NASA-CR-203831

0.1 520

P3.2 AN INVESTIGATION OF ROTOR FLOW USING DFDR DATA

Brian H. Kahn, William Chan, P. F. Lester
San Jose State University, San Jose, California

1. INTRODUCTION

At approximately 2124 UTC, 31 March 1993, Japan Airlines (JAL) flight 046, a Boeing 747-100, departed Anchorage International Airport (ANC) on an eastward heading toward the Chugach mountains. When the aircraft climbed to about 610 m (2000 ft) MSL, it encountered significant turbulence. At this time, the number two engine separated from the aircraft, falling within Anchorage city limits. The flightcrew declared an emergency and returned to ANC 23 minutes after takeoff without further incident (2145 UTC). No injuries were sustained either aboard or on the ground. Figure 1 shows the local terrain in the vicinity of ANC with the track of JAL046 and the point at which the number two engine was lost.

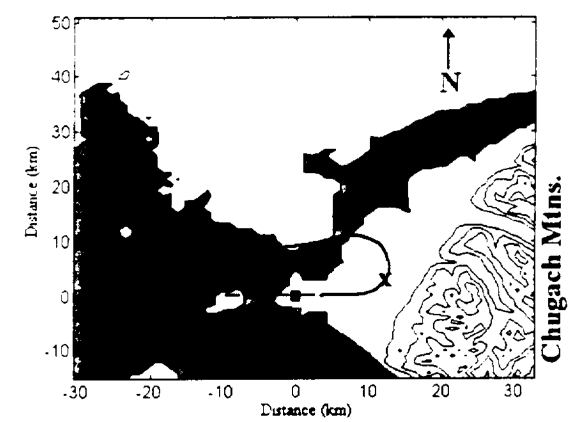

Figure 1. Plan view of the JAL046 flight track and the area surrounding ANC. 'X' indicates location of engine separation. Topographical contours are drawn at 300 meters MSL. The shaded area indicates water or marsh. Topographic data courtesy of the USGS Global Land Information System.

The National Transportation Safety Board (NTSB) investigation determined the likely cause of the accident to be "an encounter with severe, or possibly extreme turbulence that resulted in dynamic multiaxis lateral loadings that exceeded the ultimate lateral load-carrying capability of the pylon, which was already reduced by the presence of the fatigue crack near the forward end of the pylon's forward firewall web" (NTSB, 1993). Another B747-100 (JAL flight 042) that departed 5 minutes earlier, also encountered turbulence. Although the second aircraft escaped severe damage, a later inspection revealed that "the midspar fuse pins for the number two engine were slightly deformed." (NTSB, 1993).

The purpose of the present study was to identify the specific cause of the turbulence that affected flights JAL042 and JAL046. This has been accomplished by expanding on the NTSB analysis to include a detailed examination of Digital Flight Data Recorder (DFDR) information available from both JAL042 and JAL046 and the ANC rawinsonde.

2. METHODOLOGY

In order to place this incident in perspective with larger scale forcing, conventional synoptic charts near the time of the incident were examined for indications of the location and strength of lee wave activity. Direct evidence of the mesoscale structure of the waves near ANC is revealed from the analysis of aircraft DFDR information and the ANC sounding which was taken about 2.5 hours after the turbulence incident.

DFDR information yields horizontal and vertical winds. Computational procedures have been described elsewhere (e.g., Lester, Sen, and Bach, 1988; Wingrove and Bach, 1994). Approximate vertical velocities along the rawinsonde path were determined as deviations of the instantaneous balloon rise rate from the average rise rate (surface to 100 mb). Once the vertical velocities were computed, the data were smoothed using a running average to eliminate very small scale fluctuations.

Perspective and plan views of the greater ANC region, showing topography, and the trajectories of both aircraft and the ANC rawinsonde are shown in Figures 2a and 2b, respectively.

Corresponding author address: Peter F. Lester, San Jose State University, Dept. of Meteorology, San Jose, CA 95192-0104; email <pflester@sjsuvm1.sjsu.edu>

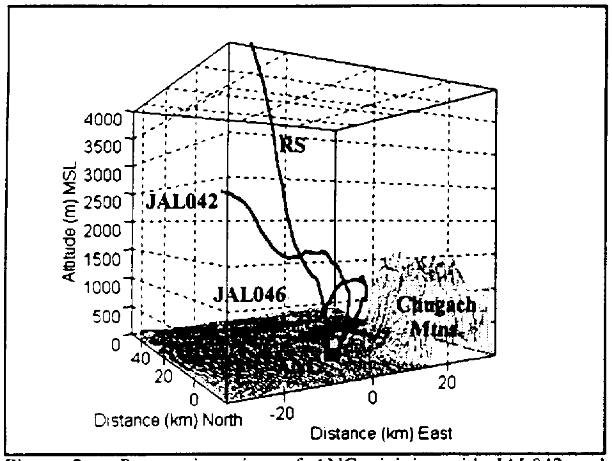

Figure 2a. Perspective view of ANC vicinity with JAL042 and JAL046 flight paths, and ANC rawinsonde trajectory.

3. RESULTS

3.1 Surface and Upper Air Analyses

The 2100 UTC 31 March 93 surface and the 0000 UTC 1 April 93 700 mb analyses are presented in Figs. 3a and 3b, respectively. A primary feature of the surface analysis is the strong pressure gradient across Alaska with the lowest pressures to the SW. In the vicinity of ANC, surface pressures are lower to the west of the Chugach mountains. This cross mountain pressure gradient is commonly observed during mountain lee wave activity.

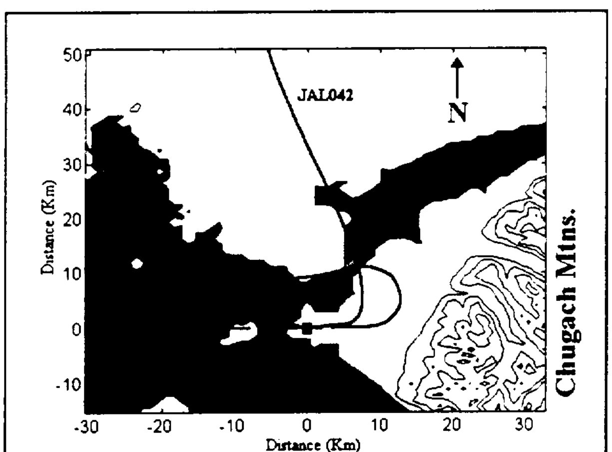

Figure 2b. Plan view of JAL042, JAL046, and rawinsonde (RS) tracks. DFDR data for JAL046 was not available for portion of track shown as a dashed line.

The 700 mb analysis (Figure 3b) also reveals conditions favorable for lee wave activity west of the Chugach mountains and over ANC. Southeasterly winds of 45 kts across the mountains indicate the possibility of significant turbulence in the lee.

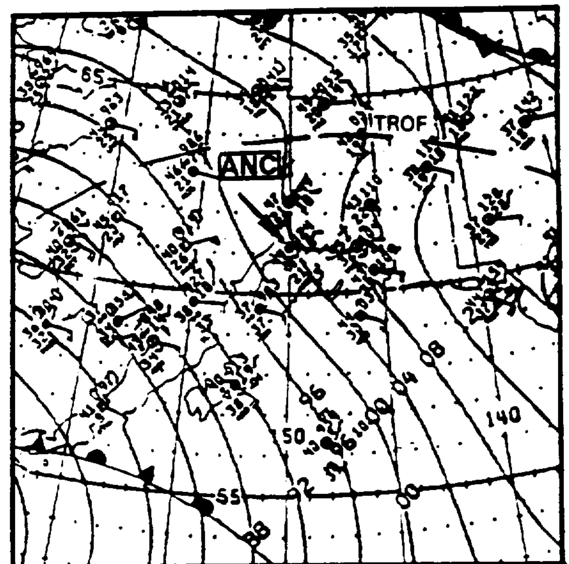

Figure 3a. Surface analysis for March 31, 1993 at 2100 UTC for southern Alaska.

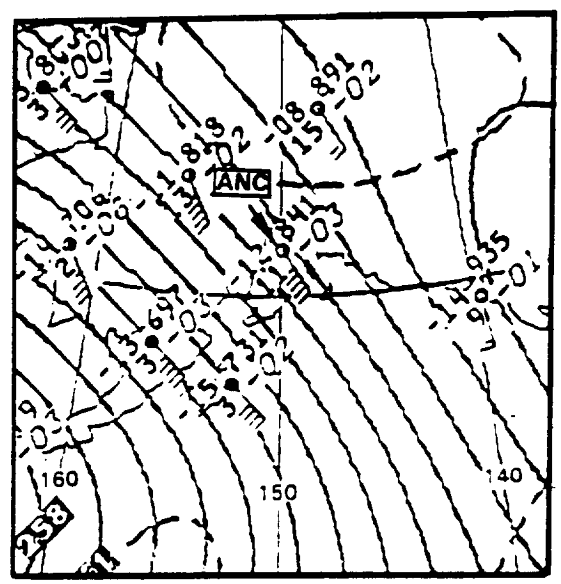

Figure 3b. 700 mb analysis for 1 April 1993 at 0000 UTC for southern Alaska.

3.2 Rawinsonde Data

The ANC sounding for 0000 UTC 1 April 93 was taken about 2.5 hours after the turbulence incident (Fig. 4). However, it offers ample evidence of continuing lee wave activity. The temperature sounding shows a series of stable layers between 1000m and 3000m and an adiabatic layer just above the surface. The stable layer aloft is a typical condition observed during the occurrence of mountain lee waves. The neutral layer is the result of daytime heating and mixing due to strong easterly surface winds (most likely generated mountain waves).

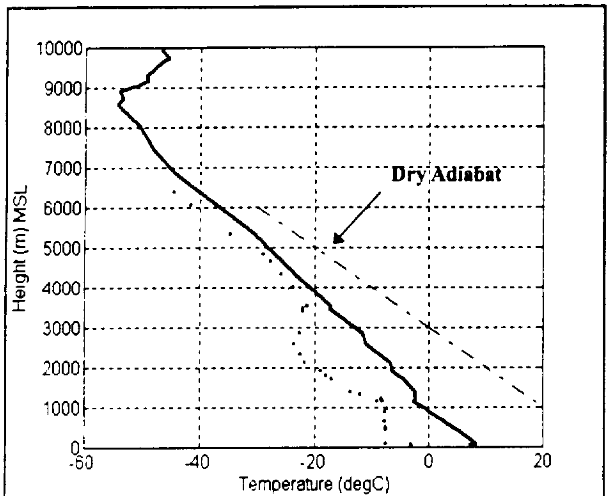

Figure 4. Temperature (solid) and dewpoint (dotted) from ANC rawinsonde for 1 April 1993 at 0000 GMT. The dry adiabat is included for reference.

Profiles of wind speed and direction from the ANC sounding are presented in Fig. 5. The wind component perpendicular to the crest of the Chugach range shows speeds over 50 kts (27 ms^{-1}) near 2000 m (i.e., near mountain top); further evidence of a strong mountain wave.

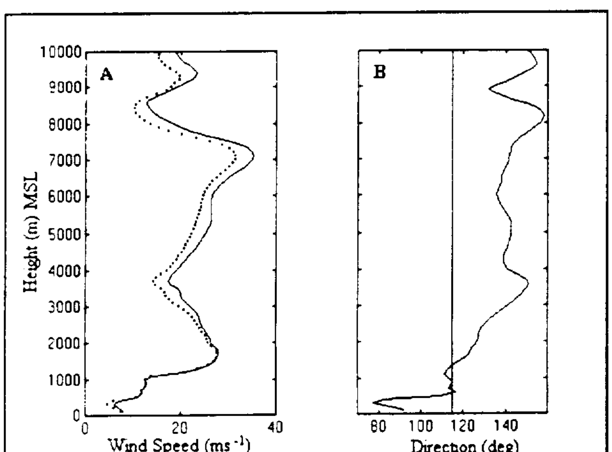

Figure 5. A) Wind speed and, B) wind direction from ANC rawinsonde. In a), solid line is the total wind speed, and the dotted line is the perpendicular component to the Chugach mountains. Vertical line indicates perpendicular direction.

A rough estimate of lee wave length in the stable layers near the mountain top can be computed from the sounding as a function of the temperature and wind conditions; that is,

$$\lambda = \frac{2\pi u}{\sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial Z}}} \tag{1}$$

where, λ is the wavelength, g is the gravitational acceleration, θ is the potential temperature, Z is height, and u is the mean wind speed. For the layer between 500 m and 4000 m ASL in Figs. 4 and 5, this yields about 10 km

A more direct measure of the wave activity is given by the local vertical air velocities derived from fluctuations of the rise rate of the ANC sounding. These are shown as a function of altitude in Fig. 6. The rawinsonde showed two large deviations in vertical velocity (approximately -5 and +6.5 ms^{-1}) as it passed through the lee wave system below 4 km. It is important to note that the balloon experienced this lee wave activity to the west of ANC. The lee waves in that area are most likely secondary or tertiary cycles, as will be shown later. This indicates that they are weaker than the primary cycle east of Anchorage. The rawinsonde traveled about 9.6 km horizontally as it traversed the strongest vertical velocities in agreement with Eqn. 1.

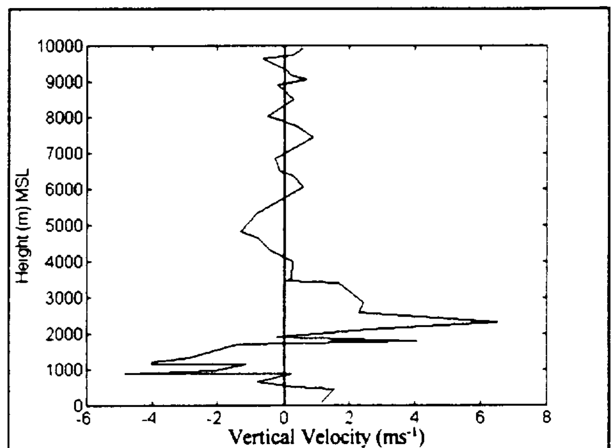

Figure 6. Vertical wind velocity data from ANC sounding.

3.3 Aircraft Data

Vertical acceleration records from JAL042 and JAL046 are shown in Figure 7. At a time of approximately 100 s on both records, incremental deviations from normal gravity of about ± 0.6 g. occurred These values were the maximum experienced by each aircraft and correspond to "moderate" turbulence. JAL046 lost its number two engine during that period of turbulence. Note that the record for JAL046 began after the aircraft departed ANC, while the JAL042 record began on the runway. The locations of the moderate or greater vertical accelerations (magnitudes of deviations >0.5 g) along the departing aircraft tracks are shown in Fig. 8. In particular, JAL046 shows that the worst turbulence was encountered as that aircraft flew parallel to the Chugach mountains about halfway between ANC and the foothills.

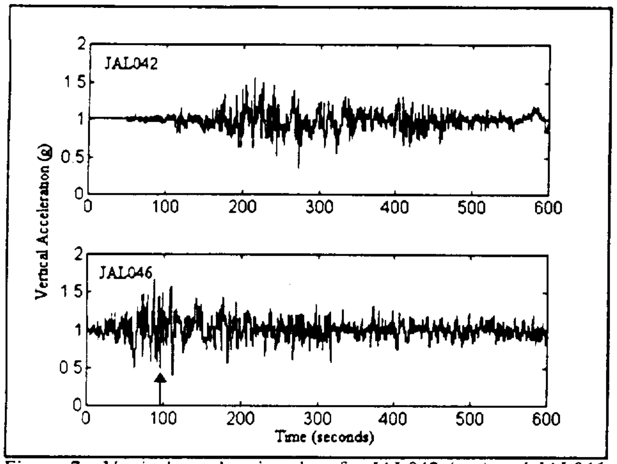

Figure 7. Vertical acceleration data for JAL042 (top) and JAL046 (bottom). The arrow points out the location of the engine separation on JAL046

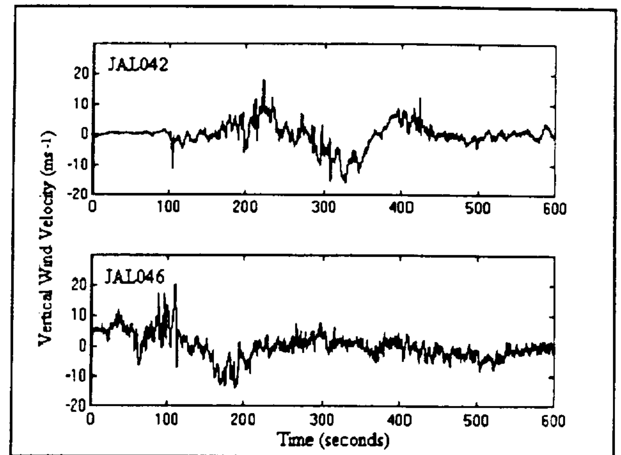

Figure 9. Vertical wind velocity data for JAL042 (top) and JAL046 (bottom).

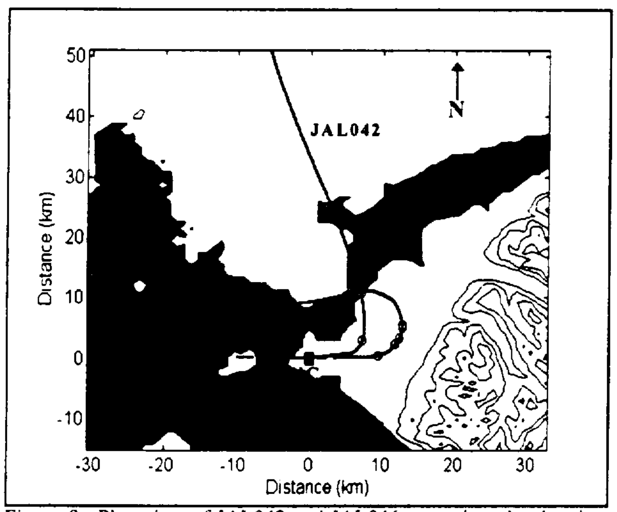

Figure 8. Plan view of JAL042 and JAL046 ground tracks showing regions of moderate turbulence (o).

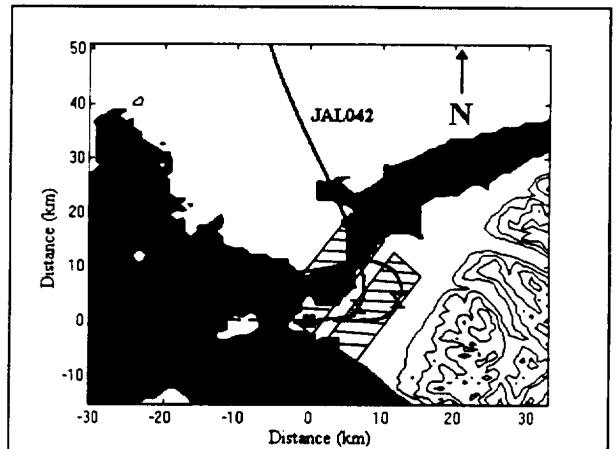

Figure 10. Plan view of maximum downward and upward vertical wind velocity distribution in lee waves estimated from JAL042, and JAL046. '•' indicates a maximum downward and 'x' indicates a maximum upward wind respectively. Hatched areas indicate approximate locations of upward and downward vertical motions.

The computed vertical velocities along the aircraft tracks are shown in Fig. 9. Values range from +18 ms^{-1} to -15 ms^{-1} for JAL042 and +21 ms^{-1} to -15 ms^{-1} for JAL046. These are more than three times the values encountered by the rawinsonde downwind of ANC 2.5 hours later (Fig. 5).

Figure 10 is a plan view of the ANC area showing the tracks of JAL046 and JAL042. The approximate locations of the maximum upward (X) and maximum downward (•) vertical velocities are indicated along the tracks. The first lee wave cycle has been located approximately on the basis of those data. As Fig. 10 shows, the crest of the primary wave is just east of ANC. This places the maximum turbulence near the region of upward motion just east of the wave crest. From previous lee wave studies, it is well known that if a rotor circulation exists, it is most likely to be found under the first wave crest downwind of the mountains. In the present case, both aircraft traversed that region after takeoff.

Some evidence of the presence of a rotor is given in Fig. 11. About 25 seconds after the record begins, wind direction along the aircraft track swings almost 180 degrees. During the same time, wind speed (not shown) decreases to values near zero. This is suggestive of the presence of a rotor under the wave crest. Surface winds observed in the same area reflect a similar pattern; that is, a region of weaker winds in the vicinity of the crest of the lee wave (NTSB, 1993).

If, indeed, JAL046 passed through the lower part of the rotor, then the turbulent region was embedded in the updraft on the upwind side of that circulation. This location has been shown to be the most turbulent region of the rotor circulation (e.g., Lester and Fingerhut, 1973).

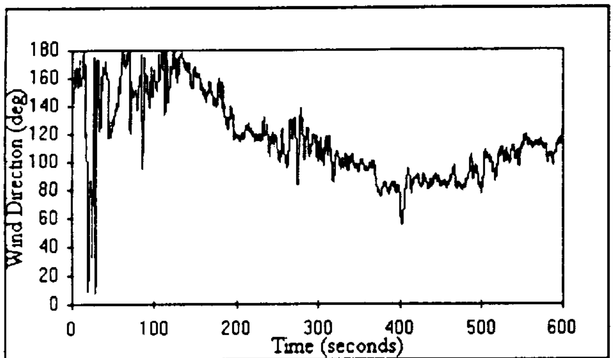

Figure 11. Wind direction along JAL046 flight track.

4 Conclusions

JAL042 and JAL046 experienced mountain wave turbulence which resulted in structural damage to each aircraft. Wind information from JAL046 suggest that the aircraft passed through a rotor under the lee wave crest and that the turbulence occurred in the updraft on the east side of the rotor.

Although the analysis of this limited set of data has not given a precise description of this lee wave system, it has provided useful quantitative information about the intensity and locations of turbulence associated with the mountain wave. It is recommended that near real-time aircraft and rawinsonde data and analysis tools be provided to controllers and meteorologists to aid in the safe routing of aircraft

5 Acknowledgments

This research was supported under NASA contract NCC 2-315. Assistance of the National Weather Office in Anchorage is greatly appreciated. Ralph Bach Jr. of NASA-Ames is thanked for his continued support and encouragement throughout the duration of this contract. The authors also thank the NTSB for providing the aircraft data.

Reference

Lester. P.F. and W.A. Fingerhut, 1973: "Lower Turbulent Zones Associated with Mountain Lee Waves". *J. Appl. Meteor.*, **13**, 54-61.

Lester. P.F. and R.E. Bach Jr., 1986: "An Extreme Clear Air Turbulence Incident Associated With A Strong Down slope Windstorm". *AIAA 24th Aerospace Sciences Meeting*, Reno, Nevada, 1-6 to 1-9.

Lester. P.F., O. Sen, and R.E. Bach, Jr., 1988: "The Use of DFDR Information in the Analysis of a Turbulent Air line Incident over Greenland". *Mon. Wea. Rev.*, **113**, 1103-1107.

Lester, P.F., R.C. Wingrove, and R.E. Bach, 1991: " A Sum -mary of Investigations of Severe Turbulence Incidents Using Airline Flight Records". *Fourth International Conference on Aviation Weather Systems*, 6-24 to 6-28.

Lester, P.F., 1994: "Understanding Turbulence Through the Analysis of DFDR Information". *32nd Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, 1-10 to 1-13.

NTSB, 1993: Aircraft Accident Report: In-Flight Engine Separation, Japan Airlines Flight 46E, Anchorage, Alaska, March 31, 1993, 103 pp.

Wingrove, R. C. and Bach, R. E. Jr., 1992: "Severe Turbulence and Maneuvering from Airline Flight Records". *Proceedings of the AIAA Atmospheric Flight Mechanics Conference*, 15 pp.