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Changing climate extremes in the Northeast United States: observations and projections from CMIP5

Jeanne M. Thibeault · Anji Seth

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Abstract Climate extremes indices are evaluated for the northeast United States and adjacent Canada (Northeast) using gridded observations and twenty-three CMIP5 coupled models. Previous results have demonstrated observed increases in warm and wet extremes and decreases in cold extremes, consistent with changes expected in a warming world. Here, a significant shift is found in the distribution of observed total annual precipitation over 1981–2010. In addition, significant positive trends are seen in all observed wet precipitation indices over 1951–2010. For the Northeast region, CMIP5 models project significant shifts in the distributions of most temperature and precipitation indices by 2041–2070. By the late century, the coldest (driest) future extremes are projected to be warmer (wetter) than the warmest (wettest) extremes at present. The multimodel interquartile range compares well with observations, providing a measure of confidence in the projections in this region. Spatial analysis suggests that the largest increases in heavy precipitation extremes are projected for northern, coastal, and mountainous areas. Results suggest that the projected increase in total annual precipitation is strongly influenced by increases in winter wet extremes. The largest decreases in cold extremes are projected for northern and interior portions of the Northeast, while the largest increases in summer warm extremes are projected for densely populated southern, central, and coastal areas. This study provides a regional analysis and verification of the latest generation of CMIP global models specifically for the Northeast, useful to stakeholders focused on understanding and adapting to climate change and its impacts in the region.

Keywords Climate extremes · Northeast · CMIP5 · ETCCDI · HadEX2

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J. Thibeault (✉) · A. Seth
Department of Geography, University of Connecticut, 215 Glenbrook Road, Unit 4148, Storrs, CT 06269-4148, USA
e-mail: jeanne.thibeault@uconn.edu

1 Introduction

A major concern with future climate change is the heightened risk to human and natural systems from more frequent and intense climate extremes (Easterling et al. 2000; Kharin and Zwiers 2000). The region defined by the northeastern United States (US) and adjacent Canada (hereafter the Northeast) is densely populated and includes many major urban centers, yet much of the area is forested or used for agriculture. The Northeast is often affected by climate and weather extremes including heavy precipitation events, river flooding, heat waves, and droughts (Hayhoe et al. 2007; Bourque and Simonet 2007; Chiotti and Lavender 2007; Bonsal et al. 2011; Ouellet et al. 2012; Horton et al. 2013). Threats to human and natural systems in the Northeast will likely increase as greenhouse warming progresses, adversely affecting human health, as well as the character and economy of the region.

Extreme heat is the top weather-related cause of death in the US (Borden and Cutter 2008; Peterson et al. 2013). High temperatures accompanied by high relative humidity can be dangerous in the major urban centers of the Northeast (Kunkel et al. 2013), and extreme heat has the potential to damage critical infrastructure, including power transmission lines, roads, and railroads (Horton et al. 2011). In summer, small streams in the Northeast are prone to flash flooding from convective precipitation (Kunkel et al. 2013). Intense rainfall can also result in urban flooding, disrupting transportation (Kunkel et al. 2013). In northern portions of the region, warm winter temperatures accompanied by rainfall can produce winter flooding, especially if heavy streamflow caused by rapid snowmelt breaks up river ice and causes ice jams (Groleau et al. 2007; Collins 2009; Ouellet et al. 2012).

Numerous studies indicate that conditions in the Northeast have become warmer and wetter in recent decades (e.g., Vincent and Mekis 2006; Bourque and Simonet 2007; Chiotti and Lavender 2007; Yagouti et al. 2008; DeGaetano 2009; Qian et al. 2012; Kunkel et al. 2013). The annual average temperature has increased by $\sim 1.1\,^{\circ}$C (2 °F). The number of days with maximum temperature above 32.2 °C (90 °F) is increasing. The growing season is becoming longer, and frost days are decreasing. Heavy precipitation events are occurring more frequently. The Northeast has seen a reduction in the return periods of extreme precipitation events large enough to cause flooding (DeGaetano 2009). These observed changes are consistent with global analyses, showing trends in temperature extremes consistent with warming and increased precipitation intensity for the eastern US (Frich et al. 2002; Groisman et al. 2005; Alexander et al. 2006).

Future projections of Northeast climate extremes, based on models from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project version 3 (CMIP3) (Meehl et al. 2007), include shorter, milder winters with increased precipitation (Hayhoe et al. 2007, 2008), a longer growing season, and a steady increase in previously rare hot summer temperatures (Duffy and Tebaldi 2012). Increased evapotranspiration from higher temperatures will have potentially severe impacts on freshwater ecosystems (Brooks 2009), and may also lead to more frequent summer drought (Hayhoe et al. 2007). High summer temperatures may disrupt the electricity supply in the Northeast by limiting the availability of cooling water required for thermoelectric power generation (van Vliet et al. 2012). An increase in the frequency and/or intensity of heavy rainfall events in the Northeast will increase the risk of flooding, heighten the risk of waterborne disease (Insaf et al. 2013), impact water quality by increasing pollutant runoff (Hodgkins and Dudley 2011), and lead to premature failure of the aging infrastructure common in parts of the Northeast (Horton et al. 2011; Kunkel et al. 2013).

The Expert Team on Climate Change Detection and Indices (ETCCDI) has defined a set of twenty-seven climate extremes indices based on daily temperature and precipitation. The

ETCCDI indices describe moderate extremes having return periods of one year or less, e.g., warm spell duration and heavy rainfall events. A complete description of the indices, including definitions and percentile computation methods, is provided by Zhang et al. (2011), and is available at the ETCCDI website: http://etccdi.pacificclimate.org/list_27_indices.shtml.

Alexander et al. (2006) examined observed changes in ETCCDI indices at the global scale. Numerous continental and regional-scale studies have also been performed (Zhang et al. 2011). Peterson et al. (2008) examined observed changes in North American extremes using ETCCDI percentile-based temperature and precipitation indices. Several previous studies have evaluated observed changes in ETCCDI indices for individual stations in the Northeast (e.g., Vincent and Mekis 2006; Griffiths and Bradley 2007; Brown et al. 2010; Insaf et al. 2013). Results from these studies show that the Northeast is already experiencing increases in warm extremes, decreases in cold extremes, and increases in wet precipitation extremes.

Tebaldi et al. (2006) evaluated CMIP3 simulated climate extremes at the global scale, using a set of ten indices defined by Frich et al. (2002). Kharin et al. (2007) analyzed 20-year return values of CMIP3 annual temperature and precipitation extremes at global and continental scales, recently updated for models participating in the 5th phase of the Coupled Model Intercomparison Project (CMIP5, Taylor et al. 2012) (Kharin et al. 2013). Several climate indices were examined in seventeen CMIP5 models for North America by Sheffield et al. (2013), showing that models perform reasonably well at simulating frost days and the length of the growing season, but they tend to underestimate summer days. A subset of eleven CMIP5 models projects a four to five-fold increase in heavy precipitation events > 25 mm (1 in) in the Northeast by late century (Maloney et al. 2013). CMIP5 simulated ETCCDI indices have been analyzed globally and regionally (Sillmann et al. 2013a, b). CMIP5 projections for eastern North America (defined as extending as far south as the Gulf of Mexico and into the Midwest U.S.) show increases in total annual precipitation, heavy rainfall days, and strong warming in low minimum temperatures, especially during winter (Sillmann et al. 2013b).

A comprehensive evaluation of Northeast climate extremes in the CMIP5 models has not been performed. This study fills that need by performing a regional analysis and verification of the CMIP5 models' ability to simulate the twenty-seven core ETCCDI indices specifically for the Northeast. A benefit of using the ETCCDI indices is that a consistent methodology is employed across observations, multiple reanalyses, and models; facilitating comparisons with other studies employing the ETCCDI indices. This research first examines trends and distribution shifts in gridded observed indices. Observations are used to validate historical simulations of ETCCDI indices in twenty-three CMIP5 models, which show some improvements since CMIP3 (Sillmann et al. 2013a). Projections from the RCP 8.5 experiment are also analyzed, including changes in winter and summer extremes and spatial patterns of change for the Northeast. The datasets and methods are described in Section 2. Observed and simulated results are presented in Section 3. Section 4 provides a summary and conclusions.

2 Data and methods

This research examines observed changes, historical simulations, and future projections of the twenty-seven core ETCCDI temperature and precipitation extremes indices for the Northeast. See Supplementary Table 1 of the Supplementary Material for a summary of the indices and their definitions/abbreviations. The Northeast is defined as the area located within 38°- 48 °N by 67°- 80 °W (shown in Fig. 6a), used for all area-averaged quantities, computed using the NCAR Command Language (NCL) weighted area average function (http://www.ncl.ucar.edu).

Observed extreme indices are evaluated using the station-based, land-only HadEX2 dataset (Donat et al. 2013) and the European Centre for Medium-Range Weather Forecasts ERA-Interim (ERA-I) reanalysis (Dee et al. 2011). The HadEX2 dataset, covering 1901-2010, was produced by computing indices from high-quality station observations, then interpolating them onto a 3.75° × 2.5° grid (Donat et al. 2013, accessed at http://www.climdex.org/index.html). Percentiles for HadEX2 indices are relative to 1961–1990. HadEX2 indices, computed from point (station) data, are not directly comparable to reanalysis or model output, which is computed for grid points representing area-averaged (smoothed) quantities (Sillmann et al. 2013a). ERA-I has an improved representation of the hydrological cycle (Dee et al. 2011; Trenberth and Fasullo 2013), useful for comparison with modeled indices. Indices were computed for ERA-I by ETCCDI and accessed at http://www.cccma.ec.gc.ca/data/climdex/index.shtml. ERA-I indices cover 1979–2010, and are available at 1.5 × 1.5 degree resolution. Percentiles for ERA-I indices are relative to 1979–2008, as computed by ETCCDI (Sillmann et al. 2013a). For analysis, ERA-I indices are masked to exclude grid points over the ocean. HadEX2 and ERA-I indices are regridded to T85 resolution ($\sim$ 1.4° × 1.4°) to facilitate comparison with simulated indices.

Indices for twenty-three CMIP5 coupled models, provided by the ETCCDI archive (Sillmann et al. 2013a; Sillmann et al. 2013b), are analyzed for the 20th century historical experiment and RCP 8.5 scenario using a single realization from each model (Supplementary Table 2 in Supplementary Material). RCP 8.5 is a high-end emissions scenario where, by 2100, anthropogenic forcing reaches 8.5 W m^{-2} and atmospheric CO_2-equivalent concentrations are $\sim$ 1370 ppm (Moss et al. 2010). All simulated indices are regridded to T85 resolution and masked to exclude grid points over the ocean prior to analysis. The base period for model simulations is 1961–1990, computed by ETCCDI.

The CMIP5 models reasonably simulate ETCCDI extreme indices and historical trends compared to HadEX2 (Sillmann et al. 2013a). Some physical processes important to extreme precipitation are not well represented in the CMIP5 models, but they simulate late 20th century precipitation extremes reasonably well in extratropical regions (O'Gorman and Schneider 2009; Kharin et al. 2013; Scoccimarro et al. 2013).

Density plots are used to show changes in distributions of Northeast HadEX2 indices for two periods: 1951–1980 and 1981–2010. Statistical significance of observed shifts is evaluated using Kolmogorov-Smirnov tests.

Time evolution of changes in simulated indices is evaluated for 1950–2099. Multimodel time series were produced by appending data from the RCP 8.5 scenario (2006–2099) to 20th century historical simulations (1950–2005) for each model. Multimodel median, minimum, and maximum values are shown for each time series, and the interquartile range is shaded, providing details about model spread specifically for the Northeast. HadEX2 and ERA-I time series are shown with simulated time series, providing information about model biases. All time series are smoothed with a 5-year running mean for visual clarity. Current trends in observed and simulated indices are evaluated for significance using Mann-Kendall trend tests. Percent changes in multimodel mean (MMA) indices are computed for the middle (2041–2070) and late (2071–2099) 21st century, relative to the current period (1981–2010). Density plots are used to show projected shifts in selected temperature and precipitation indices. Kolmogorov-Smirnov tests are used to identify significant shifts in all twenty-seven modeled indices for the middle and late 21st century. Spatial patterns of change are examined in selected precipitation and temperature indices, and differences are

Table 1 Current trends in Northeast extreme indices for HadEX2 observations (1951–2010), ERA-I reanalysis (1979–2011), and CMIP5 coupled models (1951–2010). Percent change in CMIP5 multimodel mean indices for the middle (2041–2070) and late (2071–2099) 21st century. Changes in CMIP5 percentile-based extremes are given relative to the 1961–1990 base period. Bold (italic) text indicates statistical significance at 95 % (90 %) for Mann-Kendall trend tests for the current period and Kolmogorov-Smirnoff tests for CMIP5 future periods. Indices with significant shifts in HadEX2 distributions between 1951–1980 and 1981–2010 are indicated by bold (italic) labels (first column) at the 95 % (90 %) level, positive (negative) shifts are indicated by + (−) symbols

Index	HadEX2 τ	ERA-I τ	CMIP5-current τ	CMIP5-mid %	CMIP5-late %
cdd − (days)	−0.08	0.14	0.03	**2.6**	**4.7**
csdi (days)	**−0.25**	**−0.27**	**−0.52**	**−95.2**	**−99.4**
cwd + (days)	**0.28**	0.05	−0.04	**2.9**	**5.5**
dtr − (°C)	**−0.31**	−0.01	**−0.24**	**−1.5**	**−2.7**
fd (days)	−0.11	*−0.22*	**−0.58**	**−21.2**	**−35.6**
gsl (days)	0.08	0.07	**0.57**	**12.3**	**20.7**
id (days)	0.10	−0.11	**−0.50**	**−31.7**	**−51.1**
prcptot + (mm)	**0.28**	0.08	**0.39**	**7.2**	**11.3**
r1mm (days)	NA	−0.16	0.02	−0.1	−0.3
r10mm + (days)	**0.23**	0.05	**0.38**	**7.2**	**10.2**
r20mm (days)	**0.22**	0.19	**0.42**	**18.2**	**28.6**
r95p (mm)	**0.22**	0.19	**0.46**	**30.7**	**50.7**
r99p (mm)	**0.21**	0.20	**0.49**	**57.6**	**100.4**
rx1day (mm)	**0.21**	*0.24*	**0.48**	**12.4**	**20.0**
rx5day (mm)	**0.20**	*0.23*	**0.34**	**10.4**	**17.9**
sdii (mm)	*0.17*	*0.24*	**0.49**	**7.7**	**12.2**
su (days)	−0.11	*0.22*	**0.63**	**75.6**	**124.0**
tn10p − (%)	**−0.36**	**−0.50**	**−0.61**	**1.4**	**0.3**
tn90p (%)	**0.24**	0.19	**0.62**	**32.9**	**48.7**
tnn (°C)	0.10	**0.42**	**0.49**	**24.0**	**40.7**
tnx (°C)	**0.19**	0.17	**0.55**	**12.9**	**21.3**
tr (days)	**0.22**	0.16	**0.61**	**140.7**	**257.3**
tx10p (%)	−0.10	**−0.41**	**−0.62**	**1.6**	**0.5**
tx90p (%)	0.07	**0.28**	**0.60**	**34.8**	**50.3**
txn (°C)	−0.01	**0.34**	**0.48**	**32.5**	**54.0**
txx (°C)	−0.02	**0.25**	**0.47**	**11.8**	**19.4**
wsdi + (days)	**0.34**	0.17	**0.52**	**702.4**	**1502.1**
rx1day-Jan (mm)	0.07	0.02	**0.26**	**13.0**	**23.3**
rx1day-Jul (mm)	0.09	−0.09	0.02	**3.4**	**5.8**
rx5day-Jan(mm)	0.03	0.05	0.14	**13.2**	**22.1**
rx5day-Jul (mm)	**0.19**	−0.08	*0.17*	**3.7**	**6.0**

tested for statistical significance using Student's t-tests. Stippling is used to indicate changes that are not significant at the 95 % confidence level.

3 Results

3.1 Temperature extremes

Evaluation of HadEX2 indices reveals significant trends consistent with warming in cold spell duration (csdi), cool nights (tn10p), warm nights (tn90p), highest annual T_{min} (tnx), tropical nights (tr), and warm spell duration (wsdi) (Table 1). Indices with significant trends display shifts in their current distributions (1981–2010) consistent with recent warming; significant in cool nights and warm spell duration (Fig. 1a–g). The remaining HadEX2 temperature indices (see Supplementary Fig. 1 in the Supplementary Material) show recent shifts consistent with warming temperatures, but also suggest a tendency for summer maximum temperatures to be more variable. Significant trends consistent with warming temperatures also exist in ERA-I indices (1979–2011); cold spell duration, frost days, cool nights, lowest annual T_{min} (tnn), cold days (tx10p), warm days (tx90p), lowest T_{max} (txn), and highest T_{max} (txx). The positive trend in warm nights is not significant in ERA-I, suggesting that between 1979–2011, decreases in the frequency of cool nights have outpaced increases in the frequency of warm nights.

Time evolution of multimodel temperature indices for 1950–2099 project changes consistent with the strong CO_2 forcing in the RCP 8.5 scenario (Fig. 2 and Supplementary Fig. 2). The multimodel interquartile range (IQR) generally compares well with HadEX2 and ERA-I for most indices. The offset between ERA-I cool nights and HadEX2 cool nights may be related to the base period used for percentile thresholds in ERA-I indices (1979–2008). Over the common period of 1979–2010, the linear trend in ERA-I cool nights (−0.23 %/yr) is consistent with that for HadEX2 (−0.18 %/yr). Consistent with Sillmann et al. (2013a), a cold bias is evident in the CMIP5 models relative to HadEX2 for several indices in the Northeast. For example, multimodel medians overestimate ice days (id) and underestimate summer days (su) relative to HadEX2 (Fig. 2e, f). ERA-I also underestimates summer days relative to HadEX2, but is in good agreement with the multimodel median. ERA-I and the multimodel IQR of diurnal temperature range (dtr) are low-biased compared to HadEX2 (Fig. 2b, f). The model median overestimates tropical nights (Fig. 2i) and underestimates summer days (Fig. 2f), which would result in a smaller diurnal temperature range in summer, compared to HadEX2. In winter, the model median overestimates ice days (Fig. 2e), suggesting a cold bias in winter maximum temperatures. Warm (cold) biases in minimum (maximum) temperatures offer a possible explanation for the low bias in the diurnal temperature range simulated by the CMIP5 models.

All MMA trends are significant and consistent with warming over 1951–2010, but are generally too strong compared to observed trends. Frost days provides an example; all datasets agree on a decrease, but not on the magnitude or significance of the trend (Table 1). Shifts in the distributions of all indices are significant by the midcentury, and become even larger by the late century (Table 1). The most dramatic change is in the projected lengthening of warm spells; > 700 % (> 1500 %) by the middle (late) century.

3.2 Changing summer and winter temperature extremes

Projected shifts in MMA indices that sample winter and summer extremes (Fig. 3) suggest that Northeast winters (summers) will become increasingly milder (hotter) as the century progresses. These indices display statistically significant shifts that are largely outside their current ranges by the midcentury (Fig. 3 and Table 1). By the late century, the percent change in the lowest minimum winter temperatures (tnn) is approximately double that of

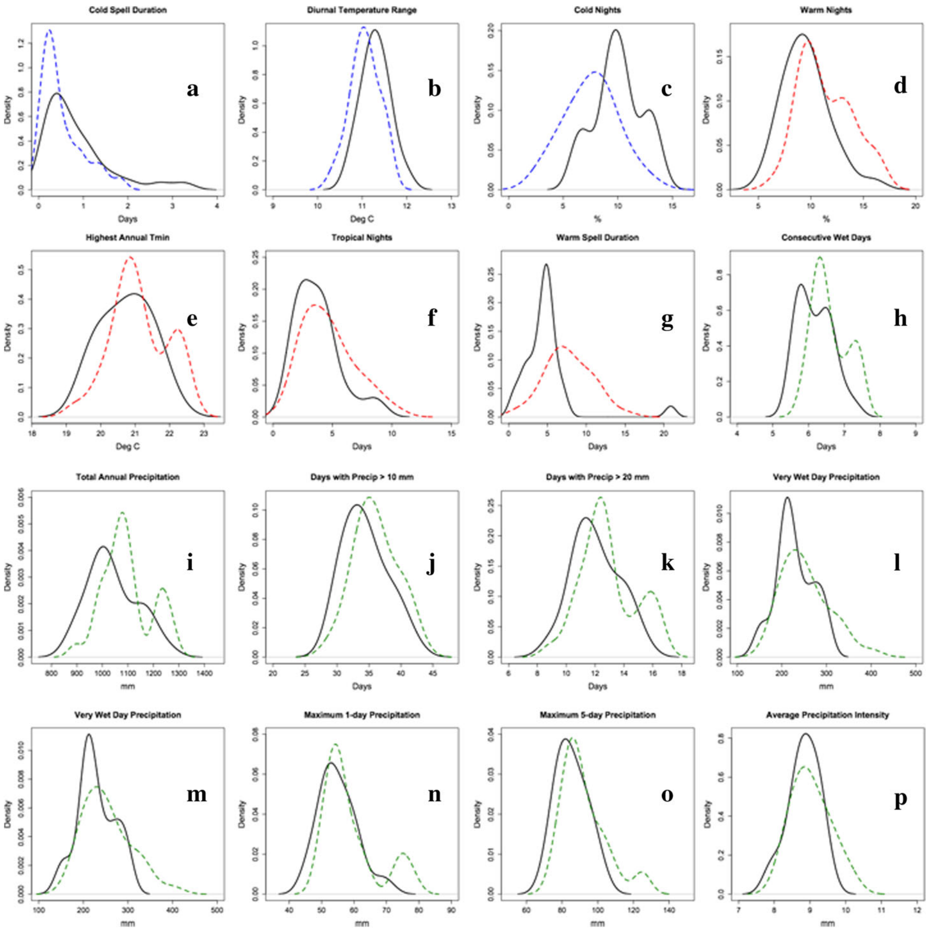

Fig. 1 Change in distributions for HadEX2 indices with significant trends over 1951–2010. Temperature indices are given in **a**–**g**; precipitation indices in **h**–**p**. Two periods are shown: 1951–1980 (*black solid*) and 1981–2010 (*colored dashed lines*). *Blue (red)* represents a negative (positive) shift in temperature indices. *Green* indicates a positive shift for precipitation indices

the highest summer maximum temperatures (txx) (Table 1), providing more evidence that decreases in cold extremes will outpace increases in warm extremes, consistent with CMIP5 global projections (Kharin et al. 2013). The largest decreases in winter cold extremes are projected for northern and interior portions of the Northeast, while the largest increases in summer warm extremes are projected for southern, central, and coastal areas (see Section S.2 and Supplementary Fig. 3 in the Supplementary Material).

3.3 Precipitation extremes

Trends in all HadEX2 wet precipitation indices are positive and significant (Table 1). Trends in ERA-I precipitation indices, which cover a shorter period, are consistent in direction with HadEX2 and significant at the 90 % level for maximum 1-day (rx1day) and 5-day (rx5day)

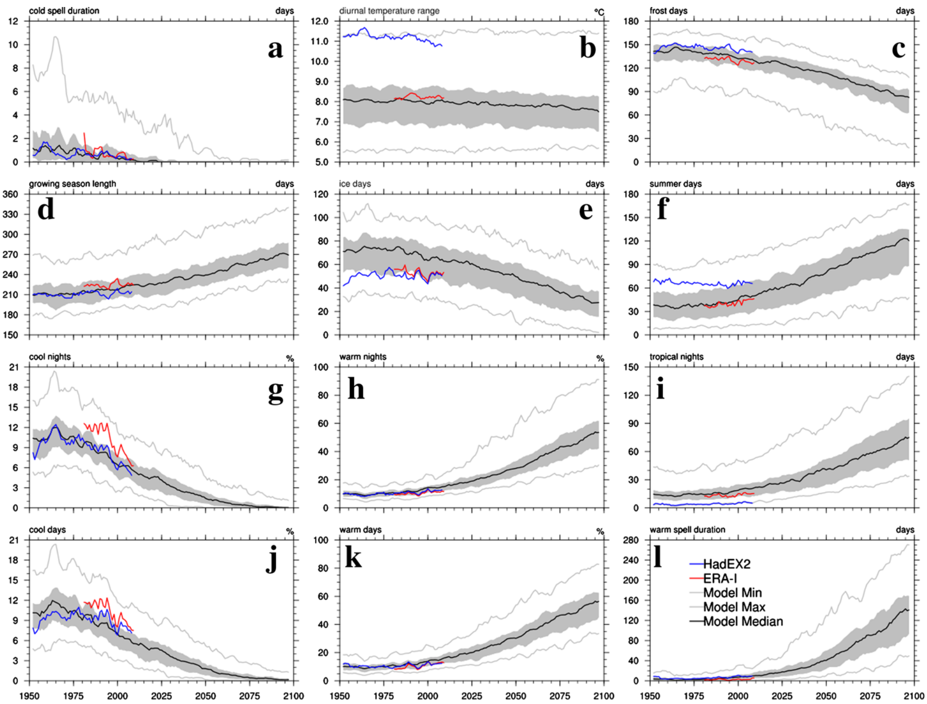

Fig. 2 Time evolution of temperature indices. Multimodel medians (*solid black*), minimum and maximum (*gray lines*), and interquartile range (*shading*) are shown. HadEX2 (*blue*) and ERA-I (*red*) observations are shown for comparison. Time series are smoothed with 5-year running means. Units for each index are given in the top right corner of each panel. Annual high and low minimum and maximum temperatures (tnn, tnx, txn, and txx) are shown in Supplementary Fig. 2

precipitation, and simple daily precipitation intensity (sdii). Observed shifts in precipitation indices show that conditions in the Northeast have become wetter with more frequent precipitation extremes (Fig. 1). Shifts in distributions are significant for total annual precipitation (90 % level, prcptot), consecutive wet days (cwd), and days with precipitation > 10 mm (r10mm). A significant negative shift is observed in consecutive dry days (cdd) (Supplementary Fig. 1i), consistent with increasing wet extremes in the Northeast.

The multimodel IQR compares well with observations for most precipitation indices (Fig. 4), but, not surprisingly, is in better agreement with ERA-I than HadEX2. An ongoing increase in total annual precipitation and wet rainfall extremes is projected over the 21st century. MMA trends for the current period are consistent with observations, but the MMA generally overestimates observed trends (Table 1). Changes in consecutive wet days, consecutive dry days, and the number of wet days are relatively small, suggesting that the projected increase in total precipitation is due to more frequent and/or intense wet precipitation extremes (Fig. 4b–d and Table 1).

Projected shifts in MMA precipitation indices show that distributions are largely outside their 1951–1980 ranges by the late century (Fig. 5). The positive shift in consecutive wet days is small, but does indicate some increased variability by the late century. Projected differences in annual MMA precipitation indices are significant at the 95 % level across the

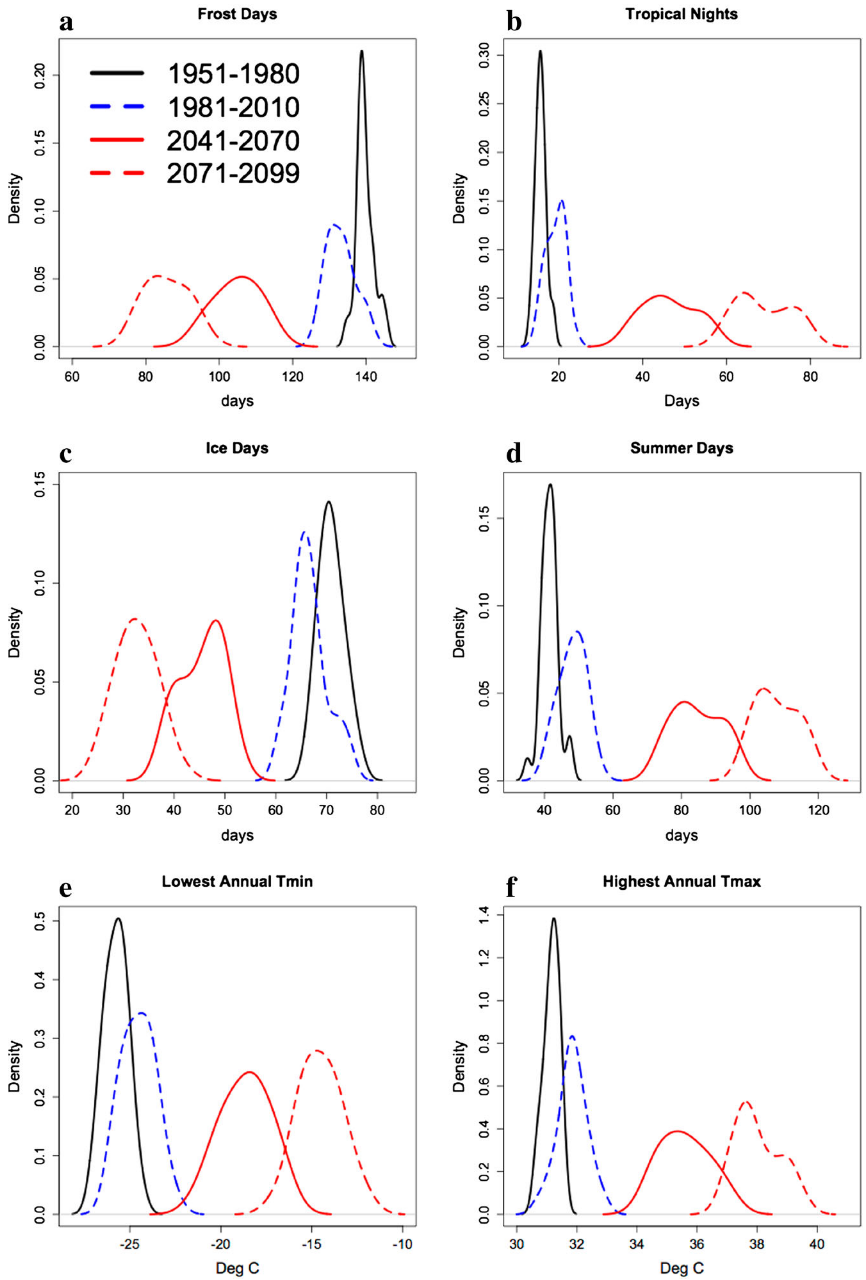

Fig. 3 Change in distributions for multimodel average historical and RCP 8.5 simulated frost days **a**, tropical nights **b**, ice days **c**, summer days **d**, lowest annual T_{min} **e**, and highest annual T_{max} **f**. Indices sampling winter (summer) temperature extremes are shown in *left (right)* column. Four periods are shown: 1951–1980 (*black*), 1981–2010 (*dashed blue*), 2041–2070 (*solid red*), and 2071–2099 (*dashed red*)

Northeast, with the largest increases in heavy precipitation events and total annual precipitation projected for northern and mountainous areas (Fig. 6). Projected changes in consecutive

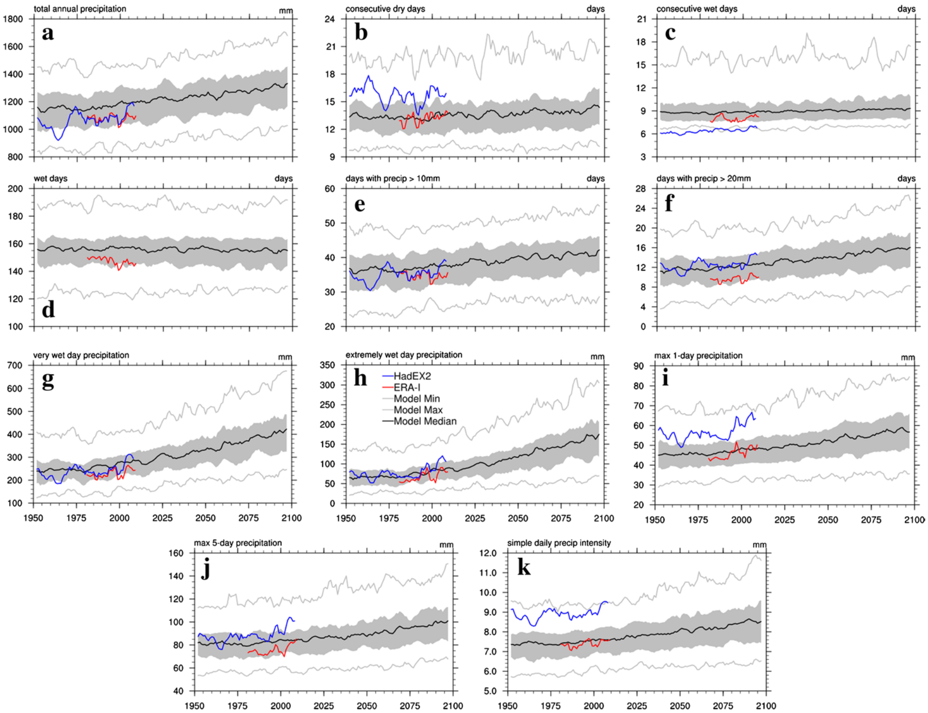

Fig. 4 As in Fig. 2, but for precipitation indices

wet days and the simple daily precipitation index are small and fairly uniform across the Northeast (not shown). Projections for January and July precipitation indices suggest that the increase in total annual precipitation is strongly influenced by winter precipitation extremes (Supplementary Material Section S.3 and Supplementary Fig. 4).

4 Summary and conclusions

Observational results from HadEX2 and ERA-Interim datasets indicate that the Northeast is experiencing more frequent warm temperature extremes, fewer cold extremes, and increased heavy precipitation events, consistent with earlier studies based on individual stations (Griffiths and Bradley 2007; Brown et al. 2010; Insaf et al. 2013). Minimum temperatures in the Northeast are warming more rapidly than maximum temperatures, consistent with observed changes in many other parts of the world (Frich et al. 2002; Alexander et al. 2006; Vincent and Mekis 2006). Increasing trends in observed wet precipitation extremes are likely driving the observed increase in total annual rainfall, rather than an increase in the number of wet days.

CMIP5 historical simulations for the Northeast are consistent with observations, showing increases (decreases) in warm (cold) extremes, and increased wet extremes. In the RCP 8.5 scenario, ongoing increases (decreases) in warm (cold) temperature extremes and wet precipitation extremes are projected for the 21st century. Decreases in cold extremes are

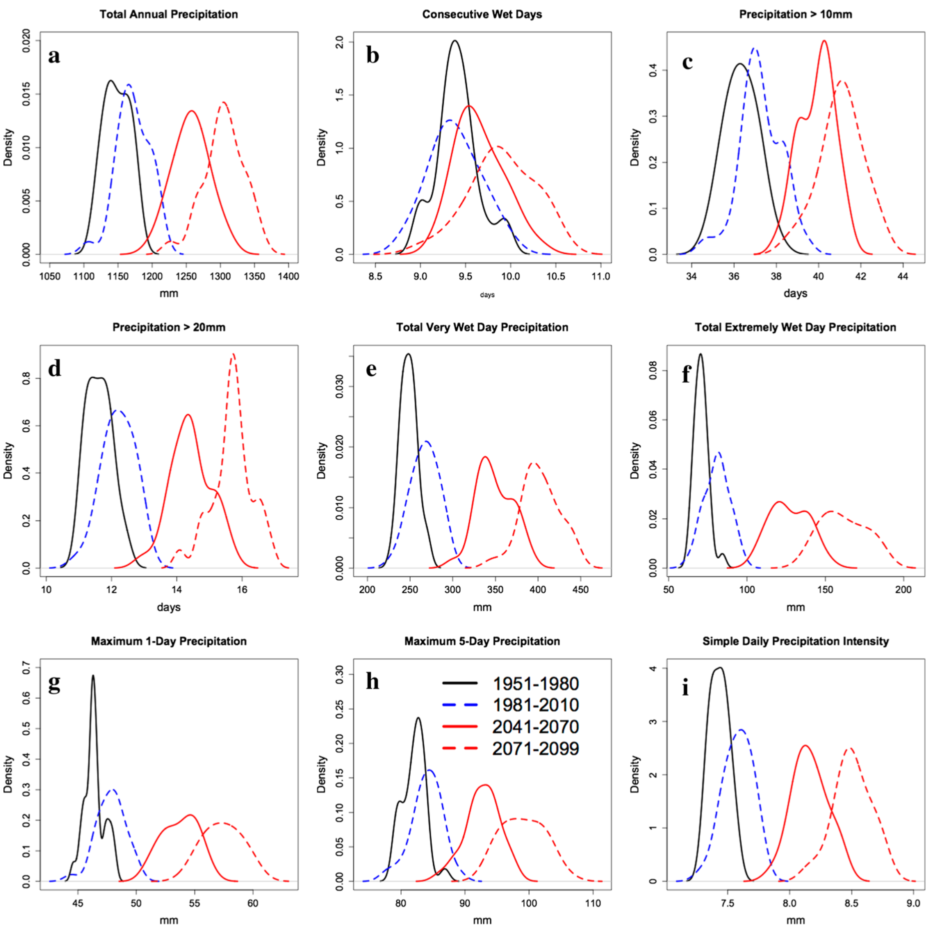

Fig. 5 As in Fig. 3, but for total annual precipitation (**a**), consecutive wet days (**b**), days with precipitation > 10 mm (**c**), days with precipitation > 20 mm (**d**), very wet day precipitation (**e**), and extremely wet day precipitation (**f**), maximum 1-day precipitation (**g**), maximum 5-day precipitation (**h**), and simple daily precipitation intensity (**i**)

projected to outpace increases in warm extremes, consistent with global and continental-scale projections (Kharin et al. 2013).

Large increases projected in warm summer extremes for southern, central, and coastal areas of the Northeast are likely to impact human populations vulnerable to extreme heat, e.g., young children, the elderly, and people with respiratory illnesses, especially those living in urban centers without access to air conditioning (Kunkel et al. 2013). The large increase projected for the number of summer days implies higher potential evapotranspiration rates will exist over a longer season, consistent with CMIP3 projections for higher spring and summer evaporation rates in the Northeast (Hayhoe et al. 2007). The large decreases in winter cold extremes projected for northern and interior portions of the Northeast are consistent with the projected pattern of mean temperature changes in the region (Lynch and Seth 2014). The largest increases in wet precipitation extremes are projected for northern, mountainous, and coastal areas of the Northeast. Projected increases in winter

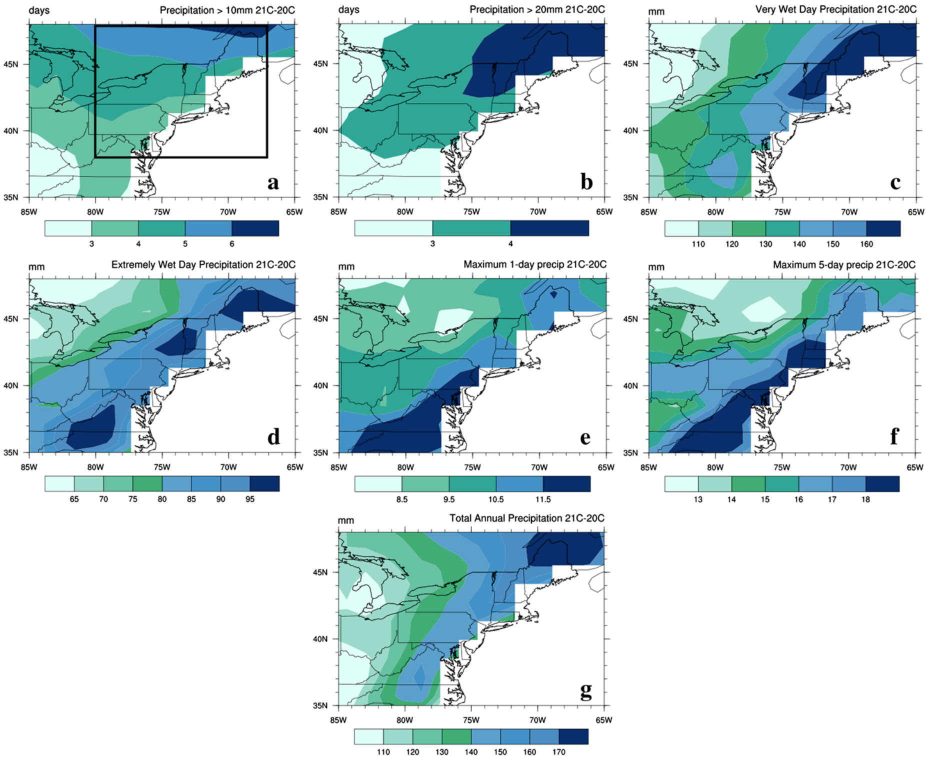

Fig. 6 Multimodel mean changes (2070–2099 minus 1971–2000) in days with precipitation > 10 mm (**a**), days with precipitation > 20 mm (**b**), very wet day precipitation **c**, extremely wet day precipitation (**d**), maximum 1-day precipitation **e**, maximum 5-day precipitation (**f**), and total annual precipitation **g**. Box in (**a**) delineates the Northeast (land only). All differences are significant at the 95 % confidence level

wet extremes are larger than for summer, consistent with projected increases in mean winter precipitation that are triple those of summer (Lynch and Seth 2014).

Important findings of this research specific to the Northeast include:

- A significant positive shift in the distribution of observed total annual precipitation over 1981–2010
- Significant positive trends in all observed HadEX2 wet precipitation indices over 1951–2010
- Results suggest that the projected increase in total annual precipitation is strongly influenced by increases in winter wet extremes
- Projected positive (negative) shifts in warm (cold) extremes in Northeast temperature indices are generally outside their current ranges by the mid-century
- Projected positive shifts in Northeast wet precipitation indices are generally outside their 1951–1980 ranges by the late century

In this research, a relatively large number of simulations is employed. The fact that the multimodel IQR generally compares well with observations, provides a measure of confidence in multimodel projections. By the late 21st century, the coldest (driest) future warm (wet) extremes are projected to be warmer (wetter) than the warmest (wettest) current extremes.

In the Northeast, large variations in climate, especially precipitation, occur over small spatial scales, i.e., coastal locations, mountainous areas, or inland regions near large water bodies (Kunkel et al. 2013). Therefore, the coarse resolution of the global models, though improved since CMIP3, should be considered when they are used to provide projections of Northeast climate extremes.

An increase in the frequency and/or intensity of climate extremes in the Northeast will increase the risks to human health and society, and likely stress sensitive natural ecosystems adapted to the current climate. This study has analyzed and verified the latest generation of coupled global climate models specifically for the Northeast, providing important information useful to researchers and stakeholders whose work is focused on understanding and adapting to climate change and its impacts in the region.

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