Article ID: 1006-8775(2015) 01-0092-09

THE DESIGN AND CORRECTION OF A QUANTITATIVE METHOD OF SNOW ESTIMATE BY RADAR

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Abstract: An optimization method is based to design a snowfall estimate method by radar for operational snow warning, and error estimation is analyzed through a case of heavy snow on March 4, 2007. Three modified schemes are developed for errors caused by temperature changes, snowflake terminal velocity, the distance from the radar and calculation methods. Due to the improvements, the correlation coefficient between the estimated snowfall and the observation is 0.66 (exceeding the 99% confidence level), the average relative error is reduced to 48.74%, and the method is able to estimate weak snowfall of 0.3 mm/h and heavy snowfall above 5 mm/h. The correlation coefficient is 0.82 between the estimated snowfall from the stations 50 to 100 km from the radar and the observation. The improved effect is weak when the influence of the snowflake terminal velocity is considered in those three improvement programs, which may be related to the uniform echo. The radar estimate of snow, which is classified by the distance between the sample and the radar, has the most obvious effect: it can not only increase the degree of similarity, but also reduce the overestimate and the undervaluation of the error caused by the distance between the sample and the radar. The improved algorithm further improves the accuracy of the estimate. The average relative errors are 31% and 27% for the heavy snowfall of 1.6 to 2.5 mm/h and above 2.6 mm/h, respectively, but the radar overestimates the snowfall under 1.5 mm/h and underestimates the snowfall above 2.6 mm/h. Radar echo may not be sensitive to the intensity of snowfall, and the consistency shown by the error can be exploited to revise and improve the estimation accuracy of snow forecast in the operational work.

Key words: weather forecast; radar-based snowfall estimate; optimization technique; correlation
CLC number: P412.25 **Document code:** A

1 INTRODUCTION

Heavy snow has great impacts on people's lives and social economy and is a disastrous weather condition of high social concern. Heavy snow has happened frequently in the southern part of northeast China in recent years, especially for the heavy snow rarely paralleled in history in 2007, 2009 and 2010. "Meteorological Disaster Warning Signal and Prevention Guide" of "Procedures on the Release and Dissemination of Early Warning Signals for Meteorological Disasters" (Decree No.16 of China Meteorological Administration) specifies that the heavy snow warning signal should be released when the snowfall intensity within 12 h is above 4 mm. That is to say, the snowfall intensity above 0.3 mm/h meets the standard of meteorological disasters. Currently, however, the automatic meteorological observing station is unable to provide 1-h snowfall in winter, and the manual observation can provide 3-h or 6-h cumulative snowfall only in some stations, which cannot fulfill the need of operational snow early warning. With construction of the meteorological station networks in China, the Doppler radar has covered most provinces in East China. Products of the Doppler radar can provide a wide range of precipitation information in a short time. Therefore, products of the new-generation Doppler radar can be applied with combination of conventional observation data to investigate the radar-based snowfall quantitative estimate technique in order to fulfill the need of operational snow early warning.

Radar-based snowfall quantitative estimate techniques have been explored by many foreign scholars. Boudala et al.[1] developed ice water content and precipitation rate retrieval algorithms as a function of temperature and radar reflectivity factor using ice particle spectra measured in stratiform ice clouds in mid-latitude and Arctic regions. Wandishin et al.[2] produced short-range ensemble forecasts of different precipitation type, which is very skillful in forecasting rain and snow but it is only moderately skillful for freezing rain and unskillful for ice pellets, with an advantage of being able to discriminate between different precipitation types. Gray et al.[3]

Received 2013-10-15; **Revised** 2014-12-01; **Accepted** 2015-01-15

Foundation item: Program for Key Fundamental Research of China (2013CB430102); Specialized Project for Forecasters from China Meteorological Administration (CMAYBY2012-012); Specialized Project for Public Welfare Sectors of Industry from CMA (GYHY201006001); Project for Research on Agricultural Science and Technology, Bureau of Agriculture, Liaoning Province (2011210002)

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Corresponding author: MIN Jin-zhong, e-mail: minjz@nuist.edu.cn summarized the snow *Z–I* relationship for different temperature and different form of snow. For Chinese researchers, most attention has been paid to the rainfall rather than the snowfall in the aspect of radar-based quantitative estimate technique (Ji et al.[4]; Zhang et al.[5]). Kuang et al.[6] estimated the snowfall of a snowstorm weather process that occurred in Shijiazhuang city in 2009 with radar data and the Kalman filter method, indicating that this method is suitable for large-range continuous snowfall estimate, but not suitable for short-term local snowfall estimate. Jiang et al.[7] analyzed the features of Doppler radar products of heavy snow processes in the southern Northeast China, uncovering that 1-h snowfall correlates positively with snow reflectivity and that the echo intensity of heavy snow is usually less than 30 dBZ. Zhang et al.[8] showed that the value of b is 1.6 and the value of a is 1 000 to 1 500 in the *Z–I* relationship of radar echo. In this paper, an optimization method is based to design a snowfall estimate method by the radar for operational snow early warning, and an experiment of snow estimate is performed for a case of heavy snow on March 4, 2007, followed by error estimation to correct the scheme for radar-based snowfall estimation. Finally, an appropriate *Z-I* relationship is built to support the timely and accurate release of operational early warning.

2 DATA

The data used are based on the reflectivity of the Yingkou CINRAD-SC Doppler radar products, intensive observation data of 1-h snowfall, conventional observation data for the heavy snow rarely paralleled in history during 12:00-19:00(Beijing Time, the same hereafter) in Liaoning province on March 4, 2007 as well as size spectrum of precipitation during 2007-2009 of the laser spectrometer Parsivel produced by the OTT company from Germany.

3 SCHEME DESIGN FOR SNOW ESTIMATE BY RADAR

The study of Boudala et al.[1] indicated that the value of a is 160-3 300 and the value b is 1.5-2.2 in the *Z-I* relationship of snow estimate by radar. These changes depend on various parameters, such as crystal structure, degree of freezing and aggregation, degree of riming, snowflake humidity, density, terminal velocity, as well as changes in the size distribution of snowflakes (Rasmussen[9]). Wilson et al.[10] discovered that compared to the snowfall observed by snow gauge, the observations by radar are characterized by more variations for different types of heavy snow. Fujiyoshi et al.[11] also demonstrated that, for a radar reflectivity factor of 20 dBZ, the range of snowfall intensity is from 0.03 to 3 mm/h, caused by the different types of snowflake crystals. Thus, the *Z-I* relationships may be different in every time period of a snow process, and it is impossible to determine a *Z–I* relationship suitable for every snow process. So how should one design a snowfall estimate scheme by radar for operational use? According to the current status of the operational snow early warning, the observed snowfall is the hourly manual observation, while the radar completes a volume scan in every 6 minutes. Therefore, relationship can be constructed between the 1-h snowfall of every station and the radar echo, which is used for snowfall estimate in the next hour. For the precondition, it is assumed that influencing factors of snow estimate, such as crystal structure and degree of freezing and aggregation, remain the same in an hour. The specific method is using an optimization method. Firstly, a *Z–I* relationship is assumed, which is changed every hour in order to get the best consistency of hourly snowfall H_i estimated by radar echo to the observed hourly snowfall G_i. Besides, the degree of consistency depends on the discrimination function (Zhang et al.[8]). In this paper, the discrimination function is

$$CTF_2 = MIN\left|\left\{\sum_{i=1}^{N}\left[\left(H_i - G_i\right)^2 + \left(H_i - G_i\right)\right]\right\}\right|$$

where $\Sigma(H_i-G_i)^2$ is the square of deviance, indicating the non-linear effects of the *Z–I* relationship. This discrimination function is used to modify the values of a and b in the *Z–I* relationship until the CTF_2 reaches its minimum value, when the *Z–I* relationship determined by a and b is optimal (Zhang and Dai[12]; Zheng et al.[13]).

4 CASE APPLICATION

This paper uses the echo intensity data detected above the observation station at a 0.5° elevation angle by Yingkou CINRAD-SC Doppler radar for the extremely heavy snow process during 12:00-19:00 on March 4, 2007. Considering that the resolution of operational PUP products has four bins and conditions of observation station, echo intensity of every station used is the average of data from 5×5 bins (about 3 to 22 km^2) above the observation station, which is combined with intensive observation data of hourly snowfall to calculate the *Z-I* relationship by means of the optimization method.

Taking into account that the radar detection at a 0.5° elevation may be blocked, comparison of radar-based snowfall estimate is performed using the observation station located at certain distances from the radar (the nearest distance is 29.4 km and the height of radar detection above the station is 289 m), as there is no distinct block in the northwest to southeast direction of the Yingkou Radar's surroundings. Only samples of the pure snow are used here. Based on the operational reality, the snowfall is estimated by substituting the optimized *Z-I* relationship of the last hour into the current hour, followed by comparison with the hourly snowfall observation (Table 1). Totally, we obtain 63 samples of hourly snowfall estimates of 20 observation stations. The ranges of a and b are 10 to 109 and 1.5 to 2.9, respectively. The numbers of a and b in Table 1 are the average of 6-h data from 14:00 to 19:00. The correla tion coefficient between the estimated snowfall and the observation is 0.52 (exceeding the 99% confidence level). For the 63 samples, the mean absolute error is 0.96 mm/h, and the average error is -0.06 mm/h, indicating that the estimated snowfall show similar degrees of overestimate and underestimate as compared to the observation. Zhang et al.[8] showed that the relative error of quantitatively estimated rainfall by radar is not less than 50%. Considering that the average snowfall of the studied process is 2.24 mm/h, much smaller than the hourly rainfall from the estimation by radar, and that the average relative error of quantitative snowfall estimate by radar is 62.43%, it is obvious that the snowfall estimate technique by radar based on the optimization method is practicable for operational application.

Table 1. Correlation coefficient and error of the hourly snow estimate by the optimization method.

Item	Number
Sample number	63
a average	32
b average	2.4
Correlation coefficient	0.52
Mean absolute error/mm/h	0.96
Average error/mm/h	-0.06
Average relative error	62.43%

In Fig.1, for the stations of Gaizhou, Dawa and Haicheng, whose distances from the radar station are less than 50 km (29 to 44 km), there are 10 samples, all showing almost the same trend with the observation, in which 7 samples overestimate the snowfall and 7 samples show large errors from 1 to 2.2 mm/h. For the stations of Panjin, Anshan, Taian, Liaoyang, Xiuyan and Liaoyang county, whose distances from the radar station are from 50 to 100 km (73 to 97 km), there are 19 samples, all showing similar trends and small fluctuation ranges with the observation, in which 8 samples show errors larger than 1 mm/h and 14 samples overestimate the snowfall, with the maximum error of 2.1 mm/h. For the stations of Liaozhong, Dengta, Caohekou, Sujiatun and Benxi, whose distances from the radar station are from 100 to 150 km (101 to 146 km), there are 18 samples, all showing relatively poor consistency with the observation, in which 13 samples underestimate the snowfall and 10 samples have errors larger than 1 mm/h, with the maximum error of 2.7 mm/h in Benxi. For the stations of Xinmin, Shenyang, Fuxin, Xinchengzi, Zhangwu and Fushun, whose distances from the radar station are above 150 km (153 to 204 km), there are 16 samples, all showing similar trends with the observation, in which 8 samples underestimate the snowfall and 3 samples have errors larger than 1 mm/h, with the maximum error of 2.3 mm/h in Fushun.

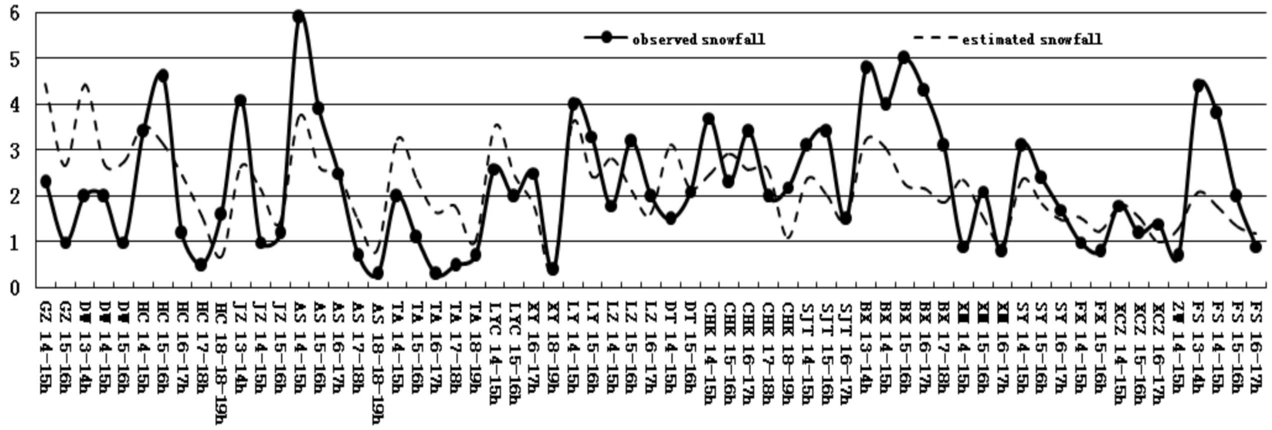

Figure 1. Distributions of the estimated snowfall using optimization method and observation (Units: mm). GZ: Gaizhou; DW: Dawa; HC: Haicheng; JZ: Jinzhou; AS: Anshan; TA: Taian; LYC: Liaoyang County; XY: Xiuyan; LY: Liaoyang; LZ: Liaozhong; DT: Dengta; CHK: Caohekou; SJT: Sujiatun; BX: Benxi; SY: Shenyang; FX: Fuxin; XCZ: Xinchengzi; ZW: Zhangwu; FS: Fushun.

Based on the general degree of correlation, the radar-based snowfall estimate basically represents the trend of the snow, in which samples 50 to 100 km from the radar show the most similar trends with the observation and also the smallest maximum errors. 72% of samples near to the radar (at distances less than 100 km) overestimate the snowfall, while 62% of samples far from the radar (at distances of 100 to 204 km) underestimate the snowfall. In many samples, the estimated snowfall is poorly correlated with the observation with large errors. 28 samples have errors larger than 1 mm/h, accounting for 44% of the total number of samples. 7 samples have errors larger than 2 mm/h, with the maximum error of 2.7 mm/h. So what is the source of errors, and how do we reduce the errors? The following analysis is done to find out the possible causes of errors and to improve the methods.

5 ERROR ANALYSIS

Based on Zhang et al.[8], reflectivity factor Z is:

$$Z = \int_0^\infty N(D) D^6 \, \mathrm{d}D \tag{1}$$

and the integral form of rainfall intensity I is:

$$I = \int_0^\infty N(D) \frac{1}{6} \pi \rho D^3 v(D) \, \mathrm{d}D \tag{2}$$

in which D is the snowflake diameter, $N(D)$ is the number of snowflake, v is the snowflake terminal velocity, and ρ is the snowflake intensity. Influences on Eqs. (1) and (2) are discussed in the following sections.

5.1 *Influence of temperature*

Yu et al. [14] found that for a 10-cm wavelength Doppler radar, backscatter of the water droplet is five times of the ice crystals with the same volume in the range of Rayleigh scattering. Reflection of snow is usually much lower than that of rain, but reflection of the melting snowflake or ice crystal, as well as the snow and ice mixture, may have abnormal increase, which will influence the results of snowfall estimate. Thus, if the temperature of the radar scanning area is around 0℃, hydrometeors may include snowflake, ice crystals, ice (snow) mixture, supercooled water and etc., and snowfall estimate by radar may have large errors. Even for pure snow, according to Eqs. (1) and (2), the amount of precipitation I is also affected by the intensity and diameter of snowflake, which is connected to changes of temperature and crystal structure of snowflake[8]. According to an analysis of the hourly temperature observations during 08:00-20:00 on March 4, 2007, from radiosonde stations in Shenyang, Dalian, and Dandong, as well as during 12:00-19:00 on March 4, 2007, from all the surface stations, the surface temperature of Benxi and Caohekou has decreased from 0 to 2 ℃ to -4 to -6 ℃, with the surface temperature change of 1-2℃/h, which may induce great changes in the intensity and diameter of snowflake by temperature changes. For other stations, the temperatures from surface to high-level are lower than -4 ℃ and the temperatures of radar scanning area (300 to 1 700 m) are lower than -5 ℃, with the average surface temperature changes below 0.2 to 0.3 ℃/h. It is then concluded that in this snow process, there are no significant changes in temperature for all samples, except those of Benxi and Caohekou, from surface to high level of the radar scanning area, along with small changes for the intensity and diameter of snowflake in an hour.

5.2 *Influence of snowflake terminal velocity and advective wind*

Statistical analysis is performed on the size spectrum of precipitation (2 893 836 samples) from the laser spectrometer Parsivel located in Liaoyang for the snow process during 2007 to 2009. It is found that the terminal velocity of snow is distinct from that of precipitation, while the average terminal velocity of snow particle is 1.78 m/s (figure not shown). If the wind speed of horizontal wind field is large, snow over the observation station is actually the snow shifting from the upstream areas. Therefore, results of the snowfall estimate will be affected in use of the radar echo intensity above the observation stations. In Table 2, the average terminal velocity of snow particle takes the number of 1.78 m/s, the falling time of snowflake from the radar scanning area to the observation station is from 2 to 16 min, while the observation points are 100 km from the radar and scanning is at a 0.5° elevation angle, with the observed horizontal wind speed of 8 to 12 m/s and the horizontal shifting distance of 4 to 6 km. Further, as the time difference makes changes of radar echo intensity earlier than changes of surface snowfall, stations farther from the radar will be 2 to 3 volume scans later (13 to 16 minutes). Thus, the time of radar echo intensity should be modified to correspond to the snow in radar-based snowfall estimate.

Table 2. Altitude, echo height and falling time of observation stations.

Name of station	Distance from the radar /m	Altitudeof station /m	Radar echo height above station/m	Falling time /s
Gaizhou	29431.7	31.1	289.2	162
Dawa	38758.5	4.8	396.9	223
Haicheng	44025.2	26.5	421.2	237
Panjin	73041.8	4.6	696.3	391
Anshan	76666.7	71.5	661.1	371
Taian	80446.0	8.5	757.0	425
Liaoyang County	88804.4	30.5	808.0	454
Xiuyan	96300.5	80.8	823.1	462
Liaoyang	97479.3	25.7	888.5	499
Liaozhong	101142.4	20.6	925.6	520
Dengta	120253.4	42.8	1070.1	601
Caohekou	139301.4	234.9	1044.3	587
Sujiatun	140563.9	35.6	1254.6	705
Benxi	145699.8	182.5	1152.5	647
Xinmin	153276.8	31.9	1369.2	769
Shenyang	153388.4	45.2	1356.9	762
Fuxin	159802.7	144.9	1313.2	738
Xinchengzi	183624.0	61.1	1604.4	901
Zhangwu	195169.4	84.2	1682.5	945
Fushun	204275.4	120.4	1725.8	970

5.3 *Influence of distance from the radar*

Radar echo is a scanning body of conical surface. The farther the station is from the radar, the higher the scanning height is. Echo intensities vary at different heights. The rain estimate is best using the radar echo intensity closest to the surface, i.e., echo intensity de tected at a lower elevation angle is most similar to the observation (Huang et al.[15]). Researches in the above paragraphs indicate that while stations in this process are far from the radar, the estimates are lower than the observations. Therefore, snowfall estimate should be performed on different *Z-I* relationships corresponding to every station, which has specific distance from the radar.

5.4 *Revised algorithm*

The observed snowfall is the hourly intensive observation. The radar completes a volume scan in every 6 min. The estimated snowfall for every 6-min can be obtained based on the *Z-I* relationship, which is unified as hourly snowfall estimate for comparison. The original algorithm is making average of hourly echo intensity, followed by snowfall estimate by means of the *Z-I* relationship. However, there is no linear relationship between the radar echo intensity and the rainfall intensity, which could increase errors through the simple sum. So 6-min snowfall should be estimated by 6-min echo intensity before summed up as hourly snowfall.

Liang et al. [16] made research into adjustment of radar-based rainfall estimate using data of rain gauge, uncovering that the precision is improved when the echo intensity is converted to rainfall intensity before summed up.

6 ESTIMATE USING MODIFIED *Z-I* RELATIONSHIP

Three modified schemes are developed based on the discussion above.

Scheme 1: According to the average falling terminal velocity of the snow particle and hourly wind direction and speed data of all stations, we calculate the horizontal shifting distance and falling time of snow particle (Table 2), modify radar echo scanning area of each station for snowfall estimate, and select the radar echo intensity at corresponding time of volume scan based on the falling time of snow particle.

Scheme 2: Referring to Table 2, stations are divided into four categories in accordance with the distance between the observation station and the radar: observation stations 29 to 44 km from the radar (Gaizhou, Dawa, Haicheng); observation stations 73 to 97 km from the radar (Panjin, Anshan, Taian, Liaoyang County, Xiuyan, Liaoyang City); observation stations 101 to 146 km from the radar (Liaozhong, Dengta, Caohekou, Sujiatun, Benxi); observation stations 153 to 204 km from the radar (Xinmin , Shenyang, Fuxin, Xinchengzi, Zhangwu, Fushun). The *Z-I* relationship is calculated for the four different categories of stations, respectively, followed by snowfall estimate.

Scheme 3: The algorithm is revised. There is no linear relationship between the radar echo intensity and the rainfall intensity. So 6-min snowfall should be estimated by 6-min echo intensity before summed up as hourly snowfall for snowfall estimate.

To facilitate comparison, samples of Caohekou and Benxi are provisionally reserved. Then the original optimization method for estimate are also divided into four categories in accordance with the distance between the samples and the radar, followed by calculation of correlation coefficients, average relative error, mean absolute error and average error for comparison.

As presented in Table 3, when using only Scheme 1, the correlation coefficient between snowfall estimated for all samples and the observation is 0.52. There is no improvement as compared to the original scheme, and no significant changes in the mean absolute error, average relative error and average error. Scheme 2 (i.e. snowfall estimate considering different distances) is applied based on the application of Scheme 1, with significant improvement in the correlation, with a correlation coefficient of 0.63. Besides, the average relative error is reduced from 63.09% to 50.52%, and the mean absolute error is reduced from 0.96 mm/h to 0.84 mm/h. While the three schemes are used together, the correlation coefficient between snowfall estimated by all samples and the observation is further increased to 0.66, the average relative error is reduced to 48.74%, and mean absolute error is also reduced.

Table 3. Correlation coefficient and error of hourly snowfall estimate for all the samples using modified optimization method (mod.=modification; sch.=scheme).

	No mod.	Sch.1	Sch.1+ Sch.2	Sch.1+Sch.2 +Sch.3
Corr. Coeff.	0.52	0.52	0.63	0.66
Average relative error /%	62.43	63.09	50.52	48.74
Mean absolute error	0.96	0.96	0.84	0.79
Average error	-0.06	-0.04	-0.04	-0.05

Detailed analysis is performed on the estimate in terms of samples at different distances from the radar station. Results show that samples 50 to 100 km from the radar (Table 4) have the highest correlation coefficient between the estimated snowfall and the observation, reaching 0.82 after modified by the three schemes. Samples 150 to 200 km from the radar (Table 5) have improvement from 0.56 to 0.72 for correlation coefficient between the estimated snowfall and the observation, whose modification effects are most significant. Samples 100 to 150 km from the radar (Table 6) have no increase in the correlation coefficient between the estimated snowfall and the observation, only 0.09 after modification. In addition, these samples have the largest mean absolute error, reaching 1.02 mm/h, which may be connected to samples of Benxi and Caohekou. It will be discussed later. Mean absolute errors of other samples decrease remarkably after being modified by the three schemes, with decrease ranges from 0.15 to 0.46 mm/h.

Samples 150 to 200 km from the radar have the smallest mean absolute error of 0.56 mm/h, while samples 0 to 50 km from the radar (Table 7) have the largest decrease range in the relative error of 47.7%. Average errors of samples at distances larger than 100 km from the radar are negative, indicating that the radar significantly underestimate the long distance echo. Average error of estimated results for samples 50 to 100 km from the radar is 0.29 mm/h, indicating that the estimated snowfall is larger than the observation.

Table 4. The same as Table 3 but for samples 50 to 100 km from the radar.

	No mod.	Sch.1	Sch.1+ Sch.2	Sch.1+Sch.2 +Sch.3
Corr. Coeff.	0.78	0.79	0.78	0.82
Average relative error/%	84.05	86.33	67.52	65.94
Mean absolute error	0.87	0.87	0.80	0.71
Average error	0.14	0.22	0.28	0.29

Table 5. The same as Table 3 but for samples 150-200 km from the radar.

	No mod.	Sch.1	Sch.1+ Sch.2	Sch.1+Sch.2 +Sch.3
Corr. Coeff.	0.56	0.63	0.69	0.72
Average relative error/%	43.02%	42.62%	39.75%	38.95%
Mean absolute error	0.71	0.71	0.57	0.56
Average error	-0.23	-0.27	-0.11	-0.11

Table 6. The same as Table 3 but for samples 100-150 km from the radar.

	No mod.	Sch.1	Sch.1+ Sch.2	Sch.1+Sch.2 +Sch.3
Corr. Coeff.	0.24	0.22	0.06	0.09
Average relative error/%	36.14	36.75	38.17	37.44
Mean absolute error	1.07	1.07	1.03	1.02
Average error	-0.64	-0.60	-0.34	-0.36

Table 7. The same as Table 3 but for samples 0-50 km from the radar.

	No mod.	Sch.1	Sch.1+ Sch.2	Sch.1+Sch.2 +Sch.3
Corr. Coeff.	0.43	0.40	0.45	0.50
Average relative error/%	99.73	99.12	57.67	52.08
Mean absolute error	1.35	1.36	0.98	0.89
Average error	0.88	0.85	0.04	-0.03

Comparisons of the three schemes are performed. Scheme 1 improves only the correlation coefficient between estimated snowfall of samples 150 to 200 km from the radar and the observation, without improvement for other aspects. Scheme 2 improves the correlation coefficient between estimated snowfall of samples at 0 to 50 km and 150 to 200 km from the radar and the observation, reduces the mean absolute error and relative error of samples 0 to 50 km, 50 to 100 km and 150 to 200 km from the radar, and reduces the absolute values of average error of samples 0 to 50 km, 100 to 150 km and 150 to 200 km from the radar, indicating effective reduction in errors of snowfall estimate by radar, which is marked by overestimate for samples at a short distance and underestimate for those at a long distance. Scheme 3 improves further the estimate precision of most samples. The radar echo for studying this process is characterized by large-area homogeneous echo, so the improvement of Scheme 1 is not significant, and the effects of Scheme 2 indicate that results of snowfall estimate by radar are very sensitive to the distance between the sample and the radar, while Scheme 3 can further increase the degree of similarity and reduce errors.

As shown in Fig. 2, results of snowfall estimate are improved distinctly by use of the three modified schemes. For the 10 samples 29 to 44 km from the radar station, errors of 7 samples have decreased markedly. Errors of stations of Gaizhou and Dawan decrease by more than 50%. For Haicheng, estimate is improved for snow at rates smaller than 2 mm/h, but errors of estimate has increased for snow at rates greater than 3 mm/h. For the 19 samples 73 to 97 km from the radar station, errors of 13 samples have decreased, with the maximum and minimum snowfall in Anshan during this process, while the observations are 5.9 mm/h and 0.3 mm/h, respectively, and the snowfall estimates are 4.2 mm/h and 0.4 mm/h, respectively, indicating that the snowfall estimate technique by radar has the capabilities of estimating heavy snow above 5 mm/h and light snow below 0.5 mm/h. For the 18 samples 101 to 146 km from the radar station, errors of 11 samples have decreased. Snowfall estimates of 5 samples of Benxi underestimate the snowfall, while the average error is -1.5 mm/h and the maximum error is -2.75 mm/h, which is also the maximum error for all the samples in this process. Mean absolute error of 5 samples from the station of Caohekou also reaches 0.77 mm/h. In the section of error analysis, it is found that the temperature changes of Benxi and Caohekou are large, which may induce great changes in the intensity and diameter of snowflake, followed by influence on the estimated results. Comparison of the estimate has been done for these two stations before and after the modification, indicating that radar-based snowfall estimate of 10 samples from the two stations is basically in negative correlation with the observation, and no significant improvement is found after being modified by the three schemes, which validates the influence of temperature change on snowfall estimate from another aspect. For 16 samples 153 to 204 km from the radar station, errors of 8 samples have decreased, in which snowfall of Fushun during 13:00 to 14:00 is 4.4 mm, the original estimate snowfall is 2.09 mm/h, and the modified estimate snowfall is 4.01 mm/h, being the sample with the largest range of improvement in this process. After modification of the three schemes and elimination of Benxi and Caohekou stations, the number of samples with error larger than 1 mm/h is decreased by 13, with 15 samples remained, which accounts for 28% of the total number of samples. Besides, the number of samples with error larger than 2 mm/h is decreased by 4, with 3 samples remained, while the maximum error decreases to 2.4 mm/h.

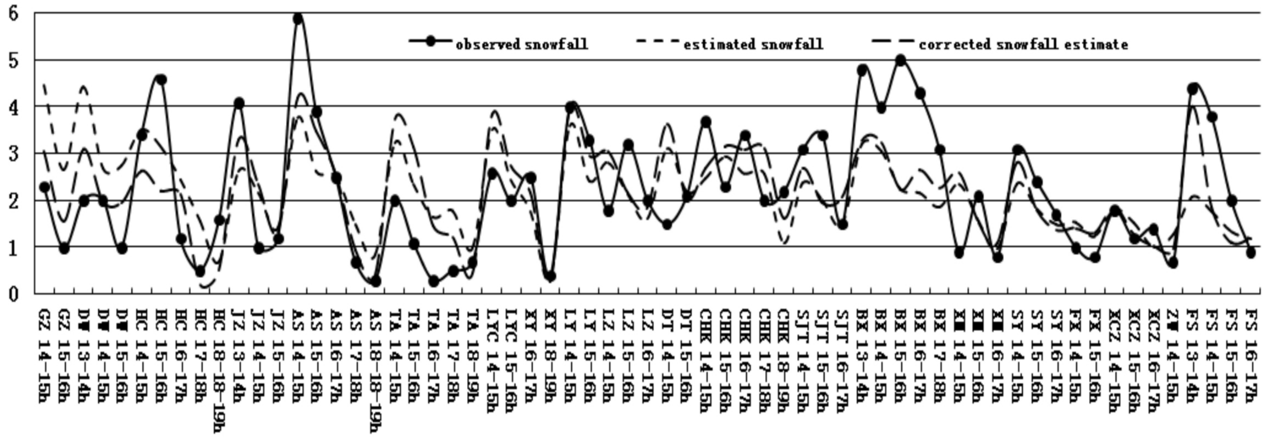

Figure 2. Comparison among the estimated snowfall by the optimization method, the estimated snowfall by the modified optimization method, and the observation (units: mm). GZ: Gaizhou; DW: Dawa; HC: Haicheng; JZ: Jinzhou; AS: Anshan; TA: Taian; LYC: Liaoyang County; XY: Xiuyan; LY: Liaoyang; LZ: Liaozhong; DT: Dengta; CHK: Caohekou; SJT: Sujiatun; BX: Benxi; SY: Shenyang; FX: Fuxin; XCZ: Xinchengzi; ZW: Zhangwu; FS: Fushun.

In the operational early warning of heavy snow, "Meteorological Disaster Warning Signal and Prevention Guide" of "Procedures on the Release and Dissemination of Early Warning Signals for Meteorological Disasters" (Decree No.16 of China Meteorological Administration) specifies that the red early warning signal for heavy snow should be released when the snowfall within 6 hours is above 15 mm, roughly corresponding to snowfall intensity above 2.5 mm/h; the orange early warning signal for heavy snow corresponds to snowfall intensity of 1.6 to 2.5 mm/h; the blue and yellow early warning signals for heavy snow correspond to snowfall intensity of 0.3 to 1.5 mm/h. Hereafter, we discuss the radar-based estimate effects of different snowfall intensity in the operational early warning of heavy snow (Table 8). Snowfall estimate for snowfall intensity of 1.6 to 2.5 mm/h has the minimum mean absolute error of 0.65 mm/h. Average errors of snowfall estimate for snowfall intensity of 0.3 to 1.5 mm/h and 2.6 to 5.9 mm/h are 0.58 mm/h and -0.93 mm/h, respectively. Average relative errors of snowfall estimate for snowfall intensity of 1.6 to 2.5 mm/h and 2.6 to 5.9 mm/h are 31% and 27%, respectively, which are relatively small. Combining with Fig. 3, it is clear that errors of snowfall estimate for samples of 0.3 to 1.5 mm/h are mainly positive, and errors of snowfall estimate for samples of 0.3 to 1.5 mm/h are consistently negative. The larger the snowfall intensity is, the larger the error is. That is to say, in this process, the radar-based snowfall estimate always overestimates the relatively weak snow and underestimates the relatively strong snow.

Table 8. Mean absolute error, error and relative error of snowfall estimate for sample of different snowfall intensities.

mm/h	Number of samples	Mean absolute error /(mm/h)	Average error /(mm/h)	Average relative error
0.3-1.5	23	0.67	0.58	75%
1.6-2.5	19	0.65	0.16	31%
2.6-5.9	21	1.05	-0.93	27%

Such consistency in errors should be taken advantage of for modification in operational and practical application, in order to increase the precision of snowfall estimate.

7 CONCLUSIONS AND DISCUSSION

In this paper, we have designed a snowfall estimate method by radar based on an optimization method for operational snow early warning, which is used for a case of heavy snow on March 4, 2007.

The radar-based snowfall estimate technique by the optimization method can well reflect trends of snow, while the correlation coefficient between the estimated snowfall and the observation is 0.52 (exceeding the 99% confidence level) and the average relative error is 62.43%, indicating that this technique is practicable for operational application.

Through investigation into errors of the radar-based snowfall estimate, it is indicated that factors such as temperature changes, snowflake terminal velocity, the distance from the radar and calculation methods may in-

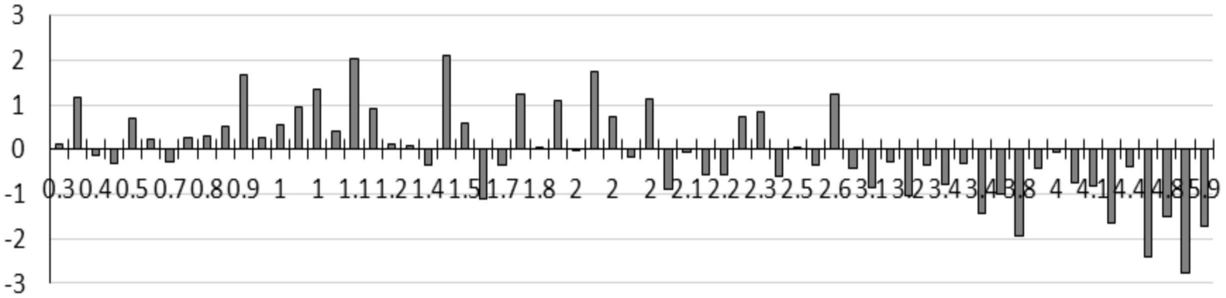

Figure 3. Errors of snowfall estimate for samples of different snowfall intensities (units: mm).

fluence estimated results. Three modified schemes are developed. After modification, the correlation coefficient between the estimated snowfall and the observation increases to 0.66, the average relative error decreases to 48.74%, and the modification makes it possible to estimate light snowfall of 0.3 mm/h and heavy snowfall above 5 mm/h. The maximum correlation coefficient is 0.82, between the estimated snowfall from the samples 50 to 100 km from the radar and the observation, while the minimum mean absolute error occurs in samples 150 to 200 km from the radar. The radar-based snowfall estimate underestimates samples at distances larger than 100 km from the radar and overestimates samples at distances of 50 to 100 km from the radar, which should be revised in operational application.

Among the three modified schemes, the modification effects concerning the influence of snow terminal velocity are not significant, which may be connected to homogeneous echo in this extremely heavy snow process. The modification effects of radar-based snowfall estimate is most significant when samples of different snowfall intensities are considered, which can not only increase the degree of similarity, but also reduce the overestimate for samples at a short distance from the radar and the underestimate for those at a long distance from the radar. The revised algorithm further improves the accuracy of the estimate.

Currently, the hourly observation for operational use depends only on the intensive manual observation, so samples for snowfall estimate are comparatively small in quantity. In this paper, the case for radar-based snowfall estimate is an extremely heavy snow, while only samples of the pure snow are used. Therefore, more snow processes are needed for verification of results.

Acknowledgement: The authors are grateful to Professor YU Xiao-ding for his help and guidance.

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Citation: JIANG Da-kai, MIN Jin-zhong and CAI Kui-zhi. The design and correction of a quantitative method of snow estimate by radar [J]. J Trop Meteorol, 2015, 21(1): 92-100.