A Multisensor Approach to Detecting Drizzle on ASOS*

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ABSTRACT

National Weather Service Automated Surface Observing System (ASOS) stations do not currently report drizzle because the precipitation identification sensor, called the light-emitting diode weather identifier (LEDWI), is thought not to have the capability to be able to detect particles smaller than about 1 mm in diameter. An analysis of the LEDWI 1-min channel data has revealed, however, that the signal levels in these data are sufficiently strong when drizzle occurs; thus, they can be used to detect drizzle and distinguish it from light rain or snow. In particular, it is shown that there is important information in the LEDWI particle channel that has not been previously used for precipitation identification. A drizzle detection algorithm is developed, based on these data, and is presented in the paper. Since noise in the LEDWI channels can sometimes obscure the drizzle signal, a technique is proposed that uses data from other ASOS sensors to identify nondrizzle periods and eliminate them from consideration in the drizzle algorithm. These sensors include the ASOS ceilometer, temperature, and dewpoint sensors, and the visibility sensor. Data from freezing rain and freezing drizzle events are used to illustrate how the algorithm can differentiate between these precipitation types. A comparison is made between the results obtained using the algorithm presented here and those obtained from the Ramsay freezing drizzle algorithm, and precipitation type recorded by the ASOS observer. The paper shows that by using data from the LEDWI particle channel, in combination with data from other ASOS sensors, the ability exists to detect drizzle with the current suite of ASOS instrumentation.

1. Introduction

Drizzle is a form of liquid precipitation that is characterized by ‘‘very small, numerous and uniformly dispersed water drops. . .that fall to the ground. . .and (are) frequently accompanied by low visibility and fog’’ (Huschke 1959, p. 179). Drizzle has been recognized as a distinct precipitation type since 1806 when Sir Francis Beaufort first developed a system of weather notations designed to facilitate the recording of weather observations (Heidorn 1998). While the human observer can detect and identify drizzle rather easily, it is much more difficult for automated precipitation identification sensors to do the same. With the trend toward replacing the human observer with automated weather observing stations, the number of drizzle observations in the United States has decreased significantly during the past decade.

One of the systems of automated weather stations that provides continuous observations of weather conditions at nearly 900 sites in the United States is the Automated Surface Observing System (ASOS), developed jointly by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD). Precipitation detection and identification on ASOS is accomplished using an optical sensor called the light-emitting diode weather identifier (LEDWI) manufactured by Optical Scientific, Inc. [formerly Scientific Technology, Inc. (ScTI)]. LEDWI provides observations of rain and snow in accordance with the specification for the ASOS precipitation identifier (PI; NOAA 1991), which states that the PI sensor must 1) be able to *detect* precipitation 99% of the time when precipitation rates are greater than or equal to 0.25 mm h^{-1} (0.01 in. h^{-1}), and 2) once detected, be able to *identify* precipitation type 97% of the time when the precipitation is solid (snow) and 90% of the time when the precipitation is liquid. False alarm rates (reporting precipitation when none is occurring) are also required to be less than 0.2%. Extensive testing of LEDWI during the early 1990s has shown that it generally meets or exceeds the ASOS specification (Burgas and Laster 1995).

Drizzle is not currently reported on ASOS except at those stations where an observer may augment the observation (approximately 15% of the nearly 900 ASOS stations provide observations that are augmented). There are two reasons for this. First, drizzle generally

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occurs at rates that are below the detection threshold of the PI specification (i.e., <0.25 mm h^{-1}). Thus, there is no requirement for LEDWI to detect drizzle. Second, there is a perception that LEDWI is incapable of detecting drizzle-sized particles (i.e., particles smaller than 0.5 mm in diameter). This arises from a statement in an ScTI document (Scientific Technology, Inc. 1995) that states that LEDWI was ''designed to be sensitive to drop sizes >1 mm in diameter'' (Burgas 1998). In other words, LEDWI was not designed to detect drizzle.

In recent years there has been increased interest in being able to detect drizzle on ASOS, particularly when temperatures are near or below freezing. Ramsay (1999) has developed a technique that *infers* the existence of freezing drizzle when the ASOS icing sensor reports ice accumulation on the probe *and* LEDWI reports no precipitation. This method assumes that LEDWI correctly identifies rain when it occurs (we will show later that some LEDWI ''rain'' is actually drizzle) and, of course, it does not detect drizzle at temperatures above freezing. The NWS has begun a search for an ''enhanced'' PI sensor that is capable of detecting and identifying drizzle at all temperatures, as well as identifying other forms of precipitation such as ice pellets, snow pellets, and hail. The enhanced PI sensor would replace the LEDWI on ASOS.

An analysis of LEDWI channel data, recorded each minute and retained on each ASOS station for a period of 12 h, shows that there is an elevated signal level in the channel data that occurs when drizzle is being reported by the station's observer. By comparing the values in the various channels there is evidence that drizzle produces a unique and characteristic pattern in the channel data that allows it to be distinguished from rain or snow.

The purpose of this paper is to describe the LEDWI channel data and show the relationships that exist between the various channels when different types of precipitation are occurring. Based on these relationships, a function is developed that allows drizzle to be detected and distinguished from light rain or light snow. Drizzle intensity is established using the LEDWI data in much the same way that rain intensity is determined.

A complicating factor in detecting drizzle using LEDWI data is that background ''noise'' exists in the LEDWI channels that makes it difficult to distinguish drizzle from the noise. The noise is due primarily to index of refraction gradients that occur near the earth's surface as a result of heat exchange processes. Thus, the noise generated by these gradients is particularly high during sunny, nonprecipitating weather and is minimal during overcast, wet weather. This is fortunate because it provides a way to eliminate those time periods when the noise level is high. This paper will propose a method of identifying these periods using data from existing sensors on ASOS.

Section 2 provides a description of how the LEDWI sensor works, while section 3 discusses the LEDWI data format and describes how precipitation type and intensity is determined using the current LEDWI algorithm. Section 4 discusses how the LEDWI channel data can be used to help identify drizzle and shows illustrations of data from a freezing rain and freezing drizzle event that occurred in Peoria, Illinois, on 18 February 2000. Section 5 compares the results of the drizzle detection analysis presented here with output from the Ramsay freezing drizzle algorithm, while section 6 shows additional comparisons between LEDWI and the ASOS icing sensor. Section 7 discusses the problem of nonprecipitation noise in the LEDWI data and shows how data from ASOS sensors can be used to eliminate this problem. Section 8 discusses the problem of establishing drizzle intensity. Section 9 provides a summary of the drizzle detection algorithm.

2. A description of the LEDWI sensor

LEDWI operates on the principle that a partially coherent infrared or visible light beam, when passed through an irregular medium, will have its frequency altered by the irregularities in the medium (Starr and Wang 1989). The phenomenon is called scintillation, examples of which are the twinkling of stars at night or the shimmering effect seen over a heated surface on a summer day. When precipitation falls through an infrared beam it also introduces frequencies in the beam that are a function of the size and fall speed of the particles. LEDWI measures the frequency composition of the beam after it has passed through precipitation, performs a Fourier transformation on the received signal, and deduces the type and intensity of the precipitation based on the power levels generated in two frequency bands: a low-frequency band from 75 to 250 Hz that is more sensitive to slower-falling precipitation, and a high-frequency band from 1000 to 4000 Hz that is more sensitive to faster falling precipitation.

Figure 1 shows a schematic diagram of the LEDWI sensor. The transmitter and receiver heads are mounted approximately 3 m above the ground and are oriented so that the receiving head faces north. Figure 2 is a schematic diagram illustrating how LEDWI works. The transmitter, located on the right side of the figure, directs a pulsed infrared beam toward the receiver, located 0.8 m away. The infrared beam is 50 mm in diameter and is pulsed at 50 000 Hz. The receiving lens contains a horizontal slit aperture that has a vertical dimension of 1 mm. The purpose of the slit is to make LEDWI more sensitive to the vertical motion of the particles rather than their horizontal motion. The receiving lens focuses the beam on a photodiode that converts the light energy into an electronic signal. A signal processor determines the components of the signal and computes the power levels in the high- and low-frequency channels (HC and LC, respectively). It also records the relative size of the largest particle observed during the sampling interval in a particle channel (PC). A carrier channel monitors

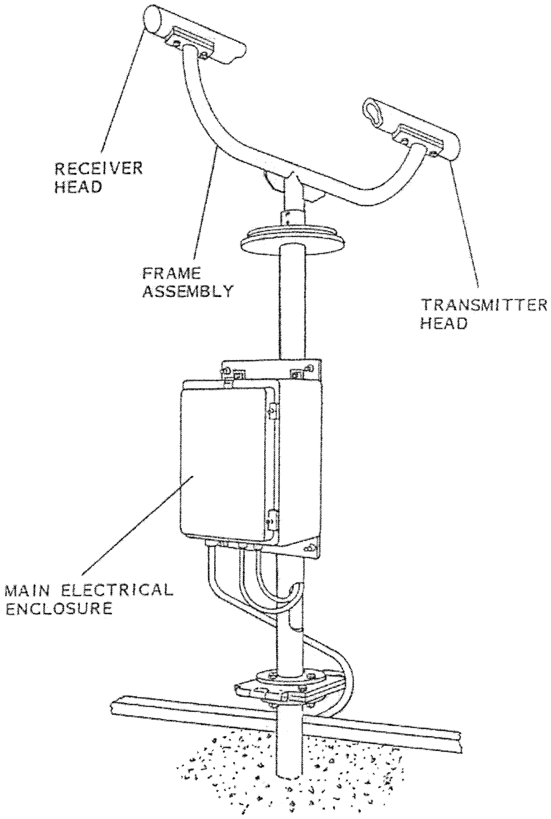

FIG. 1. A schematic diagram of the LEDWI sensor.

any change in signal strength that may occur between the transmitter and receiver. These data are used primarily to detect lens blockage that may occur, for example, during blizzard conditions.

3. Determining precipitation type and intensity on LEDWI

Each ASOS station records LEDWI data in the format shown in the following example:

$$\underset{A}{\underline{0536}}\quad \underset{B}{\underline{\mathrm{WS+}}}\quad \underset{C}{\underline{\mathrm{P}\ 7.41}}\quad \underset{D}{\underline{\mathrm{S}\ 0000\ 02}}\quad \underset{E}{\underline{\mathrm{X}\ 272}}\quad \underset{F}{\underline{000}}$$

$$\underset{G}{\underline{\mathrm{L}\ 271\ 010}}\quad \underset{H}{\underline{\mathrm{K}\ 632\ 077}}\quad \underset{I}{\underline{\mathrm{H}\ 421\ 060}},$$

where A is the local standard time; B is the weather type and intensity [R, R−, R+, S, S−, S+, undetermined (?0, ?1, ?2, ?3, P, P?), or no precipitation (blank)]; C is the precipitation rate (mm h^{-1}); D is the status channel; E is the carrier channel; F is the lock indicator [(0 = on, 1 = off) in the order low channel, particle channel, high channel]; G is the low channel (1-min average of the current low-frequency power level followed by a three-digit adaptive baseline value); H is the particle channel (1-min average of the current particle channel power level followed by a three-digit adaptive baseline value); and I is the high channel (1-min average of the current high channel power level followed by a three-digit adaptive baseline value.

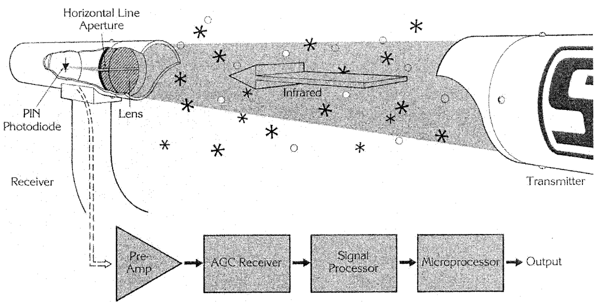

FIG. 2. Schematic diagram illustrating how the LEDWI sensor works.

The adaptive baseline for the low, particle, and high channels represents the average power level in each of these channels over the previous 20 min. They are used to establish the background levels for the various channels when it is not precipitating. When precipitation begins the channel values increase according to the type and intensity of the precipitation. When the difference between the current channel value and the baseline value exceeds a pre-established threshold, the baseline for that channel is locked, and it remains locked until the precipitation ends. The particle channel is the channel that is most sensitive to the onset and termination of precipitation. When the difference between the particle channel and its baseline value exceeds 56, precipitation is established to be occurring, and the particle baseline is locked. It remains locked until the difference between the current particle value and its baseline decreases to less than 28 and remains less than 28 for a period of 20 min. When this occurs the calculation of the particle channel adaptive baseline begins anew. The high channel thresholds for lock on and lock off are 26 and 13, respectively. The low channel adaptive baseline is typically set to -10, with a threshold of 25. Thus, the low channel typically becomes locked when its value becomes $\geqq +15$. When precipitation starts very slowly, as it sometimes does during drizzle, the various channels often never reach their threshold values since the adaptive baselines are also increasing. When this happens LEDWI will continue to report no precipitation.

Once it has been established that precipitation is occurring (i.e., the particle channel is in a locked ‘‘on’’ state), LEDWI next attempts to determine precipitation type. Precipitation type is based on the lock state and relative values in the high and low channels. This is illustrated graphically in Fig. 3. The data used to construct this diagram were gathered during the winters of 1996/97 and 1997/98 from an LEDWI sensor installed at the National Center for Atmospheric Research (NCAR) Marshall Facility, located near Boulder, Col-

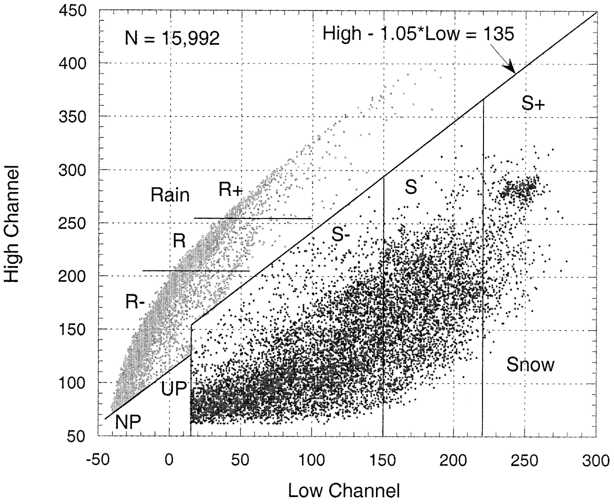

FIG. 3. A Cartesian diagram showing the relationship between the 1-min average power in the LEDWI low- and high-frequency channels, collected from nearly 16 000 min of rain and snow that occurred at NCAR's Marshall facility between 1996 and 1998.

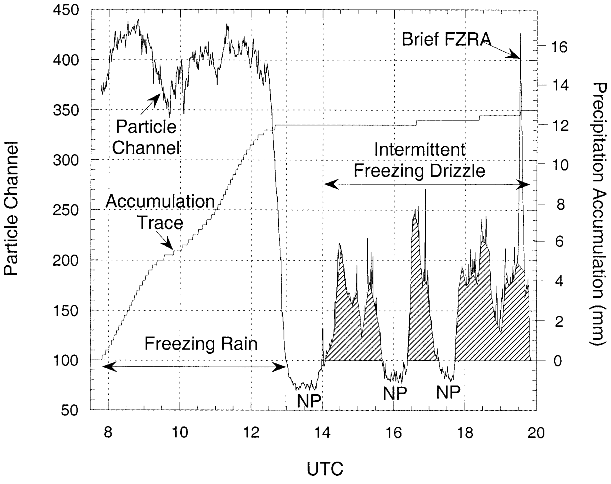

FIG. 4. A time series of particle channel and precipitation accumulation data from the ASOS station at Peoria, IL, on 18 Feb 2000.

orado. In the diagram each point represents 1 min of LEDWI data, plotted using the observed high and low channel values for that minute and the type of precipitation determined from the LEDWI algorithm. When no precipitation (NP) is occurring, the data points are generally clustered near the lower-left corner of the diagram. If the particle channel is on, but neither the low nor the high channels are on, the precipitation is very light and the type is called undetermined precipitation (UP). These points are plotted near the NP points in the lower-left corner of the diagram. Rain is said to be occurring when both the high and particle channels are on and the low channel is off ($LC < +15$), or when all three channels are on and the difference between the high and low channels [$HC - 1.05(LC)$] exceeds 135. This functional relationship between the low and high channels is represented on the diagram by a diagonal line running from the upper right to lower left. The line jogs at the point where $LC = +15$. High/low values on the upper-left side of the line are called rain, and on the lower-right side, snow.

If the precipitation type has been established to be rain, the rain intensity is determined by the magnitude of the value in the high channel. The greater the power in the high channel, the higher the precipitation rate. Section 8 shows the equation that establishes the relationship between the average 1-min power in the high channel and precipitation rate. Based on this relationship, a high channel value of 205 is approximately equal to 2.54 mm h^{-1}, which is the transition point between light and moderate rain. A high channel value of 255 is approximately equal to 7.62 mm h^{-1}, which is the transition point between moderate and heavy rain. Reference lines have been placed at these locations on Fig. 3.

Snowfall intensity is determined in a similar manner using the magnitude of the low channel. Vertical lines at $L = 150$ and $L = 220$ in Fig. 3 show where the snowfall intensity has been divided into light, moderate, and heavy categories by the LEDWI algorithm. However, when reporting snowfall intensities ASOS modifies the LEDWI-derived intensities based on the current visibility (NWS 1998).

4. Drizzle detection on LEDWI

The previous section described how rain and snow can be detected by the LEDWI sensor using the relationship between the high and low channels. The particle channel was used, but only to determine *if* precipitation was occurring. In this section we will show that the actual values in the particle channel can be used in combination with the values in the low channel to detect when drizzle is occurring. An example of LEDWI data from the ASOS station at Peoria, Illinois, collected on 18 February 2000, is presented. During this event, 5 h of freezing rain was followed by 7 h of intermittent freezing drizzle.

Figure 4 shows a 12-h time series of the particle channel and rain accumulation traces from Peoria between 0747 and 1947 UTC.[1] The elevated values in the particle channel between 0747 and about 1300, as well as the accumulation of nearly one-half in. (11.9 mm) of precipitation, are consistent with the observation that rain (in this case freezing rain) was occurring. After 1300 only 0.03 in. (0.76 mm) of precipitation was recorded during the remaining 7 h that data were collected. The particle channel values were considerably lower during this period and the precipitation was intermittent. The observer reported freezing drizzle from 1408 to 1641,

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[1] All times are given in universal time (UTC).

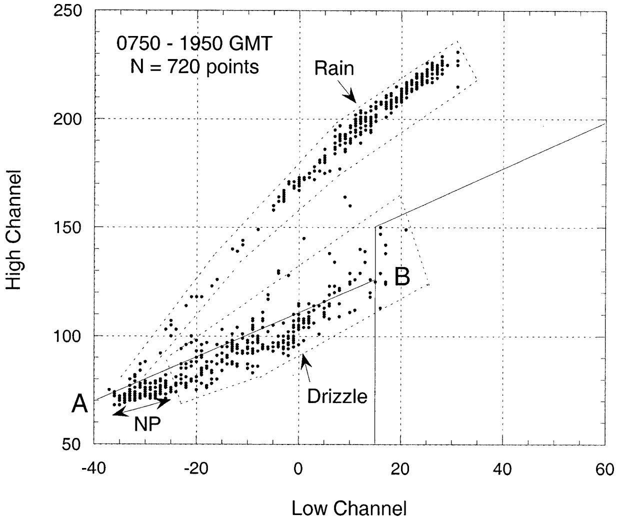

FIG. 5. A Cartesian diagram showing the relationship between the 1-min average power in the LEDWI low- and high-frequency channels, collected from the LEDWI sensor at Peoria, IL, on 18 Feb 2000.

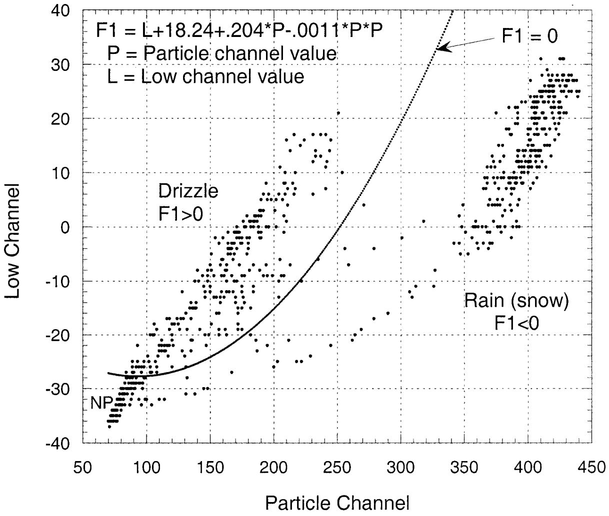

FIG. 6. A Cartesian diagram showing the relationship between the 1-min average power in the LEDWI low-frequency and particle channels, collected from the LEDWI sensor at Peoria, IL, on 18 Feb 2000.

but freezing rain during the periods 1641–1727, 1753–1900, and 1917–2034. The analysis that follows will show that all of the precipitation between 1300 and about 2000 was in the form of drizzle, except a very brief period of rain at about 1930.

Figure 5 shows a plot of the high and low channel LEDWI data from Peoria for the same 12-h period. There are two distinct clusters of points in the figure. The rain that occurred from 0747 until about 1300 produced an arclike cluster of points that stretches from the lower-left corner of the diagram upward toward the right. Their location is similar to the rain points shown in Fig. 3. The solid vertical and diagonal lines in Fig. 5 are the same as those in Fig. 3 and represent the dividing lines between different precipitation types according to the current LEDWI algorithm. All points above the diagonal lines are called rain by this algorithm. Hence, all the points in the region labeled as rain in Fig. 5 were properly identified.

The second cluster of points in Fig. 5 extends from the lower-left corner of the figure slightly upward and toward the right along the line labeled AB. These are the points associated with the 7 h of intermittent drizzle that occurred after 1300. During periods when no precipitation was occurring the points are located in the area labeled NP. During periods when drizzle was occurring the points are located farther to the right. Under the current LEDWI algorithm the points above the line AB would be called rain, while those below the line would be called either NP or UP, depending on the lock status of the particle channel. The drizzle points appear in a different region in Fig. 5 because drizzle has slower fall speeds than rain (hence more power in the low channel and less in the high channel), and drizzle occurs at lower precipitation rates (hence lower high channel values). Very light snow has similar low and high channel values as drizzle because it has similar fall speeds and similar precipitation rates. Thus, drizzle and snow cannot be differentiated based only on their high and low channel values.

In order to distinguish drizzle from both rain and snow it is necessary to incorporate data from LEDWI's particle channel. According to the manufacturer (Dr. T.-I. Wang 2002, personal communication) the values in the particle channel are proportional to the largest particle observed by LEDWI during each 1-min period. To illustrate how the particle channel data can be used we have plotted in Fig. 6 the particle and low channel values for the Peoria, Illinois, precipitation event. Once again there are two clusters of points. The points associated with drizzle appear on the left side of the diagram, while those associated with rain appear on the right side. Particle–low pairs associated with snow would also appear on the right side of Fig. 6. As in Fig. 5, a region of NP points appears in the area of lowest particle and low channel values. There is no information available on the actual particle sizes, but the fact that there are two distinct clusters of points suggests that the two groups have different number, diameter, and fall speed characteristics. The NWS has recently purchased a disdrometer for use at its Sterling, Virginia, test facility (Lewis et al. 2002), which will be used to try to establish a baseline for particle sizes and numbers against which sensors like the LEDWI can be compared.

If we assume that the cluster on the left in Fig. 6 is associated with drizzle, while the cluster on the right is associated with rain, then it is possible to divide the points in the diagram using a function based on the

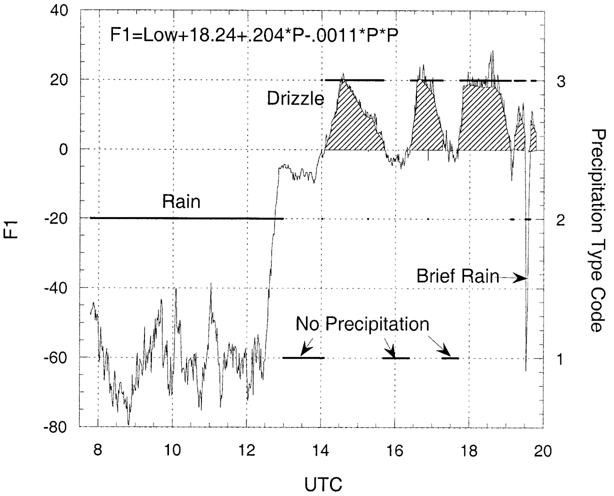

FIG. 7. A time series showing the change in the $F1$ function as rain changes to drizzle during the Peoria, IL, event. Also shown, using the precipitation code on the right, are the time periods when rain, drizzle, and no precipitation occurred as determined by the $F1$ function and the particle channel.

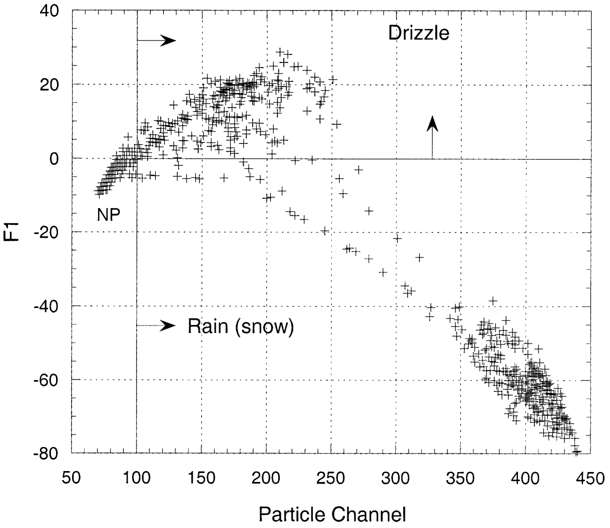

FIG. 8. A Cartesian plot of the $F1$ function and the particle channel data for the Peoria, IL, 18 Feb 2000 event showing the divisions between rain, drizzle, and no precipitation.

particle and low channel values. A curved line was drawn on the diagram between the two clusters, and a second-degree polynomial was fitted to the line. The equation for this line is given in Eq. (1),

$$F1 = \mathrm{LC} + 18.24 + 0.204(\mathrm{PC}) - 0.0011(\mathrm{PC}^2) = 0, \quad (1)$$

where LC and PC are the values in these two channels at a given time.

The curve in Fig. 6 represents the locus of points where the function $F1 = 0$. When $F1$ is positive, the precipitation will be called drizzle; and when $F1$ is negative the precipitation will be called rain or snow (the decision between rain and snow will be left to the existing LEDWI algorithm). The placement of the $F1 = 0$ curve in the low–particle Cartesian plane in Fig. 6 was based on hundreds of hours of drizzle, rain, and snow data collected from ASOS stations located over diverse geographical locations in the United States.

Figure 7 shows a time series of the $F1$ function for this event and illustrates how well the function did in distinguishing between the rain and drizzle periods, even to the extent of identifying the brief period of rain at 1930. Less clear, however, is the distinction between drizzle and no precipitation. The time series in Fig. 4 shows that during the three periods when precipitation stopped, the particle channel values decreased to near their minimum value between 70 and 80. A somewhat arbitrary line was drawn at a particle channel value of 100 to indicate the approximate point below which drizzle was no longer detectable. The particle channel value of 100 should not be viewed as a fixed cutoff point, applicable to all LEDWIs, but rather should be viewed in terms of its position relative to the lowest values observed during periods of no precipitation. In this event the cutoff point is approximately 30 units higher than the observed minimum particle channel value of 70. In later sections we will compare the particle channel data with data from other ASOS sensors in an effort to refine our selection of the particle channel cutoff criteria.

In Fig. 8 the $F1$ values are plotted against the particle channel values to illustrate a technique for distinguishing between rain/snow, drizzle, and no precipitation. The particle channel value of 100 is used to distinguish between precipitation and no precipitation, and the $F1$ value is used to distinguish between rain/snow and drizzle. Thus, drizzle is defined as those points where $F1 \geqq 0$ and $\mathrm{PC} \geqq 100$. Rain/snow is defined as $F1 < 0$ and $\mathrm{PC} \geqq 0$, and no precipitation is defined as any point where $\mathrm{PC} < 100$.

To illustrate the results of this decision-making process numbers 1–3 were assigned to precipitation categories as follows: 1 = no precipitation, 2 = rain, and 3 = drizzle. Periods when these events occurred are plotted on Fig. 7 using the scale on the right.

Overall, the technique described here identified 256 min of drizzle that is made up of 45 min originally called rain by the current LEDWI algorithm, 196 min originally called UP, and 15 min called NP. The number of minutes identified as rain increased slightly from 317 to 329, and the number of minutes of UP decreased from 206 to 0. Since temperatures were subfreezing throughout the event, all precipitation identified as rain was actually freezing rain, and all drizzle was freezing drizzle. The results generally agree with the precipitation type recorded by the observer until after 1641 when the observer recorded freezing rain rather than freezing drizzle. The analysis presented here suggests that all of the precipitation after 1300 was in the form of drizzle,

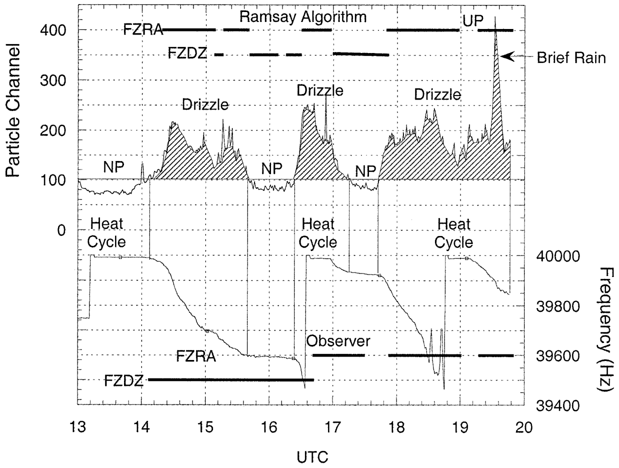

FIG. 9. A time series showing particle channel data and icing sensor frequencies for the Peoria, IL, 18 Feb 2000 event for the period from 1300 to 1947 UTC. Precipitation types recorded by the observer are shown at the bottom of the diagram, while those derived from the Ramsay algorithm are shown near the top.

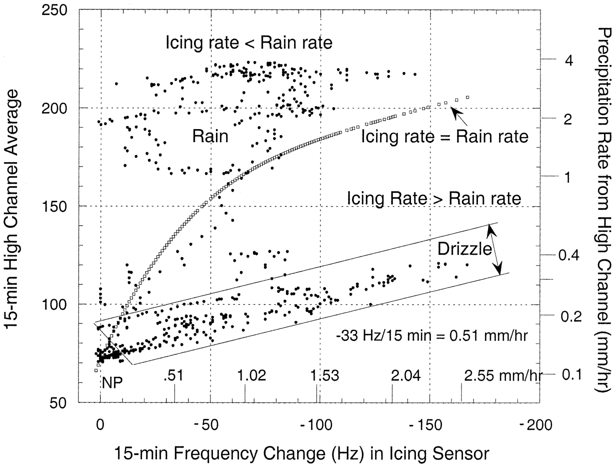

FIG. 10. A Cartesian diagram showing the relationship between the 15-min average power in the LEDWI high channel and the 15-min change in frequency recorded by the ASOS icing sensor for the Peoria, IL, event.

with the exception of a very brief period of rain at about 1930.

5. Comparison with the Ramsay freezing drizzle algorithm

Since the Peoria, Illinois, case study has both freezing rain and freezing drizzle, it is reasonable to compare the method developed here for detecting drizzle with the method proposed to detect freezing drizzle by Ramsay (1999, 2002) and Ramsay and Dover (2000). The Ramsay freezing drizzle algorithm (referred to here as the Ramsay algorithm) relies primarily on the output from the ASOS icing sensor and the precipitation type determined by the current LEDWI algorithm. Briefly, the Ramsay algorithm says that if LEDWI reports rain or UP and the icing sensor reports ice accretion and rates greater than a pre-established threshold, then freezing rain (FZRA) is reported. If the ice accretion and rates exceed the threshold and the skies are overcast, but LEDWI reports no precipitation, then freezing drizzle (FZDZ) is reported. If the skies are not overcast, no precipitation is reported.

Ramsay (A.C. Ramsay 2002, personal communication) has processed the data from the Peoria case through his algorithm and the results are presented in Fig. 9. The figure shows a time series of particle channel and icing sensor frequencies for the period from 1300 until 2000. Periods identified earlier in this paper as having drizzle are shown with cross-hatching under the particle channel curve. Start and stop times for the three drizzle events are indicated using vertical lines. Notice that the times when the particle channel values go above or below 100 match closely with the times that the icing frequencies start or stop decreasing. This is an indication that the particle channel is able to detect the entire drizzle event, since the icing sensor is sensitive to even the smallest particles.

Near the top of Fig. 9 the output from the Ramsay algorithm is shown. It shows a choppy pattern with periods of FZDZ and FZRA interspersed, and with FZRA as the predominant precipitation type. This is due to the fact that LEDWI identified these periods as rain or UP. Observer reports of FZRA and FZDZ are shown near the bottom of the figure. Overall, Ramsay reported 505 min of FZRA (including the period before 1300), and 103 min of FZDZ. The algorithm described here reported 329 min of rain and 256 min of drizzle for the overall event. Prior to 1300 there was general agreement between the observer and the two algorithms that FZRA was occurring. After 1300 there was considerable disagreement.

6. Additional comparisons between LEDWI and the ASOS icing sensor

For freezing precipitation events the LEDWI high channel data can be viewed in conjunction with data from the ASOS icing sensor to gain additional insight into the differences between freezing rain and freezing drizzle. This can be seen in Fig. 10, which plots the running 15-min change in icing sensor frequency against the corresponding 15-min average value in the LEDWI high channel. The high channel is used here because, as described earlier, it is correlated with the rate of liquid precipitation. A scale on the right side of Fig. 10 shows the precipitation rates derived using the high channel data. In section 8 we will show that this scale is a close approximation to observed precipitation rates on this day. The average relationship between ice accretion (inches) and frequency decrease (Hz) is 1 Hz = 0.000 152 in. or

0.003 860 8 mm (NWS 1998). A decrease of 33 Hz in 15 min would correspond to an icing rate of 0.51 mm h^{-1}. The scale along the bottom of Fig. 10 shows the icing rates that correspond to various frequency changes. As in previous figures for this event, there are two clusters of points. The cluster that appears in the upper portion of the figure is associated with rain rates that are generally in excess of 1 mm h^{-1}. These are the points associated with the freezing rain. The points near the bottom of the figure occur with precipitation rates that are less than about 0.4 mm h^{-1}. Some of these points are associated with very light rain, but the majority of the points occur during the time that drizzle is occurring. The curved line that runs through the figure represents the locus of points where the icing rate equals the rain rate. Points located above this line have derived icing rates that are less than the rain rates. For points located below this line the computed icing rates are greater than the precipitation rates. Ramsay, in his review of this paper, has offered the following explanation for this discrepancy (A.C. Ramsay 2002, personal communication).

> Precipitation rate is a hydrological term, and is specifically limited to the accumulation of precipitation on the ground. In contrast, ''icing rate,'' as used in the ASOS, is a term that relates to ice accumulation on objects and structures (tree limbs, power lines, communication towers, aircraft, etc.), and which may not have a strong correlation with precipitation rate—especially in instances where the horizontal flux of liquid particles is greater than the vertical flux, as in wind-blown drizzle . . . LEDWI primarily detects vertically moving particles (good for hydrologists), and the ASOS icing sensor is particularly sensitive in capturing horizontally moving particles (good for people deicing aircraft or predicting power outages).

7. Distinguishing drizzle from nonprecipitation ''noise''

Up to this point it might appear that the detection of drizzle on ASOS can be accomplished by simply using the particle channel data in combination with the LEDWI low and high channel data. Unfortunately, the existence of varying amounts of nonprecipitation ''noise'' in the LEDWI channels makes the detection of all forms of light precipitation more difficult. The nonprecipitation noise occurs primarily because of index of refraction gradients that develop due to heat transfer processes in the lowest layers of the atmosphere. Figure 11 shows a time series of channel data collected from LEDWI unit 502 that is located at the NWS Research and Development Center near Sterling, Virginia. The 6-day period from 3 to 8 August 2001 had mostly clear, dry weather with no precipitation, although there were some periods of ground fog during early morning hours. The data in all three channels are noisy, with the greatest noise occurring in the particle channel during daylight hours. There is also a significant diurnal trend in the magnitude of the low and particle channel data. The adaptive baselines and the threshold values for each of the three channels discussed earlier were designed so that rain and snow could be identified against the nonprecipitation variations shown in Fig. 11. This technique works satisfactorily in identifying when rain and snow are occurring because the channel levels in rain and snow are sufficiently greater than the noise levels. In drizzle, however, the channel values are weaker, often having values that are less than the nonprecipitation noise. Distinguishing drizzle from this noise is very difficult if only LEDWI channel data are used. Fortunately, when drizzle occurs the skies are overcast, the ground is wet, and the heat exchange processes near the surface are minimal. This greatly reduces the background noise level against which the drizzle signal must be detected. This in turn suggests that drizzle detection on ASOS can be aided by eliminating those events where drizzle is not likely to be occurring (e.g., clear skies, low humidity, etc.).

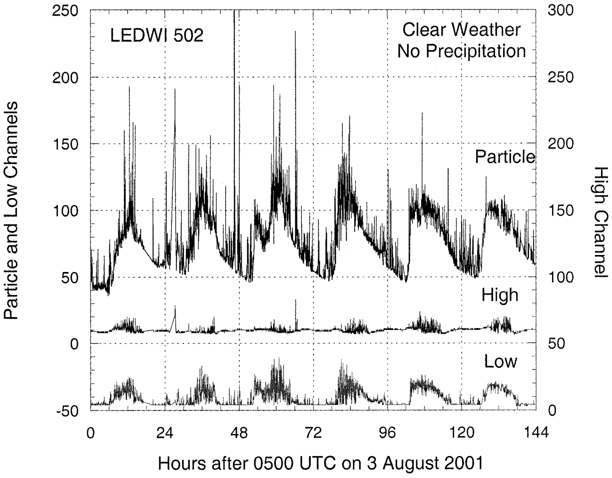

FIG. 11. A time series plot of low, particle, and high channel data from LEDWI sensor 502 located at the NWS Sterling Research and Development center, near Washington, D.C. The data are for a 6-day period from 3 to 8 Aug 2001.

Since drizzle is observed to fall from low stratus clouds, the ASOS ceilometer can be used to determine cloud cover and cloud-base height. An analysis of cloud-base heights in the United States for the 30-yr period from 1961 to 1990[2] shows that, during drizzle, more than 90% of the cloud bases were within 1500 ft of the ground. Thus, we will reject from consideration all times when ceilings are greater than or equal to 1500 ft.

The fact that drizzle is also accompanied by low visibilities and fog suggests that the relative humidity dur-

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[2] Data available from the National Climatic Data Center, Asheville, North Carolina.

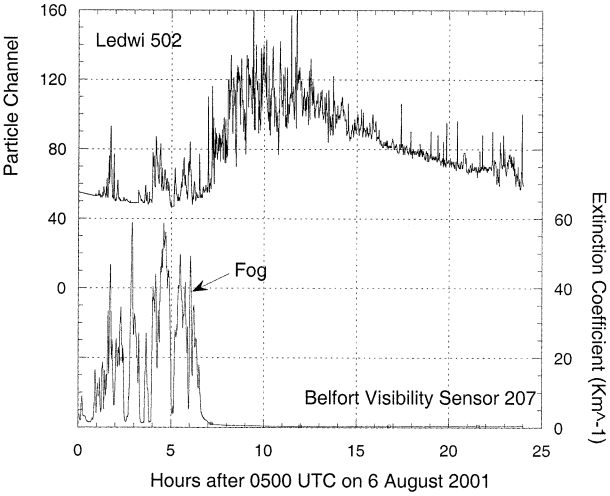

FIG. 12. A time series plot of extinction coefficients recorded by ASOS visibility sensor 207, and particle channel data from LEDWI sensor 502 located at the NWS Research and Development site near Sterling, VA. The data are from 6 Aug 2001, which is the fourth day of the 6-day period shown in Fig. 11.

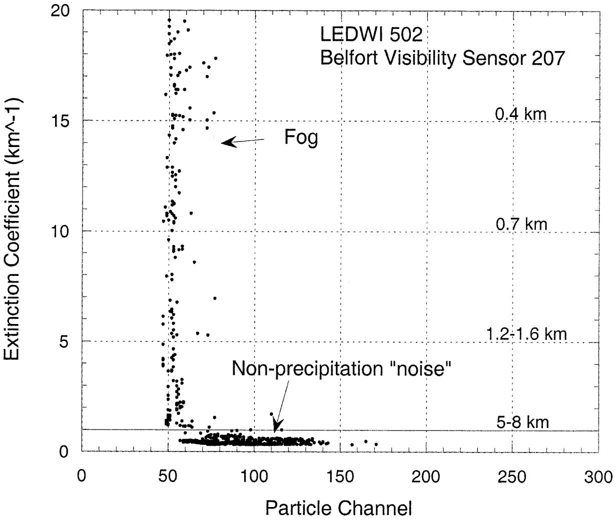

FIG. 13. A Cartesian plot of the extinction coefficient and particle channel data shown in Fig. 12. Visibilities corresponding to the extinction coefficients are shown on the right side of the figure.

ing drizzle is near saturation. This is also supported by the National Climatic Data Center (NCDC) climate data, which show that more than 90% of all drizzle occurred with dewpoint depressions less than 4°F. Thus, we can use the dewpoint information on ASOS to reject from consideration all times when the dewpoint spread was 4°F or greater.

For the Peoria, Illinois, event the ceilings were generally less than 700 ft and dewpoint depressions were 0° or 1°F.

Visibility sensors detect the extinction in light that occurs as a result of absorption or scattering. An extinction coefficient measures the amount of extinction that occurs over a given path and is inversely proportional to visibility. Figure 12 shows a time series of extinction coefficients from visibility sensor 207 located at the NWS test facility at Sterling, Virginia, for 6 August 2001 (hours 72–96 in the time series in Fig. 11). Radiation fog formed shortly after midnight EST and persisted until shortly after sunrise. The particle channel values from LEDWI sensor 502 are shown in the upper half of the diagram. Figure 12 shows that the noise level in the particle channel increases significantly at about the time that the fog dissipates and the extinction coefficient decreases to near zero.

Figure 13 shows the same data plotted in a Cartesian diagram. Visibilities corresponding to selected extinction coefficients are shown on the right, with the larger number corresponding to nighttime visibilities and the smaller to daytime visibilities. The diagram shows that when fog was present the particle channel values were near their minimum and that the noise in the particle channel occurred only when the extinction coefficients decreased to less than about 0.8 km^{-1}. Thus, to eliminate those events that are contaminated by noisy particle channel data, it is sufficient to eliminate those times when the extinction coefficient is near its minimum value. This minimum extinction value varies slightly among different visibility sensors, which is likely due to differences in the sensors and perhaps to calibration variations.

Figure 14 shows the extinction coefficients from the 18 February 2000 Peoria event, plotted versus the particle channel values, and shows that the drizzle occurred with extinction coefficients as low as 0.5 km^{-1}. Notice also that the drizzle and rain again appear in two different clusters.

Drizzle generally occurs with particle channel values

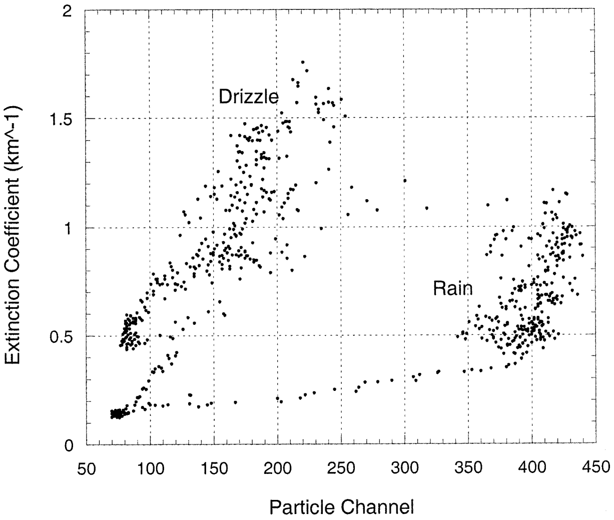

FIG. 14. Same as Fig. 13 except for the Peoria, IL, 18 Feb 2000 event.

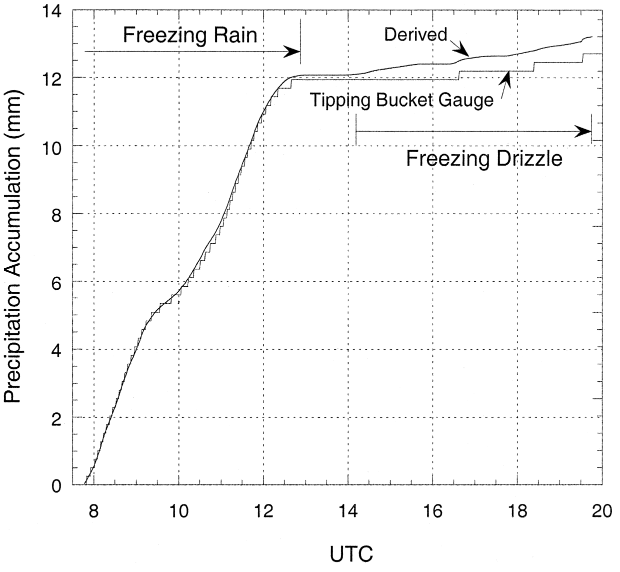

FIG. 15. A time series showing precipitation accumulations recorded from the Peoria, IL, ASOS tipping-bucket rain gauge on 18 Feb 2000, and accumulations derived from the LEDWI high channel.

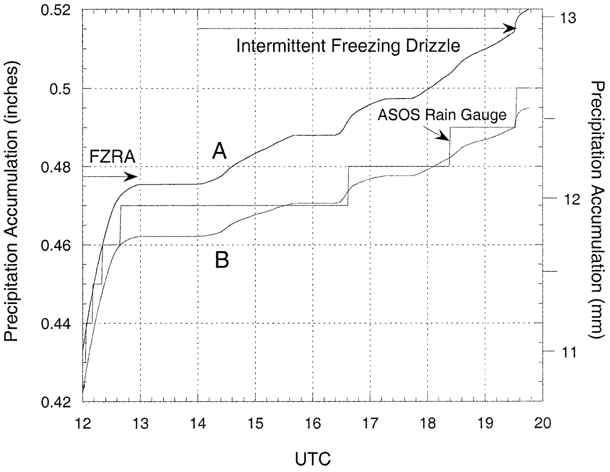

FIG. 16. Same as Fig. 15 except during the freezing drizzle period that occurred after 1400 UTC. Accumulation trace A was derived from the LEDWI high channel using the unmodified relationship, while accumulation trace B was derived using the relationship modified for drizzle and very light rain.

smaller than about 300 and will typically have a higher extinction coefficient than rain for a given particle channel value. During rain, particle channel values are generally greater than 300 except when very light rain is occurring. Overall, Figs. 13 and 14 show that extinction coefficient data can be used in combination with the particle channel data to discriminate between nonprecipitation noise, fog, drizzle, and rain.

In this study we will use an extinction coefficient threshold of 0.5 km^{-1} to separate drizzle events from nondrizzle events. Thus, if the extinction coefficient is less than or equal to 0.5 km^{-1}, it is unlikely that drizzle is occurring.

8. Establishing drizzle intensity

There are two methods used to establish drizzle intensity. The first defines drizzle intensity in terms of visibility (OFCM 1995). If drizzle is occurring and the visibility is greater than 0.5 statute miles (0.8 km), then light drizzle is reported. If the visibility is between ¼ and ½ statute miles, the drizzle is reported as moderate, and if the visibility is $\leqq$ to ¼ statute miles, the drizzle is reported as heavy. This method has its drawbacks due to the effects that fog may play in reducing visibility.

The second method used to determine drizzle intensity is based on precipitation rate. The *Glossary of Meteorology* (Huschke 1959) defines light drizzle as having a precipitation rate of less than 0.254 mm h^{-1}, while moderate drizzle occurs at a rate between 0.254 and 0.508 mm h^{-1}, and heavy drizzle falls at a rate in excess of 0.508 mm h^{-1}. Determining drizzle intensity using this method requires a sensor that is capable of resolving precipitation rates on a timescale of minutes. Precipitation gauges used by the NWS heretofore have not had this capability, so this method of establishing drizzle intensity is not used. LEDWI, however, does have the capability of resolving precipitation rates on the scale of minutes. For rainfall LEDWI uses a relationship based on the values in the high channel to determine precipitation rate (PR, in mm h^{-1}). The relationship is based on the Marshall–Palmer distribution (Starr and Wang 1989) and is given in Eq. (2):

$$\mathrm{PR} = (10^{\mathrm{HC}/100})/45. \tag{2}$$

Figure 15 shows a time series of the precipitation accumulation that occurred during the freezing rain portion of the Peoria event. The accumulation from the ASOS rain gauge (resolution 0.01 in.) is shown along with the accumulation derived from the LEDWI high channel using Eq. (2). The two curves are remarkably close. The accumulation traces for the freezing drizzle period are shown in Fig. 16. Here we see that the derived accumulation is somewhat higher than that recorded by the rain gauge, suggesting that the relationship expressed in Eq. (2) could use some minor adjustment at low precipitation rates.

Figure 17 shows the precipitation rate curve derived from Eq. (2) for rates less than 1 mm h^{-1} (curve 1). The typical minimum value for the high channel data is between 50 and 80. For a high channel value of 50, the precipitation rate is still 0.065 mm h^{-1}. To force this curve to have a precipitation rate of zero when the high channel is 50, one can simply subtract 0.065 mm h^{-1} from the rates derived in Eq. (2). The resulting curve is shown in Fig. 17 as curve 2. If the high channel values are converted to precipitation rates using Eq. (2) minus 0.065 mm h^{-1}, and these rates are then integrated over

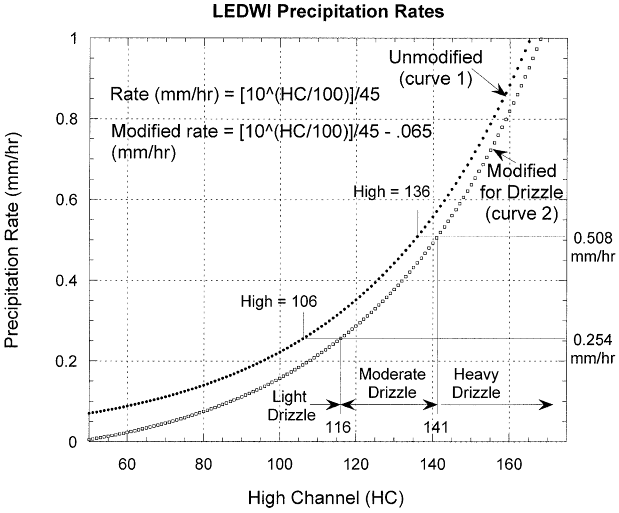

FIG. 17. A Cartesian plot showing the relationship between high channel values and precipitation rates for rain, using the unmodified equation, and drizzle using the modified equation. Based on the modified curve, the high channel value that represents the transition point between light and moderate drizzle (0.254 mm h^{-1}) is 116, while the high channel value that divides moderate and heavy drizzle is 141 (0.508 mm h^{-1}).

the period that drizzle occurred, an accumulation trace is obtained that more closely matches the ASOS rain gauge. This new trace is labeled in Fig. 16 as curve B. Clearly, a more in-depth study of precipitation rates during drizzle will have to be made to refine this relationship, but there is at least some preliminary evidence that LEDWI is able to detect precipitation at rates that are considerably below the ASOS specification, and that these rates, when integrated, match the accumulation from the ASOS rain gauge.

Using curve 2 in Fig. 17 it is possible to establish the high channel values that correspond to 0.254 mm h^{-1} (0.01 in. h^{-1}), and 0.508 mm h^{-1} (0.02 in. h^{-1}), which are the rates that separate light, moderate, and heavy drizzle. Under this scenario drizzle that occurs with high channel values less than 116 would be called light drizzle, as compared to the value of 106 derived from the rain curve. Drizzle of moderate intensity would occur between high channel values of 116 and 141, and heavy drizzle would be occurring if the high channel were above 141. There is no distinction between light and very light drizzle.

9. Summary

Automated reports of drizzle are not currently available on ASOS stations because it is believed that the current ASOS PI sensor (LEDWI) is incapable of detecting drizzle-sized particles. Also, there is no requirement for drizzle to be detected on ASOS since the precipitation rates that occur during most drizzle events are below the low-end threshold of 0.254 mm h^{-1} established by the current ASOS specification. As a result the NWS is actively looking for an enhanced PI sensor that has the capability of detecting drizzle.

The purpose of this paper has been to illustrate that, in spite of these perceived limitations, the LEDWI sensor is capable of detecting drizzle if some assistance is provided by other ASOS sensors. This is accomplished by making full use the LEDWI particle channel data, which heretofore has been used only to detect *if* precipitation was occurring. Because of the characteristic weather conditions that exist when drizzle occurs, it is possible to eliminate nondrizzle events by monitoring ceiling heights, dewpoint depressions, and visibilities (extinction coefficients). This improves detection accuracy by eliminating the contaminating noise that exists in the LEDWI channel data during nonprecipitation weather.

To review, the steps in the drizzle detection process are as follows.

1) Eliminate all events in which drizzle is not likely to occur. That is, eliminate all events in which (a) the ceiling is not overcast below 1500 ft AGL, (b) the dewpoint depression is greater than 3°F, and (c) the extinction coefficient is less than or equal to 0.5.
2) Compute a function similar to $F1 = \mathrm{LC} + 18.24 + 0.204\,(\mathrm{PC}) - 0.0011\,(\mathrm{PC}^2)$ that separates the drizzle (positive $F1$) from nondrizzle precipitation (negative $F1$). This function may vary slightly from one LEDWI to another, depending on the calibration of the low and particle channels on each LEDWI. Since there are nearly 900 LEDWI sensors, the range of channel calibrations is not known. Therefore, the development of an algorithm that fits all LEDWIs is beyond the scope of this paper.
3) Determine the particle channel threshold that separates drizzle from no precipitation. In the example shown, the particle channel threshold was set at 30 units above the particle channel minimum.
4) Drizzle is determined to be occurring if (a) the particle channel is greater than or equal to the particle channel threshold, and (b) the $F1$ function is positive. Rain or snow is determined to be occurring if (a) the particle channel is greater than or equal to the particle channel threshold, and (b) the $F1$ function is negative or zero.
5) If drizzle is occurring and $\mathrm{HC} \leqq 116$, the intensity is light; if the high channel is between 116 and 141, the intensity is moderate; and if $\mathrm{HC} \geqq 141$, the intensity is heavy. If rain or snow is determined to be occurring, return to the LEDWI program to determine precipitation type.

Freezing rain and freezing drizzle would be reported based on the output from the algorithm above and on the frequency changes determined by the ASOS icing sensor. At this point the algorithm would revert back to the thresholds recommended by Ramsay (1999, 2002). Intensity would be based on the criteria used for determining rain and drizzle intensity.

This paper has shown that LEDWI has the capability of detecting drizzle when it occurs, although the exact size of the particles detected is not known. The event chosen for analysis was selected because it had both freezing rain and freezing drizzle, as reported by the station observer. This afforded the opportunity to observe differences in the LEDWI channel data as the precipitation changed from one type to another. Although the observer only reported freezing drizzle between about 1400 and 1645, it is believed that nearly all of the precipitation after 1300 was falling in the form of drizzle. This is based not only on the relationship of the particle channel to other LEDWI channels, but also on the relationship between the particle channel data and the extinction coefficient data, and the relationship between the high channel and the icing sensor frequencies. Thus, there is an abundance of data on ASOS that can be used to detect drizzle that is not currently being used. Tapping into these data will not only enable ASOS to detect drizzle, but it is likely to reduce the number of UP observations, as well as improve the discrimination between rain and snow.

Perhaps the biggest frustration that was faced during this research was dealing with the fact that the LEDWI data are retained in memory on each ASOS station for a period of only 12 h. There is no archiving of these data, so that after the 12-h period the data are gone forever. The NCDC downloads some of the data from some of the ASOS stations by dialing into the data ports on these stations every 12 h. However, the LEDWI data are not among those data that are retained (although it would be a very simple matter to add the ''LEDWI'' command to the download routine). That means that it is virtually impossible to monitor the performance of the LEDWI channel data on any of the nearly 900 sensors that are in operation, or to develop new software based on these data. The NWS finds itself in need of an enhanced PI sensor that can detect drizzle. The analysis presented in this paper indicates that they already have this capability. All that needs to be done is to test and refine the concepts that have been proposed in this paper. The emphasis here is on *refining* the algorithm, since it is not sufficient to simply test it. This will require data from many events and from many different LEDWIs. To some extent this can be done using data from the handful of ASOS sensors that are located at the NWS research sites at Sterling, Virginia, and Johnstown, Pennsylvania, especially given that the NWS is now in possession of a device capable of analyzing particle size distributions during drizzle events. However, there still remains the question of evaluating data from some of the nearly 900 operational LEDWIs that are in the field. While this may be beyond the capability of the NWS, it represents an extremely important resource for the meteorological research community. And in the long run, it is likely to benefit the operational community as well.

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