JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 30, No. 3, May–June 1993

Turbulence Indicators for Space Shuttle Launches

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The primary objective of this paper is to report on the research and analysis on identifying turbulent regions from the surface to 16 km for Space Shuttle launches. This research has demonstrated that the results from the FPS-16 radar/Jimsphere balloon system in measuring winds can indeed indicate the presence or conditions ripe for turbulence in the troposphere and lower stratosphere. It is further demonstrated that atmospheric data obtained during the shuttle launches by the rawinsonde in conjunction with the Jimsphere provides the necessary meteorological data to compute aerodynamic parameters to identify turbulence such as Reynolds number, drag coefficient, turbulent stresses, stability parameter, vertical gradient (turbulence), Richardson number, and the turbulence probability index. These turbulence indicators were computed from 16 Jimsphere balloon releases obtained during Space Shuttle launches at KSC and presented in Table 1. Two of the launches, STS-11 and STS-41D, illustrating examples of turbulence (T) and no turbulence (NT) in the atmosphere are displayed from Table 1. There is no magic foolproof criteria in atmospheric turbulent probability of occurrence. However, enhanced temperature lapse rates and inversion rates, strong vector wind shears, and large changes in wind direction identify the occurrence of turbulence at the tropopause. When any two of the above conditions occur simultaneously, a significant probability of turbulence can occur as shown in the paper.

Nomenclature

Vg	= vertical gradient (turbulence), m/s^2
dV/dH	= vertical wind-shear measurement, 1/s
H	= scale height, 150 m
R_i	= Richardson number
g	= acceleration of gravity, m/s^2
T	= temperature, K
$\partial T/\partial Z$	= vertical temperature gradient, K/km
Γ	= dry adiabatic lapse rate, 9.8 K/km
$\partial V/\partial Z$	= vertical shear of horizontal winds, 1/s
C_D	= drag coefficient
u'	= zonal velocity perturbation, m/s
v'	= meridional velocity perturbation, m/s
w'	= vertical velocity perturbation, m/s
U^*	= turbulent stress, m/s
ξ	= stability parameter
k	= Von Karman's constant, 0.47
X	= scale height, 150 m
A	= wind directional shear, deg/s
S	= wind speed, m/s
$\Delta\alpha$	= change in wind direction, deg
ΔZ	= scale length, m
B	= change in temperature lapse rate, 1/s
$\Delta^2 T/\mathrm{m}$	= second difference operator of temperatures, deg/m
T_i	= turbulence probability indicator, 1/s^2
T	= turbulence
NT	= no turbulence
R_e	= Reynolds number

I. Introduction

THE main purpose of this paper is to report on the research and analysis in identifying turbulent regions from the surface to 16 km for the Space Shuttle launches. It will be demonstrated that the FPS-16 radar/Jimsphere balloon system, in conjunction with the rawinsonde, can indicate the presence of turbulence or that the conditions are ripe for turbulence during the day-of-launch scenario. The study of turbulence indicators was necessary due to the lack of an in situ turbulence sensor which would eliminate the uncertainty that the atmosphere is turbulent.

The existing technology for the past three decades (1960s, 1970s, and 1980s) and the present decade of the 1990s in measuring winds aloft for the Space Shuttle launches has been obtained by balloon-borne wind sensors, e.g., the FPS-16 radar/Jimsphere system (used as the standard) and the meteorological sounding system (MSS) windsonde (used as the backup), and was documented by Susko.[1] The wind profiles are measured in the lower stratosphere and troposphere of the atmosphere (0 to 16 km) for the wind load analysis of the ascent phase of the Space Shuttle as it passes through max q (maximum dynamic pressure, 10 to 16 km) where the loads are the greatest on the vehicle.

Further use of the Jimsphere can be expanded to obtain turbulence data for the Space Shuttle launches. The atmospheric data obtained during the shuttle launches by the rawinsonde provide the necessary meteorological data to compute aerodynamic parameters to identify turbulence. The aerodynamic parameters calculated from the measurements indicate the presence of turbulence or conditions ripe for turbulence are presented in Table 1 which gives a summary of turbulence indicators for 16 Space Shuttle flights between 10 to 16 km (maximum dynamics pressure region) where the ascent loads are the greatest.

The aerodynamic parameters calculated were the Reynolds number, drag coefficient, turbulent stresses, stability parameter, vertical gradient (turbulence), Richardson number, and the turbulence probability index. However, even though the indicators may be showing the presence of turbulence, an in situ sensor would eliminate the uncertainty that the atmosphere is actually turbulent when the balloon is in the air.

II. Dynamics of Turbulence—Space Shuttle

One meteorological feature used in describing the dynamics of turbulence is to delineate between turbulence (T) and no turbulence (NT) which is the vertical gradient (turbulence) as reported by Ehernberger.[2] The value of this vertical gradient has been derived as the product of wind speed and vertical wind-shear measurements obtained directly from Jimsphere data. This parameter has been analyzed during the 16 Space

Received Dec. 14, 1991; presented as Paper 92-0718 at the AIAA 30th Aerospace Sciences Meeting, Reno, NV, Jan. 6–9, 1992; revision received April 12, 1992; accepted for publication April 27, 1992.

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Shuttle flights where the vertical gradient (turbulence) was computed.

$$Vg = V(\mathrm{d}V/\mathrm{d}H) \quad (1)$$

For simplicity and clarity, two of the 16 launches from Table 1 illustrating examples of T and NT are presented, STS-11 and STS-41D. The vertical gradient (turbulence) plots which illustrate very good results between T and NT during the shuttle launches are given in Fig. 1. Note the big excursion of the vertical gradient (turbulence) at 12 to 16 km in Fig. 1a as compared to Fig. 1b.

III. Richardson Number

The dynamics and time scales of regions of active turbulence are fairly complicated. It is generally conceded that the turbulence is initiated by Kelvin-Helmholtz instability when the Richardson number decreases to a value near 0.25. Several physical processes can cause this decrease. Nonturbulent portions of the atmosphere are subjected to fluctuations in shear and/or potential temperature gradient caused by gravity wave disturbances. These fluctuations may cause turbulence. Synoptic and mesoscale dynamical processes also cause evolutions in the shear and lapse rates which can cause turbulence.

Once a layer of thickness Z becomes turbulent, it is of interest to ponder the temporal duration of the turbulent event as related to the Richardson number. If the turbulence is caused by a gravity wave fluctuation, then Fairall et al.[3] indicates that the event will last not more than a fraction of an inertial period (say, a few hours).

From the rawinsonde data obtained from the meteorological section, Cape Canaveral Air Force Station, Florida, which consists of winds, temperature, and pressure as a function of altitude and the winds from the Jimsphere, the Richardson number R_i, a stability criteria for determining the presence or absence of atmospheric turbulence, was computed and is given by the following relationship:

$$R_i = \frac{g}{T}\left[\frac{\partial T}{\partial Z} + \Gamma\right] \bigg/ \left[\frac{\partial V}{\partial Z}\right]^2 \quad (2)$$

where

$$(\partial V/\partial Z)^2 = (\partial V_x/\partial Z)^2 + (\partial V_y/\partial Z)^2 \quad (3)$$

is the square of the vertical shear of the horizontal winds.

The Richardson number plots for the two Space Shuttle launches, STS-11 and STS-41D, are given in Fig. 2. Since instabilities of turbulence increase when the Richardson number decreases to a value near 0.25, the Richardson number was inverted for clarity, indicating turbulence with the larger numbers. Note the large spike at 12 km for STS-11 in Fig. 2a, illustrating turbulence showing the large perturbation in the high dynamic pressure region (10 to 16 km) as compared to STS-41D in Fig. 2b.

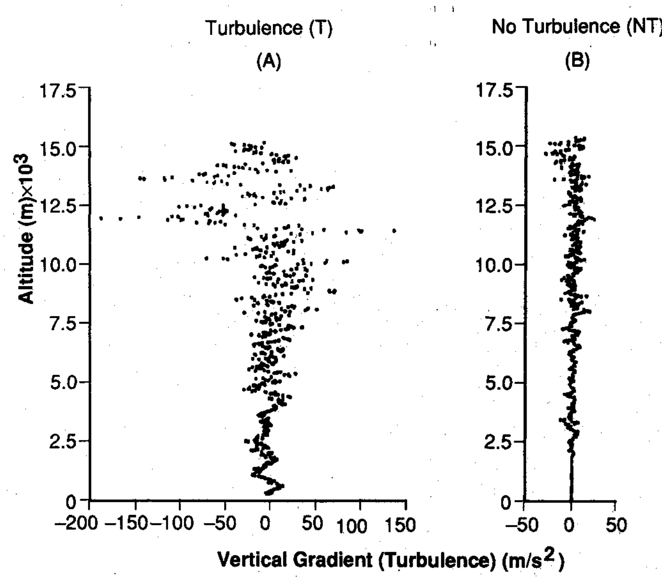

Fig. 1 Vertical gradient (turbulence) vs altitude comparison: a) STS-11 launch, Feb. 3, 1984 (1300 Z); and b) STS-41D launch, Aug. 30, 1984 (1242 Z) at KSC, Florida.

Table 1 Summary of turbulence indicators between 10–16 km (maximum dynamic pressure region) for 16 Space Shuttle flights[a]

Shuttle (STS)	Date	Time, z	Rise rate vs altitude	Turbulence probability indicator	Wind speed, wind direction, temperature (exceeding critical values) at km	Vertical gradient (turbulence) at km	Richardson number at km	Stress at km
1	4/12/81	1200	NT	NT	NT	NT	NT	NT
2	11/12/81	1510	T Spike (12.5 km)	T Spike (12.5 km)	T (12.5)	T (12.5)	T (12.5)	T (12.5)
3	3/20/82	1600	T Spike (13 km)	T Spike (13.5 km)	T (13.5)	T (13.5)	T (13.5)	T (13.5)
4	6/27/82	1500	NT	T Spike (14 km)	NT	NT	NT	NT
11	2/3/84	1300	T Spike (12 km)	T Spike (12 km)	T (12)	T (12)	T (12)	T (12)
13	4/6/84	1358	T Spike (14 km)	T Spike (14 km)	T (14)	NT	T (14)	T (14)
41D	8/30/84	1242	NT	NT	NT	NT	NT	NT
41G	10/15/84	1103	NT	NT	NT	NT	NT	NT
51D	4/12/85	1359	T Spike (13 km)	T Spike (13 km)	T (13.5)	T (13)	T (12.5)	T (13)
51B	4/29/85	1602	T Spike (13 km)	T Spike (13 km)	T (13)	T (13)	T (13)	T (13)
51G	6/17/85	1133	NT	NT	NT	NT	NT	NT
51F	7/29/85	2100	NT	NT	NT	NT	NT	NT
51J	10/3/85	1515	T Spike (15 km)	T Spike (15 km)	T (15)	T (13)	NT	NT
61A	10/13/85	1700	NT	NT	NT	NT	NT	NT
61B	10/27/85	1029	T Spike (14 km)	T Spike (14 km)	T (14)	T (14)	T (14)	T (14)
61C	1/12/86	1155	T Spike (14 km)	T Spike (10–15 km)	T (13)	T (10–15)	T (13)	T (10–15)

[a]Note: T = Turbulence; NT = No Turbulence

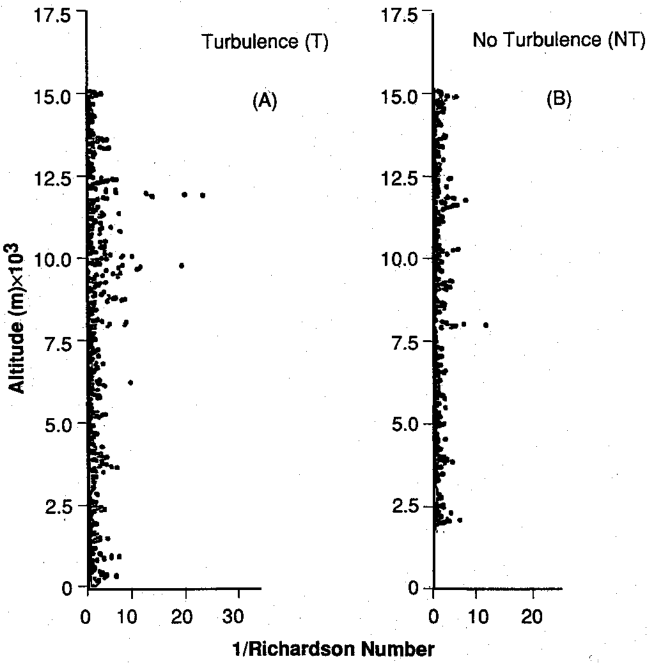

Fig. 2 Richardson number comparison vs altitude: a) STS-11 launch, Feb. 3, 1984 (1300 Z); and b) STS-41D launch, Aug. 30, 1984 (1242 Z) at KSC, Florida.

IV. Tropopause

The tropopause is an ideal boundary for the generation of large-scale turbulence due to the change with elevation from an adiabatic lapse rate to one of nearly constant temperature as reported by Otten and Rose.[4]

Tropopause height is defined as the altitude where the inflection point occurs in the ambient temperature when plotted as a function of mean sea level. The dramatic increase of the atmospheric structure constant of temperature is a behavior to assess in turbulence.

An idealized tropopause is envisioned that is an annular region concentric to the Earth's surface. In reality, the tropopause is convoluted by synoptic meteorology and varies in altitude due to changes in season and latitude.

The principle for clear air turbulence (CAT) is that CAT is found statistically more often within inversion layers and at the tropopause. The term "inversion layer" refers to a layer within which temperature, centigrade or Kelvin, increases with an increasing altitude.

From 10,000 flights and 10 years of data, the Russians, Perevedentsev and Bogatkin,[5] established the critical values for detecting turbulence: air temperature (7°C per km of altitude); for wind velocity (10 m/s per km of altitude), and for wind speed (15 deg per km of altitude). At these altitudes, where two of the conditions for increased turbulence are satisfied simultaneously, the greatest probability of turbulence is expected.

Figures 3 and 4 give the wind speed, wind direction, and temperature plots for two Space Shuttle launches, STS-11 and STS-41D. Notice in Fig. 3 that wind direction is greater than 15 deg/km, the wind speed is greater than 10 m/s per km, and the temperature near 7°C/km as an indication of turbulence (T) is clearly defined at 12 km for STS-11 illustrating the critical values of turbulence compared to Fig. 4 (STS-41D).

V. Stratosphere

In a theoretical and numerical study, Wurtele[6] used the best data to show the atmosphere dynamics for the famous United Airlines episode which occurred in the stratosphere over Hannibal, MO, where there was quite a bit of damage and injury inside the plane. The author concluded that the only thing necessary for a highly reflective and potentially turbulent situation is a reasonably deep layer of decreasing wind speed. (By decreasing, the author means it is lower at higher levels than at lower levels.) This is fairly characteristic of the lower stratosphere and so it suggests that the structure of this layer is often conducive to clear air turbulence.

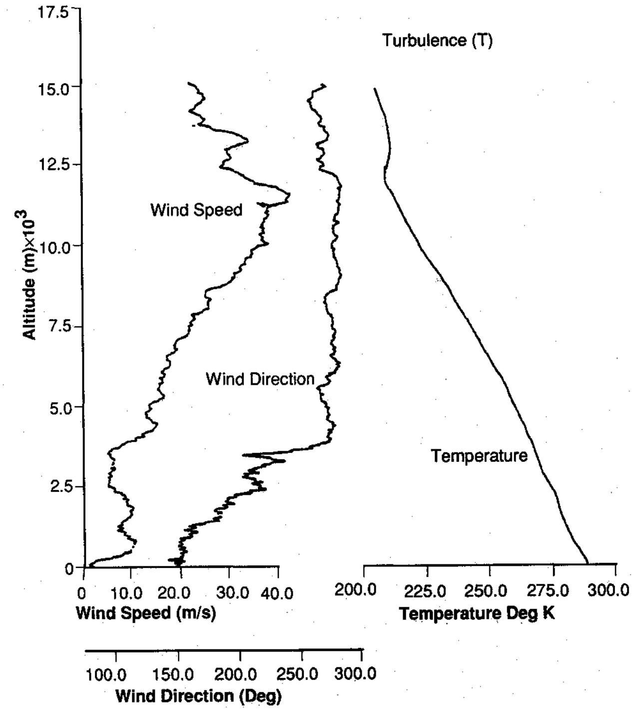

Fig. 3 Wind speed, wind direction, and temperature vs altitude plots measured during STS-11 launch, Feb. 3, 1984 (1300 Z) at KSC, Florida.

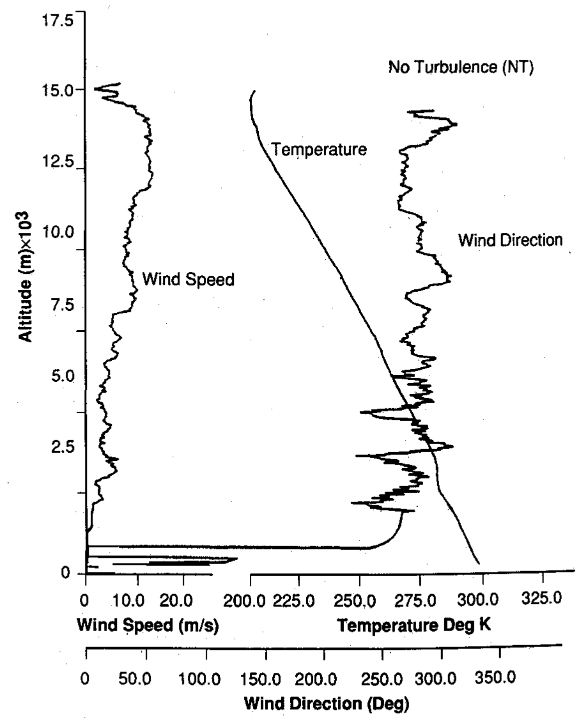

Fig. 4 Wind speed, wind direction, and temperature vs altitude plots measured during STS-41D launch, Aug. 30, 1984 (1242 Z) at KSC, Florida.

VI. Discussion—FPS-16 Radar/Jimsphere Balloon System

Vertical wind motions in the atmosphere are very easily detected by the FPS-16 radar/Jimsphere system, as described by Endlich et al.,[7] Fichtl et al.,[8] and others.[9-12] By means of low-pass filtering, high-frequency noise introduced by the

FPS-16 radar is eliminated from the vertical rise rate Jimsphere data. The remaining perturbations may be representative of the induced vertical motions. Normally, the Jimsphere rises about 5 m/s from sea level to 16 km as described by Scoggins,[13] and others.[11-12,14-16] MacCready and Jex[14] stated that the value of the drag coefficient is of primary importance in computing the response of a Jimsphere or any other balloon to a change in wind speed. This was confirmed by Scoggins[13] in his article "Aerodynamics of Spherical Balloon Wind Sensor." Kaufman and Susko[10] indicated that the drag coefficient is small at supercritical Reynolds number R_e where the turbulent wake is small, but increases sharply in the transition region. The C_D is higher in subcritical R_e where the wake is larger and the flow is laminar.

Jimsphere vertical rise rate data have been observed to vary from 4 to 10 m/s. Figure 5 illustrates some C_D vs R_e values calculated for various vertical rise rates from the U.S. Standard Atmosphere (1962) temperature profile data. Figure 6 shows the following Jimsphere vertical rise rate data: profile A was observed from the Jimsphere, released at 1525 Z, March 4, 1969, at Wallops Island and profile B shows the rise rate to be about 7 m/s at 11 km. The corresponding C_D vs R_e values from profiles A and B are plotted in Fig. 5, where the lower C_D at higher R_e suggests a smaller turbulent wake downstream from the Jimsphere. This, in turn, suggests a layer of significant turbulence compared to turbulence of the adjacent air layers. Figure 7 shows the scalar wind speed profiles A and B. Notice the jet stream wind speed of approximately 100 m/s between 10 and 12 km of profile B which relates to the resultant variation (turbulence).

The Jimsphere rise rate vs altitude for two Space Shuttle launches, STS-11 and STS-41D, are given in Fig. 8. Notice the spike of a rise rate of over 7.5 m/s at approximately 12 km for Fig. 8a at the maximum dynamic pressure region (10–16 km) for the STS-11, and no significant spike for Fig. 8b at the next launch (STS-41D). This perturbation ties in with the spike at 12 km for vertical gradient (turbulence) in Fig. 1a, Fig. 2a inverse Richardson number, and the critical values of wind speed, wind direction, and temperature for STS-11 demonstrate turbulence indicators presented in Fig. 3.

VII. Jimsphere Balloon Data Assessment

All of the data from the Jimsphere balloon presented in this paper are calculated every 30 m and averaged over a scale length of 150 m in altitude. The length scale was made at 150-m intervals because the discernible wavelengths of the Jimsphere are on the order of 100–150 m. This was confirmed from spectral analysis from 20 Jimsphere wind profiles tracked simultaneously by an FPS-16 and FPQ-14 radar.[17-18]

The meteorological data error estimates are given in Ref. 19: wind speed, surface to 18 km (60-m mean layer winds) 0.3 m/s vertical error estimate; temperature, varies linearly with altitude from 0.4°C at surface to 1.8°C at 30 km; wind direction, 0–360 deg, 2 deg. Measurements of the meteorological parameters of wind and wind direction were made by the Jimsphere and rawinsonde for temperature.

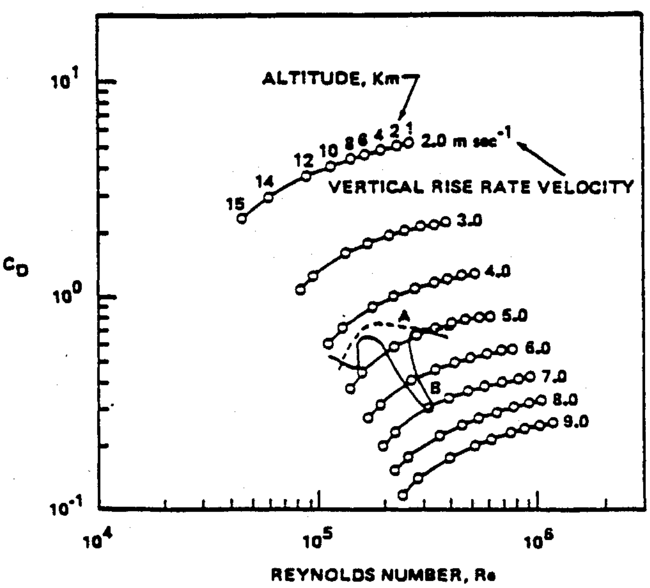

Fig. 5 Idealized C_D vs R_e curves as calculated from standard atmospheric data, and results calculated from Jimsphere release A, March 4, 1969 (1525 Z) and release B, March 6, 1969 (1933 Z).

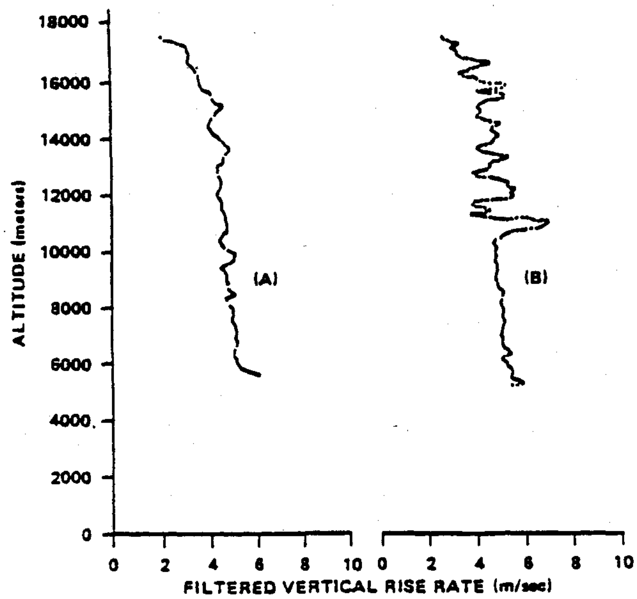

Fig. 6 Vertical rise rate of Jimsphere releases at Wallops Station, Virginia. Jimsphere A was released on March 4, 1969 (1525 Z). Jimsphere B was released on March 6, 1969 (1933 Z).

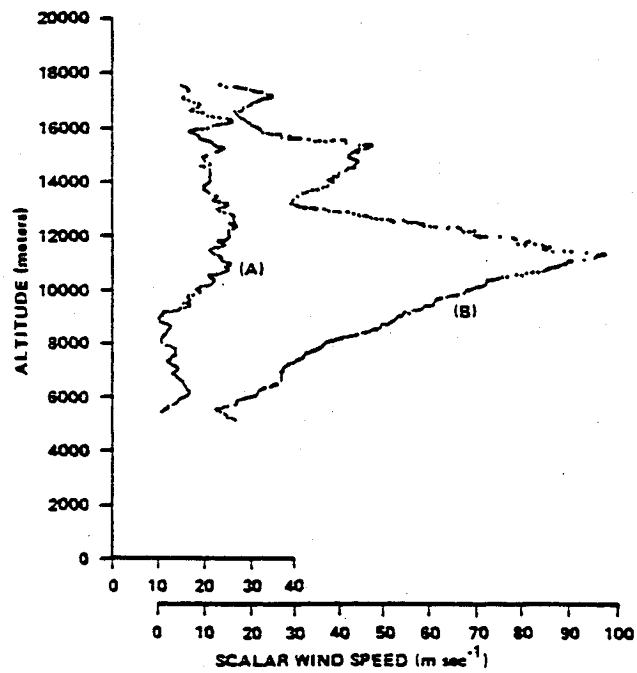

Fig. 7 Vertical wind profiles measured by the FPS-16 radar/Jimsphere at Wallops Island, Virginia. Jimsphere A was released on March 4, 1969 (1525 Z). Jimsphere B was released on March 6, 1969 (1933 Z). The wind variation depends on the sensitivity of instrumentation.

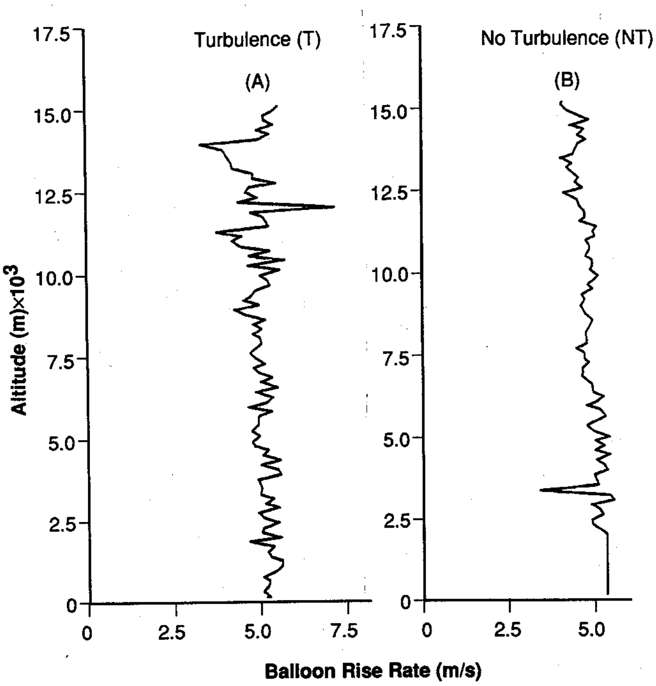

Fig. 8 Rise rate comparison of FPS-16 radar/Jimsphere balloon ascent: a) STS-11 launch, Feb. 3, 1984 (1300 Z); and b) STS-41D launch, Aug. 30, 1984 (1242 Z) at KSC, Florida.

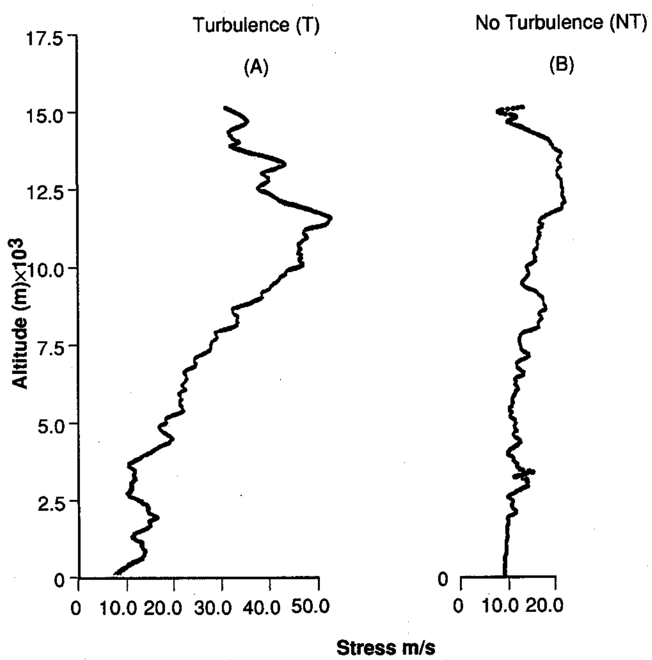

Fig. 9 Stress vs altitude comparison: a) STS-11 launch, Feb. 3, 1984 (1300 Z); and b) STS-41D launch, Aug. 30, 1984 (1242 Z) at KSC, Florida.

VIII. Stability Parameter

The stability parameter ξ, obtained from the Jimsphere balloon wind measurements and the temperature from the rawinsonde, was calculated from the equation $\xi = X/L$ where X is the scale height as reported in Ref. 20 and

$$L = \frac{\bar{T}U_*^3}{kg\; \overline{w'T'}} \tag{4}$$

where the stress parameter U_*^2 is

$$U_*^2 = \sqrt{(\overline{u'w'})^2 + (\overline{v'w'})^2} \tag{5}$$

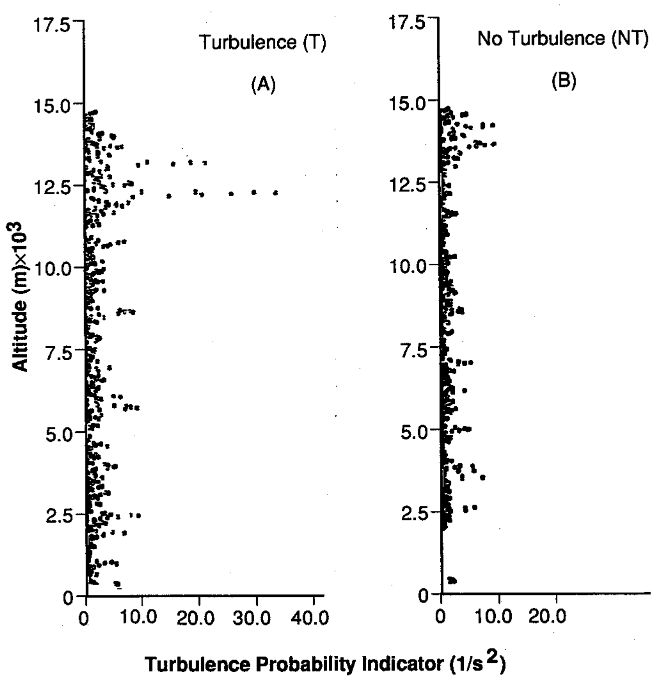

Fig. 10 Turbulence probability indicators comparison: a) during STS-11 launch, Feb. 3, 1984 (1300 Z); and b) STS-41D launch, Aug. 30, 1984 (1242 Z).

T is the temperature in °K. Note the big spike in Fig. 9 at 12 km, illustrating turbulence in STS-11 as compared to STS-41D in Fig. 9b.

IX. Turbulence Probability Index

Turbulence probability index (T_i) was reported by Endlich et al.[7] and further defined in Ref. 21 where $T_i = A\ B$.

Factor A, which is the wind directional shear, is given by the equation

$$A = S\,|\Delta\alpha/\Delta z\,| \tag{6}$$

The second factor B is equal to the change in temperature lapse rate. The equation is

$$B = [(g/T)\,|\Delta^2 T/\Delta z\,|]^{1/2} \tag{7}$$

where $\Delta^2 T$ is the second difference operator of the temperature T. The two factors are multiplied together, resulting in $T_i = AB$.

Figure 10 illustrates T_i vs altitude for turbulence (Fig. 10a) and no turbulence (Fig. 10b). Again note the turbulence indicator (spike) at 12 km for STS-11 in Fig. 10a.

X. Summary

This research has demonstrated that the results of measurements of winds aloft from the FPS-16 radar/Jimsphere balloon system during the 16 Space Shuttle flights and the results presented in Table 1 can indeed indicate the presence or conditions ripe for turbulence in the troposphere and lower stratosphere (10 to 16 km). It has been shown that wind turbulence indicators obtained by the Jimsphere balloon during two Space Shuttle launches, in conjunction with the rawinsonde which provides temperature and pressure data as a function of altitude, that the aerodynamic parameters calculated can indicate the presence of turbulence or that the conditions are ripe for turbulence. Two of the Space Shuttle launches, STS-11 and STS-41D, illustrating examples of turbulence and no turbulence are presented from Table 1. There is no magic foolproof criteria in atmospheric turbulence probability of occurrence. However, the occurrence of turbulence at the tropopause is identified by the enhanced temperature lapse rates and enhanced inversion rates, strong vector wind shears, and large changes in wind direction. When any two of the above conditions occur simultaneously, a significant probability of turbulence can occur as shown in this report. However, even though the indicators may be showing the presence of turbulence, an in situ sensor or astronaut experiencing turbulence while the balloon is in the air would eliminate the uncertainty that the atmosphere is actually turbulent.

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Associate Editor