11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

LOW-LEVEL WIND SHEAR AT SYDNEY AIRPORT

Richard MANASSEH and Jason H. MIDDLETON

School of Mathematics, Oceanography Group
University of New South Wales, PO Box 1
Kensington, NSW 2033, AUSTRALIA

ABSTRACT

This paper describes early results from an ongoing study of low-level wind shear at Sydney Airport. A set of anemometers provides data that has been recorded on a continuous basis since mid 1991. There are two aims of the study. The immediate aim is an analysis of the fluid-dynamical behaviour during strong low-level wind shear episodes, with an emphasis on thunderstorm-generated phenomena. One particular episode that occurred during a thunderstorm on 27 December 1991 is analyzed in this paper. The episode can be ascribed to oscillations propagating on a stably stratified atmospheric layer. The long-term goal is the generation of statistics (currently in progress) on the occurrence of severe wind shear in the Sydney Airport region - a hazard to aircraft.

1 INTRODUCTION

Wind shear is a condition where there is a large difference in wind velocity over a small distance: the US Low-Level Wind Shear Alert System alarm threshold is equivalent to a difference of about 7.7 ms^{-1} over 2.8 km. Thunderstorms are recognized as a source of wind shear that may be particularly dangerous when aircraft are landing or taking off (Fujita & Caracena, 1977, Spillane & Lourensz, 1986).

Several studies (e.g. Mahoney & Elmore, 1991) have focussed on the thunderstorm-generated microburst phenomenon, which has been associated with a number of aircraft accidents. However, the first observations of the present study - made during the 1991/92 Sydney summer thunderstorm season - indicate that unexpected low-level wind shear can also be caused by atmospheric waves. A necessary precursor for long wave propagation - either linear waves or nonlinear solitary waves - is the existence of a stably stratified layer. Linear long waves could propagate on the interface between the layer and the overlying atmosphere. A stably stratified layer may also be a waveguide (Benjamin, 1967, Davis & Acrivos, 1967) suitable for the propagation of solitary waves.

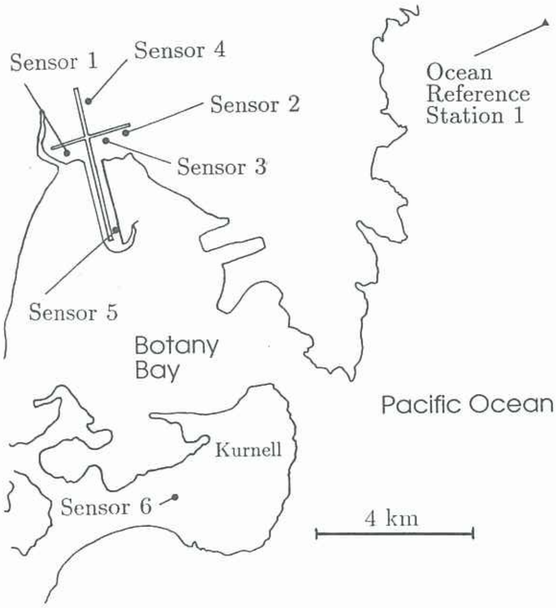

Figure 1: Sensors 1 to 5 are on the Sydney Airport airfield: Sensor 1 and Sensor 2 are at the ends of the shorter runway. Sensor 4 and Sensor 5 are at the ends of the longer runway. Sensor 6 is at Kurnell and is currently of limited use owing to poor siting.

A thunderstorm-generated solitary gust was identified by Doviak & Ge (1984) in Oklahoma, USA and a solitary-wave theory developed by Doviak et al. (1991) was subsequently applied to that event. Several observations of atmospheric waves have been made (see, for example, Clarke, 1983) owing to the solitary-wave 'Morning Glory' of northern Australia; it is associated with mesoscale phenomena. Many instrumented observations of generic thunderstorm outflows have been made (Simpson, 1987). However, observations of atmospheric waves that are thunderstorm-generated remain rare.

The instrumentation at Sydney Airport consists of five tower-mounted anemometers on the airfield (figure 1) plus a sixth at Kurnell. The wind speeds and directions and are logged every two seconds at each sensor. Air pressure is also logged. The data is transmitted in real time to the University of New South Wales for daily analysis and archival.

2 OBSERVATIONS

The period of interest is from 21:35 Eastern Daylight Saving Time (EDT) on 27 December 1991 to about 00:20 EDT on 28 December. The day was clear and warm, with a maximum surface temperature of 28° C occurring at 15:30 EDT. Balloon soundings (described in detail in § 3) indicated that a temperature inversion, present since the previous day, had persisted up to the last sounding (at 15:00) before the events occurred. The inversion was due to a layer of air about 3°C cooler than the ground temperature, which existed up to about 570 m above ground level (AGL). The warm surface air, in the first 150-200 m AGL, was therefore unstable and trapped below a stable inversion. Its relative humidity at 20:00 was about 82%. These are typical germinal conditions for summertime thunderstorms, which often occur when locally heated humid air suddenly breaks through an inversion. Low clouds did not appear until 21:00, when one octa of cumulonimbus had formed. Lightning was noted to the south-west of the airport. The wind was northerly at 10 ms^{-1}.

At 21:35 there was a sudden change in the wind direction to south-westerly. The change arrived first at sensor 6 (at Kurnell, 7.5 km south-east of the airport), then at the airport, where it hit sensors 1 and 5, then sensor 3 and finally sensors 2 and 4, indicating that it was propagating from the south-west to the north-east. It crossed the airfield in 2 minutes ±30 s, and was recorded 20 minutes later at the Ocean Reference Station (ORS1) (located about 15 km east-north-east of the airport). The timeseries of wind vectors on Figure 2 show the wind speed increase to a peak, then fall off to calm conditions, then rise and fall twice more, in an undular fashion. The net change in wind speed from before the event to the peak can be roughly estimated at 17 ± 5 ms^{-1}. The pressure record shows a co-incident set of undulations and a temperature record (which had a lower resolution than the pressure record) also showed similar oscillations. The wind velocity and pressure records show that the amplitude of the undulations decreased progressively.

Following the undulations, the wind had become temporarily calm by about 22:35. At 22:30 thunderstorm conditions were reported over the airport, reaching the 'mature' stage or climax around 24:00, when there were 5 octas of cumulonimbus. A south-easterly wind of about 5-7 ms^{-1} was blowing during most of this time and the pressure was steady. However, in the 14 minutes from 23:34 to 23:48 there was a rapid pressure change: a 200 Pa rise, then a 400 Pa drop that was accompanied by an abrupt change in the wind direction to easterly. This easterly change propagated across the airfield in 2 minutes ±30 s. The wind following it was about 12-15 ms^{-1}. Although it travelled from the south-east to the north-west across the airport, easterly winds did not arrive at Kurnell, to the south east, until the change was already at the airport, indicating that it was an event with a complex frontal structure on the local scale (5-10 km). Meanwhile, the temperature dropped from 21.4°C at 23:56 to 18.2°C at 00:04, then increased to 19.7°C at 00:20. From 24:00 to 00:15 a further change in wind direction, to north-easterly, propagated across the airfield. The cumulonimbus had gone by 00:30; the thunderstorm had dissipated. The wind remained north-easterly until 01:30, when it changed to northerly, remaining that way for the next three hours.

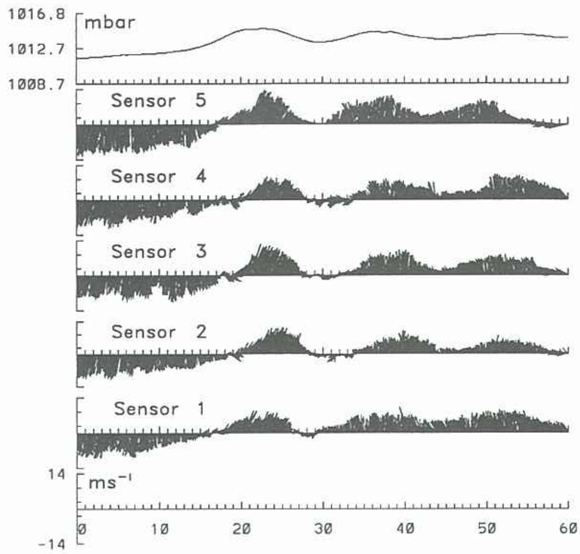

Figure 2: Event interpreted as a thunderstorm-generated atmospheric wave. Wind vectors point in the direction to which the wind is blowing; their length indicates the wind speed. Time in minutes runs along the bottom axis, where zero corresponds to 21:20 EDT.

The undular phenomenon that occurred from 21:35 EDT to about 22:35 EDT will be called *Event 1*. The wind changes, and pressure and temperature excursions from 23:34 to about 00:15 will be called *Event 2*. The speed of propagation of Event 1 can be estimated by the time lag in the arrival of the wind change at different sensors. It arrived at sensor 5 is 21:39:30±30 s, and at ORS1 at 22:00:00±60 s. The propagation speed along a line joining sensor 5 and ORS1 (which is in the approximate direction of propagation of Event 1) is 14 ± 3 ms^{-1} or 50 ± 10 kmh^{-1}.

3 INTERNAL WAVES

Balloon soundings made at the airport at 06:00 and 15:00 show that there was a stably stratified layer in the form of a temperature inversion which persisted throughout the day (Figure 3). Long waves could propagate on this layer.

In the 'wave' interpretation of Event 1, the thunderstorm noted by the airport weather station "to the SW" at 21:00 generated a disturbance (an outflow of cold air) in the stratified layer that sent waves towards the airport, well before the storm itself - or a related storm - moved into the airport area at 22:30. If this were the case then the change in wind speed at the first

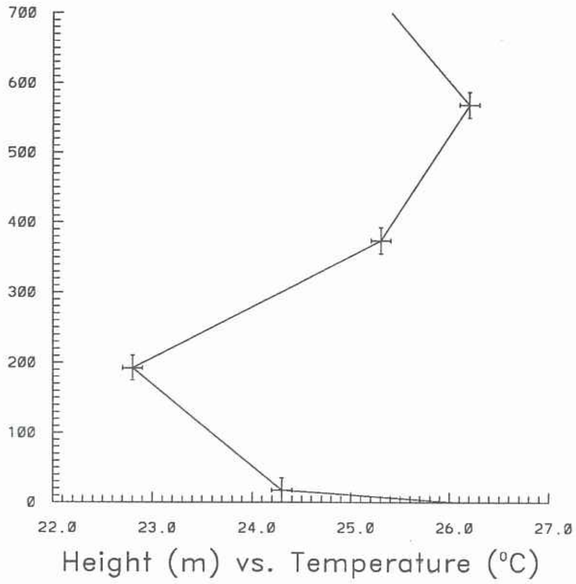

Figure 3: The temperature profile of the lower atmosphere at 15:00 EDT on 27 December 1992: detail of the inversion layer. Only the surface temperature and the first 4 balloon records are shown, as the fifth record is at 2000 m. However, part of the line joining the fourth and fifth records is shown.

peak of Event 1 (17 ± 5m s^{-1}) would be due to atmospheric wave dynamics. The undulations in pressure and temperature would be caused by the corresponding oscillations in the stratified layer. From the sequence in which Event 1 arrived at the airport sensors, it can be deduced that the disturbance came from a west-south-westerly or south-westerly direction, consistent with the location of the initial thunderstorm.

The buoyancy (or Brunt-Väisälä) frequency for an ideal atmosphere, assuming phase changes (condensation and evaporation) occur over a time-scale much longer than the motion so that they can be neglected, and assuming that motions take place isentropically, is given by

$$N = \left(\frac{g}{T}\left(\frac{dT}{dz} + \Gamma_d\right)\right)^{\frac{1}{2}}, \tag{1}$$

where g is the acceleration due to gravity, T is the temperature and Γ_d is the dry adiabatic lapse rate. The observations in §2 indicate that the lower atmosphere was unsaturated, so the use of the dry adiabatic lapse rate, which is calculated using the *dry*-air versions of the ideal gas equation of state, the hydrostatic law and the first law of thermodynamics, is a good approximation. The relation

$$z = -Z\,\ell n(p/p_0), \tag{2}$$

in which the *scale height* is $Z = RT/(M_r g)$, is derived from the dry-air versions of the ideal gas equation of state and hydrostatic law. Here R is the universal gas constant and M_r is the molecular mass of the air. These dry-air laws remain valid below the cloud base, if the liquid water content of the atmosphere below the cloud base is assumed to be small. Observations of clear air support this.

Then, (2) allows the balloon temperature data to be plotted against true height, as shown in Figure 3. The buoyancy frequency N for oscillations of the interface between the stably stratified layer and the air above it is $1.12 \pm 0.05 \times 10^{-2}$ rad s^{-1}, which corresponds to a period of 560 ± 25 s (9 minutes 20 s). The undular oscillations evident in Figure 2 seem to have a period of about $12\frac{1}{2}$ minutes. Some Doppler-shift reduction of the 'true' theoretical frequency N should be expected, since there was an ambient wind opposing the direction of wave propagation. The true theoretical wave speed is unknown; a theoretical wave speed c can be calculated, assuming that the discrepancy between N and the observed frequency is entirely due to a Doppler shift. If this is the case, the Doppler-shifted frequency N_D, given by

$$N_D = N - Uk, \tag{3}$$

where U is the component of the ambient wind opposing the wave propagation and k is the wavenumber, must be about $\left(\frac{9.33}{12.5}\right) N$. Hence $k \simeq 2.8 \times 10^{-3}/U$. Now U is between 4 and 7 ms^{-1}, thus

$$c = 22 \pm 6 \text{ ms}^{-1}, \tag{4}$$

and the Doppler-shifted wave speed c_D is about 17 ± 5 ms^{-1}, compared with the observation of 14 ± 3m s^{-1}.

Therefore, a simple linear theory for waves in a stably stratified atmosphere gives a fair estimate of the period of the observed undulations, compared by means of the Doppler-shifted wave speed. However, a more accurate explanation for Event 1 may be found in the nonlinear physics of solitary waves.

It seems unlikely that the actual air-mass that caused the waves ever arrived at the airport in a coherent form. The only significant change in temperature that might characterize the arrival of a mass of outflow air is the drop from 21.4 at 23:56 to 18.2 at 00:04, which has been allocated to Event 2. Since the associated wind is easterly, Event 2 may have been a local outflow from the thunderstorm that was at its climax above the airport at the time.

4 CONCLUSION

A disturbance in a stable temperature inversion over Sydney Airport was generated, probably by a nearby thunderstorm, on the evening of 27 December 1991. It is surmised that the disturbance caused a train of waves to propagate on the stable layer. In the few minutes taken to cross the airfield, this phenomena resulted in a 20 knot (10 ms^{-1}) wind shear across the ends of runway 16/34; this local low-level wind shear exceeded the US Low-Level Wind Shear Alert System alarm threshold and was therefore a hazard to aircraft.

The support of the Australian Research Council (grant A89030563) is gratefully acknowledged.

References

BENJAMIN, T B (1967) Internal waves of permanent form in fluids of great depth. J Fluid Mech, 29, 559-592.

CLARKE, R H (1983) Fair weather nocturnal inland wind surges and bores. Part II. Internal atmospheric bores in northern Australia. Aust Met Mag, 31, 147-160. (Corrigenda, Aust Met Mag, 32, 53.)

DAVIS, R E, ACRIVOS, A (1967) Solitary internal waves in deep water. J Fluid Mech, 29, 593-607.

DOVIAK, R J, GE, R (1984) An atmospheric solitary gust observed with a Doppler radar, a tall tower and a surface network. J Atmos Sci, 41, 2259-2573.

DOVIAK, R J, CHEN, S S , CHRISTIE, D R (1991) A thunderstorm-generated solitary wave observation compared with theory for nonlinear waves in a sheared atmosphere. J Atmos Sci, 48, 87-111.

FUJITA, T T, CARCENA, F (1977) An analysis of three weather-related aircraft accidents. Bull Am Met Soc, 58, 11, 1164-1181.

MAHONEY, W P III, ELMORE, K L (1991) The evolution and fine-scale structure of a microburst-producing cell. Monthly Weather Review, 119, pp 176-192.

SIMPSON, J E (1987) Gravity currents: In the environment and the laboratory. Ellis Horwood Limited (Wiley) 1987.

SPILLANE, K T, LOURENSZ, R S (1986) The hazard of horizontal wind shear to aircraft operations at Sydney Airport. Bureau of Meteorology Research Centre (Australia) Research report nó 3, October 1986.