

Chapter 3: Downbursts

3.1 Observations of downbursts

A *downburst* is defined as "an area of strong, often damaging winds produced by a convective downdraft over an area from less than 1 to 10 km in horizontal dimensions" (American Meteorological Society 2000). Fujita (1985) divided downbursts into two categories based on the horizontal dimension of outflow at ground level; a *microburst* has horizontal dimensions less than 4 km across, while a *macroburst* has horizontal dimensions of at least 4 km. Microburst outflow at ground level may spread out beyond 4 km over time, at which time it becomes a macroburst. Surface winds resulting from microbursts may exceed 60 m s^{-1} , and the associated wind shear has been responsible for a number of aviation accidents (Fujita 1985).

The precipitation rate at ground level associated with microbursts varies widely. Fujita (1985) divided microbursts according to the observed rate of precipitation. A *dry microburst* is associated with less than 0.25 mm of rain at the surface (typically corresponding to a radar reflectivity less than 35 dBZ), while a *wet microburst* is associated with at least 0.25 mm of rain (typically, a radar reflectivity of at least 35 dBZ). In general, wet microbursts require a higher rainwater mixing ratio to develop than dry microbursts, but may occur in environmental temperature lapse rates as stable as -7.5 K km^{-1} (Wakimoto 2001). In this study, all microbursts exhibited reflectivity factors well in excess of 35 dBZ, indicating wet microburst processes were dominant.

Wilson et al. (1984) developed a radar definition of a microburst as a divergent Doppler radial velocity signature with a peak-to-peak velocity difference of at least 10 m s^{-1} over no more than 4 km. This definition does not indicate the maximum altitude a detection may still be considered a valid ground-level microburst. For this study, a

maximum allowed altitude of 1 km was assigned for a radar detected microburst, corresponding to a range of about 75 km for a 0.5 degree radar elevation angle at standard refraction.

Aside from low level velocity divergence, numerous studies have documented other characteristics of microburst-producing storms as viewed by conventional Doppler radar. Roberts and Wilson (1989) found that radial convergence aloft, a descending reflectivity core, and an azimuthal radial velocity couplet indicative of rotation were all typically observed. Eilts et al. (1996) also found that a high reflectivity core initially at higher altitudes than surrounding storms was a good indicator of microburst potential. Experimental algorithms in downburst prediction and detection (e.g., Smith and Eilts 1997) have been developed, with some early success (Smith et al. 2000).

Only one study has examined the relation of observed PR variables to downbursts. Wakimoto and Bringi (1988, hereafter WB88) documented how changes in the Z_{DR} field corresponded to radar-indicated microbursts. A local minimum in the Z_{DR} field at low levels, typically only 1 to 2 km across, was characteristic of the microbursts studied in WB88. This " Z_{DR} hole" was interpreted as an indication of hail or melting hail being brought well below the melting height by descending air. The Z_{DR} hole was located in the middle of a large, uniform area of high Z , showing the value of this PR variable in detecting significant changes in hydrometeor characteristics over a small distance.

The findings in WB88 do not preclude the possibility that the hydrometeors detected in the Z_{DR} hole consist only of hail. As noted in Chapter 2, the Z_{DR} signal in a mixture of rain and hail will be dominated by the more reflective hailstones, which have an isotropic cross section in bulk. Simulations by Balakrishnan and Zrnic (1990a) found the identification of rain within a mixture with hail using Z and Z_{DR} is very difficult,

while the identification is quite simple using Z , Z_{DR} , and K_{DP} in unison. As discussed below, melting hail is a significant contributor to the downward accelerations driving downbursts. Therefore, determining whether a Z_{DR} hole consists of only hail or a rain, hail mixture is important.

3.2 Inviscid vertical momentum equation

Vertical accelerations are governed by the inviscid vertical momentum equation, which can be written in the form:

$$dw/dt = (-1/\rho_0) \partial p' / \partial z - g(c_v/c_p)(p'/p_0) + g \theta_v' / \theta_{v0} - g(r_c + r_r + r_i), \quad (3.1)$$

where w = vertical velocity, p = pressure, θ_v = virtual potential temperature, c_v = specific heat at constant volume, c_p = specific heat at constant pressure, r_c = mixing ratio of cloud water, r_r = mixing ratio of rain water, and r_i = mixing ratio of ice water. Primes indicate perturbations from the base state (subscript 0), which varies only in height.

The first term on the right-hand side of equation (3.1) represents the vertical gradient of perturbation pressure. This term is important in most convective storms, particularly in the case of strong environmental shear (Klemp and Rotunno 1983). The presence of a strong perturbation pressure gradient cannot be easily interpreted by examination of radar products, so this term will not be considered in this work.

The second term on the right-hand side of equation (3.1) describes the perturbation pressure buoyancy. This term can be shown to be small (Schlessinger 1980). In addition, as in the case of the perturbation pressure gradient term, determining any contribution from this term using radar would not be meaningful and is not attempted.

The third term on the right-hand side of equation (3.1) is the thermal buoyancy as described by parcel theory. This term's contribution is often a balance between

diabatic cooling due to particle phase changes, and adiabatic warming due to compression (Wakimoto 2001). Although the degree of compressional warming cannot easily be determined with radar, particle phase changes can be deduced with a PR, as discussed in Chapter 2. It is these observations in downburst-producing storms that are the focus of this work.

Diabatic cooling due to phase changes may arise from the evaporation of rain or cloud water, or from melting or sublimating ice particles. As will be shown, the downbursts observed in this study largely involved melting hail. The cooling of a 1 kg parcel of air due to the melting of hail can be estimated by the equation:

$$dT = -L_f m / c_p , \quad (3.2)$$

where L_f is the latent heat of fusion ($3.34 \times 10^5 \text{ J kg}^{-1}$), m is the mass of the ice particle melted, and c_p is the specific heat at constant pressure ($1004 \text{ J K}^{-1} \text{ kg}^{-1}$). A 1 cm diameter solid sphere of ice has a mass of $3.84 \times 10^{-3} \text{ kg}$. If completely melted at constant temperature of 0°C and at constant pressure, the temperature drop due to diabatic cooling will equal 1.3°C according to equation (3.2). This cooling increases the potential virtual temperature perturbation term in equation (3.1), aiding downward acceleration.

The buoyancy term also explains why downdrafts are stronger at low levels in high relative humidity environments (Droegemeier and Wilhelmson 1985). For a constant downdraft parcel potential temperature θ_v , the virtual temperature perturbation θ_v' between the environment and the parcel becomes increasingly negative as the environmental relative humidity is increased (Wakimoto 2001). This can serve to maintain a previously initiated downdraft at low levels in the face of upward-directed acceleration due to compressional warming. This is confirmed by model simulations by Proctor (1989). Despite the simulations, it should be noted that in the real atmosphere, a

downdraft parcel in a humid environment may have significantly different thermodynamic characteristics than a downdraft parcel in a dry environment, so a direct comparison of downdraft parcels between the two environments may have limited meaning.

The last term on the right-hand side of equation (3.1) is known as condensate loading, and is related to the amount of air pulled down by the weight of falling precipitation particles. This is a well-known contributor to downward acceleration, and is frequently cited as a contributor to the initiation of downbursts (e.g., Kingsmill and Wakimoto 1991). It has been shown (Srivastava 1985; Proctor 1989) that the exact contribution to downward accelerations by condensate loading depends on drop size, rain intensity, and downdraft speed. As noted in Chapter 2, after making some assumptions, drop size and rain intensity can be related to the radar reflectivity factor Z . This may allow some estimate of the quantitative contribution to downward acceleration in a particular downburst. Such an analysis is beyond the scope of this work, though some qualitative description regarding the role of condensate loading in the cases studied may be discussed.

The role of entrainment of environmental air into downbursts is poorly understood. Some observations (e.g., Kingsmill and Wakimoto 1991) suggest the entrainment of drier environmental air into a downward-moving parcel may aid in evaporating or sublimating precipitation particles, cooling the parcel and increasing its negative buoyancy. Some numerical simulations (e.g., Srivastava 1985) suggest mixing a downdraft parcel with dry environmental air reduces the virtual potential temperature difference, diluting the downdraft. Wakimoto (2001) suggested entrainment of dry air may help initiate downdrafts near cloud base, while hindering the maintenance of an

existing downdraft.

3.3 Numerical model simulations of wet microbursts

S87 constructed a numerical model, simulating the relative roles of evaporation, melting and condensate loading in wet microbursts over a variety of different lapse rates and environmental relative humidities. These simulations did not consider contributions from entrainment, nor pressure perturbation effects.

S87 found that ice particles in free fall melt completely in a shorter distance of fall over progressively higher environmental relative humidities. This is because water condenses more readily on the ice particle given higher relative humidity. The latent heat released by the condensation works to accelerate the melting of the ice.

S87 also found that a large portion of the latent heat sink associated with melting is concentrated in a shallow layer near where the ice particle melts completely. In addition, the simulations in S87 showed hailstones melt over a shorter distance of fall than evaporating rain drops of equal mass. These two findings help explain the model's production of stronger downdrafts in the cases with ice than equal amounts of rain water. This is especially true for increasingly stable environmental temperature lapse rates.

Finally, the model simulations in S87 showed that intense downdrafts can be driven entirely below cloud base. Melting and evaporating particles, along with condensate loading, were sufficient to initiate wet microbursts in virtually all simulated environments with temperature lapse rates of -7.5 K km^{-1} or lower.

3.4 Wind tunnel studies of melting hail characteristics

Rasmussen et al. (1984, hereafter, R84) simulated the characteristics of melting

hail in free fall using a wind tunnel. It was found that as melting commences, a "water torus" forms near the equator of the falling particle (Figure 3.1). As the torus builds, giving the particle a slightly oblate shape, strong velocity shear in the boundary layer between the water and the air causes numerous small drops to begin shedding. This shedding of drops about 1.5 mm in diameter was found to commence when approximately 20% of the mass of the original ice particle had melted.

As the mass of the particle decreases, and the particle's shape becomes more oblate (Figure 3.2), the terminal velocity of the particle begins to decrease. This allows the water torus to slowly move upstream (downward). The lower fall speed also

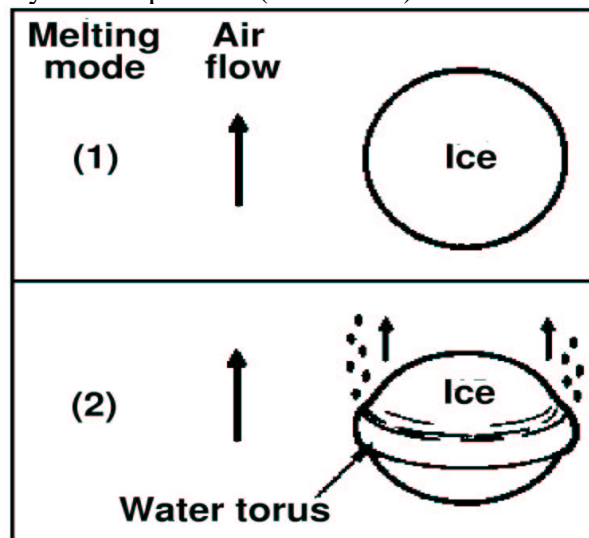


Figure 3.1. Melting modes of ice spheres in free fall from R84. Sphere is 20 mm in diameter in mode (1), and 19 to 20 mm in mode (2).

decreases the velocity shear in the boundary layer between the water and the air, allowing the torus to build to larger diameter. This decreases the drop shed rate, and increases the size of the shed drops to as much as 4.5 mm.

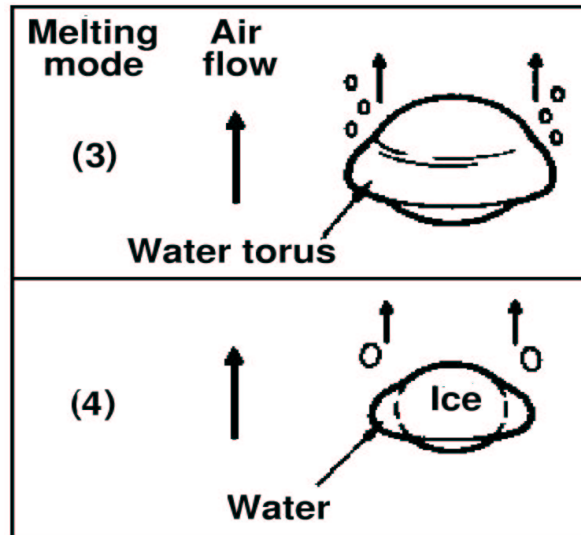


Figure 3.2. Melting modes of ice spheres in free fall from R84. Sphere is 16 to 19 mm in diameter in mode (3), and 9 to 16 mm in mode (4).

Finally, the particle fall speed decreases, and the ice melts, enough so that the water torus completely envelops the ice (Figure 3.3). At this stage, the 5 to 9 mm particle no longer sheds drops, because the ice particle acts as a stable core to what is essentially a very large rain drop. Further melting of the ice is slower, and brought about by heat transfer from the environment to the water, which is transferred to the ice through internal circulations. The overall shape of the particle at this stage was described by R84 as "pill-shaped".

R84's finding that shedding does not commence until 20% of the mass of the hailstone has melted is an important finding. It suggests a water-coated hailstone may fall a considerable distance before shedding is first observed. It should also be noted that R84 found experimentally that a smaller fractional mass is shed for a smaller initial ice sphere diameter.

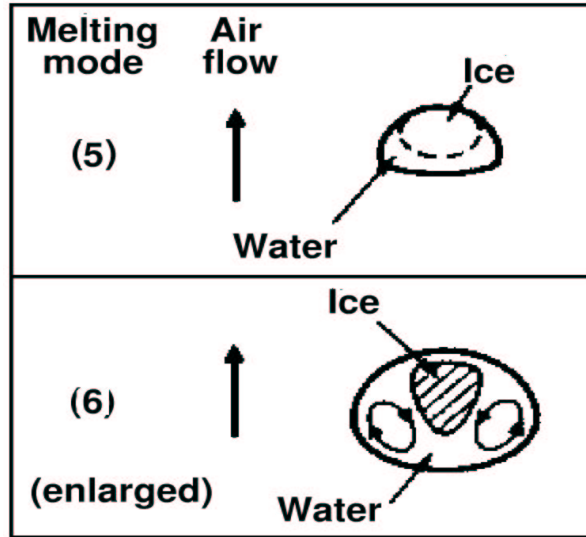


Figure 3.3. Melting modes of ice spheres in free fall from R84. Sphere is 5 to 9 mm in diameter in mode (5), and 1 to 5 mm in mode (6).