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An Automated Quality Control Procedure for the "Water Equivalent of Snow on the Ground" Measurement

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ABSTRACT

Snow water equivalent (SWE) has been measured daily by the United States National Weather Service since 1952 whenever snow depth is 5 cm or greater. These data are used to develop design snow loads for buildings, for hydrological forecasting, and as an indicator of climate change, but have not been subjected to quality control. The quality control procedure developed here for the northeastern United States checks daily SWE measurements for common digitizing errors, values beyond reasonable limits, and consistency with daily precipitation and melt. Potential effects of drifting and the intrinsic micro-scale variability of SWE are also considered. A daily SWE measurement is declared suspicious if a sufficient discrepancy is found between the measurement and the expected SWE. Data flagged as errors are checked manually.

INTRODUCTION

The 'water equivalent of snow on the ground', or snow water equivalent (SWE), is an important component of the hydrological cycle as the potential runoff (Male and Gray 1981). The SWE is also used to establish design snow loads for construction of buildings (Ellingwood and Redfield 1983; Newark et al. 1989; ASCE 1990). U.S. National Weather Service (NWS) observers began measuring SWE once daily in 1952 whenever snow depth was 5 cm or greater. These data now constitute a significant climatic record with potential use in climate change studies, in addition to hydrological and engineering applications. Recent research has found apparent errors in the historical record of SWE (Schmidlin 1990). These generally involve large (>2.5 cm) increases in daily SWE without precipitation or increases in snow depth. Other apparent errors involve misplaced decimals or large decreases in SWE without melt conditions. Previous studies using SWE data apparently did not consider quality control of the data (Ellingwood and Redfield 1983; O'Rourke and Stiefel 1983; ASCE 1990). Schmidlin et al. (1992) performed quality control on annual maximum SWE measured at ten NWS offices in Ohio and adjacent states prior to calculating design ground snow loads. It was found that 15% of annual maximum SWE values were in error and corrections led to revisions of design ground snow loads in Ohio from those presented by ASCE (1990). The National Climatic Data Center (NCDC) has conducted quality control on daily maximum and minimum temperatures, precipitation, snowfall, and snow depth from 8300 Cooperative Observer Network stations since 1982 as the data are archived (Reek et al. 1992). Procedures are being developed at NCDC to perform quality control on the pre- 1982 historical archive of these parameters (Reek et al. 1992). However, the SWE data from NWS offices continue to be archived, published, and used without quality control.

The purpose of this research is to develop an automated quality control procedure to be applied to the historical record of daily SWE measured at NWS offices in the northeastern United States.

SNOW CLIMATOLOGY OF THE NORTHEASTERN UNITED STATES

Median annual snowfall in the northeastern United States ranges from less than 50 cm in eastern Maryland and Delaware to over 250 cm at high elevations and in the snowbelt areas of the Great Lakes (Cember and Wilks 1993). Snow cover is sporadic and shallow in the southern coastal region, but is persistent and lasts for 120 days or longer in the north. Even in the north, where snow cover persists through the winter, maximum temperatures above 0°C typically occur on 5 to 10 days in both January and February and periods of melt may occur anytime (Schmidlin et al. 1987). Median annual maximum snow depth is 10 cm in the south but exceeds 70 cm in the north and mountains (Cember and Wilks, 1993). Extreme depths for the full record exceed 100 cm in the north and the Great Lakes snowbelts.

MEASUREMENT OF SWE

The measurement of SWE by the National Weather Service is usually taken over sod a few meters from the NWS office on the grounds of large airports. These are flat, open landscapes and may not be representative of SWE in the general region (Schmidlin 1989, 1990). Some NWS offices take SWE observations on a roof, cultivated field, gravel lot, or in nearby wooded terrain (Schmidlin, 1990). Data are recorded and published in inches so those units have been preserved here. Time of measurement of SWE is 1800 UTC while snow depth is measured at 1200 UTC (NCDC 1989). The SWE may be obtained by one of three methods at NWS offices -melting, weighing, or estimation (U.S. Department of Commerce 1982). The melting method requires one core of snow to be obtained from a representative location, usually with the 20 cm diameter precipitation gauge. The core is taken inside, melted, and the depth of water in the snow core is obtained. In the weighing method, a core is taken and the core and coring device are weighed to obtain the SWE. Estimation, often assuming a 10:1 snow:water ratio, is used if severe weather conditions prevent the observer from taking a core sample, although one NWS office weighed a core every Monday but estimated SWE on other days (Schmidlin, 1990). The measurement method varies with NWS office protocol and observer preference. Information on the measurement method is not preserved with the data.

THE QUALITY CONTROL MODEL

The quality control procedure described here is an automated process to identify daily SWE measurements that are unreasonable in relation to the previous day's measurement, observed precipitation, or melt (Fig. 1). We start with the assumption that the measurement of SWE is correct. Observations of SWE and other elements at NWS offices are taken by full-time NWS employees. This is in contrast to the 8300 stations in the Cooperative Observer Network where observations are taken by 'citizen volunteers' with less training and supervision. Most of the effort at quality control at the National Climatic Data Center has focused on these Cooperative stations (Reek and Crowe 1991; Reek et al. 1992) where snow data are particularly poor (Robinson 1989; T. Reek, communication 1992).

Two tactics are commonly used in climatological quality control; (1) comparisons with nearby stations to detect inconsistencies, or (2) a scheme that determines whether a datum is outside of reasonable ranges or does not logically follow with observations from adjacent periods (Brandow and Lourick, 1991; Heim et al. 1991; Reek et al. 1992; Robinson, 1993). The former is not practical with

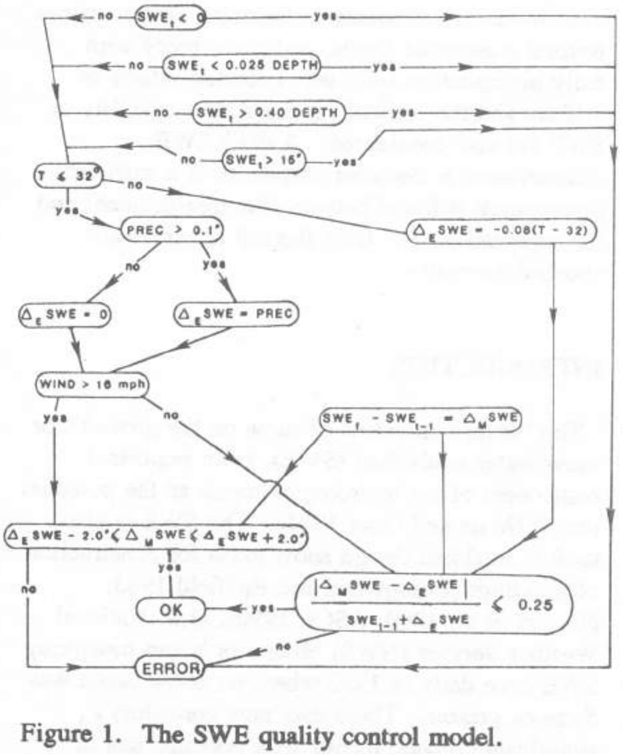

Figure 1. The SWE quality control model. Subscript 't' is today, 'E' is estimated, and 'M' is measured. Variables are defined in the text.

SWE because NWS offices are too far apart (100-300 km) for reliable comparisons among neighboring stations. Therefore, the second tactic is used here.

Errors in daily SWE may be digitizing errors or observer errors. Examples of digitizing errors are a misplaced decimal, an added digit, and reversal of sign or digits in the initial recording or during data entry at the National Climate Data Center. Observer errors include incorrect measurements, due, for example, to careless reading of gauges or incorrect melting of a snow core. Estimation of SWE for several days, possibly introducing errors, followed by a measurement that abruptly incorporates several days of change in SWE may also give an anomalous SWE. This quality control procedure is designed to identify such problems in the data. A daily SWE observation is concluded to be a potential error if it is inconsistent with the previous day's SWE, recorded precipitation, estimated melt, or potential changes due to wind drifting.

A daily increase of SWE should equal the water equivalent of new precipitation during periods of accumulation minus water lost from the snowpack. The water content of snowfall is recorded hourly as precipitation. A daily decrease in SWE during thaw should equal the melt and runoff from the snow. Although snow depth is measured daily, a decrease in depth cannot be interpreted as melt and loss of water from the snowpack because compaction may occur within the snowpack without loss of water. Therefore, loss of water through melt must be estimated from other measured elements, such as temperature. SWE may also increase or decrease due to phase changes by exchange directly with vapor in the atmosphere. Goodison (1979) showed daily sublimation from snow in southern Ontario was typically 0.1 mm to 0.3 mm of water equivalent. Daily sublimation or condensation onto the snowpack are considered insignificant with respect to the 0.1 inch (2.5 mm) precision in SWE measurement and are probably compensating over several days (Wilson 1954). Strong winds during snowfall may cause daily changes in SWE that are inconsistent with daily precipitation during snow storms. Wind drifting may also cause a change in SWE in the absence of precipitation or melt. The daily measurement of SWE may also vary without new snowfall, melt, or drifting, due to the natural small- scale spatial variability of snow covers. An acceptable range is established in the quality control procedure for this natural variability. Limit checks and ranges of acceptable anomalies in SWE from consistency with the previous day's observation, precipitation, melt, and wind, are described in the following sections.

Digitizing errors and limits checks

Each datum is initially checked for the most likely digitizing errors and for exceeding reasonable limits with respect to the local climate (Fig. 1). SWE less than zero is flagged as an error caused by an added negative sign. SWE less than (0.025 x snow depth) is flagged as a potential error since snowfall/ SWE ratios greater than 40:1 are unlikely at temperatures above 0°F (Reek et al 1992). SWE greater than (0.40 x snow depth) for two consecutive days is flagged as a potential error because these high densities are rarely encountered in the eastern United States (Edgell 1988). Two consecutive days of depth must be examined and compared to SWE because the 6 hr lag between the daily observations of snow depth and SWE may allow significant SWE to accumulate after the daily observation of snow depth. SWE greater than 15 inches (38 cm) is also flagged as a potential error. This is the maximum SWE at Caribou, Maine (Loiselle et al. 1992), generally the NWS office with the greatest annual SWE in the northeast. Daily SWE measurements that pass these tests proceed to checks for consistency with previous day's SWE, melt, precipitation, wind, and natural spatial variability of SWE.

Snow Melt

There are many schemes to estimate daily snowmelt from weather data (Male and Gray 1981; Bloschl and Kirnbauer 1991; Hughes and Robinson 1993). Most require complex energy balance calculations and are not suitable for this quality control process. Simple models of snowmelt have used air temperature as an index of melt. A base melt threshold air temperature of 0°C is a common assumption (Male and Gray 1981) although other melt thresholds are reported depending on terrain, climate, and vegetation (Carr 1988; Samelson and Wilks 1993). Carr (1988) tested several relationships and found (1),

$$M = 0.08\ (T - 32) \qquad (1)$$

where M is daily SWE decrease in inches day^{-1} and T is mean daily temperature (°F), performed best in southern Ontario. This snowmelt model is simple in its use of one readily available parameter. In this quality control procedure, (1) is used to estimate daily loss of SWE due to snowmelt. Mean temperature is taken as the average of the high and low temperature on the day of SWE measurement. For a day with mean temperature over 32°F (0°C), the expected daily decrease in SWE equals M in (1).

New Precipitation

SWE may increase by new snowfall or rain into the snow cover, if runoff does not result. New snowfall should result in an increase in SWE that is equal to the water equivalent of the new snowfall. Snowfall is measured and recorded by the NWS as hourly precipitation by weighing or melting snow that fell into the precipitation gauge or by taking one core of new snow that fell onto a snow board placed on top of the previous day's snow cover. The water equivalent of new snowfall is difficult to measure because snow does not readily fall into precipitation gauges and drifting may give large spatial variability in new snow cover, as discussed below. On days with precipitation over 0.1 inch (0.25 cm) water equivalent and mean daily temperature 32°F (0°C) or below, the expected daily increase in SWE is equal to precipitation in the 24 hr ending at 1800 UTC.

Wind Effects

Falling snow is distributed on the landscape as a function of wind speed and roughness features in the landscape. Light winds without blowing snow give a relatively even spatial distribution of depth, density, and SWE, while stronger winds cause blowing snow and result in an uneven pattern of scouring and drifts. Strong winds may also cause redistribution of an existing snow cover. Snow transport by wind is greatest over flat, extensive areas, free from obstructions to the airflow (McKay and Gray 1981). The airport sites where SWE is measured at NWS offices match this description and have the potential for considerable drifting snow.

Discrepancies between new snowfall (or lack thereof) and daily changes in SWE may sometimes be explained by effects of wind on the snow cover. Wind speed measured at 10 m height (or corrected to that height) at the NWS offices was incorporated into the model. The model does not estimate the depth of SWE added or removed by wind, because this is micro-site specific, but a minimum threshold wind speed for drifting snow was established. Winds above this threshold were assumed to have the potential to redistribute the snow cover and cause anomalous changes in SWE.

The relationship between threshold wind speeds and snow characteristics is complex (Schmidt 1980) but generalizations are available for this application. Kind (1981) showed that a 10 m wind speed of 5 ms^{-1} (11 mph) is the minimum threshold to cause drifting snow if the snow is loose, fresh, and dry, and a threshold wind speed of 11 ms^{-1} (25 mph) for drifting of old, hardened snow. Pomeroy and Gray (1990) recommended a minimum threshold 10 m wind speed of 7 ms^{-1} (16 mph) to cause drifting of typical snow covers on non-vegetated plains. This value was adopted as the threshold for this model.

The increase of wind speed with height depends on surface roughness and atmospheric stability. It is approximated by the power law in (2), where U_{10} is the wind speed at 10 m, U_z is the wind speed measured at height z, d is snow depth, and 'a' is an

$$U_{10} = U_z [(10-d)/(z-d)]^a \qquad (2)$$

exponent representing all friction components (Landsberg 1981, p. 140). The value of 'a' is relatively low over open, flat surfaces. For open terrain, it has been given as 0.14 to 0.18 by Landsberg (1981, p. 140-141) and 0.125 by Sissenwine and Cormier (1974). A value of 0.125 for 'a' was adopted to convert wind speeds measured at NWS offices to a standard 10 m height.

Hourly wind speeds were checked for each 24 hr period ending with the 1800 UTC SWE observation time on days with a mean temperature of 32°F (0°C) or below. Snow covers on days with mean temperature over 32°F (0°C) were assumed to be melting and less vulnerable to drifting. If an hourly wind speed over 16 mph (7 ms^{-1}) was recorded on a sub- freezing day, then we assume that inconsistencies of up to 2 inches (5 cm) between the measured daily change in SWE and the 'expected' daily change of SWE, based on new precipitation or melt, could have resulted from drifting. Inconsistencies greater than 2 inches are flagged as potential errors. If no hourly wind speed over 16 mph (7 ms^{-1}) occurred, then further checks were made for consistency with micro-scale variability of SWE.

Micro-scale spatial variability of SWE

The SWE cannot be measured at exactly the same location each day because it requires a destructive sampling process. In general, the daily snow cores are taken less than 10 m apart at a site adjacent to the precipitation gauges at NWS offices. Some micro-scale variability in snow depth and density, and therefore SWE, is expected within this area, even in the homogeneous terrain of airports. Variability in snowcover at the micro-scale is due to numerous interactions, principally between surface roughness and transport phenomena (McKay and Gray 1981). Goodison (1979) showed open areas of short grass have the most variable snow cover of several land use types in southern Ontario. SWE has more variability than snow depth across a landscape (Wilson 1954). Therefore, some daily variability in measured SWE at NWS offices is expected even if actual SWE does not change and the measurement is taken properly.

Literature on spatial variability of SWE has focused on snow courses, with point measurements tens of meters apart along a linear transect in forested terrain (for examples, Wilson 1954; Leaf and Kovner 1972; Brandow and Lourick, 1991). To assess micro-scale variability in SWE, field experiments on SWE were conducted during the winter 1992-93 over small uniform areas, similar to the SWE sampling sites at airports. Seven plots were sampled to measure the intrinsic variability of the SWE measurement. Two plots with nine points 2 m apart on a square grid were sampled near Kent, OH. Five plots with 8 to 12 points spaced 1 m apart on linear transects were sampled near Ithaca, NY. Each SWE value was determined by melting snow cores and measuring the liquid equivalent using a raingage (U.S. Department of Commerce, 1982). Table 1 shows the dates, locations, sample sizes, snow depth, and SWE data for each of the seven measurement groups. Dates were chosen to exclude snowpacks substantially affected by drifting. Figure 2 shows the standard deviation of SWE and the average SWE for each of the seven sets of measurements. Also shown in Figure 2 are the 95% confidence limits for the average and standard deviation of the SWE.

It is clear from Figure 2 that the intrinsic variability of the SWE measurement increases with the water content of the snowpack. The standard deviation appears to increase approximately in proportion to the mean, so that the coefficient of variation (CV = standard deviation/mean) is approximately constant. Also shown in Figure 2 is the line for CV = 0.125, which is within or above the 95% confidence intervals for the standard deviations in each measurement set. This result agrees with the estimate by Tom Carroll (communication) that ground-based SWE measurements tend to have CV's of 0.10 to 0.20.

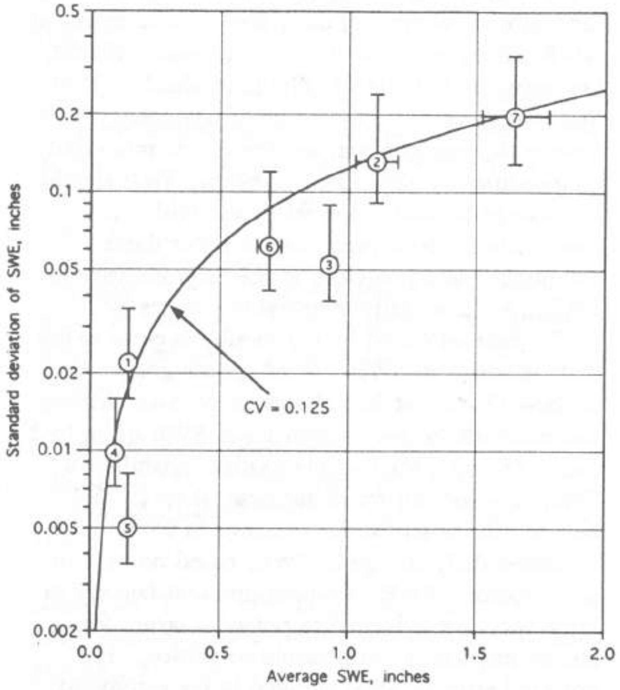

Figure 2. Mean and standard deviation of SWE over level, open sod for samples shown in Table 1. The 95% error bars are shown when possible and the 0.125 coefficient of variation (CV) curve is shown to enclose most points.

Table 1. Measured micro-scale variability in snow depth and SWE over level sod in open terrain.

Date	Location	n	Depth (in)		SWE (in)	
			mean	std dev	mean	std dev
8 Dec 1992	Ithaca, NY	15	2.9	0.46	0.14	0.02
12 Dec 1992	Ithaca, NY	10	5.8	0.89	1.11	0.13
14 Dec 1992	Ithaca, NY	12	4.9	0.50	0.92	0.05
11 Jan 1993	Ithaca, NY	15	2.2	0.21	0.10	0.01
12 Jan 1993	Ithaca, NY	13	1.8	0.28	0.14	0.01
17 Feb 1993	Kent, OH	9	5.4	0.19	0.69	0.06
3 Mar 1993	Burton, OH	9	6.9	0.49	1.65	0.20

We conclude that natural variability of SWE over small areas may account for deviations of 25% of the SWE (+/- 2σ), even if great care is taken with the SWE measurement. With wind speeds up to 16 mph (7 ms^{-1}), inconsistencies between measured daily change in SWE and the expected change in SWE, based on precipitation and melt, are accepted if they are no more than 25% of the expected new SWE. Inconsistencies greater than 25% are flagged as potential errors.

SUMMARY

The quality control model shown in Figure 1 for the historical archive of daily SWE measurement at NWS offices provides internal consistency checks, beginning with limits and digitizing checks. Data that pass these move to checks of consistency with daily melt, precipitation, and wind. At mean daily temperatures of 32°F (0°C) or below, SWE should not change beyond limits set except with precipitation. New precipitation under those conditions should be close to the daily increase in SWE. At mean daily temperatures above 32°F (0°C), melt estimated by (1) should be close to the daily decrease in SWE. Wind speeds greater than 16 mph (7 ms^{-1}) at 10 m height may cause drifting that accounts for inconsistencies in SWE of up to 2 inches (5 cm). Micro-scale spatial variability of SWE may account for differences of up to 25% between the observed daily change in SWE and estimated daily change in SWE, based on melt or precipitation. SWE measurements that fail any of these checks are flagged as potential errors for human inspection and possible correction. If a potential error in SWE is noted in the automated procedure, then subsequent days are compared to the last correct SWE measurement, rather than to the erroneous datum. As the model is tested, revisions will be made to limits and other checks and the procedure in Figure 1 will be amended as necessary.

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