THE RIME RIVER

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ABSTRACT

On January 10th, 1995 two unique rime flow events occurred at the Arizona Snowbowl near Flagstaff, Arizona. A heavy accumulation of rime ice thawed rapidly from rock, tree and snow surfaces. The loosened rime feathers tumbled down the starting zone and coalesced into either channeled or sheet flows. The rime flows displayed many of the characteristics of earthen debris flows but were not accompanied by significant amounts of free water. The rime flows interfered with skiing and the Snowbowl staff was forced to close runs and manage the event during the entire day of the 10th. The rime flows were apparently triggered by a rapid temperature increase associated with subsiding air from aloft. The loosened rime was further mobilized by high velocity winds.

KEYWORDS: snow and ice, rime, avalanche types, avalanche mechanics

1. FUNDAMENTALS OF RIME ICE FORMATION

"Rime" is the term applied to a frosting-like coating of ice that accumulates on objects in the environment under certain atmospheric conditions (Figure 1). Conditions are favorable for rime ice formation when supercooled droplets of liquid water form in a nearly saturated, to oversaturated, atmosphere (Fletcher, 1969; Knight, 1967; Rauber & Grant, 1981). As wind brings this air in contact with various objects (trees, rocks, snow crystals, radio towers, aircraft, etc.), nucleation occurs and "rime ice" freezes onto the objects. Rime grows away from the nucleating object into the direction of the wind by continued accumulation of ice (Langmuir, 1948; Macklin, 1962). Rime ice is often made up of discrete polycrystalline units referred to as "rime feathers" (Figure 6). The formation of rime ice presents serious problems to aircraft and exposed communications equipment (Schuab Jr., 1981).

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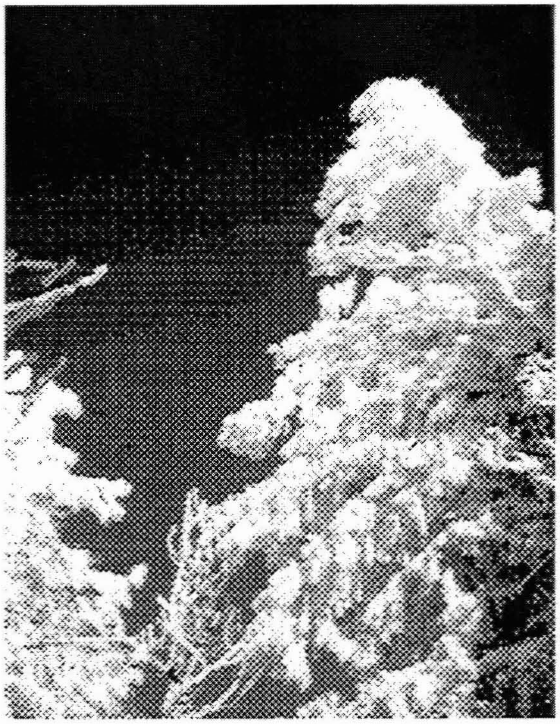

Figure 1. A tree freshly coated with rime ice.

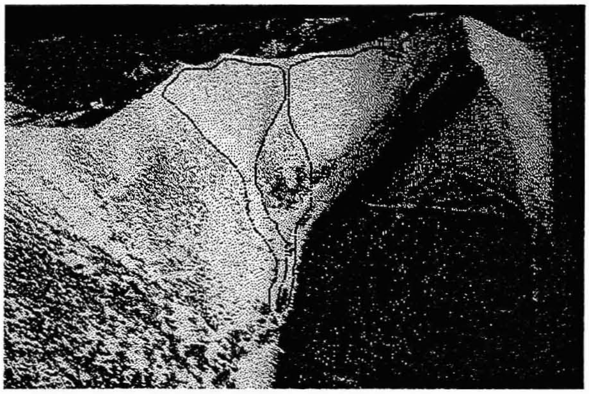

Figure 2. An oblique photo of Upper Bowl taken from the west. Sundance Bowl is outlined on the left and Bigbowl is outlined on the right.

2. OVERVIEW OF THE RIME FLOW EVENTS

On January 10th 1995, we observed and documented a unique natural phenomenon involving rime ice at the Arizona Snowbowl ski area located 15 km (9 mi) north of Flagstaff Arizona. Two "rime flows" released and ran in adjacent paths. Accumulated rime feathers thawed rapidly, thus freeing them from their nucleating surfaces (Figure 2). High velocity winds assisted in the mobilization of the loosened rime. Both flows remained active for over 12 hours, perhaps as long as 16 hours.

The events were constrained to a short two-day time window between two rime-producing storms. The flows were monitored by several Snowbowl employees and recorded on videotape. Ski Area Operations personnel at the Arizona Snowbowl had to construct a snow dam to contain the accumulating rime, which interfered with skiing.

3. FLOW DIMENSIONS AND TERRAIN CHARACTERISTICS

The major sources of the rime ice involved in the flows originated in two topographic bowls (Sundance Bowl and Bigbowl) ranging in elevation between 3660 m (12000 ft)(local ridge-top elevation) and about 3300 m (10800 ft). Local timberline is at 3500 m (11500 ft) so the initial nucleating objects for the rime consisted of a mixture of trees, rocks and the exposed snow surface itself (Figure 2). The aspects involved were west and southwest. A northwest aspect is also present within the ski area boundary but that aspect was either free of rime or the rime was not loosened sufficiently on that exposure. The slope angles ranged from 38° in the starting zones to 21° at the terminus of the flow.

Figure 3. A frame captured from video showing a fan composed of rime feathers with two entrenched gullies above in the top portion of the photo. The foreground field of view is approximately 10 m (33 ft).

The terrain configuration concentrated the flows from the starting zones into two major tracks. The southern branch, coming out of Bigbowl, funneled its flow through at least three discrete sub-channels eroded into the old snow above the Spur Catwalk. As the rime reached the hardpacked surface of the ski runs, it fanned out into cone shaped deposits reminiscent of alluvial fans (Figure 3). Once out onto the hardpacked Frontier ski run, the flow spread out into a sheet 10 m (33 ft) wide. The flow continued in this sheet fashion all the way down Frontier and turned left (south) into Lower Bowl at about 3280 m (10750 ft) (Figure 4).

The second major flow came out of Upper Sundance bowl and ran down Lower Sundance. The rime continued to move down slope until it was finally contained at 3230 m (10600 ft) elevation by a manmade snow dam (Figure 4). The flows covered a total vertical fall of 430 m (1400 ft). The total area involved in both flows was approximately 16 hectares with each flow covering about ½ the area. Based on the dimensions of the rime accumulated behind the dam and estimating that two to three times that volume was left perched along the flow path, we calculated the minimum volume of rime involved at approximately 300 m^3 (10600 ft^3) to 400 m^3 (14100 ft^3).

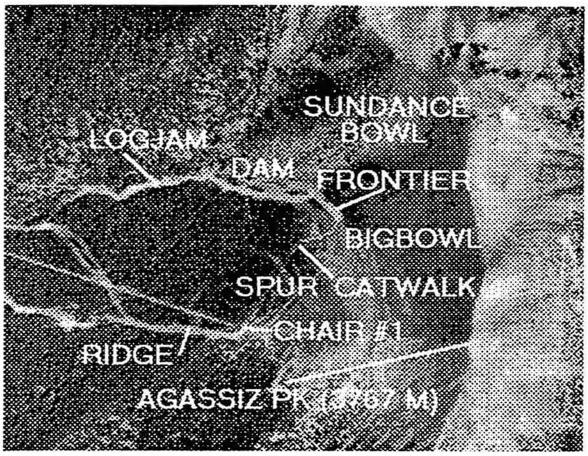

Figure 4. A vertical air photo of Upper Bowl with various features referred to in the text annotated.

4. FLOW CHARACTERISTICS AND DYNAMICS

The portions of the flows moving within the starting zones consisted of individual rime feathers that rolled or tumbled in response to gravity following release. Lower down in the track and runout zones, the flows still consisted of individual rime feathers but here groups of feathers moved in slug-like masses during sporadic surge events.

In areas of ungroomed old snow, flow was often channeled. The concentrated flow produced enough tractive force to initiate erosion and entrench into the old snow despite the rather high density of the surface. The entrenchment often produced steep walled snow "gullies" with distinct "nickpoints" and "pour-overs". Some of these gullies were 30 cm (1 ft) wide and 60 cm (2 ft) deep (Figure 5).

In areas of hardpack on the ski runs proper, the flow did not entrench but rather spread out in wide sheets. In these areas of sheet flow, only narrow sections within the sheet were usually active at any given time. In some cases "levees" of rime were deposited as the slower rime piled-up at the edges of the active portion of the flow.

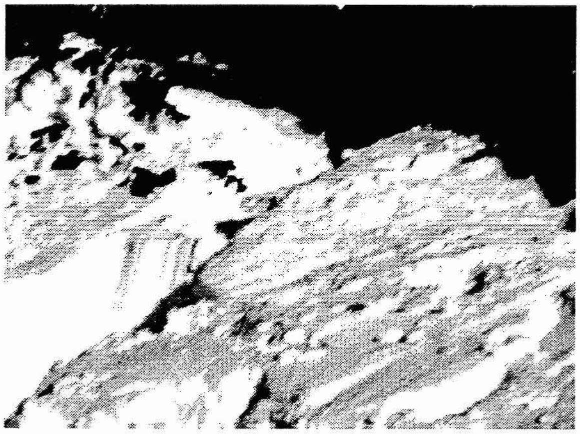

Figure 5. A frame captured from video showing details of an entrenched channel with a nickpoint pour-over. Field of view is approximately 3 meters (10 feet).

Both flows stopped and started frequently in a surging fashion. The rime feathers piled up until they exceeded the angle of repose and then the oversteepened section of the flow would start moving again. Many of these characteristics are similar to those observed in earthen debris flows however, these rime flows are notable in that free water was a very minor element unlike the earthen counterparts (Costa and Williams, 1984; Easterbrook, 1993; Statham, 1977).

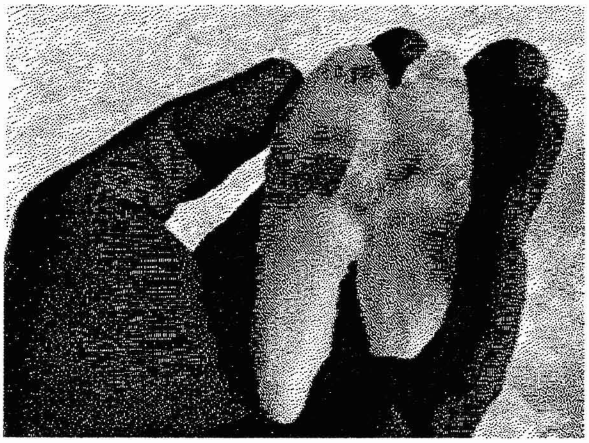

Figure 6. Detail of a pair of rime feathers taken from the debris at the terminus of the flow.

The largest rime feathers involved were up to 10 cm (4 in) long by 3 cm (1.3 in) wide and almost clear to milky in color.

Generally the clearer ice was associated with the end of the feather that had been exposed to the wind while the milky ice as associated with the attachment end (Figure 6).

The rolling and tumbling feathers were moving at approximately 0.5 m sec-1 (1 mph). Some of the channeled flow captured in the video was estimated to be flowing at 2 - 3 m sec-1 (5 - 7 mph). The more rapid portions of the flow issued a hissing sound but as the velocity slowed, the sound of individual feathers became more pronounced producing a slightly muted "tinkling" sound.

5. MANAGING THE EVENT

At 8:30 a.m. January 10th, a lift mechanic walked into the morning ski patrol meeting and reported a small pile of avalanche debris on the Spur Catwalk. We had our doubts about avalanches since the starting zones had been stripped by the wind and were mostly rock, but we checked it out on the first run. Upon arrival at the end of Spur Catwalk (Figure 4) we found a deposit of rime feathers piling up on the catwalk and fanning out onto Frontier. We radioed for some bamboo poles to mark the obstacle created by the rime and proceeded to ski down. When we reached Lower Sundance we discovered a second flow surging out of Upper Sundance and Sundance Bowl.

Skiing the rime flow was like skiing on thousands of marbles or ice cubes. It was somewhat tricky and fun for the ski patrollers (one patroller injured his knee skiing the rime) but was not safe for the skiing guests. At this point we realized the entire "bowlside" above Midway had to be closed to the guests for their safety and Spur Catwalk was closed at the top around nine a.m.

On our second run we hiked to Upper Bowl and traversed over to Bigbowl to determine the source of the rime river. We originally thought the rime was being blown out of the trees, but soon found the flow was coming from above treeline also. By the time we made our third run, the rime river was approaching Midway. We did not want to close the entire "bowlside" due to the flow so number 10 grain scoops were used to try and divert the flow into the trees. We quickly realized we had the wrong tool for the job.

A LMC snowcat was escorted with snowmobiles up "bowlside" to a point just above Midway at the 3230 m (10600 ft) elevation where it was used to build the rime river dam (Figure 7). The dam was 18 m (60 ft) long by 1.5 m (5 ft) deep. The dam stopped the rime flow above Midway by noon. The "bowlside" below Midway remained open all day. Since we had not seen anything like this before, we borrowed a video camcorder from the marketing division and documented the flow at three p.m. that day.

Figure 7. A view of the snowcat-constructed dam that contained the terminus of the flows.

That evening, the groomers worked on removing the dam and rime deposit using an implement known as a *tiller* towed behind their snowcats. They reported that it was a bit loud but the tillers effectively pulverized the rime. The rime continued to flow well into the evening when new snow started falling. As the temperature dropped with the arrival of the new storm, all flow finally stopped. The next day we had three inches of new snow and the skiing was great on "bowlside, there was no sign of the rime river.

6. WHAT CAUSED THE RIME FLOW?

Release of the rime feathers causing the flow occurred due to rapid thawing aided by the mechanical shear provided by wind. The rapid temperature increase appears to have resulted from a very transitory, but pronounced, high pressure subsidence, perhaps aided by solar radiation. Windflow increased and "backed" from northwesterly to southwesterly during the subsidence and peaked at over 15.5 m sec-1 (35 mph) on January 10th. It is interesting to note the very short duration of conditions favoring the rime flow. These flows were not triggered by a major warming trend lasting several days but rather by a brief change in conditions lasting only two days sandwiched between two cold rime producing storms.

6.1 Upper air analysis

The following summary traces the event history, as seen in the upper atmosphere, from January 6, 1995 through January 11, 1995. The National Weather Service radiosonde station at Winslow, Arizona (INW), located 90 km downwind (east) from the Arizona Snowbowl acquired these data.

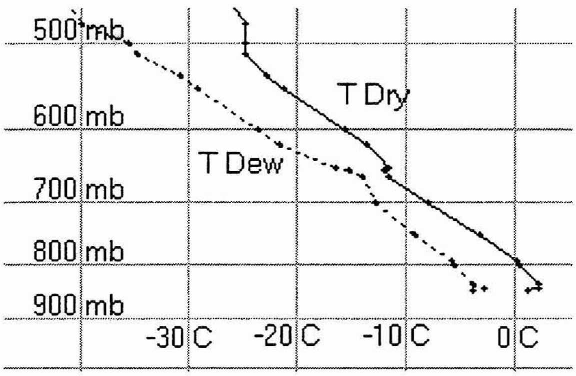

Figure 8. Stuve plot from Winslow (INW) for the 01-06-95 12Z sounding illustrating typical upper air conditions for this time of year.

January 6th 12Z (noon Greenwich time or five a.m. local time)

The 700 mb dry bulb temperature was –7° C (19.4° F) while the dew point temperature was –13° C (8.6° F) (Figure 8). Rime conditions existed at a narrow zone around 3600 m (11800 ft). Some rime accumulated on the mountain at this time.

January 7th 12Z (noon Greenwich time or five a.m. local time)

The 700 mb dry bulb temperature was 0° C, the dew point temperature was -7° C. A brief break in rime conditions occurred below 4000 m (13,100 ft).

January 8th 12Z (noon Greenwich time or five a.m. local time)

The 700 mb dry bulb temperature was –2° C, while the dew point temperature was –4° C. Strong rime conditions resumed between 2700 (8850 ft) and 3600 m (11800 ft). This was the major rime accumulation period producing most of the material involved in the rime flow events.

January 9th 00Z (midnight Greenwich time or five p.m. Jan 8th local time)

The 700 mb dry bulb temperature was +1° C (33.8° F), and the dew point temperature was –2° C (28.5° F). Riming diminished and a subsidence inversion began to form above 700 mb. The freezing level was located at 3350 m (11000 ft) and the wind direction shifted from northwest to southwest.

January 9th 12Z (noon Greenwich time or five a.m. local time)

The 700 mb dry bulb temperature remained at +1° C, while the dew point temperature dropped to –19° C. indicating much dryer air. The subsidence inversion dropped below 700 mb. The freezing level remained at 3350 m (11000 ft). Wind speed increased to 5 - 10 m sec –1 (11 – 22 mph) from the southwest.

January 10th 00Z (midnight Greenwich time or five p.m. Jan 9th local time)

The 700 mb dry bulb temperature climbed to +3° C (37.4° F), while the dew point temperature remained low at –20° C. The subsidence inversion continued to lower in elevation.

Freezing level remained high at 3600 m (11800 ft). Wind speed increased to 10 to 13 m sec-1 (22 – 29 mph) from the southwest. The rime flow event appears to have started sometime during the evening of the 9th.

January 10th 12Z (noon Greenwich time or five a.m. local time)

The 700 mb dry bulb temperature remained at +3° C (37.4° F) in spite of the early morning hour. The dew point temperature remained low at –19 C (-2.2° F) (Figure 9). Wind speed peaked at 15.5 m sec - 1 (35 mph) out of the southwest.

The rime flow intensified and continued throughout the daylight hours of the 10th.

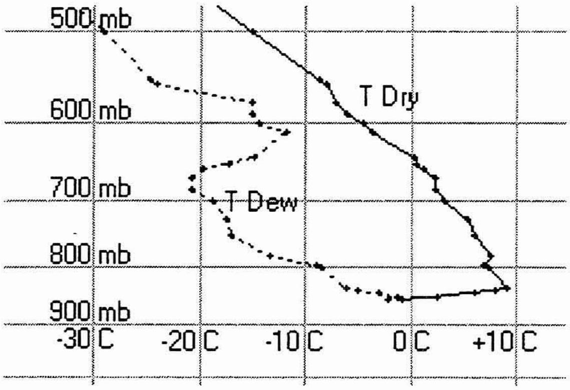

Figure 9. Stuve plot from Winslow (INW) for the 01-10-95 12Z sounding illustrating upper air conditions during the rime flow event. Compare this to figure 8.

January 11th 00Z (midnight Greenwich time or five p.m. Jan 10th local time)

The 700 mb dry bulb temperature remained warm at +2° C (35.6° F), and the dew point temperature remained low at –20° C (-4.0° F). Wind speed remained high at 15.5 m sec – 1 (35 mph) from the southwest. The rime flows diminished during the evening hours of the 10th.

January 11th 12Z (noon Greenwich time or five a.m. local time)

The freezing level lowered "behind" the subsidence as the 700 mb dry bulb temperature fell to –2° C (28.5° F). The dew point temperature climbed to –2° C (28.5° F) as a new moisture source moved in with an arriving storm. Another riming event began at 3300 to 3700 m (10800-12150 ft).

<u>6.2 Surface Weather Analysis</u>

The trends in the surface temperatures (Tables 1 and 2) follow the upper air temperatures closely with one exception. The surface low temperatures are lower than those recorded in the free air but are still relatively warm around the time of the rime flow.

January 8th was noted by the weather observer as a "heavy rime day" corresponding to the rime levels predicted by the radiosonde data. The anemometer was frozen and no data were recorded. Winds "back" at the surface preceding the rime flow and reach a maximum on the day of the rime flow as in the upper air data.

Table 1. Morning Temperatures from 2900 meters (9500 feet) at the Agassiz Lodge.

Date	Time	Temp C
1/7	8:00	-3.3
1/8	7:45	-3.9
1/9	7:40	-6.7
1/10	8:00	-1.7
1/11	8:00	-5.6

Table 2. Surface Weather Data from 3350 meters (11000 feet) at the top of Lift 1.

Date	Temp Hi C	Temp Lo C	Wind Hi m/s	Wind Lo m/s	Wind Dir deg
1/6	2.2	-23.3	13.4	0	210
1/7	3.3	-21.7	11.2	0	220
1/8	3.3	-13.9	*	*	230
1/9	3.4	-15.0	12.5	0	210
1/10	2.8	-8.9	17.4	3.1	180
1/11	-5.6	-17.8	17.4	0	200

* indicates missing data due to rimed anemometer

7. SHOULD THE RIME RIVER BE CONSIDERED A TYPE OF AVALANCHE?

Most snow-avalanche workers define "avalanches" broadly as any mass of snow or ice moving down a slope and ignore imparting a velocity constraint (Daffern, 1983; LaChapelle, 1985; Armstrong and Williams, 1986; McClung and Schaerer, 1993). Earthen-flow workers however, almost always attach the notion of rapid velocity to their definition of avalanches (Statham, 1977; Costa, 1987; Easterbrook, 1993). Generically, most hillslope failures involve either the sudden release of discrete masses of material or very slow creep or glide. It appears that the rime flows reported here occupy a relatively rare time duration in the general scheme of hillslope failures.

These events continued to receive a source of material over several hours, longer than most other rapid mass motion event types. Some debris flow events do remain active over periods of hours. One of the authors witnessed rain-induced debris flows along a reach of the Alsek River in the Yukon that remained sporadically active over a period of 6 to 10 hours. We leave the question of "typing" this event open but suggest that the rime river should probably be in a class of slower velocity snow and ice *flows* perhaps in a group along with slush flows.

8. CONCLUSIONS

This is apparently a rather rare phenomenon. The more we ask other people about their experiences with similar rime flow events, the more we find how few people report ever seeing one. These flows occurred during a period of sudden warming, and associated high velocity wind, situated between two rime producing storms. The question remains as to why this particular short and intense period of warming gave rise to such unique rime flows while others do not.

9. ACKNOWLEDGEMENTS

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