Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002

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[1] Changes in the timing and magnitude of winter-spring streamflows were analyzed for gaging stations in eastern North America north of 41° north latitude during various periods through 2002. Approximately 32 percent of stations north of 44° have significantly earlier flows over the 50, 60, 70, and 90 year periods; 64 percent have significantly earlier flows over the 80 year period; there are no stations significantly later flows for any time period examined. Flows for the average of all stations north of 44° became earlier by 6.1, 4.4, 4.8, 8.6, and 6.5 days for the 50 through 90 year periods, respectively. Changes over time in monthly mean runoff support the flow timing results—January, February, and particularly March runoff show much higher percentages of stations with increases than with decreases over all time periods and May runoff shows relatively high percentages of stations with decreases. **Citation:** Hodgkins, G. A., and R. W. Dudley (2006), Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002, *Geophys. Res. Lett.*, *33*, L06402, doi:10.1029/2005GL025593.

1. Introduction

[2] Streamflow represents the integrated response of a drainage basin to climatic variables, especially precipitation and temperature. It is essential to understand the sensitivity of hydrologic variables such as streamflow to climatic change because human societies and aquatic and riparian ecosystems depend on the hydrologic cycle. One important area of study in regions of the world that have substantial snowmelt runoff is the timing of winter-spring streamflows.

[3] Three studies analyzed changes in streamflow timing at an extensive number of snowmelt-dominated rivers in western North America for most of the second half of the 20th century [*Cayan et al.*, 2001; *Regonda et al.*, 2005; *Stewart et al.*, 2005]. Streamflow became significantly earlier for many rivers; a majority of rivers had 3 to 20 day advances in timing with the largest advances occurring at rivers draining mid-elevation basins. Few rivers showed significant changes toward later flows.

[4] Changes in winter-spring streamflow timing also were analyzed for some parts of eastern North America: southeastern Canada and the far northeastern USA [*Zhang et al.*, 2001; *Burn and Hag Elnur*, 2002; *Hodgkins et al.*, 2003]. Significant changes toward earlier streamflow during the last century were found in the areas studied with almost no significant changes toward later streamflow. Information on the magnitude of changes is available only for some rivers in the far northeastern part of the USA where streamflows became earlier by 1 to 2 weeks. This article focuses on the significance and magnitude of temporal changes in the timing of winter-spring streamflows across eastern North America since 1913.

2. Data and Methods

[5] Daily mean streamflow data from rivers that drain relatively natural basins in eastern parts of the USA and Canada were used for this study. Streamflow-gaging stations were included if they had data spanning at least 50 years through 2002, no more than 5 percent missing data, and were located north of 41° north latitude and east of 100° west longitude. Stations in Quebec, Canada were included if data were available through 2001. We were interested in temporal changes in the timing of winter-spring streamflows in eastern North America that are substantially and regularly augmented by snowmelt runoff; substantial snowmelt runoff was not expected south of 41°. In the United States, data were obtained from the U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN) which includes data from 1659 streamflow-gaging stations across the USA [*Slack and Landwehr*, 1992]. This network contains stations with good quality data whose basins are relatively free of human influences such as regulation, diversion, land-use change, or extreme ground-water pumpage. Data from stations that met HCDN criteria for daily mean flows were used. Local USGS offices were contacted to make sure the relevant HCDN basins were still considered to be relatively natural. Canadian streamflow data were obtained from Environment Canada's Reference Hydrometric Basin Network (RHBN) which contains 243 streamflow-gaging stations and has similar criteria to the HCDN network [*Harvey et al.*, 1999]. Some 179 gaging stations met the criteria of this study, with 147 in the USA and 32 in Canada. Only 1 station is north of 50° north latitude.

[6] Monthly air-temperature and precipitation time series were obtained from the U.S. Historical Climatology Network (HCN) [*Karl et al.*, 1990]. The HCN data have been subjected to quality control and homogeneity testing and have been adjusted for several known biases, such as changes in station location.

[7] For a robust measure of streamflow timing at the selected streamflow-gaging stations, we used the center of volume (CV) date, which was first suggested by *Court* [1962]. To compute the CV date, daily flow volumes from the start to the end of each year or season are summed. The CV date is then computed as the date, from the start of the year or season, by which half or more of the volume flows by a gaging station. For this study, seasonal winter-spring (January 1 through June 30) center of volume (WSCV) dates were computed so that fall high flows wouldn't

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Table 1. Mann-Kendall Test Results for Significant Changes Over Time ($p < 0.1$) in Winter-Spring Center of Volume Dates[a]

	Years of Record				
	50	60	70	80	90
All Stations					
Number of stations	179	140	81	41	25
Percent earlier dates	15.1	13.6	18.5	34.1	16.0
Percent later dates	3.4	12.1	19.8	12.2	16.0
Stations North of 44° North Latitude					
Number of stations	80	55	36	22	12
Percent earlier dates	31.2	29.1	36.1	63.6	33.3
Percent later dates	0.0	0.0	0.0	0.0	0.0
Stations Between 41° and 44° North Latitude					
Number of stations	99	85	45	19	13
Percent earlier dates	2.0	3.5	4.4	0.0	0.0
Percent later dates	6.1	20.0	35.6	26.3	30.8

[a]All years of record through 2002.

obscure any signals in the snowmelt season. To examine the magnitude of any flow changes in the winter-spring season, mean monthly flows were computed for individual months from January through June.

[8] The significance of temporal trends were evaluated using the non-parametric Mann-Kendall test. The magnitudes of trends were computed using the Sen slope (also known as the Kendall-Theil robust line). This slope is computed as the median of all possible pairwise slopes in each temporal data set [*Helsel and Hirsch*, 1992]. The slope was multiplied by the appropriate number of years of data to obtain changes over time for different time periods. The changes over time in the monthly mean flows were divided by the appropriate drainage basin areas to obtain changes in runoff over time (in cm).

[9] There must be no serial correlation for the Mann-Kendall test p-values to be correct [*Helsel and Hirsch*, 1992]. The existence of serial correlation does not affect the estimated value of the Sen slope [*Yue et al.*, 2002]. Serial correlation was analyzed by computing the Durbin-Watson statistic on the residuals of the Sen slope lines of selected data sets that had a significant temporal trend ($p < 0.1$). There was no significant positive serial correlation ($p < 0.1$) in the WSCV dates tested: the 50, 70, and 90 year data sets. There were substantial amounts of positive serial correlation in the monthly mean flow series; 43 percent of stations had significant positive serial correlation for January through June mean flows for the 70 year time period. Mann-Kendall test results are not reported for the monthly mean flows.

3. Results

[10] Winter-spring center of volume (WSCV) dates during the last 50 to 90 years through 2002 were analyzed for many streamflow-gaging stations in North America east of 100° west longitude and north of 41° north latitude. Approximately 32 percent of stations north of 44° have significantly earlier ($p < 0.1$) dates over the 50, 60, 70, and 90 year periods and 64 percent have significantly earlier dates over the 80 year period (Table 1, Figure 1). The high percentage of significant trends in the 80 year period is due to late dates, on average, from 1923 through 1932 at many of the stations and to geographical sampling bias. No stations have significantly later WSCV dates over time in eastern North America north of 44° for any time period.

[11] In areas of eastern North America between 41° and 44° north latitude, few stations have significantly earlier WSCV dates (Table 1, Figure 1). Stations in this area have percentages of significantly later streamflows ranging from 6 percent to 36 percent, depending on the time period. Most stations between 41° and 44° in the western part of the study area (Iowa, southern Wisconsin, and northern Illinois) have later WSCV dates from 1953 to 2002 (Figure 2). For the 5 grouped stations with significantly later flows (Figure 1), average increases in April through June flow over time were much larger than those in January through March, which results in a shift toward later WSCV dates. Average precipitation from 1953 to 2002 for the 7 HCN stations in the same area as the 5 grouped streamflow-gaging stations also increased much more in April through June than in January through March.

[12] Most areas north of 44° north latitude have earlier WSCV dates from 1953 to 2002 (Figure 2). Some areas have a mix of earlier and later dates, including far eastern Canada (Nova Scotia and Newfoundland), and the western

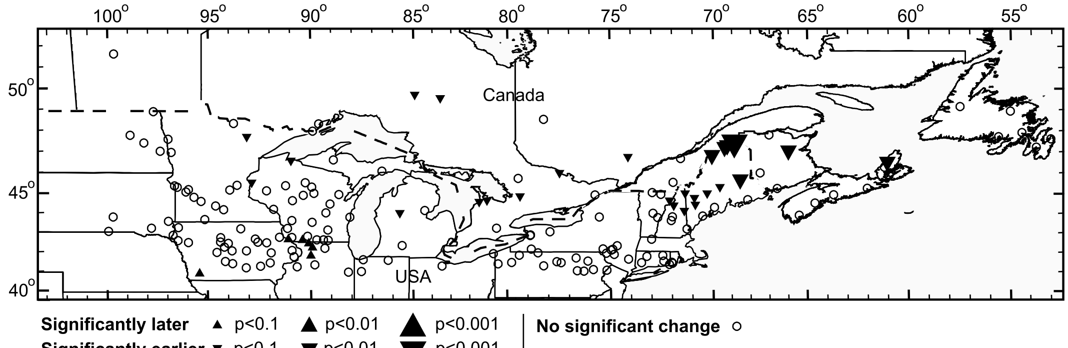

Figure 1. Significant changes in winter-spring center of volume dates, 1953–2002.

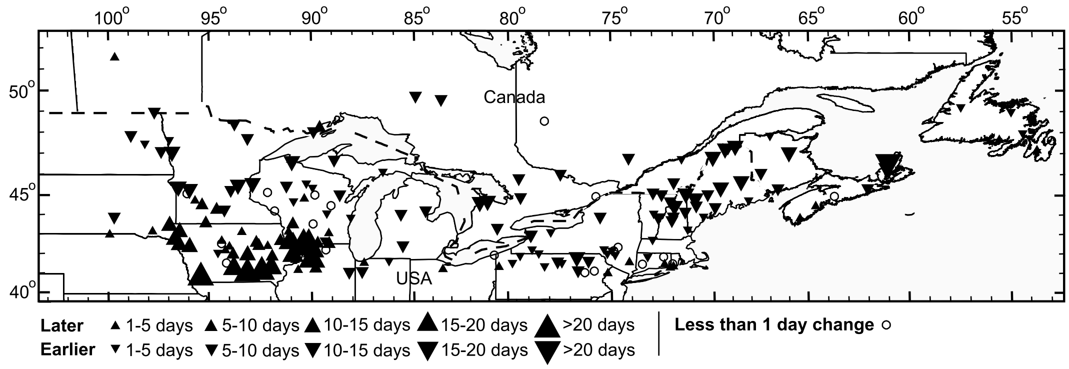

Figure 2. Magnitude and direction of changes in winter-spring center of volume dates, 1953–2002.

part of the study area in the USA (central Wisconsin and southern Minnesota). For 1953 to 2002, 76 percent of stations north of 44° had earlier WSCV dates by 1 to 15 days with 40 percent of all stations earlier by 5 to 10 days; 11 percent had a change of less than 1 day; and 11 percent had later dates by 1 to 10 days. For 1933 to 2002, 67 percent of stations had earlier WSCV dates by 1 to 15 days with 42 percent of all stations earlier by 5 to 10 days; 22 percent had a change of less than 1 day; and 6 percent had later dates by 1 to 10 days. Average WSCV dates for all stations north of 44° became earlier by 6.1, 4.4, 4.8, 8.6, and 6.5 days for the 50, 60, 70, 80, and 90 year periods (through 2002), respectively. The average WSCV dates had Mann-Kendall test p-values of 0.02, 0.14, 0.12, 0.01, and 0.01, respectively. Streamflow-gaging stations in North America north of 44° north latitude and east of about 85° west longitude generally show late WSCV dates on average from 1933 to the early 1970's and early WSCV dates on average from the early 1970's to 2002 (not shown) [see, e.g., *Hodgkins et al.*, 2003]. Stations have less consistent patterns in areas west of 85° and in the far eastern Canadian regions of Nova Scotia and Newfoundland.

[13] Changes over time in monthly mean runoff at stations north of 44° north latitude support the WSCV date results. January, February, and particularly March runoff show much higher percentages of increases than decreases over all of the 50 to 90 year time periods (Table 2). Runoff in May, and to a lesser extent in June, shows relatively high percentages of decreases. March increases from 1953 to 2002 are relatively large in the far northeastern USA in Maine, New Hampshire, and Vermont and in far eastern Canada in Nova Scotia and Newfoundland (Figure 3a). There are relatively large May decreases in the far northeastern American states of Maine and New Hampshire and the adjoining eastern Canadian province of New Brunswick (Figure 3b).

4. Discussion

[14] Earlier snowmelt runoff is likely the primary cause of changes over time toward earlier WSCV dates in eastern North America between 44° and 50° north latitude. Changes in precipitation patterns also could contribute to earlier flows. Warmer air temperatures would cause earlier flows through earlier snowmelt and increased ratios of winter rain to snow. Earlier snowmelt also could be caused by increased solar radiation, higher winds, and higher humidity.

[15] All 6 mid-high latitude rivers modeled in the northern hemisphere by *Arora and Boer* [2001] experience earlier streamflows in a warming climate due to earlier snowmelt and the increased likelihood of rain rather than snow. Studies in North America using historical data have shown air temperature in the few months before and during snowmelt to explain much of the interannual variability in the timing of snowmelt-related streamflows [*Stewart et al.*, 2005; *Hodgkins et al.*, 2003].

Table 2. Sen Slope Results for Direction of Changes Over Time for Mean Monthly Flows at Stations North of 44° North Latitude[a]

	Years of Record				
	50	60	70	80	90
January Mean Runoff					
Number of stations	80	55	37	22	12
Percent increasing flows	68.8	81.8	89.2	81.8	91.7
Percent decreasing flows	31.2	18.2	10.8	18.2	8.3
February Mean Runoff					
Number of stations	80	55	37	22	12
Percent increasing flows	75.0	81.8	86.5	100	100
Percent decreasing flows	25.0	18.2	13.5	0.0	0.0
March Mean Runoff					
Number of stations	80	56	38	22	13
Percent increasing flows	93.8	91.1	94.7	100	84.6
Percent decreasing flows	6.2	8.9	5.3	0.0	15.4
April Mean Runoff					
Number of stations	80	57	40	22	14
Percent increasing flows	55.0	61.4	70.0	54.5	50.0
Percent decreasing flows	45.0	38.6	30.0	45.5	50.0
May Mean Runoff					
Number of stations	80	58	41	22	14
Percent increasing flows	37.5	39.7	39.0	22.7	21.4
Percent decreasing flows	62.5	60.3	61.0	77.3	78.6
June Mean Runoff					
Number of stations	80	58	41	22	14
Percent increasing flows	53.8	43.1	48.8	22.7	21.4
Percent decreasing flows	46.2	56.9	51.2	77.3	78.6

[a]All years of record through 2002.

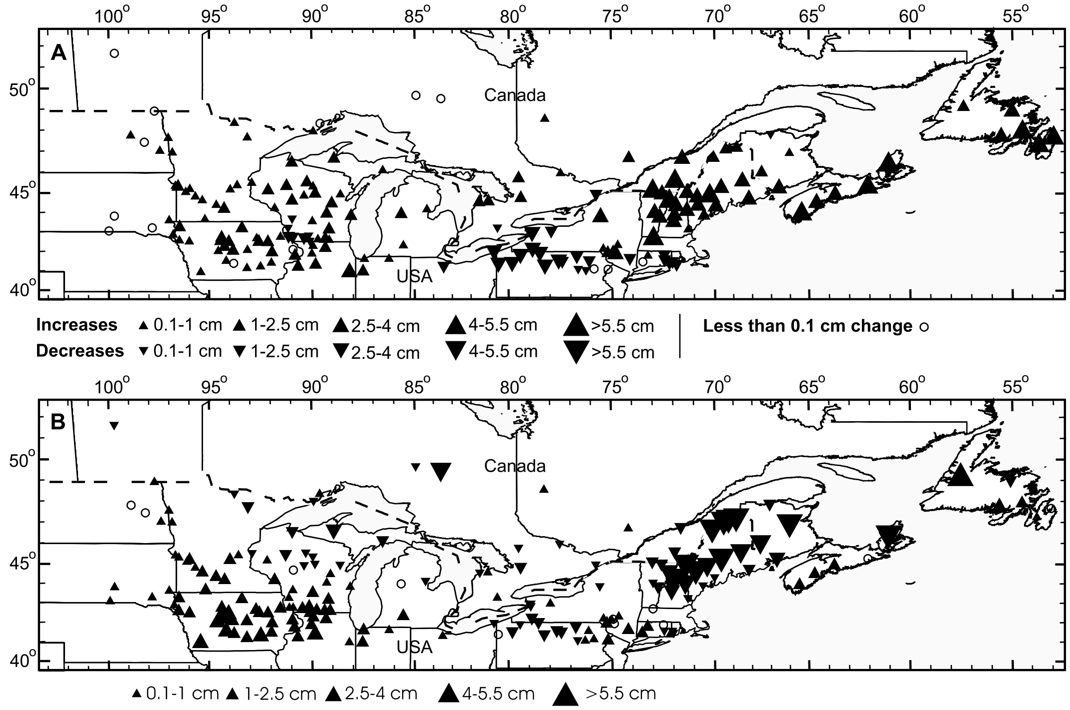

Figure 3. Magnitude and direction of changes in (a) March runoff and (b) May runoff, 1953–2002.

[16] Precipitation and air temperature data were averaged for the 10 HCN stations in the same area of the far northeastern U.S.A. that has a high concentration of significantly earlier WSCV dates (Figure 1) for 1953 to 2002. Precipitation increased more in April through June than in January through March, which runs counter to the observed trends toward earlier WSCV dates. Temperatures for this region increased over time in all months from January through June though none of the trends were significant ($p < 0.1$). Average March-April temperatures increased by 0.7°C. The precipitation and temperature data in this region support the concept of earlier snowmelt runoff being the primary cause of earlier WSCV dates.

[17] Significant changes toward earlier dates of winter-spring streamflows have now been documented across North America during the 2nd half of the 20th century (see Introduction for other studies). These changes are common in mountainous western North America for rivers draining mid-elevation basins and in eastern North America for rivers draining basins in areas from 44° to 50° north latitude. These areas have substantial winter snowpack and are warm enough to be sensitive to changes in winter and spring air temperatures.

[18] In western North America, earlier snowmelt runoff may have a large impact on water supply by 2050 due to the partial loss of natural water storage in the snowpack [*Barnett et al.*, 2005]. This may not be an important issue in mid-latitude areas of eastern North America because snowmelt here does not generally occur in the summer and summer rainfall generally is abundant. However, changes in the timing of streamflow may be important in eastern North America for other reasons. For example, higher winter flows, such as those documented in this study, can and have caused an increase in the frequency of mid-winter ice jams. River ice jams can cause major flooding and damage to river infrastructure [*Beltaos*, 2002].

[19] The ecological implications of changes in the timing of winter-spring streamflows in eastern North America are not well understood. One possible impact may be on Atlantic salmon survival rates. If the peak spring migration of juvenile salmon from freshwater rivers (which is controlled by photoperiod, temperature, and flow) becomes out of phase by 2 weeks with optimal environmental conditions in rivers, estuaries, or the ocean, salmon survival could drop substantially [*McCormick et al.*, 1998].

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