Vermont Climate Change Indicators

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(Manuscript received 16 September 2010, in final form 16 February 2011)

ABSTRACT

Climate change indicators are developed for Vermont in recent decades based on the trends in freeze dates, the length of the growing season, the frozen period of small lakes, and the onset of spring. These trends, which show a consistent pattern of a warming climate in Vermont during the past 50 yr, provide useful information for climate change adaptation planning for the state. The freeze period has become shorter and the growing season for frost-sensitive plants has become longer by about 3.7 (±1.1) days decade^{-1}, the date of the last spring freeze has come earlier by 2.3 (±0.7) days decade^{-1}, and the first autumn freeze has come later by 1.5 (±0.8) days decade^{-1}. The frozen period for small lakes, which depends on mean temperatures over longer periods, has decreased faster by 6.9 (±1.5) days decade^{-1}. Lake freeze-up has occurred later by 3.9 (±1.1) days decade^{-1}, while ice-out has come earlier by 2.9 (±1.0) days decade^{-1}. Lilac first leaf has also been coming earlier by 2.9 (±0.8) days decade^{-1}, while lilac first bloom has advanced more slowly, by 1.6 (±0.6) days decade^{-1}. The first leaf of Vermont lilacs, an indicator of early spring, is closely correlated with the ice-out of the small reference lake, Stile's Pond, because both are related to temperatures in February–April. In the past 40 yr, the growing season for frost-sensitive plants has increased by 2 weeks, and the growing season for frost-hardy plants may have increased more.

1. Introduction

The increase in atmospheric greenhouse gases, coming primarily from the burning of fossil fuels, is the likely driver of rapid climate change in recent decades (Pachauri and Reisinger 2007). However, there are considerable uncertainties in future regional climate scenarios. In addition, global indicators of ongoing climate change, such as the melting of the Arctic sea ice in recent decades (http://nsidc.org/arcticseaicenews/), are remote to most communities, and they are not closely correlated with local climate on annual time scales. On the other hand, changes in climate on local and regional scales can be directly perceived and easily understood by local communities.

In a broader sense, strategies are needed to improve climate literacy in society (Dupigny-Giroux 2008), because greenhouse gas mitigation and adaptation efforts depend on community understanding and acceptance of the reality of climate change. This paper develops some climate change indicators for the past few decades for Vermont, a midlatitude state near 44°N in the northeastern United States, using local datasets. Vermont is developing a climate change adaptation plan requested by the Governor's Commission on Climate Change (GCCC 2007). Understanding our vulnerability to climate change, and developing plans for adaptation, requires our best estimates for climate change in the coming decades. Combining regional projections from climate models with observed climate trends in New England in recent decades can be used as a basis for future planning (Hayhoe et al. 2006, 2008; Frumhoff et al. 2007). Here we will focus on the observed local trends in Vermont from recent decades. Hodgkins et al. (2009) have proposed a similar framework for updating hydrologic climate trends for the state of Maine, because these have been changing rapidly in recent decades.

Midlatitude continental regions have a large annual cycle of temperature, with warm and cold seasons (when frost is likely) of comparable lengths. As an illustration, Fig. 1 shows the mean annual cycle of temperature for Rutland at an elevation of 202 m (664 ft) in central Vermont for the past decade [derived from hourly data from Central Vermont Public Service (CVPS): see the appendix, section a], showing monthly mean daily minimum temperature $T_{\min}$, monthly mean temperature

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DOI: 10.1175/2011WCAS1096.1

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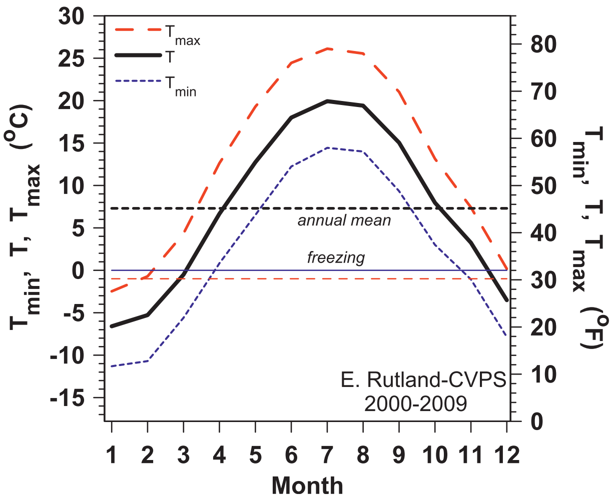

FIG. 1. Monthly mean temperature and mean daily minimum and maximum temperatures, 2000–09 for East Rutland.

T, and monthly mean daily maximum temperature T_{max}. The annual mean temperature is 7.3°C (45°F), with summer mean maximum temperatures reaching 26°C (79°F) in July and winter mean minimum temperatures falling to −11.3°C (12°F) in January. Daily temperature extremes cover a wider range than these monthly means. Killing frosts in spring and fall limit the summer growing season, and extreme minimum temperatures in winter determine the survival of some plants, shrubs, and overwintering insects. The critical climate reference temperature is the freezing point of water: 0°C (32°F). An upward mean shift of just 1°C (1.8°F) relative to the annual mean temperature has a significant impact on the Vermont climate by shrinking the length of the cold season and increasing the length of the warm season. A red dashed line at −1°C has been drawn, so the impact of this relative shift can be easily visualized.

As the global climate warms, winter temperatures over the northern latitude continents have generally been rising faster than summer temperatures (Hansen et al. 2010). The warming of global and regional climate is being driven by the greenhouse effect: as atmospheric CO_2 increases, this increases the surface warming by the downward longwave radiation from the atmosphere. This rather small effect is amplified substantially by two positive feedbacks. The increase of water vapor with temperature amplifies the warming in all seasons, because water vapor is a powerful greenhouse gas. However, there is an additional positive feedback in the cold season if snow cover is reduced, because this reduces the strong reflection of sunlight by the snow; this is called the shortwave snow– and ice–albedo feedback. These positive feedbacks operate on global scales at northern latitudes (Lemke et al. 2007) and contribute to the melting of the Arctic sea ice (Screen and Simmonds 2010), but they operate on local scales as well, and impact the winter season in New England (Betts 2011). As Vermont's climate warms, and the temperature shifts upward relative to freezing, this reduces the length and chill of the cold season. With warmer temperatures, the cold season shrinks, and the ratio of snow to rain in winter falls (Feng and Hu 2007). This tends to reduce snow cover and the reflection of solar radiation, so that the surface absorbs more heat. At the same time, evaporation and atmospheric water vapor increase with higher temperatures, and the water vapor greenhouse effect increases the downward longwave radiation that also heats the surface. Reduced snow cover and warmer winter and spring temperatures also change the hydrologic response, giving earlier spring runoff (Hodgkins et al. 2009).

There are global analyses of the variability and trends in lake and river ice cover in the Northern Hemisphere from 1846 to 1995 (Magnuson et al. 2000), which show trends toward later freezing (5.8 days century^{-1}) and earlier breakup (6.5 days century^{-1}) of ice on lakes and rivers, because temperatures have increased by about 1.2°C (2.16°F) century^{-1}. For the Lake Champlain basin, the long-term temperature records show considerable variability over the past century, with steeper upward temperature trends in recent decades of 0.5°F decade^{-1} (Stager and Thill 2010). The change in ice cover on Lake Champlain has been substantial. On average, the main body of the lake now freezes roughly 2 weeks later than during the early 1800s and about 9 days later on average than in 1900. The larger change is that during the nineteenth century the main lake remained open in winter only 3 times, but it remained open for almost half of the years between 1970 and 2007. This paper will not address the century-scale variability or the processes linked with regional climate variability, such as sea surface temperatures and atmospheric circulation modes (Wang et al. 2006; Brown 2010). The focus is on the recent (1960–present) climate trends of temperature, the length of the growing season, the freeze-up and ice-out of small lakes, and the spring leaf and bloom dates of lilacs in Vermont. The growing season and spring lilac data come from the much larger dataset of Schwartz et al. (2006), who discuss the earlier onset of spring in the Northern Hemisphere since 1961.

2. Temperature trends in Vermont since 1960

Figure 2 (left panel) shows the mean Vermont summer and winter temperatures (with Celsius temperature scale on the left and Fahrenheit scale on right). These are a mean of four Vermont climate stations in Burlington,

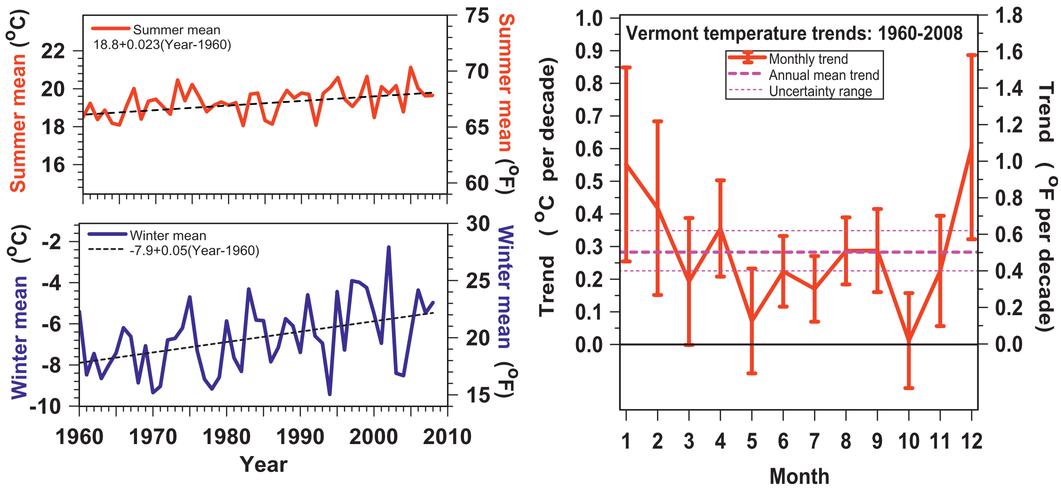

FIG. 2. (left) Summer and winter temperature trends in Vermont since 1960 and (right) monthly temperature trends and the annual mean.

Cavendish, Enosburg Falls, and Saint Johnsbury, preprocessed by Schwartz et al. (2006) and extended to 2008. Details and station locations are given in the appendix section b. The variability from year to year in winter is more than twice as large as that in summer. Trend lines have been fitted as dashed lines by linear regression. In summary, from 1960 to 2008

the summer trend is 0.23 ± 0.07°C (0.4 ± 0.12°F) decade^{-1} and
the winter trend is 0.5 ± 0.16°C (0.91 ± 028°F) decade^{-1}.

The trend in winter is about twice as large as that in summer. In 50 yr, mean winter temperatures in Vermont have risen about 2.5°C (4.5°F); while in summer, mean temperatures have risen about 1.1°C (2°F). There is an uncertainty in the trends of about 30%, because of the large variability from year to year. For these linear regression fits, the explained variance is small ($R^2 \approx 0.18$), because the interannual variability is large.

Figure 2 (right panel) shows the monthly trends from 1960 to 2008, where January is 1 and December is 12. The mean annual trend is the dashed line at 0.28 °C (0.5 °F) decade^{-1} (with the root-mean-square uncertainty range dotted above and below). This annual trend agrees with that reported by Hayhoe et al. (2006) and Frumhoff et al. (2007) for the northeastern United States from 1970 to 2000, and by Stager and Thill (2010) for the Lake Champlain basin for 1975–2005. We see the larger trends in winter (months 12, 1, and 2) than in summer (months 6, 7, and 8); as well as larger uncertainty bars in winter. The smallest trends are in May and October. This may perhaps be related to the increase in the length of the growing season (see later). More surface evaporation and cloud in these months than in earlier decades would cool the surface and reduce the trend.

3. Freeze period and growing season

For the same four Vermont climate stations, Schwartz et al. (2006) generated a table of first freeze dates in autumn and last freeze dates in spring, defined as the days when daily minimum temperature dropped below −2.2°C (28°F). The difference over the winter gives the length of freeze period. From these, we again generated a mean for the four stations for the period from 1960 to 2008 (see the appendix section b). The −2.2°C (28°F) threshold gives an estimate of nights with a killing frost (Schwartz and Reiter 2000), so the difference between the last freeze date in spring and first freeze date in autumn in the same calendar year can be considered the length of the growing season for frost-sensitive plants.

Figure 3 (left panel) shows the first and last freeze dates since 1960, and the right panel shows the length of the freeze period and the length of the growing season. The very large variation from year to year is striking. First and last frosts are single-day extreme events, which usually occur when cold, dry air is advected down from the north, so that with clear skies and less atmospheric water vapor, the water vapor greenhouse is reduced and the earth can cool rapidly to space at night. Trend lines have been fitted by linear regression. These show that in the past 50 yr, despite the large variability from year to year, on average the last spring freeze has come earlier and the first fall freeze has come later, so that the freeze period has become shorter and the growing season has become longer in Vermont. In summary, from 1960 to 2008:

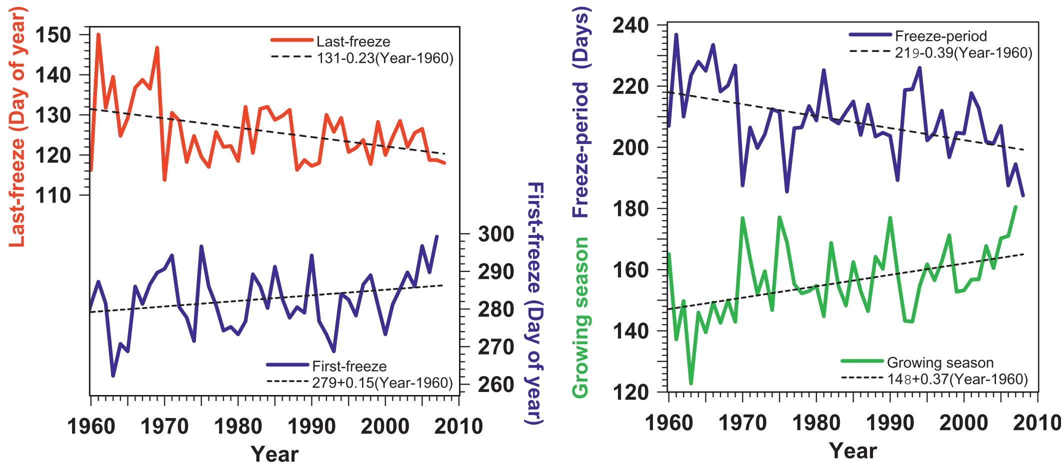

FIG. 3. (left) Last spring freeze and first autumn frost and (right) length of freeze period and growing season (data from Schwartz et al. 2006).

- the last spring freeze has come earlier by 2.3 (±0.7) days decade^{-1},
- the first autumn freeze has come later by 1.5 (±0.8) days decade^{-1},
- the freeze period has decreased 3.9 (±1.1) days decade^{-1}, and
- the growing season has increased 3.7 (±1.1) days decade^{-1}.

Thus, in the past 40 yr, the growing season for frost-sensitive plants has increased by 2 weeks. Note that because the interannual variability is large (±6 to 9 days), the explained variance is small (typical $R^2 \approx 0.15$). Because first and last frosts are sensitive to the local topography as well as to specific daily weather events, some colder locations in Vermont, such as mountain valley floors and elevated terrain, will on average have a shorter growing season than this four-station mean.

4. Freeze-up, ice-out, and freeze length for small lakes

The first and last freeze dates shown in Fig. 3 are critical to the growing season for frost-sensitive plants. In contrast, the freeze-up and ice-out dates for small lakes (called ponds in Vermont) are good "integrated" climate indicators for the length and severity of the cold season in Vermont. The date of freeze-up depends on lake and air temperatures over many weeks in the fall, ice thickness depends on the severity of the winter, and the date of spring melt/ice-out depends on the ice thickness and air temperatures in spring. These dates are important for the ecology of the lakes, and the frozen period and ice thickness are important to the public for winter recreation, including ice fishing.

There has been an annual contest to guess the ice-out date on Joe's Pond in West Danville, Vermont, so these dates and the trend have been recorded since 1988. The freeze-up and ice-out dates for Stile's Pond in Waterford, Vermont, which is at the same latitude but a lower elevation, have been recorded since 1971 by the Fairbanks Museum in Saint Johnsbury (see the appendix section c). This gives an ongoing 40-yr record.

Figure 4 (left panel) shows the day of freeze-up for Stile's Pond and the day of ice-out for both Stile's Pond and Joe's Pond (dashed). Note that the two time series for ice-out closely follow each other, but Joe's Pond melts about 4 days later than Stile's Pond, because it is 206 m (676 ft) higher in elevation.

The right panel of Fig. 4 shows how many days Stile's Pond was frozen each winter. There is a large variation from year to year (±11 days), because regional weather patterns have a large variability, but the trend has been downward for four decades. The dotted lines are the mean trends for freeze-up, ice-out, and frozen duration for Stile's Pond (linear regression fits). Over the 40 winters,

- freeze-up has occurred later by 3.9 (±1.1) days decade^{-1},
- ice-out has come earlier by 2.9 (±1.0) days decade^{-1}, and
- lake frozen duration has decreased by 6.9 (±1.5) days decade^{-1}.

The mean trend shows that as our northern climate has warmed substantially in fall, winter, and spring Stile's Pond is frozen for 4 weeks less, on average, than it was 40 yr ago. Compared with section 2, we see that these trends are greater than the trends of the first and last freeze in fall and spring and the corresponding freeze period for

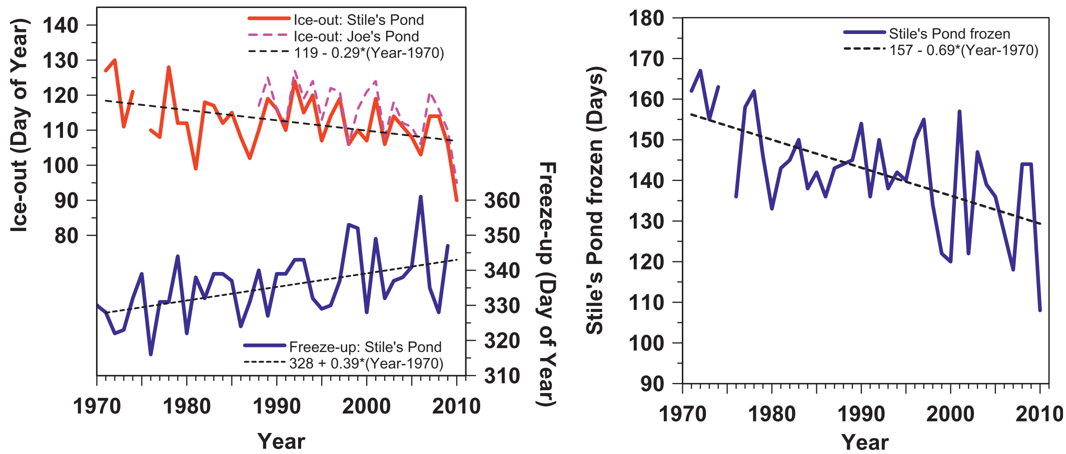

FIG. 4. (left) Freeze-up and ice-out days for Stile's Pond and ice-out for Joe's Pond and (right) winter frozen period for Stile's Pond. (Ice-out in 1975 is missing.)

frost-sensitive plants. The freeze-up and ice-out dates for small lakes depend on longer-period average temperatures in autumn and early spring, than the daily extremes that give frosts. Note that 2010 was an exceptionally early melt, well below the trend line, because the February–April mean set new high temperature records in all the New England states (see NCDC 2011).

Linear regression gives the dependence of the ice-out day of year (DOY) on February–April monthly mean temperatures in the form

$$\mathrm{DOY} = A + BT_{\mathrm{Feb}} + CT_{\mathrm{Mar}} + DT_{\mathrm{Apr}}, \qquad (1)$$

with the coefficients given in Table 1, line 1. The correlation with January temperatures is negligible. Defining a weighted temperature from the regression coefficients B, C, and D as

$$T_{\mathrm{wt}} = (0.52T_{\mathrm{Feb}} + 1.48T_{\mathrm{Mar}} + 2.21T_{\mathrm{Apr}})/4.21 \qquad (2)$$

gives the regression plotted in Fig. 5 (with rounded coefficients),

$$\begin{aligned}\mathrm{DOY(ice\text{-}out)} &= (123 \pm 4) - (4.2 \pm 0.5)T_{\mathrm{wt}}(^{\circ}\mathrm{C}) \\ &= (123 \pm 4) - (2.3 \pm 0.3)[T_{\mathrm{wt}}(^{\circ}\mathrm{F}) - 32].\end{aligned} \qquad (3)$$

The year-to-year variability in ice-out in Fig. 5 reflects the variability in this weighted February–April temperature. For every 1°C (1°F) increase in weighted temperature, ice-out comes earlier by 4.2 ± 0.5 (2.3 ± 0.3) days. In fall, freeze-up is correlated with November and December temperatures (not shown), but the cooling of the lake from its summer maximum temperature also depends on evaporation in the fall. We now turn to the first leaf and first bloom date of lilacs as climate indicators for the onset of spring, and we show that lilac leaf-out and lake ice-out are related, because both depend on February–April temperatures.

5. Lilac first leaf and first bloom dates

There is a long Vermont record (since 1965) of first leaf and first bloom dates for lilacs (*Syringa chinensis clone*) in the North American First Leaf and First Bloom Lilac Phenology Data (Schwartz et al. 2006). From six Vermont sites we generated an annual mean, spanning the time period of 1965–2008, for the first leaf and first bloom dates as indicators for the onset of spring in Vermont (see the appendix section d).

Figure 6 (left panel) shows the first leaf and first bloom dates since 1965 and the trend lines (from linear regression). Again, there is large variability from year to year, but the date of lilac first leaf in spring has advanced

TABLE 1. Regression coefficients for Figs. 5 and 6.

	A	B (T_{Feb})	C (T_{Mar})	D (T_{Apr})	E (T_{May})	R^2
Ice-out	122.8 ± 4.1	−0.52 ± 0.27	−1.48 ± 0.39	−2.21 ± 0.52		0.67
Lilac leaf	128.2 ± 4.1	−0.82 ± 0.25	−1.15 ± 0.36	−3.01 ± 0.47		0.75
Lilac bloom	187.6 ± 2.6			−1.65 ± 0.26	−2.59 ± 0.25	0.79

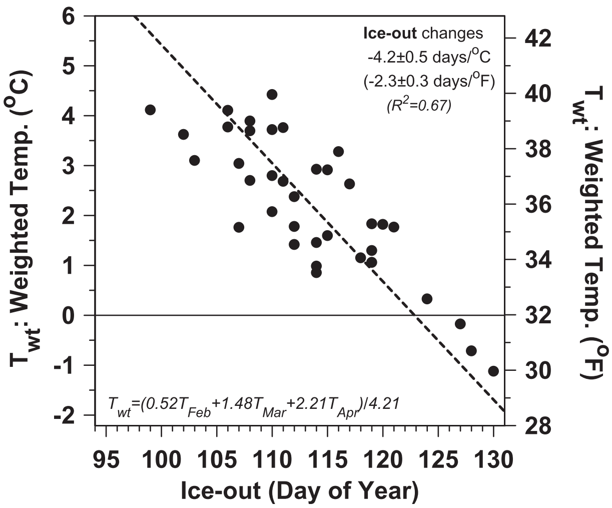

FIG. 5. Relation between ice-out and a February–April weighted mean temperature given by Eq. (2).

by about 2.9 ($\pm$0.8) days decade^{-1}, while the later date of lilac first bloom has advanced more slowly, by 1.6 ($\pm$0.6) days decade^{-1}. As a result, the mean time between first leaf and first bloom has increased from about 24 to about 30 days over the 45-yr period. The right panel of Fig. 6 shows how late winter and spring temperatures determine the year-to-year variability in first leaf and bloom dates. Lilac first leaf (in green) is well correlated with monthly mean temperatures for February–April. Defining a weighted temperature from the regression coefficients in Table 1, line 2 as

$$T_{\rm wt} = (0.82T_{\rm Feb} + 1.15T_{\rm Mar} + 3.01T_{\rm Apr})/4.98 \quad (4)$$

gives the regression plotted in Fig. 6 (with R^2 = 0. 75) with rounded coefficients

$$\begin{aligned}\mathrm{DOY(leaf)} &= (128 \pm 4) - (5.0 \pm 0.5)T_{\rm wt}(^\circ\mathrm{C}) \\ &= (128 \pm 4) - (2.8 \pm 0.3)[T_{\rm wt}(^\circ\mathrm{F}) - 32].\end{aligned} \quad (5)$$

For every 1°C (1°F) increase in this weighted temperature, lilac first leaf comes earlier by 5 ± 0.5 (2.8 ± 0.3) days.

Lilac first bloom (in magenta) is well correlated with monthly mean temperatures for April and May. Defining a weighted temperature from the regression coefficients in Table 1, line 3 as

$$T_{\rm wt} = (1.65T_{\rm Apr} + 2.59T_{\rm May})/4.24 \quad (6)$$

gives the regression plotted in Fig. 6 (with R^2 = 0.79) with rounded coefficients

$$\begin{aligned}\mathrm{DOY(bloom)} &= (188 \pm 3) - (4.2 \pm 0.4)T_{\rm wt}(^\circ\mathrm{C}) \\ &= (188 \pm 3) - (2.4 \pm 0.2)[T_{\rm wt}(^\circ\mathrm{F}) - 32].\end{aligned} \quad (7)$$

Thus, for every 1°C (1°F) increase in weighted temperature, lilac first bloom comes earlier by 4.2 ± 0.4 (2.4 ± 0.2) days. The slower decadal advance of lilac first bloom than first leaf is consistent with the fact that the long-term trend of May temperatures is less than the temperature trends in February–April (Fig. 2).

Lake ice-out and lilac first leaf are independent climate indicators, but they are correlated because both

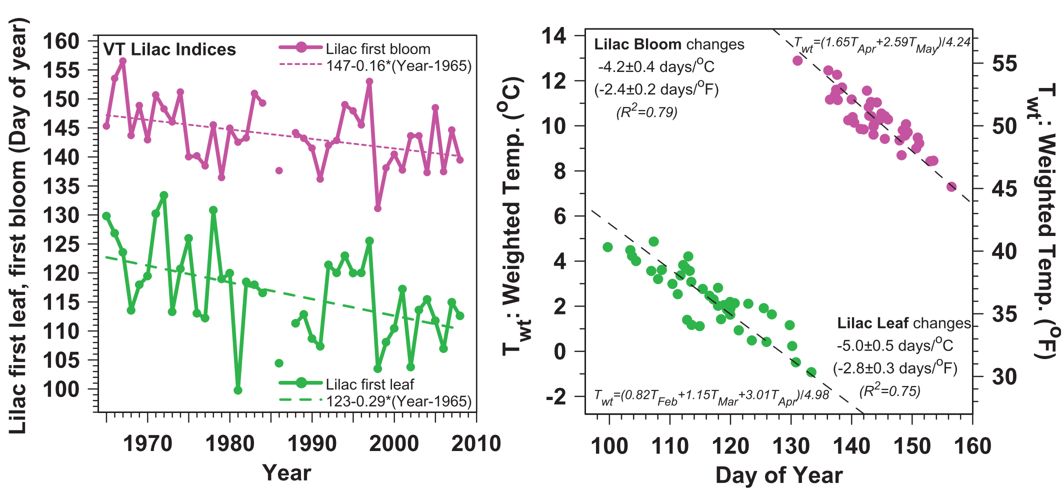

FIG. 6. (left) First leaf and first bloom days for Vermont lilacs and (right) first leaf and bloom days plotted against weighted mean temperatures, Eqs. (4) and (6). (Years 1985 and 1987 are missing.)

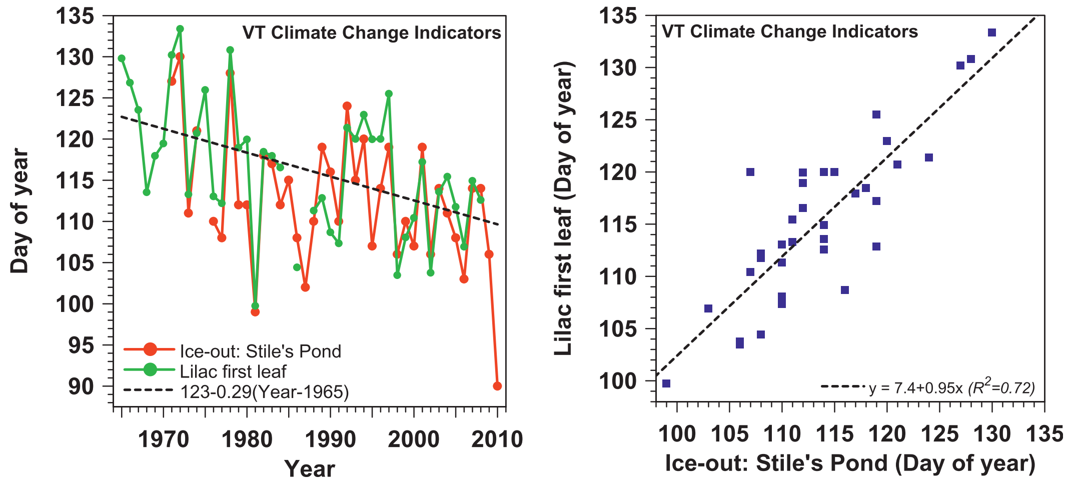

FIG. 7. (left) Ice-out days on Stile's Pond and Vermont lilac first leaf days and (right) first leaf plotted against ice-out.

depend on temperatures in February–April (although with different coefficients in Table 1). Figure 7 (left panel) plots the dates of lilac first leaf and the ice-out days for Stile's Pond together. The variations from the year to year are clearly similar, even though there are breaks where a year's observation is missing. The dashed regression fit to the lilac data is shown. The regression fit to the ice-out data has the same slope, but is shifted 2.3 days lower. The right panel of Fig. 7 plots first leaf directly against ice-out, and the dashed line is the linear regression fit. Lilac first leaf and lake ice-out are quite closely correlated ($R^2 = 0.72$). In most years lake ice-out and lilac first leaf occur within less than a week of each other, and both dates have advanced in spring by about 3 days decade^{-1}, consistent with the trend toward warmer temperatures in late winter and early spring.

6. Discussion and conclusions

The presented climate indicators show a consistent pattern of a warming climate in Vermont during the past 50 yr. The freeze period has become shorter and the growing season for frost-sensitive plants has become longer by about 3.7 ($\pm$1.1) days decade^{-1}, because the date of the last spring freeze has come earlier by 2.3 ($\pm$0.7) days decade^{-1} and the first autumn freeze has come later by 1.5 ($\pm$0.8) days decade^{-1}. The frozen period for small lakes, which depends on mean temperatures over longer periods than a single night's frost, has decreased faster by 6.9 ($\pm$1.5) days decade^{-1}. Lake freeze-up has occurred later by 3.9 ($\pm$1.1) days decade^{-1}, while ice-out has come earlier by 2.9 ($\pm$1.0) days decade^{-1}.

The first leaf of Vermont lilacs, an indicator of early spring, has also been coming earlier by 2.9 ($\pm$0.8) days decade^{-1}, which is the same trend as the ice-out date of our reference lake, Stile's Pond. Both ice-out and first leaf are correlated with temperatures in February–April, so lilac first leaf and ice-out dates are themselves closely correlated, and both are indicators of the severity of late winter/early spring temperatures. Lilac first bloom, which is correlated with April and May temperatures, has been advancing more slowly in spring by 1.6 ($\pm$0.6) days decade^{-1}.

The decrease of the frozen period of small lakes by 7 days decade^{-1} means that their unfrozen period has increased by 7 days decade^{-1}. This sets a possible upper limit for the lengthening of the growing season for frost-hardy plants. The lilac first leaf trend agrees with the ice-out trend in spring (3 days decade^{-1}), but we have no comparable phenological indicators in the fall, and plant senescence is likely to occur before lake freeze-up. Thus, in the past 40 yr, while the growing season for frost-sensitive plants has increased by 2 weeks; the growing season for frost-hardy plants may have increased more.

Climate has historically been defined in terms of 30-yr normals. This has been partly a practical matter to get a long-enough period for representative statistics, but the implicit assumption that climate can be considered stationary for 30-yr periods is no longer valid (Milly et al. 2008), because the climate system has a measureable warming trend, both globally and locally. The trends we show for the past four decades could be considered as likely first estimates for Vermont for the next few decades. They are independent of model projections; but they are also broadly consistent with the trends that are projected by global climate models through 2050 for the northeastern United States (USGCRP 2009). This suggests that these recent local historic trends and downscaled model projections for the next few decades provide a consistent reference framework for decision making. Other phenological and hydrological indicators should be developed.

In the much broader context, the steady decline of Arctic sea ice in recent decades indicates that the shrinking of the cold season seen in Vermont is part of the much larger warming trend at northern latitudes, driven by the same climate feedback processes (Screen and Simmonds 2010; Betts 2011).

Year-to-year variability is likely to continue to be large. The northern hemispheric winter (2009–10) was exceptional, with the Arctic Oscillation, related to the strength of the northern polar vortex, in an extreme negative phase (Hansen et al. 2010). Indeed, one important caveat is that the earth's climate system has instabilities, and abrupt changes in climate and weather regimes have occurred in the past (National Research Council 2002). At present, however, we are unable to predict these abrupt changes; so a strategy of extrapolating past trends, and updating them every few years, is a reasonable one. A study of the relation of Vermont climate indicators to global indices would however be useful.

Local and regional climate change indicators are very valuable. These trends provide useful information for climate change adaptation planning for the state. However, equally important, they can be directly perceived and easily understood from the collective experience of local communities. This can deepen the appreciation of the relation between local climate change and global climate change, and perhaps motivate individual and community acceptance of the need for climate change mitigation and adaptation strategies. Students in schools and colleges, as well as concerned citizens, can collect valuable observations related to the freezing of lakes, snow cover, phenology in spring and fall, river flow and chemistry, and the migration of birds; all of which are now responding to climate change. Local observations can be related to the seasons (Betts 2011) and to broader climatic indicators, such as monthly anomalies in temperature and precipitation (NCDC 2011), and inserted into ever-growing web archives for citizen scientists (NPN: http://www.usanpn.org/; Science for Citizens: http://scienceforcitizens.net/). Making and analyzing local observations reconnects us with the natural world, and this benefits climate literacy in society.

Acknowledgments. Alan Betts is supported by the National Science Foundation under Grant AGS-0529797. Thanks to Central Vermont Public Service for their hourly data from East Rutland, Vermont, and to John Ball for processing these data; to Steve Maleski of the Fairbanks Museum, St Johnsbury, Vermont, for the Stile's Pond data; and especial thanks to Mark D. Schwartz, Department of Geography, University of Wisconsin—Milwaukee for the lilac data, and the preprocessed climate station data, with the first and last freeze dates for Vermont.

APPENDIX

Methods

a. CVPS data

Central Vermont Public Service supplied their hourly data from January 2000 through December 2009 from East Rutland, Vermont, at 43.606°N, 72.956°W and 202-m (664 ft) elevation. The measurements are near a substation in a residential area on the east side of a central Vermont town with a population of about 20 000. The dataset is 99.87% complete: only 116 h are missing from 87 672 hourly records. We filled shorts gaps of a few hours by linear interpolation, and for one period of several missing days we substituted the average of the adjacent days' data. Daily means and daily maximum and minimum temperatures were generated, and these the monthly means are shown in Fig. 1.

b. Climate station data

Data from four Vermont climate stations were used (see Table A1. They range in elevation from 101 to 244 m. M. Schwartz (2010, personal communication) provided a Vermont subset of the data used by Schwartz et al. (2006), updated to 2008. For each station year of data, Schwartz et al. (2006) generated monthly mean temperatures and an annual suite of indices, including the first freeze date in autumn and the last freeze date in spring. These freeze dates are defined as when daily minimum temperature dropped below 28°F (−2.22°C). In this preprocessed dataset, for the 49 yr from 1960 to 2008, the annual record for Burlington is complete, but for the other stations the temperature data have missing months and years. We excluded 15 yr (1960, 1961, 1966, 1968, 1970, 1971, 1974, 1975, 1976, 1984, 1987, 1988, 2003, 2005, and 2008) for which data for one or more months was missing, and we generated a set of (nonstandardized) monthly temperature normals as the mean of the remaining 34 yr, for which all four stations have complete records. Then, for each station and month, we computed the temperature difference from these normals, averaged these, and added them to the mean of the normals to give a Vermont mean monthly temperature for each year. These were used for the trend plots in Fig. 2. The standard deviation of these differences (from station normals) among the four stations is 0.3°C in summer and 0.5°C in winter, which is much

TABLE A1. Vermont climate stations.

Station No.	Name	Lat (°N)	Long (°W)	Elev (m)
431081	Burlington	44.47	−73.16	101.22
431243	Cavendish	43.39	−72.6	243.9
432769	Enosburg Falls	44.72	−72.82	128.05
437054	St Johnsbury	44.42	−72.02	213.11

TABLE A2. Vermont lilac sites.

Station No.	Name	Lat (°N)	Lon (°W)	Elev (m)
430075	Swanton	44.92	−73.13	36.6
431243	Cavendish	43.38	−72.6	244
432843	Essex Junction 1N	44.52	−73.12	105
435542	Newport	44.93	−72.2	233
438556	Union Village Dam	43.8	−72.27	141.16
439099	West Burke	44.65	−71.98	274.39

smaller than the interannual variability shown in Fig. 2. Applying a less stringent filter to generate the temperature normals has little impact on our results.

The Schwartz et al. (2006) data give the freeze period, the number of days over the winter from the first freeze date in the previous autumn to the last freeze date in spring. Thus, the freeze period plotted for 2008 corresponds to the 2007–08 winter. We also calculated the growing season as the opposite difference between the last freeze date in spring and the first freeze date in autumn in the same calendar year.

We again generated a single Vermont mean from these four stations for the first and last freeze date, the freeze period, and the growing season by adding the average departures from the climate normals [given by Schwartz et al. (2006) for the period of 1961–90] to the average of the climate normals (of the 196 station years of data, only 10 yr are missing). These are the data shown in Fig. 3.

c. Frozen lake data

Joe's Pond is in West Danville, Vermont, at 44°25′N, 72°13.5′W, with an elevation of 473 m (1552 ft) and a maximum depth of 30 m (98 ft). As part of the annual contest to guess the ice-out date, these dates and the trend have been recorded since 1988 (details available online at http://joespondvermont.com/iceout.html). The ice-out date and time are defined as when an electric clock tethered to a block on the ice stops as a result of the ice break-up. The freeze-up and ice-out dates for Stile's Pond in Waterford, Vermont, which is at the same latitude but a lower elevation [44°25′N, 71°56.4′W and 267-m (876 ft) elevation] have been recorded by an observer for the Fairbanks Museum since 1971. Steve Maleski (2010, personal communication) of the Fairbanks Museum reviewed the records and supplied these dates for this study. The Stile's Pond ice-out date is missing in 1975. Both lakes are between 1.5 and 2 km in length.

d. Lilac first leaf and first bloom data

These data are archived though 2003 in the North American First Leaf and First Bloom Lilac Phenology Data (http://gcmd.nasa.gov/records/GCMD_LILAC_PHENOLOGY.html). Mark D. Schwartz (2010, personal communication) supplied an updated set for 1965–2008 for six Vermont sites that have the most complete records. We used the dates of first leaf and first bloom for these stations, given in Table A2. They span an elevation range from 37 to 274 m. Cavendish and Essex Junction have the most complete record, so their mean was used as the baseline. Data for 1985 and 1987 are missing. There are some gaps in the leaf and bloom data for the other four sites, so for each site a mean difference from this baseline was computed based on all years for which there were data. Missing years were filled in for these four sites using this mean difference, and a mean date for first leaf and first bloom in Vermont were then computed as an average of the six sites.

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