Reply

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Most comments by C. A. Knight (1991) have been already directly or indirectly addressed in the paper by List (1990). Nevertheless, some aspects will be expanded in response to Knight.

Figure 1 (List 1990) has been used as an illustration of the complexities of the heat and mass transfer of gyrating hailstones. It was incorporated in the “Introduction” to indicate the problems that need to be understood in the end. The paper in question was not intended to provide an answer to all the problems. It only serves to explain the basic heat transfer within supercooled water skins and at their bounds, a problem which, hitherto, had not been addressed in the literature. The comments by Dr. Knight show that even this step requires time for digestion.

Figure 1 (List 1990) shows that the hailstones surfaces are quite cold at low liquid water contents, rise to temperatures between −2.5° and 0°C at liquid water contents of 5–10 g m⁻³, and approach air temperature at $W_f \to \infty$. The asymptotic approach to air temperature occurs because the cloud water, transiently residing on the hailstone at high liquid water contents, is at air temperature. The maximum surface temperature is related to the onset of shedding (which had been indicated by clear symbols).

Any simple physical explanation of the spin rate dependence (Fig. 1 in List 1990 and Fig 2 in Knight's comments) is suspect because the physics of the accretion process is changing with the rotational conditions. With higher spin rates the shape of the growing hailstone is changing from a spheroid into a wheel-type form (axial cross section approximately rectangular), implying a different accretion and water-distribution process at the surface and, thus, a substantially modified heat and mass transfer. It should also not be implied that the same liquid-water dependence is found at other temperatures and pressures. Knight’s (1991) comments that spins faster than 5.5 Hz are necessary to sustain a water skin with the suggestion even “at all water contents” is incorrect. First, water skins are observed at temperatures close to the freezing point at spins lower than 5.5 Hz, and second, even at spin 0 Hz water skins have been regularly observed over a large temperature/liquid water content range (List 1960). As mentioned in List (1990) the calculated gyration rates, expected in nature, are 9.5 Hz for spin and −14 Hz for nutation/precession (Kry and List 1974).

Without any evidence Knight, in his Fig. 3, makes the assumption that the water skin bulges. Within the resolution of our equipment, this has never been observed over the range of conditions of all of our past experiments. Thus, Fig. 3 should show a continuous water skin of equal thickness at the equator; the water skin should be bound by two concentric circles. Further, the thickness of the skin is of the order of 1% of the radius, thus justifying the replacement of the local spherical surface by a planar skin for the linear treatment of transfers through the skin (effects of divergence ~ 2%).

Knight feels that there is a contradiction between the claim of no water bulges and stating that water skins occur where most accretion takes place. For gyrating hailstones, most of the accretion is observed in the equatorial region and, if permanently accreted, the water stays there. Normally, there is only a latitudinal dependence in water skin thickness. The higher accumulation at the equator, which is independent of longitude, is not considered to be a bulge. Knight may have been misled by the cases of simple rotations about a horizontal axis, where longitudinal bulges can be seen at intermediate rotation rates (Joe et al. 1980). Under gyration, accumulation of water in recognizable bulges is prevented because the surface points exposed to the highest inertial and aerodynamic forces change in a non-repetitive fashion (quite distinct from straight rotation), and the inertia of the water skin is too high to allow the water to follow the changing force field. As a consequence the water is kept essentially at the location of accretion, as is supported by the conservation of shape for the most probable gyration rates.

Knight (1990) further states that motions within the water skin and the (nonexisting) bulge are “violent”. However, the estimated Reynolds number of order one
in the skin (List 1990), which Knight (1991) does not contradict, indicates viscous flow. The flow through the sponge is even further restricted, far beyond the level advocated by Knight (as was pointed out by List, 1990). The fact that the heat transfer is far from an eddy transfer (List 1990) provides additional support for a "quiet" skin.

The water skin–ice sponge interface temperature is not associated with a thermodynamic equilibrium because the front of the ice sponge advances during growth. The water at the ice front and close to it in the sponge has to be supercooled, otherwise there would be no growth. However, after a certain distance into the sponge, the temperature should be very close to 0°C, as indicated by an adjustment region in Fig. 2 (List 1990). Therefore, the theory is not "static" as Knight claims because it deals with a nonequilibrium thermodynamic situation.

It should also be recognized that there is a lower limit to heat transfer: the heat conduction by molecular processes. List's theory (1990) demonstrates that, with simple assumptions, the total heat transferred through the water skin can be approximated by the molecular heat transport within a factor of two (which is close to the measuring accuracy). Thus there is no need to resort to a very sharp, advectively induced temperature gradient at the water skin surface (convection has been shown to be unlikely due to low Rayleigh number; List 1990). To suggest that the heat transfer in the rest of the skin is less than that by molecular heat conduction, as implied by Knight, is physically not tenable.

Knight disregards the acting control mechanism which keeps the ice sponge front moving as a smooth, convex front, and argues for positive feedback instead of a negative one. He argues that because the ice growth speed close to the water–air interface at −1°C is about 60 times the speed of the hailstone growth (List 1990, Fig. 6), ice crystals have ever growing speeds once they enter more supercooled regions. However, crystals do not and cannot break out of an otherwise smooth front into the more supercooled region because faster growth would mean that more heat of fusion is released right at the tip of the faster advancing ice crystals, thus heating up the immediate environment around the tips, which in turn would slow growth close to stand still. As stated by List (1990) the growth of the ice dendrites in the ice sponge front is controlled by the speed at which the latent heat of fusion is transported away to the water–air interface. This is negative feedback, a diffusion controlled process. This is also the physical explanation for the existence of water skins, water skins which Knight (1990) thinks do not even exist, water skins which have been observed since the first icing experiments have been performed in the range of conditions of hailgrowth in the nineteen fifties.

The assumption that the ice sponge front and the water skin–air interface (I1 and I2 in Fig. 1 of Knight) move at the same speed is based on the observation that the water skin thickness remains the same (within the limits of estimation) while a hailstone doubles in size (at constant relative air speed). It was suggested by List (1990) and is repeated by Knight (1991) that mechanical processes control the thickness of the water skin at constant icing conditions (not including particle diameter) and keep it close to constant, thus coupling I1 and I2. Why a constant water skin thickness should make a linear temperature gradient in the water skin "problematical", as Knight (1991) suggests, is without physical foundation. Note that the skin thickness, estimated to be 0.3–0.5 μm, is not important for the heat transfer, it is the temperature gradient which counts. In view of the uncertainties the upper limit of thickness was set at 1 mm.

In summary, the simple approach to the processes in and at the interfaces of water skins has provided us with a much clearer physical picture. The concepts of heat conduction, heat and mass transfer, thermodynamics and standard fluid mechanics, as applied in the theory by List (1990), are straightforward and are in conformity with the experimental data. The theory (List 1990) does not solve all the problems; however, it provides an important facet of the rather complex microphysics of hail growth.

REFERENCES


