Past and Future Changes in Frost Day Indices in Catskill Mountain Region of New York

AAVUDAI ANANDHI,1 MARK S. ZION,2 PRASANNA H. GOWDA,3 DONALD C. PIERSON,2 DAVID LOUNSBURY,2 ALLAN FREI3

ABSTRACT

Changes in frost indices in the New York’s Catskill Mountains region, the location of water supply reservoirs for New York City, have potentially important implications. Frost day is defined as a day with \( T_{\text{min}} < 0^\circ\text{C} \). The objective of this study was to investigate past and predicted changes in minimum temperature \( T_{\text{min}} \) and six frost indices in the Catskill Mountains covering six reservoir watersheds. Studied frost indices included (1) number of frost days (nFDs), (2) number of months with frost (nFM), (3) last spring freeze date (LSF), (4) first fall freeze date (FFF), (5) growing season length (GSL), and (6) frost season length (FSL). Past changes in the frost indices were studied using observed daily \( T_{\text{min}} \) for each watershed for the period 1960–2008. Future scenarios of daily \( T_{\text{min}} \) values were derived by downscaling global climate model (GCM) simulations using a 25 bin change factor methodology. GCM simulations at a daily time scale were obtained from the World Climate Research Programme’s Coupled Model Intercomparison Project Phase3 (WCRP-CMIP3) multi-model dataset. The GCM simulations were for baseline scenario (20C3M), future scenarios (A1B, A2, and B1), and two 21st-century periods (2045–2065 and 2080–2100). Results indicated a general increase in average \( T_{\text{min}} \) and GSL and a decrease in number of nFDs, nFM, and FSL, earlier LSF, and later FFF from the historical to the future periods. Increase in GSL is expected to affect hydrologic, ecosystem, and biogeochemical processes with increased net primary productivity and a resulting increase in total annual evapotranspiration.

Keywords: number of frost days (nFDs), number of months with frost (nFM), last spring freeze date (LSF), first fall freeze date (FFF), growing season length (GSL), and frost season length (FSL).

1 Department of Agronomy, Kansas State University, Manhattan, KS, 66506, USA; anandhi@ksu.edu.
2 Water Quality Modeling Group, New York City Department of Environmental Protection, Kingston, NY, USA.
3 Conservation and Production Research Laboratory, United States Department of Agriculture, Bushland, Texas, 79012, USA.
4 Department of Geography, Hunter College, City University of New York, New York, NY, USA.
5 CUNY Institute for Sustainable Cities, City University of New York, New York, New York, USA.
INTRODUCTION

Snow and ice are essential components of the global hydrological and energy cycles, and they are closely associated with the frost occurrence (Jylhä et al., 2008). Numerous indices have been used to describe frost’s impact on natural and managed ecosystems (Schwartz and Reiter, 2000; Peterson et al., 2001; Visser and Holleman, 2001; Robeson, 2002; Kiktev et al., 2003; Feng and Hu, 2004; Levine et al., 2009; Zhao et al., 2009; Ben-David et al., 2010; Cuxart and Guijarro, 2010; Liu et al., 2010; Nakazawa et al., 2010; Rusticucci et al., 2010; Davi et al., 2011; Erlat and Türkeş, 2011; Kim, 2011; Neustupa et al., 2011; Pecetti et al., 2011; Potithep and Yasuoka, 2011; You et al., 2011; Zhou and Ren, 2011; Pons and Pausas, 2012; Terando et al., 2012). Indices make it easier to communicate information about climate anomalies to diverse audiences and allow scientists to assess climate anomalies quantitatively in terms of intensity, duration, frequency, and spatial extent, thereby providing important information useful for planning, designing, and management of applications (Tsakiris and Vangelis, 2005). Commonly used frost indices include the timing of the last frost day in spring and first frost day in fall of each year, number of consecutive frost days, duration of frost-free days, and length of the growing season. Many of these indices are calculated using daily minimum air temperature (T_{min}).

Changes in frost indices have important implications in New York’s Catskill Mountains region, the location of water supply reservoirs for New York City. More than 90% of the region is covered with forests. Snow is an important component of the region’s hydrological systems, ecosystems, infrastructure, travel safety, and winter tourism and recreation (Burakowski et al., 2008). Studies have shown that an increase in temperature in the region has led to a decrease in snowpack accumulation and duration (Burns et al., 2007; Matonse et al., 2011; Pradhanang et al., 2011; Zion et al., 2011). These changes will most likely force changes in the hydrology of the region by decreasing the proportion of precipitation falling as snow, shifting the timing of snowmelt and causing snowmelt-supplemented streamflow events to occur earlier in the spring or in late winter, which as a result will decrease the magnitude of traditionally high streamflows in April (Zion et al., 2011). More runoff during winter, in turn, can cause reservoir storage levels, water releases, and spills to increase during the winter and earlier reservoir refill in the spring (Matonse et al., 2011). Changes in the last frost day in spring, the first frost day in fall of each year, and the length of growing season will change the annual evapotranspiration and have profound direct and indirect effects on forest productivity, nuisance species (including pests, pathogens, and invasive species), wildlife, and forest nutrient cycling (Huntington, 2006; Campbell et al., 2009; Mohan et al., 2009). Hence, investigating current and future climate change on a regional scale is essential to understand potential impacts on humans and the natural environment (Hayhoe et al., 2007). The main objective of this study is to investigate the past and future changes in the frost indices in the Catskill Mountains region of New York State (NY).

STUDY REGION AND DATA

The study region is in the Catskill Mountains, part of the eastern plateau climate region of NY (Figure 1). The study area encompasses an area of about 4100 km² and consists of six reservoir watersheds: Cannonsville, Ashokan, Nerversink, Schoharie, Rondout, and Pepacton. The region contributes about 90% of New York City’s water supply. The climate is classified as humid (Keim, 2010) with cool summers (with average minimum, maximum, and mean temperatures of 12, 22, and 18°C, respectively), cold winters (with average minimum, maximum, and mean temperatures of 0, 10, and 5°C, respectively), abundant snowfall, and year-round precipitation (Anandhi et al., 2011) (Figure 2).
Figure 1. A map of the six reservoir watersheds in the Catskill Mountain region that provide approximately 90% of New York City’s drinking water needs. The common grid cell to which all GCM data were interpolated to is shown in the insert.

Figure 2. (a) Boxplots of mean monthly $T_{\text{min}}$ for the six West of Hudson (WOH) watersheds. Each box is based on 49 years (1960–2008) of data × 6 watersheds. For this and all subsequent box-plots, the bounds of the box represent the 25th percentile (Q1 quartile) and the 75th percentile (Q3 quartile), and the lower whiskers extend from the 25th percentile to the minimum value while the upper whisker extends from the 75th percentile to the maximum value. The red line is the mean monthly $T_{\text{min}}$ for all the six watersheds and all years. (b) Linear trend lines of annual $T_{\text{min}}$ calculated as the mean of all daily (Jan–Dec) minimum temperatures for each of the 6 WOH watersheds. (c–f) Linear trend line (black line) and time series plot (blue line) of mean annual $T_{\text{min}}$ for each of the 6 WOH watersheds; the numbers in the top of the subplots (b–f) represent the slope in °C/decade.
Frost indices were calculated for the study region (Figure 1) using observed and future scenarios of climate inputs. Observed minimum air temperatures ($T_{\text{min}}$) were taken from four stations: Cooperstown, Liberty, Slide Mountain, and Walton (Figure 1). Each of these stations has been active since 1960 or earlier. The spatial averaging method includes applying an environmental lapse rate (6°C/km) to correct for elevation differences between the station and the mean elevation of each reservoir watershed and using inverse distance squared weighting averaging of the four stations (NYCDEP, 2004). A single time series for daily minimum air temperature for each watershed is obtained after processing the observed $T_{\text{min}}$ data from the four observing stations. The observed data used for this study are from 1960–2008.

GCM simulations at daily timescale were obtained from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. The simulations used in the study were for baseline scenario (20C3M) and future scenarios (A1B, A2, and B1) and two 21st-century time periods (2045–2065 and 2080–2100). A list of the GCM simulations (name and realization number) used in the study is provided in Table 1. The data from all the GCMs for the region surrounding the study region were extracted and interpolated to a common 2.5° grid using bilinear interpolation technique.

### Table 1. Global climate models (GCM), country of origin, and realization numbers for minimum temperatures ($T_{\text{min}}$) used in the study

<table>
<thead>
<tr>
<th>S.N</th>
<th>GCM I.D *</th>
<th>Acronym</th>
<th>$T_{\text{min}}$</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BCCR-BCM2.0</td>
<td>bcc</td>
<td>1,2,3,4,5</td>
<td>Norway</td>
</tr>
<tr>
<td>2</td>
<td>CGCM3.1(T47)</td>
<td>cc4</td>
<td>1,2,3,4,5</td>
<td>Canada</td>
</tr>
<tr>
<td>3</td>
<td>CGCM3.1(T63)</td>
<td>cc6</td>
<td>1</td>
<td>Canada</td>
</tr>
<tr>
<td>4</td>
<td>CNRM-CM3</td>
<td>cnr</td>
<td>1</td>
<td>France</td>
</tr>
<tr>
<td>5</td>
<td>CSIRO-Mk3.0</td>
<td>cs3</td>
<td>1,2</td>
<td>Australia</td>
</tr>
<tr>
<td>6</td>
<td>CSIRO-Mk3.5</td>
<td>cs5</td>
<td>1,2,3</td>
<td>Australia</td>
</tr>
<tr>
<td>7</td>
<td>ECHAM5/MPI-OM</td>
<td>mpi</td>
<td>1,4</td>
<td>Germany</td>
</tr>
<tr>
<td>8</td>
<td>ECHO-G</td>
<td>miu</td>
<td>1,2,3</td>
<td>Germany, Korea</td>
</tr>
<tr>
<td>9</td>
<td>FGOALS-g1.0</td>
<td>iap</td>
<td>1,3</td>
<td>China</td>
</tr>
<tr>
<td>10</td>
<td>GFDL-CM2.0</td>
<td>gf0</td>
<td>1</td>
<td>USA</td>
</tr>
<tr>
<td>11</td>
<td>GFDL-CM2.1</td>
<td>gf1</td>
<td>2</td>
<td>USA</td>
</tr>
<tr>
<td>12</td>
<td>GISS-AOM</td>
<td>ga0</td>
<td>1</td>
<td>USA</td>
</tr>
<tr>
<td>13</td>
<td>GISS-ER</td>
<td>gir</td>
<td>1</td>
<td>USA</td>
</tr>
<tr>
<td>14</td>
<td>INGV-SXG</td>
<td>ing</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>IPSL-CM4</td>
<td>ips</td>
<td>1,2</td>
<td>France</td>
</tr>
<tr>
<td>16</td>
<td>MIROC3.2(hires)</td>
<td>mih</td>
<td>1</td>
<td>Japan</td>
</tr>
<tr>
<td>17</td>
<td>MIROC3.2(medres)</td>
<td>mim</td>
<td>1,2,3</td>
<td>Japan</td>
</tr>
<tr>
<td>18</td>
<td>MRI-CGCM2.3.2</td>
<td>mri</td>
<td>1,2,3,4,5</td>
<td>Japan</td>
</tr>
</tbody>
</table>

*As provided by Lawrence Livermore National Laboratory’s Program for Coupled Model Diagnosis and Intercomparison (PCMDI): http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

#### METHODS

**Delta change factor methodology (CFM)**

The scenarios of future $T_{\text{min}}$ were created using delta change factor methodology (CFM). More details of this method can be found in Anandhi et al. (2011). In this method, the empirical cumulative distribution function (CDF) of the simulated baseline (GCMb) and future (GCMf) climates were estimated. The CDF was divided into 25 equal parts (bins), with each bin having 4 percentile (= 100/25) as its resolution. Then, the mean monthly values of GCMb and GCMf climates were estimated for each bin using equations (1) and (2).
The daily data in a month from all years of a scenario were pooled so Nb and Nf represent the total number of days associated with a given month during the baseline and future time periods for the nth change factor (n = 1 to 25). The Nb and Nf values varied depending on the month and number of years in the scenario time period. Additive change factors associated with each frequency bin (CF<sub>add,n</sub>) were calculated by taking an arithmetic difference between the mean bin value of a GCM variable derived from a current climate simulation and derived for the corresponding bin from a future climate scenario taken at the same GCM grid location (equation 3). Using the time series of observed local values (LOb), pooled monthly data were evaluated to similarly define the range in values associated with each of the 25 bins of the variable frequency distribution. Based on the variable range defining bin (n) during month (m), the appropriate additive change factor was applied to obtain future scaled climate scenarios (LSf<sub>add,n,j</sub>) of the variable for each day (j) of the scenario (equation 4).

\[
\overline{GCM_b}_n = \frac{\sum_{i=1}^{Nb} GCM_{b,i,n}}{Nb}
\]

(1)

\[
\overline{GCM_f}_n = \frac{\sum_{i=1}^{Nf} GCM_{f,i,n}}{Nf}
\]

(2)

\[
CF_{add,n} = \overline{GCM_f}_n - \overline{GCM_b}_n
\]

(3)

\[
LSf_{add,n,j} = LOb_{n,j} + CF_{add,n}
\]

(4)

Thus, for each month, 25 CFs are calculated for minimum air temperature for combinations of GCM, future scenarios (A1B, A2, and B1), and two time periods (2045–2065 and 2081–2100) (Table 1).

**Frost Indices**

A number of definitions of a frost or freeze day are available in the literature. In numerous studies, a frost day is defined as a day with a minimum air temperature (T<sub>min</sub>) less than a base temperature (Tb). Some of the chosen values for Tb are presented in Table 2. In this study, as with most other studies, a frost day was defined as a day with T<sub>min</sub> < 0°C (Tb = 0°C). The frost indices used in the study are listed in Table 3 and include the number of frost days (nFDs), number of frost months (nFMs), last spring freeze (LSF), first fall freeze (FFF), growing season length (GSL), and frost season length (FSL). Trend was estimated using the linear regression method.

<table>
<thead>
<tr>
<th>Frost definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; &lt; 0°C</td>
<td>Christidis et al., 2007</td>
</tr>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; &lt; −4.4 °C, −2.2 °C, 5.6 °C</td>
<td>Robeson, 2002</td>
</tr>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; &lt; 2.2 °C</td>
<td>Schwartz and Reiter, 2000; Goodin et al. 1995, 2004</td>
</tr>
<tr>
<td>T&lt;sub&gt;min&lt;/sub&gt; &lt; 2 °C</td>
<td>Potithep and Yasuoka, 2011</td>
</tr>
</tbody>
</table>
Table 3. Definition of the frost indices used in the study

<table>
<thead>
<tr>
<th>Frost index</th>
<th>Frost index definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of frost days (nFDs)</td>
<td>The number of days with frost.</td>
</tr>
<tr>
<td>Number of frost months (nFMs)</td>
<td>The number of months with frost.</td>
</tr>
<tr>
<td>Last spring freeze (LSF)</td>
<td>The last frost (freeze) day is the last day when $T_{\text{min}} &lt; 0^\circ \text{C}$ in the period starting on 1 March and ending on 30 June.</td>
</tr>
<tr>
<td>First fall freeze (FFF)</td>
<td>The first frost (freeze) day is first day when $T_{\text{min}} &lt; 0^\circ \text{C}$ in the period starting on 1 September and ending on 30 November.</td>
</tr>
<tr>
<td>Growing season length (GSL)</td>
<td>The number of days between the LSF and the FFF.</td>
</tr>
<tr>
<td>Frost season length (FSL)</td>
<td>The number of days between the FFF and the LSF.</td>
</tr>
</tbody>
</table>

RESULTS

**Minimum air temperature ($T_{\text{min}}$)**

Monthly mean daily $T_{\text{min}}$ for the six watersheds for the period 1960–2008 is plotted in boxplots in Figure 2a. January had the lowest daily $T_{\text{min}}$ values, whereas July recorded the highest value followed closely by August. The range of $T_{\text{min}}$ in the boxplots was due to the differences in six watersheds and interannual variations. The range was greatest (10–12°C) during the winter (December, January, and February), early spring (March), and mid-fall (October); and the difference during the rest of the months was 5–6°C (Figure 2a). The linear trend lines of the mean annual $T_{\text{min}}$ for the six watersheds are plotted in Figures 2b–f. In general, all six watersheds show an increase in $T_{\text{min}}$. Among the watersheds, Cannonsville had the least increase in $T_{\text{min}}$ (0.1°C/decade), and Ashokan had the largest increase (0.6°C/decade). The differing rates of change in the $T_{\text{min}}$ could be due to differences in average elevation and land-use (Table 4) between the $T_{\text{min}}$.

Table 4. General details of the watersheds adapted from Anandhi et al. (2011)

<table>
<thead>
<tr>
<th>SN</th>
<th>Name of reservoir watershed</th>
<th>Elevation range, (mean) m</th>
<th>Watershed area$^a$ (km$^2$)</th>
<th>Land use$^b$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ashokan</td>
<td>125–1275 (539)</td>
<td>661</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>Cannonsville</td>
<td>315–1234 (572)</td>
<td>1177</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>Neversink</td>
<td>435–1276 (841)</td>
<td>238</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>Pepacton</td>
<td>353–1181 (633)</td>
<td>961</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>Rondout</td>
<td>248–1175 (523)</td>
<td>247</td>
<td>96</td>
</tr>
<tr>
<td>6</td>
<td>Schoharie</td>
<td>315–1234 (632)</td>
<td>817</td>
<td>91</td>
</tr>
</tbody>
</table>

$^a$ Includes the reservoir area.

$^b$ From Mehaffey et al. (2005) (Table 1).  

Boxplots of downscaled future $T_{\text{min}}$ for 18 GCMs (in Table 1), two time periods (2045–2065 and 2080–2100), and three SRES scenarios (A1B, A2, and B1) are shown in Figure 3 (a, b). In general, all GCMs show an increase in $T_{\text{min}}$ except for a few scenarios in June and July for the 2045–2065 period. The magnitude of increase in $T_{\text{min}}$ varies with month, GCM, scenario, and time period, with a larger increase and range during the period 2080–2100 than in 2045–2065. The
increase in $T_{\text{min}}$ was 2–3°C (median values) and 4–6°C (median values) during the periods 2045–2065 and 2080–2100, respectively. During the 2045–2065 period, winter (December, January, and February) and early spring (March–April) have a greater range among GCMs of up to 6°C. The range of increase among the scenarios also is wider for the period 2080–2100 compared with the period 2045–2065.

Figure 3. Boxplot of monthly mean downscaled future $T_{\text{min}}$ for the 6 West of Hudson (WOH) watersheds for 18 global climate models (GCM) and three emission scenarios (A1B, A2, B1) for two time periods: (a) 2045–2065 and (b) 2080–2100. The daily $T_{\text{min}}$ values used to create each box are from multiple scenarios derived from the GCMs in Table 1 × 6 (watersheds). The black dots in this figure and the red line in the previous figure (2a) represent the monthly mean observed values for the six WOH watersheds.

**Number of Frost Days (nFDs)**

The nFDs in a month for the six watersheds for 1960–2008 are plotted in boxplots in Figure 4a. In general, frost occurs in the Catskill Mountains for nine months, September through May; however, a few instances of frost occurred as late as June and as early as August. The variability in nFDs during spring and fall is high compared with the winter months and in general greatest during the spring during the 1960–2008 historical period. January had the highest nFDs, followed by December, whereas September had the fewest nFDs (median values) during the normal nine-month frost period. The linear trend lines of nFDs in a year for the six watersheds are plotted in Figures 4b–h. In general, all six watersheds show a decrease in nFDs due to a gradual increase in $T_{\text{min}}$. Among the watersheds, Cannonsville showed the lowest decrease in nFDs (~0.3 days/decade) and Ashokan had the highest decrease (~6.6 days/decade). On average, the nFDs in a year for all watersheds in the Catskills declined from 177 to 163 days during the historical period examined.
Boxplots of nFDs in each month during two future time periods (2045–2065 and 2080–2100) and three SRES scenarios (A1B, A2, and B1) are shown in Figure 5 (a, b). In general, all GCMs showed a decrease in nFDs. The magnitude of the decrease varies with month, GCM, scenario, and time period. The differences between A1B and A2 scenarios were less than B1 scenarios during the 2045–2065 period; but during the 2080–2100 period, A2 had the highest decrease followed by A1B and B1 scenarios. The decrease during the period 2080–2100 is generally more than that during the 2045–2065 period, with a median decrease of 5–10 and 8–12 days during the 2045–2065 and 2080–2100 periods, respectively. Winter (December, January, and February) had a lesser decrease in nFDs compared with fall and spring. The range of the decrease is generally wider for 2080–2100 scenarios than for 2045–2065 scenarios.
Figure 5. Boxplot of number of frost days in downscaled future $T_{\text{min}}$ for six West of Hudson (WOH) watersheds for three emission scenarios (A1B, A2, B1) for two time periods: (a) 2045–2065 and (b) 2080–2100. Each box is based on the daily data from multiple scenarios derived from the GCMs listed in Table 1 × 6 (watersheds). The black dots in this figure and the red line in figure 2a represent the monthly observed values for the six WOH watersheds.

**Last Spring Frost (LSF) and First Fall Frost (FFF)**

Time series and trend lines for LSF and FFF for the six study watersheds are plotted in Figure 6. During 1960–2008, LSF occurred in May in most years (34 to 39 years out of 49 years) for all six watersheds. LSF occurred in April in about 14–15 years for Ashokan and Rondout watersheds but in June for the remaining four watersheds (7–15 years). All watersheds except Cannonsville showed a decrease in LSF (~2.6 to ~4.3 days/decade; see in Figure 6a–f), indicating that, in general, LSF occurred earlier in the spring season. Cannonsville watershed showed a slight increase of 0.1 day/decade.)
FFF occurred in either October or November in 48 of 49 years for most watersheds. All watersheds experienced an increase in FFF (2.7 to 3.2 days/decade; Figure 6 g–l), indicating that FFF generally occurred later in the fall. The number of months with frost (nFMs) decreased (Figure 7a), with the LSF occurring earlier in the season (Figure 7b) and FFF occurring later in the season (Figure 7c).
Boxplots of LSF and FFF in future from 18 GCMs for two time periods (2045–2065 and 2080–2100) and three SRES scenarios (A1B, A2, and B1) are shown in Figure 8 (a, b). All GCMs showed an earlier LSF and later FFF, which is consistent with historical trends in LSF and FFF. The range of LSF and FFF among the GCMs are higher in 2080–2100 than in 2045–2065 for A1B and A2 emission scenarios. In most GCMs simulations (about 75%), LSF occurred earlier in the spring and FFF occurred later in fall during the 2080–2100 compared to the 2045–2065 period.

Boxplots of four frost indices (LSF, FFF, GSL, FSL) based on downscaled future values of Tmin for six West of Hudson (WOH) watersheds for three emission scenarios (A1B, A2, B1) for two time periods: (a) 2045–2065 (represented as lighter shade) and (b) 2080–2100 (represented as darker shade). Each box is made of ensembles from multiple GCMs explained in Table 1 × 6 (watersheds) values. The black dots in this figure represent the mean observed values for the six WOH watersheds. The numbers in the top of subplot (a) represent the slope in days/decade.

Growing season length (GSL) and frost season length (FSL)

Time series and trend lines for GSL and FSL for the six study watersheds are plotted in Figure 9. On average, the GSL varied from 188–206 days in a year extending from May to late October. Cannonsville and Ashokan had the shortest (188 days) and longest (206 days) GSL, respectively. All watersheds except Cannonsville showed an increase in GSL of about 2.4 to 4 days/decade. With a general increase in GSL, there was a decrease in FSL. On average, the FSL varied from 159–177 days in a year extending from November to late April. Among the study watersheds,
Cannonsville had the highest FSL (177 days) and least GSL (188 days), whereas Ashokan had the least FSL (159 days) and highest GSL (206 days).

Figure 9. Linear trend line (black line) and time series plot (blue line) for frost season length (FSL; a–f) for each of the six West of Hudson (WOH) watersheds. The numbers in the top of the subplots (a–l) represent the slope in days/decade.

Boxplots of GSL and FSL from 18 GCMs for two future time periods (2045–2065 and 2080–2100) and three SRES scenarios (A1B, A2, and B1) are shown in Figure 8 (c, d). In general, all GCMs showed a decrease in FSL and an increase in GSL and were consistent with historical trends. The range in the FSL values obtained among the GCMs were higher in 2080–2100 than in 2045–2065 for A1B and A2 emission scenarios. For most GCMs (about 75%), GSL is longer and FSL is shorter for the time period 2080–2100 than for 2045–2065.

**DISCUSSION AND CONCLUSION**

Overall, our results indicated a general increase in average annual $T_{min}$ and growing season length (GSL), a decrease in the number of frost-free days (nFFDs) and frost season length (FSL), earlier occurrence of last spring freeze (LSF), and later occurrence of first fall freeze (FFF). These trends were detected in the historical record (1960–2008) and were also seen in comparisons between baseline and future climate scenarios. Our results add local precision to the earlier findings that encompassed larger areas (Schwartz and Reiter, 2000; Adger et al., 2003; Kiktev et al., 2003; Feng and Hu, 2004; Christidis et al., 2007; Hayhoe et al., 2007; Trenberth et al., 2007; Hayhoe et al., 2008). These changes have important implications in the Catskill Mountains region that meets more than 90% of New York City’s water needs. Earlier LSF, later FFF, and longer GSL could affect the hydrologic, ecosystem, and biogeochemical processes both positively and negatively (Huntington, 2006; Campbell et al., 2009; Mohan et al., 2009). Increase in GSL will generally lead to an increase in annual evapotranspiration, and changes in LSF and FFF affect phenological events in the region such as bud break in spring and senescence and dormancy in the fall. Further in-depth study is necessary to understand the direct and indirect effects of these changes on forest productivity, nuisance species (pests, pathogens, and invasive species), wildlife, and forest nutrient cycling.
ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Award No. EPS-0903806 and matching support from the State of Kansas through Kansas Technology Enterprise Corporation. This is contribution number 13-073-J from the Kansas Agricultural Experiment Station.

REFERENCES


