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WINTER PRECIPITATION TYPE

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1. Introduction

Winter weather forecasting brings many interesting and challenging situations, not the least of which is forecasting precipitation type, i.e., rain versus snow versus freezing precipitation. The prime purpose of this note is to summarize some recent research done by Atmospheric Environment Service (AES) of Canada that had application to this particular forecast problem. In reviewing their material it was discovered that a more thorough review of the rain-snow-freezing precipitation question was in order. Presented below is a brief summary of the physical aspects of winter precipitation type. It is hoped that this discussion will lead to a better understanding of winter precipitation processes, and thus to better rain versus snow versus freezing precipitation forecasts.

2. Rain Versus Snow

The rain versus snow forecast (without the complicating issue of freezing precipitation) is one of the simpler precipitation type forecasts to face the winter forecaster. This does not mean that locating the rain-snow line in time and space is easy, but the physics of this forecast situation is less complicated than those involving freezing rain or sleet (ice pellets).

The key to the rain-snow question lies in the lower tropospheric thermal structure. In the typical case, temperature decreases with height away from the surface. The type of precipitation at the surface depends upon the thermal structure between the layer where the precipitation is formed (usually as snow during winter) and the ground.

If the entire layer is below freezing (Fig. 1A), the snow remains as snow from the formation layer to the ground. On the other hand, if an above-freezing layer exists near the surface, the potential exists to melt the snow to rain (Fig. 1B/1C). Penn (1957) states that this warm layer must be sufficiently deep to provide enough heat to melt the snow to rain. Studies have found that this melting depth varied from 750 feet to 1500 feet, depending upon snowflake type, melted drop size and lapse rate. Another study expressed the probability of snow in terms of the depth of the warm layer (Table 1).

The variation of precipitation type with change in lapse rate (G = - dT/dz) is shown in Fig. 1B/1C. The rate of heat transfer is proportional to the temperature difference between the melting snow flake (at $0^{o}C$) and the surrounding air. Thus, the larger the temperature difference the faster the snow will melt. In terms of lapse rate, shallow layers with large lapse rates (Fig. 1B) can melt snow to rain with the same efficiency as deeper layers with smaller lapse rates (Fig. 1C). On the average, the freezing level must be at least 1200 feet above the surface to insure that the snow will melt to rain.

TABLE 1
Chance of Snow Versus Warm Layer Depth

chance of snow:	50 %	warm layer depth:	35 mb/920 ft
	70 %		25 mb/660 ft
	90 %		12 mb/315 ft

If the depth of the melting layer can be predicted, precipitation type can be anticipated. This vertical structure is observed at least twice a day, but must be inferred between rawinsonde runs. Factors affecting these changes will be discused in Section 5.

A typical cross-section through a rain-snow boundary might look like Fig. 2. Where all temperatures above a point are below freezing, snow is indicated. Where the freezing level is higher than some critical level, rain occurs. There also exists a zone with the freezing level between the critical level and the ground where either rain, or snow, or both occur.

In work done by the AES, Stewart (1987) found that for saturated conditions, the temperature profile near the rain-snow boundary tends to be associated with deep isothermal layers which have temperatures close to 0 C.

3. Freezing Rain and Ice Pellets

A discussion of freezing rain or ice pellets needs to start with the definition of these precipitation types from the Glossary of Meteorology (Huschke, 1959):

a. Freezing rain: rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground and on exposed objects (this implies a surface air temperature of $0^{o}C$ ($32^{o}F$) or less;

b. Ice pellets (sleet): transparent or translucent pellets of ice, 5 mm or less in diameter; they form from the freezing of rain drops or the refreezing of largely melted snowflakes when falling through a below-freezing layer of air near the earth's surface.

The vertical temperature profiles associated with both freezing rain and ice pellets are similar. Both involve an elevated warm (above freezing) layer and a below-freezing layer between the ground and the elevated warm layer. The physical processes occurring differ, however.

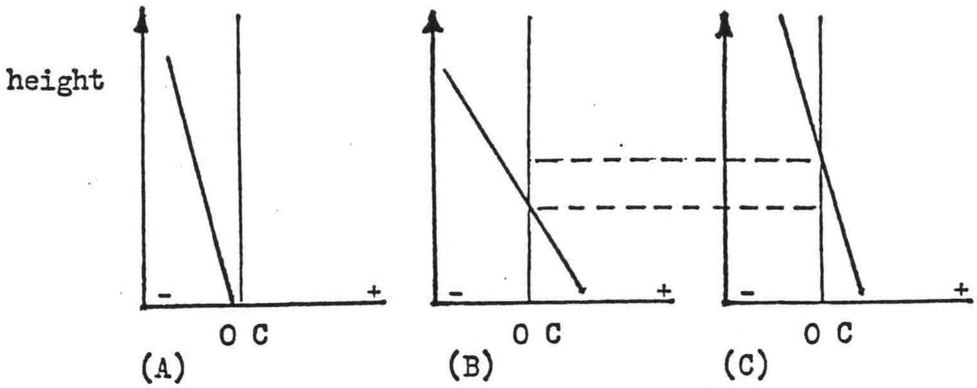

Fig. 1. Example of a rain-snow sounding.

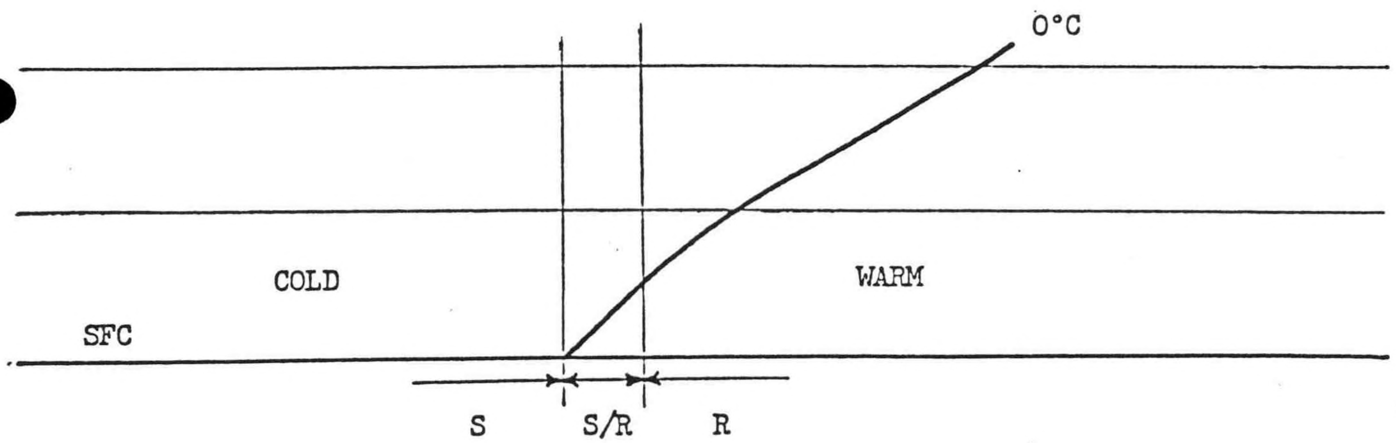

Fig. 2. Typical rain-snow cross-section.

With both precipitation types, snow falls into the elevated warm layer and begins to melt. In the case of freezing rain, the snow completely melts to liquid before falling into the below-freezing layer. In order for liquid droplets to freeze, freezing nuclei and temperatures generally below -10^{o}C must be present (heterogeneous nucleation). In the typical freezing rain case, temperatures are warmer than -10^{o}C and the number of freezing nuclei are not significant to initiate the freezing process. The droplets remain liquid and become supercooled. Upon striking the below-freezing ground, these liquid droplets freeze and glaze the surface.

This discussion implies that the depth of the below-freezing layer near the ground is not as important as the temperature of that layer. If the cool layer temperature is less than -10^{o}C (and freezing nuclei are sufficiently abundant), either snow or sleet could occur, depending upon the degree of refreezing (related to the depth of the cold air). If the cool layer temperature is warmer than -10^{o}C, the liquid droplets will be supercooled and freezing rain will occur.

In the case of ice pellets, the snow falling into the elevated warm layer partially melts before entering the lower cool layer. This partial melting produces an ice crystal surrounded by liquid water. As this combination falls into the below-freezing layer, it begins to refreeze immediately (due to the presence of the ice crystal). This results in ice pellets (sleet) at the surface.

The key difference in the above situations is the degree of melting that the snow undergoes in the elevated warm layer. Stewart and King (1987) used a model to study the melting of snow in an elevated warm layer. They found that if the maximum temperature in the warm layer exceeded 3 to 4 degrees C, snowflakes melted completely to liquid resulting in rain or freezing rain (depending upon the surface temperature) (Fig. 3). If the maximum temperature in the warm layer was less than 1 C, only partial melting occurred, followed by complete refreezing in the cool layer, and snow at the surface. Warm layers with maximum temperatures between 1 and 3 degrees had a mixture of partially melted and completely melted snowflakes. This resulted in ice pellets, or more commonly a mixture of snow, rain (or freezing rain) and ice pellets. These results imply that the maximum warm layer temperature can serve as a guide for proper interpretation of a sounding in terms of freezing rain versus ice pellet potential.

Stewart (1985) also examined the changes in the elevated warm layer due to the melting snow, in the absence of other factors (such as thermal advection). Melting snow requires latent heat to change phase. This heat is extracted from the surrounding environment. If snow falls through the warm layer for a sufficient length of time, the layer will slowly erode (cool) and finally disappear. As the maximum temperature of the warm layer decreases, the resulting precipitation type will evolve from freezing rain to ice pellets to snow (with a mixture of the various types likely during the transition). As a result Stewart (1985) refers to freezing rain as a "self-limiting" process, in the absence of other factors.

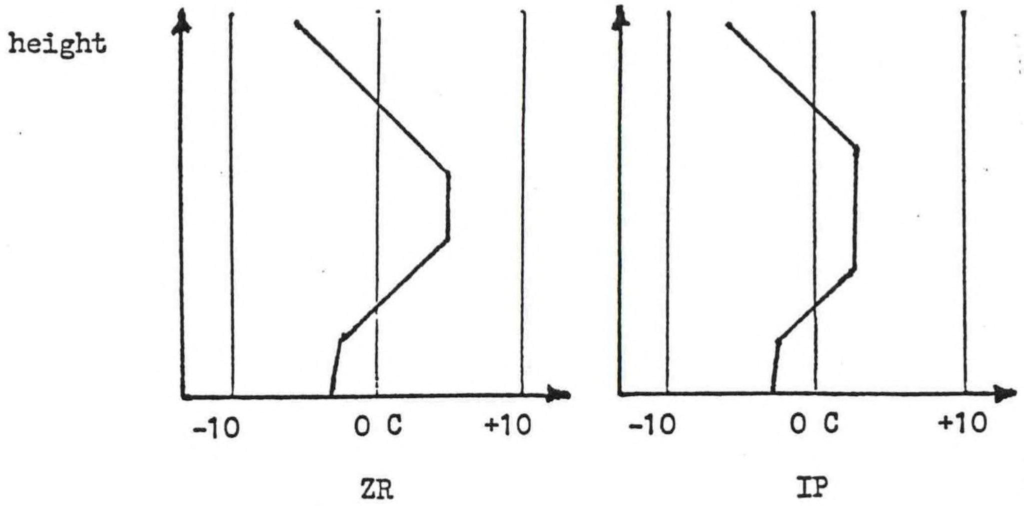

Fig. 3. Example of freezing rain and ice pellet sounding.

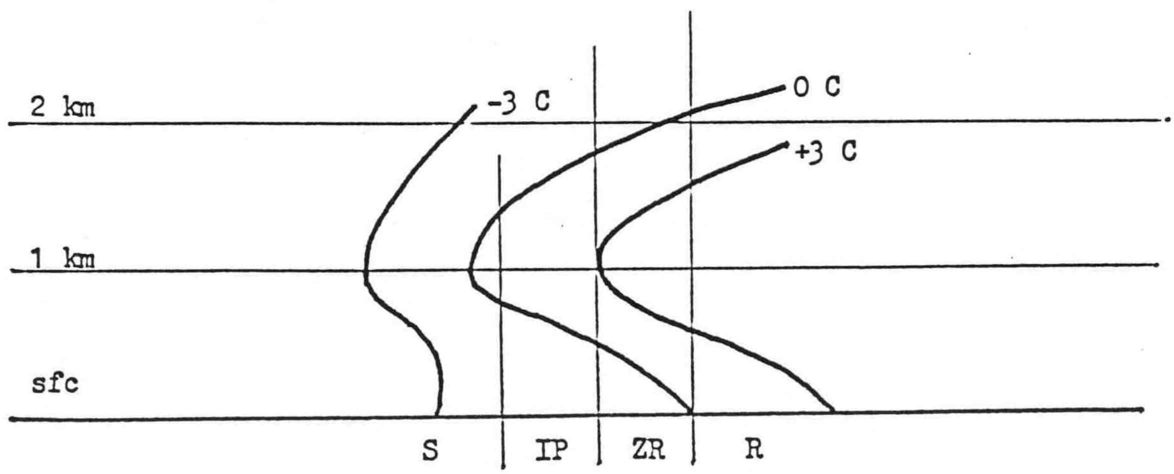

Fig. 4. Typical freezing rain/ice pellet cross-section.

Fig. 4 illustrates a typical cross-section through a freezing rain/ice pellet event.

4. Sounding Examples

Even though two cases do not a generality make, an example of an ice pellet sounding and a freezing rain sounding will lend support to the conclusions of Stewart and King (1987).

The sounding for November 27, 1987, (Fig. 5) shows an elevated warm layer between 860 mb and 775 mb with a maximum temperature of +2.2 degrees C at 852 mb. The 40 mb deep above-freezing layer at the surface precludes freezing rain in this case. However, the +2.2 degree C maximum fits Stewart and King's (1987) criterion for ice pellets. Note that the lower portion of the sounding is essentially saturated, thus satisfying the assumptions of the Stewart and King model.

Table 2 lists the precipitation type on hourlies and specials that occurred at Topeka on November 27th. Although the precipitation was mainly liquid (rain), intermittent periods of ice pellets did occur before changing completely to snow during the evening. One could speculate that the warm layer at the surface was a strong factor in making rain the predominant precipitation type, completely melting some of ice pellets falling into the layer from above.

(As a point of information, the evening sounding was entirely below freezing except for a 50 mb above-freezing layer at the surface.)

Table 2
Precipitation Occurrence at Topeka on 11-27-87

GMT	Precip	GMT	Precip
1430	R-IP-	2053	R-
1450	R-IP-	2114	RIP-
1510	R-	2151	R-IP-S-
1535	...	2238	R-
1550	...	2254	R-
1650	...	2351	R-
1750	L-	0051	R-
1835	L-	0125	R-S-
1851	L-IP-	0150	R-S-
1950	R-	0250	S-
2035	R-	0350	S-

The sounding for the morning of December 13, 1984, is shown in Fig. 6. The elevated warm layer runs from 890 mb to 740 mb with a maximum temperature of +3.4 degrees C at 793 mb. The layer below the warm layer is below freezing from 890 mb to the surface. Although the sounding is not saturated through the entire depth, the +3.4 degree maximum and the freezing temperature at the sur-

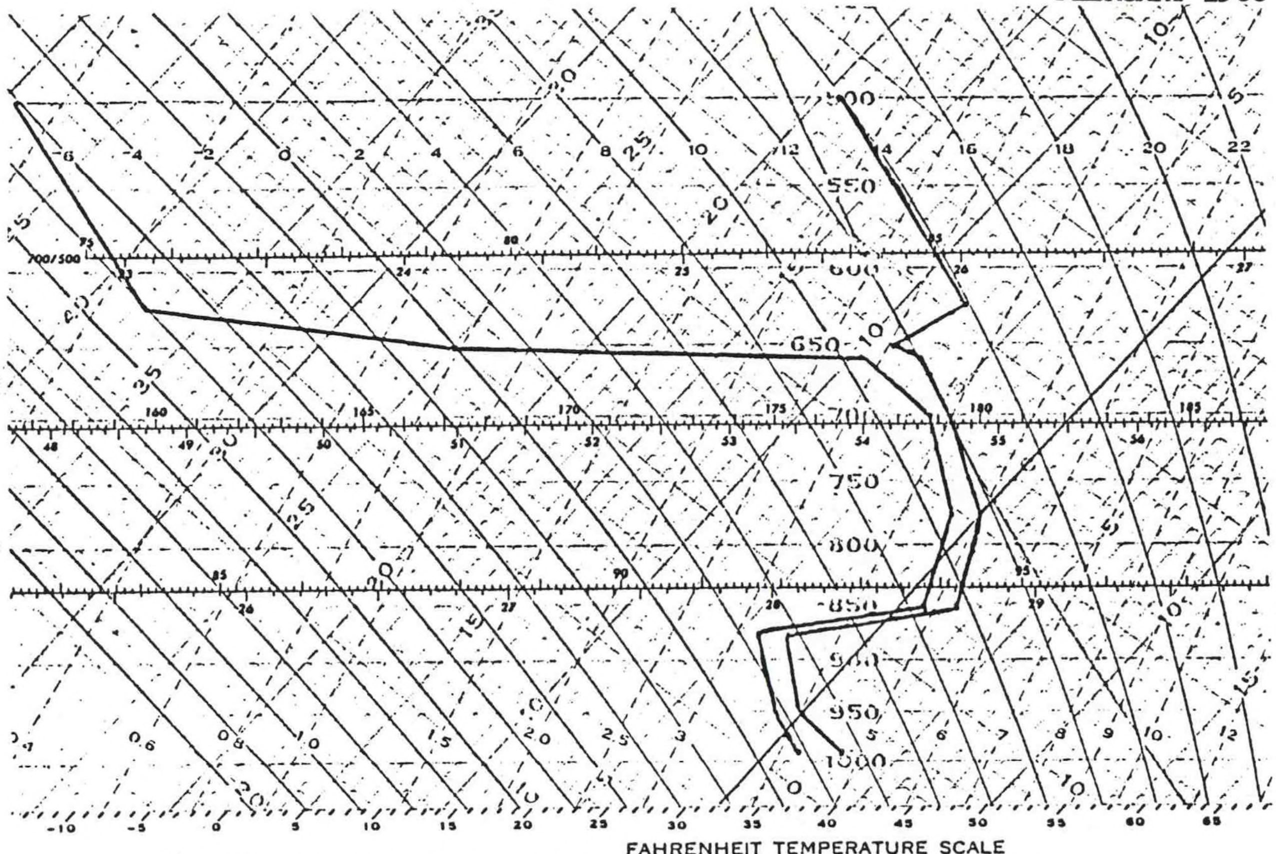

Fig. 5. Topeka, Kansas sounding for November 27, 1987.

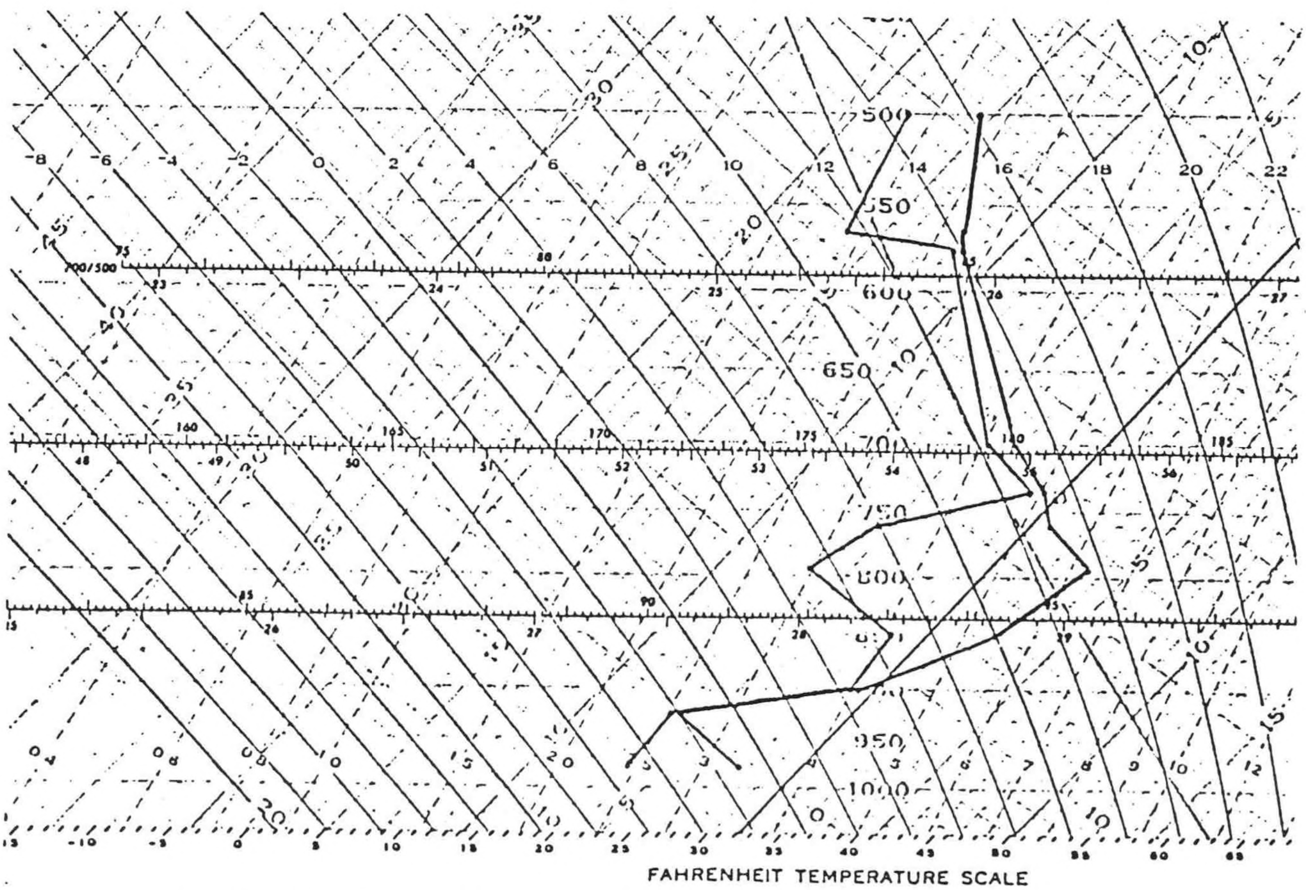

Fig. 6. Topeka, Kansas sounding for December 13, 1984.

face indicate freezing rain potential. Light freezing rain did occur at Topeka from 7:03 a.m. to 2:45 p.m., at which time the surface temperature rose above freezing.

5. Changes in the Vertical Profile

As alluded to in an earlier section the forecaster gets a detailed look at the lower tropospheric thermal structure twice a day. Between these times, changes in structure must be inferred from other factors.

Penn (1957) provides an excellent discussion of those factors which affect local temperature change in the lower troposphere away from the surface. These factors are:

(a) thermal advection by the horizontal wind;

(b) temperature changes due to vertical displacement; and

(c) effects of non-adiabatic heating or cooling.

Studies have shown that the horizontal thermal advection is the dominant process in the lower troposphere. Its effect is somewhat reduced by the change due to vertical displacement. Specifically, warm temperature advection is usually associated with upward vertical motion. Upward motion causes cooling during adiabatic ascent. The net effect is to reduce the warming expected from advection alone by about one-half. If a forecaster can determine what type of advection is occurring, vertical profile changes can be inferred, and precipitation type anticipated.

Even though the advection factor is generally dominant, there are situations where non-adiabatic effects can be significant. Two effects are important in rain-snow situations. The first is evaporational cooling. When precipitation (particularly rain) falls through an unsaturated layer between the cloud and ground, precipitation will evaporate, particularly if the below-cloud air is rather dry. When this occurs the air cools. As the air becomes saturated, its temperature approaches the wet-bulb temperature of the original drier air. If this wet-bulb temperature is below freezing, the precipitation at the surface may change from rain to snow as the freezing level lowers toward the surface. The evaporational cooling in this case overpowers any warm advection that may be occurring, and can cool the air by 5 to 10 degrees C in an hour. Once the layer becomes saturated, this non-adiabatic effect ceases and advection again becomes dominant.

A second non-adiabatic effect is the melting of snow to rain. As mentioned earlier, snow extracts heat from the surrounding environment when it melts. In the typical situation this cooling effect is not large enough to offset warming due to advection. However, in very heavy precipitation events, R+ may change to S+ due to lowering of the freezing level by latent heat absorbed by the melting snow.

The above discussion indicates that thermal advection is the dominant factor affecting temperature change in the lower troposphere. It should be asked then, "What information is routinely available to the forecaster to analyze the lower tropospheric thermal advection?" The answer is, "the surface chart and the 850 mb chart." However, a lot can happen between the surface and the 850 mb level that may or may not be obvious from either level. What is needed is a more detailed analysis system for the lower troposphere ! The current rawinsonde message has an abundance of information just waiting to be tapped. For example, using the entire temperature profile, the pressure-altitude data, and the PIBAL (wind) data, plots and/or analyses at 500 ft, 1000 ft, 1500 ft, etc. (AGL), could be generated. From these charts the interlaced thermal advection patterns frequently associated with winter storms could be better diagnosed. Such information would enhance a forecasters ability to infer changes in the vertical temperature profile, and its subsequent impact on precipitation type.

6. Concluding Remarks

The discussion in this note is not meant to imply that the only information available to the forecaster for forecasting rain versus snow versus freezing precipitation is the vertical temperature profile. Some very useful techniques involving thickness values are available. Also, MOS produces a precipitation type forecast. Either of these subjects could be a topic for an extensive discussion by itself.

Nevertheless, the information presented here should improve a forecasters understanding of the physical processes involved in winter weather precipitation forecasting. In particular, the results of Stewart and King (1987) which relate warm layer strength to precipitation type should be useful operationally. These new values should enhance the forecasters' ability to correctly anticipate precipitation type.

7. References

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