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ICE INITIATION IN WISP SHALLOW UPSLOPE CLOUDS

by

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1. Introduction

The initiation of ice in the atmosphere remains one of the fundamental unanswered questions in cloud physics today (Cooper 1991). The initiation and subsequent growth of ice crystals leads to much of the world's precipitation. The diffusional growth of ice depletes water vapor, while riming growth depletes cloud droplets. Thus, ice plays an important role in the redistribution of both vapor and cloud water within a cloud system. The Winter Icing and Storms Project (WISP) recently completed a major field program (WISP94) during the winter of 1993-94 focussed on the initiation of ice in winter storms, and its role in the production and depletion of supercooled liquid water. An instrument test program, called WISP Instrumentation Test (WISPIT), was conducted the year prior to the main field program in order to test some of the critical instrumentation planned for use during WISP94. Both programs focussed on two main cloud types, wave clouds forming over orographic terrain and shallow upslope clouds forming when cold continental air moves southward over the High Plains. The location of these projects is shown in Fig. 1. In this paper we address two main questions on ice initiation in shallow upslope clouds: 1) the cause of the one to two order of magnitude variation in crystal concentration observed at a given temperature (Cooper 1986), and 2) the relationship between ice nuclei concentration and ice crystal concentration. We will consider one case in detail, and then compare the detailed case study to the upslope cases observed during WISP and attempt some generalization.

2. 24 February 1993 Case Study

A shallow upslope cloud formed in the Front Range region of Colorado on 24 February 1993 (Fig. 1), causing wide-spread cloudiness. Two aircraft flights were conducted during this event using the NCAR King Air as part of the WISPIT program. In Fig. 2 we present vertical profiles of temperature, liquid water content, ice crystal concentration, wind speed and direction, θ_e, and condensation nuclei concentration from the aircraft during a missed approach to Greeley (GXY) (for location see Fig. 1). The ice crystal concentration was calculated from 2D-C data only considering crystals larger than 150 microns in order to avoid spurious counts from large cloud droplets.

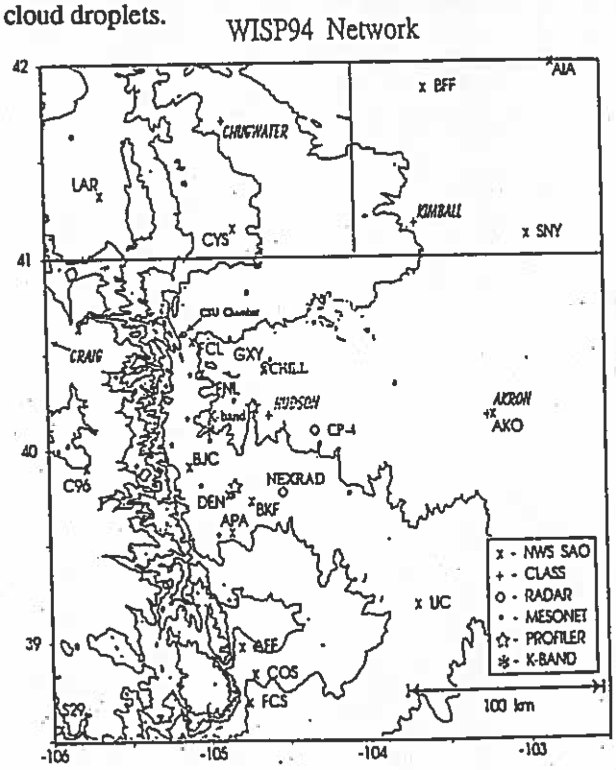

Figure 1 WISP94 Project Area. Latitude and Longitude in degrees. Terrain elevations at 1000 ft intervals starting at 5000 ft MSL in the eastern half of the area.

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The data clearly reveal the presence of two thermodynamically and microphysically distinct cloud layers. The upper layer is located between 1.8 and 2.4 km, and contains FSSP measured liquid water over 0.4 gm^{-3}, and no measurable ice crystals greater than 150 μm in size (Fig. 2a). The lower layer is separated from the upper layer by a temperature inversion and is located below 1.8 km down to the ground. This lower layer contains low values of supercooled liquid water (less than 0.05 gm^{-3}), and approximately 1-2 L^{-1} of ice (Fig. 2a). The temperature in the lower layer ranges between -8 and -9° C, while the temperature in the upper layer ranges from -7 to -10° C (Fig. 2a). The lower layer also contains higher CN counts than the upper layer (Fig. 2b), and lower ozone concentration (not shown). The wind speed in the lower layer is nearly constant at 4-5 m s^{-1} from the east, while the wind in the upper layer increases from 3 m s^{-1} northeasterly at 1.8 km MSL to nearly 9 m s^{-1} north-northwesterly at the top of the layer (Fig. 2c). The vertical profile of θ_e in the lower layer is only weakly stable, suggesting that this layer can be associated with the atmospheric boundary layer (Fig. 2b). The high value of CN also supports this suggestion. The most remarkable feature of this cloud, however, is the two layer structure in the ice crystal concentration, with ice crystals up to 2 L^{-1} in the lower cloud layer, and no measurable ice crystals in the upper layer, all in a cloud system with temperatures no colder than -10° C. A similar structure was observed in the 1990 St. Valentine's Day shallow upslope storm (Rasmussen et al. 1995) (Table 1). During that study, however, no ice nuclei measurements were made, preventing us from establishing any link to the vertical distribution of ice nuclei. During WISPIT and WISP94 ice nuclei measurements were made via in-situ bag sampling and in-situ filter sampling, as well as some ground-level sampling at the Colorado State University Cloud Simulation and Aerosol Laboratory. On 2/24/93 an in-situ bag sample was collected above the cloud top near the end of the flight. The aircraft landed at Fort Collins/Loveland Airport following the mission, and the bag sample processed within two hours using a Continuous Flow Diffusion Chamber (Rogers 1988) and an expansion cloud chamber (DeMott and Rogers 1990). Losses to the side-walls of the bag were slight and have been accounted for. Results of this analysis are given in Table 2 for 2/24/93 as well as from upslope days during WISP94. The in-situ filter sample was processed by Jan Rosinski in a thermal diffusion chamber (Langer and Rogers 1975) at the approximate temperature of the cloud. In the current case we have

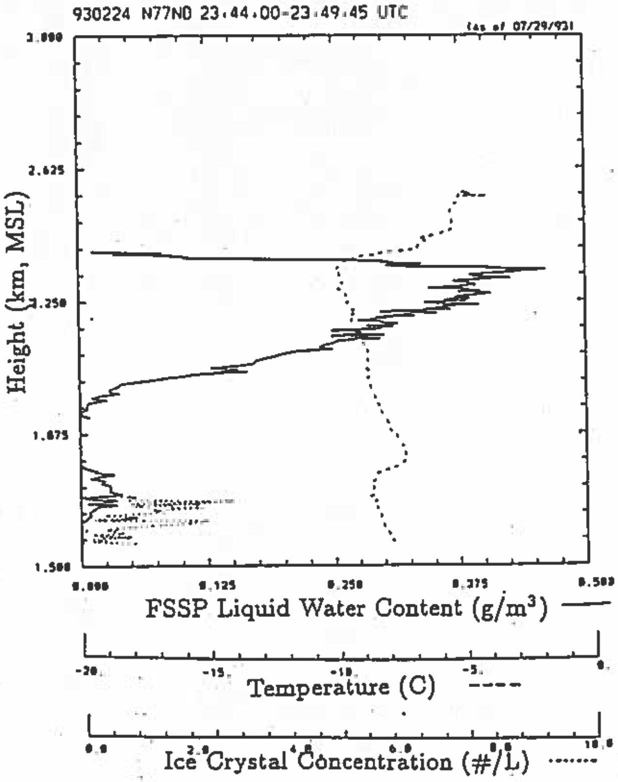

Figure 2a.

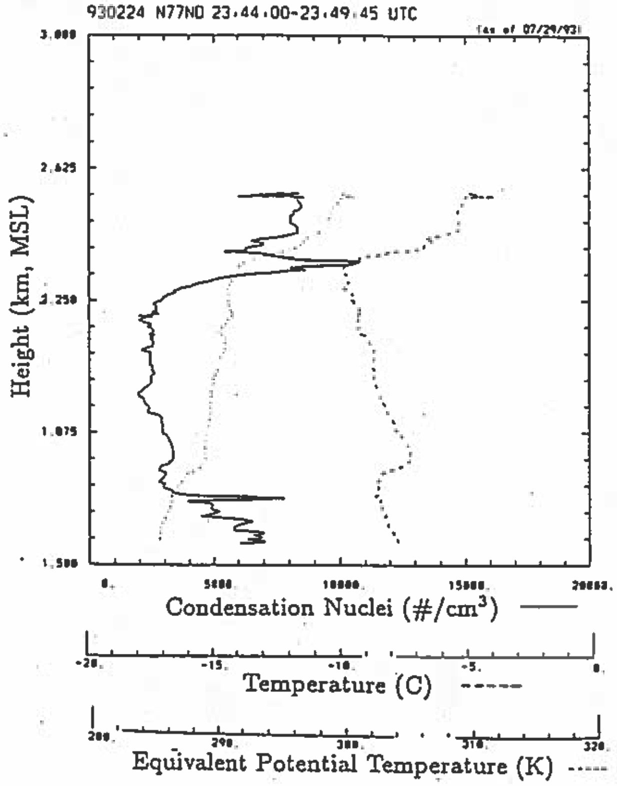

Figure 2b.

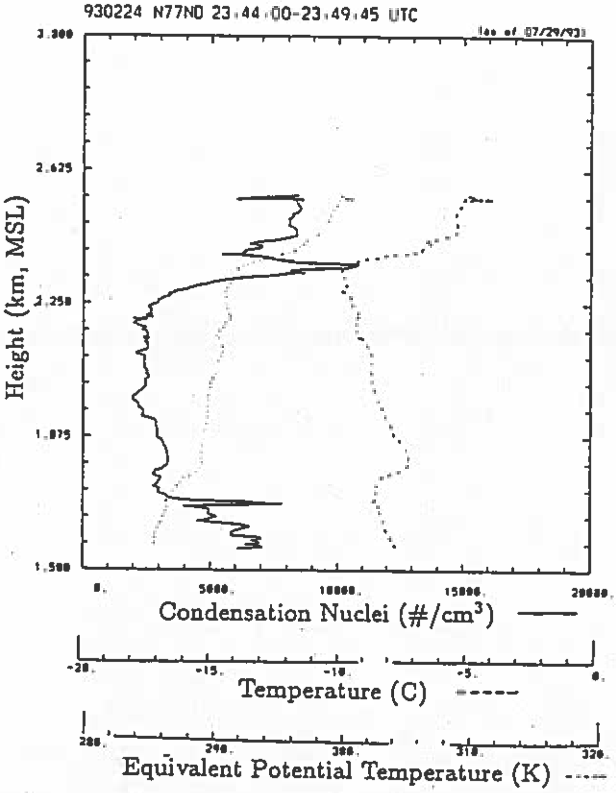

Figure 2c.

ice nuclei data from filter sampling and the CFD (both ground and airborne samples) (see Table 2).

A ground sample was obtained at Fort Collins at 0034 UTC, and processed by the CFD. The concentration of ice at the surface near Fort Collins was 0.84 L^{-1} at -16.7^0 C, water saturation from the CFD chamber. Since the processing temperature was nearly 7^{0}C colder than the cloud, actual ice nuclei concentration at the cloud temperatures (-7 to -10^0 C) is likely much less than the observed ice crystal concentration (1-2 L^{-1}). Since Fort Collins was located on the west side of the storm, this sample may not be representative of the air producing upslope cloud near Greeley (located 50 km east of Fort Collins) (Fig. 1). The high values of ice in the lower layer suggests that the boundary layer was sufficiently turbulent to provide a continuous source of ice nuclei to that layer.

The bag sample collected above cloud was processed by the CFD at a temperature of -16.8^0 C, and the filter sample at -10.5^0 C. The Rosinski filter processing technique found an ice nuclei concentration above cloud of 0.9 L^{-1} at -10.5^0 C, while the CFD processing found 1.13 L^{-1} at 16.8^0 C, both at water saturation.

The lack of ice in the upper layer suggests that the flux of ice nuclei into the layer from aloft or below was insufficient to keep up with the depletion of ice nuclei through ice crystal nucleation and subsequent growth and fallout. The temperature inversion at 1.8 km MSL likely inhibited the flux of ice nuclei from below, while the strong inversion at 2.4 km (Fig. 2a), likely limited the flux of ice nuclei from aloft (through entrainment and mixing). A calculation of Richardson number near cloud top using the aircraft data gives a value of 3.1, indicating a dynamically stable layer. Thus, the upper layer was relatively isolated from ice nuclei sources both above and below the layer, consistent with the low concentration of ice observed. Flux calculations of ice nuclei into the upper layer will be required to quantify this further.

Table 1
Summary of Aircraft Microphysical Observations in WISP Upslope Storms

			Upper Cloud Layer					Lower Cloud Layer				
Date	A/C	Time Period/UTC	Thickness (m)	Temp Range (° C)	Ice Crystal conc (#/L)	Max Liquid Water content (gm^{-3})	Precip Type	Thickness (m)	Temp Range (° C)	Ice Crystal conc (#/L)	Max Liquid Water content (gm^{-3})	Precip Type
2/13/90	W	1700–1915	800	-12 to -14	0.0	0.15	water	800	-8 to -14	4-5	0.05	ice
2/24/93	N	2344–234945	600	-7 to -10	0.0	0.45	water	225	-8 to -9	1-2	0.03	ice
2/7/94	E	1905–192030	200	-13 to -14	0	0.13	ice	300	-13 to -14	1-5	0.01	ice
2/8/94	E	1704–171030	200	-17 to -5	3-6	0.16	ice	500	-14 to -18	5-15	0.04	ice
2/8/94	W	2230–223430	350	-12	0.4	0.3	ice	700	-11 to -14	4-5	0.0	ice
2/19/94	W	221500–222000	–	–	–	–	–	200	-2° C	0	0.25	water
2/21/94	W	213600–214000	–	–	–	–	–	600	-5 to -10	1-3	1.0	freezing drizzle
2/22/94	W	203400–204900	–	–	–	–	–	100	-5 to -10	0.4	0.05	ice
2/28/94	W	175000–180900	350	-2 to -3	0.5	0.45	drizzle	250	-2 to -3	0.5	0.2	freezing drizzle
3/6/94	E	1433–1441	800	-5 to -11	0.4 to 0.8	0.2	graupel	600	-3 to -6	1-5	0.35	freezing drizzle
3/7/94	E	210000–210600	700	-8 to -10	0.4	0.05	unknown	600	-8 to -10	2-4	0.375	graupel
3/12/94	E	1526–1530	900	-7 to -10	0	0.02	water	500	-5 to -8	0.1	0.25	graupel

W – Wyoming King Air
N – NCAR King Air
E – NCAR Electra

Table 2

Date	Sample Time (UTC)	Above or Below Cloud	Type of Processing	Bag or Filter	Ice Nuclei Concentration #/L)	Processing Temperature ° C)	Water Supersaturation (%)
2/24/93	005318	Above	CFD	Bag	1.13	-16.8	1.9
2/24/93	003400	Below	CFD	Ground Sample	0.84	-16.7	0.1
2/24/94	005318	Above	Rosinski TDC	Filter	0.9	-10.5	1
2/8/94	195532	Above	CFD	Bag	0.35	-15.6	6.7
2/8/94	194719	Below	CFD	Bag	0.09	-15.6	6.8
3/6/94	183300	Above	CFD	Bag	0.0	-11.3	4.1
3/7/94	211135	Above	CFD	Bag	1.7	-9.6	1.5
3/7/94	205633	Below	CFD	Bag	0.63	-9.7	1.4
3/12/94	150030	Above	CFD	Bag	0.31	-11.5	3.1
3/12/94	151312	Below	CFD	Bag	0.1	-11.3	2.8

3. Comparison to Results from WISP90 and WISP94

As mentioned above, the two layer thermodynamic and microphysical structure described above is very similar to the structure of the shallow upslope cloud occurring 12-14 February 1990 during WISP90 (Rasmussen et al. 1995) (Table 1). Low ice crystal concentrations were also observed in the upper layer, with 1-5 L^{-1} ice crystal concentration in the lower layer. The lower layer was also well-mixed thermodynamically, and contained low values of supercooled liquid water. In contrast to the current case, the Richardson number near the top of the upper layer was less than 0.25, suggesting that the upper layer was dynamically unstable, and could have had a large flux of ice nuclei into the layer. The low ice crystal concentrations observed suggested that the concentration of ice nuclei may have been low above cloud top in this case. No ice nuclei measurements were available during WISP90, however, to confirm this suggestion.

In order to generalize this conceptual model further, we analyzed the vertical structure of 10 shallow upslope events observed during WISP94 using data from the NCAR Electra and the Wyoming King Air aircraft. Bag samples and ice nuclei filters were also collected with the Electra. Of the 10 upslope events sampled, 7 had a double layer structure, while the remaining 3 did not. Table 1 summarizes the depth, temperature range, ice crystal concentration, and maximum liquid water content in both the upper and lower layers. The upslope clouds on 2/19/94, 2/21/94, and 2/22/94 only contained a lower, well-mixed boundary layer.

4. Conclusions

The aircraft vertical profiles obtained during 12 shallow upslope storms during WISP90, WISPIT, and WISP94 show the presence of a two layer structure in 9 cases. The lower layer is near neutral stability, and contains low values of supercooled liquid water and relatively high concentrations of ice crystals. The upper layer is usually thermodynamically stable, and contains higher amounts of supercooled liquid water and relatively lower ice crystal concentrations. The above described vertical structure is consistent with the lower layer having as its source for ice nuclei the surface, with eddy transport providing a sufficiently rapid vertical flux of ice nuclei to maintain the observed concentration against depletion by fallout. The lower ice crystal concentration in the upper layer is consistent with the upper layer being dynamically isolated from the lower layer, and the overlying airmass being either dynamically isolated, or containing lower ice nuclei concentration. In most cases, the temperature of both the upper and lower layers are nearly the same, providing a significant source for ice crystal variation at a given temperature. In the future we plan to determine ice nuclei fluxes to the upper and lower layers with the hope of determining if ice nuclei concentrations can explain the observed ice crystal concentrations. We also plan on analyzing filter samples for various nucleation mechanisms for the WISPIT and WISP94 cases shown in Table 2.

5. Acknowledgements

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