Historical Trend in the Ratio of Solid to Total Precipitation in New England in Recent Decades

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ABSTRACT

The ratio of snow to total precipitation (S/P) is a hydrologic indicator that is sensitive to climate variability and can be used to detect and monitor hydrologic responses to climatic change. Changes in S/P ratio over time could influence the magnitude and timing of spring runoff and recession to summer base flow. The S/P ratio for 21 United States Historical Climatology Network (USHCN) sites in New England were examined. Annual S/P ratio decreased significantly ($p<0.05$) from 1950 through 1999 over northernmost New England. Temporal trends in other parts of New England generally were not significant, but a majority of sites in the Upper Connecticut River Valley and Coastal areas had weak decreasing S/P ratios. The four sites in northern New England showing the strongest and most coherent trends showed an average decrease in annual S/P ratio from 30% in 1950 to 22% in 1999. Trends in winter S/P ratio were also variable. Five sites, two in northern New England, two in the Upper Connecticut River Valley and one in a coastal region had significantly decreasing S/P trends. When trends in S/P were analyzed on a monthly basis for the northernmost sites, it was evident that decreasing S/P trends were significant for March and December only. Weak but significant correlations were observed between S/P ratios and the timing of spring runoff, North Atlantic Oscillation (NAO) index, and Trough Axis Index (TAI).

Keywords: snow, ratio of snow to total precipitation, hydrologic indicator variable, climate change

INTRODUCTION

Surface air temperature has increased globally during the 20th century, with substantial increases taking place in most northern temperate regions (Houghton et al., 2001). Biological responses to recent warming trends throughout northern temperate latitudes are well documented in recent reviews (Walther et al., 2002; Root et al., 2003; Parmesan and Yohe, 2003). In New England, phenological changes consistent with earlier spring warming have been reported including springtime advances in timing of lilac blooming (Schwartz and Reiter, 2000), bird migration (Dunne and Winkler, 1999), and anadromous fish migration (Huntington et al., In Press).. There is also evidence for a lengthening of the growing season in New England from the late 1700s/early 1800s to the 1930s and 1940s (Baron and Smith,1996) and in recent decades (Cooter and Le Duc, 1995).

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The warming trend over most of New England over the past 70 years is also well documented (Keim et al., 2003). Hydrologic variables in New England have shown temporally coherent trends that are consistent with winter and spring warming. For example, dates of spring lake ice-out (Hodgkins et al., 2002), river ice-out (Dudley and Hodgkins, 2002), and snowmelt-driven spring runoff (Hodgkins et al., 2003) are all becoming earlier and are correlated with warming surface air temperatures. There is also evidence for increases in late winter snow density (Dudley and Hodgkins, 2002) and decreases in river ice thickness (Huntington et al., In Press) that is consistent with climate warming in recent decades at sites in Maine. Similarly, and more broadly, there have been systematic decreases in April snow cover extent in North America (Brown, 2000).

There are also human dimensions to climate warming that are directly related to changes in snowfall in New England. For example, Hamilton et al. (In Press) report that part of the 20th century migration of New Hampshire's ski industry to the northern mountainous region, and consolidation into far fewer operations capable of large-scale snowmaking, is an adaptation to warmer and less snowy winters of recent decades. Rising sea surface temperatures during the last quarter of the 20th century (Houghton et al., 2001) have been implicated as one possible cause of the observed decline in abundance of winter flounder (*Pseudopleuronectes americanus*) in New England over that period (New England Regional Assessment Group, 2001). The decline in Maple Syrup production in Vermont, USA and the increase in Quebec, Canada in recent decades is thought to be related to both climate variability (due to systematic changes in precipitation and temperature) and socioeconomic factors (New England Regional Assessment Group, 2001).

Karl et al. (1993) found that the annual S/P ratio had decreased significantly ($P<0.01$) over Canada south of 55˚ N latitude during the period 1980 – 1990 compared with the previous three decades (1950-1979). For the period 1950 – 1990 there was also a decreasing trend (0.7% per decade) in the annual S/P ratio in southern Canada. They found a decreasing trend in annual S/P ratio over the contiguous US for the same period but it was not statistically significant. Predicted hydrologic responses to climate changes resulting from an increasing atmospheric burden of radiatively active gasses during the 21st century suggests a likelihood for reduced snow cover, earlier snow melt, and changes in the seasonal pattern of runoff (McCarthy et al., 2001). Trends in the timing of stream flow in North America are now well documented (Leith and Whitfield, 1998; Cayan et al., 2001; Dudley and Hodgkins, 2002; Hodgkins et al., 2003), strengthening confidence in model predictions, but historical analysis of shifts from nival to pluvial regimes has received far less attention. For example, changes in the S/P ratio could influence the timing of spring runoff, river ice-out, and late winter snow density.

This paper examines the S/P ratio using daily snow water equivalent (SWE) data for 21 stations in New England and relates these time series to other hydroclimatological time series within the region, the North Atlantic Oscillation Index (NAO), the trough axis index (TAI), and the Pacific North American index (PNA). It also evaluates the S/P ratio as a hydrologic indicator of climate variability for use in detection and monitoring of hydrologic response to climatic change. Such analysis can improve model development and confidence in model projections.

METHODS

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 and 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.

We used precipitation data from all USHCN stations in New England where continuous daily records were available to calculate annual or winter (here defined as December through March) composite records. Following Bradbury et al. (2002), March is included as a winter month because at many sites in New England March receives as much (or more) snowfall as December. As winter progresses, the longitudinal position of the East Coast trough migrates eastward resulting in cooler temperatures and more snowfall in March over New England than if the trough were stationary throughout the winter (Bradbury et al., 2002). Only sites where complete data were available for at least 54% of all years during the period 1950 through 1999 were included. Several USHCN sites in southern New England, most notably in western Massachusetts and Connecticut, had insufficient data for analysis.

Record completeness was defined as the total number of years having complete annual or winter records divided by the total number of years spanned by the record for each individual site. For the 21 sites included in this study data completeness averaged 77 % for the annual analysis and 84% for the winter analysis (Table 1). Time series for most USHCN sites in New England begin between 1948 and 1951. Only three sites, Ripogenus Dam, Orono, and Taunton did not contain data prior to 1955. There was somewhat more variability in the ending date. Several sites including First Connecticut Lake, Durham, Kingston, Lewiston, Orono, and Ripogenus Dam did not have any complete annual data after the mid 1990s. We controlled for temporal bias in missing data by requiring that there be no more than 40 percent missing record during any 10 year period.

Where snowfall was recorded for a given day, we used liquid precipitation amount as the SWE for the day. There can be both positive or negative biases using this procedure because on days when precipitation falls as both snow and rain, it is recorded entirely as snow or entirely as rain depending on whether there was measurable snow at the time of measurement. There are also differences among observers in terms of the number of times that snowfall is recorded on any given day. Under mixed precipitation conditions, more frequent observation may result in more days with snowfall recorded, under such circumstances, our algorithm would result in a bias towards more snowfall recorded than actually fell. We do not know how large the net effect of such bias could be, nor whether there could be systematic bias owing to changes in the 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 ratio of solid to total precipitation has decreased over time.

Time series were developed for SWE, total precipitation, and the ratio of SWE to total precipitation (S/P) for annual, winter (December through March) and monthly (October through April) periods. Time series were also developed for the timing of spring runoff using the average winter/spring seasonal center-of-volume date (WSCV) for 8 unregulated river gage sites in northern and mountainous areas of Maine and New Hampshire described by Hodgkins et al. (2003). The WSCV is defined as the Julian date (sequential day of year) on which 50% of the total runoff volume that occurs over the period January 1st through May 31st has passed the stream gage. This variable has been shown to be sensitive to late winter/early spring air temperature, particularly in this region of New England (Dudley and Hodgkins, 2002, Hodgkins et al., 2003). A subset of 7 of the USHCN sites (Presque Isle, ME; Houlton, ME; Ripogenus Dam, ME; Millinocket, ME, Farmington, ME; First Connecticut Lake, NH; Bethlehem, NH) that were closest to the 8 river gages used for WSCV analysis were averaged to develop time series for annual and winter temperature and precipitation for correlation analysis.

The North Atlantic Oscillation (NAO) index is a measure of the difference in sea-level pressure between Lisbon, Portugal and Stykkisholmur, Iceland that has been shown to be related to low-frequency climate variations over the north Atlantic (Hurrell et al., 2003) and snowfall over New England (Hartley and Keables, 1998). The NAO (also known as the northern hemisphere annular mode or NAM) has also been shown to modulate high frequency (daily) winter climatic variation in high-latitude continental regions (Thompson and Wallace, 2001; Wettstein and Mearns, 2002). Annual and winter NAO data were obtained from Hurrell et al. (2003). The trough axis index (TAI) is a measure of the mean longitudinal position of the East Coast trough and has been shown to be related to climate variability in New England (Bradbury et al., 2002). The Pacific North American Index (PNA) (Wallace and Gutzler, 1981) is another teleconnection that has been evaluated in relation to climate variability in New England (Hartley and Keables, 1998; Bradbury et al., 2002). TAI data were obtained from James Bradbury (University of Mass.) and PNA data were obtained from the University of Washington (http://tao.atmos.washington.edu/data_sets/pna/) where the record is maintained based on the approach of Wallace and Gutzler (1981). Multivariate El Nino Southern Oscillation (ENSO) and the Pacific Decadal Oscillation indices were also obtained for correlation with the winter S/P ratio because they have also been related to hydroclimate in New England (Bradbury et al. In Press). PDO data were also obtained from the University of Washington (http://tao.atmos.washington.edu/pdo/) (Mantua et al. 1997). Multivariate ENSO index (MEI) data were obtained from the National Oceanographic and Atmospheric Administration (http://www.cdc.noaa.gov/~kew/MEI/mei.html#ref_wt1) (Wolter and Timlin, 1998).

Time series for S/P ratio were plotted with a Locally Weighted Scatterplot Smooth (LOWESS) (Helsel and Hirsch, 1992) curve, with a weighting function of 66% of the period of record, for graphical interpretation of the trend. Temporal trend tests were conducted 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 was calculated to test for serial correlation. 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 the annual and winter S/P ratio and hydroclimatological variables and teleconnections. Trends or correlations having $p<0.05$ were considered statistically significant. Trends with p in the range of 0.05 to 0.20 were considered weak, but not significant.

RESULTS AND DISCUSSION

Time series analysis

Four sites in northwestern Maine or northernmost New Hampshire (northern New England) and one site in southwestern New Hampshire had significant decreasing trends in annual S/P ratios (Table 1, Figure 1). An additional eight sites had weak trends towards decreasing annual S/P ratio. Five sites had significant decreasing trends in winter S/P ratio and six additional sites had weak trends towards decreasing winter S/P ratio. The tendency for the more northern sites to show stronger annual than winter trends indicates that part of the trend in S/P ratio is driven by increases in non-winter precipitation. Aggregating data for the four northwestern sites showing the strongest trends in S/P ratio showed a significant decreasing trend for both annual and winter periods (Table 2). When the annual and winter S/P ratios for all 21 sites were aggregated for the period 1950 through 1999, Kendall’s tau trend tests indicated a significant decreasing trend on an annual basis and a weak decreasing trend on a winter basis (Table 2).

For the four sites in northern New England that showed significant decreases in S/P ratio, on average, the ratio decreased from about 0.30 to 0.22 (Figure 2). Based on the LOWESS curves, most of the decrease in S/P occurred after 1975. The fact that a majority of the change during the last 50 years occurred after 1975 is consistent with the temporal pattern of changes in annual S/P in Canada south of 55˚ N (Karl et al., 1993), the timing of other hydrologic variables in New England (Hodgkins et al., 2002; Huntington et al., In Press), and in regional surface air temperature (Houghton et al., 2001). Two of the northern New England sites, Presque Isle, ME and Millinocket, ME, had significant decreasing trends in winter S/P ratio, and one of the remaining two sites had a weak decreasing trend in winter S/P ratio (Table 1). For the four sites in northern New England, on average, the winter S/P ratio decreased from about 0.72 to 0.65 from 1950 to 1999 (Figure 2).

Table 1. Kendall's tau trend test p-values for temporal trends in the ratio of total annual and winter snowfall (snow water equivalent) to total annual and winter precipitation for USHCN sites in New England. The period of record was from 1949 through 1999 for the annual trends and for 1950 through 1999 for the winter trends.

USHCN Site	Lat., Long.	Completeness of record (%)		p-value and sign for trend in S/P ratio	
		Ann.	Wint.	Annual	Winter
Northwestern Maine and Northern New Hampshire					
Presque Isle, ME	46.65, -68.00	81	87	0.0006 -	0.013 -
Ripogenus Dam, ME	45.88, -69.18	54	68	0.0009 -	0.27 -
Millinocket, ME	45.65, -68.70	76	90	0.0047 -	0.042 -
First Connecticut Lake, NH	45.08, -71.28	79	96	0.0093 -	0.082 -
Northern Vermont					
Enosburg Falls, VT	44.92, -72.82	61	70	0.88 -	0.30 -
Burlington, VT	44.47, -73.15	98	100	0.34 -	0.42 -
St. Johnsbury, VT	44.42, -72.02	78	88	0.38 -	0.72 -
Central Maine					
Orono, ME	44.90, -68.67	70	69	0.35 -	0.12 -
Farmington, ME	44.68, -70.15	79	85	0.24 +	0.98 +
Upper Connecticut River Valley					
Chelsea, VT	43.98, -72.45	81	85	0.11 -	0.23 -
Hanover, NH	43.70, -72.28	62	72	0.11 -	0.022 -
Cavendish, VT	43.38, -72.60	88	94	0.14 -	0.44 -
Keene, NH	42.95, -72.32	88	92	0.0027 -	0.0085 -
Coastal and Near Coastal					
Eastport, ME	44.92, -67.00	78	90	0.076 -	0.53 -
Lewiston, ME	44.10, -70.22	64	84	0.35 +	0.48 -
Portland, ME	43.65, -70.3	92	97	0.10 -	0.18 -
Durham, NH	43.15, -70.95	62	72	0.13 -	0.056 -
Blue Hill, MA	42.22, -71.12	85	94	0.17 -	0.28 -
Taunton, MA	41.90, -71.07	74	77	0.098 -	0.029 -
New Bedford, MA	41.63, -70.93	79	74	0.56 -	0.11 -
Kingston, RI	41.48, -71.53	82	77	0.46 -	0.16 -

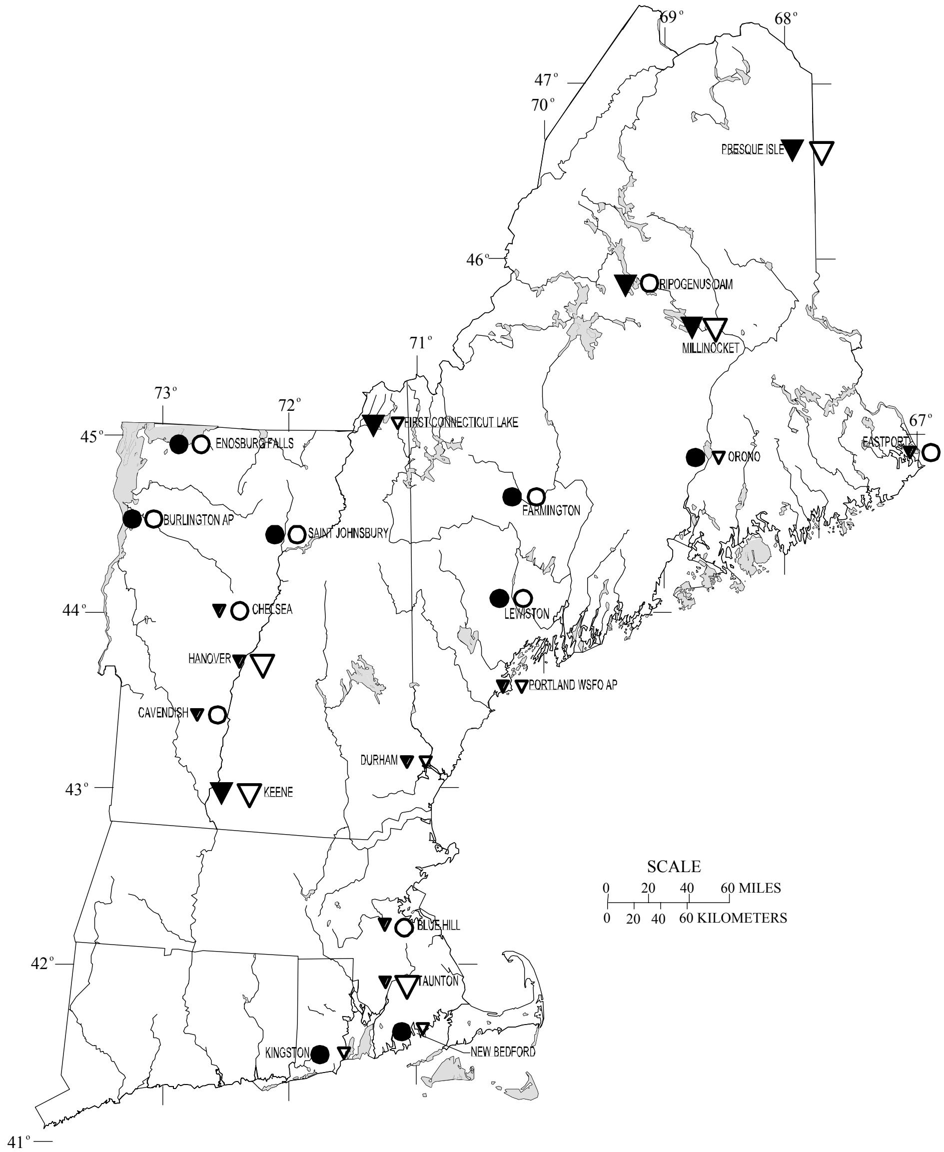


Figure 1. Locations and names of USHCN stations and temporal trend tests for changes in the ratio of snow to total precipitation (S/P). Solid symbols depict annual trends and open symbols depict winter trends. Northward-facing triangles indicate increasing trends, southward-facing triangles indicate decreasing trends, and circles indicate no trends. Large triangles denote significant trends (Kendall's tau p-values < 0.05) and small triangles denote weak trends (Kendall's tau p-values in the range 0.05 to 0.20).

Table 2. Kendall's tau tests for temporal trends in hydrologic and climatic variables for the period 1949 to 1999.

Variable	Kendall's tau p-value Annual	Winter
21 site avg. surface air temperature	0.32	0.35
21 site avg. total precipitation	0.023 (+)	0.17 (+)
21 site avg. snow water equivalent	0.067 (-)	0.14 (-)
21 site avg. S/P ratio	0.0069 (-)	0.11 (-)
4 site avg. surface air temperature	0.92	0.75
4 site avg. total precipitation	0.086 (+)	0.069 (+)
4 site avg. snow water equivalent	<0.0001 (-)	0.0080 (-)
4 site avg. S/P ratio	<0.0001 (-)	0.011 (-)
North American Oscillation (NAO)[1]	0.32	0.026 (+)
Trough Axis Index (TAI)[2]	--------	0.97
Pacific North American Index (PNA)[3]	--------	0.03 (+)
Winter/Spring Center of Volume (WSCV) date[4]	--------	0.019 (-)

[1] Average NAO for annual or winter December through February periods.
[2] Average TAI for December through March.
[3] Average PNA for November through March.
[4] Average WSCV date for 8 northwestern New England river gaging sites.

We analyzed S/P ratio for trends in individual months to determine which months had the strongest trends. For the four sites in northern New England, both March and December had significant decreasing trends in S/P (Figure 3). Both months had similar significance levels but the rate of decrease in S/P was greater in December than March. This suggests that the annual and winter trends are driven in large part by changes in S/P near the beginning and end of the winter season when temperatures are more frequently near freezing. During the coldest months, January and February, temperatures are usually well below freezing so small increases in temperature are not likely to result in a shift from snow to rain. On the more extreme shoulders of the winter season, November and April, typically less than 50% of the precipitation falls as snow. We expected to find the most significant effects at the beginning and end of the winter season based on previous studies of changes in growing season length (Cooter and LeDuc, 1995; Easterling, 2002) and model predictions for responses to climate warming (McCarthy et al. 2001).

Most of the coastal or near-coastal sites showed no significant trends in annual S/P ratio (Table 1, Figure 1). Four of eight coastal or near-coastal sites showed weak decreasing winter S/P ratio trends and one site (Taunton, MA) showed a significant decreasing trend. Northern Vermont showed no trends in annual or winter S/P ratio. The four sites in the upper Connecticut River valley showed weak, or for Keene, NH significant, decreasing annual S/P ratio trends, and two of these sites (Keene, NH and Hanover, NH) showed weak winter trends.

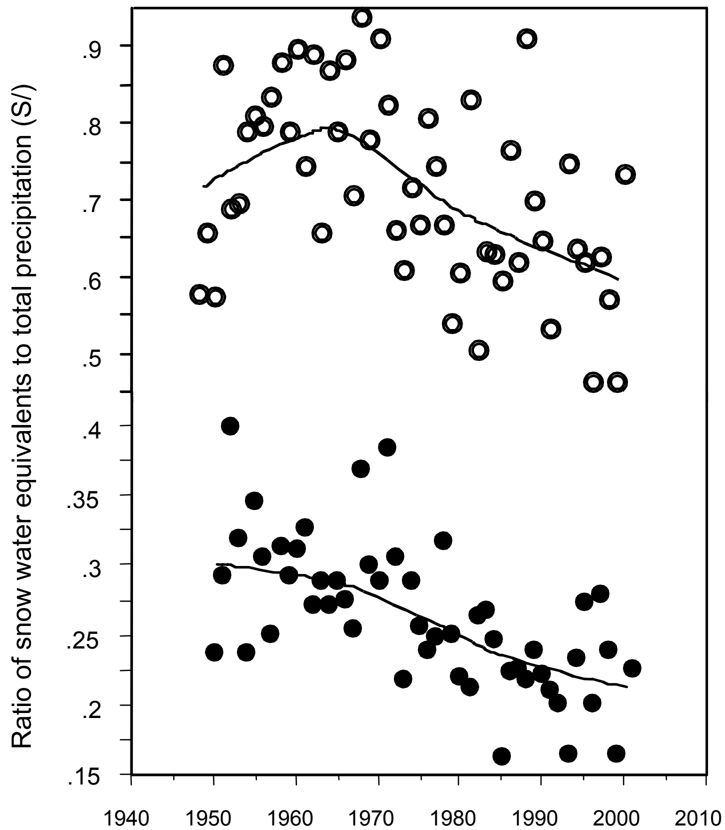
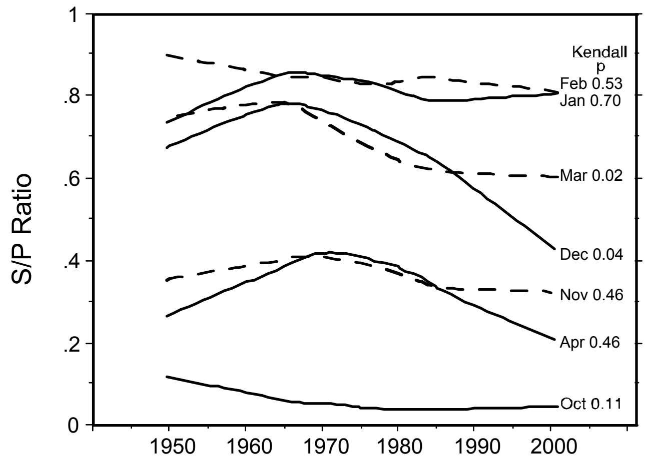


Figure 2. Long-term trends in the ratio of snow water equivalent to total annual (solid symbols) and winter (December through March) (open symbols) ratios (S/P). Data and LOWESS curves are aggregate plots for Presque Isle, Ripogenus Dam, Millinocket and First Connecticut Lake USHCN sites in northwest Maine and Northern New Hampshire.

Comparisons with other recent studies showing hydrologic responses to climate variability indicated some consistent geographic patterns in responses within New England. Northern New England had the most consistent trends in annual S/P ratio and also had the most consistently significant trends in earlier (by 1 to 2 weeks during the 20th century) high spring flows (Hodgkins et al. 2003). In this northern region, median seasonal maximum snow depths average 71 to >81 cm compared with 25 to 50 cm in southern and coastal regions, and 50 to 60 cm over other inland regions of New England (Cember and Wilks, 1993). These northern regions that had the largest trends towards decreasing S/P ratio and earlier high spring flows have substantially greater snow accumulation, thus warming would have a greater impact on snowmelt- (and rain on snow-) driven runoff than in more southerly regions.

Most of the unregulated rivers in northern New England that have been studied have also shown significant trends towards earlier river ice-out and fewer total ice-affected flow days (Hodgkins et al. Changes in the number and timing of ice-affected flow days on New England rivers, 1930-2000, submitted to *Climatic Change*). These trends revealed a geographic pattern similar to that observed for S/P ratio, such that the strongest (lowest p-values) trends occurred in northern New England. Ice thickness on March 1st on the Piscataquis River in central Maine has also decreased during the 20th century (Huntington et al., In Press.). These trends in river ice phenology and in the timing of high spring flows were all significantly correlated with late winter/early spring temperatures. These earlier papers did not attempt to correlate the observed changes in hydrologic variables to the S/P ratio. The S/P ratio time series is substantially shorter than that available for most of the other hydrologic variables. However, we expected to observe significant correlations between S/P ratio and hydrologic variables that were consistently correlated with late winter/early spring air temperatures for two reasons. First, most of the observed changes in hydrologic and climatic variables during the 20th century have occurred during recent decades for which S/P ratio data are available. Second, analyses of snow cover over the Northern Hemisphere (Brown, 2000), snowfall in parts of North America (Karl et al., 1993), frost over New England (Cooter and LeDuc, 1995; Easterling, 2002), and snow density in Maine (Dudley and Hodgkins, 2002) are all consistent with decreasing S/P ratio during the last 50 years.



Lowess curves for the ratio of snow to total precipitation (S/P) by month. Averages of four sites in northern Maine and northernmost New Hampshire. P-values are for Kendall's tau nonparametric trend test statistics.

Decreasing S/P ratio could be explained by snowfall decreases that were proportionately larger than decreases in rainfall, by constant snowfall and increasing rainfall, or increases in both, but larger increases in rainfall than snowfall. We tested for temporal trends in total annual and total winter precipitation, and we tested for trends in total snow water equivalent to determine which could best explain the observed trends in S/P ratio. For the New England region total annual precipitation (1950 through 1999) increased significantly and total winter precipitation showed a weak but insignificant increasing trend (Table 2). The four northwestern Maine and northernmost New Hampshire USHCN sites showed weak, but insignificant trends towards increasing total annual and winter precipitation. Total annual SWE and winter SWE for the period 1950 through 1997 showed weak but insignificant decreasing trends for the New England region but significant decreasing trends for northwestern Maine and northernmost New Hampshire (Table 2).

Based on these trends in nival to pluvial precipitation for the New England region, annual trends in S/P are a result of a combination of increasing rainfall (particularly during the non-winter period) and to a lesser extent, decreasing snowfall. In northern New England, significant trends towards decreasing snowfall are the dominant factor in explaining the significant decrease in S/P ratio. In this northern region, the weak trend towards increasing precipitation also contributes to the observed trends in decreasing S/P ratio. It has been suggested that climate warming may result in both increased precipitation and increased snowfall in many northern temperate latitude areas (McCarthy et al. 2001). The snowfall data for the 21 USHCN sites analyzed in this study do not support an increase in snowfall during the latter half of the 20th century in New England, on the contrary they indicate decreasing snowfall.

Others have reported increases in precipitation for northeastern USA and for southeastern Canadian provinces during the 20th century (Dai et al., 1997; Karl and Knight, 1998; Groisman et al., 2001). However, the period 1976 through 1999 showed decreasing precipitation while the period 1946 through 1975 showed increasing precipitation over this region (Houghton et al. 2001). These opposing trends during the third and fourth quarters of the 20th century may explain why we did not find stronger trends in S/P at many sites.

In southern Canada, the decreasing trend in annual S/P ratio for the period 1950 to 1990 reported by Karl et al. (1993) may have been driven primarily by a decrease in snow since total precipitation increased only slightly over the period, but neither trend was statistically significant in their study either. Karl et al. (1993) related their results to unprecedented warming trends but they did not investigate trends in winter S/P ratio so it is not clear how important increases in precipitation outside of the winter period may have been in forcing the trend they observed. More recent analyses (Houghton et al. 2001) indicate increases in precipitation over this region occurred during all seasons, when evaluated on a century scale.

Karl et al. (1993) assumed a temporally and spatially stationary ratio of snow depth to SWE for converting monthly cumulative snow depth into SWE prior to their time series analysis. This assumption could introduce a spurious trend if there had been systematic change in the SWE of the falling snow over time. Dudley and Hodgkins (2002) have shown evidence for statistically significant increasing snow density for the cumulative snowpack in late winter/early spring for coastal and eastern Maine over the period 1950 to 2000. Part of the increase in snow density observed by Dudley and Hodgkins (2002) could be a result of a systematic increase in the density of snow falling during late winter/early spring over time. The density of falling snow increases with increasing air temperature (Dube, 2003) therefore it is likely that increases in air temperature have resulted in increases in the density of falling snow. This increase in snowpack SWE in late winter/early spring, or ripening of the snowpack, is consistent with warmer spring temperatures, more frequent rain on snow, and/or denser (wetter) snow. Such a trend, if present at the sites analyzed by Karl et al. (1993) would result in a bias towards decreasing S/P ratio.

Correlation analysis

Both the annual and winter S/P ratios at the four northwestern sites were significantly and positively correlated with timing of spring runoff (WSCV date) (Table 3). The S/P ratio has decreased as the WSCV date has become earlier in spring. This correlation was expected because both variables would likely be responsive to increasing surface air temperature. For New England, winter S/P ratio was not correlated with surface air temperature, but annual S/P ratio was significantly and negatively correlated with surface air temperature (Table 3). For the northwestern Maine and northernmost New Hampshire region the reverse was true, winter S/P ratio was significantly correlated with temperature and annual S/P ratio was not.

We expected that warmer air temperature would be associated with a decrease in S/P ratio as more precipitation occurred as rain versus snow. Results are consistent with this hypothesis for the northern sites but not for the larger New England region. Together these results indicate that increases in total annual rainfall are associated with the observed trends in S/P ratio for the New England region and that both temperature and precipitation are associated with the observed S/P ratio trends in the northern region.

Winter S/P ratios for New England (and especially for northern New England) were significantly and negatively correlated with winter NAO (Table 3). The annual S/P ratio for northern New England was also significantly and negatively correlated with annual NAO. The NAO modulates the circulation pattern over the middle and high latitudes and regulates the number and intensity of significant weather events at middle and high latitudes. In the negative phase of the NAO high pressure often builds over Greenland, which produces a blocking pattern

Table 3. Pearson correlation coefficients (*r*) for relations between average S/P ratios and hydrologic and climatic variables in New England.

Variable	21 Site[1] Annual S/P *r*	p-value	21 Site[1] Winter S/P *r*	p-value
21 site[1] avg. surface air temperature	-0.49	0.0002	-0.05	0.77
21 site[1] avg. total precipitation	-0.39	<0.0001	-0.57	<0.0001
21 site[1] avg. total snow water equivalent	----	----	0.32	0.0011
NAO[3]	-0.18	0.22	-0.29	0.040
TAI[4]	----	----	0.27	0.059
PNA[5]	----	----	-0.25	0.081
PDO[6]	----	----	-0.17	0.24
ENSO[7]	----	----	0.005	0.97
	4 Site[2] Annual S/P		4 Site[2] Winter S/P	
4 site[2] avg. surface air temperature	-0.17	0.23	-0.44	0.016
4 site[2] avg. total precipitation	-0.28	0.048	-0.10	0.47
4 site[1] avg. total snow water equivalent	----	----	0.35	0.0004
NAO[3]	-0.31	0.029	-0.29	0.044
TAI[4]	----	----	0.30	0.041
PNA[5]	----	----	-0.24	0.098
WSCV date[7]	0.47	0.0005	0.53	<0.0001

[1] Average of 21 New England USHCN sites.
[2] Average of 4 northwestern New England USHCN sites (Presque Isle, ME, Ripoenus Dam, ME, Millinocket, ME, and First Connecticut Lake, NH)
[3] Average NAO for December through February.
[4] Average TAI for December through March.
[5] Average PNA for November through March.
[6] Average PDO for December through March.
[7] Average ENSO for December through March.
[8] Average of 8 northwestern New England river gauging sites.

that favors cold air advection and increased snowfall in northern New England (Bradbury et al., In Press). The positive phase of the NAO features a strong polar vortex, with the mid-latitude jet stream shifted to the north of its normal position. In the positive phase there is an increase in the occurrence of extreme warm days over much of the contiguous United States and a decrease in the occurrence of snowstorms affecting the Northeast. This out of phase relationship between the NAO index and snowfall over New England has been observed (Hartley and Keables, 1998; Thompson and Wallace, 2001; Hamilton et al., In Press). The persistence of high index polarity (positive phase) NAM during the 1980s and 1990s resulted in less cold arctic air spilling into mid-latitude regions and fewer large snowstorms ("nor'easters") during recent decades compared with earlier in the 20th century (Davis and Dolan, 1993; Thompson and Wallace, 2001). A significant decrease in snowfall has been reported for two sites (Keene and Berlin) in southern and northern New Hampshire respectively during the latter half of the 20th century (Hamilton et al., In Press). This would suggest that the observed trends towards decreased S/P ratio during the latter half of the 20th century are associated with this hemispheric-scale pattern of climate variability that has resulted in warmer winter temperatures and decreased snowfall.

There was also a significant positive correlation between winter S/P ratio and TAI for northern New England and weak, but not significant, correlations between winter S/P ratio and TAI for the New England region (Table 3). These findings are consistent with the fact that the TAI is significantly correlated with winter precipitation, particularly over more northern latitudes in New England (Bradbury et al., 2002). As the East Coast pressure trough (TAI) shifts eastward there is more winter precipitation over the New England region. Bradbury et al. (2002) have also reported a significant correlation between TAI and NAO such that negative NAO conditions accompany an eastward-displaced trough. We find that the PNA is not significantly correlated with the winter S/P ratio, which is consistent with the findings of Bradbury et al. (2002) and Hartley and Keables (1998) that PNA was not significantly correlated with northeastern climate variability. Neither PDO nor multivariate ENSO indices were significantly correlated with winter S/P ratio for New England (Table 3).

CONCLUSION

The evidence supports a decrease in annual and winter S/P ratio during the period 1950 to 1999 over parts of New England. About 25% of the sites showed significant decreasing trends and another 25 to 30% of the sites showed weak, but insignificant, decreasing trends (with Kendall's tau trend test p-values ranging from 0.05 to 0.17). The geographic patterns in the annual and winter decreasing S/P trends were similar and consistent with other hydroclimatological analyses in New England. The strongest trends were in the northernmost and Upper Connecticut Valley regions, weaker trends were found in the Coastal region and no trends were found in northern Vermont and Central Maine. High inter-annual variability, short periods of record, and lack of completeness in existing records make it difficult to make more definitive conclusions. Longer-term and more complete records have shown more definitive trends in lake ice-out (Hodgkins et al., 2002), timing of spring flow (Dudley and Hodgkins, 2002; Hodgkins et al., 2003), and river ice-out (Hodgkins et al., Changes in the number and timing of ice-affected flow days on New England rivers, 1930-2000, submitted to *Climatic Change*) in this region. Hydroclimatological time series that begin around 1950 are anchored during the period of regional cooling (1946 through 1975) (Houghton et al. 2001) that also included several years of exceptionally high snowfall in Maine (Dudley and Hodgkins, 2002). Anchoring this S/P ratio time series analysis at the beginning of this period of cooling may mask a stronger longer-term trend, but this cannot be verified without sufficient data prior to 1950.

The S/P ratio is a sensitive hydrologic indicator variable that that can be used to detect and monitor hydrologic response to climate variability in the future. The correlations between S/P ratio and precipitation and temperature are consistent with sensitivity to past and future climatic change. There is also an association between the S/P ratio and hemispheric-scale (i.e., NAO) and regional scale (i.e., TAI) atmospheric circulation patterns that indicates that part of the variation in S/P ratio is likely attributable to variability in these indices. It remains uncertain whether ongoing climate warming influences the variability in NAO (Visbeck et al . 2001) or TAI. Longer-term changes in S/P ratio over time could be quite important to the extent that they influence the magnitude and timing of spring runoff and recession to summer base flow.

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