Snow Nowcasting Using a Real-Time Correlation of Radar Reflectivity with Snow Gauge Accumulation

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ABSTRACT

This paper describes and evaluates an algorithm for nowcasting snow water equivalent (SWE) at a point on the surface based on a real-time correlation of equivalent radar reflectivity ($Z_e$) with snow gauge rate ($S$). It is shown from both theory and previous results that $Z_e - S$ relationships vary significantly during a storm and from storm to storm, requiring a real-time correlation of $Z_e$ and $S$. A key element of the algorithm is taking into account snow drift and distance of the radar volume from the snow gauge. The algorithm was applied to a number of New York City snowstorms and was shown to have skill in nowcasting SWE out to at least 1 h when compared with persistence. The algorithm is currently being used in a real-time winter weather nowcasting system, called Weather Support to Deicing Decision Making (WSDDM), to improve decision making regarding the deicing of aircraft and runway clearing. The algorithm can also be used to provide a real-time $Z_e - S$ relationship for Weather Surveillance Radar-1988 Doppler (WSR-88D) if a well-shielded snow gauge is available to measure real-time SWE rate and appropriate range corrections are made.

1. Introduction

Snowstorms affect a variety of human activities such as transportation (aviation and highways), commerce, energy, and communications. Snow accumulating on highways and runways must be cleared to ensure safe operation of surface vehicles and aircraft. The operation of aircraft during snowy conditions is a significant safety issue because of the rapid loss of lift and increase in drag for relatively thin coatings of snow on a wing (25% loss of lift and increase in drag for rough ice coatings of only 0.8-mm thickness on the wing), requiring removal before takeoff. Runways are often treated with an anti-icing fluid to prevent the accumulation of snow. Snow on highways must also be removed as quickly as possible to ensure safe and efficient operations of both commercial and public vehicles.

A key quantity in all of the above applications is the liquid equivalent amount of snow, or snow water equivalent (SWE). For instance, the performance of aircraft and runway deicing fluids is significantly affected by dilution from the water content of snow (Bernadin et al. 1997; Rasmussen 1999a). In the case of aircraft deicing (or anti-icing), accurately measured SWE is needed by pilots and ground personnel to assess whether the snow accumulation on an aircraft wing since deicing/anti-icing has exceeded the capability of the deicing/anti-icing fluid to keep the surface ice free. The Society of Automotive Engineering (SAE) Ground Deicing Committee produces Holdover Tables that indicate the amount of time a deicing/anti-icing fluid can prevent ice formation on an aircraft for a given precipitation type, rate, and temperature. The tables are based on testing of deicing fluids at 1 and 2.5 mm h$^{-1}$ liquid equivalent snowfall rates and at various temperatures. Thus, knowledge of the occurrence of rates less than 1 mm h$^{-1}$, between 1 and 2.5 mm h$^{-1}$, or greater than 2.5 mm h$^{-1}$ are critical in the proper use of this table. Current National Weather Service snow intensities are based on visibility, which has been shown to be a poor indicator of the actual liquid equivalent snowfall rate (Rasmussen et al. 1999b). Thus, the current hourly ME-TAR (a French acronym that translates as aviation rou-
tine weather report) reports of snow intensity do not meet this need.

The method of runway and taxiway snow removal also depends on whether the snow is dry and fluffy (low water content) or wet and dense (high water content). The formation of ice on a highway critically depends on the water content of the snow.

SWE rates at specific locations such as an airport or along a highway can be measured using accurate snow gauges with appropriate wind shielding (Goodison 1978; Yang et al. 1998; Rasmussen et al. 2001). The recent study by Rasmussen et al. (2001) has shown that real-time, accurate snow measurements can be made if the sidewalks of the snow gauges are heated to +2.0°C and appropriate corrections are made to account for the undercatch of snow due to wind effects. In principle, a network of these heated and shielded snow gauges could be deployed to cover a wide region, such as a metropolitan area or large airport. However, such a network is costly to deploy and maintain, and thus an attractive alternative is to use radars to estimate liquid equivalent snowfall rate. Radar measures the equivalent radar reflectivity, \( Z_e \), rather than the SWE rate. Thus, a method to correlate radar reflectivity \( Z_e \) with SWE rates is needed. Rasmussen et al. (2001) present a method to perform this correlation in real time using snow gauges on the ground and radar reflectivity measurements from aloft that will be further described in this paper.

In addition to current SWE rates, nowcasts of SWE rates are important. Forecasts with lead times as short as 30 min are of value to decision makers, who require forecasts of SWE amounts for particular locations, such as the ramps, taxiways, runways, and highway sections. Techniques such as the cross-correlation method (Tuttle and Foote 1990; Rinehart and Garvey 1978) enable determination of the motion of radar echoes. This method was adapted to track winter storm echoes by Rasmussen et al. (2001). An evaluation of the technique by Turner et al. (1999) showed it provided reasonably accurate point reflectivity forecasts out to 30 min. Therefore, a 30-min forecast of SWE could be made if a relationship existed between radar reflectivity aloft and snow gauge accumulation at the ground. Rasmussen et al. (2001) present a method to properly time-lag and wind-adjust the reflectivity and snow gauge data to achieve this relationship, and they use it to perform a snow nowcast. In this paper we present a statistical evaluation of this technique using data from New York City snowstorms.

The main motivation for this work is to provide airline and airport decision makers with accurate point nowcasts of SWE rates in support of aircraft deicing/anti-icing and runway snow removal operations. The technique is currently being used operationally in the Weather Support to Deicing Decision Making (WSDDM) win-

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1 Here, \( Z_e \) is the radar-determined radar reflectivity factor that assumes particles with a dielectric constant of water.
then be used to determine snowfall rate over the domain of the radar [Smith (1984) discusses how to convert from \(Z_e\) to \(Z\)]. In this paper this method is referred to as the traditional approach. For instance, the Weather Surveillance Radar-1988 Doppler (WSR-88D) Precipitation Processing Subsystem (PPS; Fulton et al. 1998) uses the relation \(Z_e = 300R^{1.4}\) for convective precipitation, \(Z_e = 250R^{1.2}\) for tropical rainfall, and several relations for winter precipitation (e.g., \(Z_e = 75S^{0.9}\)). However, because of the wide variety of snow crystal types, degrees of riming, aggregation and snow size distributions in natural clouds, and the possible presence of brightband echo, it is not possible to specify one \(Z_e-S\) relationship that will work for every winter storm. The \(Z-S\) relationships from previous studies (Table 1) show that the value of the coefficient \(a\) ranges from 160 to 3300, while the value of the exponent \(b\) ranges from 1.5 to 2.2. Thus, for a given radar reflectivity, a wide variation in snowfall rate is observed. A scatterplot of snowfall rate (S) versus equivalent radar reflectivity factor \(Z_e\) (dBZ) as presented by Fujiyoshi et al. (1990, their Fig. 1), for instance, shows that snowfall rate ranged from 0.03 to 3 mm h\(^{-1}\) (two orders of magnitude) for a radar reflectivity of 20 dBZ using 1-min radar and snowfall-rate data. In one of the earliest \(Z-S\) studies, Marshall and Gunn (1952) showed a factor-of-10 variation in the daily value of the coefficient \(a\) (from 46 to 465). They attributed this variation to changes in crystal type. Puhakka (1975) observed storm to storm variations in the value of \(a\) from 400 to 2150.

An example of the rapid variation of snow density (and therefore particle type) with time for nearly constant temperature and snowfall-rate conditions is shown in Fig. 1. In this figure, snow density was measured in a pan every 15 min, while the snowfall rate was determined by a weighing snow gauge. The crystal types and sizes were determined by an observer at the site. Note that the snow density changes from 0.12 to 0.03 g cm\(^{-3}\) from 2230 to 2330 UTC, despite the nearly constant conditions of temperature and liquid equivalent snowfall rate. The snowfall density is high for relatively small snowflake (aggregated ice crystals) sizes (3–4-mm diameter) and is very low for large snowflake diameters (20–25-mm diameter). This inverse relationship between snowflake diameter and snowflake density has also been documented by Rogers (1974). His study showed that snowflake density varies from 0.005 to 0.5 g cm\(^{-3}\). Gunn and Marshall (1958) observed a similar rapid change in the \(Z_e-S\) relationship with a change from single crystals to aggregates. Wilson (1975) observed large variations in radar-estimated snow amounts for different storm types as compared with snow gauge measurements.

This variation in the \(Z_e-S\) relationship can be further analyzed by considering a theoretical relationship between \(Z_e\) and \(S\) for aggregated snowflakes. The liquid equivalent snowfall rate, \(S\) (mm h\(^{-1}\)) can be written as

\[
S = 3.6 \times 10^4 \int_0^\infty [n(D)V_p,V_dD] \, (\text{mm h}^{-1}),
\]

where \(D\) (cm) is the unmelted snowflake diameter, \(n(D)\) (cm\(^{-3}\)) is the number concentration, \(V_p\) (cm s\(^{-1}\)) is the terminal velocity, and \(\rho_s\) (g cm\(^{-3}\)) is the snowflake density. If we assume an exponential snowflake size distribution (Sekhon and Srivastava 1970) with spherical aggregates of density \(\rho_s\), Eq. (2) can be written as

\[
S = 3.6 \times 10^4 \frac{\pi}{6} \int_0^\infty [N_0D^3 \exp(-\Lambda D)\rho_sV_d \, dD] \, (\text{mm h}^{-1}),
\]

where \(N_0\) (cm\(^{-3}\)) is the y intercept of the size distribution and \(\Lambda\) (cm\(^{-1}\)) is the slope. As mentioned above, snowflake density decreases inversely with size (Rogers 1974). For dry snowflakes, \(\rho_{s,dry} = 0.017/D\), while for wet and/or rimed snowflakes, \(\rho_{s,wet} = 0.072/D\), where \(D\) is in centimeters (Rogers 1974). Snowflake terminal velocity is also nearly constant with size and close to 100 cm s\(^{-1}\) (Rasmussen et al. 1999b). If we use these relations in Eq. (3) and assume that snowflake terminal velocity is constant, the following equations can be obtained for dry and wet snowflakes (in this paper, “wet” snowflakes refer to wet and/or rimed snowflakes):

\[
S_{dry\ snow} = 612\pi N_0V_d/3\Lambda^3 \, (\text{mm h}^{-1})
\]

(dry snow, constant \(V_d\)) and

\[
S_{wet\ snow} = 2592\pi N_0V_d/3\Lambda^3 \, (\text{mm h}^{-1})
\]

(wet snow, constant \(V_d\)).
Eqs. (7) and (8), the following equations can be derived while for wet and/or rimed snowflakes. Because of the low density of snowflakes, the value of $|K_s|^2$ for snowflakes is determined using a volume mixing ratio for a mixture of ice and air (Battan 1973; Bohren and Battan 1980). The Debye (1929) mixing formulation yields the following relationship: $K_s = (\rho_s/\rho_i)K_i$, where $\rho_i = 0.92$ g cm$^{-3}$ and $K_i = 0.424$. Thus, $|K_s|^2 = 0.0021$ for a typical snow density of 0.10 g cm$^{-3}$, and 0.000021 for a snow density of 0.01 g cm$^{-3}$. As a result, $|K_s|^2$ is at least two orders of magnitude smaller than $|K_i|^2$ and also varies by two orders of magnitude. As discussed above, the density for dry snowflakes can be given as

$$\rho_{s,dry} = 0.017/D \text{ (g cm}^{-3})$$  \hspace{1cm} (7)$$
while for wet and/or rimed snowflakes

$$\rho_{s,wet} = 0.072/D \text{ (g cm}^{-3}).$$  \hspace{1cm} (8)$$

Using the Debye mixing relation discussed earlier and Eqs. (7) and (8), the following equations can be derived for $|K_s|^2$ for dry and wet and/or rimed snow:

$$|K_{s,dry}|^2 = 6.15 \times 10^{-3}/D^2 \text{ and}$$  \hspace{1cm} (9)$$
$$|K_{s,wet}|^2 = 1.07 \times 10^{-3}/D^2.$$  \hspace{1cm} (10)$$

Assuming an exponential snow size distribution and the previous $|K_s|^2$ relations, Eq. (6) can be integrated to obtain

$$Z_{r,snowflakes} = 1.0 \times 10^{12}$$

$$\times \int_0^\infty [K_s]^2|n(D)D^6\,dD] \text{ (mm}^6\text{ m}^{-3}),$$  \hspace{1cm} (6)$$
where $K_s = (m^2 - 1)/(m^2 + 2)$, $m$ being the complex refractive index of water. The value of $|K_s|^2$ is 0.91–0.93. The value $|K_s|^2$ is a similar quantity but for snow. The value $|K_s|^2$ for snowflakes can be given as

$$S_{dry\,snowflakes} = [1.92 \times 10^{-3}(N_0^{2/3}V_{t,d})]Z_{v,sh}^{5/3} \text{ (mm h}^{-1})$$  \hspace{1cm} (15)$$
and

$$S_{wet\,snowflakes} = [1.46 \times 10^{-3}(N_0^{2/3}V_{t,w})]Z_{v,ws}^{5/3} \text{ (mm h}^{-1}).$$  \hspace{1cm} (16)$$

Thus, the $Z_r-S$ or $S-Z_r$ relationship for snowflakes depends on the snowflake size distribution through the y intercept $N_0$, whether the snow is dry or wet, and the terminal velocity of the snowflakes through $V_r$.

The values of $a$ and $b$ using the $Z_r = aS^b$ relationship for dry snowflakes are then given from Eqs. (13) and (14) as

$$b_{dry\,snowflakes} = 1.67 \text{ and}$$  \hspace{1cm} (17)$$
$$d_{dry\,snowflakes} = 3.36 \times 10^{-4}/(N_0^{2/3}V_{t,d}^{5/3}).$$  \hspace{1cm} (18)$$

The corresponding values for wet snow are

$$b_{wet\,snowflakes} = 1.67 \text{ and}$$  \hspace{1cm} (19)$$
$$d_{wet\,snowflakes} = 5.32 \times 10^{-4}/(N_0^{2/3}V_{t,w}^{5/3}).$$  \hspace{1cm} (20)$$

The value of the exponent $b$ is a constant and is equal to 1.67 for both dry and wet snowflakes. Previous studies (Table 1) have found $b$ to range from 1.5 to 2.21 for dry and wet snowflake aggregates, with an average value of 1.89. Thus, the theoretically derived value of 1.67 agrees reasonably well with the observational data.

The main unknown is the value of the parameter $a$. The value of $a$ can vary by a factor of 1.6 because of wet or dry snow, by a factor of 3 because of variations in terminal velocity from 100 to 200 cm s$^{-1}$, and by a factor of 5 because of variations in $N_0$ from 0.05 to 0.005 cm$^{-3}$ (Braham 1990). Thus, specification of the value of $a$ for snowflakes requires a knowledge of the snowflake size distribution, whether the snow is rimed or partially melted, and the mean terminal velocity of the snowflake size distribution. In addition, variations of the snow size distribution from exponential can also add variability.

Figure 2a shows the $Z_r-S$ relationship for dry and wet snow assuming that $N_0$ varies from 0.005 to 0.05 cm$^{-3}$ (Braham 1990) and a terminal velocity of 100 cm s$^{-1}$ for dry snow and 200 cm s$^{-1}$ for wet snow. The curves show that the observed variation in $N_0$, leads to a factor-of-2 variation in snowfall rate for a given radar reflectivity value. The difference between wet and dry snow leads to an additional factor-of-2 variation, resulting in a factor-of-4 overall variation. This amount of variation is very consistent with previous observations such as those by Fujiyoshi et al. (1990). They show even larger variability, most likely due to other factors such as measurement error and evolution and/or drift of snow between the height of the radar beam and the snow gauge.

The value of the coefficient $a$ for the curves in Fig. 2a ranges from 57.3 for wet snow with an $N_0$ of 0.05
F I G . 2. Relationship between radar reflectivity $10 \log Z_e$ (dB$Z_e$) and snowfall rate $S$ (mm h$^{-1}$): (a) theory for dry and wet and/or rimed snow with $N_0 = 0.05$ and 0.005 cm$^{-4}$, and (b) theory for dry snow with $N_0 = 0.005$ cm$^{-4}$ and wet snow with $N_0 = 0.05$ cm$^{-4}$, and previous observation-based $Z_e-S$ relationships given in Table 1.

cm$^{-4}$, to 533.5 for dry snow with an $N_0$ of 0.005 cm$^{-4}$. Estimates of the coefficient $a$ for snowflakes from the previous studies listed in Table 1 have a range of 90–739 for $Z_e-S$ relations, very similar to the range of the theoretical values. Figure 2b compares these previous relationships with the current theoretical predictions. As shown, nearly all of the previous relationships are contained within the bounds of the current theoretical curves. Thus, both theory and observation show a factor-of-4 variation in SWE rate for a given reflectivity value.

Thus, one must know whether the snow is wet or dry, the $y$ intercept of the size distribution, and its terminal velocity in order to accurately specify a $Z_e-S$ relationship. As a result, it is misleading to use only one $Z_e-S$ relationship for a specific region or specific storm because of the difficulty in predicting the type of snowfall that will occur. Passarelli (1978) reached the same conclusion in a theoretical and observational study of snow. He concluded that “it is very unlikely that a single $Z_e-R$ relation for snow will be suitable for any quantitative radar–hydrometeorological studies of snowfall amounts.”

Wilson (1975) and Collier and Larke (1978) have demonstrated that well-shielded weighing snow gauges can be used to adjust radar estimates of snow instead of using a fixed $Z_e-S$ relationship. In this paper, we present a method to determine the time-varying $Z_e-S$ relationship in real time using well-shielded weighing snow gauges and demonstrate a technique to make use of this real-time $Z-S$ relationship to nowcast snowfall.

3. 30-min point nowcast of snowfall rate using a real-time $Z_e-S$ relationship

The previous discussion has shown the difficulty of using a climatological $Z-S$ relationship to estimate SWE rate for 1 h or shorter periods within a storm. In this section we summarize and extend the technique presented in Rasmussen et al. (2001) to 1) determine the $Z_e-S$ relationship in real time using radar and snow gauge data, and 2) make a 30-min forecast of SWE rate based on the extrapolated radar echo motion. The basis for this technique is the observation that radar echo aloft is correlated with snowfall rate at the ground. An example of this correlation from the 10 December 1997 snowstorm in New York City is shown in Fig. 3. A time series of SWE from the snow gauge at LaGuardia Airport is compared with a time series of snowfall rate as derived from the radar reflectivity taken directly over-
head of the gauge (∼900 m above) lagged by approximately 15 min to allow time for the snow particles to fall to the gauge (winds in this case were relatively light). The reflectivity was converted to snowfall rate using the following relation: \( Z_e = 414S^{1.5} \). The traces show that SWE rate as measured by the gauge correlates fairly well with radar-measured reflectivity aloft. This forms the basis of the nowcasting technique presented in this paper.

The 30-min point nowcast technique for snowfall consists of two steps: 1) a 30-min nowcast of the radar reflectivity at a point, and 2) conversion of the 30-min nowcast of reflectivity into SWE rate using an adjustment procedure based on the radar reflectivity aloft and the snow gauge SWE at the ground during the previous 30–60 min. The details of this procedure are described next.

**a. 30-min radar reflectivity nowcast**

The 30-min nowcast of reflectivity is based on the Tracking Radar Echoes by Correlation (TREC) technique (Tuttle and Foote 1990; Rinehart and Garvey 1978). This technique compares two consecutive radar images (typically 5–10 min apart for a WSR-88D, depending on the scan strategy) and determines through a pattern matching technique the most likely direction and speed of motion of 10 km \(^3\) 10 km reflectivity blocks throughout the radar domain. The assumption is made that the future snow echo motion (over the next 30 min) will be very similar to the previous motion during the past 12–24 min. A description of the TREC technique, as applied to winter storms, is given in Rasmussen et al. (2001). An evaluation of TREC performance to nowcast radar reflectivity using radar reflectivity data from Chicago (Lockport, Illinois) and New York City [Fort Dix, New Jersey (KDIX), and Stonybrook, New York (KOKX)] WSR-88D radars by Turner et al. (1999) showed that the 30-min TREC echo nowcast consistently beat persistence in terms of probability of detection at a point for similar false alarm ratio by up to 21% for winter storms in these regions.

**b. Real-time \( Z_e - S \) and 30-min snowfall rate and accumulation nowcast**

The 30-min snow echo motion estimated from TREC is used to produce a 30-min liquid equivalent snowfall rate and accumulation nowcast at the snow gauge locations. To do this, a real-time calibration between radar reflectivity and SWE rate is required.

1) **Real-time \( Z_e - S \) Algorithm**

In the \( Z_e - S \) equation [Eq. (1) using equivalent radar reflectivity], the exponent \( b \) is assumed to be a function of temperature. For pure rain events (\( T > 5^\circC \)), the Marshall–Palmer value of \( b = 1.6 \) is used. For snow events (\( T < 0^\circC \)), a value of \( b = 1.75 \) is used based on the assumption of constant terminal velocity. This value is consistent with published \( Z_e - S \) relationships in Table 1 and the theoretical discussion in section 2. For mixed events, the value of \( b \) is interpolated assuming a linear relationship with temperature.

At each radar scan time, the storm motion at the gauge is computed using TREC. An average fall time (\( t_f \)) for the snow particles from the radar beam height to the gauge is computed using 0.9 m s\(^{-1}\) for dry snow (\( T < 0^\circC \)), a mean value based on 3 yr of snow particle fall speed measurements at the National Center for Atmospheric Research (NCAR) Marshall snow measurement site using a vertically pointing Doppler radar called Precipitation Occurrence Sensor System (POSS) (Sheppard 1990). For rain events (\( T > 5^\circC \)), a fall speed of 10 m s\(^{-1}\) is assumed. For mixed events, the fall speed is assumed to vary linearly between these two values of surface temperature. Future enhancements to the technique may involve the assignment of terminal velocity based on precipitation type from Automated Surface Observing System (ASOS).
Fig. 6. Snow gauge catch efficiency as a function of 3-m wind speed for a Geonor snow gauge in a double Alter shield (upper solid line) and in a single Alter shield (lower solid line). The dashed line represents the curve used to correct the single Alter snow gauge data used in this study.

The radar reflectivity associated with the precipitation falling into the snow gauge resided \( t_f \) seconds ago at a distance \((t_f \times \text{storm speed})\) upwind of the gauge site (Fig. 4). Storm speed is calculated using a weighted sum of the TREC storm motion and the surface wind \([c_1V_{\text{trec}} + c_2V_{\text{surf}}] \times t_f\). Based on the storm speed and direction, a search back in time and upwind in space is executed to locate the relevant reflectivity region associated with the snow gauge measurement. This upwind reflectivity is averaged over a 10 km \( \times \) 10 km square. In this fashion a time series of correlated \( Z_e - S \) pairs is created.

The \( Z_e - S \) adjustment procedure is then simple. The coefficient \( a \) in the \( Z_e - S \) relationship is suitably adjusted to make the radar-estimated and gauge-estimated accumulations equal using the following equation:

\[
a = \left[ \frac{\int (Z_e^{(b)}) \, dt}{\int S \, dt} \right]^{1/b},
\]

where \( \int S \, dt \) is the SWE accumulation from the snow gauge over the chosen time period.

No attempt is made to adjust the exponent \( b \) in real time (other than the earlier discussed temperature adjustment) because the data are too sparse and noisy for calibration with 2 degrees of freedom. In addition, both observations (Table 1) and theory (section 2) show that its value is nearly constant. Integral quantities were used because it was found that the relationship was much more stable if snowfall rate and reflectivity are integrated over time [Fujyoshi et al. (1990) also found that the regression between snowfall rate and radar reflectivity was much more stable if at least a 30-min averaging time was used]. A typical integration time to establish the real-time value of the coefficient \( a \) is 30–60 min. The value of \( a \) is constrained to be within climatological limits in order to ensure algorithm stability during startup and low-data periods. An example of the variation in \( a \) and \( b \) based on the real-time algorithm is shown in Fig. 5. Of note is the jump in \( a \) from values near 400 before 2200 UTC to values around 1000 after 2300 UTC, indicative of two different regimes of precipitation in this storm.

2) 30-MIN NOWCAST ALGORITHM

Once the real-time coefficient \( a \) is found, the 30-min forecast is made using the following steps:

(i) Determine the average TREC storm motion vector \( V_{\text{trec}} \) for the most current radar scan over the location of the gauge by averaging all of the TREC vectors over a 20 km \( \times \) 20 km box centered over the gauge. A large box size is used because of the variation inherent in the TREC vectors.

(ii) Determine the time for the snow to fall to the ground from the closest radar elevation scan (typically the 0.5° scan for WSR-88D radars) overhead of the gauge \( t_f \).

(iii) Based on the fall time \( t_f \), determine the most likely distance and direction upwind of the gauge from which the snow particles that fall at the airport originated. This is done using the TREC wind and the surface wind in a weighted sum \([c_1V_{\text{trec}} + c_2V_{\text{surf}}] \times t_f\), where \( c_1 \) and \( c_2 \) are weights currently set at 0.75 and 0.25, respectively for the New York WSR-88D radars (these weights are likely to change from site to site because of factors such as storm type and distance of the radar beam overhead).

At this upstream point, calculate the 0-, 5-, 10-, 15-, 20-, 25-, and 30-min forecasts of reflectivity based on the TREC storm motion at this location using the reflectivity from the lowest elevation scan.

(iv) Centered on the upwind location, average the forecasted reflectivity pattern over a 10 km \( \times \) 10 km area for each of the forecast times.

(v) Convert the forecasted averaged reflectivity into snowfall rate using the calibrated \( Z_e - S \) relationship.

(vi) Add \( t_f \) to the forecast times above to get the actual forecast times for snowfall rate at the ground. Thus, the upstream forecasts at 0, 5, 10, 15, 20, and 30 min at the upstream radar altitude become the ground forecasts at 0 + \( t_f \), 5 + \( t_f \), 10 + \( t_f \), 15 + \( t_f \), 20 + \( t_f \), 25 + \( t_f \), and 30 + \( t_f \). As a result, particle fall time adds additional time to the forecast.

(vii) Integrate the ground forecast rates over time to produce an accumulation forecast.

The technique just described can be shown to be equivalent to
Table 2. Optimal parameter values and associated rmse.

<table>
<thead>
<tr>
<th>Case</th>
<th>Forecast site</th>
<th>Radar</th>
<th>Accumulation time (s)</th>
<th>Wind method</th>
<th>Gauges</th>
<th>Rmse (mm)</th>
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<td>EWR</td>
<td>KDIX</td>
<td>1800</td>
<td>T + S</td>
<td>EWR</td>
<td>0.19</td>
</tr>
</tbody>
</table>

*T + S refers to the weighted average of TREC and surface winds.

Future snow accumulation

\[
Z_{\text{future}} = (\text{Past snow accumulation}) \times \left( \frac{\int (Z_{\text{forecast}}^{1/b} \, dt)}{\int (Z_{\text{past}}^{1/b} \, dt)} \right).
\] (22)

The forecast snow amount is based on the previous n-minute snow amount times the ratio of the integral of the future forecast reflectivity raised to the 1/b power to integral of the past forecast reflectivity raised to the same 1/b power. If the reactivity time integral is forecast to increase (decrease) over the past reflectivity time integral, then the ratio will be greater (less) than 1.0 and an increased (decreased) accumulation over the past accumulation will be forecast. Thus, the technique is equivalent to modifying the snow gauge persistence forecast by the reflectivity trend.

A desirable feature of this technique is that it takes into account snow sublimation, melting, and growth between the radar beam and the snow gauge as long as these processes are uniform over the calibration and forecast periods. The technique also assumes that the wind field is stationary in time during the calibration and forecast periods. In other words, it is assumed that changes in the past and future reflectivity trends in Eq. (22) are due to real changes in the snow intensity and not to changes in evaporation/growth/melting processes or the wind field.

4. Statistical evaluation of the 30- and 60-min liquid equivalent snowfall nowcast

In this section, a statistical evaluation of the algorithm is presented using a number of cases from New York. The results show that the algorithm consistently beats snow gauge persistence in terms of probability of detection (POD) and false alarm ratio (FAR). This was especially true for cases with strong horizontal gradients of reflectivity, such as storms with snowbands. In these cases, the algorithm beats snow gauge persistence 30-min snow accumulation POD values by up to 25% for similar FAR values. For uniform echo cases, snow gauge persistence and the real-time algorithm performed similarly, as expected. In the following we describe this evaluation in more detail.

a. Data sources

The data used to evaluate the real-time $Z_e - S$ algorithm were WSR-88D reflectivity data from the KDIX and KOKX radars and liquid equivalent snowfall rates from

Table 3. Number of times the Z-S algorithm exceeded the climatological limits.

<table>
<thead>
<tr>
<th>Date</th>
<th>No. volumes</th>
<th>Forecast site</th>
<th>No. times lower limit exceeded</th>
<th>No. times upper limit exceeded</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Dec 1997</td>
<td>65</td>
<td>LGA</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EWR</td>
<td>0</td>
<td>21</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JFK</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21 Mar 1998</td>
<td>29</td>
<td>LGA</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EWR</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JFK</td>
<td>7</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>22 Mar 1998</td>
<td>59</td>
<td>LGA</td>
<td>0</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EWR</td>
<td>0</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JFK</td>
<td>9</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>8 Jan 1999</td>
<td>64</td>
<td>LGA</td>
<td>0</td>
<td>60</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EWR</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>587</td>
<td></td>
<td>78</td>
<td>48</td>
<td>(78 + 48)/587 = 0.21</td>
</tr>
</tbody>
</table>
three snow gauges located at LaGuardia (LGA), John F. Kennedy International (JFK), and Newark International (EWR) Airports. These data were collected during an operational demonstration of the WSDDM system for LaGuardia Airport from December 1997 to March 1999 (Rasmussen et al. 2001). The snow gauges used were Geonor gauges with an Alter shield and a sidewall heater. The sidewall heater maintained the sidewall temperature at $+2^\circ$C for ambient temperatures less than $+2^\circ$C to prevent sidewall snow accumulation from blocking the collection orifice (Rasmussen et al. 2001). The wind correction for undercatch for this particular snow gauge–windshield configuration was determined from extensive testing at the NCAR Marshall test site (Rasmussen et al. 2001). The correction factor used in this study is shown in Fig. 6. As shown, gauge undercatch is nearly linearly related to wind speed for wind speeds up to 8 m s$^{-1}$.
Data from four snowstorms from this period will be analyzed, representing a variety of storm types.

b. Parameter optimization

Prior to performing the statistical evaluation of the performance of the real-time $Z-S$ algorithm, key parameters of the algorithm were optimized. These included 1) the calibration time (the amount of time over which the radar reflectivity accumulations are compared with the gauge accumulations to adjust the coefficient of the $Z-S$ relation), 2) wind shear parameter (i.e., how to combine the TREC storm motion and surface wind speed to account for snow drift), 3) the minimum allowable $a$ coefficient, and 4) the “rain temperature” (i.e., the temperature above which to set the value of the exponent in the $Z-S$ relationship and the hydrometeor fall velocity to that of rain). The optimal parameters were determined by changing one parameter at a time and computing the root-mean-square error (rmse) of the difference between the 30-min forecast and the actual gauge accumulation. The optimization yielded the following results: 1) calibration time is 30 min, 2) weights for calculation of the snow drift wind are 0.75 for TREC wind and 0.25 for
surface wind, 3) minimum $a$ coefficient is 50, and 4) the rain temperature is $+2^\circ$C. The evaluation that follows is conducted using these values.

Tests were done to determine the best calibration based on individual gauges or a combination of two or more gauges. If more than one gauge is used, the calibration is the result of an average of the individual gauge accumulations as compared with the average of radar reflectivity accumulations for the sites. Because of the radar location relative to the airport, it was found that EWR results were best when the EWR snow gauge was used in tandem with the KDIX radar, and that JFK and LGA results were best when using a combination of JFK and LGA snow gauges and the KOKX radar (Table 2).

The number of times the algorithm hit the climatological limits of the $a$ coefficient as given above is indicated in Table 3. As shown, climatological limits were reached an average of 21% of the time, showing that...
limits to the coefficient $a$ are required for successful application of the algorithm.

c. Scoring methodology

Forecasts for each gauge location were evaluated using probability of detection, false alarm ratio, and critical success index (CSI; Donaldson et al. 1975). A forecast is issued every radar volume scan ($\sim 6–10$ min depending on the volume coverage pattern (VCP)) and is converted from a 30-min accumulation to an hourly rate. Each forecast is then assigned a rate of either light, moderate, or heavy, where light is $<1$ mm h$^{-1}$, moderate is between 1 and 2.5 mm h$^{-1}$, and heavy is $>2.5$ mm h$^{-1}$. A hit ($H$) occurs when the forecast descriptive rate (light, moderate, heavy) verifies, a miss ($M$) is an underforecast of the actual rate, and a false alarm ($F$) is an overforecast of the actual rate. Thus, $POD = H/(H + M)$, $FAR = F/(H + F)$, and $CSI = H/(H + M + F)$.

The evaluation metrics are compared with persistence forecasts. Persistence is defined as the current gauge rate (with the gauge efficiency wind correction) forecast for the next 30 min. Gauge data from the most recent 10 min are used to determine the rate. Again, rates are defined in

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**Fig. 10.** Radar reflectivity from the KOKX radar at 1200 UTC 21 Mar 1998. Reflectivity scale is the vertical color-coded bar at the right. Superimposed are the TREC storm motion vectors representing 30 min of motion. Location of the KOKX radar is indicated in yellow. Range rings (km) are centered on LGA.
terms of light, moderate, and heavy. This type of persistence forecast is called gauge persistence. As will be demonstrated later, the use of no winds in the forecast is essentially a “radar persistence” forecast, whereby overhead reflectivity data are forecast to remain constant, that is, upstream reflectivity data are not considered.

d. Case studies

Data from four days were analyzed: 10 December 1997, 21 and 22 March 1998, and 8 January 1999. As mentioned earlier, WSR-88D data from KDIX in New Jersey and KOKX on Long Island were used, as well as data from the three snow gauges at JFK, LGA, and EWR. JFK gauge data were not available for the 8 January 1999 case. Hourly snowfall rates were heavy for a substantial amount of time on 10 December 1997 and 21 March 1998. The echoes on 10 December 1997 tended to form in small bands. The radar echoes on 21 and 22 March 1998 also exhibited banding but for shorter time periods. Echoes on 8 January 1999 were fairly uniform. As will be shown later, the echo structures have a direct bearing on how well the WSDDM system performs.

1) 10 December 1997

This case had a variety of radar echo intensities and shapes providing for a rigorous test of the WSDDM real-
The choice of radar had a large effect on the algorithm performance. As an example, at 2047 UTC, KDIX was indicating heavy echoes just upstream from EWR (Fig. 7a). However, KOKX indicated little echo in that region as the beam was overshooting the storm (Fig. 7b). Also, EWR is ~30 km closer to KDIX than it is to KOKX, resulting in better sampling of echoes near EWR. A comparison of forecasts for EWR using KOKX and KDIX (Fig. 8) illustrates the dramatic effect of reflectivity forecast accuracy on the 30-min SWE prediction. Although the reflectivity forecast and verification using KDIX are not perfectly aligned, the forecast is much more accurate than the KOKX radar forecast.

The computation of the effective wind has a marked effect on the reflectivity forecast. Figure 9 shows EWR forecasts using the three wind schemes discussed in section 3. With no winds (reflectivity persistence), SWE values are underforecast. The most accurate forecast results from using the weighted combination of TREC and surface wind vectors.

Note on radar operation: At the onset of the storm, the KOKX radar was operating in clear-air mode. While the radar may be slightly more sensitive in clear-air mode, the maximum reflectivity reported in that mode is 28 dBZ; higher values will also be given the value of 28 dBZ. Thus, a forecast based on clear-air reflectivity will miss peaks in the echoes over 28 dBZ, causing an underforecast. Fortunately, the radar was switched to
VCP 21 soon after the storm began and only an hour or so of data were affected.

2) 21 March 1998

Precipitation on 21 March was brief although rates were heavy—at times exceeding 5 mm h$^{-1}$. A snowband moved across the area that was seen equally well by both radars (Fig. 10). For this reason, only data from KOKX radar are shown in Fig. 10. Thus, the forecast for EWR using KDIX data was similar to the forecast using KOKX data. However, as for the 10 December 1997 case, the WSDDM Z–S algorithm performance was heavily dependent on the wind scheme, with the most accurate scheme being the TREC-surface wind average (not shown).

3) 22 March 1998

Radar echoes on this day were weaker and smaller and snowfall rates were mostly moderate (Fig. 11). While KDIX provided more complete coverage southwest of EWR, both radars saw echoes southeast of EWR equally well. Since echo motion was from the south-southeast, the echoes were equidistant from both radars, and thus no appreciable difference between the forecasts from the two radars was found in this case (not shown).

4) 8 January 1999

As seen in Fig. 12, radar echoes on 8 January were very uniform with little change in structure with time. Note that the area of most significance was the northern edge of the heavier precipitation.

e. Scoring results

This section presents the scoring results for the cases described above. Values of POD for both the WSDDM real-time Z–S algorithm (W) and gauge persistence 30-min forecasts (P) are shown in Fig. 13a.

For all but the 8 January 1999 case, WSDDM Z–S
algorithm PODs are significantly higher than persistence PODs. The average WSDDM Z–S algorithm POD is 0.81 as compared with 0.70 for persistence. There is a much larger difference in FARs (Fig. 13b): the WSDDM Z–S algorithm had an average FAR of 0.09 as compared with 0.31 for persistence. In general, these results indicate that the WSDDM Z–S algorithm slightly underforecasts and rarely overforecasts. Persistence resulted in large overforecast errors.

A comparison of CSIs (Fig. 13c), an indicator of overall skill, shows that the WSDDM Z–S algorithm beats persistence with an average value of 0.73 as compared with 0.54 for persistence. The persistence forecast CSI on 8 January is nearly equal to the WSDDM algorithm CSI. Note that nearly one-half of the nowcasts were made on 10 December 1997, which was considered the most rigorous test for the WSDDM algorithm. For these events WSDDM had a CSI of 0.70.

The WSDDM Z–S algorithm and persistence scoring were also performed for 1-h forecasts (Fig. 14). The 8 January case was not scored because rates were not significant and results would not have been any different. Interestingly, the WSDDM Z–S algorithm performance did not change significantly overall while the average persistence CSI dropped from 0.54 to 0.35.

While the WSDDM Z–S algorithm rarely overforecasts precipitation, there was a slight tendency to underforecast. However, the bulk of the underforecast problem was caused by cases in which echoes increased in intensity after the forecast was made. The algorithm usually takes 10–15 min to adapt to changes in echo intensities. For situations in which an echo, especially a band, simply advected over a site without changing, the forecast tended to be good.

Because FAA Terminal Doppler Weather Radars (TDWR) with a finer beamwidth (0.5° vs 1.0° for WSR-88D) are located near major airports, these data will likely improve the performance of the real-time Z–S algorithm. The TDWR also provides rapid updates of higher-resolution data very close to the ground (often within 100 m).
that could mitigate problems caused when the WSR-88D beam is high above the ground (sometimes overhanging the storm). The advantage in this case is the reduced vertical distance to calculate snow drift, thereby reducing one of the main sources of error in the algorithm.

5. Summary and conclusions

An algorithm for nowcasting snowfall has been developed that uses a real-time correlation of radar reflectivity with snow gauge data. It was shown that a real-time correlation is needed in order to take into account the natural variations in the Z–S relationships that occur during a storm because of changes in snow crystal type, degree of riming and aggregation, wetness, and size distribution. The algorithm was shown to have skill in nowcasting snowfall (SWE) out to at least 1 h when compared with persistence. The algorithm is currently being used in a real-time winter weather nowcasting system called WSDDM to improve decision making with regard to the deicing of aircraft and runway clearing (Rasmussen et al. 2001). The algorithm can also be used to provide a real-time Z–S relationship for WSR-88D radars if a well-shielded snow gauge measuring real-time liquid equivalent snowfall rate is available and appropriate range corrections are made.

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