Influence of Method of Measurement of Daily Snowfall on Climate Normals in Ontario, Canada

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ABSTRACT

Canadian Climate Normals 1971–2000 include, for some locations, the monthly total water equivalent of daily snowfalls measured with a Nipher-shielded gauge, as well as the monthly total of ruler-measured daily snowfall depths. For these stations it is possible to calculate density of daily snowfall on a monthly-mean basis. In this study monthly Climate-Normal-Precipitation data from 34 Ontario locations with Nipher-shielded gauges have been analyzed to obtain the month-by-month pattern of the average density of daily snowfalls. The temporal pattern of snowfall density has been related to location and monthly mean temperature. A predictive relationship for snowfall density based on air temperature has been developed for the 26 inland locations that showed no lake-effect and station-specific adjustments have been developed for the eight locations showing reduced snowfall density due to lake-effect snow. The error in Climate-Normal SWE and Monthly Precipitation that would occur at these 34 stations if SWE were calculated from snow depth using a standard snowfall density of 100 kg/m^3 has been assessed. Errors in SWE are all over estimates, ranging from 2% to 18% for inland stations and from 19% to 45% for lake-effect stations. This corresponds to relatively small errors in total annual precipitation of from 0.5% to 5.3% for inland stations and from 3.4% to 12% for lake-effect stations. Results from this study are classified as preliminary since undercatch of snow by the Nipher-shielded gauge, relative to snow reaching the ground for ruler-depth measurement, has not been considered. Correction of the Nipher-shield-gauge data for undercatch would result in reduced magnitude of over-estimate error in annual precipitation associated with the use of a standard 100 kg/m3 snowfall density.

Keywords: snowfall density, Nipher-shielded gauges, Ontario Climate Normals, monthly precipitation.

INTRODUCTION

The presence of systematic errors (bias) in measurement of solid precipitation is a continuing problem faced by hydrologists. The Final Report of the WMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998) contained a recommendation that "methods to adjust solid precipitation measurements for systematic errors should be tested and implemented on current and archived precipitation data for use by members". This recommendation certainly applies to the use

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of a standard density to convert ruler-measured new-snow depth to SWE as well as to wind-speed-based corrections of SWE measurements made in Nipher-shielded gauges.

Data on new-snow density in Canada were examined by Goodison et al. (1981). They reported that seasonal-average new-snow density obtained from cumulative daily measurements of ruler-made snow depth and Nipher-measured SWE varied from 72 to 114 kg/m^3 at Toronto Airport and from 74 to 96 kg/m^3 at Thunder Bay Airport. They also note a 1971 report by Ferguson and Pollock that contains an average density for northern Ontario locations of 81 kg/m^3 and an average density of 82 kg/m^3 for southern Ontario. Goodison et al. (1981) report an undercatch at Nipher-shielded gauges of 9% for open-flat locations compared to snow measured on a snow board at a nearby sheltered location. Goodison et al. (1998) report an undercatch of 14% at a Nipher-shielded gauge at the Valdai test site in Russia, compared to a nearby bush-sheltered gauge.

Canadian Climate Normals for 1971–2000, including data for monthly amounts of rain, monthly total of depths of daily-measured snowfalls, and total precipitation are now available on line (www.climate.weatheroffice.ec.gc.ca). This data base provides an opportunity for the examination of possible bias in solid precipitation measurement in Ontario at locations that measure snowfall depth and use a standard density for snowfall to calculate snow-water equivalent (SWE). At 34 locations in Ontario both ruler depths of daily snowfall and daily SWE measurements in a Nipher-shielded gauge are made. At these locations snowfall density can be calculated.

This paper describes an analysis of Climate Normal data undertaken to assess the influence of snowfall density on systematic error in precipitation data and on Climate Normal Precipitation. In the course of the analysis, relationships were developed for snowfall density as a function of air temperature and monthly snow as a proportion of monthly precipitation as a function of air temperature. Special attention was given to influence of lake-effect snow on snowfall density.

METHOD OF ANALYSIS OF CLIMATE-NORMAL DATA

Canadian Climate Normal data (1971–2000) for 34 locations in Ontario with Nipher-shielded gauges are set out in Table 1. Monthly and annual totals for SWE were not provided in the primary data and were calculated as (total precipitation—rain) . Annual totals are shown in Table 1. Additional analyses of monthly data were done for months in which the monthly total for new-snow depth was greater than 4 cm. For southern Ontario the months were November through April. For more northerly locations October and May were added. At the most northerly station, Big Trout Lake, the months with appreciable snowfall are September through June. Using 47º north latitude as a demarcation line, 19 stations are in southern Ontario and 15 in northern Ontario.

Snowfall density was calculated as [SWE (mm)/snow depth(cm)]*100. Results using annual totals are shown in Table 2. Table 2 also shows the error in total annual SWE, and in total annual precipitation, that would result from the calculation of SWE from daily snowfall depth using a snowfall density of 100 kg/m^3.

Monthly-mean air temperature is also provided in the Climate Normal data for each station. The mean monthly-temperature was related to snowfall density and to proportion of total monthly precipitation that is snow at each location. The specific form of these analyses are given below.

Table 1. Canadian Climate Normal data for selected Ontario stations 1971–2000

Location	Lat	Long	Rain mm	Snow Depth cm	Precip mm	SWE Mm
Windsor	4216	8258	805	127	918	113
Sarnia	4300	8218	733	125	847	114
Hamilton	4310	7955	765	162	910	145
St Cath.	4312	7910	746	137	874	128
W.W.A	4327	8022	765	160	908	143
Toronto	4340	7936	685	115	793	108
Monticel	4358	8024	774	245	991	216
Peterbor.	4413	7822	682	162	840	158
Kingston	4413	7636	795	181	968	174
Muskoka	4458	7908	809	334	1099	290
Ottawa	4519	7540	732	236	943	212
Petawa	4557	7719	616	228	816	200
North B	4621	7925	775	273	1008	233
Sudbury	4637	8048	657	274	899	243
Earlton	4742	7951	554	247	785	231
Timmins	4834	8122	558	313	831	273
Kapusk	4924	8228	545	313	832	287
Geraldt	4946	8655	546	244	760	214
Kenora	4947	9422	514	158	662	147
Dryden	4949	9245	536	170	701	166
Sioux L	5007	9154	517	204	716	199
RedLake	5104	9347	473	193	640	167
Mooson	5116	8639	494	213	682	188
Pickle L	5127	9013	493	263	717	225
Lansdo	5213	8752	489	242	700	211
Big Trou	5349	8952	398	227	609	211
London	4301	8109	818	202	987	169
Trenton	4407	7731	759	169	894	135
Wiarton	4445	8106	740	427	1041	301
Gore B	4552	8234	625	267	809	184
Sault St	4628	8430	634	303	889	254
Wawa	4758	8446	727	329	1002	275
Thund B	4822	8919	559	188	712	153
Atikokan	4845	9137	568	220	740	171

DISCUSSION OF RESULTS

The most noticeable feature of the calculated snowfall densities shown in Table 2 is the lower values for snowfall density for the eight locations listed at the bottom of the table. Each of these locations is downwind of one of the Great Lakes. The eight "lake-effect" stations are London, Wiarton, and Gore Bay (downwind of Lake Huron); Trenton (downwind of Lake Ontario); Sault Ste. Marie, Wawa, Thunder Bay and Atikokan (downwind of Lake Superior). All other stations are termed "inland."

The average snowfall density for all 19 stations in southern Ontario is 87 kg/m^3 (89.5 kg/m^3 for inland stations and 77 kg/m^3 for lake-effect stations). For the 15 northern Ontario stations the average density is 89 kg/m^3 (91 kg/m^3 for inland stations and 81 kg/m^3 for lake-effect stations). For the inland stations these results are appreciable higher than the values given by Ferguson and Pollock (1971) of 82 kg/m^3 for southern Ontario and 81 kg/m^3 for northern Ontario.

Table 2. Calculated new-snow density and possible errors in SWE and precipitation

Location	Snowfall Density kg/m^3	Error SWE %	Error in Precipitation %	Lake Effect
Windsor	89	12	1	
Sarnia	91	9	1	
Hamilton	90	11	2	
St Catharines	94	7	1	
Wat.Well A	90	12	2	
Toronto	94	7	1	
Monticello	88	13	3	
Peterborough.	98	2	0	
Kingston	96	4	1	
Muskoka	87	15	4	
Ottawa	90	11	3	
Petawawa	88	14	3	
North Bay	85	17	4	
Sudbury	88	13	4	
Earlton	94	7	2	
Timmins	87	15	5	
Kapuskasing	92	9	3	
Geraldton	88	14	4	
Kenora	93	7	2	
Dryden	98	3	1	
Sioux Lookout	98	3	1	
Red Lake	87	15	4	
Moosonee	88	13	4	
Pickle Lake	85	17	5	
Lansdowne	87	15	4	
Big Trout	93	8	3	
London	84	20	3	Yes
Trenton	79	26	4	Yes
Wiarton	71	42	12	Yes
Gore Bay	69	45	10	Yes
Sault St Marie	84	19	5	Yes
Wawa	84	20	5	Yes
Thunder Bay	81	23	5	Yes
Atikokan	78	29	7	Yes

Since all the calculated snowfall densities are less than 100 kg/m^3, an over-estimate in annual total SWE, compared to the gauge-measured SWE, results when SWE is calculated from snow depth using a density of 100 kg/m^3. The over-estimate for total SWE for each station is given in Table 2. For the 26 inland locations the average over-estimate error for SWE is 11%, with a range from 2% to 17%. For lake-effect stations the average error in SWE is 28% with a range from 19% to 45%.

The error in annual precipitation is of course much less. For inland stations the error in annual total precipitation due to use of a density of 100 kg/m^3 is 2.5% with a range from 0.5% to 5%. For lake-effect stations the average error is 6.5% with a range from 3% to 12%.

INFLUENCE OF AIR TEMPERATURE ON SNOWFALL DENSITY AND PROPORTION OF PRECIPITATION THAT IS SNOW

The monthly data for snowfall density from the inland stations were analyzed to see the effect of monthly-mean air temperature on monthly-mean snowfall density. Monthly-mean air temperature is influenced by periods within the month when air temperature is above 0 °C; thus mean-monthly air temperature is higher than the mean temperature during snow events since these events generally are limited to periods with air temperature below 0 °C. A reference temperature for each month for events that would produce snow rather than rain was calculated based on an assumed range of temperature within the month. The intention was to emulate the exclusion of periods in the month with temperature above 0 °C without recourse to daily data. The following equation for snow-event index temperature was found to provide the best fit for prediction of snowfall density. A range of 24 °C between maximum and minimum daily-mean temperature within the month is implicit in the equation.

$T_{snow\text{-}events} = [(T_{mean} - 12) + (T_{mean} + 12)]/2$; if $(T_{mean} + 12) > 0$ then 0 is used for this term.

A linear-regression analysis was then done to establish a prediction equation for snowfall density based on the monthly snow-event-temperature index. The results are shown in Figure 1. About 40% of the variation in monthly-mean snowfall density was explained by the equation:

$$\text{Density (kg/m}^3) = 101.7 + 1.124\, T_{snow\text{-}events}\text{ ; T in °C} \quad (1).$$

This equation was then used to predict snowfall density for lake-effect stations. The snowfall densities predicted by equation 1 for lake-effect stations were all greater than the snowfall densities for these stations calculated from the Nipher-gauge data. Monthly density adjustments that produce close agreement between adjusted equation 1 results and "observed" snowfall density at lake-effect stations are shown in Table 3.

Table 3: Lake-effect adjustments in new-snow density (kg/m^3)

Station	November kg/m^3	December kg/m^3	January kg/m^3	February kg/m^3	March Kg/m^3
London	–10	–10	–10	–10	–5
Trenton	–14.5	–14.5	–14.5	–14.5	–7.25
Wiarton	–23	–23	–23	–23	–11.5
Gore Bay	–24	–24	–24	–24	–12
Sault Ste.	–6.5	–13	–13	–6.5	0
Wawa	–6	–12	–12	–6	0
Thunder B	–6.5	–13	–13	–6.5	0
Atikokan	–7	–14	–14	–14	–7

In Figure 2 observed monthly-mean snowfall densities are plotted as a function of calculated snowfall densities from equation 1 (with station-specific adjustments from Table 3 for the lake-effect stations). The predicted densities are unbiased (regression slope of 1.00) and about 62% of the variation in monthly-mean snowfall density is explained by the equation.

The Climate Normal monthly precipitation data were analyzed for proportion of monthly precipitation that is snow. Mean-monthly temperature can be used to predict this proportion. A good fit for the proportion of monthly precipitation that is snow is provided by a cumulative probability function calculated using a mean temperature of –3 ºC and a standard deviation of 8.5 ºC. In Figure 3 the observed proportion of monthly precipitation as snow are plotted against the proportion predicted from the probability function. The fit is very good with a slope of 1.00 and an R^2 of 0.93.

To check the fit of equation 1 for snowfall density to individual monthly data equation 1 was used to calculate monthly snowfall density at London Ontario for the period January 1962, when Nipher-shield data were first taken, to April 2002. The prediction procedure used equation 1 with the lake-effect adjustments given in Table 3 for London. Results are shown in Figure 4. The prediction is an unbiased estimate of snowfall density (slope of 0.98) but is no improvement over the use of a single mean value of new-snow density for all months (R^2 of 0.017). The predictor for proportion of monthly precipitation as snow was also checked and was more effective as shown in Figure 5. The estimate is unbiased (slope of 0.97) and is considerably better than the mean as estimator with an R^2 of 0.63.

A further test of the unbiased nature of predicted snow density was done by predicting SWE from measured snow depth at London for the period January 1940 to December 1961. For this period no Nipher-shield data were taken. A cumulative plot of SWE versus snow depth is shown in Figure 6 for the period January 1940 through April 2002. The upper line, with a distinct change of slope, is the station record of SWE, which uses a density of 100 kg/m^3 and snow depth for the period January 1940 through December 1961 and the Nipher-shield data for SWE from January 1962 on. The lower line shows the effect of using snowfall density predicted from temperature together with measured snow depth to obtain SWE for the January 1940 through December 1961 period. The straightness of this cumulative line shows the density estimates based on temperature provide results consistent with the period of Nipher-shielded gauge data.

As a side note the adjustments for density at London are similar in magnitude to changes in SWE estimates that can be caused by changes in gauge location. The measurements at Stratford , 45 km from London, changed location in 1959. Using London snow-depth measurements as a standard for the period January 1940 through April 2002 the Stratford snow depths were compared to those at London. This comparison shows that the post 1959 location in Stratford had 10% lower snow depths than the location used from 1940 through 1959.

EFFECTS OF GAUGE UNDERCATCH ON CALCULATED SNOWFALL DENSITY

The data for SWE from Nipher-shielded gauges that have been reported as part of the Climate Normal Precipitation was not adjusted for wind-induced undercatch. This is an important limitation on the validity of the results reported here. The results should be treated as preliminary, subject to review once wind-speed-adjustments have been applied for SWE. The undercatch adjustment could be appreciable. For an average wind speed at the gauge of 2 m/s (quite low) the wind-speed adjustment for a Nipher-shielded gauge would be 6% (Goodison et al. 1998). The effect of such an adjustment would be to raise calculated snow density by 6%, an adjustment that for most inland locations would bring on-site snow-density very close to the standard value of 100 kg/m^3 that is used to calculate SWE from daily ruler-depth measurement of snowfall at locations lacking a Nipher-shielded gauge.

CONCLUSION

For most locations in Ontario that have been analyzed in this study the effect of method of measurement of snow on Climate Normal precipitation is not large and is likely smaller than differences caused by location of the measurement station. For stations where lake effect snow is important calculation of SWE from ruler depth using a standard density of 100 kg/m^3 will result in an overestimate of SWE.

The results obtained here are based on Nipher-shield data that have not been adjusted for undercatch as estimated by wind speed. It is thus probable that for most inland locations corrections of the Nipher-shield gauge data for undercatch (likely in the range 5% to 10% increase) would roughly compensate for the apparent overestimate of SWE (averaging 11%) that has been found in this analysis to be caused by the use of a new-snow density of 100 kg/m^3 combined with snowfall ruler measurements. For lake-effect locations the undercatch of the Nipher-shield gauge will not remove all of the overestimate of SWE that is introduced by the use of the 100 kg/m^3 standard density.

The prediction of snowfall density from temperature provides an unbiased estimate. To be used at all locations in Ontario monthly, location-specific, lake-effect adjustments are needed. It may be possible to relate these adjustments to location (distance and direction from one of Great Lakes). The relationship for proportion of monthly precipitation as snow seems robust and applies to all locations.

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