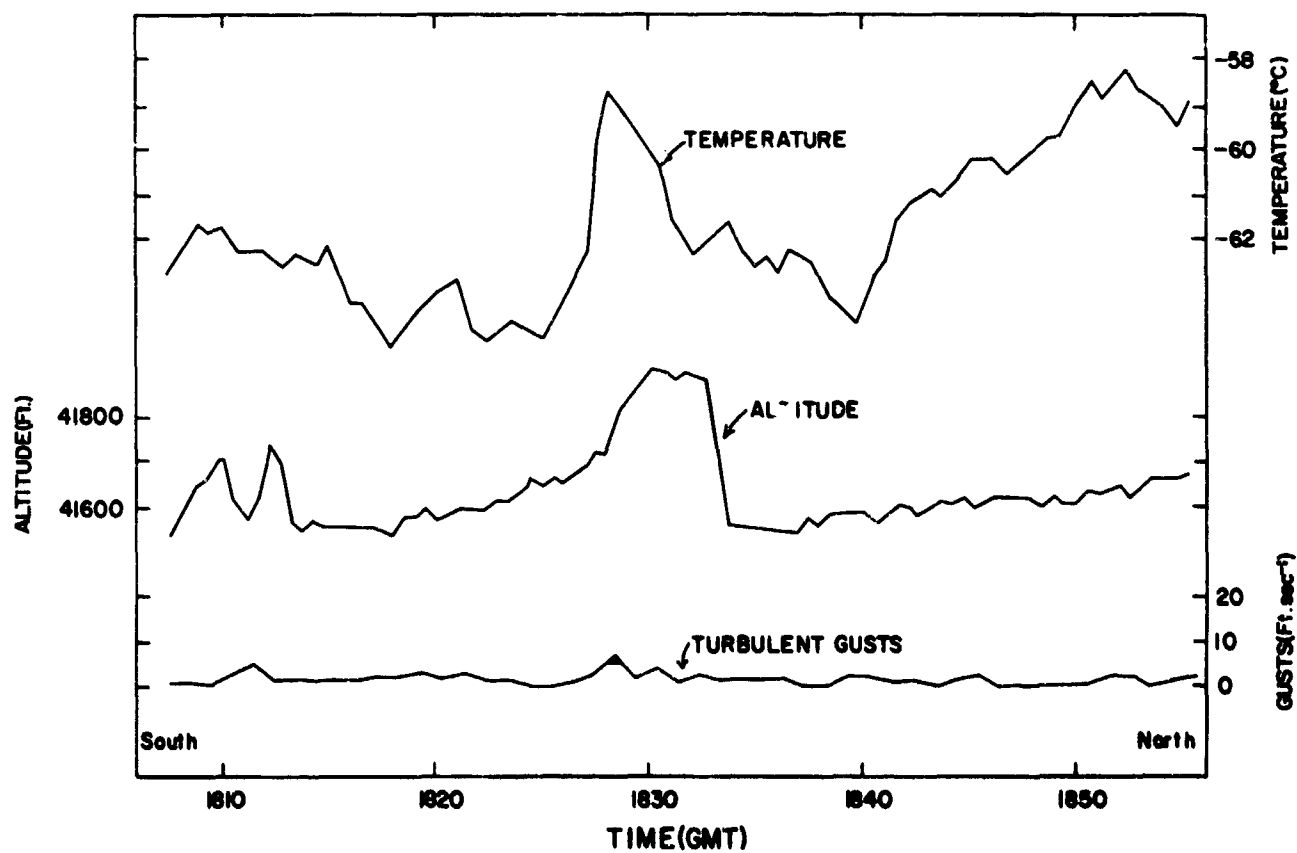FIG. A-4 TEMPERATURE, ALTITUDE, AND GUSTS, 1540 – 1610 GCT, FLIGHT 27

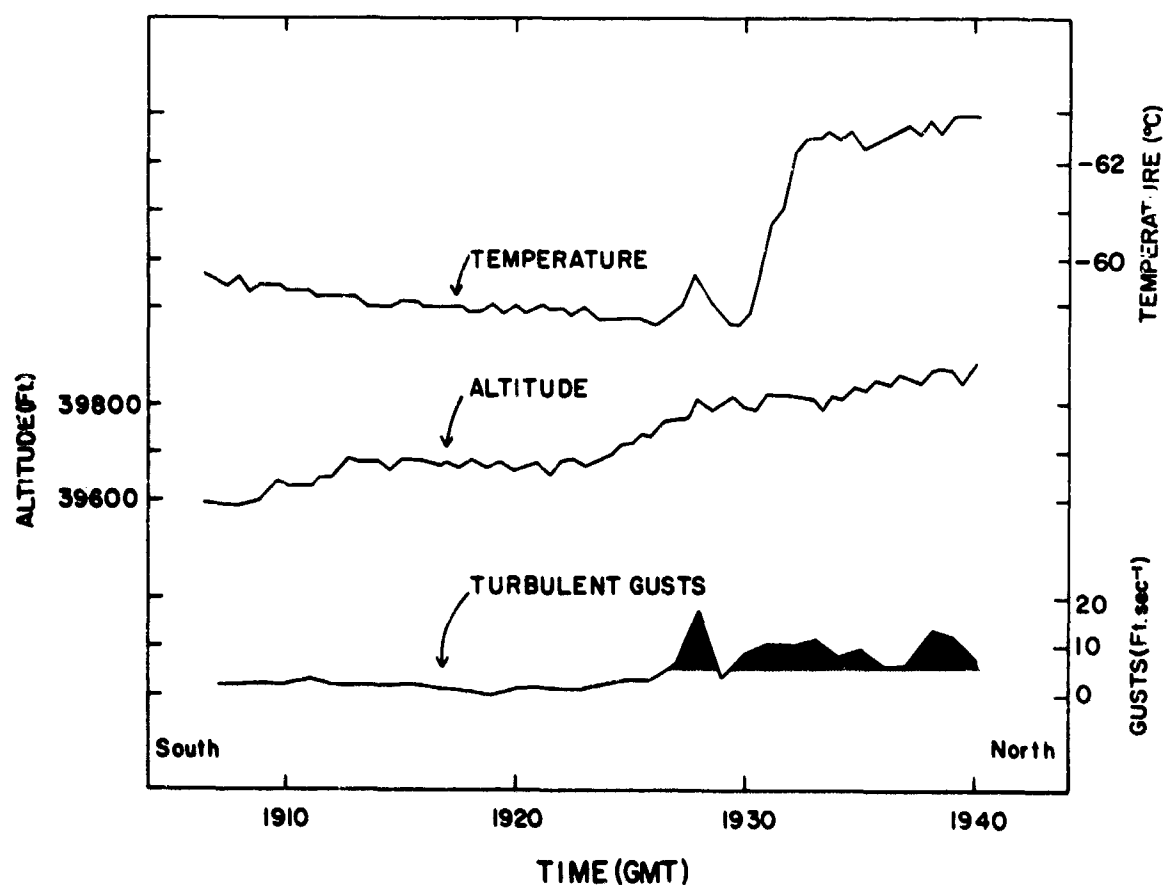FIG. A-5 TEMPERATURE, ALTITUDE, AND GUSTS, 1810 – 1850 GCT, FLIGHT 27

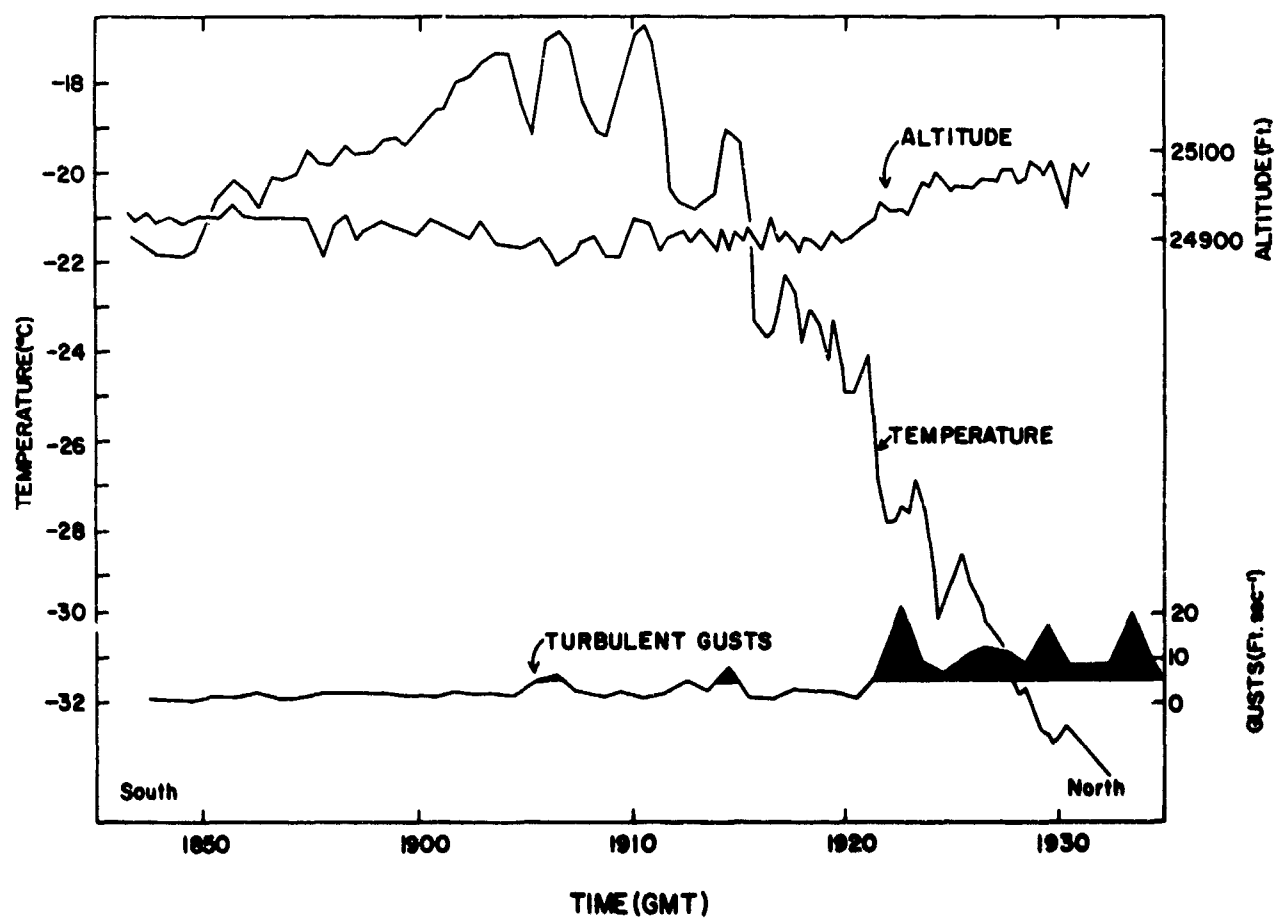FIG. A-6   TEMPERATURE, ALTITUDE, AND GUSTS, 1910 – 1940 GCT, FLIGHT 29

FIG. A-7 TEMPERATURE, ALTITUDE, AND GUSTS, 1850 – 1930 GCT, FLIGHT E-36

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