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Changes in late-winter snowpack depth, water equivalent, and density in Maine, 1926–2004

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Abstract:

Twenty-three snow-course sites in and near Maine, USA, with records spanning at least 50 years through to 2004 were tested for changes over time in snowpack depth, water equivalent, and density in March and April. Of the 23 sites, 18 had a significant decrease (Mann-Kendall test, $p < 0{\cdot}1$) in snowpack depth or a significant increase in snowpack density over time. Data from four sites in the mountains of western Maine–northern New Hampshire with mostly complete records from 1926 to 2004 indicate that average snowpack depths have decreased by about 16% and densities have increased by about 11%. Average snowpack depths and water equivalents in western Maine–northern New Hampshire peaked in the 1950s and 1960s, and densities peaked in the most recent decade. Previous studies in western North America also found a water-equivalent peak in the third quarter of the 20th century. Published in 2006 by John Wiley & Sons, Ltd.

KEY WORDS snowpack; trends; Maine

INTRODUCTION

Snowpack data (including the areal snow-cover extent and the snowpack depth and water equivalent) have been used extensively as indicators of climate change in North America. They are important indicators for multiple reasons. Changes in snow-cover extent affect hemispheric and regional heat balances through changes in albedo and outgoing longwave radiation (Groisman *et al*., 1994; Leathers *et al*., 1995). Changes in snowpack depth can also affect heat balances because of the energy required to melt snow and evaporate water (Zhang *et al*., 2004). Changes in snowpack water equivalent (also referred to as the 'equivalent water content', i.e. the amount of water contained in the snowpack if it were melted) can impact regional water supply (e.g. Dettinger and Cayan, 1995) and the timing and magnitude of snowmelt runoff, which is often an important factor in regional flooding. As an example, snowmelt runoff added materially to the widespread March 1936 river flooding in the northeastern USA (Grover, 1937).

Snowpack in Maine is obviously affected by the local winter climate. The winter climatic gradient in Maine generally parallels the Atlantic Coast, with the warmest weather near the coast and the coldest weather in the western mountains (part of the Appalachian Mountains are located in northern New Hampshire and western Maine), and in far northern Maine (see Figures 1 and 2 for maps of Maine). The median seasonal maximum depth of the snowpack varies from about 500 mm along the coast to more than 800 mm in the western mountains and in northern Maine (Cember and Wilks, 1993). The average water equivalent on or near 1 March ranges from 80 to 130 mm along the coast to 180 to 230 mm in the western mountains and in northern Maine (Loiselle and Hodgkins, 2002). Almost all of the snow-course sites analysed by Loiselle and Hodgkins (2002) are at elevations less than 600 m and thus do not represent the full range of average water equivalent in Maine, since many mountains have elevations higher than 600 m. The average date of

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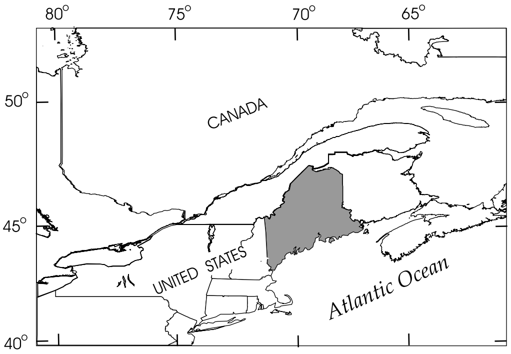

Figure 1. Location of Maine in eastern North America

maximum water equivalent varies from 10 March near the coast to between 25 March and 30 March in the western mountains and in northern Maine (Hayes, 1972).

The snowpack in Maine typically accumulates throughout the winter and reaches its maximum depth and water equivalent in March (Figure 3). Snowpack depth, water equivalent, and density data presented in Figure 3 were averaged from four snow-course sites in the mountains of western Maine–northern New Hampshire (sites 1027, 1028, 1030, 1031; Table I, Figure 2) for each date (e.g. 1 February, 1 March) that had at least 30 years of data at all four sites. Singular dates were used here rather than the sampling windows used later in this study. Because the actual day of historic snow-course sampling varied for different years, the dates have different years of record used in the computation of the average snowpack variables. The snowpack data used in this study are discussed in the 'Data and methods' section and these four sites are discussed more in the 'Results and discussion' section.

The average snowpack depth increases throughout the winter (Figure 3) and reaches a maximum of 720 to 730 mm on 1 March and 15 March. It then drops rapidly to 480 mm by 15 April, a decrease of 34%. The average water equivalent also increases steadily throughout the winter, reaches a maximum of about 187 mm on 15 March, and then drops to 176 mm by 15 April. This drop of 6% is much smaller than the percentage drop in snowpack depth. The snowpack density increases through the winter and early spring from a density of 190 kg m^{-3} in December to 270 kg m^{-3} on 15 March and 330 kg m^{-3} on 15 April. The density increases by 22% between 15 March and 15 April. Hendrick and DeAngelis (1976) observed that snowpack in the northeastern USA normally compacts from about 100 kg m^{-3} at snowfall to about 260 kg m^{-3} in late winter due to mechanical compaction, crystal metamorphosis, and rain on snow, even without significant inputs of sensible energy.

The seasonal development of the snowpack density for the four snow-course sites is very similar to that documented by Brown (2000) for boreal forests in southeastern Canada. The densities in Canada in December and January were slightly higher than the densities in western Maine–northern New Hampshire (by about 5 to 8%) and were slightly lower in March and April (by about 3 to 5%).

The average snowpack density is 270 kg m^{-3} at the time of maximum depth and water equivalent on 15 March. The density of melting snow usually ranges from 300 to 550 kg m^{-3} (Gray and Prowse, 1993). The average density for the four sites in western Maine–northern New Hampshire is 310 kg m^{-3} and 330 kg m^{-3} on 1 April and 15 April respectively, when some water equivalent is lost. The snowpack does not, on average, produce meltwater by 15 March in western Maine–northern New Hampshire. The snowpack depth for this date, in this area, is a good indicator of total winter snowfall, and the water equivalent is a good indicator of total winter precipitation. This likely holds true for areas from northern New Hampshire and western Maine through to northern Maine. The average date of maximum water equivalent in these areas varies from 15 March to 30 March. Southern and coastal areas in Maine, on the other hand, have an average date of maximum water equivalent near 10 March (Hayes, 1972).

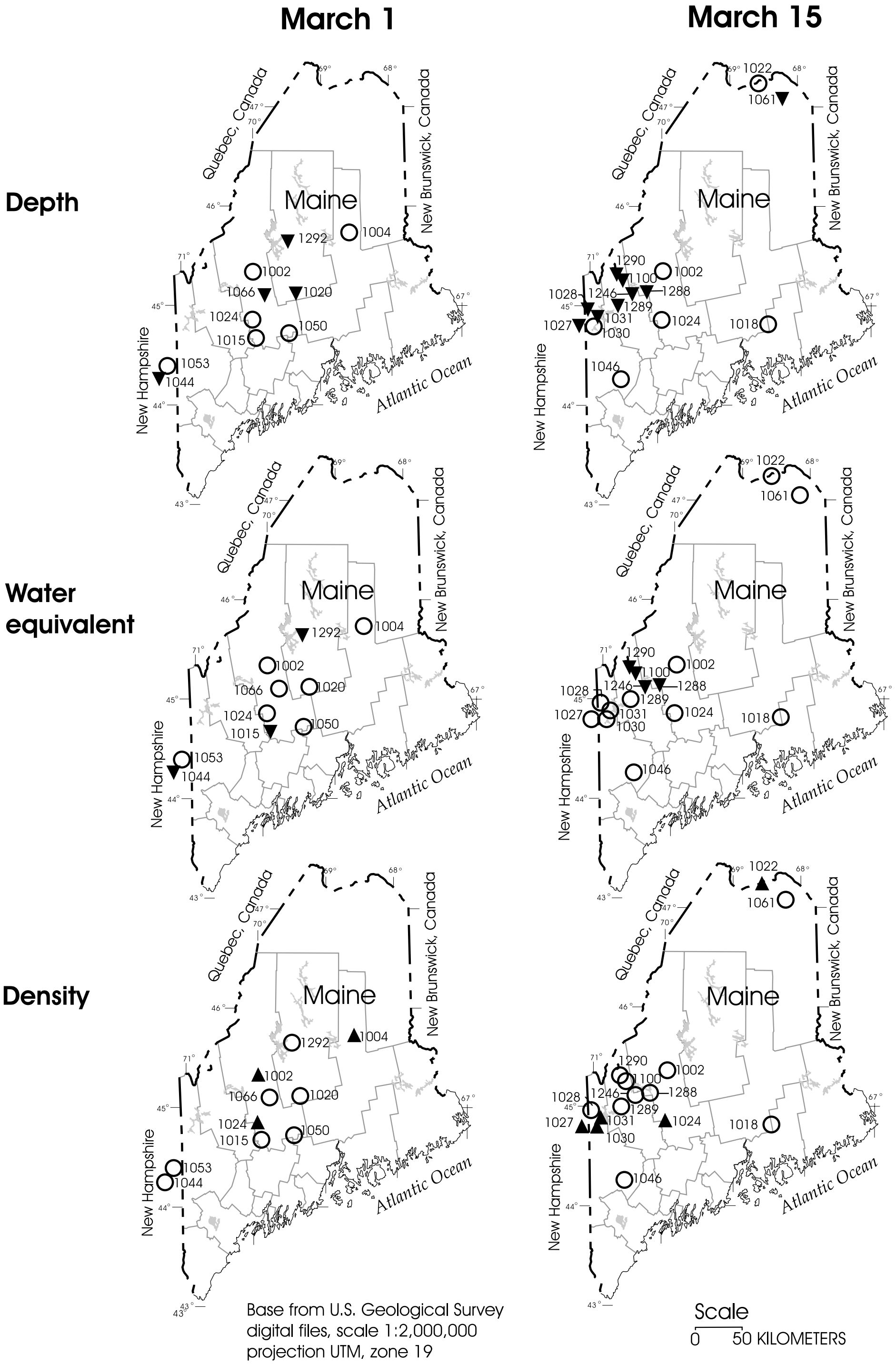

Figure 2. Location of snow-course sites and Mann–Kendall trend test results for changes over time in snowpack depth, water equivalent, and density for 1 March and 15 March sampling windows. Downward-pointing triangles represent significant ($p < 0{\cdot}1$) decreases over time, upward-pointing triangles represent significant increases over time, and open circles represent insignificant results

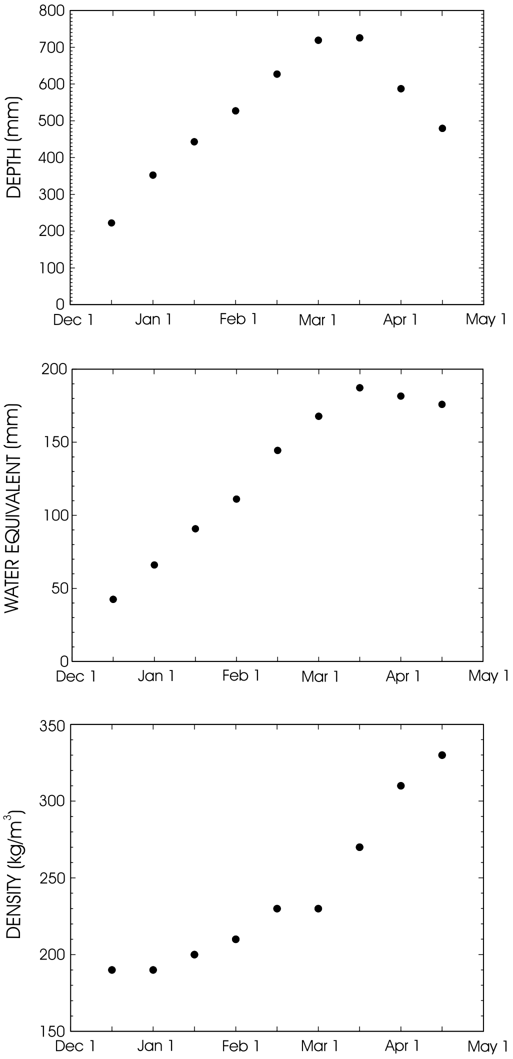

Figure 3. Average seasonal development of snowpack depth, water equivalent, and density for the average of four snow-course sites in western Maine–northern New Hampshire

DATA AND METHODS

Flood-forecasting agencies, people who live near streams, and many water-dependent industries need to know how much water to expect each year from snowmelt. Primarily for this reason, the Maine Cooperative Snow Survey Program, run jointly by the Maine Geological Survey (MGS) and the US Geological Survey (USGS), compiles snowpack data collected by several agencies and private companies on a regular basis (currently weekly, historically biweekly) in late winter and spring. This information on snow depth and water equivalent has been collected by electric-power utilities, water-power companies, pulp and paper companies, the National Weather Service, the USGS, the MGS, and others.

The depth and water equivalent of the snowpack have been measured at selected snow-course sites in Maine since the early part of the 20th century (Hodgkins *et al.*, 2005a). Most of the snow-course sites are in flat or gently sloping areas of mixed hardwood and conifer forest. Measurements are not taken near conifers.

Table I. Attained significance levels (p values) of Mann–Kendall trend test results for changes over time in snowpack depth, water equivalent, and density for selected sampling windows in late winter–early spring at snow-course sites in and near Maine (all sites in Maine unless noted as being in New Hampshire). Values in bold are significant at $p < 0.1$. Plus signs indicate increases over time and minus signs indicate decreases over time

Site no.	Site name	Sampling window	Snowpack depth		Snowpack water equivalent		Snowpack density		First year of record	Completeness of record (%)
1002	The Forks	1 March	0·24	–	0·89	–	**0·045**	+	1927	51
1004	Grindstone	1 March	0·15	–	0·78	–	**0·0067**	+	1932	63
1015	Mercer	1 March	0·27	–	**0·027**	–	0·13	–	1930	59
1020	Dover-Foxcroft (B)	1 March	**0·056**	–	0·15	–	0·19	+	1932	62
1024	North Anson	1 March	0·17	–	0·45	–	**0·020**	+	1926	63
1044	Pinkham Notch (UWP), NH	1 March	**0·018**	–	**0·070**	–	0·69	+	1939	55
1050	Pittsfield (B)	1 March	0·8	–	0·55	–	0·67	+	1938	63
1053	Gorham, NH	1 March	0·43	–	0·98	–	0·19	+	1941	52
1066	Mayfield (Bingham Upper)	1 March	**0·061**	–	0·12	–	0·17	+	1941	70
1292	Kokadjo (KWP)	1 March	**0·018**	–	**0·056**	–	0·29	+	1952	87
1002	The Forks	15 March	0·91	–	0·48	+	0·24	+	1921	55
1018	Amherst (BH)	15 March	0·49	–	0·24	–	0·91	+	1930	73
1022	Fort Kent	15 March	0·44	–	0·99	+	**0·038**	+	1931	58
1024	North Anson	15 March	0·47	–	0·86	–	**0·070**	+	1936	59
1027	Errol/Errol Dam (UWP), NH	15 March	**0·031**	–	0·14	–	**0·041**	+	1914	82
1028	Aziscohos/Aziscohos Dam (UWP)	15 March	**0·062**	–	0·14	–	0·17	+	1914	82
1030	Middle Dam (UWP)	15 March	0·18	–	0·99	+	**0·014**	+	1911	83
1031	Upper Dam (UWP)	15 March	**0·056**	–	0·61	–	**0·0035**	+	1914	84
1046	South Paris	15 March	0·23	–	0·25	–	0·45	+	1937	56
1061	Guerrette	15 March	**0·059**	–	0·33	–	0·94	–	1939	53
1100	Eustis (KWP)	15 March	**0·040**	–	**0·030**	–	0·39	+	1951	70
1246	Stratton (KWP)	15 March	**0·023**	–	**0·015**	–	0·27	+	1951	70
1288	Carrabassett (KWP)	15 March	**0·020**	–	**0·029**	–	0·67	+	1951	72
1289	Dallas (KWP)	15 March	**0·074**	–	0·12	–	0·49	+	1954	71
1290	Chain of Ponds (KWP)	15 March	**0·022**	–	**0·024**	–	0·44	+	1952	68
1027	Errol/Errol Dam (UWP), NH	1 April	**0·023**	–	**0·026**	–	0·33	+	1911	80
1028	Aziscohos/Aziscohos Dam (UWP)	1 April	**0·050**	–	0·18	–	0·15	+	1906	77
1030	Middle Dam (UWP)	1 April	0·24	–	0·57	–	0·40	+	1911	80
1031	Upper Dam (UWP)	1 April	**0·015**	–	0·19	–	**0·0001**	+	1911	81

Most data are collected at locations with an elevation of less than 600 m. There is very little historical site information available for the snow-course sites in this report. Some sites have been moved away from the local effects of development, extensive logging, or unacceptable amounts of conifer growth.

In 1991, the USGS and the MGS began to compile all historical snowpack data for Maine. The compilation was completed in 1993, and has been supplemented with additional measurements annually since then. Locations of snow-course sites were digitized into a geographic information system and linked to a tabular database containing the date of measurement, snowpack depth, and water equivalent. Several quality-assurance checks of the data were performed. Site identification numbers, dates, and measurements were examined to eliminate duplicate entries in the tabular database. Snowpack depths, water equivalents, and calculated snow densities (water equivalent divided by depth) were screened for unreasonable values, and anomalous entries were checked. As of summer 2004, the database contained approximately 24 400 measurements made at 319 snow-course sites; however, many sites have only sporadic measurements. Currently each year, about 70 sites are measured weekly in the late winter–early spring and about 200 sites are measured on or near 1 March.

For this article, data through to 2004 were screened again for unreasonable values. During snowmelt, snowpack densities usually range between 300 and 550 kg m^{-3} (Gray and Prowse, 1993). Values exceeding

600 kg m^{-3} are suspicious, if not erroneous. Snowpack in eastern North America can include a basal ice layer that can affect the average density of a snowpack, particularly that of a shallow snowpack (Dr R. E. Davis, Technical Director, US Army Corps of Engineers, Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, personal communication, 2002). All snowpack measurements with densities greater than 600 kg m^{-3}, and measurements with zero density, were examined. Data used in this article were censored if the density was zero, or if it exceeded 600 kg m^{-3} and the snowpack depth was greater than 150 mm, unless other measurements at the site (prior to or after the measurement in question) corroborated the measurement. There were only seven snowpack measurements from six sites that were censored.

Snowpack depth and water-equivalent data were analysed for those sites with data spanning at least 50 years, up to the present (2004). The exact date of sampling at a snow-course site varies from year to year. Sites often do not have data for every year for a given sampling window. Sampling windows are defined as 15-day windows centred on 15 February, 1 March, 15 March, 1 April, 15 April, and 1 May. To be included for analysis in this study, the sites were required to have at least 50% complete data for the first and second half of their record, for at least one sampling window. As an example of the 50% complete criteria, if a site had data from 1941 through to 2004 (64 years) for a given sampling window then that site must have had at least 16 years of data in the sampling window for the period 1941 through to 1972 (32 years) and for the period 1973 through to 2004 (32 years). Thirty-seven snow-course sites in and near Maine met the criteria described. All of the historical snow depth and water-equivalent data for these sites are reported in Hodgkins *et al.* (2005a). For any given year, if snowpack data were available for two or more dates in a sampling window, then the data collected closest to the centre of the window were used. In the case of a tie, the data were averaged. Missing values were left as missing and not estimated with data from nearby sites.

Because sampling windows were used, it is possible to have biased sampling over time. If sampling tends to be earlier or later over time, then any significant trends in the snowpack data could be the result of sampling bias. All data sets (individual snow-course sites for each applicable sampling window) that met the criteria for inclusion described in the previous paragraph were tested for significant changes over time in the date of sampling by using the nonparametric Mann–Kendall test (see 'Methods of analysis' section). Any data sets with attained significance levels (p values) less than 0·1 were considered to be biased and were removed from the study. Many sites with data for the 1 March sampling window were found to be biased, with many sampling dates prior to 1 March early in their record and dates after 1 March later in their record. Fourteen sites were eliminated from this study because of significant bias in the date of sampling. Twenty-three sites with data for at least one sampling window did not show significant sampling bias; this included 10 sites with data for the 1 March sampling window, 15 sites for the 15 March window, and four sites for the 1 April window (Table I). Some sites had acceptable data for more than one sampling window.

Methods of analysis

Temporal trends in the snowpack data were evaluated using the Mann–Kendall test. This test indicates whether a variable increases or decreases over time. No assumption of normality is required (Helsel and Hirsch, 1992). The data were smoothed for plots and for serial correlation testing by use of locally weighted regression (LOESS; Cleveland and Devlin, 1988) with locally linear fitting, a robustness feature, and a weighting function of 45 years. LOESS, using these parameters, is very similar to LOWESS (Cleveland, 1979). These locally weighted regression techniques allow the data to dictate the pattern of the smooth line and do not assume linearity (Hirsch *et al.*, 1993). Pearson's r was used as the measure of correlation in this paper.

There must be no serial correlation for the Mann–Kendall test results to be correct (Helsel and Hirsch, 1992). Serial correlations were analysed by computing the Durbin–Watson statistic on the residuals of the LOESS smooths for each of the 33 snowpack time series (16 for depth, eight for water equivalent, and nine for density) with significant trends ($p < 0{\cdot}1$) in Table I. None of these snowpack data series had significant positive serial correlation ($p < 0{\cdot}1$).

RESULTS AND DISCUSSION

Temporal trends

Twenty-three snow-course sites were tested for changes over time in snowpack depth, water equivalent, and density (Table I, Figure 2). Significant trends ($p < 0{\cdot}1$) were most common for snowpack depth: there were significant decreases in depth at 4 out of 10 sites for the 1 March sampling window, 9 out of 15 sites for the 15 March sampling window, and three out of four sites for the 1 April window (not shown in Figure 2). There were significant decreases for sites with long-term records (data extending from before 1940 to 2004), as well as for sites with short-term records. Most of the sites with significant trends were in central and western Maine and northern New Hampshire; however, this is also where most of the sites are located. All sites for all dates indicated decreases in depth over time, whether or not their trends were significant.

Similar trends in snowpack depth have been documented in areas of Canada near Maine. Brown and Braaten (1998) analysed mean monthly snowpack-depth data from observation stations across Canada from 1946 to 1995. They found a mixture of significant ($p < 0{\cdot}1$) and insignificant trends toward decreasing depths in February and March for areas of Canada to the west, north, and east of Maine.

There were significant decreases in water equivalent in this study at 3 out of 10 sites for the 1 March window, 4 out of 15 sites for the 15 March window, and one out of four sites for the 1 April window. There were only three sites with long-term water-equivalent records (data extending from before 1940 to 2004) that had significant decreases. As discussed later, the sites with shorter-term records may be anchored in a period of high average snowpack in the 1950s and 1960s. Nearly all of the sites with insignificant trends indicated decreases in snowpack water equivalent over time.

Similar temporal trends in water equivalent have been documented in western North America. Selkowitz *et al.* (2002) analysed spring snowpack water equivalent in the high elevations of northwestern Montana and southeastern British Columbia. The mean 1 April water equivalent for 21 sites decreased significantly (linear regression, $p = 0{\cdot}001$) from 1950 to 2001. The mean 1 May water equivalent for three sites from 1922 to 2001 did not have a significant trend ($p = 0{\cdot}42$). Annual mean water equivalents from these three sites tended to be low from 1922 to 1950, high from 1950 to 1975, and low from 1975 to 2001. Mote (2003) examined changes over time in water equivalent for sites in the high elevations of the US Pacific Northwest and adjacent areas of Canada. Nearly all of 230 snow-course sites showed decreasing 1 April water equivalent from 1950 to 2000. For a subset of sites with data from 1925 to 2002, average 1 April water equivalents were generally low from 1925 to 1950, high from 1950 to 1975, and low from 1975 to 2002. In Mote *et al.* (2005), 824 snow-course sites in western North America from the Rocky Mountains to the Pacific Ocean had 1 April records spanning 1950 to 1997. Most sites over this time period showed decreases in water equivalent, except in New Mexico, the southern Sierra Nevada Mountains of California, and some other locations in the southwestern USA, where increases predominated. Regional mean 1 April water equivalents generally had low values from 1925 to 1945, high values from 1945 to 1980, and low values from 1980 to 2002. Regonda *et al.* (2005) found significant decreases in water equivalent for 1 March, 1 April, and 1 May at approximately half of their sites (469, 501, and 239 sites respectively, in western North America) from 1950 to 1999. Some sites in the southwestern USA showed significant increases in water equivalent.

Five known studies in North America (Selkowitz *et al.*, 2002; Mote, 2003; Mote *et al.*, 2005; Regonda *et al.*, 2005; this study) have analysed changes over time in late-winter–early-spring snowpack water equivalent from snow-course sites where the water equivalent was measured directly. There are substantial water-equivalent data for western North America and Maine for the second half of the 20th century, but there are much less data available for the first half of the 20th century. The limited available data suggest that the snowpack in the third quarter of the 20th century tended to have high water-equivalent values and that there has been no substantial change in water equivalent from the 1920s to the start of the 21st century.

The trends from these five studies may or may not be representative of water-equivalent trends across all of North America. Brown (2000) analysed temporal trends in monthly mean (November through to April) North American water equivalent from 1915 to 1992 for areas south of approximately 55°N latitude. Water equivalent was estimated by use of monthly mean snowpack depths, snow-covered area, and assumed mean monthly snow densities. Snow densities were based on snowpack measurements from 1964 to 1993 across southern Canada. There was no evidence of trends in density for this period, despite rapid snow-cover reductions over much of southern Canada. Brown (2000) found significant (linear regression, $p < 0{\cdot}05$) increases in mean monthly water equivalent for December, January, and February, an insignificant increase for March, and a significant decrease for April. It is difficult to compare these results with the five previously mentioned studies because of differences in methodology, area, and time period studied.

There were significant increases in snowpack density (water equivalent divided by depth) in this study at 3 out of 10 sites for the 1 March window, 5 out of 15 sites for the 15 March window, and one out of four sites for the 1 April window. All of the significant increases were at sites with long-term records (data extending from before 1940 to 2004). Data from all but two of the sites with insignificant trends indicated increases in density over time.

Hydrologists often compute snowpack water equivalent indirectly using measured snowpack depth and assumed densities (Gray and Prowse, 1993). It is well known that snowpack density changes over the course of a winter season. It is less well known that snowpack density for a given date in the winter season can change over time. This study documents a significant change in density over time at several long-term (data extending from earlier than 1940 to 2004) snow courses in and near Maine. The estimation of snow water equivalent assuming a fixed snow density over time, as in Brown (2000), would in this case introduce a bias into water-equivalent trend analyses.

Overall, 18 of 23 snow-course sites in and near Maine had a significant decrease in snowpack depth or a significant increase in snow density over time in the late winter–early spring (Table I). All of the significant changes over time at the 23 sites were toward decreasing snowpack depth, decreasing water equivalent, and increasing density.

The longest and most complete snowpack records are from four sites (1027, 1028, 1030, 1031; Table I, Figure 2) in the mountains of western Maine–northern New Hampshire at elevations of approximately 400 to 500 m. These sites have mostly complete data for the 15 March sampling window from 1926 to 2004 and were used to quantify the magnitude of changes over time in snowpack depth, water equivalent, and density. Data from these sites were averaged for the 15 March window for all years that had data at all four sites. The average annual depths, water equivalents, and densities are shown in Figure 4 with a LOESS smooth through the data. Snowpack depths are significantly decreasing over time ($p = 0{\cdot}084$) for the four-site average. Based on the LOESS smooth, average depths have decreased from near 700 mm in the late 1920s to near 600 mm in the most recent decade. Depths peaked near 800 mm in the 1950s and 1960s. Snowpack water equivalents are getting insignificantly lower over time ($p = 0{\cdot}45$), with average water equivalents near 180 mm in the late 1920s, peaking near 195 mm in the 1960s, and falling to near 170 mm in the most recent decade. Snowpack densities have become significantly higher over time ($p = 0{\cdot}036$), with average values near 260 kg m^{-3} in the late 1920s, dipping to 250 kg m^{-3} in the 1950s, and rising to near 290 kg m^{-3} in the most recent decade. Average snowpack depths decreased by about 16% and densities increased by about 11% from 1926 to 2004.

Potential reasons for changes in snowpack variables

Because of the relatively high amount of missing snowpack data at the snow-course sites in this study and the low density of high-quality (US Historical Climatology Network (USHCN)) meteorological sites in the study area, the causal mechanisms for temporal changes in snowpack variables were not investigated. Insight can be gained, however, from previous studies of climate-related variables in winter in northern New England. Possible reasons for the change in late winter–early spring snowpack in Maine include changes in air temperature, total precipitation, and total snowfall (which is related to both temperature and precipitation). Snowpack variables can also be impacted by changes in solar radiation, humidity, and wind speed.

There is evidence that changes in late winter–early spring snowpack depth, water equivalent, and density are related to changes in the ratio of winter snowfall to total precipitation. The ratio of December through to March

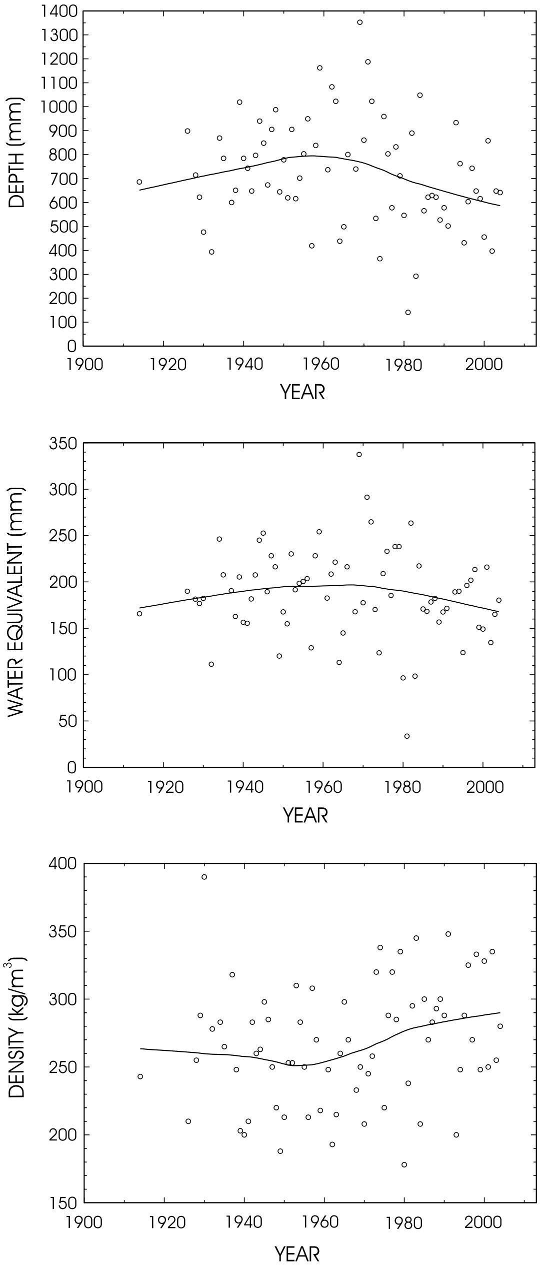

Figure 4. Changes over time in average annual snowpack depths, water equivalents, and densities for four snow-course sites in western Maine–northern New Hampshire for the 15 March sampling window. Solid lines are LOESS smooths through the data

snowfall to total precipitation decreased significantly ($p = 0{\cdot}043$) for the average of four USHCN stations in northern Maine and northern New Hampshire from 1949 to 2000 (Huntington *et al.*, 2004). Snowpack depth and water equivalent decreased and density increased in this time period (Figure 4). Snowpack depth and density are directly affected by more winter rain. Winter rain can melt part of the snowpack and result in lower water equivalent. The ratio of snowfall to total precipitation in northern New England was correlated with air temperature from the average of the four USHCN stations ($r = -0{\cdot}45$, $p = 0{\cdot}008$). The ratio of snowfall to total precipitation was correlated with total snowfall (snowfall liquid water equivalent, $r = 0{\cdot}48$, $p = 0{\cdot}0003$), but not with total precipitation ($r = -0{\cdot}078$, $p = 0{\cdot}59$) (Huntington *et al*., 2004).

Additional evidence of temperature-driven snowpack changes comes from studies of winter river-ice occurrence and thickness in northern New England. On average, for the nine longest-record rivers in northern New England, the total days of ice-affected flow (days when the amount of ice at a streamflow gauging station was substantial enough to affect the relation between stream height and flow) decreased significantly ($p = 0{\cdot}0013$) from 1936 to 2000 (Hodgkins *et al*., 2005b). The annual total number of days of ice-affected flow were significantly correlated with November through April air temperatures ($r = -0{\cdot}70$, $p < 0{\cdot}0001$) and with November through April precipitation ($r = -0{\cdot}52$, $p < 0{\cdot}0001$) for 17 USHCN temperature sites in the same area as the nine rivers. Both temperature and precipitation (November through to April) were tested for changes over time: neither had a significant change from 1936 to 2000 ($p = 0{\cdot}25$ and $0{\cdot}18$ respectively). There was a significant correlation between November through to April temperature and precipitation ($r = 0{\cdot}42$, $p = 0{\cdot}0006$): higher air temperatures were associated with higher amounts of precipitation. In the only other known study of winter geophysical or biological changes in northern New England, Huntington *et al.* (2003) found a significant decrease ($p = 0{\cdot}0021$) from 1912 to 2001 in average ice thickness around 28 February on the Piscataquis River in central Maine. The annual ice-thickness values were significantly correlated ($r = -0{\cdot}62$, $p < 0{\cdot}0001$) with December through to February air temperatures. Correlations with precipitation were not performed. In southern New England there was a northward shift in winter ranges of bird species on Cape Cod, Massachusetts, from 1930 to 2001 (Valiela and Bowen, 2003). The northward shift was positively correlated with local winter air temperatures ($r = 0{\cdot}81$ to $0{\cdot}91$).

Overall, the available evidence points toward warming temperatures in the winter in northern New England during the second half of the 20th century as the primary driver of changing late winter–early spring snowpack variables in Maine. Snow and ice variables may be more sensitive climatic indicators than air temperature. Increased temperatures are related to decreased ratios of winter snowfall to total precipitation (more winter rain), and increased temperatures could also be related to increased snowfall density and more frequent winter thaws. All of these mechanisms would lead to lower snowpack depths and higher snowpack densities.

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