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The Density of Falling Snow in New England, 1949–2001

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ABSTRACT:

Long-term records of the density of falling snow in New England were examined using time-series analysis to investigate the hypothesis that climate warming has increased snow density in recent decades. Trends in monthly average snow-to-liquid ratio (SLR) from 26 stations in the United States Historical Climatology Network (USHCN) during 1949–2001 were analyzed using the nonparametric Kendall's tau trend statistic. Statistically significant trends were observed in 19% of all site-by-month trend tests; weaker trends were observed in an additional 21% of all site-by-month trend tests. Approximately half of all trends indicated increasing density, and half indicated decreasing density. The sign of the trends in SLR was seasonally biased. There were more negative trends (increasing snow density) in November, March, and especially December and more positive trends (decreasing snow density) in January and February. Increases in density in December, and to some extent in November and March, are consistent with the hypothesis of an increase in surface air temperature causing an increase in the density of falling snow and with earlier findings on trends in the ratio of snow-to-total precipitation in New England. A significant decreasing trend in the frequency of reporting of 10:1 SLR could explain part of the decrease in snow density in January and February. An increase in wind speed also could explain part of the decrease in snow density in January and February.

Keywords: snow density, hydrologic indicator, climate change

INTRODUCTION

The density of falling snow is related to the vertical temperature and moisture structure of the atmosphere and wind speed at the time snow is falling (Ware et al., in press; Judson and Doesken, 2000). In general, snow density increases with increasing temperature, although some data indicate that snow density also can increase at very cold temperatures (LaChapelle, 1962, McGurk, et al., 1988; Dube, 2003; Judson and Doesken, 2000; Roebber et al., 2003). Snow density increases with increasing wind speed (Dube, 2003; Roebber et al., 2003), but is not correlated with snowfall amount (Judson and Doesken, 2000). In one study in the central Rocky Mountains, USA, the relationship between temperature and density was significant (Pearson r = 0.52) but variable depending on wind speed, humidity, and elevation (Judson and Doesken, 2000).

Snow density has been shown to decrease from fall to early winter and then to increase from mid-winter to late winter and early spring (Dube, 2003). These seasonal patterns are consistent with a positive relation between temperature and density. Similarly, northern sites have a lower falling snow density than do more southerly sites in a given region and snow density decreases with increasing elevation (Roebber et al., 2003; Ware et al., in press).

Recent studies indicate that surface air temperature has increased during the 20th century in New England (Keim et al., 2003; Trombulak and Wolfson, 2004). Positive trends are indicated for all seasons and may be strongest during winter (Jones and Moberg, 2003). Several studies have

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reported hydrologic changes in New England during the 20th century that are consistent with increasing surface air temperatures, particularly during winter and early spring. For most sites, the annual timing of lake (Hodgkins et al., 2002) and river (Dudley and Hodgkins, 2002) ice-out shifted towards earlier times in the year and there were fewer days when ice affected river discharge (Hodgkins et al., in press). High spring flow, associated with snowmelt, occurs earlier in the year in many parts of northern New England; that timing is highly correlated with March–April air temperatures (Hodgkins et al., 2003). Earlier high spring flow also may be related to the observed decrease in the ratio of snow to total precipitation (Huntington et al., 2004) in this region. Other hydrologic indicators, such as thinning river ice (Huntington et al., 2003) and an increase in the density of the accumulated late-winter snow pack at sites with sufficiently long-term data in Maine (Dudley and Hodgkins, 2002), also are consistent with surface warming. In addition, phenological indicators including dates of blooming in woody plants (Schwartz and Reiter, 2000; Wolfe et al., 2005), bird breeding dates (Dunn and Winkler, 1999), and migration of anadromous fish (Huntington et al., 2003; Juanes et al., 2004) are consistent with earlier spring warming. Model forecasts suggest continued warming over New England during the 21st century (Cubasch and Meehl, 2001).

The density of falling snow could be a useful indicator of climate change because of the sensitivity of snow density to temperature. Several studies have reported high variability in snow density, the importance of meteorological variables, and the inadequacy of the simple 10:1 rule. Studies have highlighted the importance of forecasting snow density from the standpoint of risk assessment for avalanche hazard and in planning for snow removal (Roebber et al., 2003; Dube, 2003). The density of falling snow has not been studied to evaluate whether it could be a sensitive hydrologic indicator of climate change and whether the available data indicate any change in the historical period. This study was conducted to assess these questions, and in particular, the hypothesis that recent warming has resulted in an increase in the density of falling snow in New England.

METHODS AND DATA

The density of falling snow can be estimated by using measurements of snow depth (measured on a snow board rather than in a precipitation collector because of the problems associated with such collectors for accurate snow depth) and snow liquid equivalent measured in a collector (Doesken and Judson, 1996). Several factors including gauge undercatch, compaction, and changes in measurement practices like the frequency of measurement can adversely influence the quality of the data for trend analysis (Doesken and Judson, 1996; Roebber et al., 2003). These are serious concerns that must be considered in the interpretation of this data. Unfortunately, differences in measurement practices are not necessarily recoded at each station over time. Sometimes these differences can be inferred, as is the case with changes in the frequency of reporting of a fixed SLR of 10 that will be discussed further. In this paper I will address how the some common problems might influence the interpretations. The “undercatch problem” arises in that the collectors used to measure the liquid equivalent of snowfall can underestimate snowfall, particularly at higher wind speeds (Doesken and Judson, 1996). It is possible that a real trend towards increasing snow density would result in a decreasing undercatch bias over time, and vice versa, thereby amplifying a real increasing density trend. Arguing against the increasing significance of an undercatch problem over time is the fact that undercatch bias is exaggerated by increasing wind speed, but there is evidence that wind speed is actually decreasing over the study period (Groisman et al., 2004). There is no reason to suspect that snowfall compaction has increased over time because of increasing snowfall amounts since snowfall appears to have decreased (Hamilton et al., 2003; Huntington et al., 2004). Small decreases in snowfall amount could lead to somewhat less compaction that, in turn, would tend to decrease estimated snow density over time.

Snow density is commonly referred to as the snow ratio or snow-to-liquid ratio (SLR). The SLR is the inverse of density. An SLR of 10 (for example, 10 cm snow and 1 cm liquid equivalent precipitation) is equivalent to a snow density of 100 kg m^{-3} (0.1 g cc^{-1}). Similarly, an SLR of 20 is equivalent to a snow density of 50 kg m–3. Increasing SLR indicates decreasing snow density.

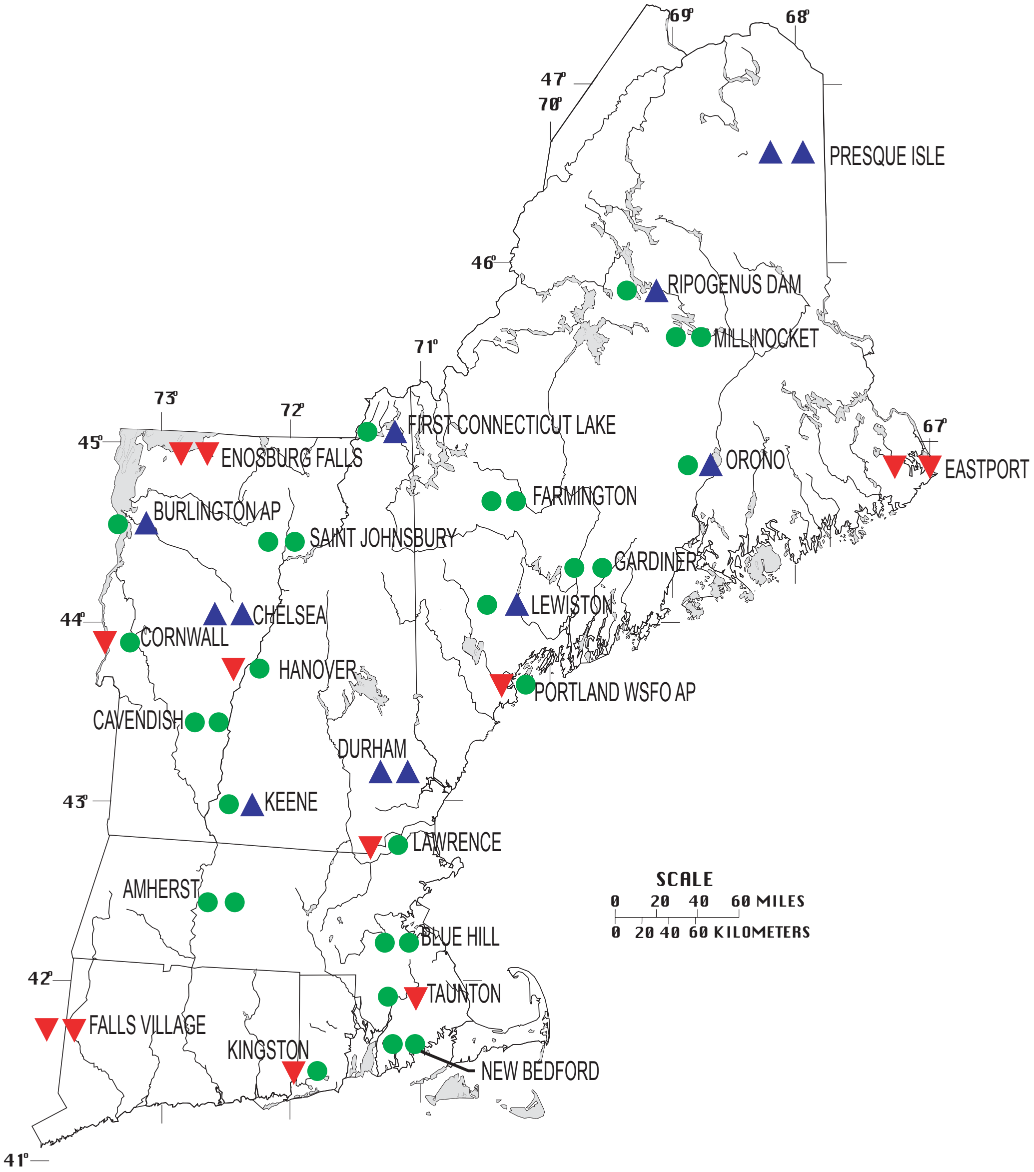

Figure 1. Locations and names of USHCN stations included in the analysis of the density of falling snow (1949–2000). Symbols to the left are for trend tests for December and symbols to the right are for January. Northward-facing triangles indicate increasing SLR (decreasing snow density) trends, southward facing triangles indicate decreasing SLR (increasing snow density) trends, and circles indicate no trends. Trends denote Kendall's tau p-values < 0.20.

Temperature and precipitation data were obtained from the United States Historical Climatology Network (USHCN) (Karl et al., 1990). USHCN data have been subjected to quality control, homogeneity testing, and adjustment procedures for bias originating from changes in time-of-observation (Karl et al., 1986), station moves (Karl and Williams, 1987), and urban warming (Karl et al., 1988). Keim et al. (2003) showed that this data set is more reliable for long-term trend analysis than the larger data set of the National Climate Data Center's Climate Divisions. The data were downloaded from the publicly accessible NOAA–National Climatic Data Center's USHCN web pages (ftp://ftp.ncdc.noaa.gov/pub;data/ushcn/daily).

Temperature and precipitation data from all USHCN stations in New England where continuous daily records are available were used to calculate monthly composite temperature and the ratio of snow depth to snow liquid equivalent. Time series were compiled for average SLR for each month at 26 sites in New England (Figure 1). Sites in southern New England frequently had relatively few years with snowfall recorded in November or April. SLR was determined for all months with significant snowfall in New England (November through April). Only sites where data were available for at least 70% of all years during the period 1949 through 2001 were included. To control for temporal bias in missing data, it was required that there be no more than 40% missing record during any 10-year period. Many sites had some missing data for certain periods (usually days and, infrequently, months) within some years. Very few sites had more than 10% missing years during 1949 through 2001. This missing data never constituted more than 5% of the total numbers of days in the otherwise continuous daily records within a given year so these sites were included in the analysis. Almost all USHCN sites in New England met these criteria. Time series for most USHCN sites in New England begin in 1949 and end in 2001. Three sites, Presque Isle, Orono, and Ripogenus Dam (all in Maine), did not have any complete annual data after the mid-1990s.

When snowfall was recorded for a given day, the SLR was computed as the ratio of snow depth-to-liquid precipitation amount for the day. When computed SLR was >45 or <2, the data were censored because these extreme values could represent errors. Such extreme values were found in less than 5% of all recorded snowfall events. There can be biases using this procedure when there are mixed-precipitation (snow and rain) storms. Following a mixed precipitation storm, if the observer records snow on the snowboard this procedure will assume that all of the precipitation fell as snow and therefore the SLR will be biased low (higher density). If, on the other hand, the observer records no snow following a mixed-precipitation storm (because there was sufficient rain to melt all of the snow), then the snow that fell during this storm will not enter into the analysis. In this latter case it is likely that some lower SLR snowfalls will simply not be recorded, thus introducing a bias in the direction of higher SLR (lower density).

There are also differences among sites and for a given site over time in terms of the number of times that snowfall is recorded during a 24-hr period. Under mixed precipitation conditions, more frequent observations may result in more days with snowfall being recorded; under such circumstances, the algorithm would result in a bias towards more snowfall recorded than actually fell and a bias towards an increase in snow density. It is unknown how large the net effect of such bias could be, or whether there could be systematic bias because of changes in the frequency of mixed precipitation events. Huntington et al. (2004) found a generally decreasing ratio of snow to total precipitation indicating that, proportionately, more wintertime precipitation was occurring as rainfall than snowfall. This observation is consistent with an increasing frequency of mixed precipitation events. If there were a bias towards an increasing frequency of mixed precipitation events over time, this would lead to an overestimation of snowfall in more recent times. This type of bias, if present, would result in a more conservative test of the hypothesis that the density of snow has increased over time.

Hourly surface wind speed data for Portland, Maine (1949–1999) were obtained from the National Climate Data Center, Asheville, NC. The hourly data were computed from 1-min duration-averaged wind speed (mph). The wind data were compiled as average monthly wind speed to develop a time series for this site that could be related to monthly SLR time series.

Temporal trend tests were conducted on SLR time-series data for all sites with a nonparametric test for monotonic trend based on Kendall's tau statistic (Helsel and Hirsch, 1992). Using this test, no assumptions of normality of the distribution are required, and serial correlation is assumed to be negligible. The Durbin-Watson statistic (Helsel and Hirsch, 1992) was calculated using the residuals from a simple linear regression model to test for serial correlation where significant trends in SLR were determined. Significant positive serial correlation ($p<0.05$, based on test statistics published by Draper and Smith (1998)) was observed for Cornwall (March), Eastport (February), and Presque Isle (November) only. There was no temporal bias in the distribution of missing values. Correlation analysis (Pearson's r with Fisher's p-value for significance of the Pearson's r) was used to determine relations between monthly SLR and temperature and wind speed. The significance level for all trend and correlation $p=0.05$ (95%). Trends with p in the range of 0.05 to 0.20 were reported as weak, but not significant.

RESULTS AND DISCUSSION

Trends in SLR

Trends in SLR (p-value<0.20) were observed in 56 (40%) of all site-by-month trend tests where sufficient data were available (Table 1). Of these trends 27 (19%) were significant (p-value<0.05). Monthly time series showing large interannual variability and long-term trends for January at Presque Isle, Maine and for December at Eastport, Maine are shown in Figure 2. There were slightly more positive trends (decreasing snow density) than negative trends, and most of the significant trends were positive. The sign of the trends in SLR were strongly seasonally biased. There were more negative trends (increasing snow density) in November, March, and especially December, and more positive trends (decreasing snow density in January and February (Figure 3, Table 1). This seasonal bias indicates that most trends are towards increasing density of falling snow at the beginning of the snow season in late fall and early winter. During the cold winter months of January and February, trends reverse towards decreasing snow density, and in March there are slightly more trends towards increasing snow density.

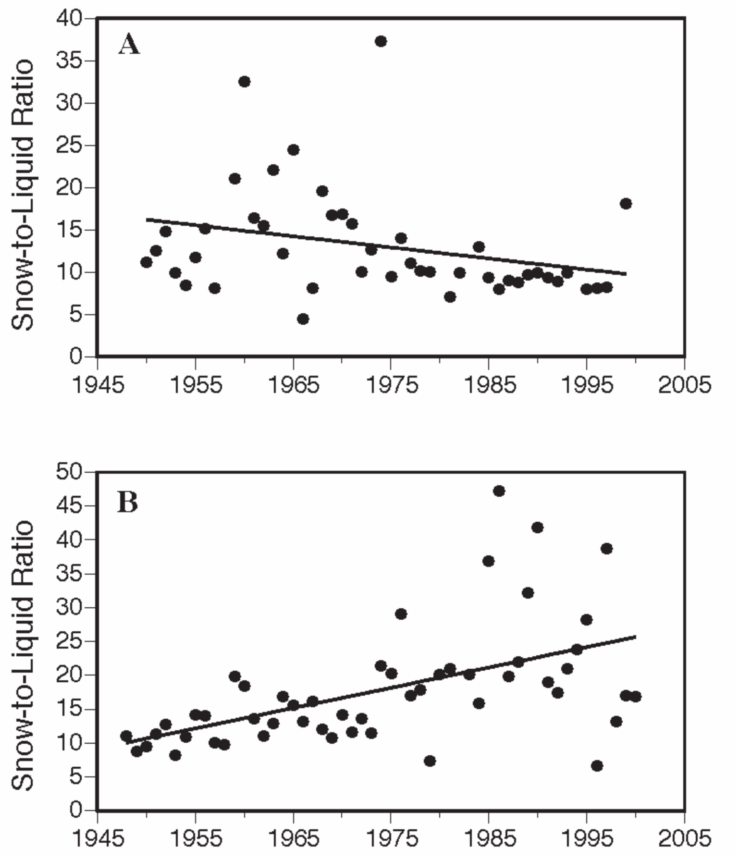

Figure 2. Time series for mean monthly snow-to-liquid ratio (SLR) for (A) December at Eastport Maine and (B) January at Presque Isle, Maine. Simple linear regression lines are shown

Table 1. Kendall's tau trend test values and p-values for temporal trends in the snow-to-liquid ratio (SLR) of daily snowfalls for USHCN sites in New England (1949–2001). Negative sign for tau value indicates decreasing SLR and positive sign indicates increasing SLR. Kendall trend test p-values < 0.05 are shown in bold. NS = not significant (p-value > 0.2). ID = insufficient data for trend test.

		Nov		Dec		Jan		Feb		March		April	
Station Name	State	tau	p	tau	p	tau	p	tau	p	tau	p	tau	p
Amherst	MA	0.114	NS	0.055	NS	–0.009	NS	0.204	**0.037**	0.051	NS	0.103	NS
Blue Hill	MA	ID	ID	0.041	NS	–0.020	NS	0.233	**0.017**	0.004	NS	ID	ID
Burlington	VT	–0.038	NS	0.037	NS	0.218	**0.021**	0.118	NS	0.017	NS	0.181	0.080
Cavendish	VT	–0.111	NS	–0.080	NS	–0.113	NS	0.006	NS	–0.071	NS	0.108	NS
Chelsea	VT	–0.115	NS	–0.125	0.196	0.131	0.175	–0.045	NS	–0.041	NS	0.256	**0.022**
Cornwall	VT	–0.152	0.191	–0.174	0.093	–0.030	NS	0.022	NS	–0.247	0.017[1]	ID	ID
Durham	NH	0.177	0.186	0.140	0.166	0.271	**0.007**	0.171	0.094	0.007	NS	ID	ID
Eastport	ME	–0.161	0.162	–0.295	**0.004**	–0.380	0.0001[1]	–0.245	**0.013**	–0.238	**0.017**	ID	ID
Enosburg Falls	VT	–0.167	0.097	–0.092	0.078	–0.167	0.086	–0.056	NS	–0.061	NS	–0.138	NS
Falls Village	CT	ID	ID	–0.289	**0.013**	–0.239	0.051	0.003	NS	–0.283	**0.018**	ID	ID
Farmington	ME	–0.157	0.144	0.073	NS	–0.052	NS	0.010	NS	–0.016	NS	0.213	0.063
1st CT Lake	NH	0.010	NS	–0.104	NS	0.264	**0.008**	0.026	NS	0.007	NS	0.230	**0.020**
Gardiner	ME	ID	ID	–0.080	NS	–0.091	NS	–0.044	NS	–0.127	NS	ID	ID
Hanover	NH	–0.278	**0.012**	–0.203	0.0947	–0.031	NS	–0.040	NS	–0.172	0.096	–0.059	NS
Keene	NH	0.155	NS	0.027	NS	0.234	**0.014**	0.192	**0.043**	–0.022	NS	ID	ID
Kingston	RI	ID	ID	–0.206	0.064	–0.043	NS	0.121	NS	–0.070	NS	ID	ID
Lawrence	MA	0.124	NS	–0.171	0.116	–0.112	NS	–0.003	NS	–0.155	0.154	–0.212	NS
Lewiston	ME	0.011	NS	–0.052	NS	0.287	**0.002**	0.110	NS	0.172	0.072	0.077	NS
Millinocket	ME	0.032	NS	–0.029	NS	0.026	NS	0.197	**0.042**	0.162	0.096	–0.013	NS
New Bedford	MA	ID	ID	–0.011	NS	–0.010	NS	0.091	NS	0.089	NS	ID	ID
Orono	ME	0.059	NS	0.025	NS	0.291	**0.004**	0.208	**0.039**	0.075	NS	–0.071	NS
Portland	ME	0.297	**0.020**	–0.216	**0.026**	0.006	NS	–0.033	NS	–0.107	NS	0.041	NS
Presque Isle	ME	0.230	0.019[1]	0.334	**0.001**	0.434	**<0.0001**	0.264	**0.006**	0.417	**<0.0001**	0.144	0.153
Ripogenus Dam	ME	–0.078	NS	–0.034	NS	0.291	**0.005**	0.169	0.106	0.200	0.058	0.007	NS
Saint Johnsbury	VT	–0.003	NS	0.117	NS	–0.023	NS	0.108	NS	–0.080	NS	0.078	NS
Taunton	MA	ID	ID	–0.065	NS	–0.265	**0.016**	–0.080	NS	–0.205	0.094	ID	ID

[1] Test was not significant at $p<0.05$ because serial correlation was detected.

Increases in density in late/fall and early winter and in March are consistent with the hypothesis of increasing surface air temperature causing an increase in the density of falling snow and with earlier findings on trends in the ratio of snow-to-total precipitation in New England (Huntington et al., 2004). Huntington et al. (2004) found the strongest trends in snow-to-total precipitation ratio during 1949 to 2000 to occur in December and March; trends were not significant in other months. It is possible that the density of falling snow would be more sensitive to incremental increases in air temperature in the relatively warmer months of November, December, and March than the colder months of January and February. Roebber et al. (2003) have shown that snow density increases with increasing temperature in the lower atmosphere (<850 hPa) more rapidly between –10 and 0 ˚C than at temperatures less than –10 ˚C.

Kendall trend tests were also performed on selected sites after first removing all storms where an SLR of 10 had been recorded to determine whether the interpretations obtained by analysis of the full data set would be changed. Minor differences in the strength of trends and in the significance of the tests were observed but the overall interpretations remained unchanged. Specifically, a strong seasonal bias was retained in which there are substantially more trends towards increasing density in the warmer winter months and decreasing density in January and February.

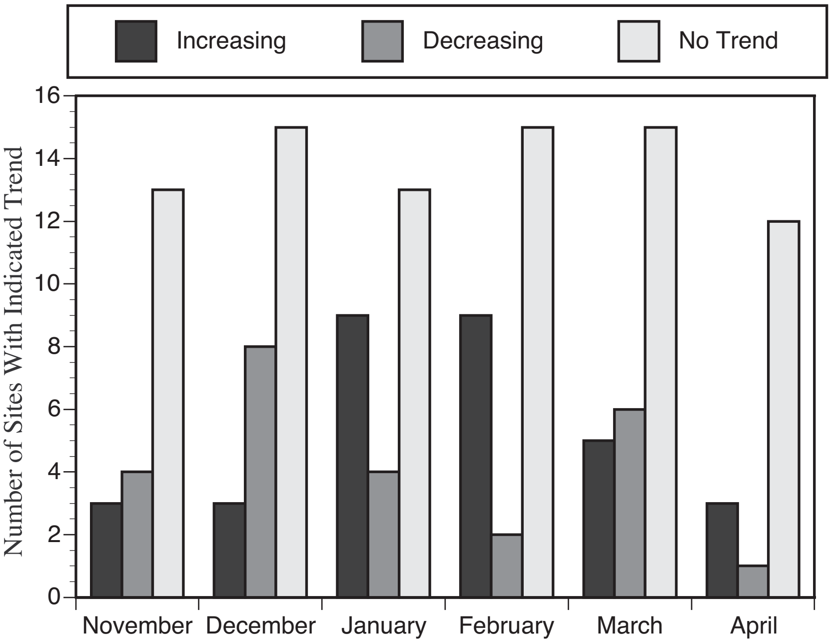

Figure 3. Histogram showing numbers of sites having increasing, decreasing, or no average monthly trends in snow-to-liquid ratios (SLR) for the period 1949–2000. Numbers of sites do not sum to 26 for November and April because some sites had insufficient data for analysis in these months.

Possible explanations for decreasing snow density

Trends towards decreasing snow density (increasing SLR) that were most strongly expressed in January and February were unexpected and not consistent with the warming-induced increase in snow density hypothesis. Recent, unpublished analyses for the Great Lakes region have found increases in SLR during the 2nd half of the 20th century (Kenneth Kunkel, Illinois Water Survey, written commun. 2005). According to Kunkel, these increases may be partly, or largely, attributable to systematic reporting bias. Kunkel has observed that the frequency of reporting an SLR of 10:1 has decreased from approximately 20% to 10% for all observations between 1950 and 2000. This observation, together with the fact that where SLR is reported from independent measures of snow depth and liquid equivalent average SLR values are usually substantially greater than 10 (Judson and Doesken, 2000; Roebber et al., 2003), suggests that more accurate reporting over time has introduced a spurious and increasing SLR (decreasing density) trend in the data.

This study included 39,435 individual storms for which 9.7% reported 10:1 SLR values. This overall frequency is substantially lower than the approximately 15% found for the contiguous United Sates (Kenneth Kunkel, Illinois Water Survey, written commun. 2005). SLR values of 15 and 20 were reported at frequencies of 2.2% and 4.4% respectively. To address the question of whether the frequency of reporting 10:1 SLR values changed over time (temporal bias) in this study the aggregate 26-site average monthly reporting frequency of SLR values of 10:1 was computed by year. This statistic captures the average (for all sites) number of SLR values of 10:1 that were reported per month in each year. There was a decrease in the reporting frequency of SLR values of 10:1 over time (Figure 4). This decreasing trend was significant ($p=0.0114$) using Kendall's nonparametric trend test. This trend could explain part of the trend towards decreasing snow density in January and February. There was substantial variability in reporting of 10:1 among sites but not among months (data not shown). The linear trend in New England is a decrease from 0.54 to 0.41 storms per month (24%). In comparison, over a comparable time period 10:1 SLR reporting decreased by about 50% for the contiguous United States (Kenneth Kunkel, Illinois Water Survey, written commun. 2005) indicating that this reporting bias is less influential in New England than the in the United States in general.

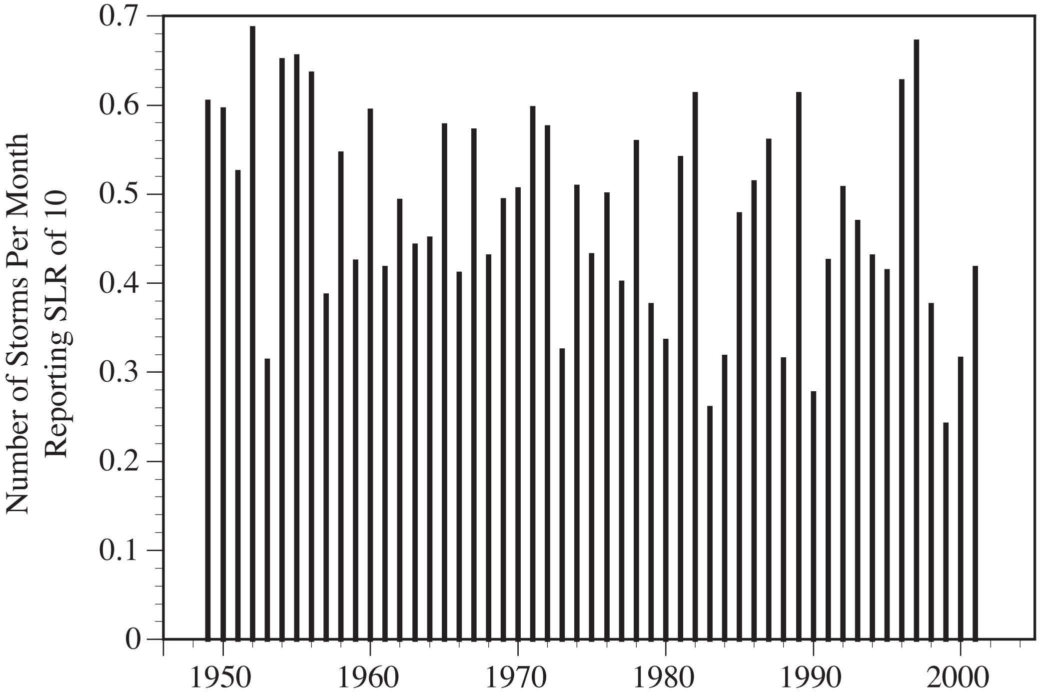

Figure 4. Histogram showing the 26-site average number of storms per month for which a snow-to-liquid ratio of 10 was reported during each year 1949 through 2001.

Reporting bias can likely explain only a part of the trend towards decreasing snow density in January and February; therefore it is worth examining trends in other variables that could explain any part of this trend that may be real. It is unlikely that a decrease in temperature can explain these trends because temperature has been shown to be increasing over this region annually (Keim et al., 2003; Trombulak and Wolfson, 2004) and in winter (Jones and Moberg, 2003). Increasing temperature should result in increasing rather than decreasing snow density.

Snow density also is influenced by humidity such that more humid air results in higher snow density. There is uncertainty about the trends in humidity during the second half of the 20th century; however, some recent analyses indicate increases in humidity and atmospheric water vapor in recent decades (Folland et al., 2001; Groisman et al., 2004; Trenberth et al., in press). The diurnal temperature range (DTR) is strongly and inversely related to cloudiness (Dai et al., 1999) and has decreased over most global land areas over the latter half of the 20th century (Easterling et al.,1997). Spatially extensive cloudiness data series extend back only to 1981, but given the strong relation between cloudiness and DTR, the long-term downward trend in DTR suggests that cloudiness also has increased over the same time period. In addition, there is evidence that precipitation has increased over the New England region in recent decades (Keim et al., 2005) which is also consistent with increasing humidity (DelGenio et al., 1991; Held and Soden, 2000). Increasing humidity should result in increasing rather than decreasing snow density.

If increasing surface air temperature and humidity are inconsistent with decreasing snow density, it is possible that a decrease in wind speed could explain part of the observed trends in snow density. The density of falling snow decreases with decreasing wind speed. Recent reports indicate that average surface (10-m elevation) wind speed decreased by 5% between 1950 and 2000 over the contiguous United States (Groisman et al., 2004). Other recent analyses have shown decreases over the North Atlantic Ocean (Mark Saunders, Univ. College, London, UK, written commun., 2005).

Hourly wind speed data from Portland, Maine for 1948 through 1999 were analyzed for this study. Average January wind speed decreased significantly (p = 0.014) using the nonparametric Kendall's tau trend test (Figure 5). Wind speed also trended downwards in February (p = 0.059) and March (p = 0.15). Trends were negative in all months except June, but these trends were not significant (p > 0.20). Wind data from one site are certainly not representative of the region, but given the regional trend towards decreasing wind speed reported by Groisman et al. (2004) the trend in Portland provides insight into a possible mechanistic explanation for decreasing snow density in January and February.

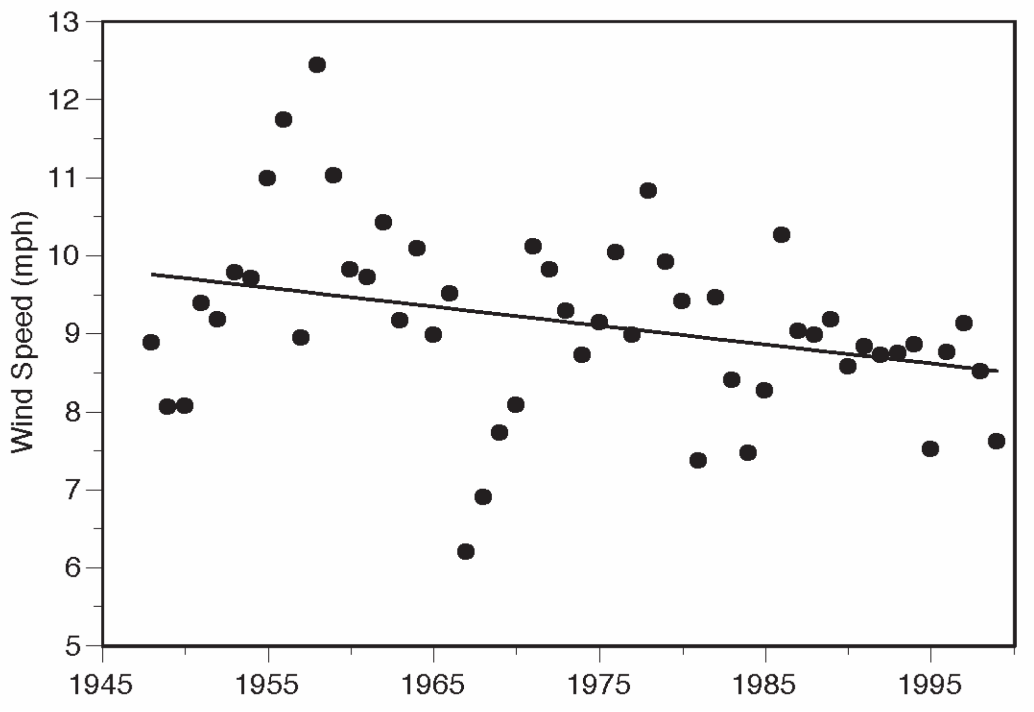

Figure 5. Average January wind speed at 10-meter elevation at Portland, Maine, Portland Jetport (PWM). Data from NOAA National Climatic Data Center, Asheville, NC. Linear regression line is shown.

Correlation analysis

There was a significant negative correlation (r=0.49 p<0.001) between the regional average December surface air temperature and the 26-site average December SLR for 1949 through 2001. This correlation explained about 25% of the variation in SLR. This inverse correlation is consistent with the hypothesis that warming would result in a decrease in SLR (an increase in snow density). Air temperature was not correlated with SLR in any other month.

Correlation analysis indicated no significant correlations between monthly average wind speeds at Portland and monthly average SLRs at Portland, or between monthly average wind speeds at Portland and monthly average SLRs computed as an aggregate yearly value for all sites. The lack of correlation could indicate that SLR is not sensitive to average monthly wind speed. It could be that monthly SLR is sensitive to wind speed during snowfall events only. An analysis of wind speed during snow storms was beyond the scope of this study but would lend insight into the importance of trends in wind speed.

CONCLUSIONS

There is some supporting evidence for an increase in snow density during the warmer snowfall months, most notably in December, and there was a significant correlation between surface air temperature and SLR in December during 1949–2001. Observed trends towards decreasing snow density in January and February were unexpected, and may be partly explained by trends towards decreased reporting of 10:1 SLR and decreasing wind speed. Reporting bias and decreases in wind speed could mask a more consistent underlying response to the observed warming in most months. Because of high interannual variability, sensitivity to wind speed and humidity, and measurement problems, including reporting bias, snow density computed from independent measures of snow depth from a snow board and snow liquid equivalent from a precipitation collector appears to be a less robust hydrologic indicator variable to detect hydrologic responses to climate change than some others that have been studied in New England.

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REFERENCES

Cubasch U, Meehl GA. 2001. Projections of future climate change. In: Houghton, J. T. Ding, Y., Griggs, D. J., Noguer, M., van der Linder, P. J., Dai, X., Maskell, K., and Johnson, C. A. (Editors), Climate Change 2001: The Scientific Basis. Cambridge Univ. Press, Cambridge, pp. 525–582.

Dai A, Trenberth KE, Karl TR. 1999. Effects of clouds, soil moisture, precipitation, and water vapor on diurnal temperature range. *Journal of Climate* **12**: 2451–2473.

DelGenio AD, Lacis AA, Ruedy RA. 1991. Simulations of the effect of a warmer climate on atmospheric humidity. *Nature* **351**: 382–385.

Doesken NJ, Judson A. 1996. The Snow Booklet: A guide to the science, climatology, and measurement of snow in the United States. Colorado State University, Fort Collins, CO.

Draper NR, Smith H. 1998 Applied Regression Analysis, Third Edition, John Wiley and Sons, Inc., New York, 706 p.

Dube I. 2003. *From mm to cm: study of snow/liquid ratio over Quebec*, Technical Note, SMC Region of Quebec, 127 p.

Dudley RW, Hodgkins GA. 2002. Trends in streamflow, river ice, and snowpack for coastal river basins in Maine during the 20th century, U.S. Geological Survey, Water-Resources Investigations Report 02-4245, 26 p.

Dunn PO, Winkler DW. 1999. Climate change has affected breeding date of tree swallows throughout North America. *Proceedings of the Royal Society of London* **B266**: 2487–2490.

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK. 1997. Maximum and Minimum Temperature Trends for the Globe. *Science* **277**: 364–367.

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlemans J, Salinger MJ, Wang S-W. 2001. Observed climate variability and change. In *Climate Change 2001: The Scientific Basis,* Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linder PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge Univ. Press: Cambridge; 99–181.

Groisman PY, Knight RW, Karl TR, Easterling DR, Sun B, Lawrimore J. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends. *Journal of Hydrometeorology.* **5**: 64–85.

Hamilton, Keim BD. 2003. Warming winters and New Hampshire's lost ski areas: An integrated case study. *International Journal of Sociology and Social Policy*. **23**: 52–73.

Held IM, Soden BJ. 2000. Water vapor feedback and global warming. *Annual Review of Energy and the Environment* **25**: 441–475.

Helsel DR, Hirsch RM. 1992. Statistical methods in water resources, Studies in Environmental Science 49, 522 p. Elsevier, New York.

Hodgkins GA, James IC, Huntington TG. 2002. Historical changes in lake ice-out dates as indicators of climate change in New England. *International Journal of Climatology* **22**: 1819–1827.

Hodgkins GA, Dudley RW, Huntington TG. 2003. Changes in the timing of high river flows in New England over the 20th century. *Journal of Hydrology* **278**: 244–252.

Hodgkins GA, Dudley RW, Huntington TG. In Press. Changes in the number and timing of ice-affected flow days on New England rivers, 1930–2000. *Climatic Change*.

Huntington TG, Hodgkins GA, Dudley RW. 2003. Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine. *Climatic Change* **61**: 217–236.

Huntington TG, Hodgkins GA, Keim BD, Dudley RW. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). *Journal of Climate* **17**: 2626–2636.

Jones PD, Moberg A. 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. *Journal of Climate* **16**: 206–223.

Juanes F, Gephard S, Beland KF. 2004. Long-term changes in migration timing of adult Atlantic salmon (Salmo salar) a the southern edge of the species distribution. *Canadian Journal of Fisheries and Aquatic Sciences* **61**: 2392–2400.

Judson A, Doesken NJ. 2000. Density of freshly fallen snow in the central Rocky Mountains. *Bulletin of the American Meteorological Society* **8**: 1577–1587.

Karl TR, Williams CNJ, Young PJ, Wendland WM. 1986. A model to estimate the time of observation bias associated with monthly mean maximum, minimum, and mean temperature for the United States. *Journal of Climate and Applied Meteorology*, **25**: 145–160.

Karl RR, Diaz HF, Kukla G. 1988. Urbanization: its detection and effect in the United States climate record, *Journal of Climate* **1**: 1099–1123.

Karl TR, Williams CNJ, Quinlan FT, Boden TA. 1990. United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data, Environmental Science Division, Publication No. 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389 pp.

Karl TR, Williams CNJ. 1987. An approach to adjusting climatological time series for discontinuous inhomogeneities. *Journal of Climate and Applied Meteorology* **26**: 1744–1763.

Keim BD, Fischer MR, Wilson AM. 2005. Are there spurious precipitation trends in the United States Climate Division database? *Geophysical Research Letters* **32**: L04702 04710.01029/02004GL021985.

Keim BD, Wilson A, Wake C, Huntington TG. 2003. Are there spurious temperature trends in the United States Climate Division Database? *Geophysical Research Letters* **30(27),** 1404, doi:10.1029/2002GL016295 **30**: 1404, doi:1410.1029/2002GL016295.

LaChappelle ER. 1962. The density distribution of new snow. Project F, Progress Rep. 2, USDA Forest Service, Wasatch Nat'l Forest, Alta Avalanche Study Center, Salt Lake City, UT, 13 pp.

McGurk B, Azuma D, Kattlemann R. 1988. Density of new snow in the central Sierra Nevada In *Proc. of the 56th Annual Meeting, Western Snow Conference, Kalispell, MT.*158–161.

Roebber PJ, Bruening SL, Schultz DM, Cortinas JV. 2003. Improving snowfall forecasting by diagnosing snow density. *Weather and Forecasting* **18**: 264–287.

Schwartz MD, Reiter BE. 2000. Changes in North American spring. *International Journal Climatology* **20**: 929–932.

Trenberth KE, Fasullo J, Smith L. In Press. Trends and variability in column-integrated atmospheric water vapor. *Climate Dynamics*.

Trombulak SC, Wolfson R. 2004. Twentieth-century climate change in New England and New York, USA. *Journal of Geophysical Research* **31**: L19202, doi:19210.11029/12004GL020574.

Ware EC, Schultz DM, Brooks HE, Roebber PJ, Bruening SL. In Press. Improving snowfall forecasting by accounting for the climatological variability of snow density. *Weather and Forecasting*.

Wolfe DW, Schwartz MD, Lakso AN, Otsuki Y, Pool RM, Shaulis NJ. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. *International Journal of Biometeorology* **49**: 303–309.