Snow Depth and Snow Water Equivalent Data at Stations Included in the GHCN Database

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ABSTRACT

The Global Historical Climatology Network is a worldwide database of daily weather data from over 107,000 surface stations compiled by NOAA's National Centers for Environmental Information. Snow depth is one of five core elements reported. More than 15,000 of these stations also report snow water equivalent (SWE) as the depth of melted snow. We have extracted snow depth and SWE data for the days at stations at which both elements are reported. In this paper, we present statistics of the snow to liquid ratio (SLR) and underlying snow depth and SWE data to a) identify issues with the data and b) characterize the snow pack using SLR quantiles. SLR can be an indicator of problems with the snow depth data, the SWE data, or both. Some ratios occur more frequently than would be expected statistically or physically. This may be due to measurement errors, recording or transcription errors, inconsistent units, or rule-of-thumb estimates reported as observations. We remove the values flagged by GHCN as questionable and compute SLRs for the remaining data, compiled into the Sturm *et al*. (1995) snow classes. Quantiles of SLR in these snow classes, binned by snow depth and day of year, characterize the median density and density variation of the snow on the ground.

Keywords: GHCN, snow depth, snow water equivalent, snow liquid ratio, snow class

INTRODUCTION

The Global Historical Climatology Network (GHCN) is a worldwide database of daily weather data from over 107,000 surface stations compiled by NOAA's National Centers for Environmental Information (Menne *et al*., 2012a,b). The depth of snow on the ground is one of five core elements reported. More than 15,000 of these stations also report the water equivalent of the snow on the ground, as the depth of the melted snow. Our focus is the ratio of the snow depth to the snow water equivalent, the snow-to-liquid-equivalent ratio (SLR) used in Baxter *et al*. (2005) and Alcott and Steenburgh (2010) to describe the ratio of new snowfall to the depth of the melted water equivalent. Huntington (2005) calculates monthly average SLRs for November through April in New England. Meyer *et al*. (2012) use the SLR climatology for December, January and February to investigate discrepancies between SWE and accumulated precipitation.

In this paper, we use SLR as the ratio of the reported depths of snow on the ground and water equivalent snow on the ground. In a study of snow loads in Alaska (Jones and Daly, 2016) we found that daily SLR reported at many airport weather stations in Alaska is exactly 10 relatively frequently, which we attributed to the reported SWE being calculated from the snow depth rather than measured. In this paper, we examine the distribution of SLR for the networks providing snow data

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to GHCN, using all the available pairs of daily measurements in the database. We also compile the data into snow classes and use SLR quantiles to determine typical values and the range of values. A comparison of the GHCN SLR quantiles with the SLR determined from the Sturm *et al*. (2010) (S2010 in the following) bulk densities is also presented.

In the station files in the GHCN database, the snow depth and SWE elements are identified as SNWD and WESD, respectively. SNWD is reported in whole millimeters and WESD in 0.1-mm increments. Simultaneous pairs of these elements have been reported at 13,772 stations in the database at least once. Most of these stations are in one of four networks. In Section 2, we provide information on each these networks. Cumulative distributions and probabilities for the network SLRs are discussed in Section 3. In Section 4, we present and discuss the snow class SLR statistics, using the Sturm *et al*. (1995) snow classes.

NETWORKS

Station names in the GHCN database begin with the country code followed by a one-character network code. The networks with SWE and snow depth data have the following network codes (*ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/readme.txt*):

- 0: unspecified (one station in Canada)
- 1: Community Collaborative Rain, Hail, and Snow (CoCoRaHS) (11,117 stations in the US and 373 in Canada)
- C: U.S. Cooperative Network (COOP) (942 stations)
- M: World Meteorological Organization (one station in Antarctica)
- S: U.S. Natural Resources Conservation Service SNOwpack TELemtry (SNOTEL) (820 stations)
- W: Weather Bureau Army Navy (WBAN) (435 stations in the US and 83 stations in Austria, Antarctica, Canada, France, Greenland, Iceland, Italy, Japan, North Korea, South Korea, or United Kingdom)

The station in Canada with an unspecified network is at Stephenville Airport in Newfoundland and has depth and SWE measurements between 1954 and 1958. The station in Antarctica in the WMO network is at McMurdo Sound NAF (Naval Air Facility). Snow depth and SWE measurements were made there between 1958 and 1964. Based on those station characteristics we group both stations with the WBAN network for this paper.

We describe the characteristics of the snow reports from the CoCoRaHS, COOP, SNOTEL, and WBAN networks in the following.

CoCoRaHS

The Community Collaborative Rain, Hail, and Snow Network was started at Colorado State University's Colorado Climate Center in 1998. The network is sponsored by NOAA and the National Science Foundation. Observers are volunteers. The network spread to other states beginning in 2003 and as of 2013 included locations in all 50 states and the District of Columbia (*https://www.cocorahs.org/Media/Docs/StateAdmissiontotheCoCorahsUnion2018.pdf*). Locations in Canada were added beginning in 2012. Observers purchase the CoCoRaHS 4-inch-diameter high-capacity manual rain gauge and measure daily precipitation at 7 am. The CoCoRaHS web site has training slide shows on measuring snow depth and snow water equivalent (*https://www.cocorahs.org/Content.aspx?page=training_slideshows*). At the observation time, observers use a snow ruler to measure the snow depth on the ground and record the average depth to the nearest 0.5 inch. If there is snow on more than half of the area, the snow depth is reported as the average of the bare and snow-covered depths. If more than half of the ground is bare, Trace is reported. Reporting the water equivalent of total snow on the ground is optional. Observers who choose to measure this parameter are asked to make that measurement once a week, with Monday suggested as a good day. Observers are instructed to take a snow sample from an area with the average snow depth. They use their 4-inch rain gauge to collect the snow core. In deeper and/or denser snow, instructions for making and using a core tube, made from a section of 2-inch ABS black plastic drain pipe, with teeth filed in one end and a cap for the other end, are provided. Observers melt the snow core and measure the depth of the water to the nearest 0.01 inch using the inner tube of the precipitation gauge. Instructions are also provided for measuring the snow water equivalent by weight using a digital balance, such as a commercial nutrition scale. The document *https://www.cocorahs.org/Media/Docs/CoCoRaHS_QA_QC_Nov_2018.pdf* describes quality control of the data. The automated checks on the web-based data entry forms require that reported SWE is not more than 90% of the snow depth. Manual QC includes creating national maps and checking to identify very high values of total snow depth that seem erroneous. They find that most errors are reporting rather than measuring problems, including misplaced decimal points.

COOP

In the National Weather Service's Cooperative Observers Program, volunteers or contractors in the United States make daily observations (*https://www.weather.gov/coop/Overview*). At COOP sites that are collocated with standard observing stations, the COOP data is documented independently. The equipment at COOP sites must meet NWS standards and may be owned by the NWS, the observer, or some other entity. COOP observers making snow measurements are referred to NWS (2014) for the procedures for measuring the depth of snow on the ground and the snow water equivalent. Snow depth is measured with a measuring stick, sometimes by averaging a number of depths within 300 ft of the official observing location, excluding paved areas or those disturbed by human activity. At locations where snow tends to be deep, snow stakes, ideally located on level ground in an area without trees, buildings, and other obstructions may be used instead. Observers are to use their good judgement in determining the average snow depth in an area where it varies markedly. If less than 50% of the ground is covered by snow, Trace should be reported. Where drifting has occurred, the observer averages measurements taken in areas least affected by drifting. Depths are reported to the nearest whole inch, rounding up at 0.5 inch and greater. For measuring the water content of the snow, using the outer cylinder of a 4-inch rain gauge to get a snow core is suggested. The water equivalent is measured either by allowing the snow in the cylinder to melt, or melting the snow by adding a measured amount of warm water, which is subtracted after the liquid measurement is made. In either case, the liquid that results is poured through the funnel into the inner measuring tube of the rain gauge. The water content is to be reported "…in accordance with the directions provided by the observing program…". In NWS (2017) in Appendix B COOP Observer - Observation Instructions, *Section 2 Precipitation* says that snow depths are recorded in whole inches and the water content of the snow on the ground is reported in hundredths of an inch. In *Section 7 River Stage Observations*, observers who are instructed to measure the water content of snow or ice are to report to the nearest 0.1 inch.

SNOTEL

The SNOTEL network currently consists of 867 automated sites at remote high elevations in the western U.S. states including Alaska. The sites are powered by batteries charged by solar cells and are intended to operate unattended without maintenance for at least a year. Measurements are made hourly and stored on a data logger in the equipment shelter at the site. Data transmission from the sites to the National Water and Climate Center (NWCC) is by telemetry. The site instrumentation includes a sonic snow depth sensor and a snow pillow instrumented with a pressure transducer. The snow depth sensor has 0.5-inch resolution and an accuracy of ± 2 inches or 0.4% of the distance to the snow surface. The snow water equivalent is calculated from the snow pillow measurements with a 0.1-inch resolution up to 250 inches of water and an accuracy of ± 4% (*https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=27630.wba*).

WBAN

NOAA (2017) requires snow depth reports at designated stations at 0000, 0600, 1200, and 1800 UTC, whenever there is more than a trace of snow on the ground. Snow depth is reported using three digits in whole inches in group 4 after RMK (remark) in a METAR (Meteorological Terminal

Aviation Routine Weather Report). For example, 5 inches of snow is coded as 4/005. The water equivalent of snow on the ground is reported at designated stations at 1800 UTC if the average snow depth is at least 2 inches. The value is recorded to 0.1 inch using three digits beginning with 933 after RMK. For example, a SWE of 1.2 inches is coded as 933012. SWE is never estimated, assuming, for example, a 10 to 1 ratio or temperature/snow water equivalency tables.

Comparison

Differences in the locations of these stations and in the way the snow measurements are made result in differences in the distribution of SLR for these networks. Here we provide general information about the station data. In plots of this network data, we identify CoCORaHS by nw1, COOP by nwC, SNOTEL by nwS and WBAN by nwW.

Figure 1 shows the distribution of the elevation of stations in each of the networks. The SNOTEL stations are the highest, with a median elevation of 2366 m. Most of the CoCoRAHS stations are at relatively low elevations (median=289 m), but 24% of stations are at elevations greater than 1000 m. The COOP stations are all at low elevations, with a median of 281 m. The WBAN stations also tend to be at low elevations, with a median at 199 m, but 12% are above 1000 m.

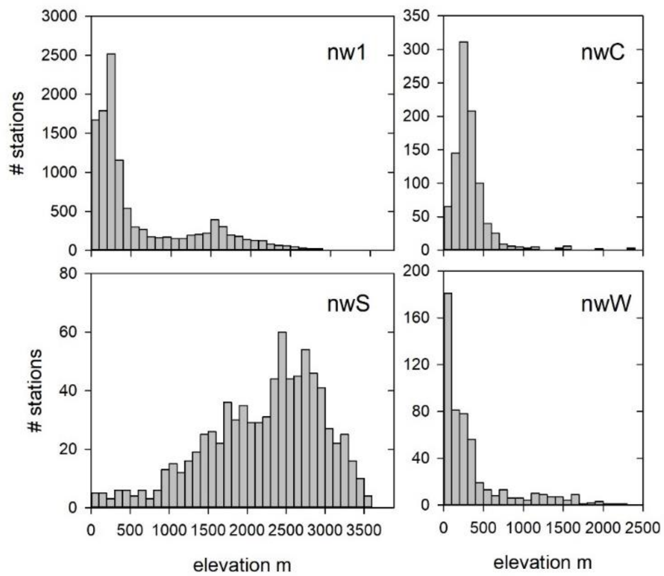

Figure 1. Station elevation distribution for each of the networks (nw1= CoCoRaHS, nwC=COOP, nwS=SNOTEL, nwW=WBAN).

Figures 2 and 3 show the number of snow-SWE pairs in each year and month, respectively, for each network. Most of the measurements in the CoCoRaHS network and the vast majority of those in the COOP network are since 2005. Snow depth and SWE pairs began being reported in the SNOTEL network in the early 1980s, with most reports after 1995. In contrast, the WBAN report counts began decreasing in the 1990s, perhaps in conjunction with the change from human observers at most of the first-order weather stations in the United States to ASOS (Automatic Service Observing System). After three years with no snow reports at all, a few WBAN stations resumed reporting snow data in 2009. The differences between networks in the distribution of the number of reports in each month (Figure 3) is consistent with the higher elevations of the SNOTEL stations, with many reports in May and June.

Frequency of reporting may vary by day of week (Figure 4). CoCoRaHS observers who measure SWE are asked to do that once a week, preferably on Monday. The reports on other days may indicate observers who choose a different day for their weekly reports, or observers who measure more frequently. COOP observers also tend to make their observations on Mondays. SNOTEL and WBAN observations are daily.

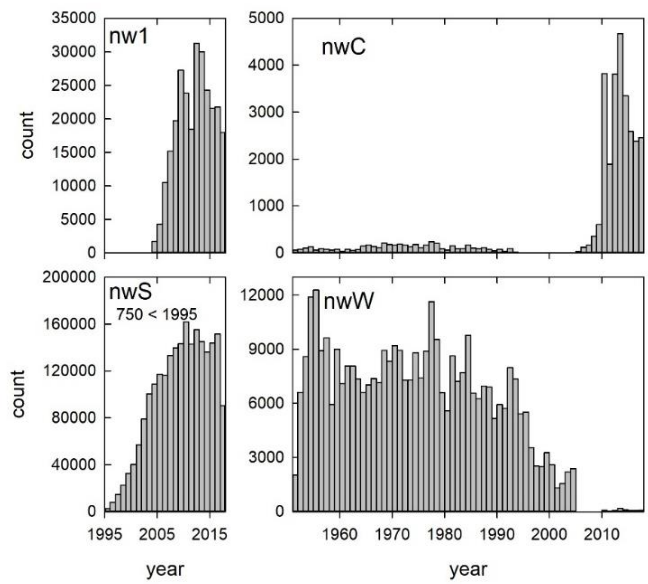

Figure 2. Number of snow depth-SWE data pairs by year for each network. In the SNOTEL network, 750 data pairs between 1983 and 1994 are not shown.

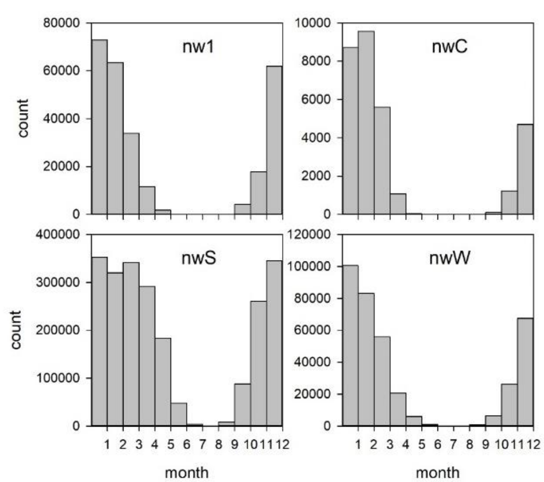

Figure 3. Number of snow depth-SWE pairs by month for each network.

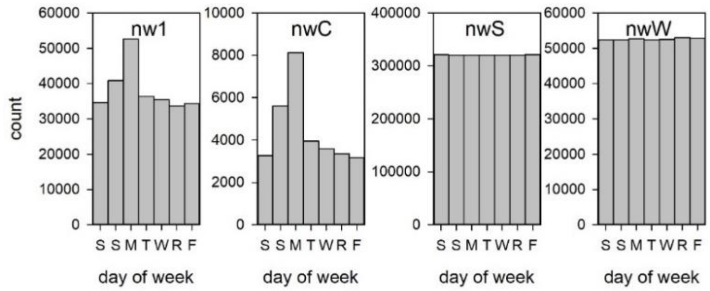

Figure 4. Number of snow depth-SWE pairs by day of week for each network. Observers in the CoCoRaHS network are asked to measure SWE once a week.

Figures 5 and 6 show the distributions of snow depth and SWE, respectively, for these networks. The SNOTEL network is clearly different from the others, with frequent occurrences of large snow depths and large SWE. The CoCoRaHS stations have somewhat smaller depth and SWE values than the stations in the COOP and WBAN networks. We can characterize the snow in these networks by the 10th and 90th percentile snow depth and SWE values, shown in Table 1. The deep, dense snow at the SNOTEL stations stands out.

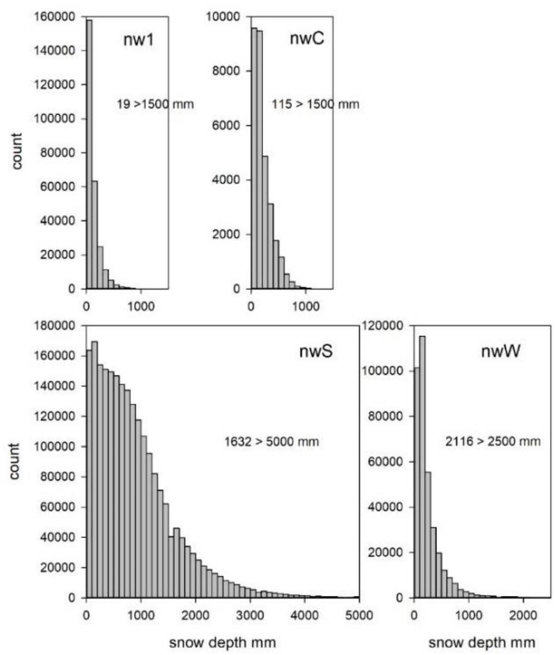

Figure 5. Snow depth frequencies for each network.

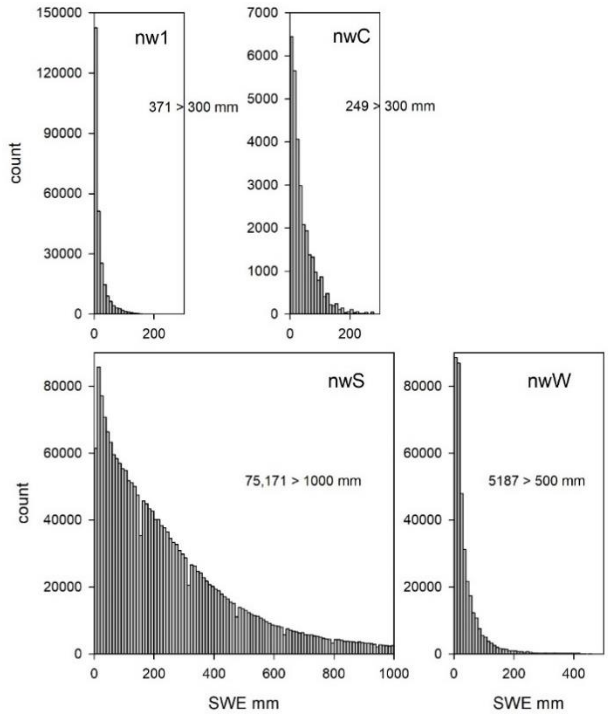

Figure 6. SWE frequencies for each network.

Table 1. 10th and 90th percentile snow depth and SWE for each of the networks.

Network	Snow depth (mm)		SWE (mm)	
	10th%	90th%	10th%	90th%
CoCoRaHS	13	264	1.0	47.2
COOP	46	419	4.8	101.6
SNOTEL	102	1829	27.9	645.2
WBAN	51	559	5.1	101.6

The precision of the snow depth and SWE reports from the stations in each network can be shown by the probabilities of each 1 mm increment in snow depth and each 0.1-mm increment in SWE. These probabilities are plotted in Figures 7 and 8, respectively, for snow depths up to 15 inches and SWE up to 1.5 inches. Figure 7 shows that snow depths are sometimes reported to 0.1 inch even though observers are asked to report in 0.5- or 1-inch increments. The only network that never violates their 1-inch rule is SNOTEL. Observers in both the CoCoRaHS and COOP networks are asked to report SWE in 0.01-inch increments. While CoCoRaHS observers do that, most COOP observations are in 0.1-inch increments (Figure 8). In contrast, many WBAN reports are in 0.01-inch increments, even though the required METAR report only allows for 0.1-inch increments. Those reports must predate this METAR format. We list the snow depth and SWE increments commonly used in reports for each network in Table 2. The snow to liquid ratio SLR is the ratio of these simultaneous reports of snow depth and SWE at a station. In the next section, we look at the distribution of SLR values for these networks.

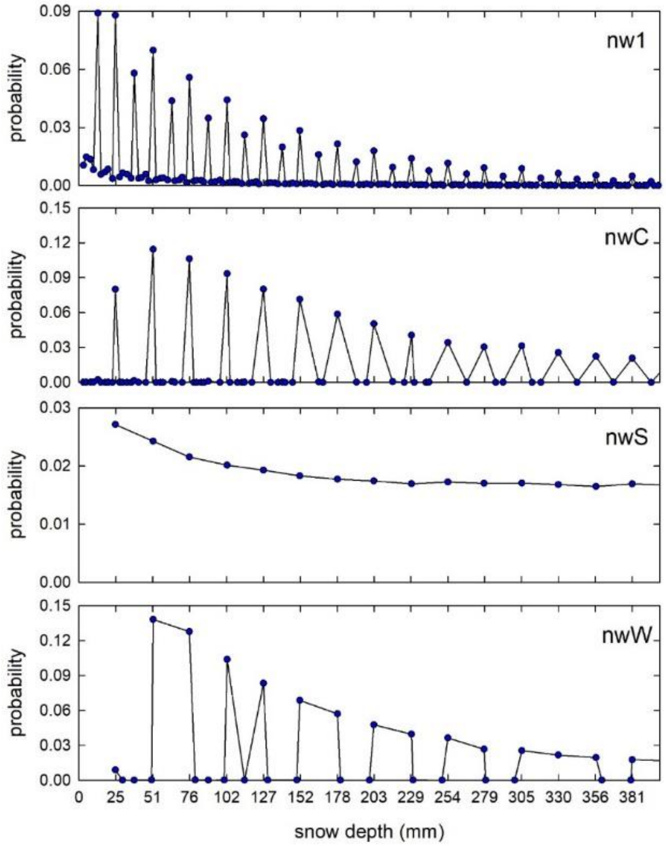

Figure 7. Probability of occurrence of reported snow depth in 1-mm increments for each network. Ticks along the x-axis are in 1-inch increments. Snow depth are reported in whole inches most of the time, except for the CoCoRaHS network where half-inch increments are commonly used.

Table 2. Typical snow depth and SWE report increments

Network	Snow depth (in.)	SWE (in.)
CoCoRaHS	0.5	0.01
COOP	1	0.1
SNOTEL	1	0.1
WBAN	1	0.1

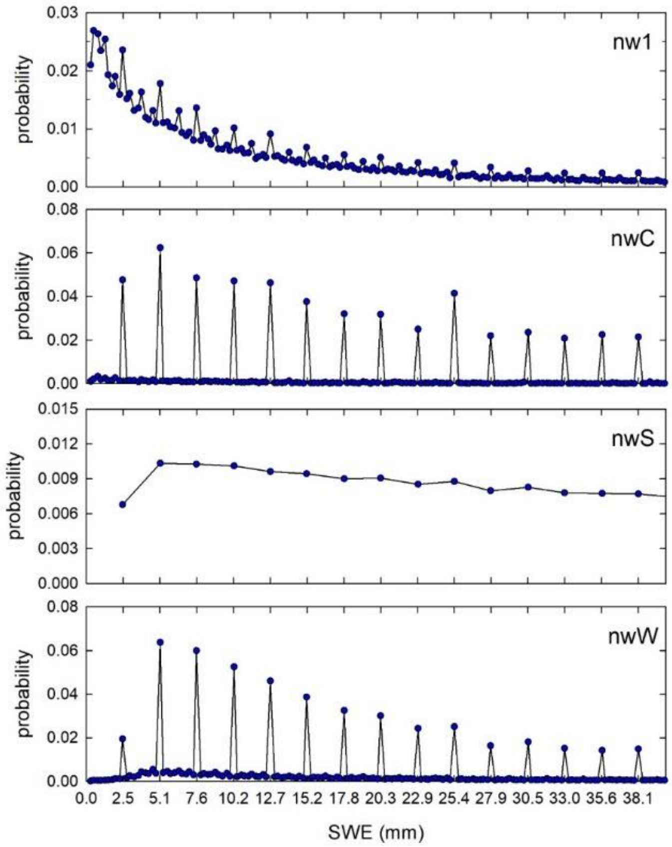

Figure 8. Probability of occurrence of SWE in 0.1-mm increments for each network. Ticks along the x-axis are at 0.1-inch increments. SWE is reported in 0.1-inch increments most of the time, except for the CoCoRaHS network where 0.01-inch increments are commonly used.

SNOW TO LIQUID RATIO

Cumulative distribution

For each snow depth-SWE pair, we calculated SLR and, for each network, ordered the N SLR from smallest to largest and generated the cumulative distribution of SLR (Figure 9) by assigning the probability of non-exceedance to the ordered SLR beginning with $1/(N+1)$. The physical lower bound for SLR is 1.09, which would only occur if the snow were bubble-free ice with a density of 0.92 g cm^{-3}. It is likely that many of the snow depth-SWE pairs that result in SLRs slightly larger than 1.09 are also erroneous. Values smaller than 1.09 occur most frequently in the COOP network In each network, there is a significant fraction of SLR exactly equal to 10, indicated by the length of the vertical line along the gridline at 10. The occurrence rates of SLR < 1.09 and SLR = 10 for all four networks are shown in Table 3.

Table 3. Occurrence rates of SLR anomalies by network. SLR < 1.09 (first column) is a physical anomaly. Too frequent occurrences of SLR exactly equal to 10 is a statistical anomaly.

Network	SLR < 1.09	SLR = 10	Synthetic SLR = 10
CoCoRaHS	1.1%	5.6%	1.0%
COOP	6.8%	11.2%	5.2%
SNOTEL	0.3%	1.4%	0.9%
WBAN	0.3%	16.9%	5.3%

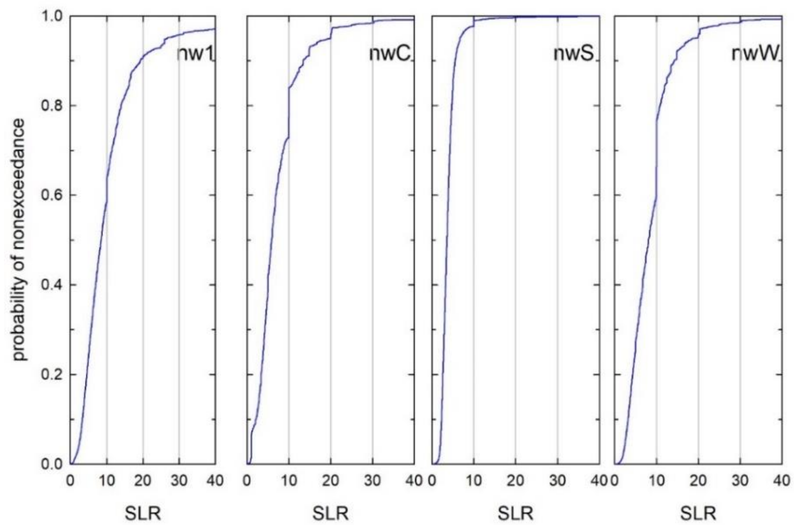

Figure 9. Probability of exceedance plots for SLR for each of the GHCN network with snow depth and SWE data. A long vertical line at SLR = 10 may indicate that the reported SWE is frequently calculated from the snow depth by dividing by 10, rather than measured.

Small SLR

The frequency of SLR < 1.09 varies by year. It is relatively high from 1983-1993 in the SNOTEL network, when there were only 504 reports altogether. During those years, the SNOTEL QC effort was apparently spinning up, as there are relatively few small SLR subsequently. In the COOP and WBAN networks, the frequency of small SLRs is relatively high from 2011 to the present. Those years are characterized by a dramatic increase in simultaneous COOP reports of snow depth and SWE and an increase in WBAN reports following three years of no snow depth-SWE reports. At the WBAN stations, this change may be associated with replacing human observers by ASOS for most weather elements and then ultimately restarting snow measurements at some stations. The current QC program at COOP and WBAN stations is apparently not catching these low SLR discrepancies as well as it did in the past. These anomalous SLRs may result from measurement errors or from misplaced decimal points or missing or extra leading zeros in recording or transcribing the data.

If snow depth reports are too low by a factor of ten and/or SWE reports are too high by a factor of ten, associated with recording or transcription errors, we would expect many of these reports to be outliers. Table 4 lists the fractions of the snow and SWE values resulting in SLR < 1.09 that are smaller than the 10^{th}% values or greater than the 90^{th}% values for each network. Note that in the SNOTEL network small SLR values are typically associated with very small snow depths. In the other three networks, very small snow depths and very large SWE are about equally likely. By careful examination of the snow depth and SWE time series at a station before and after these anomalous SLRs, one might be able to correct many of these outliers by moving the decimal point. That is beyond the scope of this paper.

Table 4. Fraction of the snow depth and SWE values resulting in SLR < 1.09 that are below the 10^{th} and above the 90^{th} % values

Network	Snow depth		SWE	
	<10^{th}%	>90^{th}%	<10^{th}%	>90^{th}%
CoCoRaHS	47%	2%	0	38%
COOP	24%	4%	0	47%
SNOTEL	77%	0	16%	5%
WBAN	42%	1%	0	48%

SLR = 10

With snow depth in whole mm and SWE in 10^{th}s of mm, SLR values of 10.000 occur only when the snow depth is exactly 10 times SWE up to snow depths of 20000 mm (20 m). That is, there are no values, like 10.0001 or 9.9996, that would round to 10.000. The largest snow depth of 15240 mm (WBAN) in our compilation is less than 20000, so SLR = 10.000 occurs only when the snow depth is exactly 10 times SWE. We compared the occurrence rates in Table 3 with expected occurrence rates calculated for synthetic distributions of snow depth and SWE obtained by fitting to their cumulative distributions between the 10^{th}% and 90^{th}% values (Table 1). That distribution provides the relative probabilities for the increments in Table 2. We then calculated SLR for all snow depth and SWE values in that range weighted by their probability. The expected rates for the four networks are in the third column of Table 3. The actual occurrence rates for exact 10 SLRs is substantially higher than these expected rates in the WBAN network, and, to a lesser extent, the COOP and CoCoRaHS networks.

Quality Assurance

The GHCN database includes a quality assurance flag for each snow depth and SWE report. Overall, 0.7% of the snow depth-SWE pairs fail the QA check, with the fraction varying from 0.3% for the WBAN network to 0.7% for the SNOTEL network. Snow depth QA failures are ten times more frequent than SWE failures, with the three most common failure reasons being 1) gap check, 2) bounds check, and 3) internal consistency check. The most common reason for a SWE report to fail the QA check is “failed temporal consistency”. There is no indication the QA checks include a comparison of the snow depth and SWE measurements: fewer than 2% of the QA failures would result in SLR<1.09 and only 3% of the failures would produce SWE = 10.000. The most common reason a record with SLR = 10.000 fails is “failed streak/frequency check”. Those records are almost all from Point Barrow, Alaska, when 6 inches of snow was reported every day from 19 January to 25 April 1974 and 4 inches was reported from 20 December 1975 to 4 May 1976.

SNOW CLASS AND SLR

We compiled the snow-SWE pairs into their Sturm *et al*. (1995) snow class, using nl_sclass (*https://arcticdata.io/catalog/view/doi:10.5065/D69G5JX5*), which has 25 km rasters. Of the 13,772 GHCN stations with simultaneous snow depth and SWE reports, 641 are in the nl_sclass Water class because of the rough definition of the coastline by the 25 km rasters. We assigned those stations to the snow class of the closest land raster, most of them to Ephemeral (310) or Maritime (289). Note that other GHCN stations may also not be in to the correct snow class because of the rough boundary definition. This problem may be most pronounced for the Alpine region because of its large perimeter to area ratio, resulting in some stations that should be designated as Alpine falling in the surrounding Prairie rasters. Table 5 shows the snow classes with the total number of GHCN snow depth-SWE reports without a QA flag and the fraction of reports in that snow class from each network. The snow class with the most reports is Prairie, followed by Alpine and Maritime. The Taiga snow class has the fewest cases. The SNOTEL network is the source of the majority of cases in every snow class except Tundra. The majority of the Tundra data is from WBAN and there is no contribution from COOP. Figure 10 shows the distribution of stations, identified by network, for the North American extent of each snow class.

We examined the statistics of SLR for this GHCN data set for each snow class to determine typical snow pack characteristics and quantify the variation. We also compare the GHCN SLR quantiles to SLR from the S2010 fitted bulk snow density based on day of year *DOY* and snow depth *snd* [cm]:

$$\rho_b[\mathrm{g\ cm^{-3}}] = (\rho_{max} - \rho_0)(1 - e^{-k_1 snd - k_2 DOY}) + \rho_0 \qquad (1)$$

Values for parameters ρ_{max}, ρ_0, k_1, and k_2 depend on the snow class and are listed in Table 6 (S2010). There are no parameter values for the Ephemeral snow class.

Table 5. Contribution of the four networks to each of the snow classes

Snow class	Tundra	Taiga	Maritime	Ephemeral	Prairie	Alpine
# cases	61,027	36,427	772,633	115,262	1,003,883	872,505
Network						
CoCoRaHS	0.1%	0.7%	15.2%	25.8%	8.3%	4.0%
COOP	0.0%	2.4%	2.0%	1.3%	0.8%	0.6%
SNOTEL	7.7%	57.5%	62.2%	62.4%	81.7%	92.7%
WBAN	92.2%	39.4%	20.7%	10.5%	9.2%	2.7%

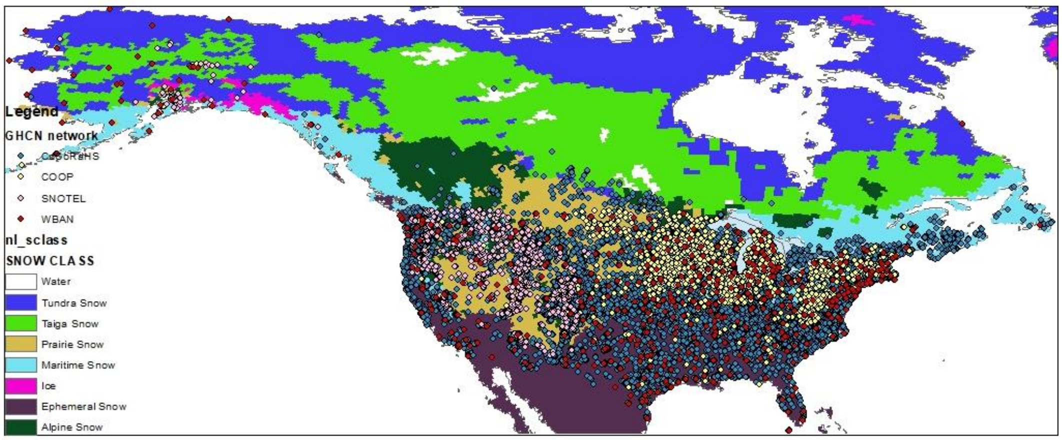

Figure 10. Stations in the GHCN database, identified by network, with snow depth and SWE data, mapped on the Sturm *et al*. (1995) snow classes in North America

Table 6. Parameter values for (1) for each snow class.

Snow Class	ρ_{max}	ρ_0	k_1	k_2
Tundra	0.3630	0.2425	0.0029	0.0049
Taiga	0.2170	0.2170	0	0
Maritime	0.5979	0.2578	0.0010	0.0038
Prairie	0.5940	0.2332	0.0016	0.0031
Alpine	0.5975	0.2237	0.0012	0.0038

To compute the GHCN SLR statistics and compare to S2010, we separated the data into 1-inch increments (0.025 m) of snow depth and 2-day increments of *DOY*. This two-day grouping somewhat ameliorates the less-than-daily measurements of SWE at CoCoRaHS and COOP stations, making it more likely that the bins have enough data to calculate useful quantiles. We assigned data to a day-depth bin by rounding the measured depth to the nearest inch and assigning even Julian days to the next-earlier Julian day. This conveniently moves leap day (366) to 365. As used in the S2010 model, *DOY* is calculated by subtracting 366 from Julian day 274 (1 October) or greater. Thus it begins at *DOY*= -92 and then continues from -1 to 1 (1 January) and up to 181 (30 June). In each day-depth bin of each snow class, we counted the number of cases. If there are at least ten, we sorted from smallest to largest SLR and determined the 10th, 50th (median), and 90th percentile values.

We plotted those SLR quantiles for a) snow depths up to 3 m at eight *DOY* slices in ~25 day increments from -49 to 125 and b) *DOY* from -92 to 181 at eight snow depth slices ranging from 0.13 to 1.52 m (5, 10, 15, 20, 30, 40, 50, and 60 inches). SLR is plotted on a log scale so that if a 90th% SLR is say, twice, the median and the 10th% SLR for that bin is half the median, the distance to the median in the plot is the same for both. The twice and half SLR ratios in this example correspond to half and twice density ratios.

SLR quantiles and the S2010 fit from (1) for each snow class are in Figures 11a through f, in the same order as in Table 6. Note that there is no S2010 fit for the Ephemeral snow class in Figure 11d. For the GHCN stations, the Tundra and Taiga snow classes (Fig 11a and b) are similar and the Maritime, Prairie, and Alpine classes (Fig 11c, e, and f) are similar.

In the Tundra and Taiga snow classes, snow depths at GHCN stations are shallow, similar to the limited depth range for the data in the S2010 training dataset. The median number of cases in the *DOY*-snow depth bins is 21 for Tundra and 16 for Taiga. The 10^{th}% GHCN SLR tends to be near the S2010 fit for both snow classes, indicating that most of the reported values result in higher SLRs (lower snow densities) than (1) provides. Many of the median Tundra SLRs are 10, so it is likely that SWE was often calculated rather than measured at those WBAN stations.

The GHCN data in the Ephemeral snow class represent somewhat deeper snow than the data in the Tundra and Taiga classes (Fig 11d). That occurs even though the Ephemeral snow season is shorter than for those snow classes, starting later and ending earlier. The median number of cases in the *DOY*-snow depth bins for this class is 19. As the snow depth increases, the 10^{th} and 90^{th} percentile Ephemeral SLRs move toward the median, indicating less variation in the density of deeper snow.

GHCN data in the Maritime, Prairie, and Alpine snow classes represent relatively long snow seasons and deep snow. The median number of cases in each *DOY*-snow depth bin (up to 3 m) is 35, 79, and 66, respectively. For snow depths greater than about 0.5 m (Prairie and Alpine) or 0.75 m (Maritime) the 10^{th} and 90^{th}% SLRs are close to the median values. As the snow gets shallower, the spread between these quantiles increases, indicating increasing variation in snow density. For these three snow classes, all of the SLR quantiles for shallow snow tend to increase in the middle of the snow season and then decrease again at the end of the season, consistent with regularly occurring snowstorms adding relatively low-density snow to the snowpack. This midwinter SLR increase (density decrease) is apparent even for deep snow, particularly for the Alpine snow class and, to a lesser extent, for Prairie snow.

For snow depths over 0.75 m, the GHCN Maritime median SLR (Fig 11c) appears to agree well with S2010. Over that depth range, the median of the 90^{th}% to 50^{th}% ratio is 1.22 and the median of the 10^{th}% to 50^{th}% ratio is 0.81. The ratio of the GHCN 50^{th}% SLR to S2010 is 1.03. Expressed in terms of snow density, 80% of the samples in this class from snow depths of at least 0.75 m have densities within about 20% of the median, and that median is about 97% of the S2010 density fit. These statistics are compiled in Table 7 for the Maritime, Prairie, and Alpine snow classes—the classes that have deep snow at stations in the both the GHCN database and the S2010 test dataset. The median ratios of the 10^{th} and 90^{th}% SLRs to the 50^{th}% value vary only slightly among these snow classes. The median ratios of the GHCN 50^{th}% SLR to the S2010 fit for the Prairie and Alpine snow classes, however, are significantly higher than for the Maritime data, corresponding to snow densities less than 90% of the S2010 density.

For the shallower snow in the Tundra, Taiga, and Ephemeral classes, the 90^{th}% and 10^{th}% SLRs are significantly different from the 50^{th}% SLRs. There is no trend of these quantiles with *DOY* or depth (Fig 11a, b, d) except for a slight trend with *DOY* for Ephemeral snow. Therefore, in Table 8 we show the medians of all three quantiles. The frequent occurrence of SLR = 10 in the Tundra snow class, likely related to the large fraction of cases from WBAN stations, has a significant effect on the calculated quantiles; the 50th% SLR for the snow depth and *DOY* bins is often 10. Therefore, the Tundra SLRs in Table 8 probably do not reflect reality. There is, however, a much smaller contribution of WBAN station data to the Taiga class, and smaller still to the Ephemeral

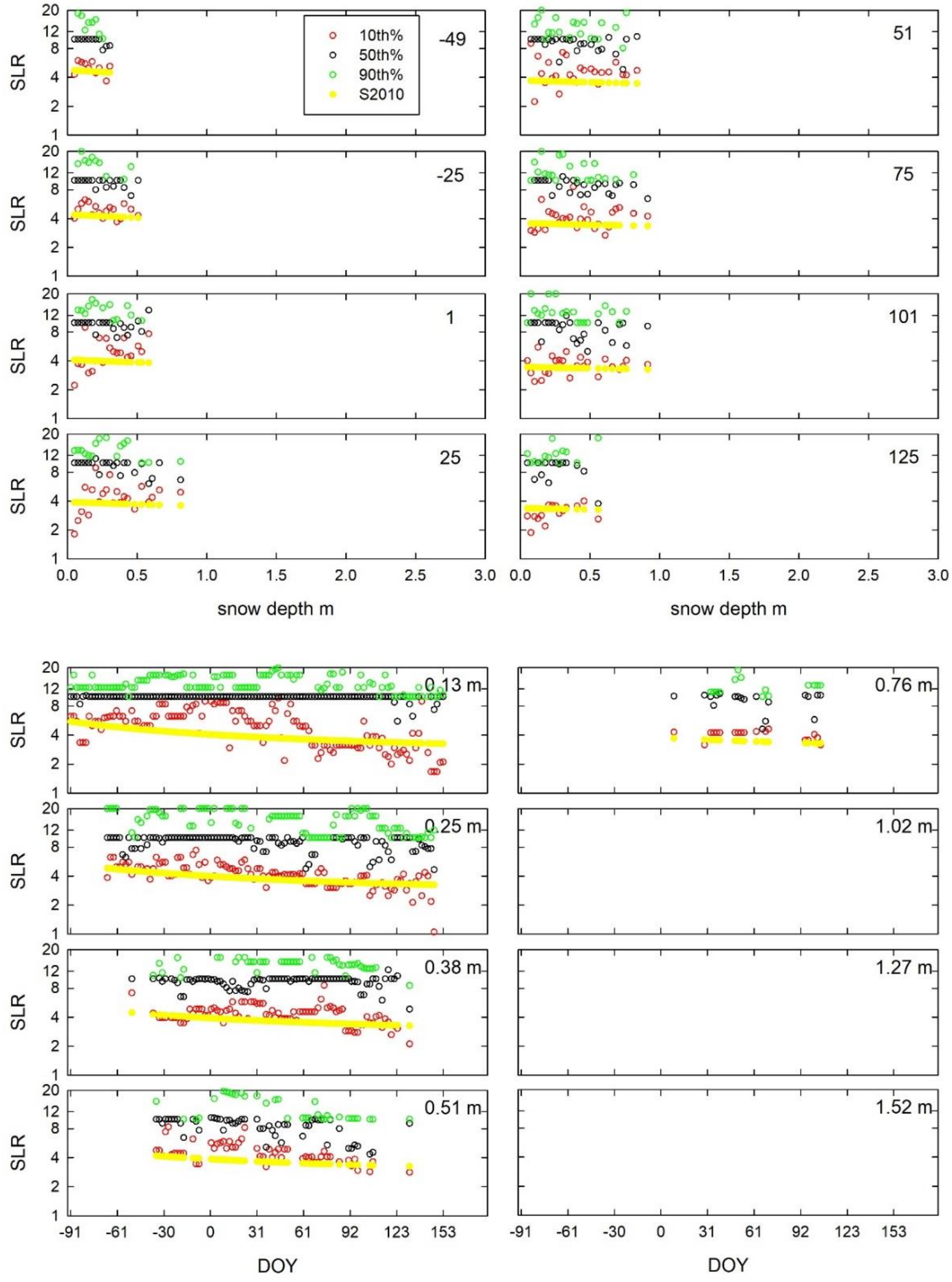

Figure 11a. SLR quantiles for GHCN data in the Tundra snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. SLRs calculated from the S2010 fit are also shown.

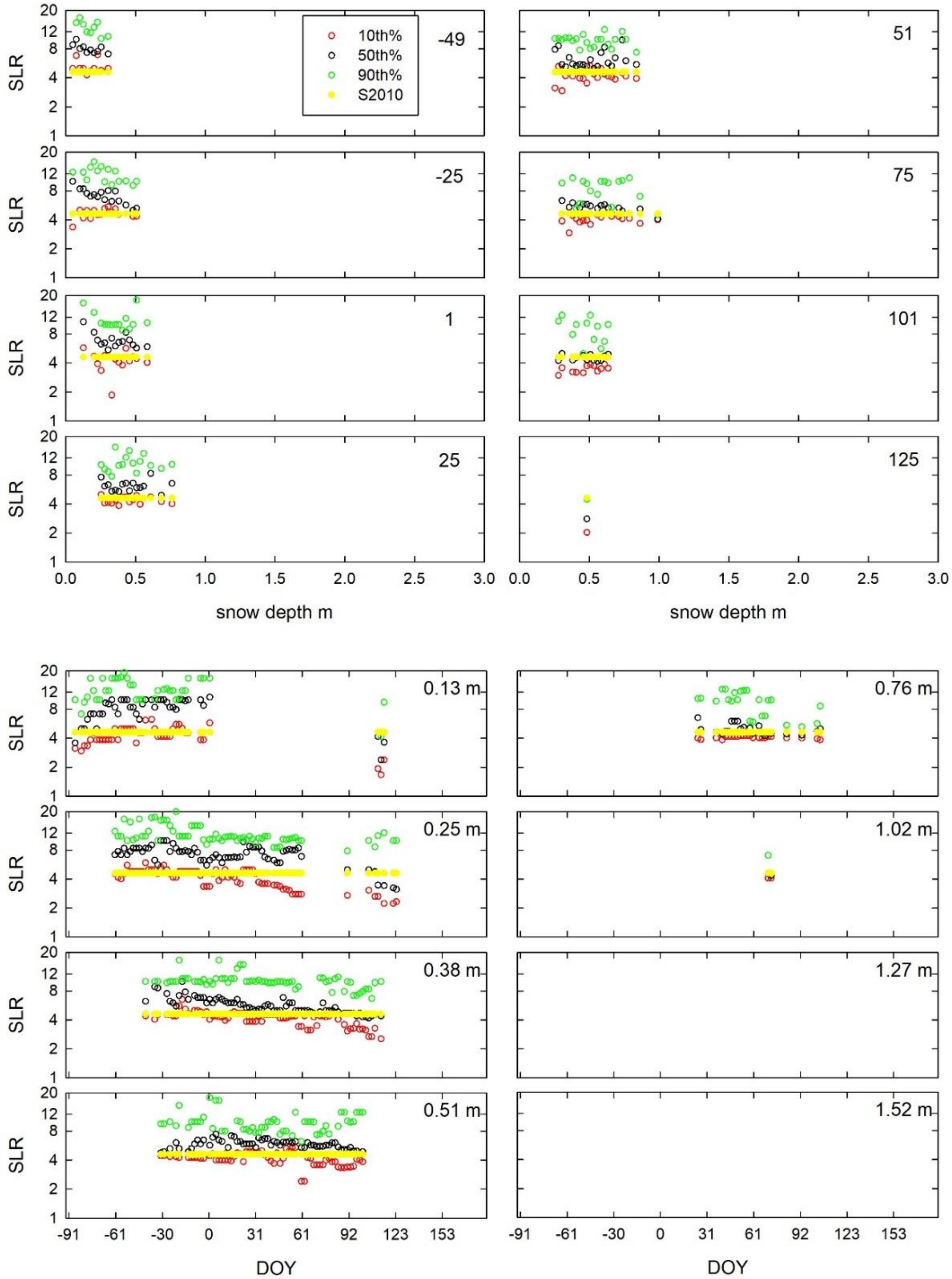

Figure 11b. SLR quantiles for GHCN data in the Taiga snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. SLRs calculated from the S2010 fit are also shown.

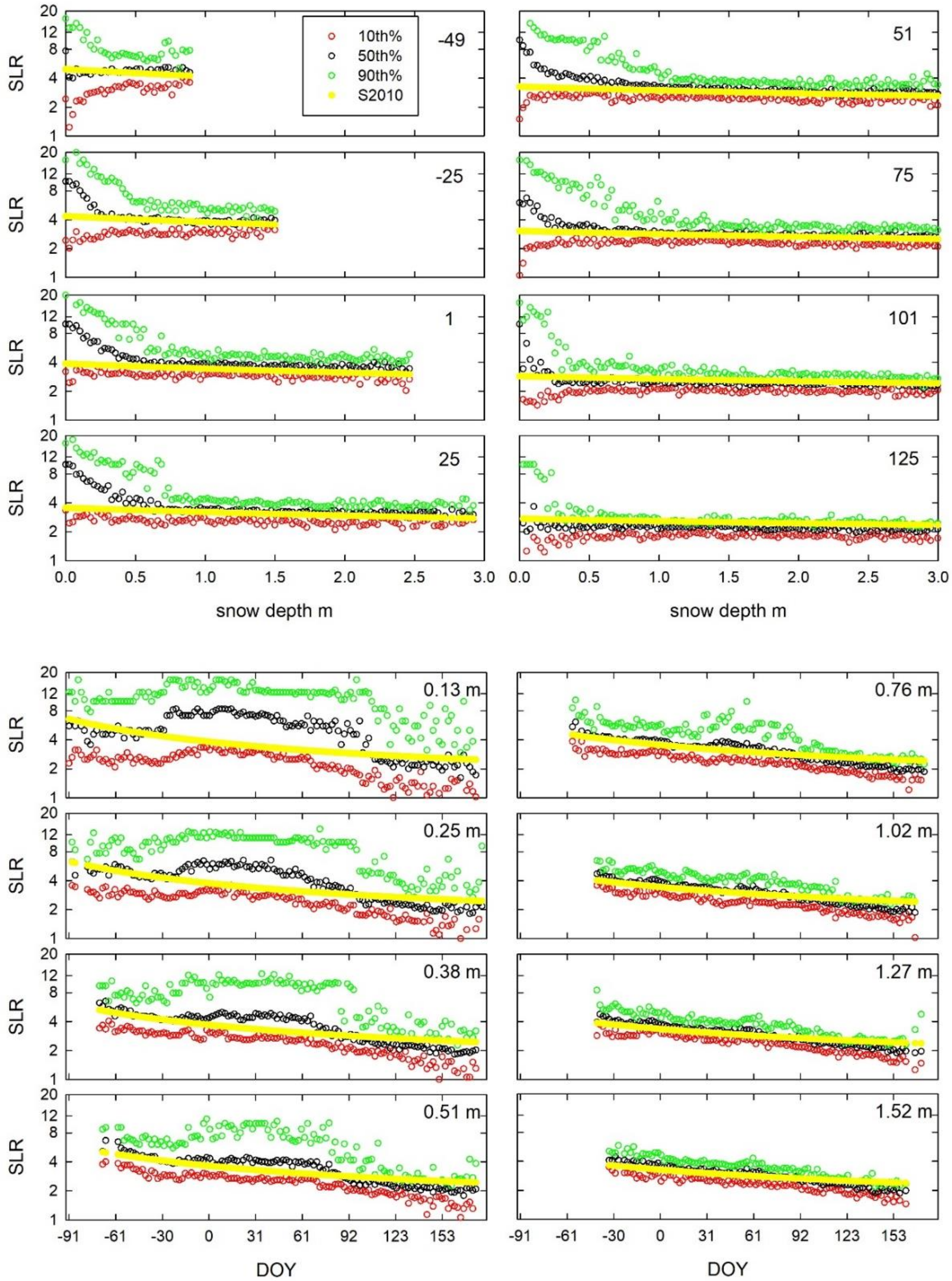

Figure 11c. SLR quantiles for GHCN data in the Maritime snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. SLRs calculated from the S2010 fit are also shown.

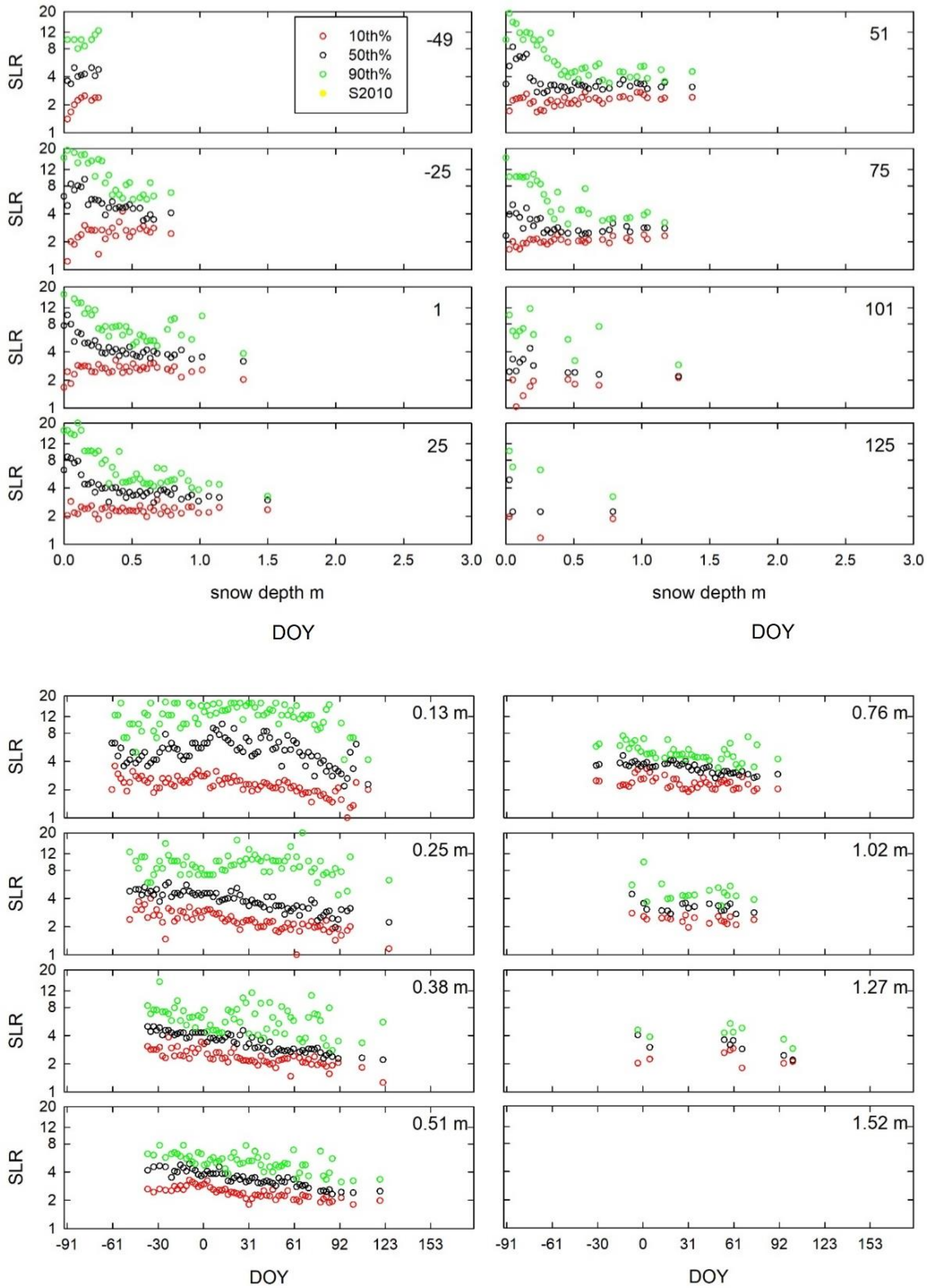

Figure 11d. SLR quantiles for GHCN data in the Ephemeral snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. S2010 did not determine a fit for this snow class.

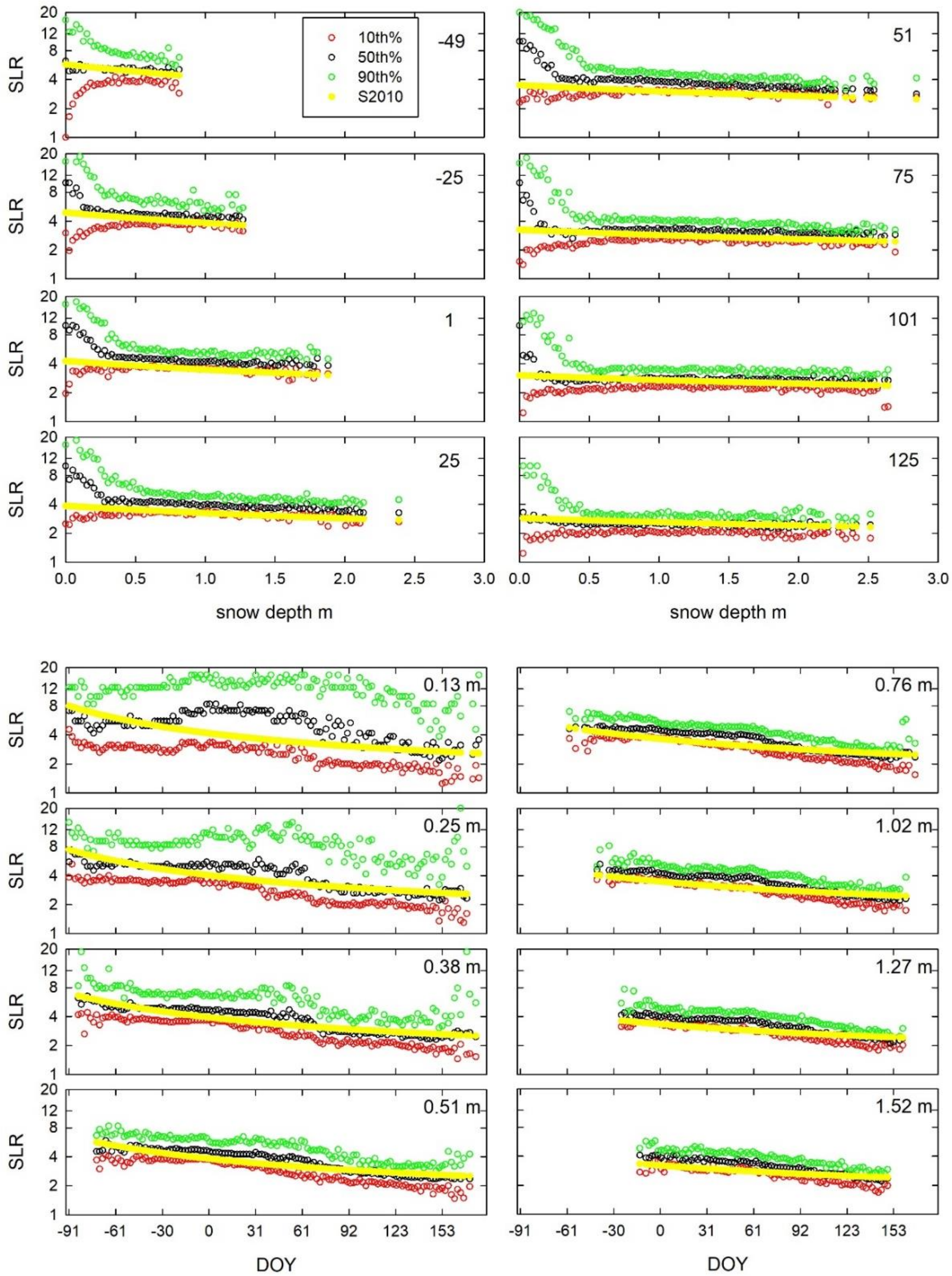

Figure 11e. SLR quantiles for GHCN data in the Prairie snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. SLRs calculated from the S2010 fit are also shown.

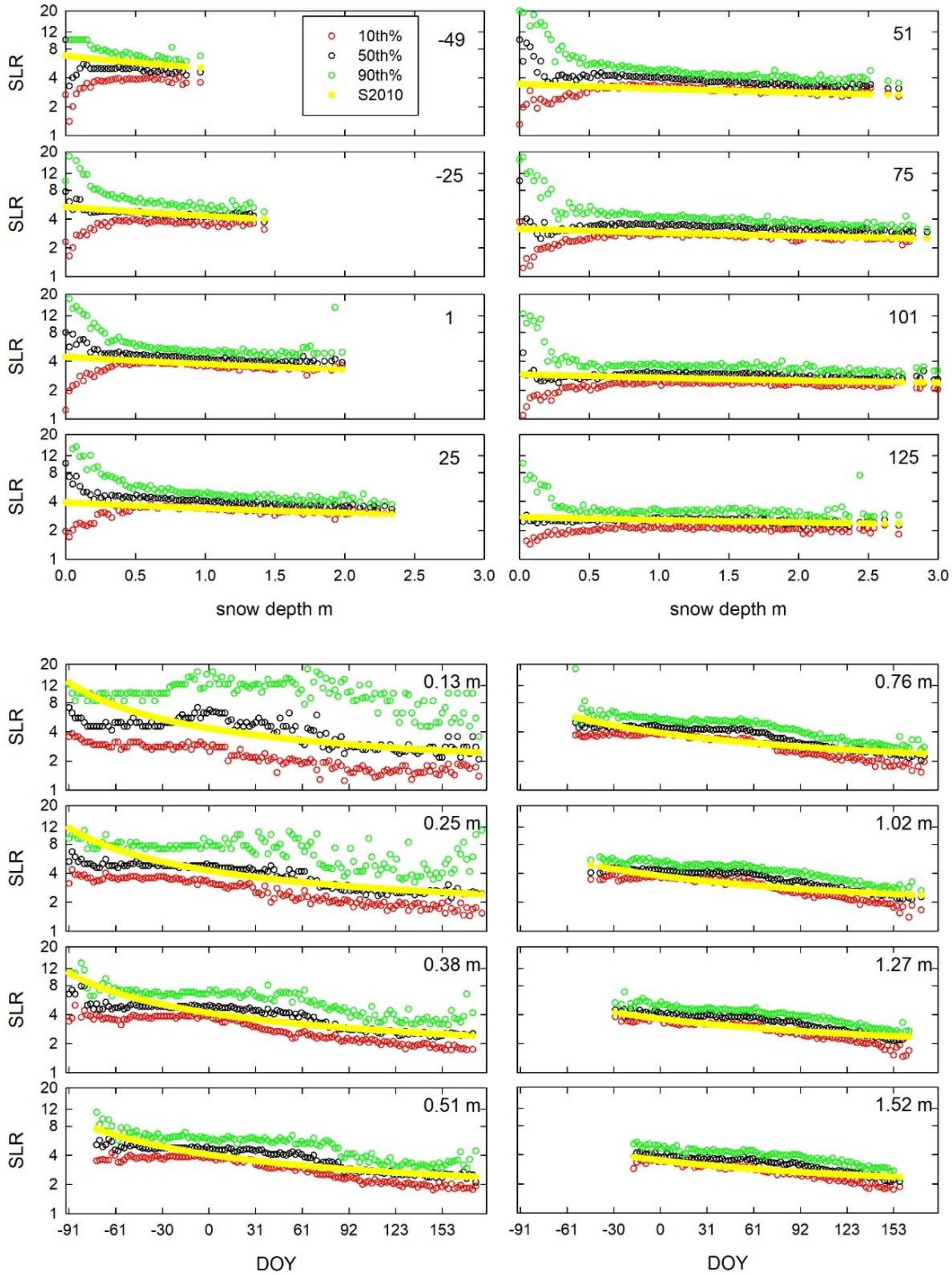

Figure 11f. SLR quantiles for GHCN data in the Alpine snow class: (top) as a function of snow depth for eight *DOY*, (bottom) as a function of *DOY* for eight snow depths. SLRs calculated from the S2010 fit are also shown.

class. Taking the inverse of the SLR quantiles in Table 8 to get snow density, the typical Taiga density is 0.17 g cm^{-3} with 80% of the values between 0.1 and 0.24 g cm^{-3}. Ephemeral snow densities are higher, with 80% of the values between 0.18 and 0.43 g cm^{-3} around a typical density of 0.29 g cm^{-3}.

Table 7. Median of the ratios of the 90th% and 10th% to the 50th% SLR for deep snow at the GHCN stations in three snow classes. The last row is the median of the ratio of the 50th% SLR to the S2010 fit.

Snow class	Maritime	Prairie	Alpine
Minimum depth	0.75 m	0.5 m	0.5 m
Ratio 90th% to 50th%	1.22	1.23	1.21
Ratio 10th% to 50th%	0.81	0.81	0.83
Ratio 50th% to S2010	1.03	1.16	1.13

Table 8. SLR quantiles for snow deeper than 0.15 m (6 inches) at the GHCN stations in the Tundra, Taiga, and Ephemeral snow classes.

Snow class	Tundra	Taiga	Ephemeral
Minimum depth	0.15 m	0.15 m	0.15 m
10th% SLR	4.2	4.2	2.3
50th% SLR	9.9	5.8	3.5
90th% SLR	14.9	10.	5.7

With the exception of the Tundra class, with data primarily from WBAN stations with too many SLR = 10, Figure 11 is dominated by reports from SNOTEL stations. The Maritime snow class, however, has both many cases and a significant fraction of data from other networks. To compare the SNOTEL SLRs with those computed from manual snow depth and SWE measurements, we plotted the SLR quantiles as a function of snow depth for this snow class separately for the SNOTEL and non-SNOTEL networks in Figure 12. Because all the CoCoRaHS, COOP, and WBAN station in this snow class are at low elevations, this comparison is limited to data from stations with elevations below 1000 m. This includes 99% of the 4746 non-SNOTEL Maritime stations and 17% of the 168 SNOTEL Maritime stations. There is somewhat deeper snow at the SNOTEL stations, and the 10th% and 90th% quantiles are closer together. The most obvious difference, however, is the good agreement between the GHCN 50th% SLRs and S2010 for the SNOTEL stations, while S2010 is close to the 10th% SLR at the non-SNOTEL stations. While this comparison between SNOTEL and non-SNOTEL SLRs is limited to stations at elevations below 1000 m in the Maritime snow class it is not clear whether the cause of the differences is the way snow depth and SWE measurements are made or the properties of the snow. These 29 SNOTEL stations, at an average elevation of 607 m, experience deeper snow than the 4696 non-SNOTEL stations, at an average elevation of 217 m. Perhaps the larger SLRs at the non-SNOTEL stations are due to the thinner snow pack. We looked at further refining the stations for this comparison to better match elevations, choosing the nine SNOTEL stations at the lowest elevations, or 309 non-SNOTEL stations at the highest elevations. This would reduce the number of samples in each snow depth-DOY bin so much that the quantiles would be meaningless.

SUMMARY AND CONCLUSIONS

The GHCN database provides valuable data on snow depth and snow water equivalent. The vast majority of these data pairs are from North America. The manual measurement protocols for snow depth and SWE for the CoCoRaHS, COOP, and WBAN networks are similar. The parameters are measured automatically at the remote SNOTEL stations. All networks report these data in inches, which are converted to millimeters in the GHCN database. We used simultaneous snow depth and SWE data from the stations in these networks to calculate the snow to liquid ratio. By computing the cumulative distribution of SLRs from each network, we determined that the reported SWE data are apparently sometimes calculated from the snow depth by dividing by 10 rather than measured. This has occurred more frequently at stations in the WBAN and COOP networks than at CoCoRaHS stations. Exact 10 SLRs occur about as frequently as expected at SNOTEL stations. Physically impossible SLR values, indicating snow densities greater than the density of bubble-free ice also occur, most frequently at stations in the COOP network. The GHCN QA algorithms check snow depth and SWE separately but do not test the resulting SLR. Users relying on the snow depth or SWE data in GHCN should consider calculating their ratio, when both parameters are available, as a further QA check.

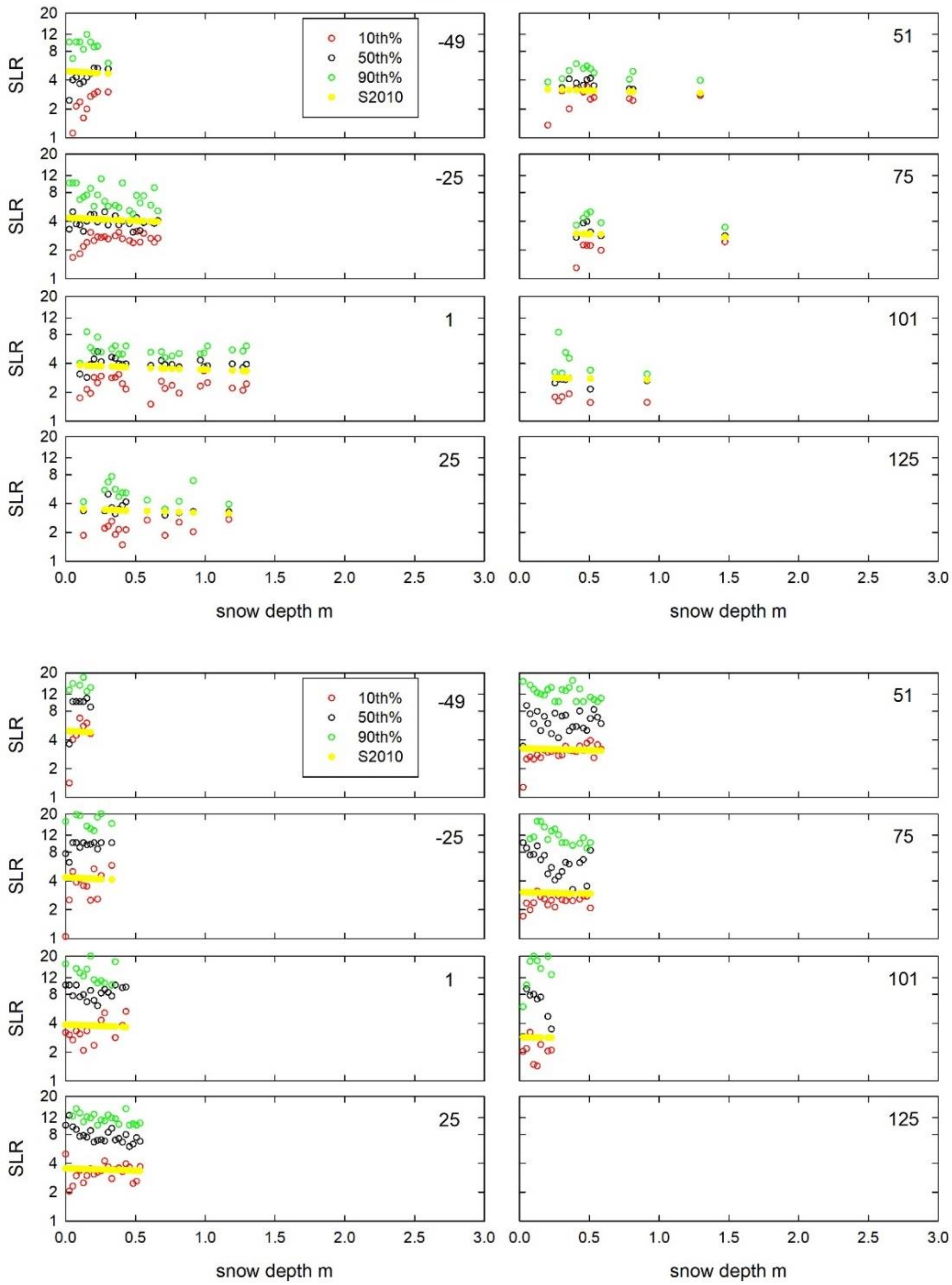

Figure 12. SLR quantiles, for GHCN data in the Maritime snow class at stations with elevation ≤ 1000 m, as a function of snow depth for eight snow classes; (top) SNOTEL data, (bottom) CoCoRaHS, COOP, and WBAN data. SLRs calculated from the S2010 fit are also shown.

We eliminated the snow depth-SWE pairs that failed the GHCN QA checks and assigned the data to the Sturm *et al*. (1995) snow classes. For each DOY-snow depth bin, we quantified the GHCN SLRs by the 10th%, 50th% (median), and 90th% quantiles to identify the center and range of the SLR distributions in each snow class. We compared these GHCN SLR quantiles to those calculated from the S2010 snow density fit.

Our results indicate substantial variation in SLR for snow depths less than 0.75 m, or less than 0.5 m for Alpine and Prairie snow. In the Tundra, Taiga, and Ephemeral snow classes, the snowpack tends to be shallow. There are excessive SLR = 10 in the Tundra snow class, associated with the large fraction of data from WBAN stations, so our results probably do not reflect actual snow properties at those stations. The SWE at GHCN stations in the Taiga and Ephemeral snow classes appears to be measured rather than calculated for most reports. Most (80%) of the Taiga SLRs are between 4.2 and 10, while the Ephemeral SLRs between 2.3 and 5.7 indicate denser snow with less density variation.

In deep snow in the Maritime, Prairie and Alpine classes, 80% of the snow measurements fall within about 20% of the median SLR, which varies with snow depth and *DOY*. The median is only slightly higher than the S2010 fitted SLR in the Maritime class but about 15% higher than the Prairie and Alpine S2010 SLR. The slopes with respect to *DOY* of the GHCN SLR quantiles increase at about *DOY* 61, likely caused by much less new snow and a densifying snow pack.

We used data from the Maritime snow class to try to compare manual and SNOTEL snow measurement. The data from stations at elevations below 1000 m show a significantly higher SLR at the non-SNOTEL stations. It is not clear if this difference is related to a systematic difference between manual and automatic snow depth and SWE measurements or to the lower elevations of the non-SNOTEL stations.

REFERENCES

Alcott TI, Steenburgh WJ. 2010. Snow-to-liquid ratio variability and prediction at a high-elevation site in Utah's Wasatch Mountains. *Weather and Forecasting*, **25**: 323-337.

Baxter MA, Graves CE, Moore JT. 2005. A climatology of snow-to-liquid ratio for the contiguous United States. *Weather and Forecasting*, **25**: 729-744.

Huntington TG. 2005. The density of falling snow in New England, 1949-2001. *Proceedings of 62nd Eastern Snow Conference*, Waterloo, Canada.

Jones KF, Daly SF. 2016. Effect of Arctic Amplification on design snow loads in Alaska, ERDC/CRREL MP-16-1, 56 pp.

Menne MJ, Durre I, Vose RS, Gleason BE, Houston TG. 2012a. An overview of the Global Historical Climatology Network-Daily Database. *Journal of Atmospheric and Oceanic Technology*, **29**: 897-910, doi:10.1175/JTECH-D-11-00103.1

Menne MJ, Durre I, Korzeniewski B, McNeal S, Thomas K, Yin X, Anthony S, Ray R, Vose RS, Gleason BE, Houston TG. 2012b. Global Historical Climatology Network - Daily (GHCN-Daily), Version 3.24 NOAA National Climatic Data Center. http://doi.org/10.7289/V5D21VHZ [9.4.2018]

Meyer JDD, Jin J, Wang S-Y. 2012. Systematic patterns of the inconsistency between snow water equivalent and accumulated precipitation as reported by the Snowpack Telemetry Network. *Journal of Hydrometeorology*, **13**: 1970-1976.

NOAA. 2017. Federal Meteorological Handbook No.1 Surface weather observations and reports, FCM-H1-2017.

NWS. 2014. Snow Measurement Guidelines for National Weather Service Surface Observing Programs, https://www.weather.gov/media/coop/Snow_Measurement_Guidelines-2014.pdf.

NWS. 2017. National Weather Service Manual 10-1315 (17 Oct 2017), Operations and Services, Surface Observing Program (Land), NDSPD 10-13, Cooperative Station Observations and Maintenance. https://www.nws.noaa.gov/directives/sym/pd01013015curr.pdf

Sturm M, Holgren J, Liston GE. 1995. A seasonal snow cover classification system for local to global applications. *Journal of Climate,* **8**: 1261-1283.

Sturm M, Taras B, Liston GE, Derksen C, Jonas T, Lea J. 2010. Estimating snow water equivalent using snow depth data and climate classes. *Journal of Hydrometeorology,* **11**: 1380-1394.