Further Investigation of a Physically Based, Nondimensional Parameter for Discriminating between Locations of Freezing Rain and Ice Pellets

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ABSTRACT

The general applicability of an isonomogram developed by Czys and coauthors to diagnose the position of the geographic boundary between freezing precipitation (freezing rain or freezing drizzle) and ice pellets (sleet or snow grains) was tested using a 25-yr sounding database consisting of 1051 soundings, 581 where stations were reporting freezing drizzle, 391 reporting freezing rain, and 79 reporting ice pellets. Of the 1051 soundings, only 306 clearly had an environmental temperature and moisture profile corresponding to that assumed for the isonomogram. This profile consisted of a three-layer atmosphere with 1) a cold cloud layer aloft that is a source of ice particles, 2) a midlevel layer where the temperature exceeds 0°C and ice particles melt, and 3) a surface layer where $T < 0°C$. The remaining soundings did not conform to the profile either because 1) the freezing precipitation was associated with the warm rain process or 2) the ice pellets formed due to riming rather than melting and refreezing. For soundings conforming to the profile, the isonomogram showed little diagnostic skill. Freezing rain or freezing drizzle occurred about 50% of the time that ice pellets were expected. Ice pellets occurred in nearly a third of the cases where freezing precipitation was diagnosed. Possible reasons for the poor diagnostic skill of the method are suggested.

1. Introduction

Freezing rainstorms are among the most severe winter weather events. Surface ice accumulation can halt air and ground transportation, weigh down and snap power lines, severely damage trees, and cause numerous traffic and pedestrian accidents. Forecasters closely monitor storms producing freezing rain; however, the mesoscale nature of freezing rain events makes their location and severity inherently difficult to forecast. A particularly difficult problem of weather forecasting is distinguishing regions that will receive freezing rain from regions that will receive ice pellets. Czys et al. (1996, hereafter CZ) reported a method to diagnose the boundary between freezing rain and ice pellets using a simple nondimensional parameter. An advantage of the CZ method is its simple application in the forecasting environment; easily measured quantities from either actual or forecast model-generated soundings can be used along with values of a nondimensional parameter obtained from a nomogram (Fig. 1) to map the boundary between ice pellets and freezing rain. Czys et al. (1996) suggested that after further testing their method could be combined with mesoscale model data. Forecast maps delineating the freezing rain–ice pellet boundary could then be generated. To derive the parameter, CZ assumed the atmosphere had a three-layer structure similar the sounding shown in Fig. 2, with 1) a cold ($T < 0°C$) cloud layer aloft that is a source of ice particles, 2) a midlevel layer where the temperature exceeds 0°C and ice particles melt, and 3) a surface layer where $T < 0°C$. If ice particles from aloft completely melt into raindrops within the warm layer, the drops will supercool in the surface layer and reach the ground as freezing rain. If ice particles from aloft partially melt in the warm layer, they will refreeze in the surface layer and reach the ground as ice pellets.

Czys et al. (1996) suggested that the parameter τ, defined as the ratio of the residence time of an ice particle in the warm layer (t_{res}) to the time required for complete melting (t_{melt}), might be useful to discriminate regions of freezing rain and ice pellets in forecasts. (The terminology used here follows CZ.) Czys et al. estimated t_{res} by considering the depth of the melting zone (ΔZ_w) and the velocity at which a particle falls through

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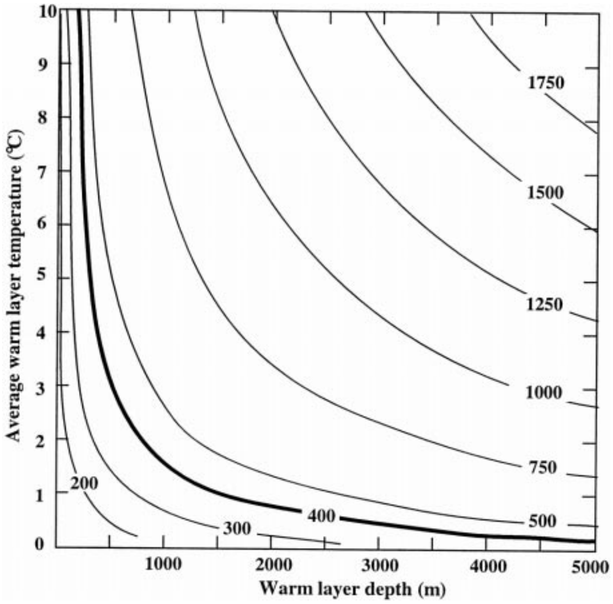

FIG. 1. Isonomogram of $\tau = 1$ for different critical ice particle radii, a_c (μm), computed over a range of warm-layer depths and mean temperatures (from Czys et al. 1996). The bold line, $a_c = 400$ μm, was the value suggested by Czys et al. (1996) to delineate freezing rain and ice pellets.

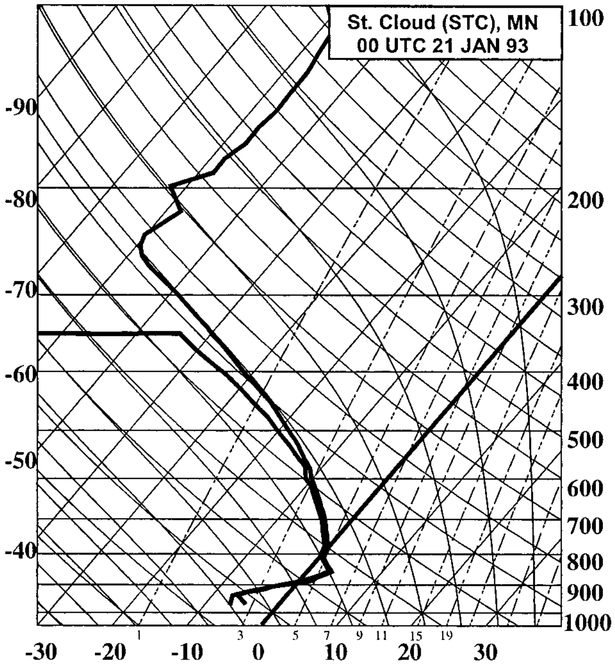

FIG. 2. Example sounding that satisfies the Czys et al. (1996) criteria of having a cold ($T < 0$°C) cloud layer aloft that is a source of ice particles, a midlevel layer where the temperature exceeds 0°C and ice particles melt, and a surface layer where $T < 0$°C.

the layer $[U(a) - \overline{V}]$. Here $U(a)$ is the particle terminal velocity, a function of drop radius a, and $\overline{V}$ is the ambient air vertical velocity. The time t_{melt} was estimated by considering a balance between the rate of energy required to transform the solid to liquid and the rate at which the environment can supply the needed energy. The net result for τ was

$$\tau \equiv \frac{t_{\text{res}}}{t_{\text{melt}}} = \frac{\Delta Z_w k_w a}{[U(a) - \overline{V}]L_{\text{sl}}\rho_i \displaystyle\int_a^0 \frac{r(a - r)\,dr}{T_0 - T_a(r)}}, \quad (1)$$

where k_w is the thermal conductivity of water, L_{sl} is the latent heat of melting, ρ_i is the density of ice, r is the radius of the ice core in the drop, T_a the temperature of the particle–environment interface, and T_0 the temperature of the ice–water interface, assumed to be 273 K.

Since particles occupy a range of sizes in clouds, CZ considered the critical radius, a_c, to be the radius of the largest particle falling through the warm layer. If $\tau = 1$ for this particle, $\tau > 1$ for all other particles and the precipitation will fall as freezing rain. Otherwise, the precipitation will be a mixture of freezing rain and ice pellets, or ice pellets alone. To determine a representative value for a_c, CZ considered radar reflectivity measurements from the Valentine's Day ice storm of 1990 (Martner et al. 1992, 1993; Rauber et al. 1994; Rasmussen et al. 1995). They further assumed an exponential size distribution for the particles with the parameters for the distribution taken from Marshall and Palmer (1948) and Gunn and Marshall (1958). For the 1990 ice storm, a value of critical radius a_c was found to be 400 μm. Czys et al. (1996) used this value with soundings from across the geographic area affected by freezing rain to diagnose the location of the boundary between freezing rain and ice pellets. Their results closely matched the observations.

Subsequent cursory evaluations of τ were conducted in operational environments at the St. Louis and Indianapolis National Weather Service Forecast Offices during the 1995/96 winter. Qualitatively, the method tended to identify where freezing rain and ice pellets occurred when a_c was assumed to be 400 μm. A cautionary situation mentioned by CZ are cases where freezing drizzle occurs and the sounding is everywhere colder than 0°C. In these cases, freezing precipitation forms through the warm rain process (Bocchieri 1980; Huffman and Norman 1988; Rauber et al. 2000). Czys et al. (1996) note that their 1995/96 experience suggests that this situation is ''a highly localized phenomena.''

Based on initial successes, CZ developed a simple isonomogram that could be used with soundings as a diagnostic tool to distinguish freezing rain and ice pellet occurrences. The isonomogram, reproduced in Fig. 1, shows isopleths of $\tau = 1$ computed over a range of critical particle radii, warm-layer depths, and warm-layer mean temperatures. Czys et al. (1996) suggested that the value $a_c = 400$ μm be used to delineate the freezing rain–ice pellet boundary. The technique proposed by CZ can be applied to model forecast soundings and can be used to produce forecast products such as maps delineating freezing rain–ice pellet (ZR–IP) boundaries. It is important, therefore, to test the CZ isonomogram with independent data. The purpose of this note is to evaluate the general applicability of the CZ isonomogram as a forecasting tool by testing it with a 25-yr sounding database.

2. Database

Soundings from all United States stations east of the Rocky Mountain states during the 25-yr period from 1 January 1970 through 31 December 1994 were considered for this analysis. The upper-air data were obtained from the National Climatic Data Center's Radiosonde Data of North America. Freezing rain, freezing drizzle (ZL), and IP events were first identified using the National Climatic Data Center's *Storm Data* reports (NCDC 1970–94). Each state report was carefully screened for any occurrence of ZL, ZR, or IP (sleet or snow grains). The 3-hourly surface charts (obtained from National Climatic Data Center microfilms) for the entire storm associated with each event identified in *Storm Data* were then analyzed to determine the regions where these events occurred. With this procedure, we identified 1091 12-h periods, an average of 43 per winter or about 8 per month (Nov–Mar). We then examined the 0000 and 1200 UTC charts to identify those sounding sites within the area of ZR, ZL, or IP that reported one of these conditions at the time of launch. In the case where there was not a surface report at the site itself, nearest-neighbor stations surrounding the site had to be reporting the same condition for the sounding to be included in the database. These soundings were retained for analysis. A total of 1051 soundings were identified, 581 reporting freezing drizzle, 391 reporting freezing rain, and 79 reporting ice pellets.

This method of choosing soundings has two obvious drawbacks. The first is that the surface observations and sounding data are not coincident in time and space. Surface observations are normally taken 10 min prior to the synoptic time, while soundings are launched 50 min prior to the synoptic time, a 40-min time difference. In addition, the rawinsondes drift downwind of the station, and the surface and sounding stations are not always collocated. This problem cannot be avoided using conventional data. We do not consider this issue to be significant to the results of this study, based on individual examination of each of the sounding profiles and the fact that similar conditions were, in most cases, reported at several nearby stations simultaneously.

The second drawback is that minor events, covering a small area over a short time, would be excluded from our analyses because they never would be reported in *Storm Data*. Recall that *Storm Data* was used to initially identify IP, ZL, and ZR events. Subsequent analysis of the surface charts nearly always identified a much broader area of IP, ZL, or ZR than indicated in the state reports in *Storm Data*. Much of the coverage area in any event received only minor amounts of these precipitation types. Most of the soundings in our database were associated with ZL, which, aside from air traffic hazards and automobile accidents, is generally associated with minor property damage. Furthermore, the conditions had to occur at the sounding site at the synoptic time. We believe that the odds are low that minor, short-lived events would have occurred at sounding stations at specific times at a high enough frequency to bias our results significantly.

This is the second paper reporting analyses from this database. The first paper (Rauber et al. 2000, hereafter RB), discussed the importance of the warm rain process in freezing events. Rauber et al. expanded upon earlier work on this same topic by Huffman and Norman (1988) and other researchers. The sounding database used by RB did not contain the 79 soundings from stations reporting ice pellets, nor did RB consider processes concerned with ice pellet formation. In this evaluation of the CZ method to diagnose the boundary between freezing precipitation and ice pellets, we use RB's sounding categorization to identify freezing rain and drizzle soundings that conform to CZ criteria. We also introduce the database of 79 soundings from stations reporting ice pellets, and compare data from soundings in each of these databases to diagnostic predictions of the CZ nomogram.

3. Reduction of the database

Although 1051 stations reported ZL, ZR, or IP at the time of the soundings, only 306 clearly conformed to the environmental vertical temperature and moisture profile assumed by CZ. This profile consisted of a three-layer structure, with a cold cloud layer aloft that is a source of ice particles, a midlevel layer where the temperature exceeds 0°C and ice particles melt, and a surface layer where $T < 0°\text{C}$.

Warm rain process

Rauber et al. (2000) divided the ZL and ZR soundings into six categories based on the cloud-top temperature (CTT), the presence or absence of a warm layer, and the altitude of cloud top relative to the warm layer. Cloud top was defined by these authors as the first level above the low-level cloud layer where the dewpoint depression exceeded 3°C, provided that the dewpoint depression remained $>3°\text{C}$ through a layer of at least 1-km depth. The six categories were 1) no warm ($>0°\text{C}$) layer present, 2) cloud top below the warm layer, 3) cloud top within the warm layer, 4) cloud top above the warm layer and $0°\text{C} > \text{CTT} \geq -5°\text{C}$, 5) cloud top above the warm layer and $-5°\text{C} > \text{CTT} \geq -10°\text{C}$, and 6) cloud top above the warm layer and $\text{CTT} < -10°\text{C}$. Rauber et al. provided composite soundings in each of these categories and showed the geographic distribution of the soundings by category. Table 1 from RB contains the critical information important to this paper. Rauber

TABLE 1. Categories for the analysis of 972 soundings taken during freezing precipitation events (from Rauber et al. 2000).

Category	Description	No. of soundings	Percent of total soundings	Percent of category soundings with freezing drizzle	Percent of category soundings with freezing rain
1	No warm (>0°C) layer	152	15.6	95.4	4.6
2	Cloud top below warm layer	43	4.4	83.8	16.2
3	Cloud top in warm layer	260	26.8	72.3	27.7
4	Cloud top above warm layer and 0°C > CTT ≥ −5°C	149	15.3	62.4	37.6
5	Cloud top above warm layer and −5°C > CTT ≥ −10°C	126	13.0	53.1	46.8
6	Cloud top above warm layer and CTT < −10°C	242	24.9	21.5	78.5

et al. found that the warm rain process was unambiguously responsible for freezing precipitation (ZL or ZR) in nearly 47% of the soundings in the database. In these soundings, the clouds either had temperatures entirely below freezing (categories 1 and 2), or had top temperatures that were above freezing (category 3). Since CZ did not consider the warm rain process, we excluded these soundings from the final database. Another 28% of the soundings had cloud-top temperatures between 0° and −10°C. Clouds with top temperatures >−10°C are also likely to support an active warm rain process, since ice nucleation is not very effective at these warm temperatures (Pruppacher and Klett 1997). It is uncertain whether the CZ criteria is applicable in these cases. To reduce uncertainty, these soundings were also removed from the final database to eliminate the possibility that the warm rain process was responsible for the precipitation. The ZR and ZL soundings comprising RB's category 6 had cloud-top temperatures <−10°C. Under these conditions, ice particles should form aloft and fall into the warm layer, conditions conforming to those required by the CZ criteria. The category 6 soundings (about 25% of the original ZL and ZR database) were retained for further analysis. Of the 242 category 6 stations, 190 (78.5%) reported ZR and 52 (21.5%) reported ZL.

The 79 IP soundings were divided into two categories based on the presence or absence of a warm layer (>0°C) aloft. Fifteen soundings did not have a warm layer. Ice pellets in these cases must have formed by riming of small ice crystals as they fell through a layer of supercooled water, rather than by the melting and refreezing process required by CZ. The remaining 64 soundings had a warm layer aloft so that ice particles from aloft could partially melt. These 64 soundings conformed to the CZ environmental profile and were retained for further analysis.

4. Results

Figure 3 shows the average warm layer temperature (°C) plotted as a function of warm layer depth (m) for (a) each of the 190 category 6 soundings where ZR was reported, (b) each of the 52 category 6 soundings where ZL was reported, and (c) each of the 64 IP soundings. The method for estimating the average warm layer temperature is described in the appendix. An obvious correlation between the depth and mean temperature of the warm layer appears in the data on all three diagrams; however, none of the diagrams supports a relationship between a specific critical radius and a freezing rain–ice pellet boundary. For example, if we consider the value of the critical radius suggested by CZ (400 μm), then 48.4% of the ZR soundings and 51.9% of the ZL soundings would lie in the IP regime (Figs. 3a,b). Similarly, 32.8% of the IP soundings would lie in the ZR and ZL regime (Fig. 3c). Other values of the critical radius have poor diagnostic skill as well.

Reasons for the lack of diagnostic skill most probably relate to the variability in ice particle shapes and size distributions in clouds that produce ZR and IP. Czys et al. (1996) calculations were based on the assumption that spherical ice particles were falling into the warm layer. In situ observations of particles entering the melting layer by Ohtake (1969), Stewart et al. (1984), Fujiyoshi (1986), Barthazy et al. (1996), and others show that aggregates, rather than graupel, are the common ice particle type falling into the melting layer in winter stratiform clouds. In fact, microphysical models of winter stratiform clouds (e.g., Passarelli 1978; Szyrmer and Zawadski 1999) typically do not even consider graupel. Spherical particles can be expected to form when elevated convection occurs above the warm layer leading to heavy riming. The soundings represented in Fig. 3 generally do not correspond to conditions associated with elevated convection. Figures 4a–c shows the geographic distribution of soundings appearing in Figs. 3a–c, respectively. Although the soundings occur throughout the United States east of the Rockies, most occur on the east side of the Appalachian Mountains and just north of the Ohio River Valley. These locations commonly experience freezing precipitation or ice pellets during warm frontal overrunning and Appalachian cold air damming and trapping events (Kocin and Uccel-

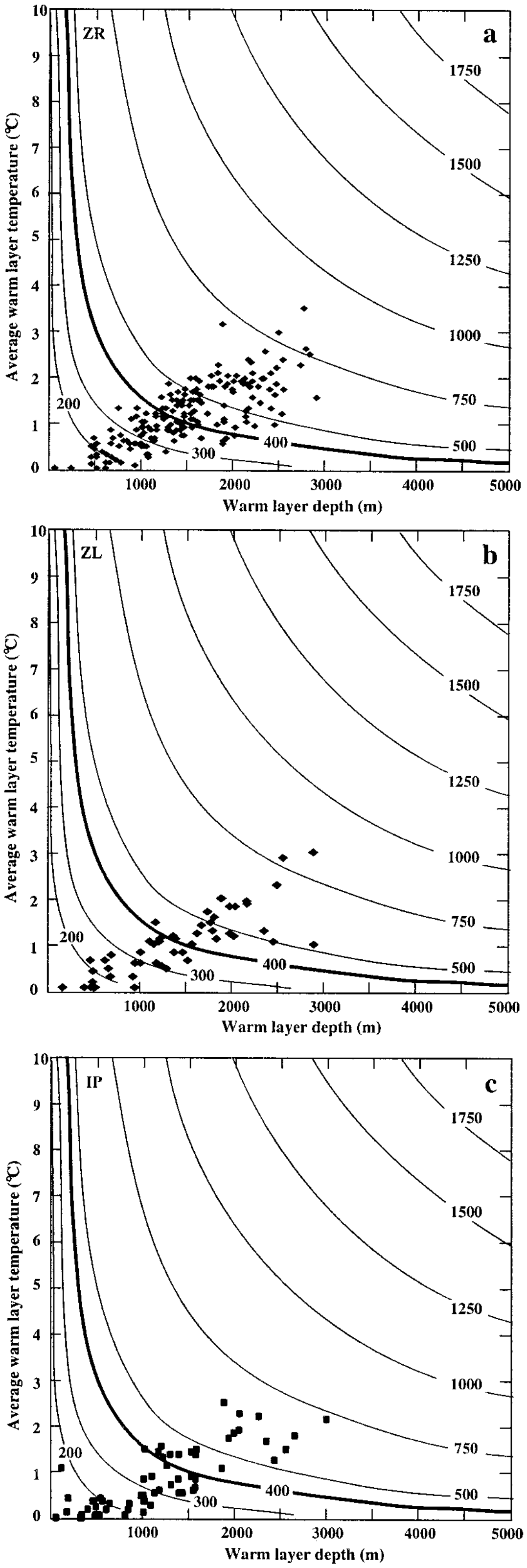

FIG. 3. The isonomogram in Fig. 1 with (a) data points from soundings where stations reported ZR, (b) data points from soundings where stations reported ZL, and (c) data points from soundings where stations reported IP. Data are shown only for those stations that met the criteria discussed in section 3.

lini 1990). To determine the likelihood that convection could lead to spherical particles in conditions represented by these soundings, each sounding in Fig. 3 was examined to determine if elevated convection was possible above the low-level stable layer. Of the 242 ZR–ZL soundings in Figs. 3a and 3b, 93% were absolutely stable. Of the IP soundings in Fig. 3c, 97% were absolutely stable. These findings conform to surface reports of freezing precipitation analyzed by Robbins (1998). Robbins analyzed a 15-yr database of surface observations and found that 97% of the freezing precipitation reports were of light precipitation, 3% of moderate precipitation, and none of heavy precipitation characteristic of convection. These data suggest that elevated convection is infrequent and generally not strong during freezing precipitation and IP events, and are consistent with the idea that ice particles falling into the melting level are typically aggregates.

Aggregates and ice crystals both have a large surface to volume ratio and undoubtedly melt at a different rate than spherical particles. This in itself might account for many of the ZR and ZL cases in the IP regime in Fig. 3a. It is also possible that particles that are almost completely melted do not have sufficient time to refreeze in their fall through the low-elevation cold layer if the layer is neither too cold nor deep. Many IP points occur in the ZR regime in Fig. 3b. Apparently, complete melting of these falling particles did not occur at the predicted rate. One possible reason for this would be that the air through which melting particles were falling was unsaturated. In this case, evaporation would cool the particles to the wet-bulb temperature, reducing the rate at which melting proceeds.

Another issue complicating the application of the CZ nomogram, even if it showed diagnostic skill, would be the real-time choice of a critical radius. Although CZ found that a critical radius of 400 μm “applied well to the 17 cases examined during the 1995/96 forecast experiment,” it is not clear what general criteria one could use to assign a critical radius in more general application of the CZ technique. Czys et al. (1996) recommended using rain-rate or reflectivity data to establish a critical radius, but these parameters have large temporal and spatial variability, making assignment of a unique value of a critical radius difficult.

5. Summary

The general applicability of the isonomgram developed by Czys et al. (1996) for diagnosing the position of the boundary between freezing precipitation (freezing rain or drizzle) and ice pellets (sleet or snow grains) was tested using a 25-yr sounding database consisting of 1051 soundings, 581 reporting freezing drizzle, 391 reporting freezing rain, and 79 reporting ice pellets. It was found that only 306 of the 1051 soundings clearly conformed to the Czys et al. (1996) environmental temperature and moisture profile, which consisted of a three-layer atmosphere with a cold cloud layer aloft that is a source of ice particles, a midlevel layer where the temperature exceeds 0°C and ice particles melt, and a surface layer where $T < 0°C$. The remaining soundings did not conform either because freezing precipitation formed due to the warm rain process or ice pellets formed due to riming rather than melting and refreezing. For the soundings conforming to the CZ profile, the isonomogram showed little skill in delineating between ZR–ZL and IP. Freezing rain or drizzle occurred about 50% of the time that ice pellets were diagnosed. Ice pellets occurred in nearly a third of the cases where freezing precipitation was expected. These results can probably be attributed to the fact that the physics of the melting process are more complicated than those used to develop the simple isonomogram.

Although these results are discouraging, it may be possible in the future to develop a forecasting technique that incorporates more of the complex physics of ice particle melting. This information may then be used to improve weather-type prediction algorithms in numerical forecast models (e.g., Baldwin and Contorno 1993). Key to the development of any technique are observations of the habits of ice particles falling into the melting layer, and observations that can delineate warm rain from ice processes. Polarization radar techniques hold promise for addressing these issues (e.g., Reinking et al. 1997; Vivekanandan et al. 1999; Zrnic and Ryzhkov 1999). Hopefully, when polarization capabilities are incorporated into the national Doppler network, the identification of precipitation types in the zone of freezing rain and ice pellets will become possible.

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APPENDIX

Average Warm-Layer Temperature

For forecasting applications, a simple method of calculating the average warm layer temperature, T_{avg}, is desirable. Soundings conforming to the CZ profile typically have an elevated warm layer with a temperature profile similar to that shown in Fig. A1. For this profile, the warm-layer area can be approximated as a triangle, two sides along the sounding and the third at the 0°C isotherm. Considering the large triangle ABC in Fig. A1, T_{avg} can be estimated as that temperature where the area of the trapezoid AEDC equals the area of the small triangle BDE. From geometric considerations, this occurs when

$$T_{\mathrm{avg}} = \left(1 - \frac{1}{\sqrt{2}}\right)T_{\mathrm{max}} = 0.3T_{\mathrm{max}}, \qquad \text{(A1)}$$

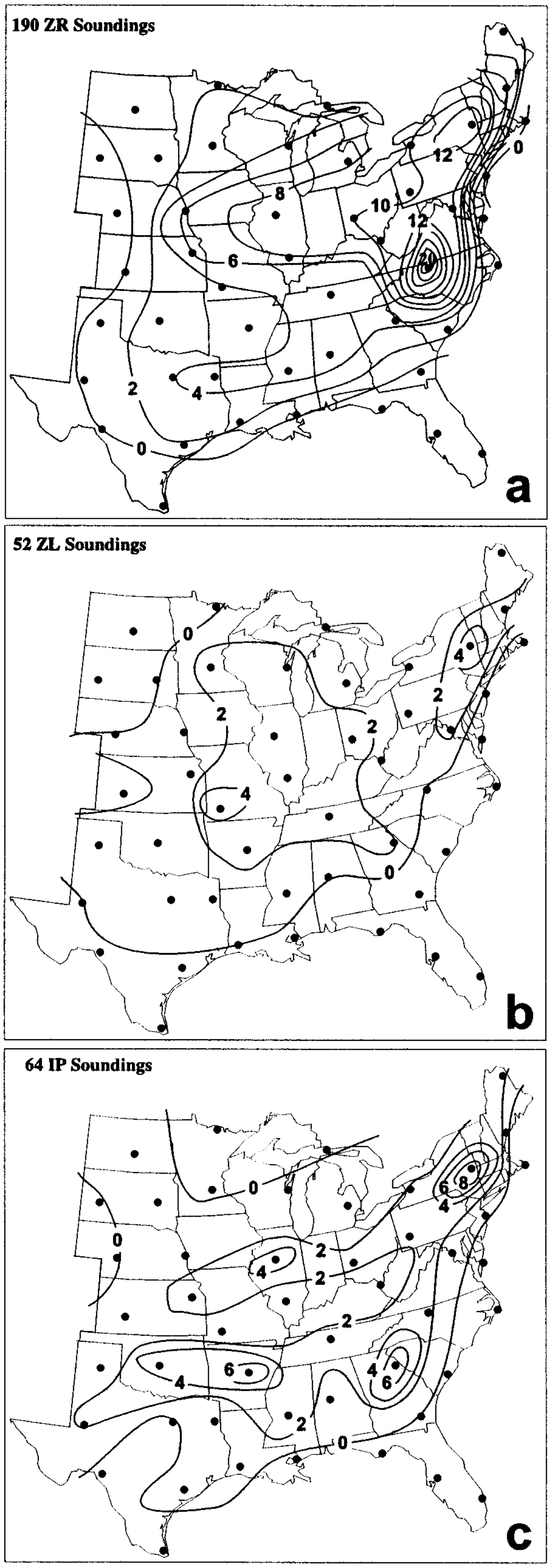

FIG. 4. Geographic frequency distribution of soundings appearing in Figs. 3a–c.

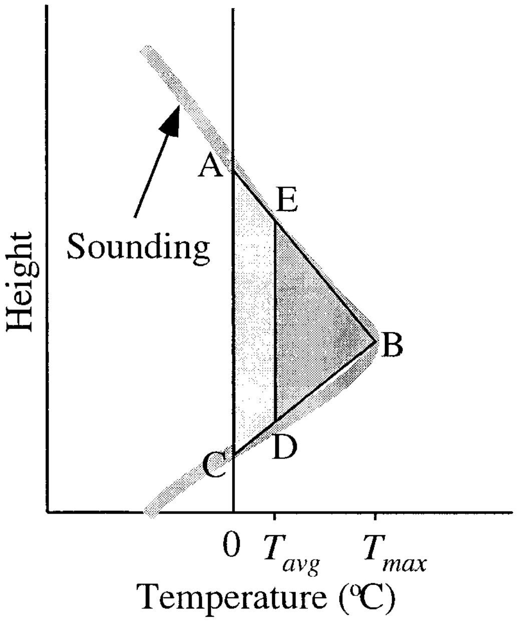

FIG. A1. Sounding with triangle illustrating the method used to calculate the average warm-layer temperature.

where T_{max} is the maximum temperature in the warm layer. Equation (A1) was used with T_{max} values from the soundings to calculate T_{avg} values appearing in Fig. 3.

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