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Comments on cumulus glaciation papers by P. V. Hobbs and A. L. Rangno

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Hobbs and Rangno (1985, 1990) and Rangno and Hobbs (1991, 1994) have made a series of detailed field studies of the glaciation of both maritime and continental cumulus clouds in the vicinity of Washington State. Rangno and Hobbs (1991), for example, concluded from a simple calculation that the measured rates of glaciation in some situations were too high to be explained in terms of the Hallett–Mossop riming/splintering process (H–M): although the conditions required for the efficient function of H–M (temperatures embracing the Hallett–Mossop band, and the presence of growing graupel pellets and a broad size-distribution of supercooled droplets) prevailed in many of these clouds.

In an effort to improve the realism and quantitative validity of estimates of the rates of glaciation of cumulus clouds, Blyth and Latham (1997) have developed a multi-thermal model of cloud glaciation via H–M, in which the trajectories and life-histories of all ice particles (graupel and ice crystals) are tracked as these particles move around, grow and (eventually) produce their own splinter progeny before falling out of the cloud. This model, the prescribed features of the first version of which were based on radar and airborne information emanating from cumulus studies over New Mexico, revealed that the rate of glaciation via H–M was sensitive to dynamical features such as updraught speed, thermal depth, inter-thermal interval and downdraught characteristics, but was especially dependent upon the values of liquid-water content L that existed (with different values) in the updraught, debris and downdraught regions of the cloud.

In the discussion which follows, we use an ice particle multiplication factor f, defined simply as the ratio of the total number of ice particles at a given time t to that number existing at $t = 0$.

We now utilize this multi-thermal model to predict the rate of glaciation via H–M within a cumulus cloud subjected to intensive study by Rangno and Hobbs (1991) on 21 November 1988. Glaciation was especially rapid, and these authors concluded from a simple analysis that it was too great to be explicable in terms of H–M. This cloud had a base pressure and temperature of 940 mb and 6 °C respectively. Rangno and Hobbs reported that in the 8-minute interval between the final overflight of the cloud and the first penetration (near cloud top), the ice crystal concentration increased from less than $1\ \mathrm{l}^{-1}$ to more than $100\ \mathrm{l}^{-1}$, corresponding to a value of f of at least 100. These authors made a simple calculation from which they concluded that over this 8-minute period the multiplication factor via H–M was a maximum of only about 6.

However, if our multi-thermal model is run for input-parameter conditions reported by Rangno and Hobbs for this cloud, and with a maximum normalized liquid-water content value, $L/L_{\mathrm{AD}} = 0.9$, which was the value measured in the cloud, we find that a value $f = 100$ can be achieved in 8 minutes, as reported. Further observations made on this cloud by Rangno and Hobbs, later in its life-history, provided additional values of glaciation rate which were more modest, and which could thus readily be predicted on the basis of the multi-thermal model.

Other predictions of our model are consistent with the general results obtained by Rangno and Hobbs (1994). In particular the model is consistent with the two-stage ice-forming process whereby, during the first stage, the concentration of ice particles is low, and in the second stage high concentrations of ice crystals appear very rapidly at cloud top. In the model, during the first stage, only ice particles produced by primary nucleation are present. In the second stage the splinters produced in the Hallett–Mossop temperature zone ($-8\ ^\circ\mathrm{C} \leqslant T \leqslant -3\ ^\circ\mathrm{C}$) are carried to cloud top in the updraught. The model results are also consistent with the observation that narrow, short-lived, 'chimney' clouds with subsiding tops do not contain as many ice particles as wider clouds. Narrower thermals decay faster than wider ones (e.g. Sánchez *et al.* 1989) and hence the liquid-water content is significantly less.

We conclude, therefore, that the Hobbs–Rangno statement that many of the clouds studied have glaciation rates too high to be attributable to H–M—and that therefore, by implication, a further, more powerful, glaciation process needs to be identified—is not correct. We re-iterate that our model indicates that H–M is especially sensitive to the liquid-water content, and we note that adiabatic regions are reported to exist in the thermal cores almost to the maximum cloud top (Heymsfield *et al.* 1978; Jensen *et al.* 1985; Blyth *et al.* 1988; Sánchez *et al.* 1989). However, these adiabatic regions are transitory and will often be missed during observations. It is necessary, in our view, in making quantitative assessments of glaciation rates, to take account of the dynamical characteristics of the clouds in question and, particularly, to utilize a realistic description of their liquid-water-content structure.

We cannot conclude from the foregoing analysis, of course, that the cumulus glaciation observations of Hobbs and Rangno were necessarily a consequence of H–M. It might be relevant to point out, however, that considerable

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evidence has accumulated in recent years (e.g. Mossop 1985; Harris-Hobbs and Cooper 1987; Blyth and Latham 1993) indicating that the Hallett–Mossop process is of primary importance in the glaciation of a variety of cloud types.

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Reply to "Comments by Alan M. Blyth and John Latham on 'Cumulus glaciation papers by P. V. Hobbs and A. L. Rangno' "

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Before considering Blyth and Latham's (1998) claim that the riming–splintering (R–S) mechanism can explain the high rates of ice formation that we measured in many small polar maritime clouds off the Washington Coast and in some continental cumuliform clouds, we will review briefly the R–S mechanism and the field observations that led us to the conclusion that the R–S mechanism as currently formulated is not powerful enough to explain the most rapid cases of ice production that we observed.

(*a*) *The Hallett–Mossop riming–splintering mechanism*

The R–S mechanism, as currently formulated, is based on laboratory experiments. According to the results of these experiments, appreciable concentrations of ice splinters are produced when supercooled droplets collide with ice provided that:

(i) cloud temperatures are between -2.5 and -8 °C (Mossop 1985a);
(ii) droplets $\geqslant 24$ μm diameter are present (Mossop and Hallett 1974; Mossop 1976);
(iii) droplets <13 μm diameter are present in appreciable concentrations (Goldsmith *et al.* 1976; Mossop 1978, 1985a); and
(iv) relatively fast falling (>0.7 m s^{-1}) ice particles are present (Hallett and Mossop 1974; but see also Mossop (1985a)).

In the context of a cloud, the R–S mechanism is postulated to act as follows. A few ($\leqslant 1$ per litre) graupel particles form in the upper regions of a supercooled cloud. As these particles fall through the cloud they intercept droplets $\geqslant 24$ μm diameter and droplets <13 μm diameter at temperatures between -2.5 and -8 °C, and during the riming process ice splinters are ejected. The ice splinters grow over a period of 4–5 minutes to sizes where they themselves can rime ($\sim$200–300 μm long for columnar crystals) and produce ice splinters over the next several minutes while they remain in the R–S temperature zone. This sequence continues as long as ice particles grow large enough to rime under conditions appropriate for ice-splinter production. Laboratory experiments indicate that the maximum rate of ice-splinter production, under optimum conditions, is 1 ice splinter per 80 of the larger droplets accreted (Mossop 1985a).

Application of the above criteria to polar maritime clouds with top temperatures of about -10 °C has produced estimates of $\sim$25–50 minutes for ice particle concentrations to rise from about 0.01 per litre (assumed to be produced by primary ice nucleation) to 100 per litre (e.g. Mossop 1985c; Beheng 1987; Rangno and Hobbs 1991; Mason 1996).

(*b*) *Field observations of Hobbs and Rangno*

Cumulus clouds over the coastal waters of Washington State during onshore flow conditions in the cooler half of the year are virtually identical to those studied in the Australian Pacific by Mossop and his co-workers (e.g. Mossop *et al.* 1967, 1968, 1970, 1972; Mossop and Ono 1969; Mossop 1985b). Therefore, when we undertook our studies of these clouds, we expected to replicate the findings of Mossop, who found that the R–S mechanism could explain the high ice particle concentrations he observed over clouds over the Australian Pacific. However, after compiling data on more than a thousand maritime clouds (e.g. Hobbs and Rangno 1985, 1987, 1990; Rangno and Hobbs 1991), together with studies of hundreds of continental clouds in the interior of Washington State (Hobbs and Rangno 1985; Rangno and Hobbs 1994), we came to the conclusion that while, under the appropriate conditions, the R–S mechanism operated in nearly all of the maritime clouds, and in some of the continental clouds, it was probably subsidiary in importance to a more powerful ice-forming mechanism that operated under less restrictive conditions than the R–S mechanism is currently thought to operate.

We reached this conclusion because:

(i) The glaciation of the small, polar maritime clouds that we studied appeared to be much faster than can be explained by the R–S mechanism (e.g. Hobbs and Rangno 1985; Rangno and Hobbs 1991, 1994).

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(ii) The conditions required for the R–S mechanism were often not met, or only marginally met, in many clouds containing high ice particle concentrations (e.g. Hobbs and Rangno 1985; Rangno and Hobbs 1994). For example, the maritime clouds we studied typically had very low concentrations (<20 cm^{-3}) of droplets <13 μm diameter in the R–S zone temperature.

(iii) The habits of the ice crystals present in high concentrations were often incompatible with formation in the R–S temperature zone of -2.5 to -8 °C (where columnar crystals grow).

(iv) Extremely high concentrations of small ice particles (up to 100 per litre) appeared virtually simultaneously with frozen drizzle drops, rather than following them in a process of relatively slow build-up by the R–S mechanism.

(v) Within a few minutes, small pristine ice particles appeared to glaciate an entire cloud turret head spontaneously over a wide temperature range (-5 to -20 °C), including all its protuberances (which is difficult to explain by the transport of ice splinters from a few isolated shafts of graupel).

(vi) In support of a nearly instantaneous glaciation mechanism, we have shown that the appearance of high concentrations of small pristine ice particles in clouds is virtually indistinguishable from ice produced by seeding a cloud with dry ice (Rangno and Hobbs 1991, 1994).

(vii) Our data show that the occurrence of high ice particle concentrations is statistically related to the presence of a few large cloud droplets in the tail of the droplet spectrum, regardless of whether or not all the other criteria suggested by laboratory experiments for R–S are satisfied.

The first stage of the more powerful ice-forming process that we have hypothesized involves the formation of frozen drizzle drops and small graupel; in this respect it resembles the R–S process. However, the concentrations of these frozen particles, in highly localized cloud regions, are already 10 to 1000 times greater than expected ice nucleus concentrations at cloud-top temperature (Hobbs and Rangno 1985; Rangno and Hobbs 1991). Thus, the first ice particles that appear, typically in concentrations of 0.1 to a few per litre in clouds with top temperatures $\geqslant -12$ °C, cannot be explained by the R–S mechanism as currently formulated.

Blyth and Latham refer specifically to our case study of 21 November 1988. Our calculation of the efficiency of the R–S mechanism for this case (Rangno and Hobbs 1991) was based on the measured concentrations of droplets <13 μm and $\geqslant 24$ μm diameter, the measured graupel concentrations, and the rate of ice-splinter production by R–S measured in the laboratory experiments referred to in (a) above.

(*c*) *A brief critique of the Blyth–Latham model*

Blyth and Latham state that their model calculations show that the R–S mechanism can explain the high ice particle concentrations we observed in polar maritime clouds off the Washington Coast. However, in our view, their model is not adequate to address this issue because:

(i) The concentrations of the two critical droplet sizes (<13 μm and $\geqslant 24$ μm diameter) in the R–S temperature zone are not specified in the Blyth–Latham model.

(ii) The scheme for predicting primary ice particle concentrations is not specified.

(iii) The model is valid only for the specific situation where a rising turret rises through the debris of an adjacent turret.

(iv) An unrealistic turret–turret interaction lifetime of 1 h or more is assumed.

In the many cumulus clouds we have studied, turrets ascend on the backside or flanks of a column of precipitation. As these new turrets arrive at their peak height they glaciate and are carried downwind to form, in some cases, a long plume of stratiform ice consisting of single crystals and largely unrimed aggregates. During this process the new turrets glaciate completely in a few minutes, even though their summit temperatures may be $\geqslant -12$ °C. While the new rising turrets on the up-shear side are usually (although not always) attached to older portions of the cloud downwind that contain considerable ice, they remain identifiable as individual turrets throughout the glaciation process. The older turrets do not, as a rule, serve as 'seeder' clouds for the new ascending turrets, as assumed in the Blyth–Latham model. In this regard, the clouds we studied were very much like those studied by Mossop, who reported that he did not observe new turrets rising through old turrets full of ice. No doubt in the quiescent barotropic summertime environment of New Mexico, the lack of wind shear allows multi-thermal 'seeder–feeder' cumulus cloud interactions of the type modeled by Blyth and Latham. However, our experience supports the earlier observations of Workman and Reynolds (1949) who noted that the total time of rise and fall of cumulus tops in New Mexico is about 20 minutes.

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