Observations of Severe Turbulence near Thunderstorm Tops

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ABSTRACT

Data derived from the flight tapes of two airliners that experienced severe turbulence near thunderstorm tops are used to produce quantitative descriptions of the turbulence and its environment. The likely turbulence-producing processes include a three-dimensional turbulent wake in the lee of a squall line and an updraft in the top of a thunderstorm. Results suggest that current procedures for using surface and airborne weather radar for routing aircraft near thunderstorm tops should be reexamined. Also, although useful rules for safe flight near thunderstorm tops already exist, there is evidence that they are not universally applied.

1. Introduction

Since the early days of aviation, it has been known that turbulence occurs not only within and below thunderstorms, but above thunderstorm tops, in the clear wake, and in the cloudy anvil (e.g., Burns and Harrold 1966; Prophet 1970; Burnham 1970; Vinnichenko et al. 1980). However, because of inadequacies in the numbers and details of observations, and predictions of turbulence near thunderstorm tops (TNTT) are usually based on simple conceptual models [e.g., National Weather Service (NWS) 1974; Camp and Frost 1987]. The result is that potentially turbulent areas are often overpredicted with a subsequent loss in time and revenue as aircraft seek to avoid TNTT. Furthermore, some regions of extreme TNTT are occasionally underpredicted resulting in passenger and/or crew injuries (e.g., Nation Transportation Safety Board (NTSB) 1981, 1984).

The increasing availability of digital flight data recorder (DFDR) tapes from commercial airliners offers a partial solution to this problem by allowing the study of more turbulence encounters in a quantitative and objective fashion (Bach and Wingrove 1985; Gysel and Richner 1986). Scientists at NASA-Ames have developed an archive of DFDR tapes from a number of incidents involving severe turbulence (e.g., Parks et al. 1985; Lester et al. 1989). To date, about half of those cases have occurred in or near convective activity. Documentation of two of these events will be presented in this paper.

* Based partially on an M.S. Thesis.

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2. Data

The details of the accuracies and the processing of commercial aircraft data by the NASA-Ames group have been discussed thoroughly elsewhere (Bach and Wingrove 1989; Lester et al. 1989). For reference purposes, a brief summary is presented here.

Preliminary processing includes the standardization of the raw data format to account for the different sample rates (1.0 to 8.0 Hz) among measured parameters that include inertial data (e.g., pitch, roll, accelerations, etc.) and air data (temperature, pressure altitude). Missing data are interpolated and filtering is applied to eliminate high frequency noise. The final sample rates are 4.0 Hz for all parameters. Horizontal and vertical wind velocities are then computed by combining inertial data, air data, estimates of the angle of attack, and where available, ground-based air traffic control (ATC) radar data to position the aircraft independently of onboard measurements. A conservative estimate of the smallest scales of air motions resolvable from the processed data is of the order of 250–500 m for a typical aircraft speed of 250 m s^{-1}. The resolution is probably better for the computations involving the vertical acceleration (e.g., vertical velocity), which is commonly available in raw form at either 4.0 or 8.0 Hz. The estimated rms error in the horizontal wind is ±2.5 m s^{-1}, and ±2.2 m s^{-1} in vertical velocities.

3. Cases

a. Hannibal

At 0125 UTC on 4 April 1981, a DC-10 traveling from Los Angeles to New York encountered severe turbulence at 37 000 ft. (11.3 km MSL) near Hannibal, Missouri. A portion of the aircraft flight path and the location of the turbulence incident is shown in Fig. 1 on a composite surface/250 mb analysis for 0000 UTC 4 April 1981. According to the aircrew statements, the aircraft was passing through thin cirrus just prior to the incident. Lightning flashes could be seen below and to the sides; the aircraft's radar antenna had to be tilted down six to seven degrees before echoes were observed "approximately twenty miles to the right and twenty miles to the left of course." The aircraft exited the cirrus a few seconds later and encountered a second "clearly formed cloud" that was illuminated "by a lightning flash off to the side and below." Subsequently, "a strong jolt [occurred], followed by several others in quick succession." Although the turbulence lasted "only a brief time," it resulted in twenty-nine injuries (NTSB, 1981).

The analysis in Fig. 1 shows a southwesterly jet stream with winds exceeding 140 knots (72 m s^{-1}) located northwest of Hannibal, Missouri, about an hour and a half prior to the turbulence incident. The axis of the jet was propagating eastward at about 5 m s^{-1}. At the surface, a squall line was located just west of Hannibal. The heights of cloud tops near Hannibal were estimated by combining cloud top temperatures deduced from infrared satellite imagery (not shown) with sounding data from Peoria, Illinois (PIA in Fig. 1). The highest cloud tops were near an altitude of 11.4 km. Also, 0000 UTC tropopause heights at PIA were 11.7 km. Thus, the reported aircraft flight level was very close to both the tropopause and the cloud tops.

Figure 2 is an enlargement of the area within the rectangle shown in Fig. 1. The radar echoes associated with the squall line, as observed by the St. Louis, Missouri, (STL) weather radar, are shown for 0130 UTC. The aircraft track and turbulence location are shown for reference purposes. The point of the turbulence occurrence is clearly over the band of echoes, just east (downstream) of the most intense returns. The echoes are oriented south-southwest to north-northeast, with the 250 mb winds (Fig. 1) intersecting the line at about a 40 degree angle. Echo intensities show a region of maximum reflectivity (50–57 dBZ) as a small black dot to the southwest of the turbulence location. Evidently intensification was taking place in that area. Fifteen minutes earlier, radar reports (not shown) indicated lower reflectivities (in the range 46–50 dBZ); furthermore, echo tops grew from about 30 000 ft to 35 000 ft (9146 m to 10 671 m) in the next hour.

Figure 3 shows the records of vertical acceleration and aircraft altitude for a six minute (about 110 km) segment of the aircraft track, which includes the turbulence event. The location of the line of intense radar echoes (Fig. 2) is indicated by the words "squall line" in the lower part of the figure. The flight was relatively

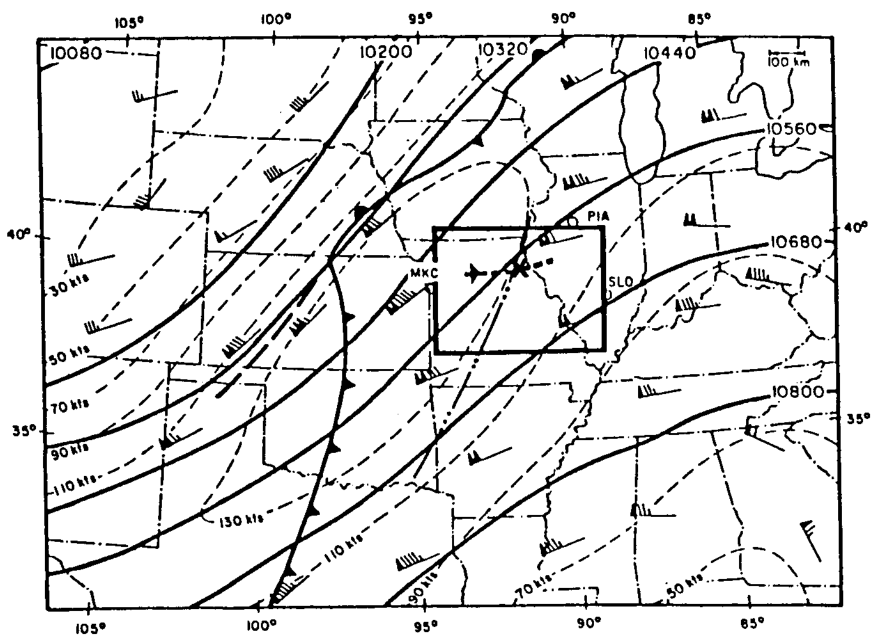

FIG. 1. Surface fronts and squall line position for 0000 UTC 4 April 1981 with superimposed 250 mb winds (knots), isotachs, and contours (gpm). The dashed line within the rectangle shows the flight path. The "×" indicates the severe turbulence location near Hannibal, Missouri.

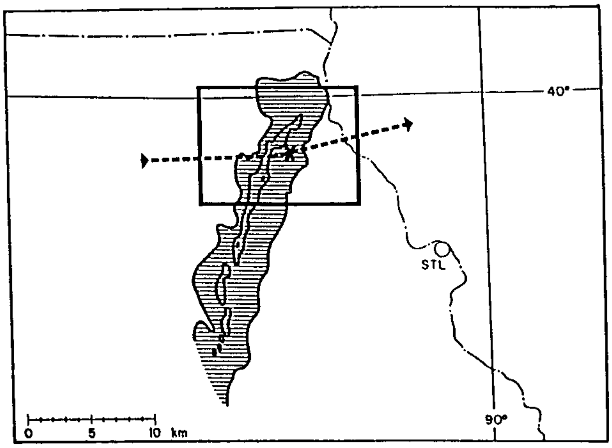

FIG. 2. Hatched area indicates the distribution of radar echoes at 0130 UTC on 4 April 1981. The STL radar returns are shown for the region enclosed by the rectangle in Fig. 1. Isopleths are shown for reflectivity levels 1 (30 dBZ) and 3 (41–46 dBZ). Levels 5 (50–57 dBZ) and greater appear as small dots on the interior of the level 3 isopleths. The dashed line and "×" indicate the flight path and incident location, respectively.

smooth for the first 200 s. Thereafter, vertical accelerations became large. A maximum deviation (g') of -1.9 g from normal gravity ($+1.0$ g) occurred at an elapsed time of about 210 s (0124 UTC). Such acceleration values correspond with extreme turbulence. Light turbulence continued for about 80 s after that point and then smooth flight was resumed. Height excursions of as much as 152 m resulted from both controlled (pilot induced) and uncontrolled aircraft responses to the turbulence.

Computed vertical velocities (i.e., with aircraft motions removed) and potential temperatures along the aircraft track are shown in Fig. 4. A bias was removed from the vertical velocity (w) to ensure that the mean was zero in nonturbulent regions. Excluding the turbulent region, nodes ($w = 0$) in the vertical velocity record are noted at elapsed times of 50, 150, 250 and 350 s. These suggest some type of wave in the w field with a period of 200 s. Crests are found at elapsed times of about 50 and 250 s, and troughs near 150 and 350 s. For a standing wave, a period of 200 s yields a wave length of 60 km, assuming an aircraft ground speed of about 300 m s^{-1}. That distance corresponds closely to the width of the squall line, which the aircraft traversed prior to encountering the turbulence. For illustration purposes, the deduced wave pattern is shown as a simple schematic streamline at the top of Fig. 4. The aircraft passed over the midpoint of the squall line (i.e., most intense radar echoes) at about 135 s into the record. The most intense turbulence as indicated by large, high frequency fluctuations in w is located in the updraft region of the 60 km wave described above. The turbulence itself was characterized by very large vertical velocities (i.e., -24 m $s^{-1} < w < +15$ m s^{-1}).

If the quasi-periodic motions in the vertical velocity record (Fig. 4) are associated with a relatively slow moving gravity wave, a strong correlation with the potential temperature (θ) record would be expected. However, in Fig. 4, such a relationship is not immediately obvious. If the aircraft altitude changes due to the turbulence were such that the slope of the aircraft track was much steeper than the slopes of the isentropes (streamlines), then it is likely that θ and z would show a more obvious relationship; i.e., in a stable atmosphere, increases (decreases) in θ would occur during ascents (descents). Disregarding the approximately ± 0.67 K noise band in θ, it appears that this is indeed the case (compare Figs. 3 and 4).

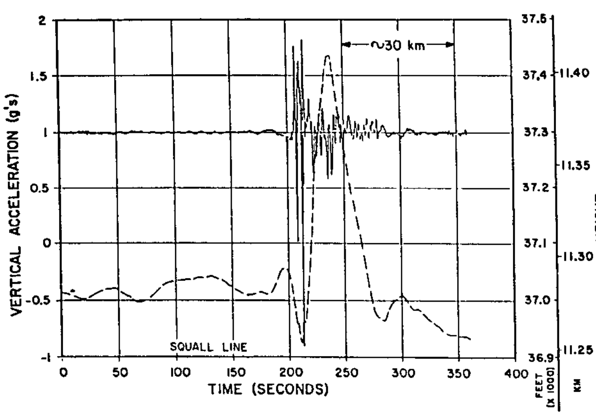

FIG. 3. Flight data: Vertical acceleration (solid) and altitude (dashed) along the flight path for the Hannibal, Missouri, case from 0121 to 0127 UTC on 4 April 1981. The words "squall line" indicate the approximate time the aircraft crossed over that feature.

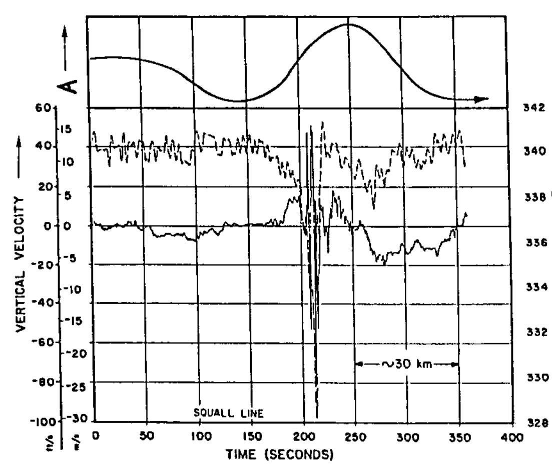

FIG. 4. Flight data: Vertical velocity (solid) and potential temperature (dashed) along the flight path for the Hannibal, Missouri, case from 0121 to 0127 UTC on 4 April 1981. A streamline of schematic amplitude A, which is consistent with the large scale features of the θ and w records, is shown at the top of the diagram.

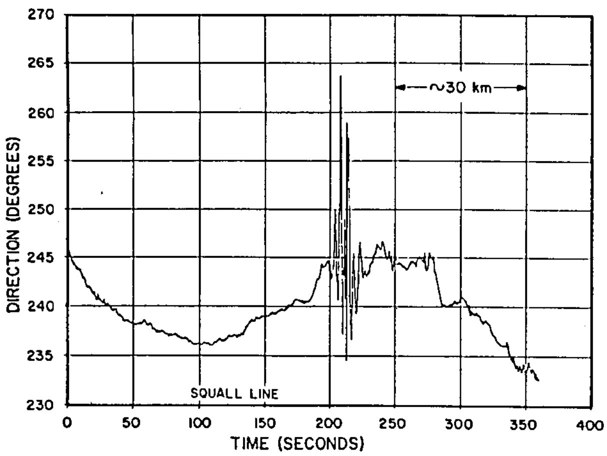

FIG. 5. Flight data: Horizontal wind direction along the flight path from 0121 to 0127 UTC on 4 April 1981.

The horizontal wind direction record (Fig. 5) also displays a wave-like pattern along the flight track, with the exception of the large, direction variations associated with the turbulence event. Wind directions gradually back about ten degrees as the aircraft passes over the squall line, then veer ten degrees through the turbulence region, finally backing about twelve degrees to the end of the record. Windspeeds (Fig. 6) smoothly increased to a maximum of more than 150 knots (77 m s^{-1}) as the aircraft flew downwind across the squall line. Speeds decreased to about 130 knots (67 m s^{-1}) in the vicinity of the turbulence, jumped to more than 170 knots (88 m s^{-1}), then decreased irregularly thereafter. Vertical velocities are also superimposed on the horizontal windspeeds of Fig. 6. Large negative vertical velocities are present at the same location as relative wind maxima, near elapsed times of 100 s and 280 s. Although at the latter time, the relationship is somewhat masked by turbulence; the total pattern is suggestive of the downward momentum transport commonly found in mountain lee waves (e.g., Lilly 1978).

The data discussed earlier suggest that the squall line acted as a barrier to the flow, resulting in "mountain wave-like" disturbances downstream. This interpretation has been used in a previous analysis by NTSB (1981) who concluded that the cloud that the aircraft entered just prior to the turbulence was a lenticular type, produced by flow over the thunderstorm and that the turbulence occurred when "the aircraft transversed the updrafts that were producing the cloud." Keller et al. (1983), simulated the flow over the same squall line with a two-dimensional, nonlinear primitive equation model. Their experiment, initialized with available upstream sounding data and a "barrier" of squall line dimensions produced a large amplitude "mountain wave" disturbance downwind, at and above flight level. Regions of low Richardson number within the simulated disturbance were interpreted as localized turbulence zones. Parks et al. (1985) noted that the vertical velocity profile in the immediate vicinity of the turbulence (Fig. 4) exhibited small scale structures suggestive of the so-called "cat's eye" vortex pattern produced by K-H instabilities (e.g., see Scorer 1978). They constructed a simple two-dimensional analytic model to simulate the horizontal and vertical wind fields that would be experienced during the passage of an aircraft through such vortices.

Although the two-dimensional interpretations of the Hannibal data (NTSB 1981; Keller et al. 1983; Parks et al. 1985), seem to give reasonable first approximations of processes that forced the turbulence, a closer examination of both the topography of the squall line and the variation of the wind along the flight track reveals potentially important three-dimensional features. An expanded view of the radar echo distribution near the aircraft track is shown in Fig. 7. Flight level winds determined from the DFDR data are shown at 15 s intervals (about 4.5 km). The wind vectors are approximately parallel, except immediately east of the turbulence location where the winds veer along the aircraft track and increase over a distance of about 30 km. In Fig. 7, lines have been drawn from the boundaries of the disturbed region along the aircraft track, upwind to the isolated area of high intensity radar returns (50–57 dBZ) indicated by the black dot. The lines enclose an apparent wake with a wedge angle somewhat smaller but similar to those in ship wake patterns that occur in stable airflow in the lee of three-dimensional obstacles (Scorer 1978; Gjevik and Marthinsen 1978; and Sharman and Wurtele 1983). The implication here is that the obstacle that generated the turbulent wake was actually a growing convective cell in the vicinity of the high radar reflectivity region located 14 km to the south of the flight path. In a similar case study (Pantley 1989), severe turbulence was experienced by an aircraft that flew within the anvil downwind of a line of thunderstorms. The turbulence

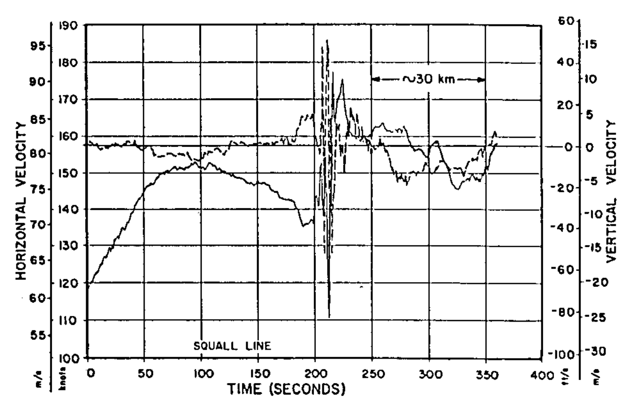

Fig. 6. Flight data: Horizontal wind speed (solid) and vertical velocity (dashed) along the flight path from 0121 to 0127 UTC on 4 April 1981.

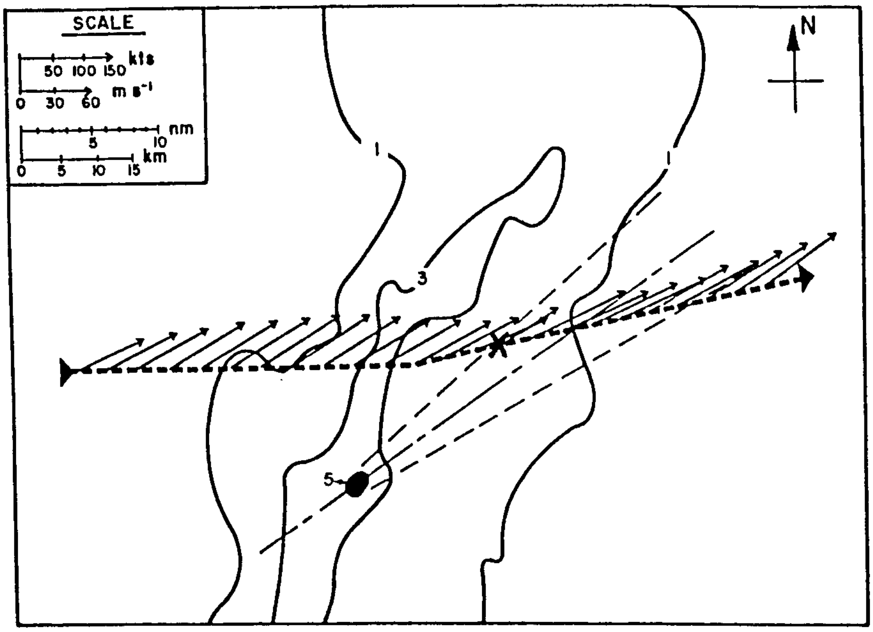

FIG. 7. Enlarged view of area within the rectangle in Fig. 2. Wind direction and speed are plotted at 15 s intervals along flight path. Dot–dashed line indicates mean wind direction. Dotted lines indicate apparent wake. Reflectivity levels 1 (30 dBZ) and 3 (41–46 dBZ) are shown by solid lines; level 5 (50–57 dBZ) is shown by black dot.

in that case was also apparently confined to the area within the wake of an individual thunderstorm cell.

b. Bermuda

At 0418 UTC 12 October 1983, a DC-10 also flying at 37 000 ft (11.3 km), encountered severe turbulence at 27.00°N, 68.65°W, approximately 700 km SSW of Bermuda (Fig. 8). According to the Pilot's description,

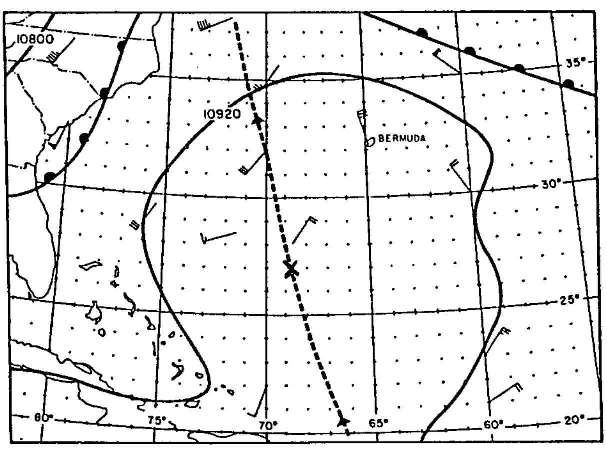

FIG. 8. Surface frontal position for 0600 UTC 12 October 1983, superimposed on NMC 250 mb winds (knots) and contours (gpm) for 0000 UTC. The dashed line shows the approximate flight path. The "×" indicates the approximate site of the severe turbulence incident along the flight path (dashed).

the incident began with a few minutes of "light to moderate chop." Although it was reported that no echoes appeared on the aircraft radar, the aircraft "seemed to pass through the top of a cumulus cloud." Within the cloud, severe turbulence was encountered "that seemed to last for 30 seconds." As a result, twelve passengers were injured (NTSB 1984).

A composite of 250 MB contours and winds (0000 UTC) and surface frontal positions (0600 UTC) is shown in Fig. 8. Plotted winds in the figure are from conventional aircraft reports (AIREPs) and available radiosonde observations (Bermuda). The aircraft track intersects an extensive upper level anticyclone where 250 mb winds were generally less than 30 knots (16 m s^{-1}).

An enhanced infrared (IR) satellite image (GOES) near the time of the accident is shown in Fig. 9, in lieu of weather radar data. An area of convective activity (cellular cloud features with cold tops) extends from the site of the turbulence encounter to about 30°N, 70°W. Surface ship reports verified the presence of cumulonimbus clouds in the area of the same time. The convection is embedded in the periphery of the anticyclone described in Fig. 1 and was likely associated with a meso-α disturbance that was rotating clockwise around the anticyclone, but was unresolved by the available surface and upper air observational data (Fig. 8).

Since neither aircraft position data from ATC radar nor weather radar data are available for this case, exact details of the aircraft location relative to individual

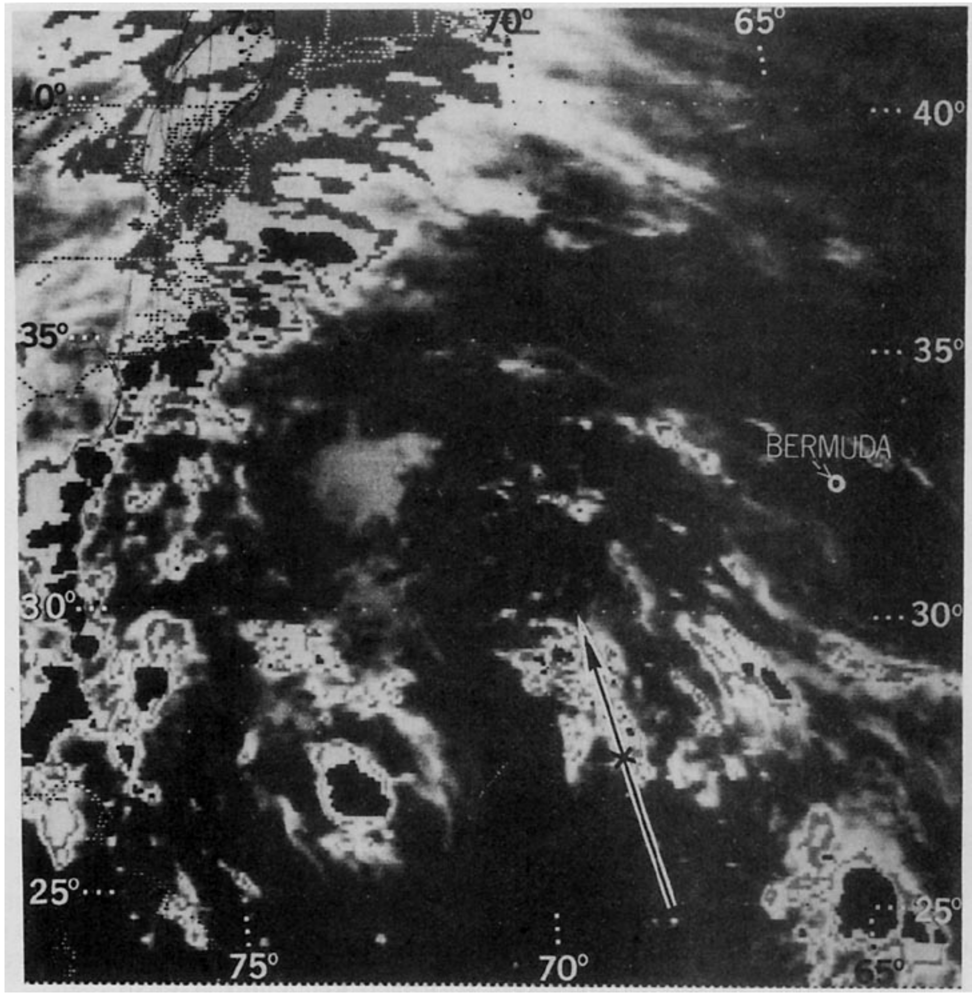

FIG. 9. Enhanced GOES IR satellite image for the Bermuda case valid at 0400 UTC on 12 October 1983. The black arrow shows the approximate flight path. The "×" indicates the approximate severe turbulence location. The enhancement is curve MB.

thunderstorms and unambiguous horizontal wind directions are impossible to deduce. However, there are still several useful aircraft measurements that are not

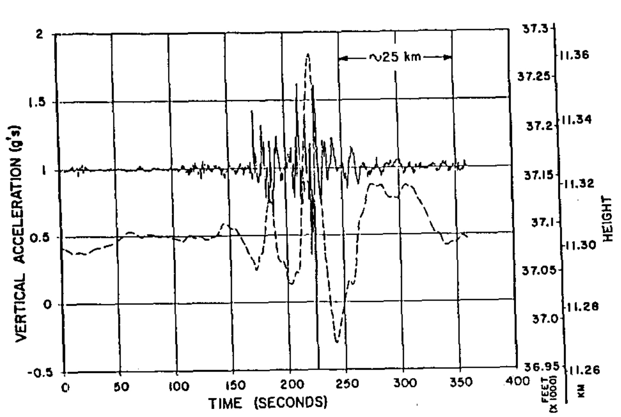

FIG. 10. Flight data: Vertical acceleration (solid) and altitude (dashed) along the flight path from 0415 to 0421 UTC on 12 October 1983.

dependent on the missing information. For example, vertical acceleration and aircraft altitude records for a six minute (about 90 km) segment of the track are shown in Fig. 10. The DC-10 encountered its most significant vertical accelerations ($g' = -1.5$ g) at 0418 UTC or about 225 s elapsed time in Fig. 10. The total extent of light or greater turbulence ($|g'| \geqslant 0.15$ g) was about 87 s or about 22 km along the flight track. In that region, aircraft altitude variations of up to 91 m occurred.

The potential temperature record along the flight track is presented in Fig. 11. The altitude of the aircraft is also given in the figure for reference. Except for the very large deviations near the turbulence region, θ shows a decreasing trend of about 1 K from the south (left) to the north (right) end of the track. There are two notable features when the two records in Fig. 11 are compared. At about 185 s elapsed time, the aircraft ascends and θ decreases, while at about 210 s, the aircraft again ascends, but here θ increases.

An examination of composite w and θ records along

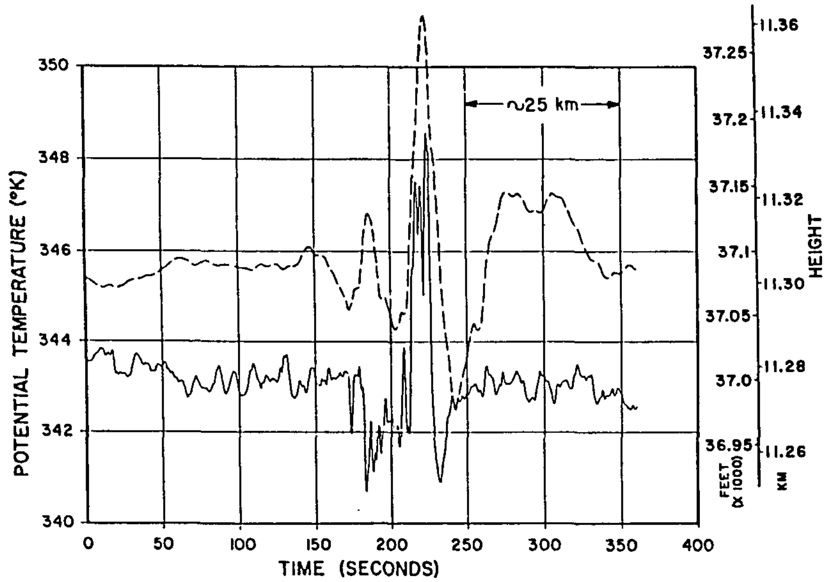

FIG. 11. Flight data: Potential temperature (solid) and altitude (dashed) along the flight path from 0415 to 0421 UTC on 12 October 1983.

the aircraft track (Fig. 12) helps to clarify the patterns in Fig. 11. The phase of the potential temperature minimum near 185 s lags a vertical velocity maximum ($w \approx 10$ m s^{-1}) near 175 s slightly. This pattern is strongly suggestive of what would be expected when traversing a gravity wave of about 10 km in length (at an airspeed of 250 m s^{-1}); i.e., high values of θ with $w \approx 0$ in a wave trough, lower values of θ and large positive vertical velocities at the downstream inflection point, and finally lowest values of θ with $w \approx 0$ in the wave crest. The θ and w patterns in the region of intense turbulence near 210 s ($w \approx 25$ m s^{-1}), however, do not show an obvious phase lag. This pattern (large w with large θ) corresponds more closely with flight through convection; i.e., with strong upward heat flux.

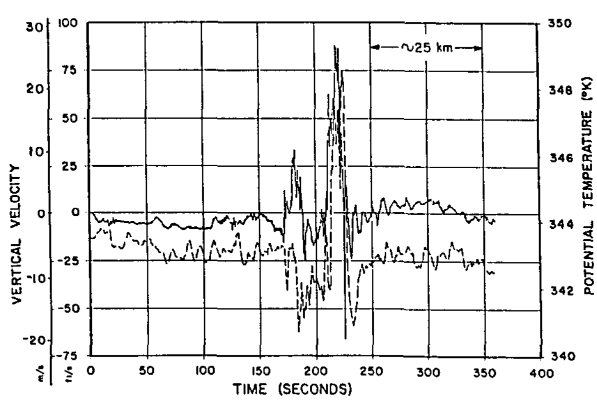

FIG. 12. Flight data: Vertical velocity (solid) and potential temperature (dashed) along the flight path from 0415 to 0421 UTC on 12 October 1983.

A third feature is also noted in Fig. 12. A series of small amplitude sinusoidal fluctuations are evident in both the w and θ records after about 230 s elapsed time. The wave periods of about 10 seconds correspond to a wave length of 2.5 km at an airspeed of 250 m s^{-1}. Although the asymmetry of the θ record does not allow a conclusive statement about the phase relationship between θ and w, it is conjectured that the observed patterns are caused by gravity waves.

The interpretations above suggest the following: the aircraft was flying in a relatively stable environment. Initially it flew through a gravity wave of about 10 km in length with moderate turbulence in the updraft of the wave just outside of the convection. The aircraft then encountered the convective cloud, very likely a thunderstorm top, during which severe turbulence was experienced. As the aircraft exited the thunderstorm updraft, it traversed a train of shorter gravity waves associated with light turbulence. It is likely that the gravity waves encountered by the aircraft both before and after the severe turbulence were excited by the convection.

c. Case comparison

Table 1 summarizes the turbulence characteristics of the cases as well as some of the properties of the meteorological environment. "Mean" values, ($\bar{\ }$), are averages through the turbulent portions of the six minute flight segments presented in the previous sections. Although horizontal wind directions could not be completed with confidence in the Bermuda case, the calculations of the wind vectors relative to one another are valid. Therefore, wind-related computations not

TABLE 1. Case summaries.

Case	Hannibal	Bermuda
$\langle\bar{\theta}\rangle$ (K)	338	334
$\langle\bar{V}\rangle$ (m s^{-1})	80.1	5.1
Duration of turbulent record* (s)	43.75	86.50
g' (Extremes)	−1.91, +0.82	−1.50, +0.62
Percent of turbulent record*		
Light	31	28
moderate	10	3
severe or greater	1	1
$\underline{\text{TKE}}$ (m^2 s^{-2})	51	60
$(\overline{w'^2}/2)$/TKE	0.30	0.48

* The "turbulent record" is the shortest continuous portion of flight data that includes all measurements of $|g'| \geq 0.15$ g.

sensitive to absolute direction errors such as the magnitude of the mean vector $\bar{V}$, are presented for that case in Table 1.

Turbulence statistics were determined by using World Meteorological Organization (WMO) criteria for *moderate* turbulence: $0.5 \leq |g'| < 1.0$, and *severe* or greater turbulence $|g'| \geq 1.0$ g. Light turbulence was specified for $0.15 \leq |g'| \leq 0.5$. The stratification of vertical accelerations into the various turbulent categories in Table 1 shows that the turbulent patches were highly intermittent in both cases. Furthermore, the duration of severe or greater turbulence was only one percent (or less) of the total turbulent periods in both cases.

A statistical measure of turbulence intensity that is more closely related to the physics of the problem (e.g., see Lester 1972) is the mean turbulent kinetic energy per unit mass (TKE), given by

$$\text{TKE} = \frac{\overline{u'^2 + v'^2 + w'^2}}{2}$$

where u', v', and w' are the deviations of horizontal and vertical wind components from their respective means. Table 1 shows both $\underline{\text{TKE}}$ and the ratio of the mean vertical component $(\overline{w'^2}/2)$ to TKE. Both values are largest in the Bermuda case, likely due to the large (convective) turbulence scale in that incident versus the smaller scales characteristic of the stable environment of the Hannibal case.

4. Conclusions

Although TNTT is not a new subject, past studies of the associated physical processes and forecast/nowcast capabilities have been limited by sparse and mostly qualitative data. As demonstrated in this study, the analysis of DFDR information from commercial airliners offers an opportunity to expand our understanding of TNTT via objective, quantitative descriptions of the turbulence in and around thunderstorm tops.

The analysis of the Hannibal case raises questions about previous two-dimensional interpretations of the turbulence producing processes in that case. Evidence suggests that the turbulence may have occurred in a three-dimensional wave downwind of an individual, rapidly growing convective cell embedded in the squall line. With regard to the Bermuda incident, the turbulence occurred when the aircraft passed through an intense and rapidly growing convective element. Although such an occurrence is certainly not unique, this conclusion could not have been reached in this case in the absence of the DFDR data; i.e., on the basis of the semiquantitative pilot report alone.

Although many more cases of TNTT must be carefully analyzed before one can expect TNTT forecast ("nowcast") techniques to be improved significantly; the results of these analyses suggest that current strategies for the use of ground-based weather radar and of aircraft radar for the routing of aircraft in the vicinity of thunderstorms and squall lines should be reexamined. For example, off track, rapidly growing, upwind echoes should not be ignored, especially in strong winds. In addition, in the TNTT cases considered here and by Pantley (1989), one or more of the following well-known rules of thumb for TNTT avoidance were violated: (i) do not fly within the anvil of a thunderstorm, (ii) do not fly within 20 nmi of a thunderstorm, (iii) do not fly in thunderstorm tops, and (iv) for a wind velocity of 100 knots ($\approx$50 m s^{-1}), an aircraft should be at least 10 000 feet ($\approx$3 km) above the thunderstorm; 1000 feet (300 m) should be added (subtracted) for every 10 knot ($\approx$5 m s^{-1}) increment above (below) 100 knots. Although most will agree that these guidelines are conservative, it is clear that adherence to them in the cases considered here would most likely have prevented the turbulence encounters.

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