

Surface Hoarfrost Measurement and Climatology

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ABSTRACT

Surface hoarfrost modifies snowpacks and reduces travel safety, and it is neither measured nor forecast by weather services. Our objectives are to show the reliability of hoarfrost measurements made with an ice detector, and to simulate hoarfrost events. During evaluation of a Rosemount glaze ice detector, we found that it reliably indicated hoarfrost accretion. We compared the ice detector probe's frequency to the accreted frost weight on vertically and horizontally oriented metal test plates on 22 mornings. Ice detector probe frequency drop and plate frost weight correlated with $R^2 > 0.6$. The ice detector probe's vertical axis indicated the onset of frost accretion on vertical surfaces well, but horizontal surfaces typically began to frost a few hours earlier. Weather conditions at the onset and cessation of frost events were used to develop a rule-based forecast technique that successfully predicted most frost events observed by the ice detector.

Key words: Hoarfrost, ice detector, frost prediction, frost accretion, frost ablation

INTRODUCTION

Surface hoarfrost results when water vapor is deposited directly on surfaces that are supersaturated with respect to ice (Minsk 1980, Lock 1990). Hoarfrost creates several problems for society. Hoarfrost on a snowpack surface is eventually buried under fresh snow, creating a weak layer that persists, and which can cause avalanches (Colbeck 1988, Lang et al. 1984). Frost formation on electrical transmission lines adds little mass, but increases line sensitivity to wind-induced galloping, and increases the collection area for possible rime ice formation (Pohlman 1994). Hoarfrost

decreases travel safety by decreasing visibility through automobile windshields, decreasing traction on pavements, and decreasing the lift of aircraft wings by increasing turbulent flow.

Despite the hazards it creates, hoarfrost is not measured by the National Weather Service (NWS), nor is it forecast. This may be in part because there have been no reliable automated methods of measuring it. Therefore, this paper demonstrates the reliability of hoarfrost mass deposit measurements made with an ice detector designed specifically to measure glaze deposits. The characteristics of hoarfrost accretion and ablation events are analyzed and used to create a synthetic time-series of these events.

BACKGROUND

Collocated with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) Meteorological Team's standard array of instruments are several heated anemometers and ice detection systems. Among the ice detection systems is a new ice detector, developed by Rosemount Aerospace, designed specifically to measure glaze for the NWS Automated Surface Observation System (ASOS) program (Stein 1993). Our unit is a commercial version of the NWS unit, model 872G.

The instrument operates using the same fundamental principles as other Rosemount ice detectors. Ice accretes on a vertically oriented 0.6-cm-diameter by 2.5-cm-long cylindrical probe that vibrates axially at a nominal 40 kHz (our probe vibrates at an actual 39.7 kHz) (Ryerson 1988). Increasing mass on the probe decreases the probe's frequency. At a preset frequency, the probe is deiced by a heater brazed into it. During normal operation, probe frequency is converted to an ice thickness using an internal microprocessor, and a

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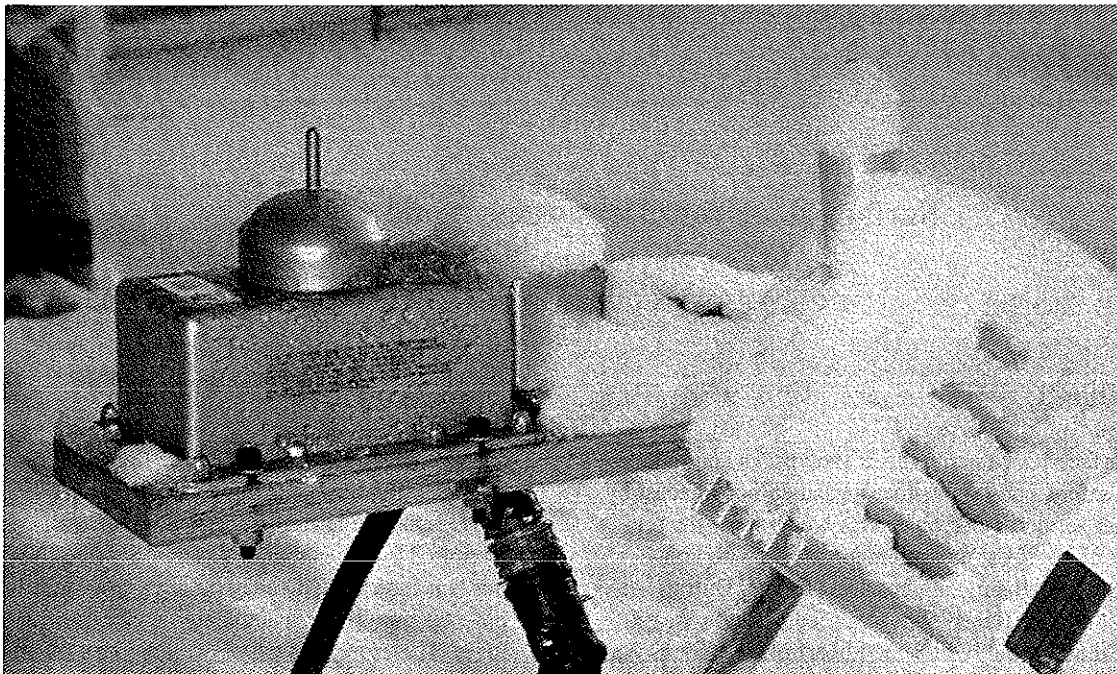


Figure 1. Glaze ice detector on right, with heat sink below probe and mountaintop detector on left. Wet snow, with air temperature near 0°C, adheres to colder glaze ice detector, and completely melts from mountaintop detector.

digital thickness is output. We monitor both the digital signal and the probe frequency continuously; however, for this paper only the probe frequency is used.

This ice detector is different from other Rosemount ice detectors because of the heat sink located immediately beneath the probe. Other models, including the mountaintop model 872B12 used by CRREL on Mount Washington, are constructed to measure rime ice accretion in cold and windy environments. However, glaze often accretes in temperatures near 0°C with little wind (Bennett 1959) where heat generated by the electronics has a deleterious effect upon an instrument's ability to detect ice. We observed evidence of this by operating both instruments side-by-side at CRREL. Snow accumulated on the glaze detector, whereas it melted from most locations on the mountaintop unit (Fig. 1). The ability of the 872G's probe to remain near or below ambient air temperature is important to the new use we have found for this instrument.

The 872G ice detector was installed at CRREL's meteorological station during the winter of 1992–93. We periodically plot the instrument's probe frequency to assess how well it is performing. These plots indicated that, even though no freezing rain nor rime

events were occurring, probe frequency often decreased regularly and significantly (often more than 100 Hz) for hours and then returned to normal (Fig. 2). We determined that precipitation was not the cause of these frequency drops. Precipitation-caused drops are typically irregular and of less than 25 Hz because

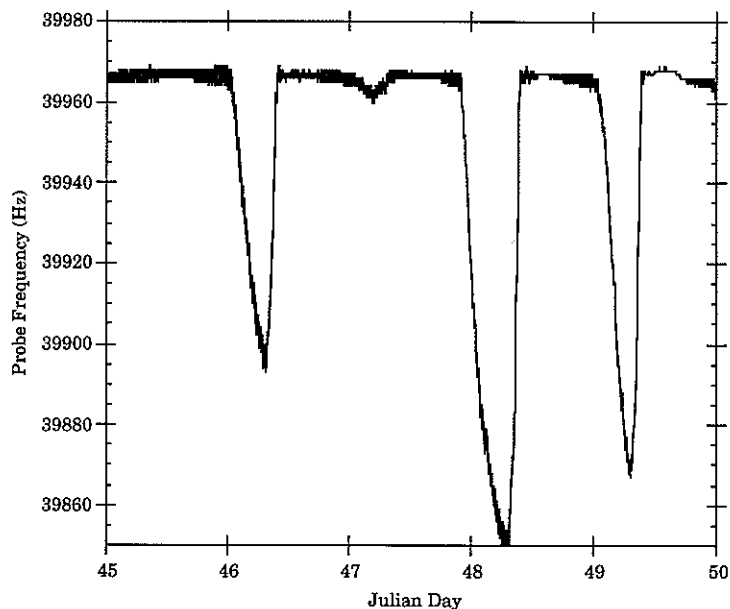


Figure 2. Ice detector probe frequency drops during hoarfrost events.

rain and snow do not strongly adhere to the probe surface.

The frequency drops were mostly nocturnal. Probe frequency would usually begin to decrease near midnight, and continue to decrease until sunrise. We suspected that hoarfrost was forming on the probe surface, even though the probe's structure, being small in diameter and vertical and thus with little exposure to the night sky, might argue against this.

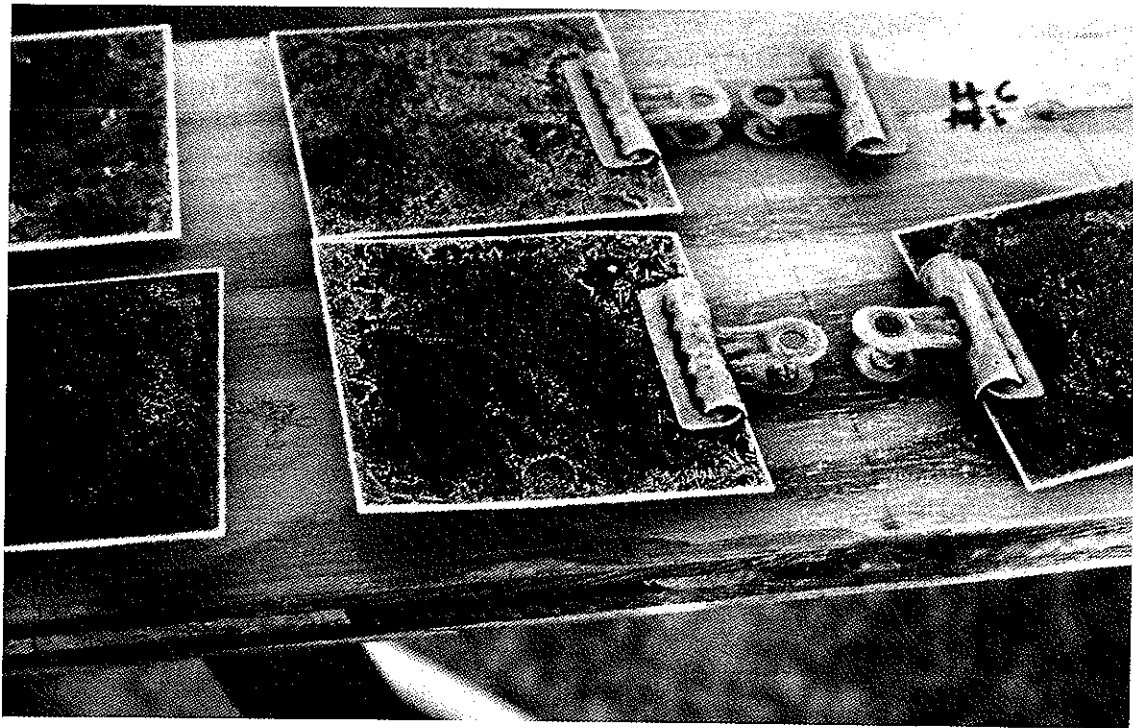
So, we designed a simple observation program to see if the instrument was responding to frost. Since the ice detector is designed to measure the onset and magnitude of glaze accretions, we were also interested in its ability to accurately and consistently measure the mass of frost accretion, and to identify frost accretion and ablation episodes as a function of time.

OBSERVATION METHODOLOGY

Hoarfrost accretes largely as a result of radiative exchange. Cold, clear, calm nights allow surfaces exposed to the sky to cool rapidly, often to well-below the air temperature (Lock 1990). Our observation program consisted of exposing 10-cm-square aluminum plates (100 cm² each) to the night sky. Plates ranged

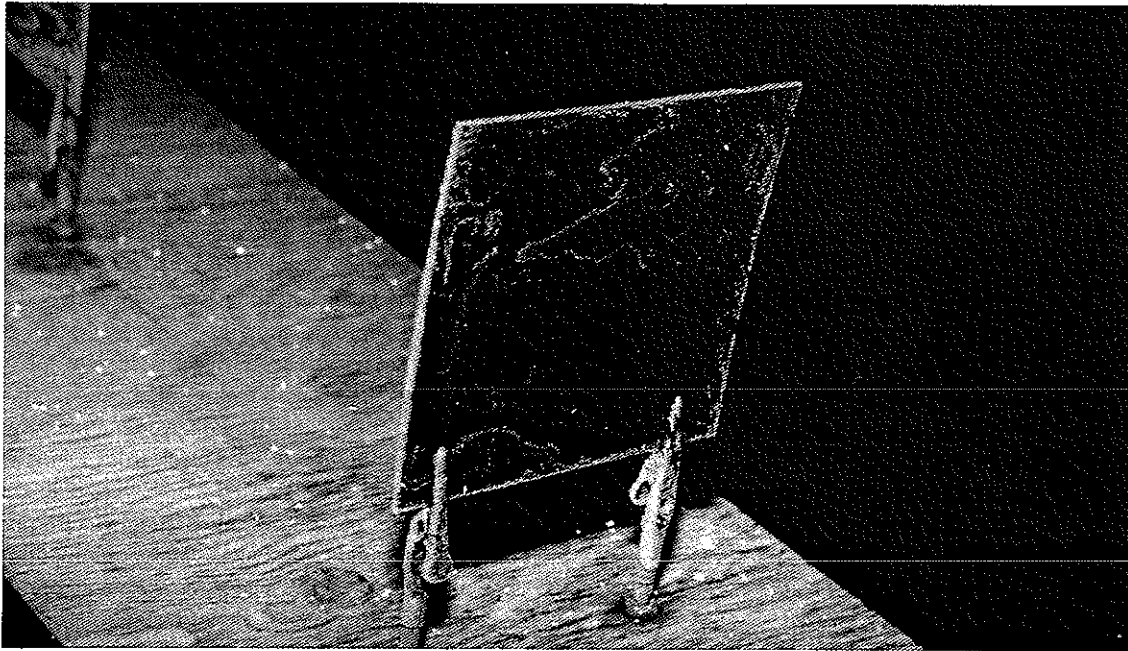
from 0.4 to 0.6 mm in thickness and were painted flat black on one side, with the second side left bare. Plates were mounted horizontally with the black surfaces exposed to the sky, or vertically. Horizontal plates were attached with paper clasps about 1.0 cm above a 1.2-cm-thick sheet of plywood that was itself exposed about 1.0 to 1.5 m above the snow surface, depending upon the snow depth (Fig. 3a). The space between the plates and plywood allowed air circulation around all sides of the plates. The plywood was mounted at approximately the same height above the ground or snow surface as was the ice detector. Vertical plates were mounted about 2.0 cm above plywood on alligator clips (Fig. 3b). Four vertical plates were exposed each night, with the black sides facing north, south, east and west. Frosted plates were placed in a plastic freezer bag and weighed on an electronic balance. Frost weight was calculated by subtracting the bag and plate weights. These measurements provided a comparison between the total weight of frost accreted on the plates during the night and the ice detector probe frequency.

Morning measurements allowed the total frost that had accreted on the horizontal or the vertical plates over the entire night to be compared to the probe frequency. Overnight time series were also produced by



a. Horizontal plates.

Figure 3. Mounting of sampling plates.



b. Vertical plates.

Figure 3 (cont'd). Mounting of sampling plates.

exposing about twenty horizontal plates and four vertical plates to the night sky, and measuring the ice mass on one or two horizontal plates each hour, or one vertical plate each 3 hours, after frost was observed to begin. The overnight observations created time-series that demonstrated how well the ice detector measured the onset and progression of frost accretion.

ICE DETECTOR-FROST WEIGHT COMPARISONS

Plate frost weight and ice detector frequency were concurrently measured on 22 mornings between 10 November 1993 and 2 May 1994. These measurements do not represent all mornings when hoarfrost occurred because observations were not made on weekends, holidays and during other times. Overnight observations were completed on four nights.

During the observation program, 210 frost weights were obtained: 40% of all frost weight measurements were made on vertical plates, and 50% were made during overnight observations. Maximum frost weights, i.e., those measured in the morning immediately before ablation, averaged about 1.1 g on the horizontal plates, and 0.7 g on the vertical plates. Though it may be tempting to compute a frost yield from these measurements in the form of grams per square

centimeter of plate surface, plates frosted unevenly on the two sides because, as mentioned, one side was painted black and the other side left bare. In addition, the bottom sides of the horizontal plates, though exposed to the air, were only 1 cm away from the plywood. Although frost formed on both sides of the plates, much less frost formed on the bare, unpainted side of both vertical and horizontal plates.

Frost normally accreted in random locations on the ice detector probe, and occasionally formed evenly over the entire probe (Fig. 4). It never accreted sufficient frost for its heater to be activated. The probe frequency simply decreased during the night as frost accreted, and then increased to its ice-free frequency in the morning after all frost had ablated.

One purpose of our observations was to determine how reliably the ice detector's frequency changes corresponded to frost weight on the plates. Correlations are strong between probe frequency drop and ice weight on the horizontal and vertical plates measured during the four overnight observation periods (Fig. 5). Both relationships are linear, yield high R^2 values, and each is highly significant. However, scatter is large, especially at the lower frost masses, producing a large RMS residual for the horizontal plates. The RMS residual is smaller for the vertical plates, and the relationship is statistically strong, but the number of vertical plates measured was small when compared to the horizontal plates.

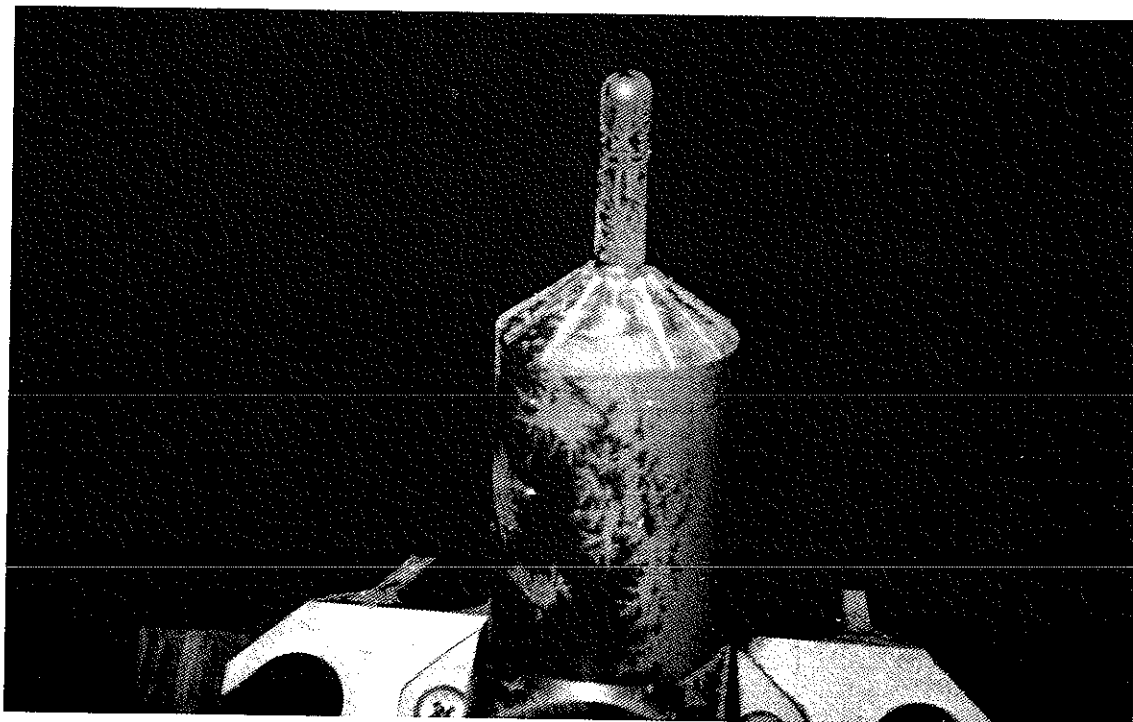


Figure 4. Frost deposit on ice detector probe.

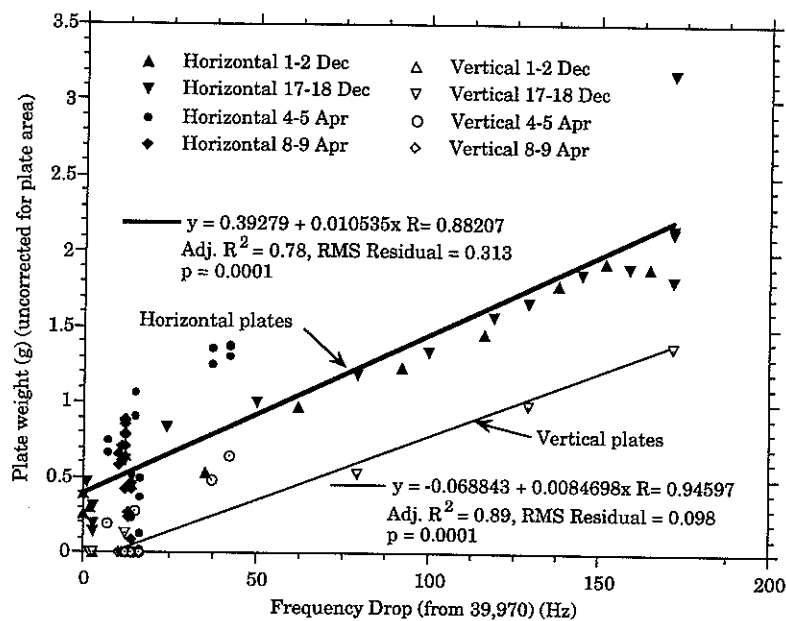


Figure 5. Plate frost weight versus probe frequency drop from 39,970 Hz for overnight observations on 1-2 December 1993, 17-18 December 1993, 4-5 April 1994, and 8-9 April, 1994.

The large scatter, especially at smaller frequency drops, may be the result of an apparent seasonal effect (Fig. 5). Overnight observations in December had little scatter compared to those in April. In December, probe frequency began to decrease within a few hours of the onset of plate frosting, and thereafter plate ice weight increased and probe frequency decreased concurrently and nearly linearly. In April, however, delays between

plate frost formation and probe frequency drop were longer. This seasonality difference may be attributed to less darkness and thus a shorter time for radiative cooling in April. It may also be caused by increased radiation in April from the warmer surrounding hills, which suppresses cooling of the sides of the vertical probe as compared to the horizontal plates exposed only to the sky. The results scatter at lower frequency

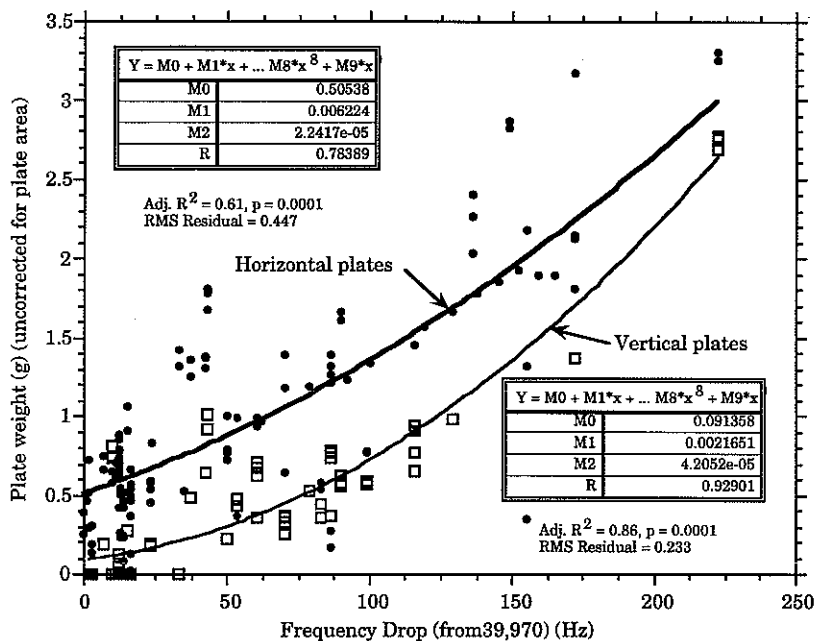


Figure 6. Plate frost weight versus probe frequency for all cases: 10 November 1993 through 2 May 1994.

drops in April because plate weight is increasing, even though probe frequency is not dropping.

Relationships between all frost weights, whether determined overnight or only in the morning, and probe frequency drop are also strong (Fig. 6). Relationships using all of the data are weaker than those using only the overnight measurements, especially with the frost weights on the horizontal plates. In addition, although the R^2 values are generally high, and the relationships are highly significant, the RMS residuals also increase.

There may be several reasons for the scatter in the relationships between probe frequency drop and plate frost weight. First, two observers randomly made morning observations, which could have caused observational error. Second, small amounts of frost would occasionally be accidentally scraped from the plates as they were slid into the plastic freezer bags, thus affecting the weight measurements. Third, the weighings, made on an electronic balance kept in a warm room, may have been affected by the buoyancy of the bags as they warmed.

Despite the scatter, the relationships between frost weight and probe frequency drop suggest that the ice detector can indicate the weight of plate frost reliably. However, it is difficult at this time to relate probe frequency or frost weight on the plates to frost accreted on other objects. This will require measurements on surfaces that represent objects such as automobile windshields or highway pavements.

The ice detector probe represents frost accretion on vertical surfaces more effectively than that on horizontal surfaces. This difference is evident from overnight observations on 17–18 December when frosting began on the vertical plates about 2.5 hours after the horizontal plates (Fig. 7). This plot also suggests that once frosting begins, accretion is somewhat more rapid on the horizontal plates. Therefore, the horizontal plates weighed more by morning because they accreted ice more rapidly and accretion began several hours earlier than on the vertical plates.

We speculate that the vertical plates accrete less ice because they are responding to a different radiative environment than are the horizontal plates. Horizontal plates are cooled by the clear night sky. Measurements of the radiative temperature of the plate surfaces, even with frost, indicate that they are radiatively cooled below the air temperature (assuming their emissivity to be 1.0). For example, during overnight observations on 17–18 December 1993, the temperatures of the black surfaces of the horizontal plates averaged about 3.2°C lower than the ambient air, whereas the temperatures of black surfaces of the vertical plates averaged only 1.1°C lower than the ambient air. Plate temperature depressions varied by several degrees from plate to plate, and could be attributable to variations in plate emissivity. The colder horizontal plates thus frost more rapidly because they are supersaturated more completely with respect to ice.

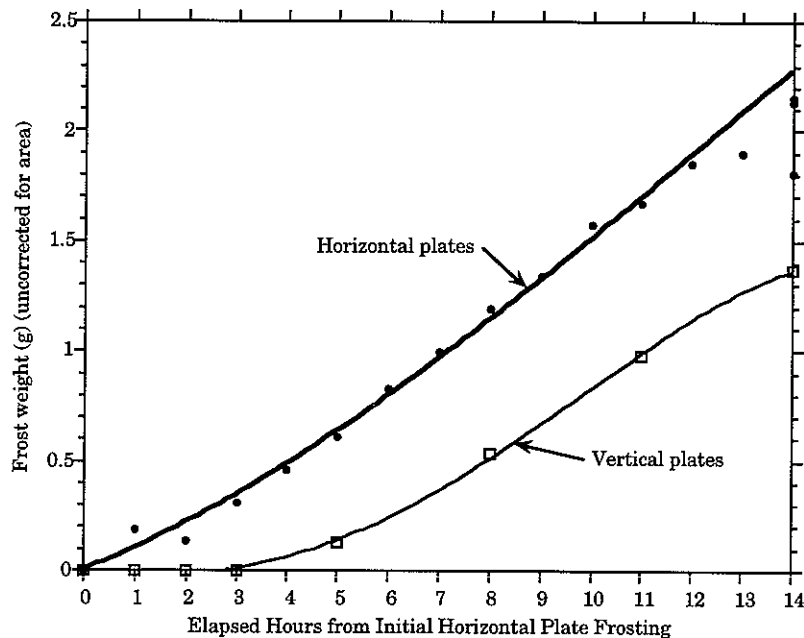


Figure 7. Time of initial frost deposit for horizontal and vertical plates, 17–18 December 1993. Time starts when deposits first observed on horizontal plates.

ACCRETION AND ABLATION CONDITIONS

The ability of the ice detector to successfully measure the relative intensity of frost events encouraged us to isolate weather conditions associated with frost formation and ablation, so we isolated 37 of the most significant frost events between 10 November 1993 and 7 April 1994. Events were isolated by specifically determining the times of initial frost accretion, the cessation of accretion, the initiation of ablation, and the cessation of ablation. Frost was judged as accreting from the time that probe frequency first began to decrease until the minimum frequency was reached. Ablation was judged as occurring when frequency was steadily increasing from its minimum during the event to its ice-free frequency. The purpose of isolating these conditions was to better understand the accretion–ablation process, and to determine if consistent information could be found to predict frost events. Weather conditions in each accretion event were analyzed to isolate conditions conducive to frost formation, and weather conditions in each ablation event were analyzed to isolate conditions conducive to frost ablation.

Frost accretion is encouraged by any meteorological conditions that cool surfaces to the saturation vapor pressure of ice. Air temperatures near or below 0°C are necessary, but not sufficient, and air temperatures were below freezing at the beginning of all 37 frost events. Subtracting air temperature at 1 m height from air temperature at 2 m height indicated that there is also usually a strong inversion present in the lower at-

mosphere during frost formation. Inversions as strong as $1.4^{\circ}\text{C m}^{-1}$ were observed, though the mean was $0.5^{\circ}\text{C m}^{-1}$. This is ascribable to the radiative cooling of the near-surface atmosphere.

Hoarfrost accretion is often associated with high pressure. Radiation-induced hoarfrost is less common in low pressure, with its associated higher winds, cloudy skies and precipitation. Synoptic charts of these frost events indicate that high pressure cells covered the area in most cases. Radiative cooling is more effective at the low wind speeds associated with small pressure gradients found in center of high pressure cells. Winds at 1 m were typically less than 0.9 m s^{-1} at the start of frosting.

Generally, sky radiative temperature must be lower than air temperature to promote frost formation because the lower sky temperature is needed to cool objects to the ice saturation temperature. Under the assumption that the sky has an emissivity of 1.0 in the infrared, about 67% of sky temperatures computed from radiometer measurements from 3 to $30\text{ }\mu\text{m}$ were lower than surface air temperature during frost accretion, with a mean difference of 4.8°C .

Comparison of the vapor pressure of the air at the beginning of frost formation to the saturation vapor pressure of ice for the 37 events observed indicates that the air was nearly always saturated with respect to ice (Fig. 8). The additional 1 to 3°C cooling applied to the plates radiatively apparently is sufficient to saturate or supersaturate the air with respect to ice immediately over the plate surfaces and produce frost. This supports the observations of earlier and more rapid frost

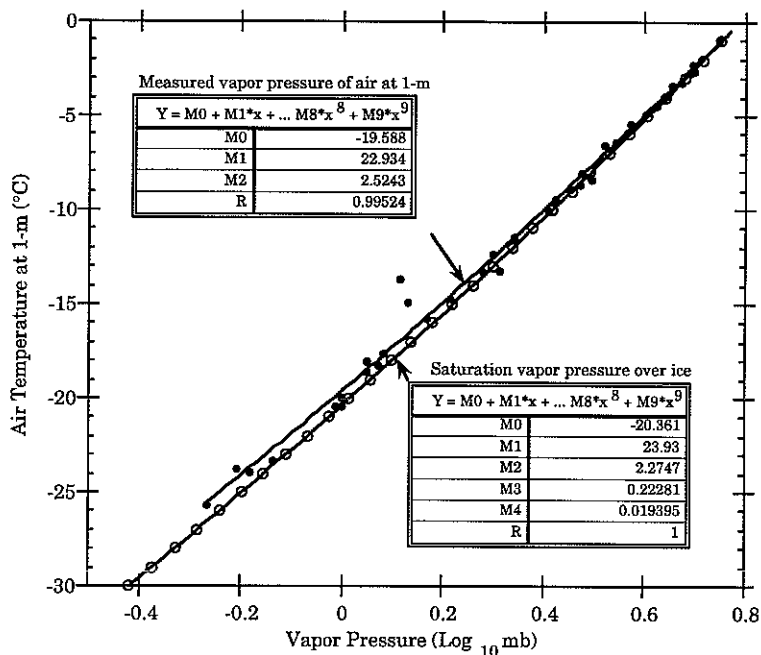


Figure 8. Vapor pressure of air and saturation vapor pressure over ice versus air temperature at time of initial frost accretion.

formation on the horizontal plates because they cool more by radiative exchanges with the cold sky.

Many conditions must necessarily coincide to produce frost, such as low winds, temperatures below 0°C, and air vapor pressures above saturation with respect to ice. That is, they are all necessary to produce frost; no one of the frost-producing criteria is sufficient. Only one factor, however, is necessary or sufficient to ablate frost. Ablation is caused by either melting frost, or by sublimation through lowering the vapor pressure of the air relative to that of the frost. The frost can ablate by being warmed, and thus having its vapor pressure raised, or by the air drying.

Air temperatures often were lower at the beginning of ablation events than at the beginning of accretion because of cooling during the night. Furthermore, temperatures were only greater than 0°C once at the beginning of ablation, and only higher than 0°C 22% of the time even at the end of ablation. This suggests that melting is probably not the primary cause of frost ablation, though it is a factor. However, sunlight striking the probe can possibly raise the probe and frost temperature above 0°C before the air temperature rises above 0°C, thus melting the frost. Also, strong inversions often present during frost accretion usually disappeared when ablation began. Conditions varied from inversions of 0.6°C m⁻¹ to superadiabatic. Mean cooling with height from the surface was 0.2°C m⁻¹. Breaking of the surface inversion indicates that warmer, and probably drier, air is mixing with air near the surface and promoting ablation.

Wind dries surface air by mixing drier air from aloft with surface air. Higher wind speeds were associated with ablation rather than with frost accretion, though the differences were not large. Wind speeds at the beginning of ablation ranged up to 1.4 m s⁻¹. Winds continued to increase as ablation progressed, probably because of mixing caused by solar heating of objects at the surface. Winds, however, were never greater than 1.7 m s⁻¹ at the end of ablation events.

Most ablation occurred at sunrise, suggesting that solar heating of the frost and the ice detector probe may have caused the frost to sublime. When ablation began, solar radiation between 0.3 and 3.0 μm ranged from 0 to 84 W m⁻², and reached 0 to 273 W m⁻² by the end of ablation events.

Finally, except in the case of melting, the frost vapor pressure must be greater than that of the air for ablation to occur. Through all of the ablation events, the vapor pressure of the frost surfaces was about 0.4 mb greater than that of the air, promoting sublimation.

The duration of a frost event is the number of hours that frost resides on the ice detector probe as indicated by the probe frequency. Because the probe represents frost accretion on vertical surfaces more reliably than on horizontal surfaces, approximately 2.5 hours must be added to probe-derived accretion and total-event durations for horizontal surfaces.

During the 37 frost events we isolated for further study during the winter of 1993–94, frost resided on the ice detector probe an average of 10.7 hours from initial accretion to the end of ablation, the periods

ranging from about 5.3 to 17.8 hours. This is partly because of changing night length during the winter, but is also a result of conducive frost conditions occurring later in the evening, or changes in weather, such as increased cloudiness during the night, that cause ablation before sunrise. If all frost events during the winter had been analyzed, the minimum event duration probably would have been smaller. Accretion periods ranged from 1.5 to 13.3 hours during the 37 analyzed events. Of the entire period of frost duration, accretion occurred during 70% of the time on the average. Ablation periods ranged from 1.5 to 6.3 hours, about 30% of each entire frost event.

FROST OCCURRENCE SIMULATION

We analyzed weather conditions associated with frost accretion and ablation, in part, to attempt to simulate the onset of frost, its duration, and its ablation. This task is most appropriately accomplished through models that explicitly simulate the accretion and ablation processes. We chose a simpler approach, simulating only the occurrence of frost, and not its magnitude, using rules.

As discussed earlier, several weather conditions must take place simultaneously to drive the surface of objects to a temperature below the saturation vapor pressure of ice. They are all necessary; no single condition is sufficient to produce frost. However, only one factor may be necessary and sufficient to produce a

sufficient difference between the vapor pressure of ice and air for ablation to occur.

Six conditions were established to predict frost occurrence—1) air temperature less than 0°C and 2) saturated with respect to ice, 3) wind speed at 1 m less than 1.4 m s⁻¹, 4) incoming solar radiation less than 60 W m⁻², 5) sky radiative temperature less than air temperature at 1 m and 6) no precipitation. These thresholds were all derived from the statistical analyses described above. Precipitation served as a surrogate for cloud cover, which typically prevents frost formation. All of these conditions were necessary for frost to occur. Weather measurements, and thus frost occurrence tests, were made every 15 minutes from 1 November 1993 through 7 April 1994.

The simulated frost events compare reasonably well with frost events indicated by probe frequency (Fig. 9). A Chi-square test between probe-measured and simulated frost events each 15 minutes failed to demonstrate that there was a significant difference between the distributions ($p > 0.30$). To obtain this result, some adjusting of variable thresholds, especially solar radiation, were necessary. Also, measured frost events were determined by finding only those periods when probe frequency was less than 39,950 Hz.

Since the probe often responds to precipitation with a 10–20 Hz frequency drop, precipitation events were used to strip possible false frost events from probe frequency measurements. Close inspection of Figure 9 indicates that occasional frost was predicted during precipitation events, such as during lulls in precipitation. This is most obvious near days 89, 102 and

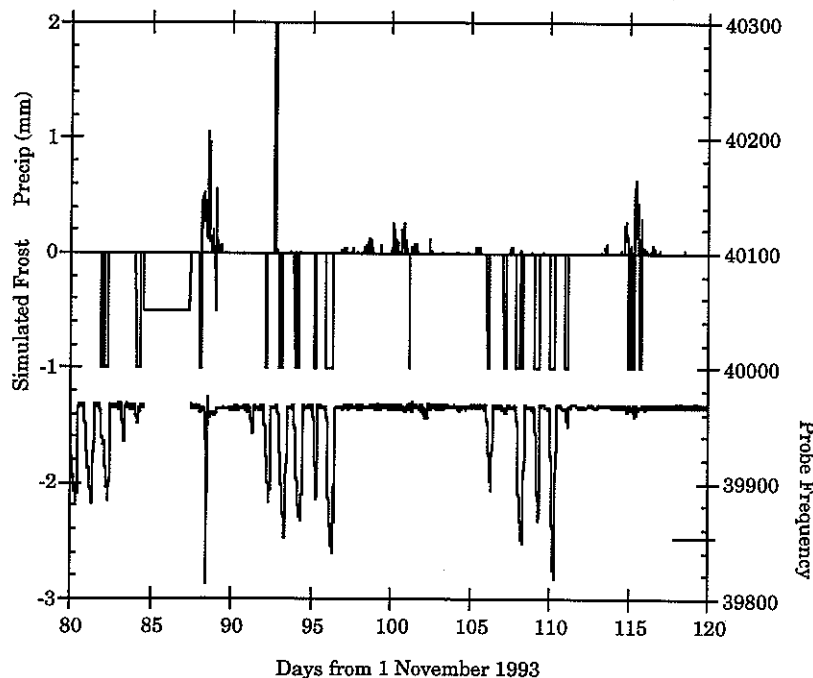


Figure 9. Simulated frost occurrences versus probe frequency and precipitation during 40 days of study period. Half-height bars in simulated frost record represent periods of ice detector outages.

115. It appears that both the ice detector or the logic tests of weather conditions may be useful tools for predicting frost occurrence.

DISCUSSION AND CONCLUSIONS

Our observations suggest that the Rosemount 872G glaze ice detector may be a useful tool for detecting the onset and magnitude of frost accretion on vertical surfaces. However, the unit is not an ideal device for measuring the onset of frost on horizontal surfaces because it responds to the warmer radiative environment of its surroundings in addition to that of the colder sky. We also noticed that frost events were missed in the spring after the surrounding hills had begun to warm, and after the spring equinox when hours of daylight exceeded darkness. This limits the detector's ability to warn of the onset of frost on important horizontal surfaces such as bridges, highway pavements and runways.

The ice detector often responds to conditions without frost, which must be recognized and removed if it is used for frost warnings or frost research. For example, it responds to glaze, but also occasionally to snow and rain, albeit with a smaller and less regular frequency drop. The instrument should be paired with a rain gauge to reduce false frost indications. This is also true if the instrument is used primarily to detect glaze accretion.

Though we have demonstrated that the instrument can track the amount of frost on horizontal and vertical surfaces with a degree of success dependent upon the surface orientation, the weights of frost measured on the plates are only relative. The measurements are not known to represent frost accretion on any common object in the environment.

The ice detector can be used to detect, and thus study, hoarfrost events because it can create a fairly reliable time-series of these events. This allows weather conditions producing hoarfrost to be determined and helps to develop rules for the prediction of frost. It will also provide information useful for modeling frost, because the time-series of probe frequency provide details of subtle changes in accretion rates as radiation, temperature and humidity change. The Rosemount detector should also be useful for verifying model predictions and, for the first time, it allows frost ablation periods to be uniquely identified.

Creating the time-series of frost occurrence from the weather conditions producing frost was only a simple exercise to demonstrate that a short period of monitoring can provide useful forecasting information. Though prediction was statistically acceptable, the

events simulated were also those used to establish the weather conditions. Predictions probably would be less successful if another time period was used as the test. In addition, the threshold of solar radiation was experimentally adjusted to obtain the best possible forecast.

We will develop a climatology of frost return periods by frost accretion magnitude after additional monitoring. Attempts will be made to relate the detector's response to frost accretion on surfaces other than metal plates. In addition, our weather condition tests for frost formation will be refined, and attempts at modeling accretion mass will be renewed as our understanding of frost accretion and ablation processes improves.

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