SURFACE SOURCE OF ICE PARTICLES IN MOUNTAIN CLOUDS

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1. BACKGROUND

This paper focuses on wintertime orographic clouds not associated with major synoptic disturbances, but formed by strong winds across major barriers. Such clouds constitute a major source of precipitation in many regions of the world and are frequent targets of cloud seeding activities aimed at increasing the mountain snowpack. For these reasons such clouds have been extensively observed and modelled. However, these systems are no exception to the general difficulty of predicting the concentrations of ice particles that form in them at different temperatures. The most frequently made assumption is that ice particle concentrations follow ice nucleus concentrations, which in turn are assumed to be an exponential function of temperature. This assumption is justified by the absence of processes of secondary ice generation and the relatively simple dynamics of these clouds. Yet, it is known that the observed ice concentrations vary over large ranges and are not well predicted by available models.

2. OBSERVATIONS OF SURFACE SOURCES OF ICE

The data to be here presented provide one explanation for unexpected ice concentrations. With the help of the Wyoming Cloud Radar (WCR) carried on the Wyoming King Air (WKA) aircraft, observations have been obtained that provide direct evidence for significant input to ice concentrations from surface sources.

The WCR operates at a wavelength of 3 mm, has a 0.7° beam angle and 15...45-m rangegate spacing. Data used in this paper was collected using antennas pointed upward and downward from the aircraft so that a vertical cross-section is obtained in a plane containing the flight track. The downward pointing beam provides data right to the surface; data that cannot be obtained by other observational systems with comparable resolution.

The minimum detectable signal is about -25 dBZ (at 1 km range). Because of small droplet sizes and low liquid water contents in the sampled clouds, the radar echoes are due almost entirely to scattering by ice crystals and regions with only liquid and no ice particles are not detected.

Flights were carried out over the Medicine Bow Range (41°N; 106° W) in southeast Wyoming during Jan-Feb 2006. The mountain range has a dominant N-S axis, but contains additional minor peaks. The highest point of the range is about 1500 m above the valley to the West from where the dominant windflow is.

The first example, shown in Fig. 1, has two cloud layers. The lower one had its base, estimated from the upwind sounding, at 2.9 km and echo top that increased from about 4 to 5 km as the mountain slope rose. The upper cloud appears to be a wave that dips down into the lower cloud just downwind of the mountain crest. The aircraft at its 4260 m flight level was out of cloud until just a kilometer W of the crest. Beyond that point, the in situ data indicated ice concentrations up to 50 L^{-1} over 7 km of flight and max. 0.1 g m^{-3} of LWC over a 1 km stretch. Temperature and wind information are included in the figure. Wind direction was within 15° of the plane depicted in the figure.

The radar echo reveals the main message: there is a deepening layer of echo hugging the surface right up to the crest. Beyond the crest, the upper and lower echoes merge. A notable feature of the echo in the surface layer is that the highest values tend to be found near the ground and reflectivities decrease with height.

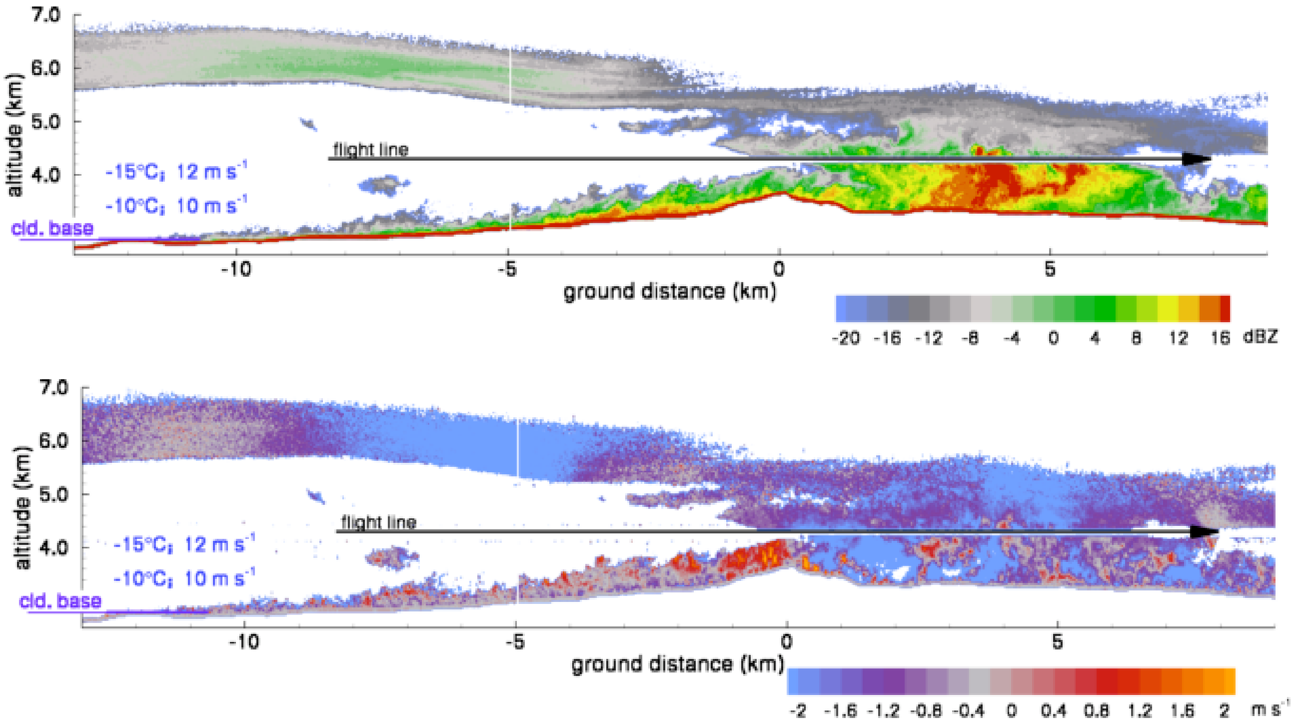
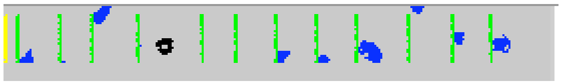


Fig.1. Reflectivity (upper panel) and vertical Doppler velocity (lower panel) for a vertical section across the mountain range from pass at 22:22 – 22:31 on Jan 27, 2006. Images are shown with 1:1 axis proportions. Wavy line at the bottom of the images delineates the ground.

The large-scale pattern in the vertical velocity data reflect the wave motion of the upper layer and the orographic forcing in the lower cloud. Superimposed on that one can see a considerable degree of turbulence in the boundary layer. The measured Doppler velocity is a sum of the air velocity and the fall velocity of the scatterers. For small ice crystals the fall velocity is 0.5...1 m s-1; so that areas with the grey to the warm colors represent likely upward air velocities. Large patches of significant upward velocities are apparent in the surface layer upwind of the peak, and again downwind. Just upwind of the ridge the upward velocities approach 2 m s^{-1}.

In looking at the images in Fig. 1. it should not be forgotten that the area below flight level down to the surface is mostly filled with cloud even though the reflectivity is below the minimum detectable signal. The cloud is visible on the video images from the cockpit. The frame shown here was taken from about the -14 km position; the leading edge of the cloud is seen, as well as trees, and the snow covered ground in the clrearcut patches.

Right upon cloud entry, the detected crystals were (from the 2D-C imaging probe) irregular in shape and roughly 150 to 200 μm in size:



In this image, the vertical dimension of the strip is 800 μm.

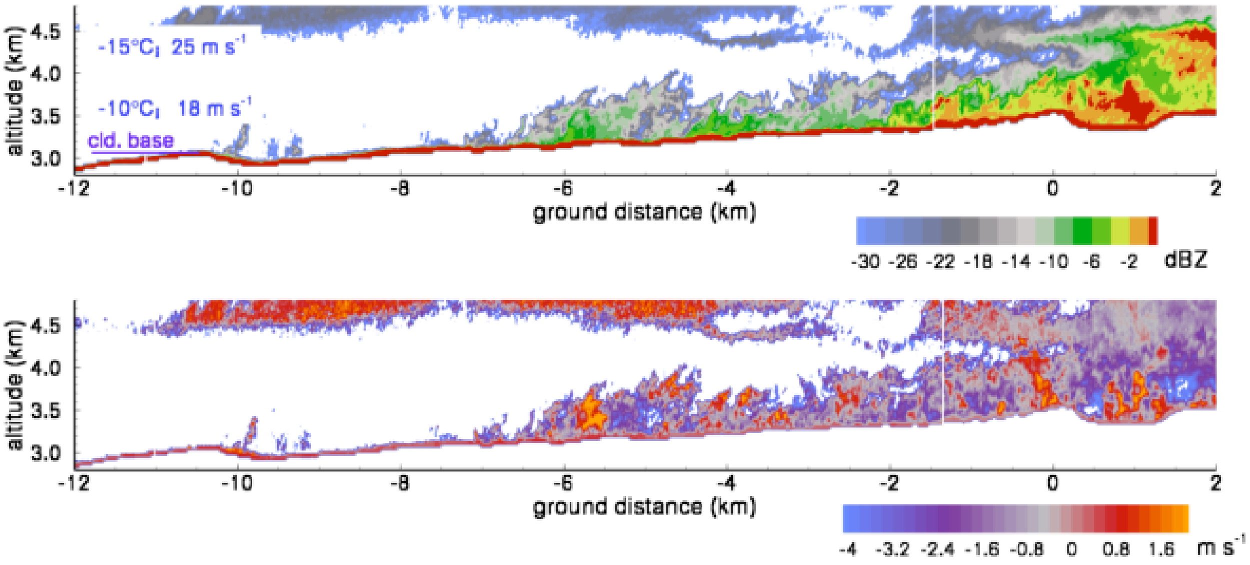


Fig. 2. Similar to Fig. 1 but for Jan. 18, 2006, 22:09-22:22 pass. Upper panel shows reflectivity (dBZ) and the lower panel the vertical Doppler velocity (m s^{-1}). The flight altitude was 4.8 km, and the images shown are from the nadir pointing antenna.

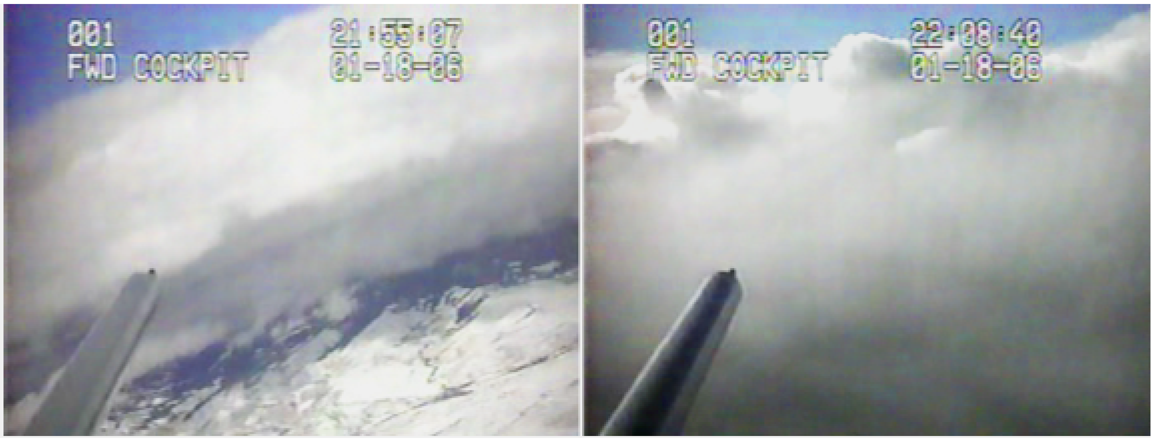


Fig. 3. Upwind and downwind views of the cloud sampled during the pass depicted in Fig. 2.

A second example of radar echoes hugging the mountain surface is shown in Figs. 2 and 3. Wind speeds were higher on this day than for the case shown in Fig. 1; cloud base height and temperatures were not much different. Both the sounding and the photographic evidence point to somewhat more instability and the development of convection. The surface echo also exhibits more plume-like appearance. However, the main characteristics are the same: more intense echoes near the surface and upward air motion coincident with reflectivity plumes. Probably because of the higher wind velocities and shear, another important aspect is apparent in this example, namely that the plumes have convex curvatures (slopes decreasing with height). That pattern, for wind that increases with altitude, is consistent only with a rising plume; a fall-trail would have concave curvature as is seen for cirrus trails and other precipitation shafts in wind shear.

At flight level, LWC of about 0.2 gm^{-3} was encountered, together with 1...5 L^{-1} of small (<200 μm) irregular ice crystals, over the stretch between -11 and 3 km ground distance (0 km marks the ridge). That was followed within about a kilometer by a transition to ice concentrations of about 20 L^{-1} with sizes up to a millimeter. That transition corresponds to the merging of the echo near the surface and the upper level echo.

3. WHAT GOES ON?

The evidence is strong that radar echoes are generated near the surface. The radar's sensitivity to ice, the decreasing reflectivity with altitude, and the inhomogeneity of the echo, argue against the possibility that the echoes are due to liquid cloud condensing. We also know from other cases that droplet clouds are not detected by the radar along the mountain slope due to the low LWC that develops. Thus, it seems certain that the surface echoes are due to ice particles.

There is support for the conclusion of the preceding paragraph in the observations reported by Rogers and Vali (1987; RV87). Ice concentrations measured at the Elk Mountain Observatory when the Observatory was inside mountain clouds (cap clouds) were about two orders of magnitude larger than those measured about 1 km above the Observatory during aircraft passes through the same clouds. That difference was evident at temperatures ranging from -5ºC to -25ºC, with a slight indication that stronger winds are accompanied by higher concentrations.

The vertical gradient of reflectivity, the association with upward motions, and the curvatures of the plumes provide strong support for the assumption that the origin of the ice is at the surface and that an upward transport of this ice is involved.

Given those characteristics, the most ready explanation for the echoes would seem to be that snow is being lofted from the surface. Blowing snow is a well-known phenomenon and has extensive literature documenting its characteristics. There is broad agreement that the mass concentration of blowing snow decreases exponentially with height above the surface and that the size distributions shift toward smaller and smaller particles with increasing height. Using data from the few studies that report size distributions of blowing snow (Schmidt, 1972, 1982; Nishimura and Nemoto, 2005; Nishimura, private communication) we estimate the radar reflectivity during blowing snow conditions at 10 m altitude (the maximum for which such data are available) to be between -20 and -10 dBZ. Extrapolating to altitudes consistent with the observed echoes in Figs. 1 and 2 would yield -30 to -20 dBZ at 100 m, and -35 to -25 dBZ at 300 m. These are lower than the observed values. However, the comparison is really not satisfactory since the blowing snow observations are taken under conditions when the lofted snow rapidly sublimates, whereas the conditions of our observations are with a supercooled cloud present. The presence of the cloud no doubt assures that snow particles can survive and grow, subject only to the limitation imposed by fallout. We have no good basis to estimate what to expect under such conditions.

There is one factor that casts somewhat of a doubt on the viability of the blowing snow explanation: no surface echoes have been observed where the mountain surface is below cloud base, not even in the range (to the extent that we can determine that from available data) where ice supersaturation can be expected.

None of the other possible explanations suggested in RV87 can be confirmed or discounted by the new observations. These include rime shedding from trees, generation of new ice crystals during riming, or the activation of ice nuclei in regions of high temperature and vapor pressure gradients.

The main novelty from the current observations is the definitiveness of the diagnosis of ice crystal lofting from or near the surface into clouds. The radar evidence indicates that the surface sources are not uniform, but show some relation to surface features such as small local ridges and increased slope; the echo layer is definitely within a turbulent boundary layer. The echoes also show that many of the ice particles fall back to the surface. Apart from the smaller-scale turbulence, there is a monotonic increase in the depth and intensity of the surface echo with distance along the mountain slope. This could be an indication that (i) the boundary layer is deepening, though there is no strong reason to think that that should happen, (ii) that the process of ice generation somehow depends on the sizes of cloud droplets, (iii) that rime intensity on trees is a factor, (iv) that the amount, or state of the snow on the surface is important, or (v) something less evident.

4. IMPLICATIONS

The findings here presented demonstrate the phenomenon of surface origin of ice crystals only in a qualitative sense and without delineating the range of conditions under which it is operative.

The most evident consequence of the findings is that models, and predictions, of ice crystal concentrations for clouds that are in contact with mountain surfaces have to take into account the surface source as well. Since, the quantitative aspects of this phenomenon are not yet known, a large uncertainty is introduced. It can be expected that the process alters the quantity and distribution of snow over a mountain barrier. The cases shown in this paper indicate spreading of the surface generated ice into the main part of the cloud at points downwind of the ridge. Other cases suggest, albeit less clearly, that even the upwind portions of the cloud can ingest plumes of ice from the surface.

For cloud seeding projects which aim at increasing snowpack from mountain clouds, the surface source represents a competition with the artificial ice nuclei introduced into the cloud. Supercooled liquid is depleted, or is prevented from forming by the increased concentrations of ice crystals. It is premature to estimate the potential magnitude of this effect.

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