Supplemental Material for

Twenty-First-Century Projections of Snowfall and Winter Severity across Central-Eastern North America

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SNOW-17 parameters and model evaluation

SNOW-17 requires regionally-specific calibration to produce quality snow simulations. The model applies six major parameters (SCF, MFMAX, MFMIN, UADJ, SI, and ADC) and six minor parameters (MBASE, NMF, DAYGM, PLWHC, PXTEMP, and TIPM) (Supp. Fig. 5). Of the major parameters, SCF is the snowfall multiplying factor, MFMAX is the maximum solar melt factor, MFMIN is the minimum solar melt factor, UADJ is the wind function, SI is the water equivalent for 100% snow cover, and ADC is the areal depletion curve. Of the minor parameters, MBASE is the threshold temperature for melting, NMF is the maximum negative melt factor, DAYGM is the average daily ground melt, PLWHC is snow liquid water-holding capacity, PXTEMP is the rain-snow temperature index, and TIPM is the antecedent temperature index. Allowable parameter ranges are specified by Anderson (2002). Based on station observations of temperature and present weather, a land cover map, NARR climatologies of snow depth and soil temperature, and recommended values from the National Weather Service (NWS), spatial maps of reasonable parameter values are developed as inputs to SNOW-17. Subsequently, the model is tuned to best capture climatological patterns of annual snowfall and DJF snow depth, compared to station observations. While expected ranges are available for the SNOW-17 parameters and their values are often loosely a function of environmental variables (e.g. climatological snow depth, forest cover fraction), the exact values for these parameters are somewhat subjective and can be challenging to determine across a large study region.

PXTEMP is the rain-snow temperature index (temperature that separates rain from snow), which determines the form of precipitation. When the hourly temperature is less than the (greater than) PXTEMP threshold, then all of the precipitation in that hour is assumed to fall as snow (rain). Typical thresholds for the 50-50 chance of rain versus snow given in the literature
include 1.0°C (Anderson 2002), 1.3°C (Notaro et al. 2011), 1.5°C (Snow Hydrology 1956), and 2.5°C (Auer 1974). To address this uncertainty and the potential for spatial heterogeneity in the threshold value, hourly observations of air temperature and present weather for 1980-1999 at 135 weather stations across the study region are used to quantify the mean air temperature threshold for rain versus snow, which was fit to a grid using inverse distance weighted interpolation and spatial smoothing to create the PXTEMP field (Supp. Fig. 5a). Across the study region, PXTEMP has a mean value of 0.98°C, a standard deviation of 0.81°C, and a large range from -2.2°C to 2.8°C (Supp. Fig. 6), with the greatest threshold values at northern latitudes and higher elevations. Among the 135 stations, the correlations between PXTEMP and both latitude and elevation are 0.59 and 0.52, respectively. The threshold exceeds the freezing point at 91% of the stations. The density of new snow (ρn in g/cm³) is calculated as a function of air temperature (Ta), given that colder air masses tend to support snow with a lower liquid water equivalent. When the air temperature is less than, or equal to, -15°C, then the new snow density is set to 0.05 g/cm³. Otherwise, the following equation is applied (Anderson 2006):

\[
\rho_n = 0.05 + 0.0017 (T_a + 15)^{1.5}.
\]  

(1)

The depth of new snow is computed by dividing the hourly precipitation by the hourly estimate of new snow density.

Spatial fields of recommended values of MFMAX, MFMIN, and UADJ across the United States are obtained from the National Oceanic and Atmospheric Administration (NOAA) (Naoki Mizukami, pers. comm.) and spatially extrapolated into southern Canada to cover the entire study region. MFMAX (MFMIN) is the maximum (minimum) solar-driven melt rate, assumed to occur on June 21 (December 21), in mm/°C/6 hours. For non-rain periods, surface snowmelt is determined by temperature, using a melt factor with seasonal variations provided by a sine
function using MFMAX for June 21 and MFMIN for December 21. Specifically, during non-rain periods, the depth of snowmelt (mm), $M$, is computed as:

$$M = M_f (T_a - MBASE)$$  \hspace{1cm} (2)

where $M_f$ is the seasonally varying melt factor (mm/°C), $T_a$ is the hourly air temperature (°C), and MBASE is the temperature above which melt occurs (set to 0°C). The seasonal variation in the non-rain melt factor is computed as:

$$M_f = \frac{\Delta t}{6} \left\{ \frac{1}{2} \left( \sin \frac{2\pi T}{366} + 1 \right) (MFMAX - MFMIN) + MFMIN \right\}$$  \hspace{1cm} (3)

where $\Delta t$ is the time step and $T$ is the day number since March 21. MFMAX and MFMIN are related to latitude, slope, aspect, forest cover type, and wind climatology. The mean and range of MFMAX (MFMIN) in the study region are 1.45 and 0.57-2.30 (0.37 and 0.05-1.19), respectively (Supp. Fig. 5b-c). UADJ is the average wind function for rain-on-snow periods in mm/hPa/6 hours, which is related to the wind climatology and only important where rain-on-snow events occur frequently. The mean and range of UADJ are 0.03 and 0.003-0.146 (Supp. Fig. 5d). Snowmelt is calculated by a different set of equations for rain-on-snow and non-rain periods. For rain-on-snow events, energy and mass balance equations are applied, using several assumptions about meteorological conditions during rain events and the wind parameter, UADJ. A higher value of UADJ produces greater melt during rain-on-snow events when the air temperature is well above freezing and sufficient rainfall occurs (He et al. 2011).

SI is the mean areal water equivalent, in mm, above which there is always 100% areal snow cover (Supp. Fig. 5e). Based on an IGBP land cover map and parameter tables for the Noah Land Surface Model (Mitchell et al. 2005), the following values of SI are assigned: 30 mm for woody savannas; 35 mm for open shrublands; 40 mm for grasslands, croplands, urban, and cropland/natural vegetation mosaics; and 80 mm for evergreen needleleaf forests, deciduous
broadleaf forests, and mixed forests. Changes in the heat content of the snowpack are a function of the gradient between the antecedent and current air temperature (Anderson 1973; Franz et al. 2008b). The antecedent temperature index parameter, TIPM, impacts the energy exchange during non-melt periods. During such times, the temperature of the snowpack follows the air temperature, but with a delay. Smaller values of TIPM indicate that the air temperature during more previous time intervals (e.g. past week) needs to be considered for adjusting the snowpack temperature. TIPM is a function of the climatological snow amount, with recommended values of 0.5 for the Upper Midwest, 0.2-0.5 for northern New England, and 0.1-0.2 for regions with a typical deep snowpack (NWS 2005). Based on climatological snow depths in NARR and these recommended TIPM values, the following crude relationship is developed:

\[
TIPM = -11.667 \times SND + 0.9167
\]  

(4)

where SND is the climatological annual-mean snow depth in meters and the range of TIPM is limited to 0.1-1.0. The spatial climatology of snow depth in NARR is then used to derive a spatial map of TIPM values (Supp. Fig. 5f). DAYGM is the average daily ground melt (mm/day), treated as a constant daily amount of melt occurring at the snow-soil interface to account for the geothermal heat flux at the ground surface (Anderson 1973; Franz et al. 2008b). The recommended values are 0.0 for areas with generally frozen soils under the snowpack and 0.3 for temperate areas with intermittent snow cover (NWS 1999). Using these recommended values and the DJF surface soil temperature climatology from NARR, the following crude relationship is formed through linear regression:

\[
DAYGM = 0.0227 \times SOILT + 0.1635
\]  

(5)

where SOILT is the climatological DJF soil temperature in °C and the range of DAYGM is limited to 0.0-0.4. Based on the spatial climatology of DJF soil temperature from NARR, a
spatial map of DAYGM is produced (Supp. Fig. 5g). MBASE, which is the temperature above which melting typically occurs, is set to 0°C, according to recommendations by Anderson (2002) and Raleigh and Lundquist (2012). NMF is the maximum negative melt factor, which determines the rate of heat transfer between the snowpack and the air during non-melt periods and is assigned a value of 0.15 mm/°C/6 hours as suggested by Anderson (2002). The snow cover is considered ripe when the heat deficit is zero and the amount of liquid water held in the snowpack equals the holding capacity (Anderson 2006). The liquid water-holding capacity for ripe snow as a decimal fraction, PLWHC, is set to 0.04, according to Anderson (2002).

SCF is a multiplying factor that adjusts new snowfall amounts before adding them to the existing snow cover, which accounts for gauge catch deficiencies and losses during accumulation periods due to sublimation and redistribution, attributed to blowing snow. Anderson (2002) recommends a value of 1.15, with a typical range of 0.7-1.6. Using the specified values for the aforementioned SNOW-17 parameters, four test simulations are performed for 1981-2000 using the statistically downscaled output from four select CMIP3 models. Ratios between the observed and simulated mean annual snowfall are computed at 196 stations (Fig. 1), using the NCDC Local Climatological Data Publications and Environment Canada’s Canadian Climate Normals and assigned to SCF; through inverse distance weighted interpolation, these estimated SCF values are fit to a grid across the study region (Supp. Fig. 5h). The mean and standard deviation of these SCF parameters are 1.11 and 0.44, respectively. Depletion curves indicate how the areal extent of snow cover changes during the melt season. The areal depletion curve, ADC, consists of eleven values and determines the areal extent of snow cover versus bare ground in a region. The following three ADCs are considered:

\[ A2 = [ 0.05, 0.40, 0.61, 0.72, 0.79, 0.85, 0.89, 0.92, 0.95, 0.98, 1.00 ] \]
C2 = [ 0.05, 0.22, 0.35, 0.43, 0.50, 0.55, 0.59, 0.64, 0.70, 0.78, 1.00 ]

D1 = [ 0.05, 0.06, 0.08, 0.10, 0.14, 0.18, 0.22, 0.28, 0.36, 0.53, 1.00 ].

In the four test simulations of SNOW-17, at each of 196 stations, the ADC is selected which produces the greatest agreement with observations in DJF mean snow depth; these optimal ADCs are then interpolated to a grid as an input to SNOW-17.

**Supplemental Figure Captions**

Figure S1. (a) The daily maximum temperature standard deviation (°C) in winter (DJFM) for the stations used in the downscaling. (b) The daily maximum temperature standard deviation (°C) for winter (DJFM) averaged over nine downscaled climate models (DJFM). (c) Same as (a), but for daily minimum temperature. (d) Same as (b), but for daily minimum temperature.

Figure S2. (a) The 99.9th percentile daily precipitation amount (mm) for winter (DJFM) estimated from the stations used for downscaling. (b) The 99.9th percentile daily precipitation amount (mm) for winter (DJFM) averaged over nine downscaled climate models. The 99.9th percentile is estimated directly from the downscaled PDF and so is less subject to sampling errors than the station estimates. (c) Same as (a), but for the 99.99th percentile. (d) Same as (b), but for the 99.99th percentile.

Figure S3. (a) The correlation between daily maximum temperature and precipitation in winter (DJFM) for the stations used in the downscaling. (b) The correlation between daily maximum temperature and precipitation for winter (DJFM) averaged over nine downscaled climate models
(DJFM). (c) Same as (a), but for daily minimum temperature and precipitation. (d) Same as (b), but for daily minimum temperature and precipitation.

Figure S4. Flow chart of the subroutines in SNOW-17, their function, and applied parameters.

Figure S5. SNOW-17 parameter values for (a) PXTEMP (rain-snow temperature index, °C), (b) MFMAX (maximum solar melt factor, mm/°C/6 hours), (c) MFMIN (minimum solar melt factor, mm/°C/6 hours), (d) UADJ (wind function, mm/mb/6 hours), (e) SI (water equivalent for 100% snow cover, mm), (f) TIPM (antecedent temperature index, unitless), (g) DAYGM (average daily ground melt, mm/day), and (h) SCF (snowfall multiplying factor, unitless).

Figure S6. Histogram of snow-rain temperature threshold at 135 stations across the study region for 1980-1999, based on hourly observations of present weather and air temperature from NCDC. The x-axis represents air temperature (°C) and the y-axis represents the number of stations. The vertical dashed line indicates the mean threshold value of 0.98°C.

Figure S7. Scatter plot of observed versus simulated annual snowfall (cm) (based on converting raw GCM output of liquid-equivalent snowfall to simulated snowfall depth using a standard 10:1 ratio) for 196 stations, based on a climatology for 1981-2000. Each set of colored dots represents one of nine GCMs. Among the models, the temporal correlation ranges from 0.78 to 0.86 and the root-mean-square-difference ranges from 44.5 to 106.1 cm.
Supplemental Figure 1. (a) The daily maximum temperature standard deviation (°C) in winter (DJFM) for the stations used in the downscaling. (b) The daily maximum temperature standard deviation (°C) for winter (DJFM) averaged over nine downscaled climate models (DJFM). (c) Same as (a), but for daily daily temperature. (d) Same as (b), but for daily minimum temperature.
Supplemental Figure 2. (a) The 99.9th percentile daily precipitation amount (mm) for winter (DJFM) estimated from the stations used for downscaling. (b) The 99.9th percentile daily precipitation amount (mm) for winter (DJFM) averaged over nine downscaled climate models. The 99.9th percentile is estimated directly from the downscaled PDF and so is less subject to sampling errors than the station estimates. (c) Same as (a), but for the 99.99th percentile. (d) Same as (b), but for the 99.99th percentile.
Supplemental Figure 3. (a) The correlation between daily maximum temperature and precipitation in winter (DJFM) for the stations used in the downscaling. (b) The correlation between daily maximum temperature and precipitation for winter (DJFM) averaged over nine downscaled climate models (DJFM). (c) Same as (a), but for daily minimum temperature and precipitation. (d) Same as (b), but for daily minimum temperature and precipitation.
### Subroutine Function Parameters

<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Function</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX19</td>
<td>Execution control subroutine</td>
<td></td>
</tr>
<tr>
<td>AESC19</td>
<td>Computes areal extent of snow cover using areal depletion curve, based on conditions at start of run.</td>
<td>SI, ADC</td>
</tr>
<tr>
<td>PACK19</td>
<td>Executes operation for one computational time interval. Determines form of precipitation. Corrects precipitation using SCF.</td>
<td>SCF, UADJ, DAGYM, PLWHC, PXTEMP</td>
</tr>
<tr>
<td>MELT19</td>
<td>Computes surface energy exchange at snow-air interface and surface melt for non-rain conditions, using MBASE and melt factor (using MFMAX, MFMIN).</td>
<td>MFMAX, MFMIN, MBASE, NMF, TIPM</td>
</tr>
<tr>
<td>AESC19</td>
<td>Computes areal extent of snow cover based on conditions at the beginning of the time interval, adjusted for the new snowfall.</td>
<td>SI, ADC</td>
</tr>
<tr>
<td>ROUT19</td>
<td>Routes excess water from rain or melt through snow cover as outflow.</td>
<td></td>
</tr>
<tr>
<td>ZERO19</td>
<td>Sets carryover values to zero when no snow exists.</td>
<td></td>
</tr>
<tr>
<td>SNDEPTH19</td>
<td>Computes snow depth for each computational interval.</td>
<td></td>
</tr>
<tr>
<td>SNEW</td>
<td>Computes density and depth of new snowfall.</td>
<td></td>
</tr>
<tr>
<td>SNOWT</td>
<td>Computes temperature of existing snow.</td>
<td></td>
</tr>
<tr>
<td>SNOWPACK</td>
<td>Computes changes in density due to compaction and destructive metamorphism.</td>
<td></td>
</tr>
<tr>
<td>AESC19</td>
<td>Computes areal extent of snow cover based on conditions at the end of the period.</td>
<td>SI, ADC</td>
</tr>
</tbody>
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Supplemental Figure 4. Flow chart of the subroutines in SNOW-17, their function, and applied parameters.
Supp. Fig. 5 SNOW-17 parameter values for (a) PXTEMP (rain-snow temperature index, °C), (b) MFMAX (maximum solar melt factor, mm/°C/6 hours), (c) MFMIN (minimum solar melt factor, mm/°C/6 hours), (d) UADJ (wind function, mm/mb/6 hours), (e) SI (water equivalent for 100% snow cover, mm), (f) TIPM (antecedent temperature index, unitless), (g) DAYGM (average daily ground melt, mm/day), and (h) SCF (snowfall multiplying factor, unitless).
Supp. Fig. 6 Histogram of snow-rain temperature threshold at 135 stations across the study region for 1980-1999, based on hourly observations of present weather and air temperature from NCDC. The x-axis represents air temperature (°C) and the y-axis represents the number of stations. The vertical dashed line indicates the mean threshold value of 0.98°C.
Supp. Fig. 7 Scatter plot of observed versus simulated annual snowfall (cm) (based on converting raw GCM output of liquid-equivalent snowfall to simulated snowfall depth using a standard 10:1 ratio) for 196 stations, based on a climatology for 1981-2000. Each set of colored dots represents one of nine GCMs. Among the models, the temporal correlation ranges from 0.78 to 0.86 and the root-mean-square-difference ranges from 44.5 to 106.1 cm.