Reply

PETER V. HOBBS AND ARTHUR L. RANGNO

Atmospheric Sciences Department, University of Washington, Seattle, WA 98195

21 March 1986 and 6 October 1986

We welcome Telford et al.'s (1987, hereafter referred to as TCI) entry into the fray on ice enhancement in clouds, and we thank them for their kind comments on our paper (Hobbs and Rangno, 1985, hereafter referred to as HR).

Telford et al.'s comments can be grouped under the following topics: the region of origin of high ice particle concentrations in cumuliform clouds, factors affecting ice enhancement, the role of entrainment in ice enhancement, and the mechanism for ice enhancement. Each of these topics is considered below.

Region of origin of high ice particle concentrations

Since we measured the smallest ice particles near cloud tops, we favor the hypothesis that these particles originated near this location. This hypothesis is supported by the following additional observations. The ice particles in question appeared to be pristine ice crystals; large ice particles were generally not encountered. As described by HR, newly formed ice particles near cloud tops were encountered in small clusters, from which strands of ice particles extended through the depth of the cloud and were often visible below cloud base. Also, as noted by HR, in the regions where we measured high ice particle concentrations near cloud top the vertical air motions were generally negligible or directed *downward.*

Perhaps most importantly, particularly with regard to the maritime cumulus we studied, there appeared to be but one cycle of convection: a turret rose to about the −6°C level, and it glaciated in ~4–7 minutes. There was little chance that "turbules" originating at cloud top descended to the freezing level (near cloud base usually) and then rose again to produce ice.

For the reasons listed above, we doubt that the high ice particle concentrations that we measured, particularly those very close to cloud top, originated far below the flight level, as hypothesized by TCI. However, more definitive measurements, in particular continuous measurements of the concentrations and nature of very small ice particles in clouds, will be needed to unambiguously resolve this issue. We are now preparing to obtain such measurements.

Factors affecting ice enhancement

We found that there is an excellent correlation ($r = 0.90$) between maximum ice particle concentrations in cumuliform clouds and the broadness of the droplet spectrum, as measured by the parameter D_T, over a wide range of cloud top temperatures (see Fig. 4 in HR). A similar relationship exists between maximum ice particle concentrations and the concentration of droplets $\geqslant 20$ μm diameter. The droplet parameters were measured in younger turrets, prior to the development of high ice particle concentrations. We have also shown that maximum ice particle concentrations decrease as total cloud droplet concentrations increase (Hobbs and Rangno, 1984). Since maritime clouds generally have broader droplet size distributions and smaller total droplet concentrations than continental clouds (e.g., Fletcher, 1962), the former class of clouds is more likely to exhibit ice enhancement than the latter.

Telford et al. now point out that our dataset reveals an additional interesting relationship, namely, that those cumuliform clouds with base temperatures > -3°C generally exhibit ice enhancement and those with base temperatures < -3°C generally do not. They postulate that this cloud base temperature separates two different ice-forming processes. However, the effect of cloud base temperature on ice enhancement follows naturally from the HR criteria, since the warmer the base of a cloud, the more likely it is to develop a sufficiently broad droplet size distribution ($D_T > 20$ μm) for ice enhancement to occur at cloud top. This is demonstrated in Fig. 1 (a plot similar to TCI's Fig. 1 except that D_T is the abscissa), where it can be seen that $D_T = 20$ μm separates cases of ice enhancement from those with no ice enhancement for clouds with top temperatures between −6 and −20°C.

In their Fig. 2, TCI have combined a considerable amount of our data into single diagrams. We find these diagrams difficult to interpret. For example, it is exceedingly difficult to distinguish between clouds that had a few ice particles per liter and those without ice. This distinction is important, since it can determine whether or not a cloud precipitates. Also, one must use a micrometer on TCI's Fig. 2 to deduce the con-

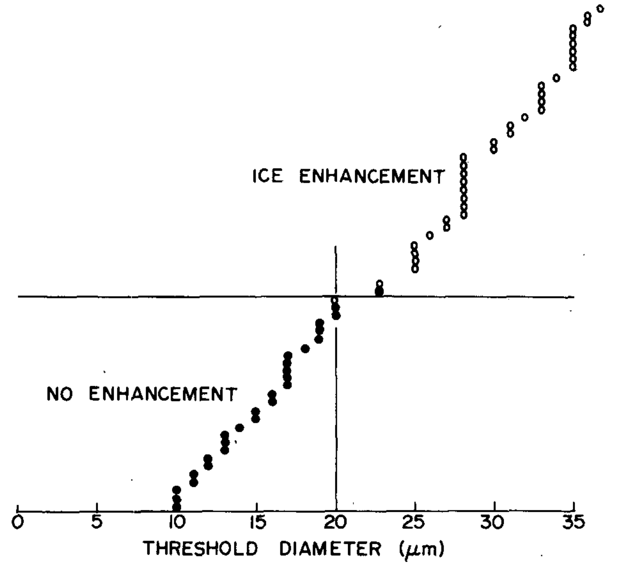

FIG. 1. Ice enhancement as a function of the threshold diameter (D_T) in cumulus clouds with top temperatures between −6° and −20°C. Solid circles denote no ice enhancement and open circles denote ice enhancement. Data from Hobbs and Rangno (1985).

centration of drops ≥ 20 μm in diameter or the D_T values. More importantly, this figure does not shed any new light. Thus, the two left-hand diagrams in TCI's Fig. 2 illustrate the onset of ice as the concentration of drops with diameters ≥ 20 μm increases (and, as discussed above, as cloud base temperatures increase). The two right-hand figures show that drops with diameters ≥ 20 μm can be present in clouds with a wide range of cloud top temperatures. Also, in the lower right-hand diagram, if one subtracts from the lines on the data points a length equivalent to $D_T = 20$ μm, it will be seen that the maximum ice particle concentration increases with increasing D_T. All of these points were noted by HR.

Telford et al. note that clouds with higher droplet concentrations tend to have both lower concentrations of large drops and lower ice particle concentrations. These points were made by Hobbs and Rangno (1984) and HR.

Telford et al.'s Fig. 5 is a replot of much of the data that is shown more clearly in HR's Fig. 5. HR's Fig. 5 shows a strong onset of high concentrations of ice particles [O(100 L^{-1})] as the concentration of droplets ≥ 20 μm diameter increases beyond ~20 cm^{-3}, followed by a more gradual increase in ice particle concentrations with increasing droplet concentration. It can be seen from TCI's Fig. 5 that clouds with top temperatures ≥ −15°C and base temperatures > −3°C generally produce droplets ≥ 20 μm in diameter in concentrations > 20 cm^{-3} near cloud top. This, in turn, produces high ice particle concentrations, as noted by HR.

We disagree with TCI's contention that ice particle concentrations remain approximately constant as the concentration of drops with diameter ≥ 20 μm decreases and cloud base temperature increases (represented by the downward sloping parallel lines in TCI's Fig. 5). This conclusion is based on the use of a subset of HR's data; it is not borne out by the larger dataset depicted on HR's Fig. 5. However, we do agree with TCI that more data is needed on this point, in order to further test their speculation.

There is insufficient data to support TCI's conclusions that ice particle concentrations near cloud top increase as cloud base temperature increases, and that the concentration of drops ≥ 20 μm *decreases* with increasing cloud depth. If these statements were true, they would, perhaps, be the most startling findings from the HR dataset. However, these conclusions are based on the subset of the HR dataset shown in TCI's Figs. 6 and 7. Again, as will be shown below, the conclusion is not supported by the complete dataset presented by HR.

Hobbs and Rangno identified two modes of glaciation. In the first, found in maritime cumulus clouds with a plentiful supply of large (≥20 μm diameter) drops, ice particle concentrations at cloud top increased rapidly to 10s per liter as cloud top temperatures fell to −4 to −6°C (open symbols in Fig. 2 of HR). For clouds with lower top temperatures, the ice particle concentrations continued to increase to hundreds per liter, although very gradually. This same behavior is seen when maximum ice particle concentrations are plotted against cloud depth for maritime clouds (Fig. 2), since these clouds have fairly uniform base temperatures. The data in TCI's Fig. 6 is restricted to cloud top temperatures ≥ −15°C. For cloud depths > 3 km, they show only four data points. Three of these are marked by crosses in Fig. 2, where it can be seen that they are not representative of the overall trend of the dataset for maritime clouds, which shows ice particle concentrations increasing slowly with decreasing cloud top temperature and increasing cloud depth. Use of the three data points marked by crosses in Fig. 2 led TCI to their erroneous conclusion concerning ice particle concentrations and cloud depth.

The second mode of glaciation identified by HR occurs in clouds with relatively high average droplet concentrations (>300 cm^{-3}) (half-filled and filled symbols in Fig. 2 of HR) and cold bases (≤0°C). In these clouds, ice particle concentrations steadily increased as D_T (near cloud top just before glaciation) increased. The dataset for these clouds shows a generally clear relationship of increasing ice particle concentrations with increasing cloud depth (Fig. 3).[1] The fourth data point

---

[1] Six of the data points in Fig. 3 (shown by open circles) do have unusually low ice particle concentrations. However, 4 out of these 6 clouds had very high drop concentrations (≥1000 cm^{-3}), which probably resulted in a narrow droplet size distribution (i.e., a small D_T value), 5 out of the 6 had cloud top temperatures (≥ −8°C) marginal for ice formation, and 5 out of the 6 formed in tropical air (θ_E > 330°K) far from its maritime source region.

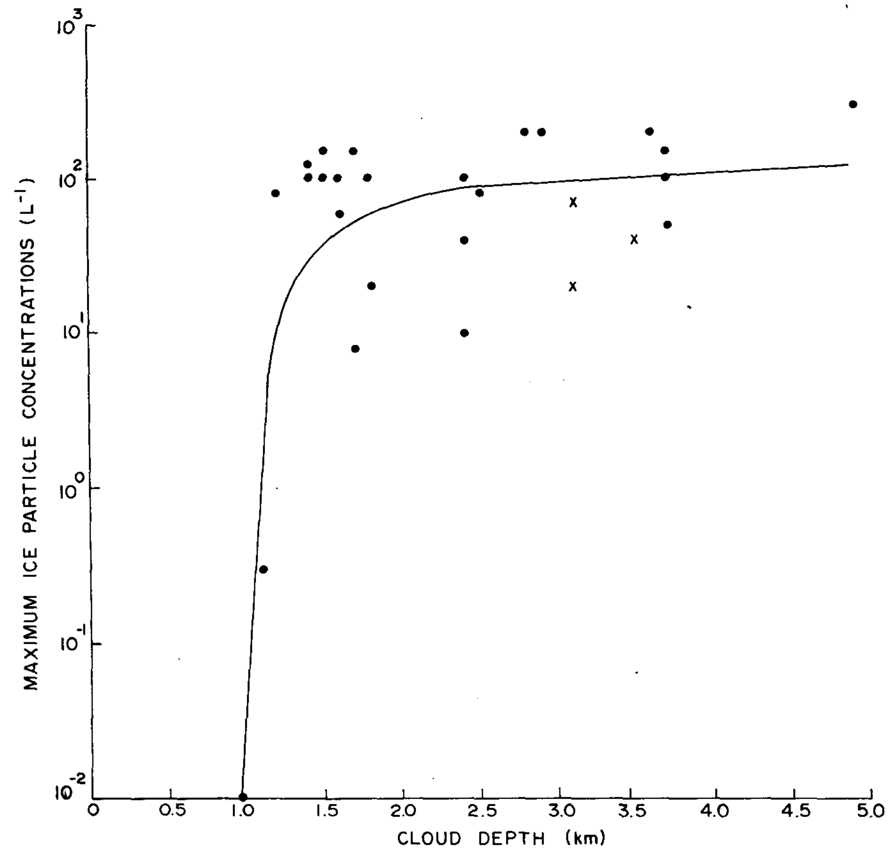

FIG. 2. Maximum ice particle concentrations vs cloud depth in maritime cumulus clouds (droplet concentrations ≤ 300 cm^{-3}). Crosses denote points used by TCI. Data from Hobbs and Rangno (1985).

for cloud depths > 3 km plotted in TCI's Fig. 6 is shown by an × in Fig. 3; it is also associated with a rather low concentration of ice particles.

Telford et al. question (surprisingly) whether the concentrations of cloud droplets with diameter $\geqslant 20$ μm generally increase with height above cloud base. This pattern is clearly demonstrated in HR's Fig. 28 for both continental clouds with droplet concentrations $\geqslant 800$ cm^{-3} and maritime clouds with droplet concentration $\leqslant 300$ cm^{-3}. There are some exceptions. For example, if the maximum concentration of droplets in a maritime cloud is very low ($\leqslant 100$ cm^{-3}), it clearly cannot produce a high concentration (>100 cm^{-3}) of 20 μm diameter droplets, no matter how deep the cloud. On the other hand, a quite shallow maritime cloud with a modest droplet concentration (≈ 250 cm^{-3}) may produce a relatively large number of droplets with diameter $\geqslant 20$ μm. Consequently, if one considers a highly heterogeneous sample of clouds (from the point of view of droplet concentration), the increase in concentration of large droplets with increasing cloud thickness may be masked (as it is in TCI's Fig. 7).

To reduce the masking effect of varying droplet concentration, we have selected data from Table 1 of HR,[2] where measurements of droplet concentrations were made at two or more heights above cloud base within the same general sampling region (i.e., Pacific coastal waters, Puget Sound, or Cascades and eastern Washington) where droplet concentrations are relatively uniform. Shown in Fig. 4 is the concentration of droplets $\geqslant 20$ μm diameter as a function of height above cloud base for these cases. These data reveal (as expected) a general increase in the concentration of 20 μm diameter droplets with increasing height above cloud base.

Entrainment and ice enhancement

Telford et al. attempt to explain the preferential occurrence of ice enhancement in maritime cumuliform clouds by hypothesizing that entrainment is less vigorous in these clouds than in continental cumuliform clouds and that less vigorous entrainment leads to a broader droplet size distribution and higher ice particle concentrations. It should be noted that this argument appeals to the role of large droplets in ice enhancement (i.e., the HR criterion).

Hobbs and Rangno postulated that entrainment plays an important role in ice enhancement, but

---

[2] The cloud base temperature and cloud depth for the 27 March 1980 entry in HR's Table 1 should have read 1°C and 1.6 km.

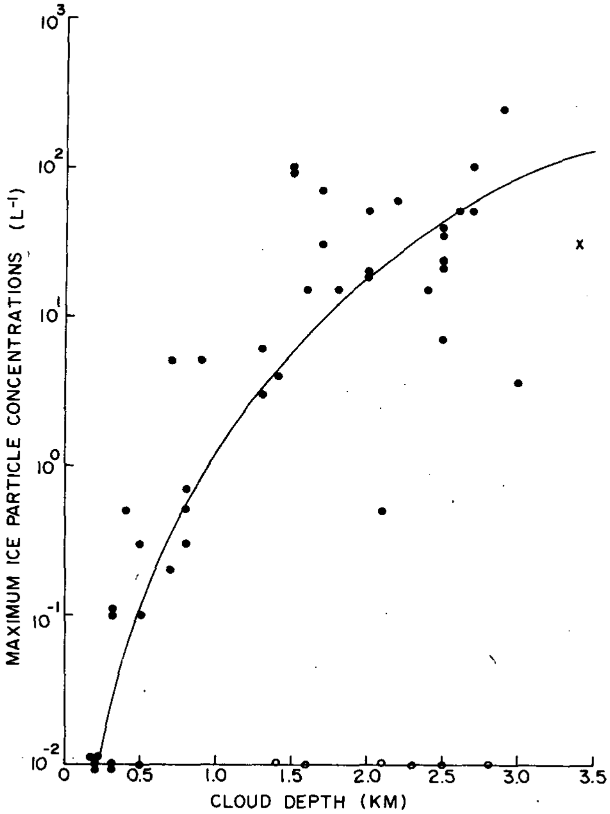

FIG. 3. Maximum ice particle concentrations vs cloud depth for continental and transitional cumulus clouds (droplet concentrations > 300 cm^{-3}). Small open circles denote cases not considered in curve fit (see text). Cross denotes data point used by TCI. Data from Hobbs and Rangno (1985).

through a quite different mechanism than that proposed by TCI. Since entrainment of dry air at cloud top will cause some droplets to evaporate (and cool) and there will be a flux of aerosol particles to these droplets, we suggested that this might cause numerous droplets to freeze through contact nucleation.

TCI's proposed mechanism for ice enhancement

TCI and Telford (1986) propose a mechanism by which ice enhancement might occur near the melting level. This mechanism involves the break up of ice particles during melting and refreezing. We join with Mossop (1986) in questioning that this type of mechanism could produce ice enhancement ratios on the order of 10^3. We also admit to considerable skepticism that Faraday's (1860) liquidlike layer on ice plays any role at all in ice enhancement.

Concluding remarks

The data base on the occurrence of ice enhancement in natural clouds is now sufficiently great to provide fertile ground for speculations as to the mechanism(s) that might be responsible for this phenomenon. However, the data base is still insufficient to provide critical tests of these hypotheses. The time is now ripe to mount field programs designed to test specific hypotheses, such as those proposed by Hobbs and Farber (1972), Hallett and Mossop (1974), Mossop and Hallett (1974), Mossop (1978), HR and TCI.

If, as both we and TCI have postulated, entrainment plays an important role in ice enhancement, as it may also do in the development of cloud droplet size distributions (e.g., Telford and Chai, 1980; Baker and Latham, 1982), we could be on the brink of a unifying theory for several long-standing mysteries in cloud microphysics.

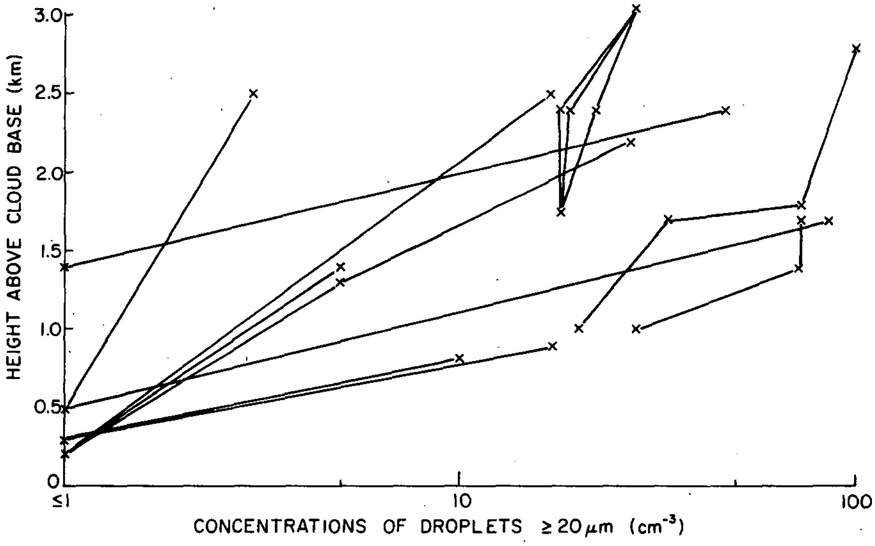

FIG. 4. Concentration of cloud droplets ≥ 20 μm in diameter versus height above cloud base for cumulus clouds. Data from Hobbs and Rangno (1985).

Acknowledgments. Our studies of ice in clouds are supported by the Atmospheric Research Section of the National Science Foundation under Grant ATM-8609376.

REFERENCES

Baker, M., and J. Latham, 1982: A diffusive model of the turbulent mixing of dry and cloudy air. *Quart. J. Roy. Meteor. Soc.,* **108,** 871–898.

Faraday, M., 1860: Notes on regeletion. *Proc. Roy. Soc. London,* **10,** 440–450.

Fletcher, N. H., 1962: *The Physics of Rainclouds.* Cambridge University Press, p. 115.

Hallett, J., and S. C. Mossop, 1974: Production of secondary particles during the riming process. *Nature,* **249,** 26–28.

Hobbs, P. V., and R. Farber, 1972: Fragmentation of ice particles in clouds. *J. Rech. Atmos.,* **6,** 245–258.

——, and A. L. Rangno, 1984: Ice particles in marine and continental clouds. *Proc. Ninth Int. Cloud Physics Conf.,* Tallinn, Estonia, Vol. 1, 71–72.

——, and ——, 1985: Ice particle concentrations in clouds. *J. Atmos. Sci.,* **42,** 2523–2549.

Mossop, S. C., 1986: Reply to Telford's Comments. *Quart. J. Roy. Meteor. Soc.,* **112,** 558–559.

——, 1978: The influence of drop size distribution on the production of secondary ice particles during graupel growth. *Quart. J. Roy. Meteor. Soc.,* **104,** 323–330.

——, and J. Hallett, 1974: Ice crystal concentration in cumulus clouds: Influence of the drop spectrum. *Science,* **186,** 632–634.

Telford, J. W., 1986: Comments on "Microphysical properties of supercooled cumulus clouds in which an ice particle multiplication process operated". *Quart. J. Roy. Meteor. Soc.,* **112,** 555–558.

——, and S. K. Chai, 1980: A new aspect of condensation theory. *Pure Appl. Geophys.,* **118,** 720–742.

——, —— and S. Ionescu-Nissov, 1987: Comments on "Ice particle concentrations in clouds". *J. Atmos. Sci.,* **44,** 902–909.