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Microbursts: a hazard for aircraft

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Microbursts are believed to have been responsible for several aircraft accidents in recent years. We report here laboratory experiments which show that when a descending column of dense fluid reaches the ground and begins to spread out horizontally, an intense vortex with a horizontal axis forms at the leading edge of the outflowing air. The intensity of this vortex results from the increase in vorticity due to the rapid stretching of the length of the leading edge. The properties of such a horizontal vortex with its associated updrafts and downdrafts are consistent with those found in microbursts which are a severe hazard to aircraft when taking-off or landing.

The crash of the TriStar on 2 August 1985 as it came in to land at Dallas-Ft Worth has been attributed to a small but intense thunderstorm outflow, called a microburst. Microbursts are produced by localized downdrafts of cold air which originate at high altitudes. The downdrafts are typically a few kilometres across, and can have vertical velocities $>10\text{ m s}^{-1}$ (refs 1, 2). When the downcurrent reaches the ground the air is diverted horizontally, rather like the water from a tap hitting a horizontal plate, producing a radial outflow from the centre of the downdraft. Horizontal winds of 20 m s^{-1} are often produced by this spreading flow. In the Dallas disaster, gusts of up to 80 m.p.h. (35 m s^{-1}) were reported at the time of the crash. These intense flows have quite short lifetimes (2-5 min) and produce rapid changes of wind-shear in a small region.

A simple idealized picture of a downburst[1,2], in the absence of significant synoptic winds, is shown in Fig. 1. The depth of the outflowing cold air is typically several hundred metres, so that an aircraft taking-off or coming in to land may fly directly into an area of strong wind-shear. Observing an increase in air speed the pilot will decrease the aircraft's forward thrust, and it is believed that the aircraft may stall when it enters the tailwinds associated with the radial flow on the far side of the downdraft.

With the high wind speeds involved, the parts of the leading edge of the cold air on either side of the downdraft will separate at, say, 40 m s^{-1}, and so during the short lifetime of a microburst these fronts will be 7-10 km apart. A microburst is thought of as a localized disturbance at the leading edge of the downdraft; in the case of the Dallas accident it appears that the aircraft hit the ground a few hundred metres after entering the microburst.

To explain some of the characteristics of observed microbursts, we introduce some laboratory experiments dealing with the spreading of dense fluid in a diverging radial gravity current. These observations, described below, suggest that the lift reduction experienced by the aircraft is caused by a strong wind-shear and downdraft produced by an intense horizontal vortex, which itself is intimately linked with the front of the expanding ring of cold air. The horizontal scale of this vortex is comparable with the depth of the outflow and is much smaller than the overall horizontal extent of the cold air. A secondary vortex can follow the first and it is the variability in lift produced by the air currents in these vortices that produces the serious hazard to aircraft. The location of these vortices is shown in Fig. 2.

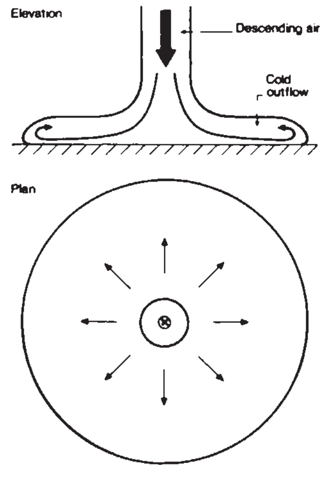

Fig. 1 A simple idealized picture of the descent of cold air from a thunderstorm. The hazard to aircraft is thought to be due to the variations of horizontal wind. The width of the descending air is <4 km, and the depth of the outflow along the ground is a few hundred metres.

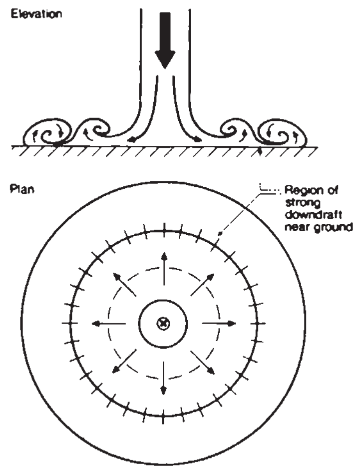

Fig. 2 The early stages in the development of a microburst. Most of the spreading mass of cold air is concentrated into an intense leading-edge vortex. This is sometimes followed by a second vortex. The scale is similar to that of Fig. 1.

The outflowing cold air is an example of a diverging three-dimensional gravity current. The flow is driven primarily by the buoyancy forces produced by the density difference between the cold air and the warmer air surrounding it. In the case of a microburst, some of the initial horizontal momentum comes from the momentum of the descending air. Recently, successful numerical models of two-dimensional gravity currents at appropriate resolution have been run[3]. The essential feature of a microburst, however, is that the radially spreading outflow is three-dimensional. These flows have not yet been numerically modelled at a sufficiently fine scale in three dimensions and we turn to laboratory models for a description of the flow.

The flow is modelled in the laboratory using aqueous salt solutions with different densities to simulate the excess density of the cold air. The experiments produce, both qualitatively and

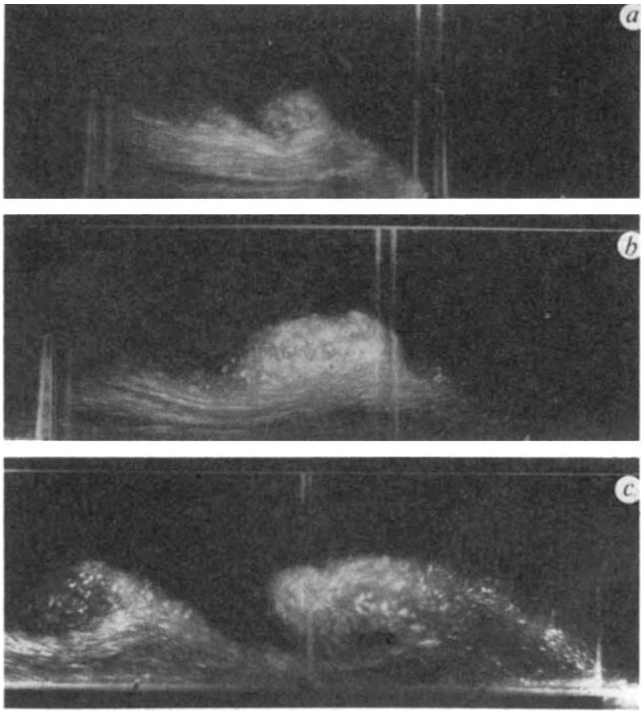

Fig. 3 Sequential streak photographs of the collapse and spread of a volume of salt water into a sector-shaped tank containing fresh water. The flow is from left to right. Note how the downdraft at the rear of the vortex at the leading edge penetrates almost to the ground in *c* as the dense fluid collapses. The vertical struts are at 30, 60 and 90 cm from the starting end of the tank, which is a sector of 10° angle. The photographs were taken at 2-s intervals and $g' = 12\ \text{cm s}^{-2}$.

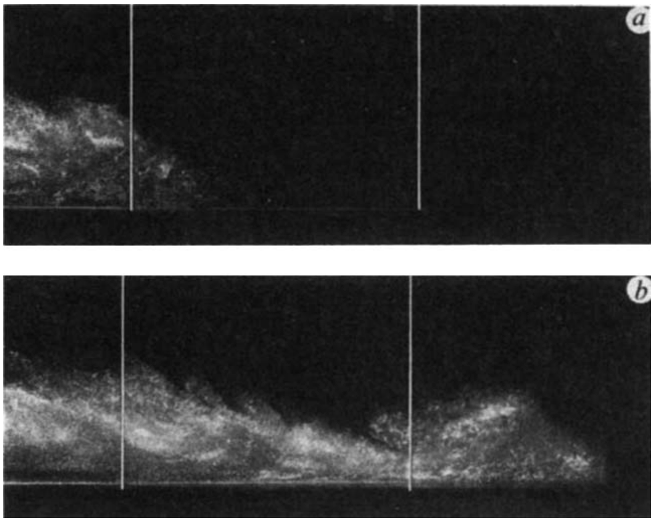

Fig. 4 The behaviour of the leading edge of a saline gravity current as it is allowed to increase its width. The width of the tank increases from 10 to 20 cm between the two white lines which are 30 cm apart. Upstream and downstream of this section the tank is of constant width. The front of a two-dimensional current is shown approaching the divergent part of the tank in *a*. Note how the leading-edge vortex has rolled up as the width of the front increases and it has reached almost down to the ground in *b*. The time interval between *a* and *b* is 5.7 s, and $g' = 14\ \text{cm s}^{-2}$.

quantitatively, the properties observed in two-dimensional atmospheric gravity currents[4,5]. They show that the leading edge, or head, consists of a series of Kelvin–Helmholtz billows with associated vortex motions. In a two-dimensional current, these motions are restricted to the upper half of the current and do not penetrate to the ground.

An example of a rapidly spreading radial gravity current produced in the laboratory is shown in Fig. 3. In this case, there are two billows visible behind the leading edge, but in marked contrast to the two-dimensional current the billows temporarily occupy the full depth of the outflow. The vorticity in the billows has been increased by the radial spreading of the flow. This intensification results from the fact that the centre line of the vortex lies on a circle in plan view (Fig. 2), and so its length increases with time as the circle expands. Because the fluid volume in a vortex is (approximately) conserved, its cross-sectional area must decrease. Conservation of angular momentum about the centre line of the vortex then implies that the vorticity increases. The intensification is largest during the rapid expansion near the source and produces a leading-edge vortex which occupies almost the full depth of the dense fluid[6].

A further demonstration of the intensification of the vortex by this stretching is shown in Fig. 4, where a steady gravity current in a channel of constant width encounters a section with diverging side walls. Once the current enters the diverging part of the tank the vortex is rapidly intensified and it becomes virtually cut off from the following flow. This experiment confirms that it is the lateral divergence of the flow that causes the descent at the rear of the leading-edge vortex to extend to within a short distance from the ground.

These experiments, although small-scale, have sufficiently high Reynolds numbers for viscous effects to be unimportant[4,5]. The results agree with those obtained from larger-scale experimental releases of dense gas in the atmospheric boundary layer in which, in relatively calm conditions, an intense leading-edge vortex was also observed.[7] The laboratory results suggest that the leading edge will propagate at a speed $U = 0.88(g'H)^{1/2}$, where $g' = g\Delta T/T$ is the reduced gravity associated with a temperature difference ΔT and H is the depth of the outflow. For a microburst with a temperature drop of 10 K and $H = 500$ m, $U = 11\ \text{m s}^{-1}$. This velocity is less than the speed of the observed flows which suggests that the momentum of the descending air contributes to the strength of the outflow. In addition, the circulation of the descending air may further increase the intensity of the leading-edge vortex. All experiments to date have been conducted with dense fluid released from rest, and this is an area where further research is needed. But we emphasize that the enhancement of vorticity by lateral divergence will still be present, and is likely to be a strong effect.

The laboratory results (see Fig. 3) also show that the horizontal scale of the leading-edge vortex is comparable with the depth of the outflow (~1 km) and the velocities within it are of the order of the speed of advance of the leading edge ($\geq 20\ \text{m s}^{-1}$). A similar strong vortex has been described in measurements of the leading edge of a large-scale downburst by Doppler radar[8]. It is the wind-shear and downdraft at the rear of this vortex, occurring relatively close to the leading edge of the outflow, that are probably responsible for the danger of flying through a microburst.

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