Regional and Local Influences on Freezing Drizzle, Freezing Rain, and Ice Pellet Events

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(Manuscript received 15 November 1999, in final form 2 March 2000)

ABSTRACT

Regional and local influences on frequency and type of freezing precipitation (freezing drizzle, freezing rain, and ice pellets) are investigated via in-depth climatologies of six continental United States (CONUS) sounding sites. For each site, wind roses of precipitation type occurrences are compared with those for nearby stations and the aggregate values for the CONUS. Synoptic scenarios and sounding structures are identified for prolonged events of each precipitation type and probable formation mechanisms are discussed. Station location relative to topographic features smaller than 1 km in height, water bodies ranging in size from oceans to small bays, and dominant wintertime storm tracks are shown to play a major role in the determination of the frequency and type of freezing precipitation at each site. Results help to explain the regional maxima and minima of freezing precipitation across the CONUS, as well as the dominance of certain precipitation types and formation mechanisms in different portions thereof. Understanding these differences is necessary for proper development of techniques used to diagnose and forecast surface precipitation type and the occurrence of hazardous aircraft icing conditions associated with freezing precipitation aloft.

1. Introduction

Freezing precipitation has been well documented as the cause of extensive damage to property, utility service wires, and disruption to surface transportation (Regan 1998; Rauber et al. 1994; Martner et al. 1992; Bendel and Paton 1981). Primarily thought of as surface phenomena, freezing drizzle and freezing rain can extend from the surface to altitudes of 10 000 ft or more (Jeck 1996), have been observed as high as 20 000 ft (Cober et al. 1999; Isaac et al. 1999), and can be just as insidious to aircraft. Both freezing drizzle and freezing rain can have a significant impact on aircraft performance (Bernstein et al. 1999; Isaac et al. 1999; Ashenden and Marwitz 1997; Jeck 1996; Politovich 1989; Cooper et al. 1984; Sand et al. 1984; Lewis 1951), and may have been a contributing factor in several recent commercial aircraft crashes (Sand and Biter 1999; Paull and Hagy 1999; Marwitz et al. 1997; Pike 1995; Politovich and Bernstein 1995).

The formation mechanisms for these precipitation types, as well as ice pellets, have been documented thoroughly (Rauber et al. 2000; Zerr 1997; Isaac et al. 1996; Cober et al. 1996; Stewart and King 1987; Stewart 1985; Ohtake 1963). Their structures and vertical extents have been examined with soundings (e.g., Robbins 1998; Jeck 1996; Stewart et al. 1990) and remote sensors (e.g., Martner et al. 1993; Prater and Borho 1992), and their geographic distributions have been well described (Cortinas 2000; Stuart and Isaac 1999; Bernstein and Brown 1997; Strapp et al. 1996; Robbins and Cortinas 1996; Vilcans and Burnham 1989; McKay and Thompson 1969). The geographic studies have indicated that regional maxima of freezing precipitation (FZPCP) exist across the contiguous United States (CONUS) and Canada. These maxima have been shown to be related to major storm tracks, topographic features, and moisture sources. Recent sounding climatologies by Strapp et al. (1996) and Rauber et al. (2000) demonstrated regional differences in the occurrence of FZPCP and probable formation mechanisms by examining cloud-top temperatures (CTT) and the existence of potential melting zones aloft.

In an effort to more closely examine the regional differences in the processes that form FZPCP, in-depth climatologies of surface wind observations, synoptic-scale weather patterns, and radiosonde data are examined for six sites across the CONUS for prolonged (five or more hour duration) events of freezing drizzle (FZDZ), freezing rain (FZRA), ice pellets (PL), and mixtures thereof. The sites were chosen because they each received an average of at least 10 h of FZPCP per year and were the locations of regular soundings during the period for which surface maps were readily available

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for study (1975–90). To highlight local effects, distributions of FZDZ, FZRA, and PL as a function of wind direction for the period 1961–90 were compared with distributions from nearby stations and for all CONUS stations combined. Ice pellets are included in this discussion because their formation mechanisms are very similar to those for FZRA and FZDZ, and the occurrence of PL at the surface implies the presence of FZRA and/or FZDZ aloft.

Young (1978) noted that surface winds during FZPCP were highly variable from station to station, and that differences in surface wind direction may be important when considering the influences of location and topography. Stuart and Isaac (1999) demonstrated this by revealing the importance of the local effects of Hudson's Bay and the Atlantic Ocean on FZPCP in Canada, but they only briefly speculated on their causes. Strapp et al. (1996) demonstrated similar effects from these moisture sources, as well as the Beaufort Sea. Cortinas (2000) observed that winds off of several of the Great Lakes appeared to suppress the occurrence of FZRA by advecting low-level above-freezing air to stations immediately downwind. In this paper, the relationship between surface winds, and their potential relationship to the enhancement or suppression of FZPCP, will be explored in a more systematic manner.

2. Formation mechanisms

The two mechanisms firmly established as the causes of FZPCP are the collision–coalescence (CC, or ''warm rain'') and ''classical'' melting processes (e.g., Huffman and Norman 1988; Bocchieri 1980; Ohtake 1963). The CC process typically occurs in situations where clouds are primarily composed of liquid water, at above and/or below freezing temperatures. For this to occur, CTTs are typically greater than $-10°C$, where significant snow production is not expected (Politovich 1989; Rauber et al. 2000). Rasmussen et al. (1995) noted that low concentrations of cloud condensation nuclei combined with significant liquid water content (>0.25 g m^{-3}) may be important in the growth of cloud-sized drops to drizzle sizes by the CC process.

The classical melting process occurs when snow falls into a layer of above-freezing air, melts to form rain or drizzle, then falls into a layer of subfreezing air to become supercooled rain or drizzle (FZRA or FZDZ). It generally has been accepted that most FZRA forms via the melting process, and Huffman and Norman (1988) found that about 62% of all FZRA was associated with warm layers aloft. Rauber et al. (2000) found that CC was the likely formation process in many of those instances, however, since CTTs were greater than $-10°C$. They state that the melting process likely was responsible for only 24% of all of the FZPCP cases they studied.

Ice pellets have also been shown to form by either process. Hanesiak and Stewart (1985) and Zerr (1997) each used observational and modeling studies to determine that the primary formation mechanism for PL appears to be incomplete melting of snowflakes during the classical process. They concluded that melting zones were too cool and/or shallow to completely melt snowflakes, that ice particles remained suspended within the raindrops, and that subsequent supercooling caused the water drops to freeze and form ice pellets. Freezing of completely melted droplets in the subfreezing zone below was considered a secondary mechanism. Ice pellets can also form by freezing of supercooled drizzle droplets that were formed via the CC process (Kajikawa et al. 1988).

3. Datasets and analysis techniques

Surface data used in this study were taken from the National Climatic Data Center Solar and Meteorological Surface Observation Network dataset (NOAA 1993). This dataset includes hourly and 3-hourly observations of present weather, including precipitation type and intensity, wind speed and direction, temperature, ceiling, and other standard fields that appear in National Weather Service observations. While the data cover the years 1961–90, gaps appear for certain years at certain stations, and there was some inconsistency in the reporting of precipitation. The 207 stations used in this study (see Fig. 1 for locations) had complete or nearly complete data for the 30-yr period. Since gaps in the data did not occur during particular times of the day or year when FZPCP did/did not commonly occur, the gaps could be accounted for by extrapolating the number of occurrences of FZPCP for all observations taken to the number expected if all observations were available. Slight inaccuracies from this approach only affected the average annual counts of FZPCP mentioned at the beginning of the discussion for each station, and had little or no effect on the remaining topics discussed.

Soundings were obtained from an NCDC database covering the period 1946–92 (NOAA 1996). Pressure, temperature (T), dewpoint, wind speed, and wind direction were available at standard and significant levels. In this paper, soundings are plotted versus height to more easily identify melting, supercooling, and refreezing zones, and their characteristics. Soundings were only examined if the FZDZ, FZRA, or PL observations were made during the flight of the sonde (at 1100 or 1200 UTC for 1200 UTC soundings; at 2300 or 0000 UTC for 0000 UTC soundings). National Weather Service facsimile maps from 0000 and 1200 UTC were used for the analysis of synoptic-scale surface weather patterns present during FZPCP events.

4. National climatology

In this section, a national climatology is developed to provide a reference frame for the regional discussions to follow. Using data from all 207 CONUS stations,

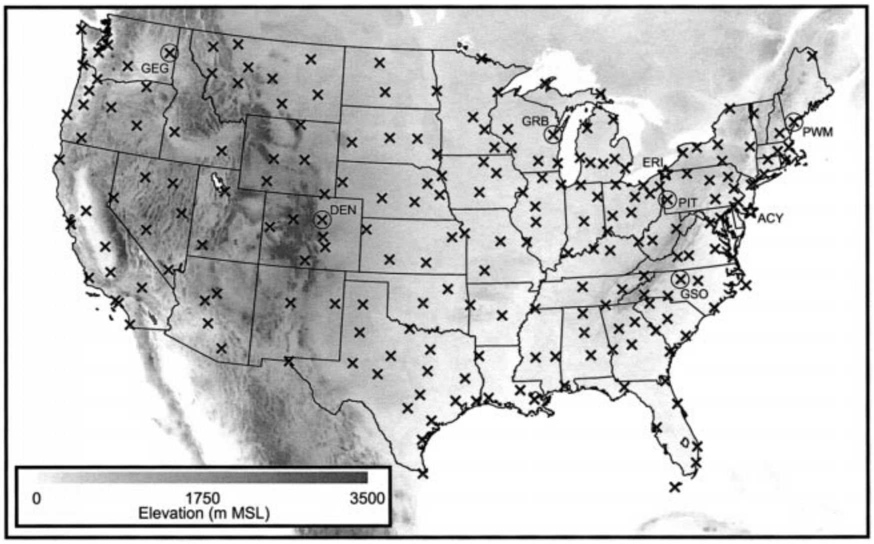

FIG. 1. Locations of the 207 surface stations (X) and six sounding sites (circled Xs) used in this study. GEG is Spokane, WA; DEN is Denver, CO; GRB is Green Bay, WI; PIT is Pittsburgh, PA; PWM is Portland, ME; and GSO is Greensboro, NC. The locations of Erie, PA (ERI), and Atlantic City, NJ (ACY), are indicated with stars.

more than 100 000 observations of FZPCP were found. Approximately 44% of these were FZDZ, 32% were FZRA, and 24% were PL (Fig. 2). Distributions of FZDZ, FZRA, and PL occurrences with wind direction (every 10°) were compiled for all stations combined (Fig. 3). The jagged nature of these distributions is the result of irregular reporting of wind direction in surface observations. An examination of the number of reports of wind direction alone, regardless of the weather present, also exhibits a jagged nature. Since these observations were taken manually, it appears that there was a slight preference to report certain wind directions. For example, winds from 170° and 190° were each reported roughly half as often as those from 180°. It is possible to adjust for these overall biases, but since they are unlikely to have been consistent from station to station, the original counts of each precipitation type versus wind direction were left intact. If winds were calm at the time of the observation, then it was counted as such, and no wind direction was applied to it.

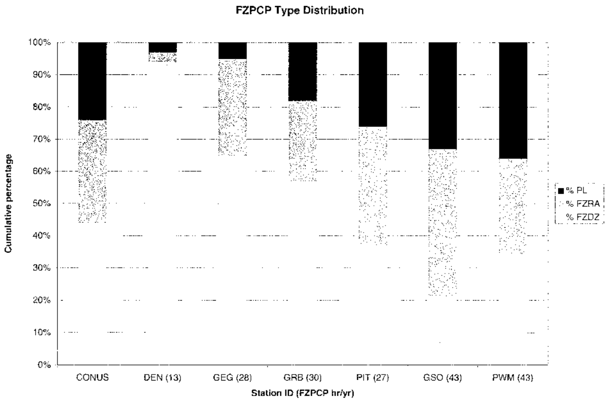

FIG. 2. Percentage of FZPCP that fell as FZDZ (light gray bars), FZRA (dark gray bars), and PL (black bars) at the six sounding sites and for the CONUS. Average annual hours of FZPCP are shown in parentheses for each sounding site.

Overall, FZPCP occurred most often with winds from between north and east, and least often with winds from between the south-southwest and west-northwest. This is roughly the opposite of the general wind direction tendencies seen in Fig. 3b. The FZRA wind rose has a distinct peak with winds from between northeast and east. Values for FZRA gradually decrease clockwise to near zero with winds from the southwest and west, rise gradually with winds from the northwest, then sharply peak with winds from the east-northeast. Patterns for PL are very similar, but the peak is broader, covering wind directions from north to east-northeast. The shift to a slightly more northerly wind direction for the broad PL maximum relative to the FZRA maximum is consistent with expectation of slightly colder air in the supercooling and/or melting layers during PL events. Also, when FZRA and PL occur simultaneously in a given area, the PL tends to fall closer to the surface cold air source, where winds are likely to have more of a northerly component.

FZDZ is most common with winds from the north and the distribution has a broad maximum with winds from between north and east. Occurrences of FZDZ drop off gradually as surface winds change clockwise from the east to the south, are at a relative minimum when winds are from between south-southwest and west-northwest, and increase sharply as winds go from west-northwest to the peak at due north. The weaker minimum with winds from the southwest and west gives

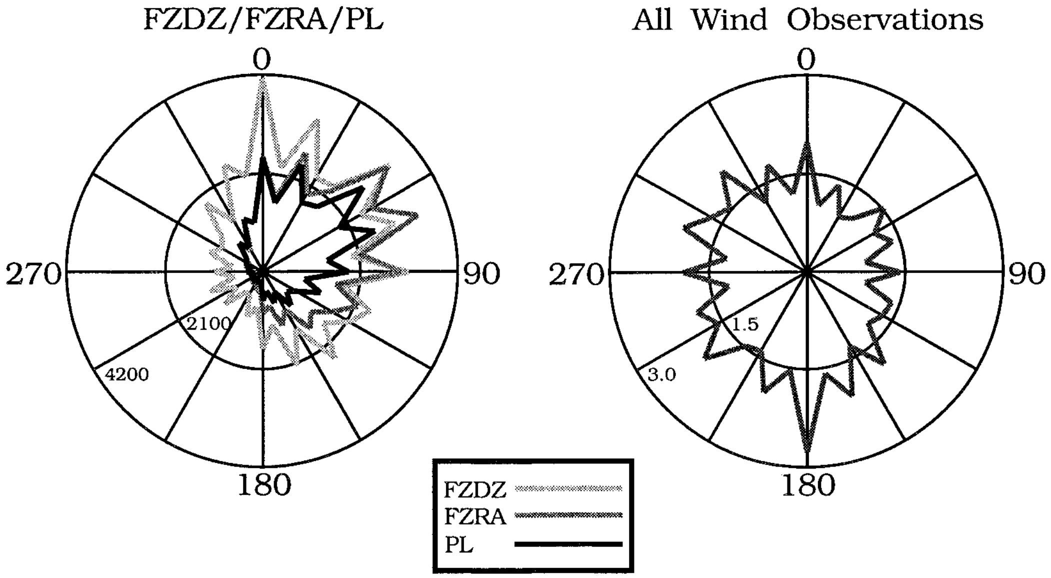

FIG. 3. (a) Distribution of the number of hours of FZDZ (light gray), FZRA (dark gray), and PL (black) with wind direction for all 207 stations combined. (b) Distribution of the number of hours of reported wind direction for all 207 stations combined. Values in (b) are × 10^6.

evidence that while it is relatively uncommon for FZDZ to occur with these wind directions, it is still much more common than FZRA or PL. These results compare well with those from Bernstein et al. (1998), who indicate that FZDZ, FZRA, and PL occur most often on the cold side of stationary fronts and warm fronts, to the northeast of low pressure centers, where winds from between the north and southeast tend to dominate. That study indicated that FZDZ occurs in a broader range of locations relative to synoptic systems, including deep within Arctic high pressure areas, and immediately surrounding low pressure centers. Politovich (1989) also identified a variety of cloud types and related forcing mechanisms that can lead to FZDZ aloft. The somewhat broader distribution of FZDZ with wind direction corroborates the findings of those earlier studies.

The relative depth of the saturated layer needed for the formation of FZDZ versus FZRA and PL may be partially the cause of the more common occurrence of FZDZ with winds from the southwest and west. Since the primary mechanism for FZDZ formation is CC, it can form in relatively warm (CTT $> -10°C$), shallow clouds that are sometimes less than 1000 m deep (Cober et al. 1995; Isaac et al. 1999; Ohtake 1963). Local topography and/or moisture sources can help to form or enhance such clouds in environments where they would otherwise not form or reach adequate depths to produce precipitation. Regardless of whether FZRA is formed via melting or CC, it typically requires greater cloud depths, which are uncommon in most of the CONUS when surface winds are from the southwest and west. If CC is the formation mechanism, then greater residence time is necessary for the drops to grow to FZRA sizes. If melting is the formation mechanism, then substantially deeper clouds are typically necessary to cover the range of temperatures needed for snow to form aloft, fall into a melting layer, then a surface-based supercooling layer.

5. Freezing precipitation at selected sites

In this section, National Weather Service surface maps and sounding data are examined for events in which FZPCP was observed for a period of five or more hours at selected sounding sites. Breaks in the FZPCP of up to 2 h were allowed within a given event. For a case to be considered, the FZPCP had to occur at the site during the time of balloon flight (1100, 1200, 2300, or 0000 UTC). ''Pure'' events discussed in this section are those where only one FZPCP type was reported within ±3 h of the sounding launch time. Other precipitation types, such as snow, could be mixed into pure events. For each site, the distribution of FZDZ, FZRA, and PL occurrences with wind direction will be discussed, and compared with those from nearby stations and the aggregate distribution for all CONUS stations. For commonly observed FZPCP scenarios, prototypical surface maps and soundings compiled from several cases are presented. Sounding statistics for all sites are given in Table 1.

a. Denver, Colorado

Denver is located to the west of the main FZPCP maximum found across the Midwest and plains states, receiving approximately 13 h of FZPCP per year, with 94% as FZDZ, 3% as FZRA, and 3% as PL (Figs. 2 and 4). Denver's FZDZ wind rose (Fig. 5a) shows that

TABLE 1. Sounding features for each FZPCP type and mixtures thereof for the six sounding sites examined. N/A = no data, CC = collision–coalescence, MLT = melting.

Type	Category	DEN	GEG	GRB	PIT	GSO	PWM
Pure FZDZ	Soundings	15	14	7	5	9	9
	Primary forcing	Upslope	Unknown	Overrunning	Upslope	Overrunning	Overrunning
	Supercooled layer depth (m)	300–1800	400–1000	900–3800	1000–2400	200–1900	300–1500
	$T_{\min}$ range	−14° to −5°C	−10° to −2°C	−12° to −3°C	−12° to −6°C	−7° to −1°C	−8° to −2°C
	Primary mechanism	CC	CC	CC	CC	CC	CC
FZDZ–FZRA mixture	Soundings	0	1	1	7	15	9
	Primary forcing	N/A	Overrunning	Overrunning	Overrunning	Overrunning	Overrunning
	Potential melting layer depth (m)	N/A	1000	0	1300–2000	600–2200	300–2700
	$T_{\max}$ range	N/A	2°C	0°C	2°–6°C	2°–9°C	0°–9°C
	Supercooled layer depth (m)	N/A	100	1200/3300*	200–1000	300–1300	200–1300
	$T_{\min}$ range	N/A	−1°C	−4°/−8°C*	−7°C to −2°C	−8° to −3°C	−6° to −1°C
	Primary mechanism	N/A	CC to MLT	CC	CC and MLT	CC and MLT	CC and MLT
Pure FZRA	Soundings	0	6	4	1	11	6
	Primary forcing	N/A	Overrunning	Overrunning	Overrunning	Overrunning	Overrunning
	Potential melting layer depth (m)	N/A	500–1400	1200–1400	1100	1200–2700	800–2800
	$T_{\max}$ range	N/A	1°–3°C	2°–4°C	3°C	4°–10°C	3°–7°C
	Supercooled layer depth (m)	N/A	100–700	300–1000	300	300–900	100–1400
	$T_{\min}$ range	N/A	−3° to −1°C	−5° to −1°C	−4°C	−6° to −1°C	−7° to −1°C
	Primary mechanism	N/A	MLT	MLT	MLT	MLT	MLT
FZRA–PL mixture	Soundings	0	0	3	8	17	5
	Primary forcing	N/A	N/A	Overrunning	Overrunning	Overrunning	Overrunning
	Potential melting layer depth (m)	N/A	N/A	400–700	200–1300	400–2600	0–1500
	$T_{\max}$ range	N/A	N/A	0°–2°C	0°–4°C	0°–8°C	0°–4°C
	Supercooled layer depth (m)	N/A	N/A	1600–2200	500–2100	300–1400	500–1800
	$T_{\min}$ range	N/A	N/A	−10° to −6°C	−7° to −3°C	−8° to −2°C	−14° to −4°C
	Primary mechanism	N/A	N/A	MLT	MLT	MLT	MLT
Pure PL	Soundings	0	1	0	0	5	5
	Primary forcing	N/A	Unknown	N/A	N/A	Overrunning	Overrunning
	Potential melting layer depth (m)	N/A	N/A	N/A	N/A	500–1400	0–2300
	$T_{\max}$ range	N/A	N/A	N/A	N/A	0°–3°C	0°–7°C
	Supercooled layer depth (m)	N/A	1100	N/A	N/A	600–1800	1000–2000
	$T_{\min}$ range	N/A	−9°C	N/A	N/A	−12° to −2°C	−11° to −2°C
	Primary mechanism	N/A	CC	N/A	N/A	MLT	MLT

* Values for below potential melting zone and for entire cloud layer, including above the potential melting zone.

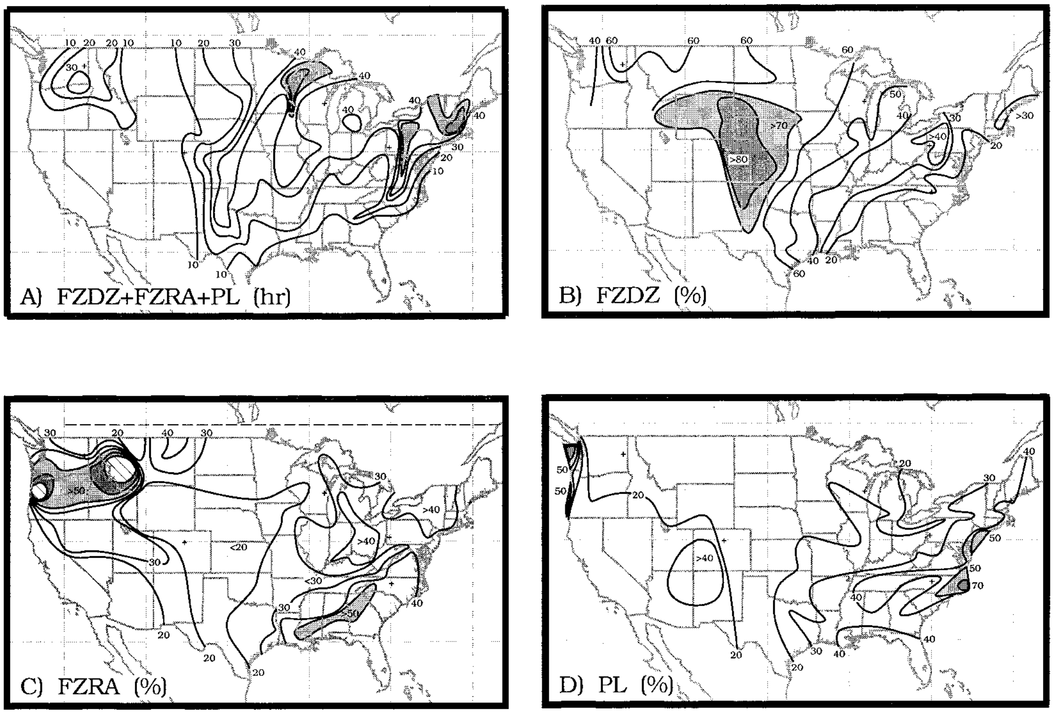

FIG. 4. Geographic distribution of (a) average annual hours of freezing precipitation (FZDZ + FZRA + PL), and the percentage of freezing precipitation that fell as (b) FZDZ, (c) FZRA, and (d) PL. Light and dark gray shading is for (a) >50 h and >60 h, (b) >70% and >80%, (c) >50% and >70%, and (d) >50% and >70%. Hatching in (c) is for >80%.

nearly all of it occurred when surface winds were from between north and east. This distribution is linked to Denver's location just east of the Rocky Mountains and north of the Palmer Divide, a rise of ~700 m to its south (Fig. 6). Winds from between south and northwest were downslope and tended to cause low-level drying, while winds from between north and east were upslope and were more likely to form clouds and FZDZ. In all but one FZDZ event, Denver received the FZDZ following the passage of Arctic cold fronts, when high

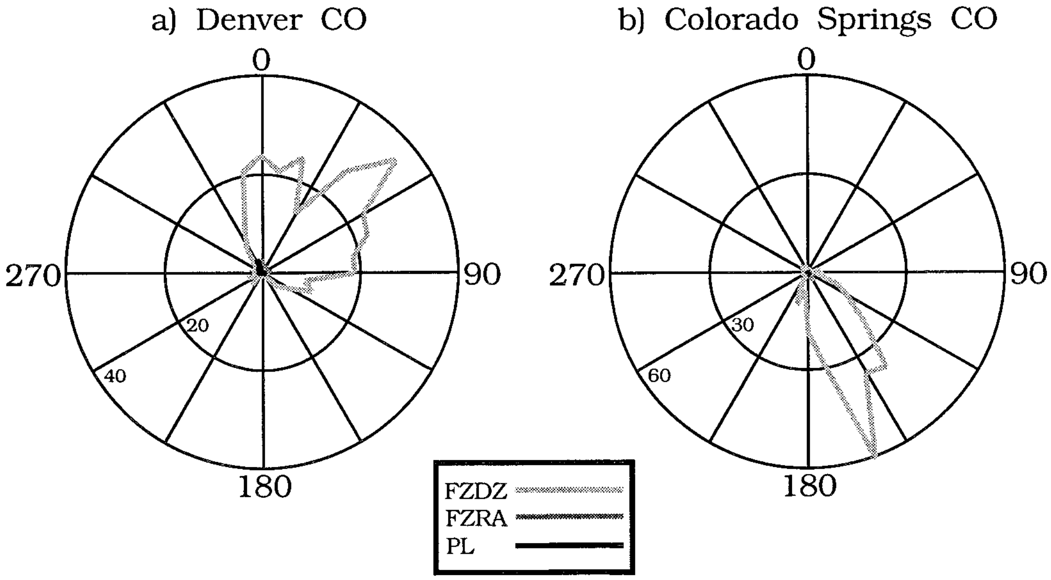

FIG. 5. Distribution of the number of hours of FZDZ (light gray), FZRA (dark gray), and PL (black) with wind direction for (a) Denver and (b) Colorado Springs, CO. Outer rings are for (a) 40 and (b) 60 h.

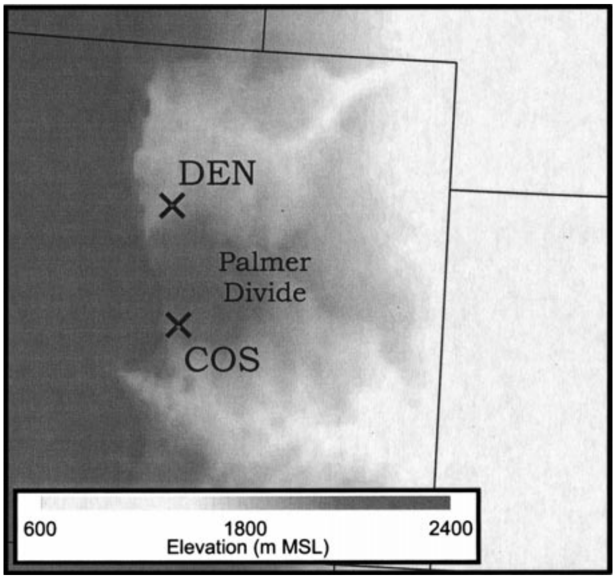

FIG. 6. Map of the regional topography surrounding Denver (DEN). COS = Colorado Springs, CO.

pressure was over the northern Great Plains (Figs. 7a,b). In about 40% of the events, a low pressure center in southern Colorado worked in conjunction with the Great Plains high to produce the upslope flow (Fig. 7c).

The occurrences of FZDZ with winds from the north-northwest was sometimes associated with the ‘‘Denver Cyclone,’’ a local cyclonic circulation that set up as surface high pressure centers moved southward into the central plains states or low-pressure was located to the south (Szoke 1991; Figs. 7b,c). The Denver Cyclone has been noted in several well-documented Denver-area FZDZ events (Politovich and Bernstein 1995; Rasmussen et al. 1995; Bernstein et al. 1995). Sounding data indicated that all of the FZDZ in the three primary synoptic setups was formed via the CC process, since no melting layers were present. Supercooled cloud layers were 300–1800 m in depth, with minimum temperatures ($T_{\min}$) of -14°C to -5°C (Table 1), and were often capped by dry air and downslope winds above. These results are consistent with those of Jeck (1996) and Strapp et al. (1996), who found similar sounding structures and noted the dominance of FZDZ at Denver.

Several mechanisms have been proposed for the en-

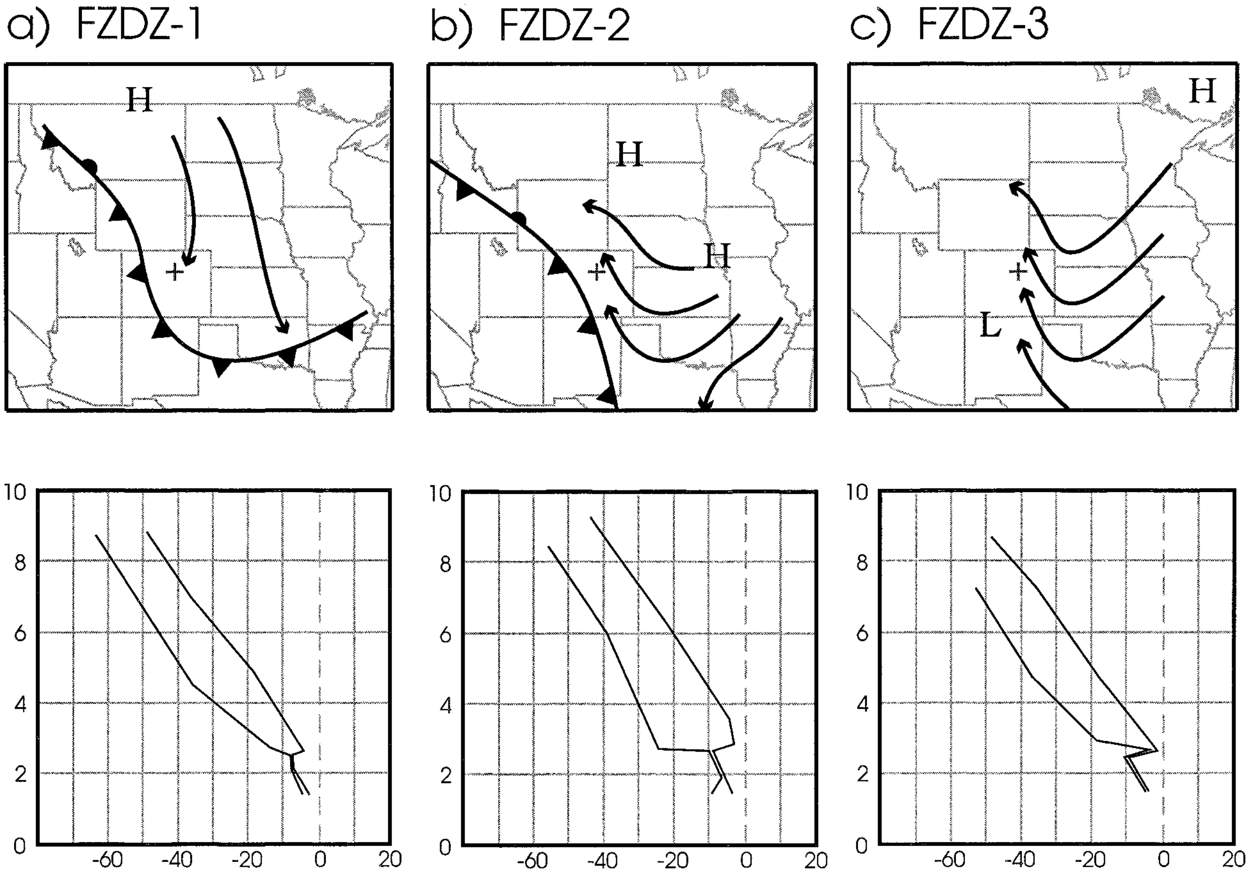

FIG. 7. Common synoptic setups and sounding structures for FZDZ in (a) post-cold-frontal upslope, (b) southeasterly return flow, and (c) hybrid cyclonic and aniticyclonlic southeasterly flow at Denver (+). Streamlines (black arrows) and standard symbols for fronts, high and low pressure centers are plotted. On sounding plots, heights are in km MSL and temperatures and dewpoints are in °C.

hancement of the potential for FZDZ formation via the collision–coalescence process. Cooper (1989) suggested that inhomogeneous mixing at cloud top may help to enhance droplet sizes in such clouds, and Pobanz et al. (1994) proposed that this mixing process may be enhanced by wind shear at cloud top, possibly leading to FZDZ formation. Bernstein and Politovich (1996) found that similar shear layers located well below cloud top were associated with marked increases in droplet sizes in one Denver FZDZ event. Cober et al. (1996) also found shear well within a stratiform cloud deck that contained FZDZ. They noted that low aerosol concentrations helped initiate the CC process by furnishing a cloud drop distribution that had fewer droplets, and included some with diameters larger than 40 μm. In their case, the shear criteria of Pobanz et al. (1994) was not met at cloud top, yet droplets with radii of 100 μm were present within 100 m of cloud top. Rasmussen et al. (1995) noted shear as a possible contributor in their FZDZ case but stressed the importance of warm cloud tops (CTT > -10°C) that suppressed the formation of ice crystals at cloud top, the existence of low concentrations of cloud condensation nuclei, and liquid water contents of 0.25 g m^{-3} or more. At this point, a consensus on this issue has not been reached, and it is still unclear what the primary mechanisms are for the enhancement of the droplet sizes.

The importance of the Palmer Divide for FZDZ in this area is clearly borne out by comparing the Denver wind rose with that for Colorado Springs (Figs. 5b and 6). Colorado Springs is located on the south side of the Palmer Divide, where winds from the southeast are upslope and those with a north or west component are downslope. This difference is quite evident in the wind rose, which shows that nearly all FZDZ occurred with southeast winds there. Clearly, topography plays a major role in the formation of FZDZ in the Denver area. Denver's location to the northwest of a common wintertime storm track, which runs from a cyclogenesis zone in southeastern Colorado up to the central Great Lakes, is also important. It is not common for Denver to be located within the northeast quadrant of well-developed, low pressure centers [Reitan (1974); Zishka and Smith (1980); also 3 of the 15 cases studied here], where most FZPCP occurs, especially that formed by the melting process (Bernstein et al. 1998). It also may partially explain the strong gradient in FZPCP occurrences across Kansas and Colorado, and the high percentage of FZPCP that falls as FZDZ in the high plains (Fig. 4b), since FZDZ falls in a wider variety of locations relative to synoptic-scale weather systems than FZRA and PL do.

FZRA and PL were extremely rare in Denver, despite the occasional storm that combined strong low pressure to the south or southwest with an influx of Arctic air from the north. While such systems have sometimes brought significant snowfall to the Denver area (e.g., Cotton et al. 1994; Marwitz and Toth 1993), they did not tend to bring FZRA or PL. FZRA and PL, and probably the classical melting scenario, in general, rarely occurred west of about 100° longitude, with the exception of in the Columbia Basin. Rauber et al. (2000) support this assertion, as very few of the high plains soundings they examined had both CTT < -10°C and a potential melting zone. Their study showed a distinct west-to-east gradient in the occurrence of the melting mechanism across the Great Plains.

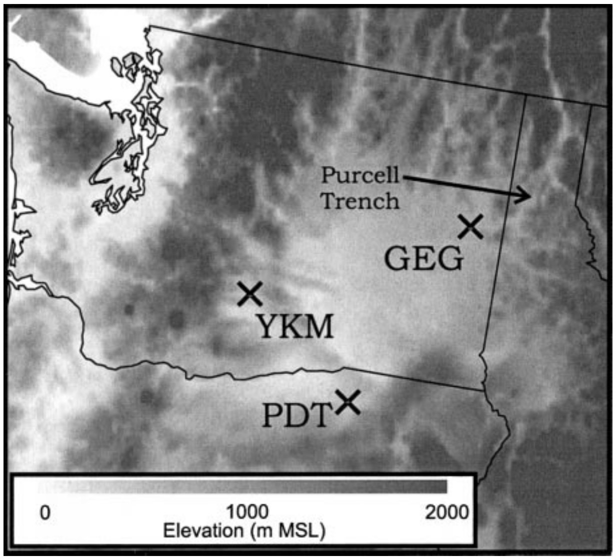

FIG. 8. Same as Fig. 6 but for Spokane (GEG). PDT = Pendleton, OR; YKM = Yakima, WA.

b. Spokane, Washington

Spokane is located within the Columbia Basin regional FZPCP maximum and just south and west of the ~2 km high Bitterroot Range [Fig. 8; the Spokane airport is at an elevation of 723 m above mean sea level (MSL)]. This site receives approximately 28 h of FZPCP per year, with 65% as FZDZ, 30% as FZRA, and 5% as PL (Figs. 2 and 4). Most of the FZDZ at Spokane occurred when the winds were either calm (15%), from the northeast, or between the south and southwest (Fig. 9a). The most common (8 out of 14 cases) synoptic setup for FZDZ had strong high pressure centered in southern Idaho or southeastern Washington, with calm conditions or weak southwesterly geostrophic flow across the region (Fig. 10a). Zhiska and Smith (1980) showed that wintertime high pressure centers were common in this area, and tracked to the southeast with time. Soundings had saturated layer depths of 400–1000 m, $-10°\text{C} < T_{\text{min}} < -2°\text{C}$, and weak winds ($<5$ m s^{-1}) throughout the cloud layer and a dry layer above. This setup is indicative of cold air pooling within the basin and a CC formation process for the FZDZ. Above-freezing temperatures were occasionally found within or above cloud top, and CTTs were between $-7°$ and 1°C.

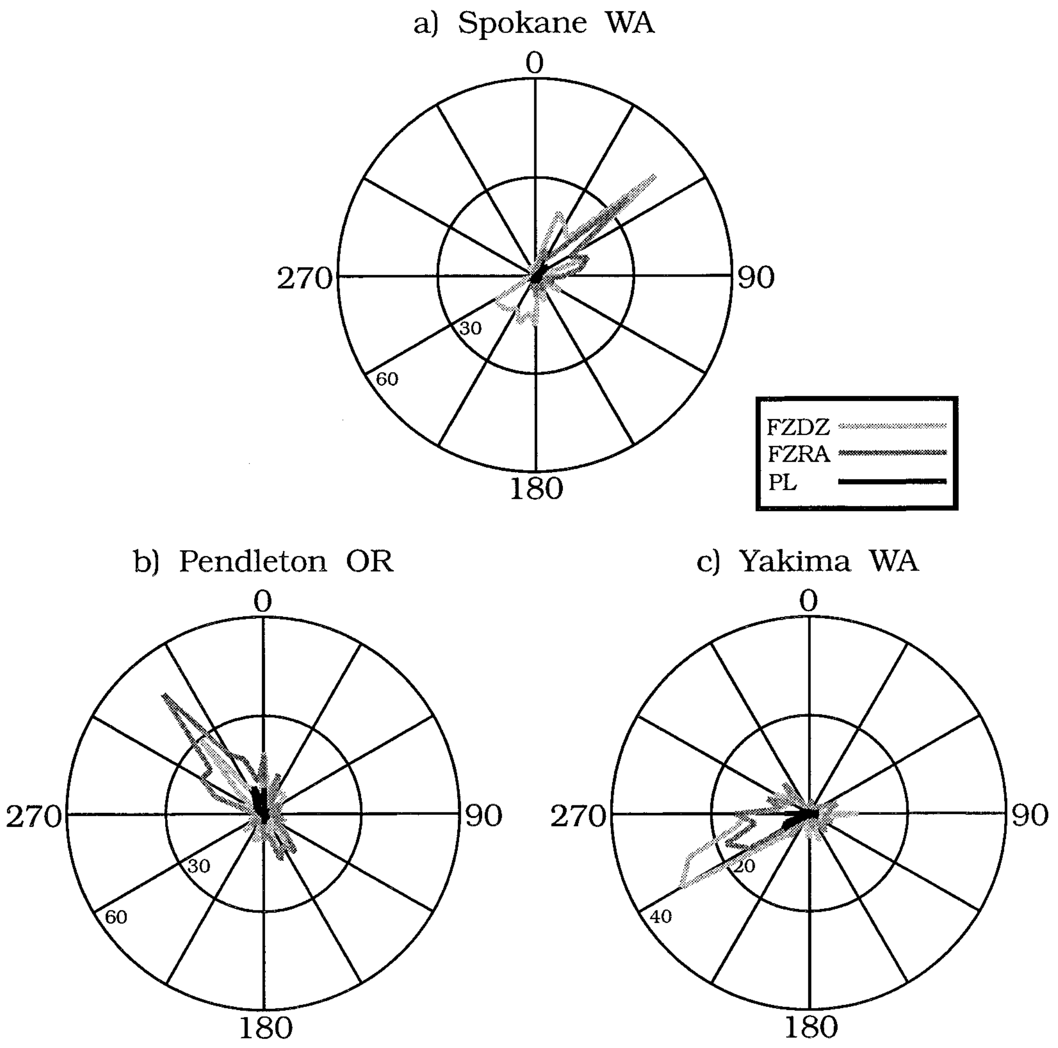

FIG. 9. Same as Fig. 5, but for (a) Spokane, (b) Pendleton, and (c) Yakima. Outer rings are for 60 h, except 40 h in (c).

Since significant upslope flow was not evident in the sounding data at any level below mountaintop, the FZDZ in these cases was unlikely to have formed by upslope forcing. All 14 of the prolonged pure FZDZ events were preceded by or embedded within prolonged fog events that lasted for between 24 and more than 100 h. In these cases, the transition from fog to FZDZ may have been brought about by prolonged residence time of supercooled fog/cloud droplets that eventually reached FZDZ sizes, deepening of ground-based cloud layers, or changes in stability and/or wind shear at or below cloud top.

In 4 of the 14 cases, FZDZ occurred when high pressure was centered over British Columbia, Alberta, or Saskatchewan, with ridging and a weak pressure gradient across the Spokane area. In these cases, similar cloud and wind structures to those described in the previous paragraph were present below 1 km above ground level (AGL), and sounding data indicated that the FZDZ was from a CC process. Light winds and even calm conditions persisted in the Columbia Basin, but deep cold air built westward through gaps in the Bitterroot Range, and seeped into the Columbia Basin. FZDZ with light (<5 m s^{-1}), very shallow, northeast flow often occurred with this synoptic setup and appeared to be associated with cold air drainage from a gap in the mountains to the northeast, locally known as the "Purcell Trench" (Fig. 8). Low-level, northeast winds were also found when the high pressure areas were centered in Idaho, or when weak lows and warm or occluded fronts were coming onshore. The approach of low pressure from the west and/or increasing pressure to the east may have set up an isallobaric gradient that would have drawn cold air down through the gaps to the northeast. There is no clear reason why the low-level northeast winds would have fostered the development of FZDZ at Spokane.

FZDZ formed with a potential melting zone present

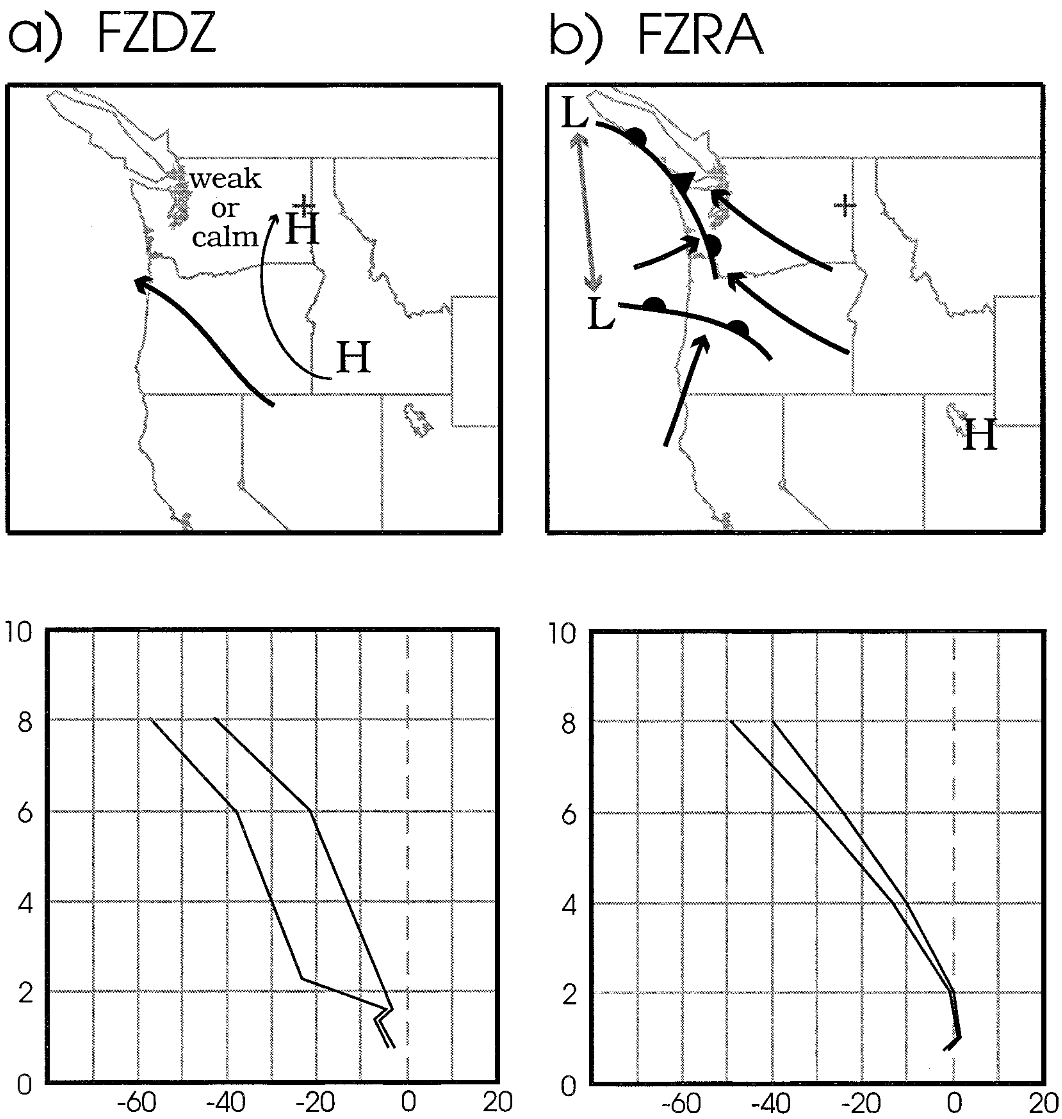

FIG. 10. Same as Fig. 7 but for (a) FZDZ and (b) FZRA at Spokane. Two-headed gray arrows indicate the variability in the locations of highs, lows, and/or fronts.

in the lowest cloud layer and potential significant snow-producing clouds (CTT $< -15°C$) aloft during only two of the prolonged FZPCP events. In one case, the FZDZ quickly changed over to FZRA, apparently as a 2-km-deep break between cloud layers became saturated. Initially, the lower cloud deck that had a CTT of $-2°C$ produced the FZDZ, and/or light snow from the upper cloud deck survived to reach the lower deck, resulting in classical FZDZ. As the dry layer became saturated, the lower deck merged with the upper deck to form a deep, precipitating cloud, and allowed the melting process to form FZRA. A midlevel dry layer was also present in the other case, but the colder clouds above it were <1 km thick, and the potential melting zone was both shallow (~200 m) and cool ($T_{max} = 0.6°C$). A mixture of FZDZ and light snow was observed at the surface. The melting zone was probably too cool and shallow to melt most snow that may have fallen into it. The upper clouds may have produced light snow that fell into the 2500-m-deep liquid cloud below, where it was likely to have rimed significantly. Some light snow may have also developed within the lower deck. Temperatures within the lower deck were between $-9°$ and 0°C, at which secondary ice production was possible due to the likely simultaneous presence of rimed snowflakes and large supercooled water droplets (Hallet and Mossop 1974; Mossop 1976).

Of the six pure FZRA events at Spokane, four occurred after high pressure sagged southward into Utah, leaving cold air in place at low levels in the Columbia Basin. Deep moisture and warm air were advected into the region aloft ahead of warm or occluded fronts that extended from low pressure areas off the coasts of Oregon, Washington, or British Columbia (Fig. 10b). This scenario often caused snow to form aloft, which fell into a melting layer, then into the cold surface air, forming classical FZRA. The melting zones had $1°C < T_{max} < 3°C$, while the supercooled layers were shallow (100–700 m thick) and warm, with $-3°C < T_{min} < -1°C$. Robbins (1998) noted similar low and high pressure center positions, cold-air trapping, and thin cold-layer depths with FZRA events at Spokane. Robbins hypothesized that the relatively cool nature in the melting zone may be related to the cold water temperatures off the Pacific Northwest coast. With such cool, shallow melting zones, one might expect more frequent PL occurrences, but the shallow, warm supercooling layers below appear to have been insufficient to allow refreezing to occur in most cases. Thus, explaining the relative lack of PL observations at Spokane, despite the occasional occurrence of FZRA there.

Spokane's FZRA events were usually short lived, since the influx of warm air quickly eroded the weak surface cold layer (Livingston et al. 1998). No FZRA events exceeded 10 h in the 1961–90 time period. Livingston et al. described a damaging November 1996 case that persisted for about 10 h, and attributed its longevity to strong high pressure that held firm to the northeast. Nearly all FZRA occurred when winds were from the northeast and east-northeast (Fig. 9). The dramatic peak in FZRA occurrences with winds from 50° may be indicative of cold drainage flow from the Purcell Trench, as discussed earlier.

The occurrence of PL at Spokane was rather rare, but one event of intermittent pure PL lasted approximately 12 h. Synoptically and structurally, this event was most similar to an FZDZ scenario, with no melting layer and little or no winds within the cloud deck. The lack of a melting zone ($T_{max} = -4°C$) indicated that the PL formed in an entirely subfreezing environment that was both relatively cold ($T_{min} = -9°C$) and deep (1100 m), similar to that described in Kajikawa et al. (1988). The existence of some cooler clouds and a thin dry layer aloft, however, implies that some light snow may have fallen into the supercooled liquid cloud below and formed graupel. FZDZ events with such cold temperatures and similar cloud depths were observed in three cases, but PL was not reported.

In contrast with Spokane, FZPCP at Pendleton, Oregon, and Yakima, Washington, occurred with completely different wind directions (Figs. 9b,c). At Pendleton, northwesterly winds, driving up the slope of the Blue Mountains, were most commonly observed with FZPCP. When FZPCP occurred at Yakima winds were nearly always from the west and southwest. These winds were likely related to the Ahtanum River valley to the west, and gaps in the Cascade Mountains to the southwest. Little FZPCP was found at either site with synoptically favored easterly winds due to downslope drying of air masses entering the Columbia Basin by the Rocky Mountains and Blue Mountains (PDT only) to the east. In general, topographic effects of mountain ranges and river valleys were key to the distributions of FZPCP occurrences with wind direction in the Columbia Basin. Shallow surface winds in this region often did not reflect the synoptic pattern.

c. Green Bay, Wisconsin

Green Bay (GRB) is located well within the Midwestern FZPCP maximum and receives approximately 30 h yr^{-1}, with ~57% as FZDZ, ~25% as FZRA, and ~18% as PL (Figs. 2 and 4). Jeck (1996) found a similar breakdown of the FZPCP types at Green Bay. Five of the seven prolonged FZDZ events occurred when Green Bay was located north of warm or stationary fronts that extended from surface lows centered anywhere from Iowa to the Oklahoma Panhandle, accompanied by a surface high in central Ontario (Fig. 11a). Sounding data reveal that a CC process was operating in all cases of this type, with supercooled layer depths of 900–3800 m and $-12°C < T_{min} < -3°C$ (Table 1). Two other cases of prolonged FZDZ also had a CC sounding structure, but occurred under different synoptic setups. All but one of the pure FZDZ events at Green Bay occurred within large swaths of FZDZ that were associated with widespread synoptic lift.

Seven of the eight events that featured FZRA at Green Bay also occurred with warm, stationary, or occluded fronts to the south that extended from low pressure centered over Iowa, while the high pressure was centered between the Quebec–Ontario border and the mid-Atlantic states (Fig. 11b). The FZRA layers were 300–1000 m deep for pure FZRA events, with $-5°C < T_{min} < -1°C$, while the melting layers were 1200–1400 m deep and had $2°C < T_{max} < 4°C$. In an examination of FZRA events in the western Great Lakes, Cortinas (2000) found a similar mean low pressure center location along the Iowa–Missouri border, and a mean sounding structure at Sault St. Marie and Flint, Michigan, that was similar to those from Green Bay.

There were three additional cases where the FZRA was mixed with PL at Green Bay. In these mixed cases, the supercooled layers were deeper (1600–2200 m) and colder ($-10°C < T_{min} < -6°C$), while the melting layers were shallower (400–700 m), and cooler ($0°C < T_{max} < 2°C$). All prolonged PL events were mixed with FZRA at times, except one case where PL was mixed with FZDZ. On that day, the synoptic conditions and sounding structure were comparable to the FZRA–PL cases discussed in the previous paragraph, but there was evidence of dry air aloft, and CTTs in the midlevel snow-producing layer were near −10°C. In this case, the FZDZ could have formed by either CC or the melting of small snowflakes and subsequent supercooling of drizzle-sized drops. The melting layer was 800 m deep and had $T_{max} = 3.5°C$, so incomplete melting was probably not the cause of the PL, especially since significant

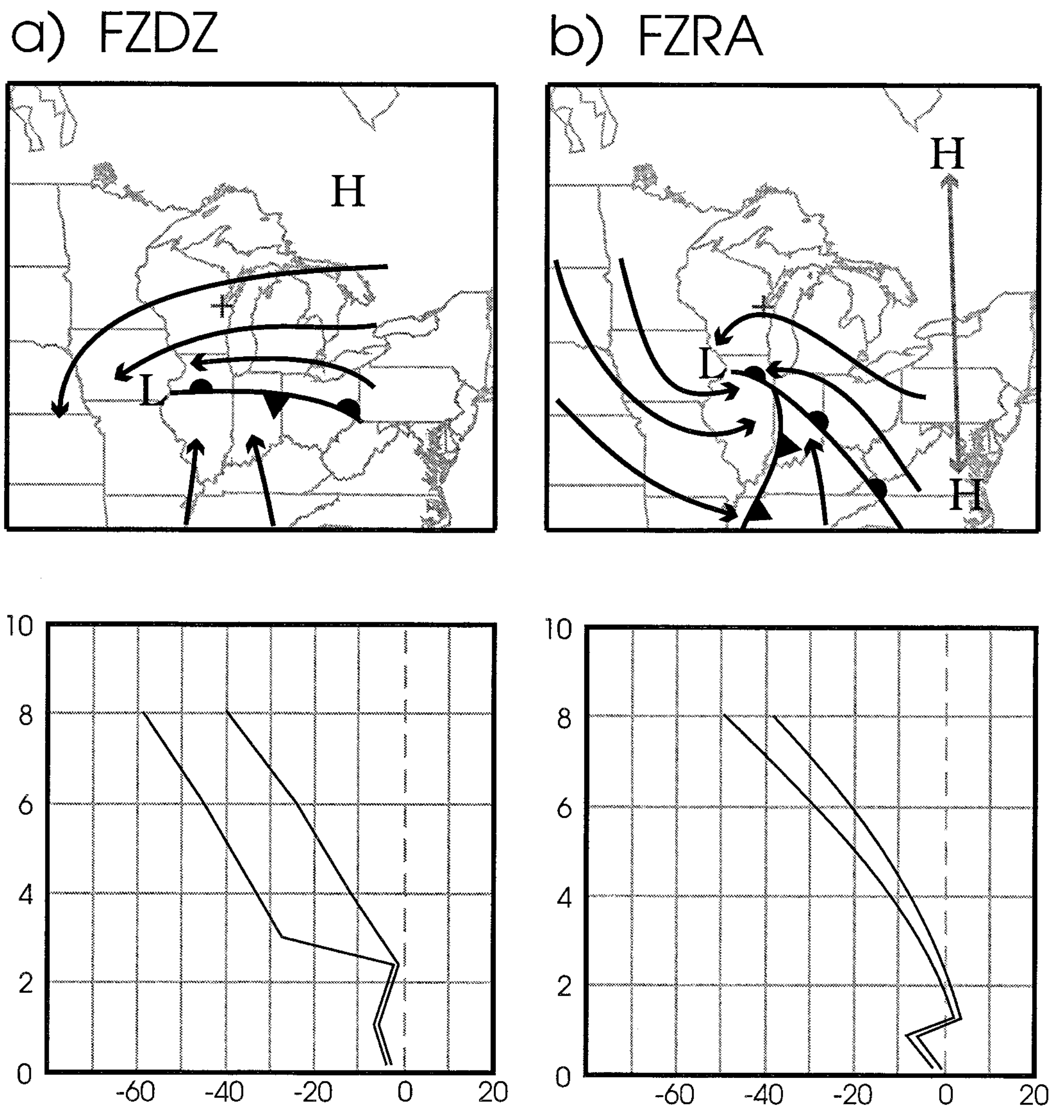

FIG. 11. Same as Fig. 10 but for (a) FZDZ and (b) FZRA at Green Bay.

snow did not appear to have fallen from above. The supercooled layer had $-10°C < T < -7°C$ through a 1000-m depth, possibly indicating that the PL formed via the freezing of FZDZ drops that formed by either the classical or CC process.

The distribution of FZPCP with wind direction at Green Bay shows that most occurred with northeast winds and that relatively little FZPCP occurred with winds from other common directions of southeast, east, north, and northwest (Figs. 3 and 12a). The Green Bay FZDZ wind rose had a distinct peak with north-northeast winds, which were likely to have had a long fetch over Green Bay, itself (Fig. 13). Overall, winds from this direction were roughly twice as common as those from the surrounding wind directions, possibly due to flow along or around the slightly higher terrain of the peninsula that runs to the northeast. Nearby stations Eau Claire and Madison showed no evidence of such strongly favored, narrow bands of wind directions, with or without FZDZ (Figs. 12b,c).

Other stations bordering the Great Lakes have shown relatively frequent occurrences of FZDZ with winds off of the lakes (S. Cober 1999, personal communication), even with wind directions that are not preferred synoptically. For example, Erie, Pennsylvania, had a marked increase in FZDZ occurrences with west and southwest winds that had a long fetch across Lake Erie (Figs. 1 and 12d). It was uncommon for FZDZ to occur with these wind directions in the national climatology (Fig. 3). Anecdotal evidence from flights made by the National Aeronautics and Space Administration–Lewis Research Center's Twin Otter research aircraft (Miller et al. 1998) within isolated FZDZ events downwind of Green Bay–Lake Michigan and Lake Erie support this

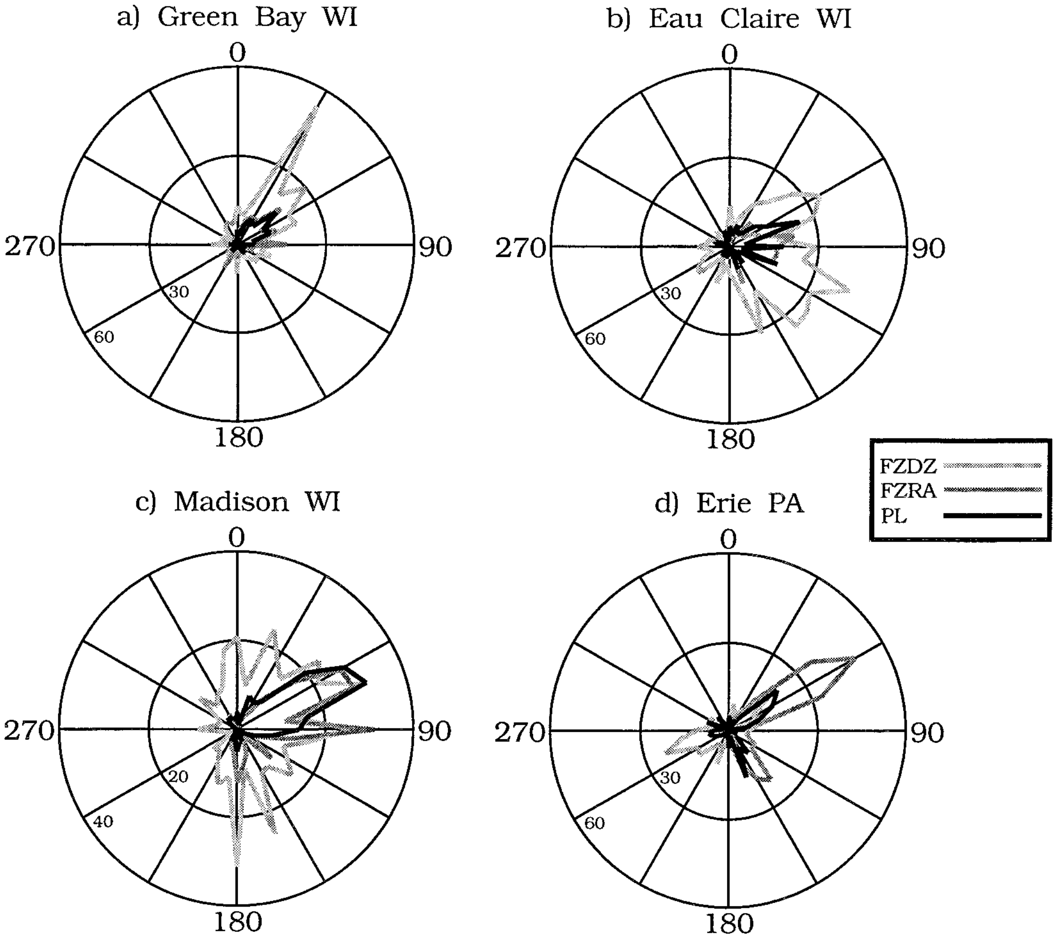

FIG. 12. Same as Fig. 5 but for (a) Green Bay, (b) Eau Claire, (c) Madison, WI, and (d) Erie. Outer rings are for 60 h, except 40 h in (c).

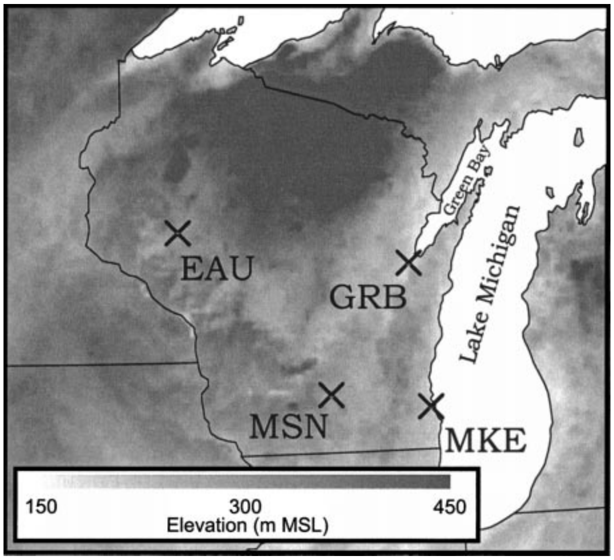

FIG. 13. Map of the regional topography and major water bodies surrounding Green Bay (GRB). EAU = Eau Claire, MSN = Madison, and MKE = Milwaukee, WI.

hypothesis. When the aircraft flew downwind of these water bodies, FZDZ was much more consistent and droplet sizes tended to be larger than when the aircraft flew in areas that were not downwind of the lake fetch. Removal of cloud condensation nuclei via precipitation scavenging (Twomey and Wojciechowski 1969) may have played a role in providing a clean environment for FZDZ growth in these cases, as snow was observed upstream of and/or coincident with the FZDZ.

Stuart and Isaac (1999) found a similar propensity for both FZDZ and FZRA to occur with winds off of Hudson's Bay, but the cause was not determined. Their examination was for May, when the bay was covered with ice. Strapp et al. (1996) and Isaac et al. (1996) both reported that FZDZ at St. Johns, Newfoundland, was well correlated with wind directions off of sea ice. It may be that many of the FZDZ and FZRA occurrences at GRB occurred when the bay was ice covered, but this potential influence was not investigated here.

The relative infrequency of FZPCP with east through southeast winds may have been due to the influences of the slightly higher terrain of the peninsula or the relative

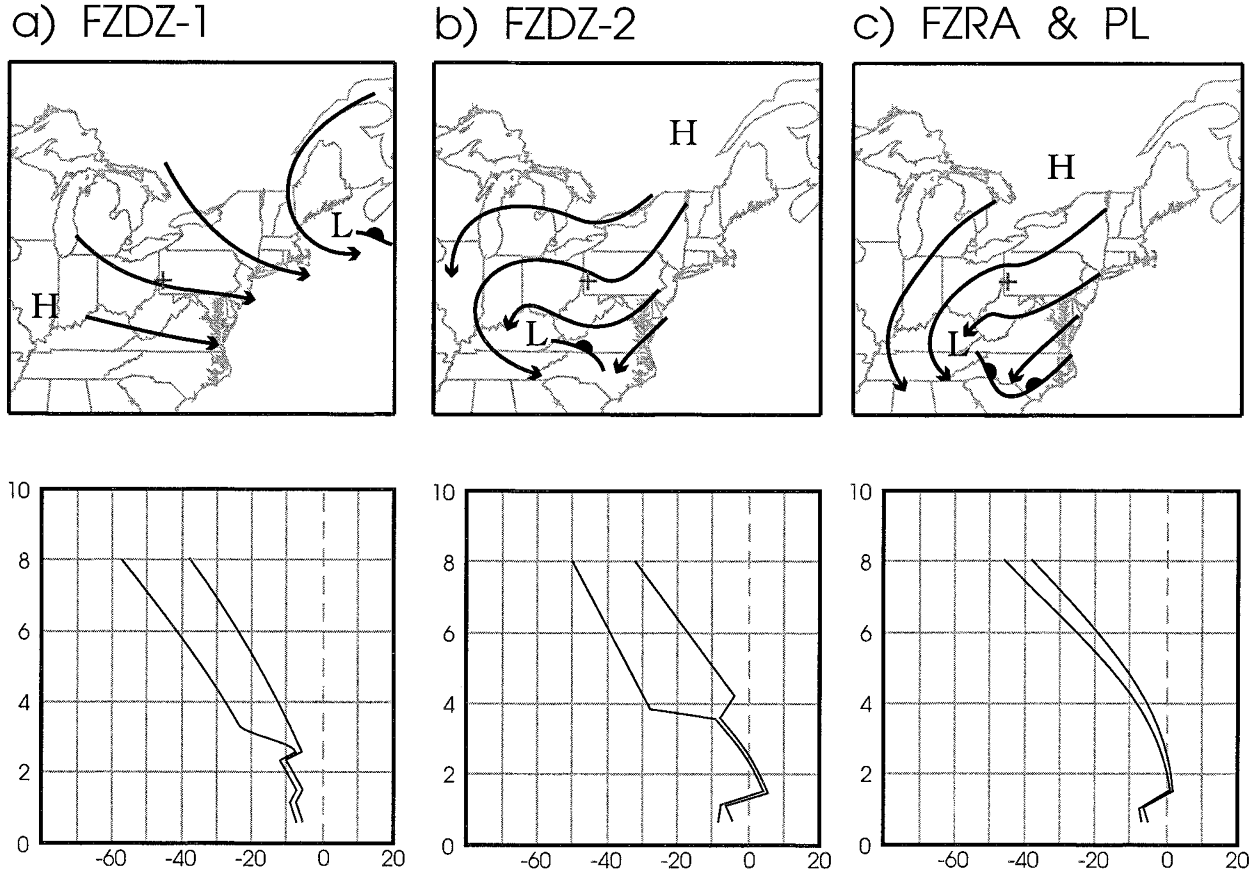

FIG. 14. Same as Fig. 7 but for FZDZ with (a) westerly and (b) easterly flow, and (c) FZRA mixed with PL at Pittsburg.

closeness of the warm waters of Lake Michigan. Cortinas (2000) found this effect for FZRA at several stations bordering the eastern Great Lakes, but did note exceptions where FZRA was *more* common with onshore flow. Such effects were not evident at Milwaukee (not shown) on Lake Michigan's western shore, or at Eau Claire and Madison, located well inland of the lake (Figs. 12 and 13). North and northwest winds had to cross the elevated terrain of northern Wisconsin, and Michigan's Upper Peninsula, to reach Green Bay. The 300–400-m descent from the elevated terrain may have produced some compressional warming and drying. The lack of FZPCP with downslope north and north-northeast winds was also evident at Eau Claire. Madison, which is farther removed from the higher topography, did not show this effect for FZDZ. Interestingly, nearly all of the FZRA and PL at these three stations occurred with east and northeast winds. These results roughly match those of Cortinas (2000), who found that the median winds were from the east during FZRA in the Great Lakes region.

d. Pittsburgh, Pennsylvania

Pittsburgh is located at the northeastern end of a regional *minimum* in FZPCP that runs along the western slope of the Appalachians, and divides the predominant maxima in the Midwest from that just inland of the East Coast. Pittsburgh receives approximately 27 h of FZPCP per year, with ~37% as FZDZ, ~37% as FZRA, and ~26% as PL (Figs. 2 and 4). Four of the five prolonged pure FZDZ cases at Pittsburgh were associated with high pressure building into the Illinois–Indiana area, in the wake of strong storms moving past Maine and into the Canadian Maritime Provinces (Fig. 14a). This setup caused surface winds from the west and northwest at Pittsburgh, which traveled up the western slope of the Appalachians. The Appalachians run from southwest to northeast and are ~1000 m tall in this region (Fig. 15).

Soundings taken during these events revealed west and northwest winds below the mountain range and that the FZDZ appeared to be formed by CC in all cases examined. The supercooled clouds were 1000–2400 m deep, with $-12°C < T_{\min} < -6°C$ (Table 1). This upslope scenario explains the unusual peak in FZDZ occurrence with westerly winds, the least favorable wind direction for FZDZ in the national climatology (Figs. 3 and 16a). Other nearby stations (Akron–Canton, OH; Youngstown, OH; and Charleston, WV) had similar FZDZ wind roses and support the important role of westerly component upslope flow in this region (Figs.

16b–d). In west-northwest flow, Youngstown is located downwind of a long fetch across Lake Erie. As discussed in the previous section, this may play some role in the tendency for FZDZ to occur there with west-northwest winds.

The remaining cases of FZDZ at Pittsburgh show up as a peak with winds from the east-southeast (Fig. 16a) and were mixed with or changed to FZRA and/or PL. A melting layer was evident in all of those soundings, but cloud tops in several cases appeared to be too warm for the production of significant snow aloft, indicating that a CC process was likely. Intermittent periods of or changeovers to and from FZRA with this structure may have been caused by intermittence in the snow supply from aloft or variability in the depth of the liquid clouds, which allowed longer residence time for droplets to have grown. The common synoptic setup for these cases featured a warm front or stationary front across Virginia, extending from low pressure centered between Missouri and western Virginia, while high pressure or strong ridging was found to the north, northeast, or east of Pittsburgh, keeping cold surface air in place (Fig. 14b). The

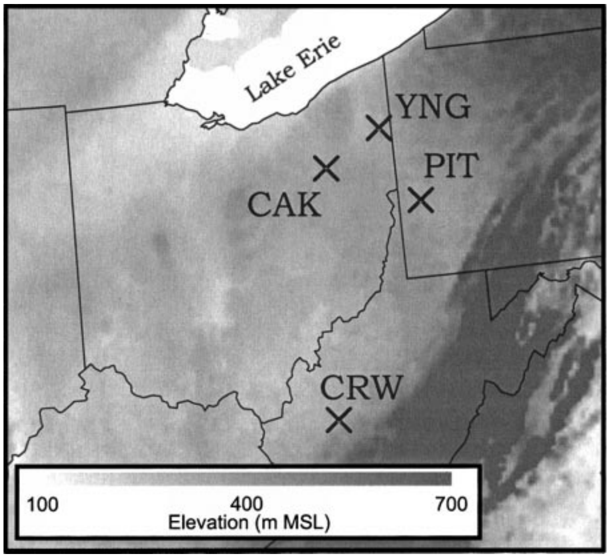

FIG. 15. Same as Fig. 13 but for Pittsburgh (PIT). YNG = Youngstown, OH; CAK = Akron–Canton, OH; and CRW = Charleston, WV.

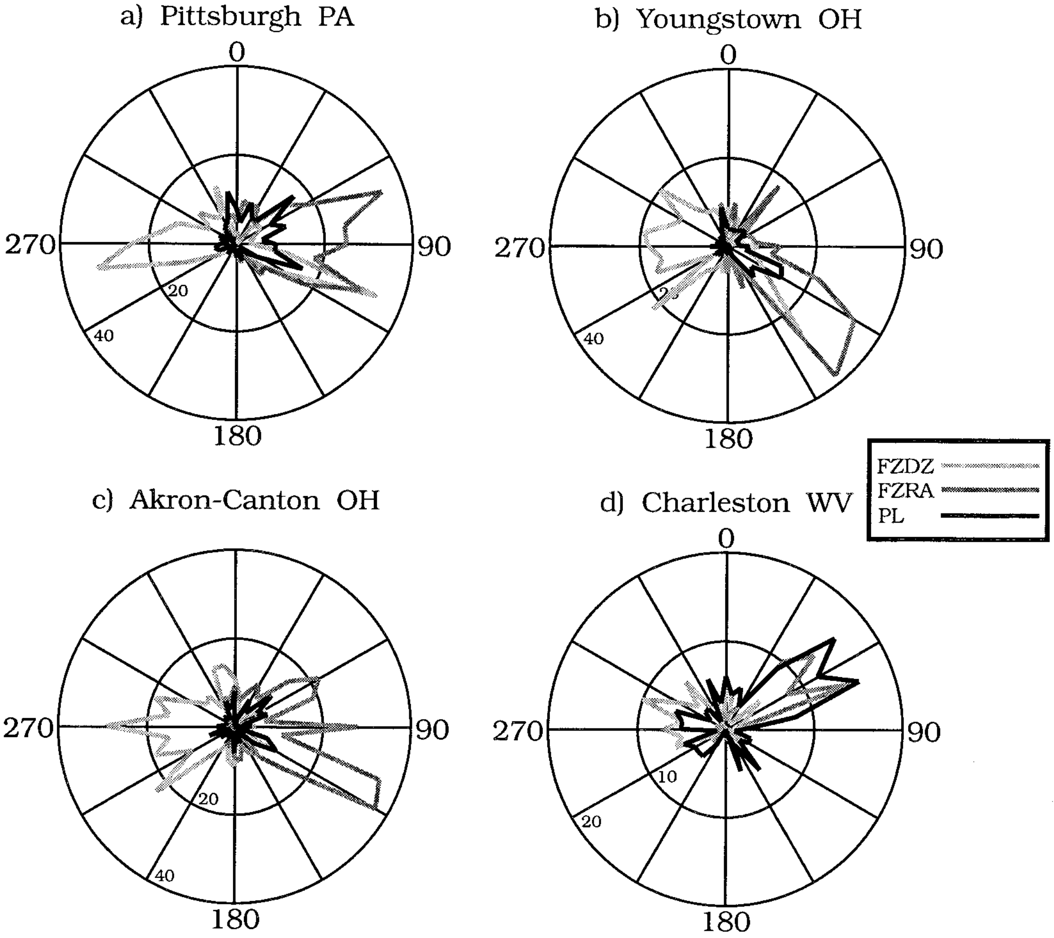

FIG. 16. Same as Fig. 5 but for (a) Pittsburgh, (b) Youngstown, (c) Akron–Canton, and (d) Charleston. Outer rings are for 40 h, except 20 h in (d).

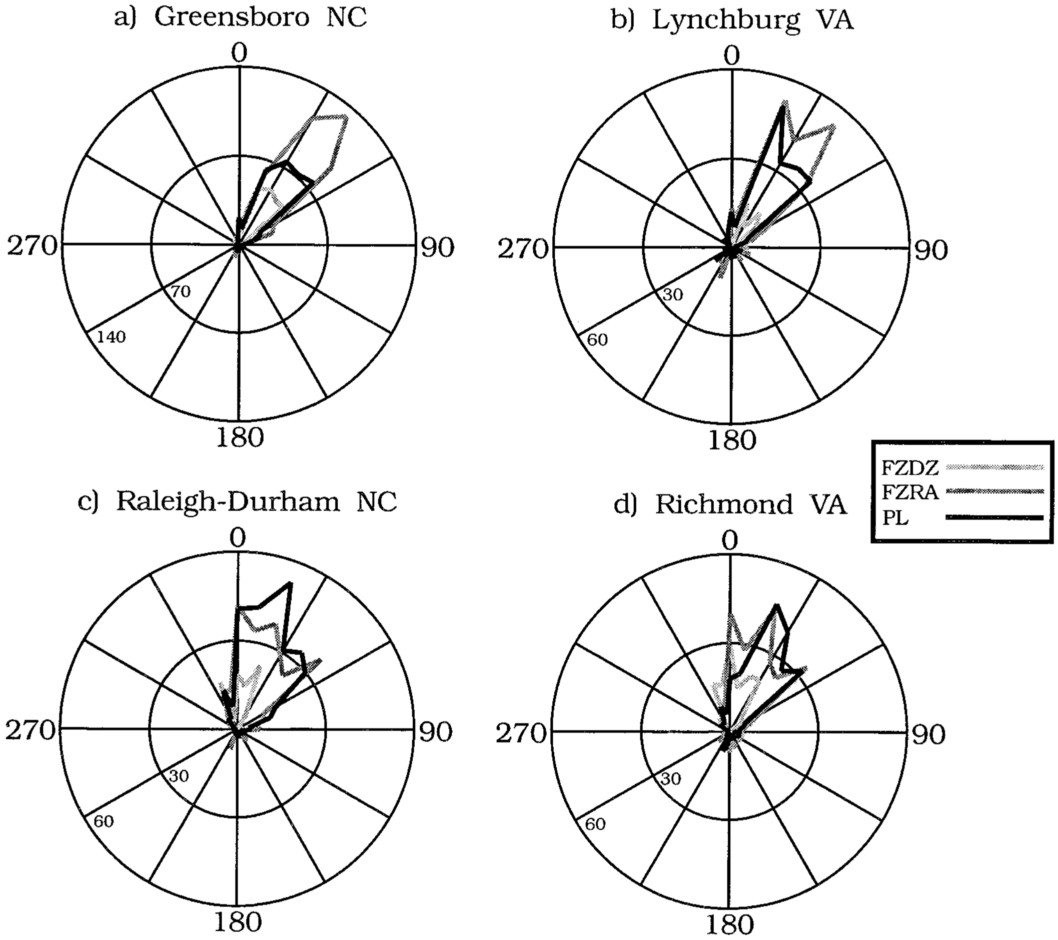

FIG. 17. Same as Fig. 5 but for (a) Greensboro, NC; (b) Lynchburg, VA; (c) Raleigh–Durham, NC; and (d) Richmond, VA. Outer rings are for 60 h, except 140 h in (a).

supercooled layers were 200–1000 m deep, with $-7°C < T_{min} < -2°C$, and the potential melting zones had $2°C < T_{max} < 6°C$ (Table 1).

Only 1 prolonged case of FZRA at Pittsburgh was purely FZRA, while the remaining 15 were mixed with PL or FZDZ at times. Many of the cases mixed with PL occurred when strong low pressure was centered between Tennessee and central Ohio, while a strong ridge of high pressure extended down the east side of the Appalachian Mountains (Fig. 14c). As seen at other stations, the soundings taken simultaneous with the occurrence of PL had a warm layer that was usually shallow and/or had T_{max} values that were not much greater than 0°C, while the supercooled layers had $-7°C < T_{min} < -3°C$. The fact that most prolonged FZRA cases were mixed with either PL or FZDZ at times indicate that it was difficult to sustain a process at Pittsburgh that both caused complete melting and efficiently formed significant precipitation. The synoptic scenario described here for FZRA and PL is consistent with their tendency to occur when surface winds had an easterly component. Similar patterns were apparent for FZRA and PL in wind roses from nearby stations (Figs. 16b–d). Downslope flow in this region provides a leeside rain shadow with synoptically favored easterly and southeasterly winds and partially explains the regional minimum in FZPCP along the west slope of the Appalachian Mountains.

e. Greensboro, North Carolina

Greensboro is located at the southern tip of the inland East Coast FZPCP maximum. It receives approximately 43 h of FZPCP per year, with 21% as FZDZ, 46% as FZRA, and 33% as PL (Figs. 2 and 4). Nearly all FZPCP occurred when surface winds were from the northeast (Fig. 17a). Close proximity to the Atlantic Ocean made it difficult for surface temperatures to stay below freezing when winds were from between the east and southeast (onshore), while the nearby Appalachian Mountains caused downslope conditions when winds were from between the west and north-northwest (Fig. 18). Only northeast winds had a long fetch over land without being downslope and tended to bring cold air to the region. The most common way for this flow to develop was for

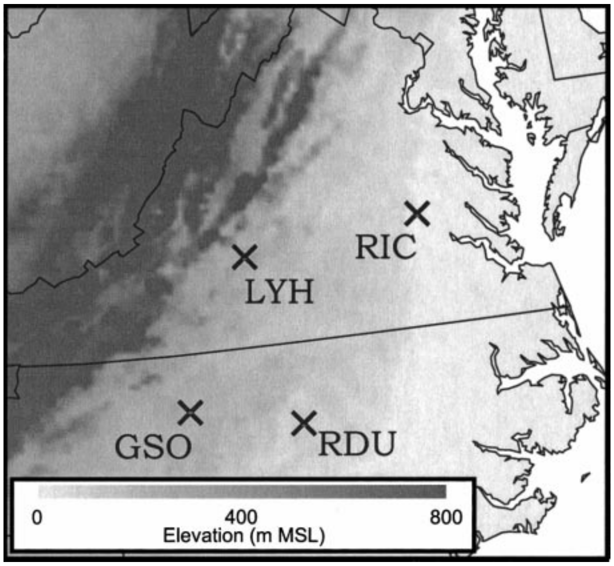

FIG. 18. Same as Fig. 13 but for Greensboro (GSO). RDU = Raleigh–Durham, LYH = Lynchburg, and RIC = Richmond.

high pressure to the north to force cold, moist, easterly winds into the eastern slope of the Appalachians, which eventually led to cold air damming. As the damming developed, surface winds turned to flow along the northeast–southwest-oriented barrier, away from the high pressure, and caused northeast surface winds and a dome of cold air to be maintained there (Forbes et al. 1987; Richwein 1980). Cool northeasterly winds were also drawn into the area by low pressure that passed to the southeast and east of Greensboro, usually in conjunction with varying strengths of ridging and cold air damming associated with high pressure to the north.

Nearly all of the prolonged pure FZDZ cases occurred under the second scenario, with a low pressure center off of the North Carolina coast, and a variety of setups for surrounding weather features (Fig. 19a). Sounding data indicated the existence of warm cloud tops ($-6°C < \mathrm{CTT} < 4°C$) and, thus, a high likelihood of the CC formation process. Although potential melting layers existed aloft in seven of the nine cases, CTTs were not cold enough to produce much, if any, snow. The supercooled layers were 200–1900 m thick with $-7°C < T_{\min} < -1°C$ (Table 1). There were 15 cases where FZDZ occurred simultaneously with or transitioned to/from FZRA and occasionally PL. In all of these cases, a potential melting layer was present and the transitions between FZDZ and FZRA appeared to be due to changes in the precipitation efficiency of the clouds above the warm layer, similar to that observed at Pittsburgh. The synoptic scenarios for these transition cases were a mixture of what was described for pure FZDZ cases above and the pure FZRA cases to be discussed in the next paragraph.

All but 2 of the 11 prolonged pure FZRA cases occurred when at least some cold air damming was evident and a low pressure center tracked from the Florida Panhandle to the North Carolina coast (Fig. 19b). This caused deep moisture and warm air to overrun the preexisting surface cold pool. The melting layers that formed in these cases were quite warm ($4°C < T_{\max} < 10°C$) and deep (1200–2700 m), while the supercooled layers had widely varying temperatures ($-6°C < T_{\min} < -1°C$) and depths (300–900 m). CTTs were less than $-15°C$ in nine cases. These scenarios and sounding statistics are similar to those reported by Robbins (1998), who found that 68% of all FZRA cases at Greensboro were associated with cold air damming.

Rauber et al. (2000) found that freezing precipitation formed by the melting process was more common at Greensboro than at any other CONUS site to the east of the Rocky Mountains. They showed that about half of the FZPCP (only FZDZ and FZRA in their paper) that fell there was formed by the melting mechanism. Potential melting zones were present in nearly every sounding they examined, but only about half had CTTs $< -10°C$. Their results are consistent with those presented here.

The five prolonged pure PL events at Greensboro mostly occurred under similar synoptic conditions to those for pure FZRA, though high pressure was centered over North Dakota, with strong ridging along the East Coast in two cases. The main differences in the soundings were relatively shallow and/or cool melting layers, similar to those noted at other sites. The supercooled layers also tended to be rather cold and deep, with all but one having $-12°C < T_{\min} < -7°C$ and depths of 600–1800 m (Table 1). There were many cases of PL that mixed or transitioned with FZRA. In general, the synoptic scenarios for these mixed events were similar to those for pure FZRA and PL cases, but sometimes the low pressure centers were as far west as Texas, with warm fronts and overrunning conditions that extended across the Gulf Coast states. Five soundings had isothermal layers at 0°C that were up to 1500 m deep. Deep isothermal layers at 0°C were noted in several previous studies of PL, and have been linked to cooling of the melting zone and warming of the supercooled layer by the removal and addition of latent heat within the respective layers (Hanesiak and Stewart 1995; Zerr 1997). Several PL soundings had dry layers extending from the surface to as high as 1500 m AGL, through which the PL apparently survived (Fig. 20). Evaporational cooling may be important to the refreezing process when the dry layers are present, as evidenced by the relatively warm temperatures within them.

Examination of the wind roses for other nearby stations situated close to the east slope of the Appalachians (e.g., Lynchburg, VA; Fig. 17b) reveals very similar patterns to those seen at Greensboro. Essentially all of the FZPCP at these sites occurred with winds from the northeast. In contrast, stations about halfway between the mountains and the ocean (e.g., Raleigh–Durham, NC, and Richmond, VA; Figs. 17c,d) were still domi-

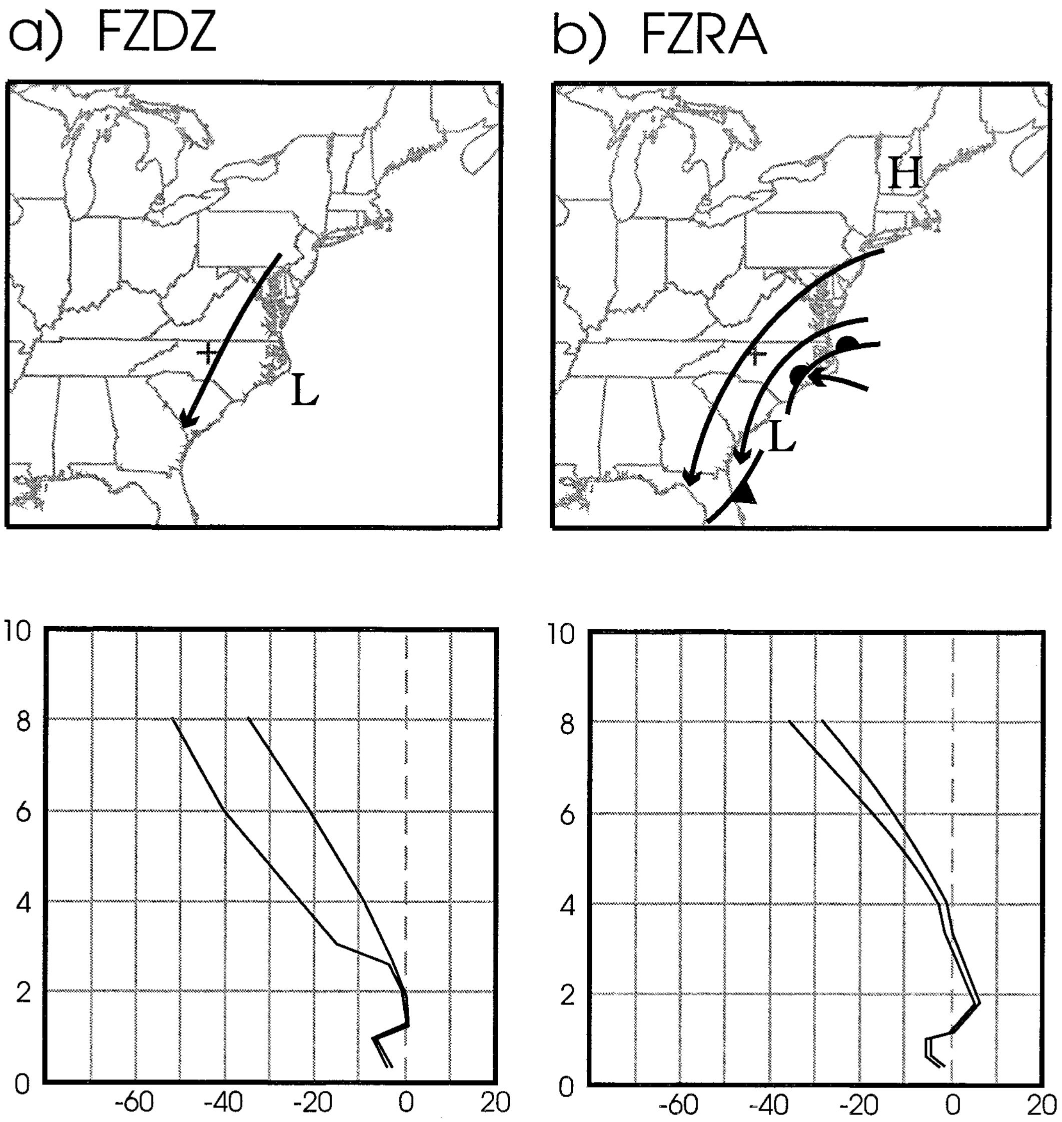

FIG. 19. Same as Fig. 7 but for (a) FZDZ and (b) FZRA at Greensboro.

nated by northeast flow, but their wind distributions broadened to include winds from the north. Unlike sites closer to the mountains, northerly flow at these sites did not have a downslope wind component.

f. Portland, Maine

As expected, the Atlantic Ocean strongly influences the occurrence of FZPCP along the eastern seaboard. This is certainly true at Portland, which is situated just inland of the shore (Fig. 21). Portland receives approximately 43 h of FZPCP per year, with 34% as FZDZ, 30% as FZRA, and 36% as PL. It is located at the northeastern end of regional maxima in both PL and FZDZ, and a minimum in FZRA occurrence, with a strong gradient in the amount of these phenomena running between central Massachusetts and southeastern Maine (Figs. 2 and 4).

The distribution of FZPCP with wind direction clearly shows that winds were from between northwest and northeast when FZDZ or FZRA occurred and that peak frequencies were with north winds (Fig. 22a). FZDZ and FZRA rarely occurred with winds from between 60° and 310°, which were either onshore or downslope off of the Appalachians. While significant topography also exists to the north-northwest and north, cold air damming events in this region often allowed for such winds to exist between the ocean and the mountains without them being downslope. The cold dome was sometimes overrun by maritime air from the Gulf of Maine to produce FZPCP, as will be described later in this section. This scenario was often associated with the development

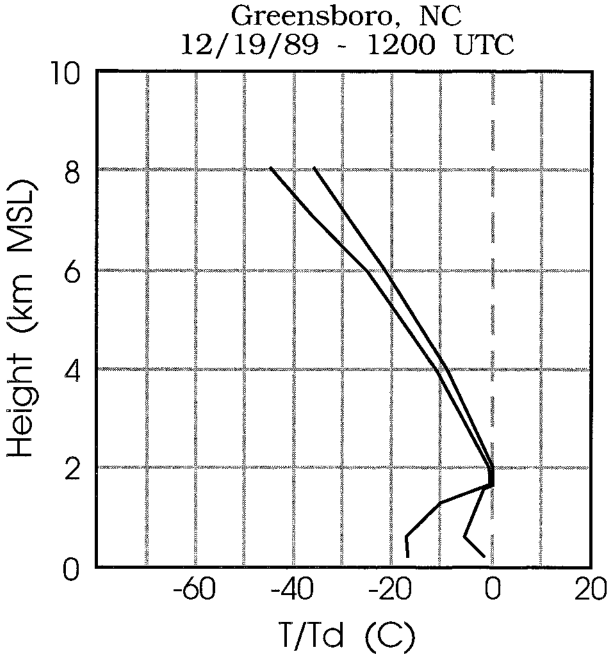

FIG. 20. Example sounding of a PL occurrence with a deep, low-level, dry layer at Greensboro on 19 Dec 1989.

of the New England coastal front (Bosart 1975; Nielsen and Neilley 1990).

The PL distribution was somewhat broader than that for FZDZ and FZRA, and included some easterly winds. While the onshore wind directions between 60° and 110° were synoptically favored for all three precipitation categories, in general (Fig. 3), winds off the Atlantic tended to advect above freezing temperatures inland at Portland. The reason that only PL occurred with east winds there is the fact that PL commonly occurred with surface temperatures are as warm as $+4$°C, while almost all FZDZ and FZRA occurred with temperature less than 1°C (Robbins 1998; Fig. 23). For the supercooled water droplets to have frozen upon impact, surface objects had to be at freezing or colder temperatures (Huschke 1959). That could only occur when the air was either subfreezing, or the objects remained at or below freezing while the air temperature, measured ~2 m above the ground, was slightly above freezing (Gay and Davis 1993). When all 207 stations used in this study were considered, approximately 24% of all PL, and less than 1% of all FZDZ and FZRA, was observed at temperatures in excess of 1°C.

The melting mechanism commonly occurred aloft at Portland when surface winds were from the east and southeast, yet the above-freezing temperatures near the surface did not allow the supercooled rain or drizzle falling from aloft to freeze upon reaching the ground. Ice pellets that developed by these same mechanisms maintained their solid form despite falling into above-freezing temperatures. Wind roses from other stations along the East Coast, including Boston and Atlantic City, displayed even stronger evidence of differences between PL and the two supercooled liquid precipitation types (Figs. 22b–d). Even Concord featured this disparity, despite its somewhat inland location. The common occurrence of the melting mechanism aloft, combined with the fact that PL can survive at well above-freezing surface temperatures, explains the relatively high percentage of FZPCP that falls as PL along the East Coast as well as the coasts of Washington and Oregon (Bernstein and Brown 1997; Gay and Davis 1993; see Fig. 4d). Subfreezing temperatures are difficult to attain during precipitation episodes along the Pacific Northwest and East Coasts.

Two equally prevalent primary synoptic scenarios brought about the pure FZDZ events at Portland. The first involved a low of variable strength centered within or just east of the Gulf of Maine. The stronger the low, the farther offshore it tended to be. Strong high pressure was typically centered over eastern Quebec or Newfoundland (Fig. 24a). In these situations, CC was the formation mechanism. Although above freezing temperatures often existed within the cloud deck ($0°C < T_{max} < 9°C$), CTTs were always greater than -10°C and often hovered near 0°C. In cases with $-10°C <$ CTT $< 0°C$, FZDZ may have existed both above and below the above-freezing layer. The cloud decks were between 1200 and 3500 m thick, but the supercooled layers were only 300–1500 m thick, and had $-8°C < T_{min} < -2°C$ (Table 1). The second pure FZDZ scenario had high pressure over Newfoundland or Nova Scotia, low pressure over the Great Lakes, and a warm front positioned across New York State and Pennsylvania (Fig. 24b). While potential melting zones were again present and FZRA occurred in the vicinity in all cases, CTTs were between -9° and -2°C at Portland. As usual, the deeper

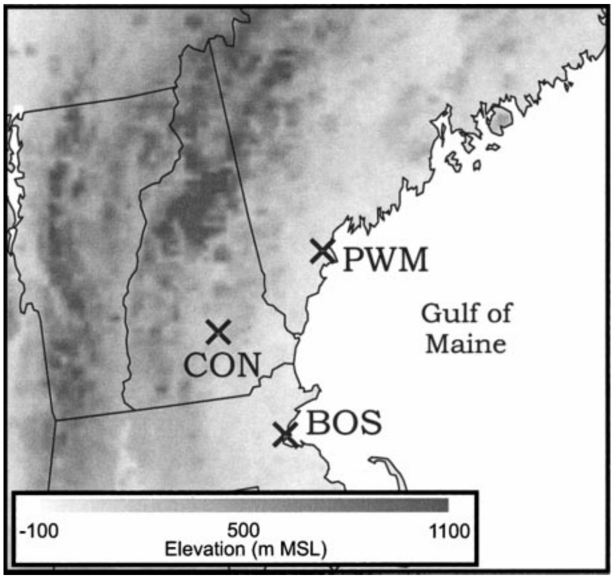

FIG. 21. Same as Fig. 13 but for Portland (PWM). CON = Concord, NH; BOS = Boston, MA.

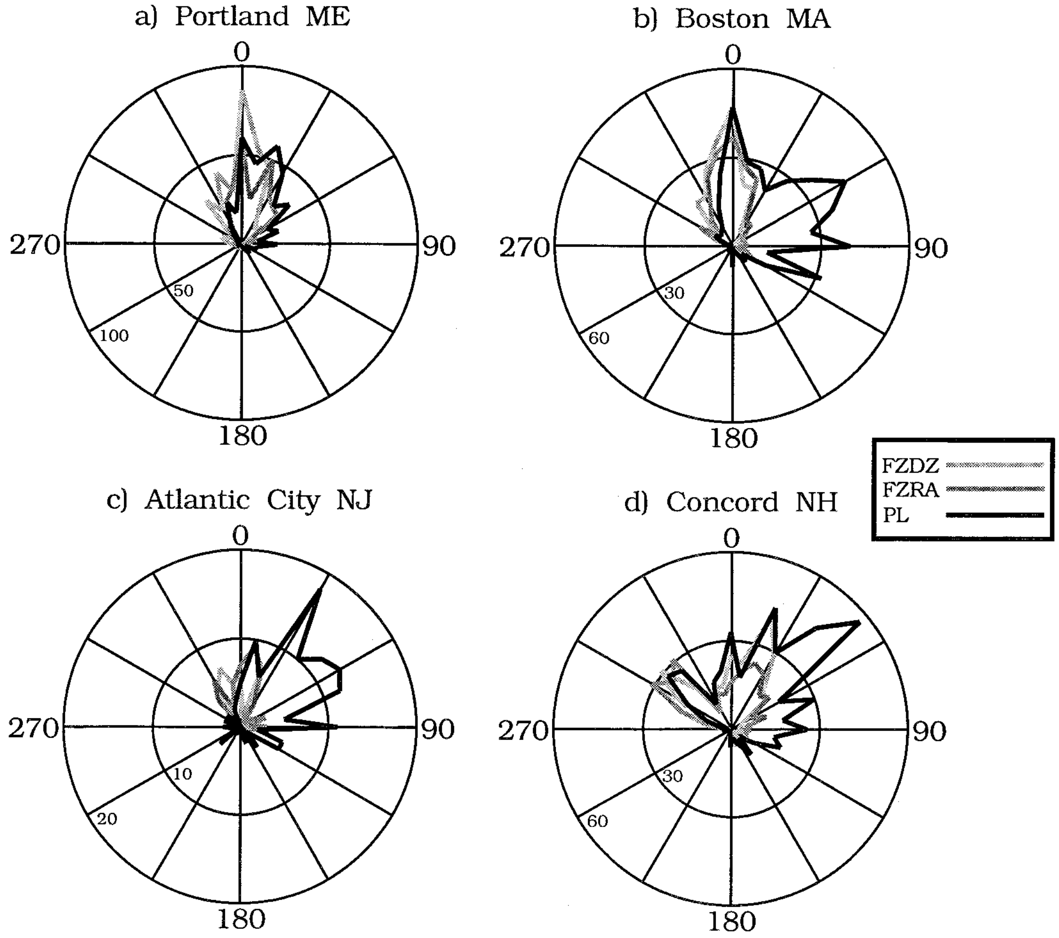

FIG. 22. Same as Fig. 5 but for (a) Portland, (b) Boston, (c) Atlantic City, NJ, and (d) Concord. Outer rings are for 60 h, except 100 h in (a) and 20 h in (c).

the supercooled layers were, the colder the minimum temperatures were within them. In several of the FZDZ events, both the offshore and Great Lakes lows were present.

There were nine instances of FZDZ changing to FZRA and vice versa (Table 1). The synoptic scenarios were essentially the same as those for pure FZDZ events, and the CTTs were still usually -10°C or warmer, but the clouds were all 2500–4000 m thick. This compares well to the pure FZDZ events that formed in relatively deep clouds and had FZRA reported in the vicinity. Some of the pure FZRA events also had similar features, and FZDZ was often reported in the vicinity. Since a CC mechanism was likely to have formed the FZPCP, the greater cloud depths support the idea that deeper clouds were required to form FZRA via the CC process. Snow falling from pockets of colder CTTs likely caused some of the changes to FZRA at and in the vicinity of Portland, since potential melting zones were present.

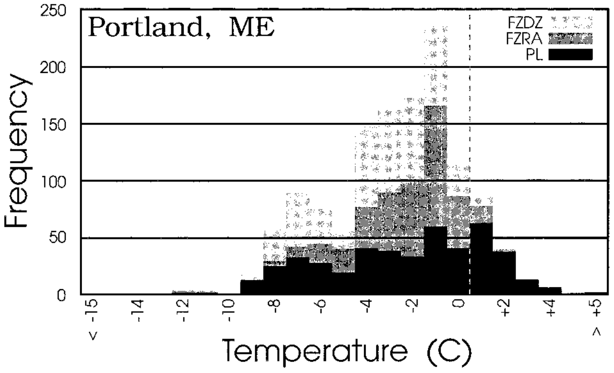

FIG. 23. Distribution of FZDZ (light gray), FZRA (dark gray), and PL (black) occurrences with surface temperature at Portland.

Portland's pure FZRA cases appeared to be caused by classical melting, as CTTs were less than -10°C in all six cases, and less than -15°C in five of them. No one synoptic setup dominated the pure FZRA cases, as low pressure was centered anywhere from the Great Lakes to the Gulf of Maine. The subfreezing layers varied in depth from 100 to 1400 m, with $-7^\circ\mathrm{C} < T_{\min} < -1^\circ\mathrm{C}$. The melting zones had depths of 800 to 2800 m, and $3^\circ\mathrm{C} < T_{\max} < 7^\circ\mathrm{C}$. Rauber et al. (2000) similarly

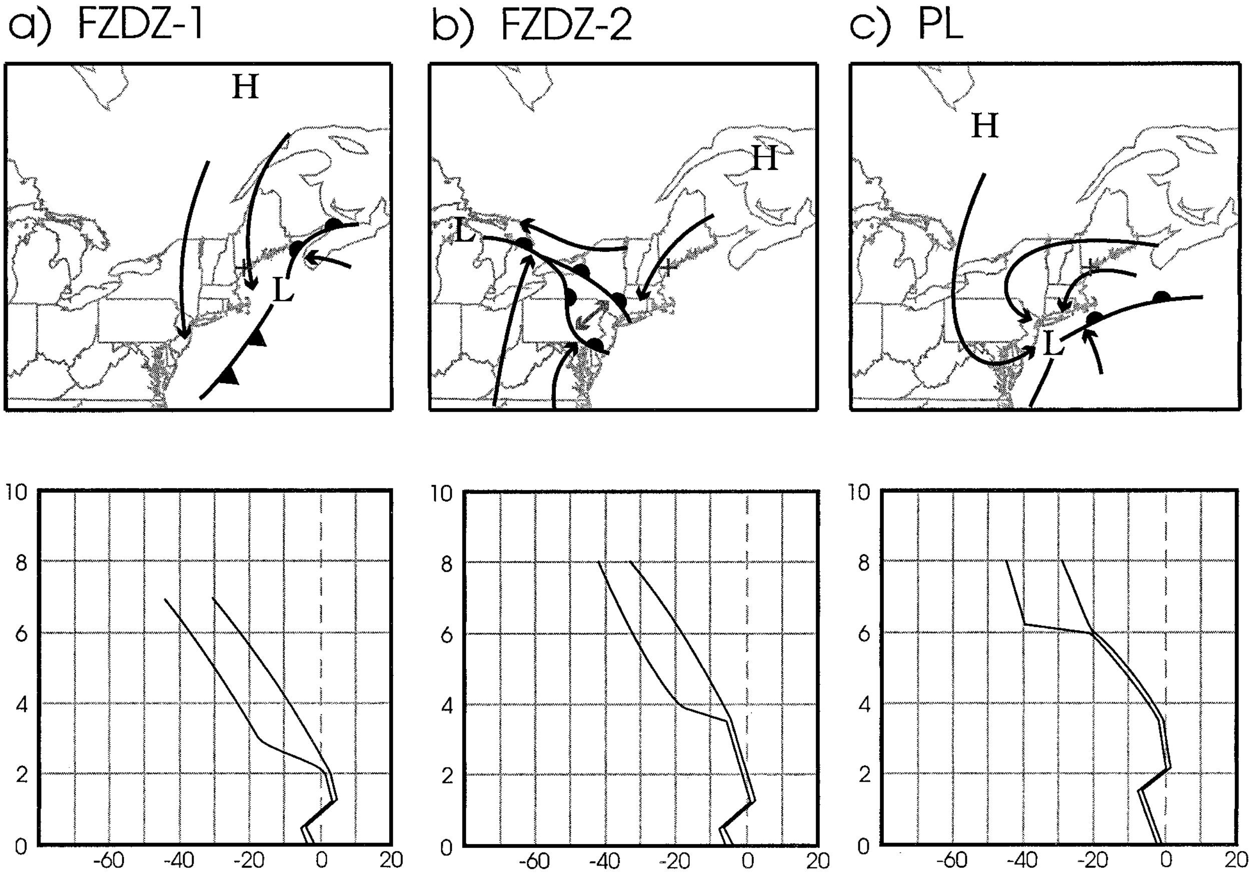

FIG. 24. Same as Fig. 10 but for FZDZ with low pressure (a) off the coast and (b) over the Great Lakes, and (c) PL at Portland.

found potential melting zones in nearly all FZPCP soundings they examined for New England.

The primary setup for the five pure PL events had a low centered between eastern Pennsylvania and off the Massachusetts coast, with a warm front or stationary front that extended to its east or northeast, sometimes up to the Gulf of Maine (Fig. 24c). The low pressure centers had tremendous variability in strength (from 980 to 1012 mb). High pressure was anchored either to the east of Nova Scotia or over northern Quebec, with strong ridging into the Maritime Provinces. CTTs were less than $-10°C$, and the subfreezing layers were all fairly deep (1000–2000 m) and cold (all but one had $-11°C < T_{\min} < -4°C$), while the melting zones had $0°C < T_{\max} < 2°C$ in four of the five cases. Cases where mixtures of PL with FZRA and/or FZDZ occurred had a mixture of the synoptic scenarios and sounding structures described for the pure events.

When the melting process appeared to cause PL, layers of $T > 2°C$ with depths in excess of 500 m were sometimes present. These relatively strong melting zones were accompanied by supercooled layers with $T_{\min} < -4°C$ and usually with $T_{\min} < -7°C$. Such occurrences seem to indicate that the strength of the supercooled layer may be very important for PL production when complete melting is expected above Portland. Similar PL sounding structures were present at Green Bay, Pittsburgh, and Greensboro, though not as frequently.

6. Summary and conclusions

In-depth climatologies were developed for six sites across the CONUS using surface observations, synoptic-scale weather maps, and balloon-borne sounding data. Investigation of these data has indicated that proximity to topography and moisture sources plays an important role in which mechanisms dominate the production of FZPCP, as well as how much and what type is received at each site. Through the understanding of the driving forces (or lack thereof) behind the formation of FZPCP for these six stations, we better understand the causes of the regional maxima and minima in the geographical distribution of FZDZ, FZRA, and PL. The individual distributions of FZDZ, FZRA, and PL with wind direction are the result of the superposition of regional and local effects with synoptically favored wind directions. This has been demonstrated via comparison of distributions for individual stations with the aggregate distribution for the CONUS, and with other nearby stations.

Even relatively small topographic features and water bodies, like the Palmer Divide and Lake Erie, can play a significant role in the occurrence of FZPCP, especially FZDZ. The roles of the cleanliness of upstream air masses, and the potential importance of whether the water bodies are frozen or open, should be investigated further. Past research has shown the importance of clean air for the growth of precipitation via the CC process, and there is evidence here that some stations have enhanced FZDZ occurrence with wind directions that have a long fetch over the Great Lakes. The fact that some stations bordering the lakes do not show this trend well merits further investigation.

Columbia Basin cold-air pooling FZDZ events preceded by or embedded within prolonged fog events also warrant further examination. Issues such as the deepening and aging of clouds, increases in shear at or below cloud top, as well as cloud-top cooling may play a role in the transition of such small-drop clouds to those containing FZDZ. This transition remains one of the longstanding issues in cloud physics. It is important to the understanding of development of supercooled warm rain and drizzle, as well as potentially hazardous icing conditions aloft.

Leeside rain shadowing in synoptically favored easterly winds explains the relative minimum in FZPCP along the western slope of the Appalachians. The dominance of PL along the east and west coasts of the CONUS is explained by the fact that ~24% of all PL, and less than 1% of FZDZ and FZRA occur with $T > 1°\mathrm{C}$. Evidence of strong supercooling via exposure to rather cold and/or dry air beneath the melting zone indicates that these features may play a more important role in the formation of PL than previously thought. In particular, the role of dry air should be examined further. Evidence of relatively shallow, cool melting zones lends support to past theories on the importance of incomplete melting in the formation of PL, rather than FZRA. The relatively deep, cold supercooling layers present in PL soundings, however, also support the possible importance of those conditions in the refreezing process when complete melting of snowflakes has occurred in the melting zone.

Regional commuter, and especially prop-driven aircraft, spend much of their flight time at lower altitudes, and thus are frequently exposed to FZDZ and FZRA aloft. Their ice protection systems are not designed to handle these conditions, and planes are not certified for flight into them. Forecasters preparing surface precipitation type forecasts or guidance for flights in FZPCP-prone areas should familiarize themselves with the regional differences in formation mechanisms, synoptic forcing, local effects, and supercooled layer depths and temperatures. Such differences could affect the rules of thumb generally used to find and circumvent these conditions in flight. Also, the application of such rules of thumb should be carefully considered in the development of model-based precipitation type (e.g., Czys et al. 1996; Baldwin et al. 1994; Tremblay and Glazer 2000) and in-flight icing (e.g., McDonough and Bernstein 1999; Thompson et al. 1997) diagnositc and forecast algorithms.

Acknowledgments. The author would like to express his sincere thanks to J. Walter Strapp and Stewart Cober of the Atmospheric Environment Service of Canada for their experience and insight on freezing precipitation mechanisms, especially regarding the Great Lakes and southern Canada. Ronald Miller of the National Weather Service, Spokane, Washington, was very helpful in the understanding of some physical processes of the weather in the Columbia Basin region. Thanks to Tiffany Bernstein and Frank McDonough for their help with several of the figures and datasets, and review of this document. Thanks also to Peter Neilley, Marcia Politovich, and Roy Rasmussen for their helpful reviews.

This research is sponsored by the National Science Foundation through an Interagency Agreement in response to requirements and funding by the Federal Aviation Administration's Aviation Weather Development Program. The views expressed are those of the authors and do not necessarily represent the official policy or position of the U.S. government.

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