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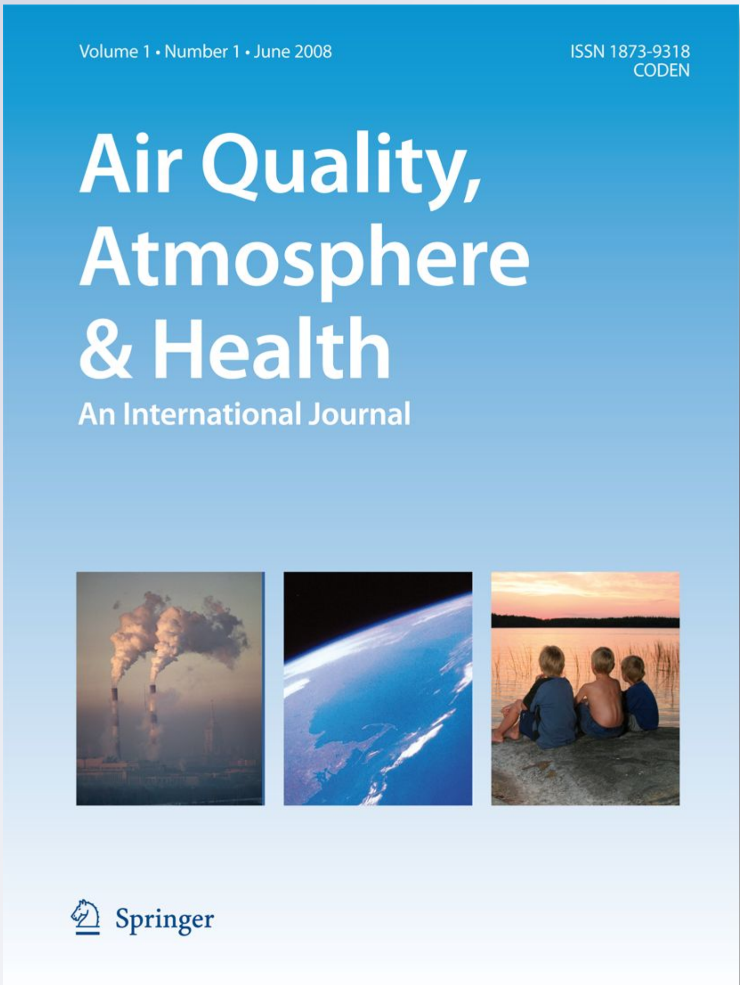
Air Quality, Atmosphere & Health
An International Journal

ISSN 1873-9318

Air Qual Atmos Health
DOI 10.1007/s11869-011-0168-x



Springer

Air Qual Atmos Health
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Climate trends in indices for temperature and precipitation across New York State, 1948–2008

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Received: 12 October 2011 / Accepted: 5 December 2011

Abstract New York State (NYS) is a geographically diverse area susceptible to climate change, but trends in climate extreme indicators have not been extensively studied. Our objectives are to describe temporal and spatial trends in various extreme indicators and their sensitivity to climate change and to demonstrate geographic differences in indicator trends in NYS. We analyzed data from the US Historical Climatology Network for NYS from 1948 to 2008. We assessed trends in 15 temperature and 11 precipitation indicators using linear regression with bootstrapping in SAS and RClimDex software. The indicators showing the most substantial change per decade were *frost days* (−0.97 days per decade) and *diurnal temperature* (−0.11°C). For precipitation indicators, the number of *heavy precipitation days* (+0.99 days), *consecutive wet days* (+ 0.42 days), the *total wet day precipitation* (+30.19 mm), and the *simple daily intensity index* (+0.18 mm/day) showed the most change per decade. The most representative indicators that showed significant trends for more than half of the stations were *number of cool nights*, *diurnal temperature*, and number of *frost days* and increase in *total wet day precipitation* and *simple daily intensity index* for precipitation. The most sensitive regions for changes in extreme indicators were the eastern and Great Lakes regions of NYS. In light of these consistent temporal trends of warming and increasing precipitation in NYS with large geographic variation, the indicators that have been identified should be further evaluated and assessed for their health impact. Geographical differences in climate trends may be of use in informing policy and resource allocation for climate change adaptation.

Keywords Climate change · Extremes · Temperature · Precipitation · Trend indicators

Introduction

Average temperatures have risen in the USA in recent decades (Trenberth et al. 2007). Since the frequency of extreme events may have a greater environmental and public health impact as compared to changes in average weather conditions, there has been considerable recent interest in evaluating trends in extreme weather events as evidence of climate change (Alexander et al. 2006; Nicholls and Alexander 2007). Changes in extreme weather indicators in the northeastern USA have been evaluated in some previous studies, such as Griffiths and Bradley (2007), who noted an increase in heat waves across the US northeast. A number of reports from other parts of the world have been published using standard indices outlined in the guidelines by the World Meteorological Organization (WMO) for assessment of climate change (New et al. 2006; Peterson et al. 2008; Tank et al. 2006), but there have been few previous US reports using these indices (Brown et al. 2010; dos Santos et al. 2011; Tank et al. 2009). Brown et al. (2010) used WMO standard indices to evaluate climate change in the US northeast and

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Published online: 17 January 2012

found increased warming and increasing precipitation. There is some suggestion in these reports that there are geographical differences in climate trends. No studies have been done in New York State (NYS) that describe temporal trends in these weather indicators and compare geographical variations in these trends. None of the previous studies compared the representativeness of each indicator to climate change across different geographical regions in NYS. The objectives of this paper are to describe temporal trends in average annual and seasonal weather at the NYS level, to identify indicators which are representative of climate trends across NYS and to describe trends in indicators of extreme events by geographic regions in NYS. Our use of standard indices allows for comparison of temporal trends as well as trends across geographical regions. Also, the comparison of these multiple standard indices will facilitate identifying representative indicators of climate trends across NYS. The most representative indicators can then be used as predictors in climate-health research. Identification of geographic variation in sensitivity to climate change may be helpful in resource allocation and policy decisions.

Materials and methods

Data sources

The climate data used in the study were obtained from the US Historical Climatology Network (USHCN) (Williams et al. 2006), a high-quality dataset of daily records of basic meteorological variables from 1,062 observing stations across the 48 contiguous USA. Daily data include observations of maximum and minimum temperature, precipitation amount, snowfall amount, and snow depth. The temperature data were converted to degrees Celsius, and precipitation, snow depth, and snowfall to millimeters to allow comparison with global reports. Snowfall is the amount of fresh snow that has fallen during the 24-h measurement period, while the snow depth is the total amount of snow on the ground. Most of the USHCN stations are US Cooperative Observing Network stations located generally in rural locations, while some are National Weather Service First-Order stations that are often located in more urbanized environments. The period of record varies for each station. USHCN stations were chosen to minimize bias due to length of record, percent of missing data, number of station moves, and other station changes that may affect data homogeneity, and resulting network spatial coverage (Williams et al. 2006). The details of station locations are shown in Appendix A1, Fig. 3. The dataset is a consistent network through time, which minimizes any bias due to network changes through time. Prior to publication of the USHCN daily dataset, extensive quality control (QC) checks were conducted by the National Oceanographic and Atmospheric Administration's National Climatic Data Center (Williams et al. 2006). These QC checks involved examining the data for completeness, reasonableness, and accuracy. Apart from the quality checks instituted by the USHCN, we made further quality checks as follows. We checked for outliers greater than 3 standard deviations from the average values for that date and station. We replaced all unreasonable values for the meteorological variables as missing. These include: (a) daily precipitation amounts less than zero and (b) daily maximum temperature less than daily minimum temperature. Out of 57 stations in NYS, 31 stations with the most complete data (less than 10% of missing data for a period of 60 years from 1948 to 2008) were chosen (Appendix A2, Table 4).

Climate factor definitions and classification

A summary of all the temperature and precipitation indicators is presented in Table 1. These indices were developed by the World Climate Research Programme's Expert Team on Climate Change Detection and Indices (ETCCDI) (Tank et al. 2009). Some of the indices have the same name and definition as those used in previous studies (Frich et al. 2002; Griffiths and Bradley 2007; Tank et al. 2002), but they may differ slightly in the way they are computed. Both temperature and precipitation indicators can be broadly classified into four different categories based on the method of calculation: (1) Percentile-based indices: The percentile-based temperature indices represent the highest (90th) and lowest (10th) deciles for maximum and minimum temperature. The percentile-based indices for precipitation include the upper first and fifth percentile. Percentile thresholds are more evenly distributed in space and meaningful for every region; (2) Threshold indices are defined as the number of days on which a temperature or precipitation value falls above or below a percentile threshold. These thresholds were set to assess moderate extremes that typically occur a few times every year rather than high impact, once-in-a-decade weather events; (3) Absolute indices represent maximum or minimum values within a month; (4) Duration indices define periods of extreme weather (except *growing season length* (GSL) which signifies periods of mild weather). The GSL variable is especially meaningful in the mid-latitude regions, and, aside from agricultural use, can be considered an indicator of the duration of mild/favorable weather; and (5) Other indices include indices of *annual precipitation total* (PRCPTOT), and *simple daily intensity index* (SDII). They do not fall into any of the above categories but may still be of interest.

Statistical analysis

We calculated statewide linear trends in average maximum temperature, minimum temperature, total precipitation, snow depth, and snowfall. Secondly, we calculated indices of weather extremes for individual stations. We used linear regression to assess trends in these extreme indicators for each

Table 1 Definition of extreme weather indicators and their statewide trends in New York State 1948–2008

Indicator name	Definition	Average trend in New York State/decade
Temperature indicators		
Percentile indicators		
Warm days	Percentage of days when TX>90th percentile	**−0.03 days**
Warm nights	Percentage of days when TN>90th percentile	**+0.33 days**
Cool days	Percentage of days when TX<10th percentile	**+0.04 days**
Cool nights	Percentage of days when TN<10th percentile	−0.50 days
Threshold indicators		
Summer days	Annual count when TX(daily maximum)>25ºC	−0.81 days
Tropical nights	Annual count when TN(daily minimum)>20ºC	**+0.26 days**
Ice days	Annual count when TX(daily maximum)<0ºC	−0.06 days
Frost days	Annual count when TN(daily minimum)<0ºC	**−0.97 days**
Absolute indicators		
Warmest night	Monthly maximum value of daily minimum temp	**+0.16°C**
Warmest day	Monthly maximum value of daily maximum temp	**−0.14°C**
Coldest night	Monthly minimum value of daily minimum temp	**+0.32°C**
Coldest day	Monthly minimum value of daily maximum temp	−0.03°C
Diurnal temperature range	Daily maximum temperature–daily minimum temperature	**−0.11°C**
Duration indicators		
Growing season length	Annual (1st of January to 31st of December count between first span of at least 6 days with TG>5ºC and first span after July 1 of 6 days with TG<5ºC	**+1.66 days**
Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	**−0.21 days**
Cold spell duration indicator	Annual count of days with at least six consecutive days when TN<10th percentile	**−0.15 days**
Precipitation indicators		
Percentile indicators		
Preceipitation on very wet days	Annual total PRCP when RR>95th percentile	**+17.97 mm**
Precipitation on extremely wet days	Annual total PRCP when RR>99th percentile	**+7.35 mm**
Threshold indicators		
Number of heavy precipitation days	Annual count of days when PRCP>=10 mm	**+0.99 days**
Number of very heavy precipitation days	Annual count of days when PRCP>=20 mm	**+0.62 days**
Number of days above 25 mm	Annual count of days when PRCP>=25 mm	**+0.42 days**
Absolute indicators		
Max 1-day precipitation amount	Monthly maximum 1-day precipitation	**+1.81 mm**
Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	**+2.45 mm**
Duration indicators		
Consecutive wet days	Maximum number of consecutive days with RR>=1 mm	**+0.42 days**
Consecutive dry days	Maximum number of consecutive days with RR<1 mm	**−0.21 days**
Other indicators		
Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1 mm)	**+30.19 mm**
Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as Prcp>=1.0 mm) in the year	**+0.18 mm/day**

Bold values represent trends significant at α=0.05 level

TX maximum temperature, *TN* minimum temperature, *PRCP* precipitation

station. A trend was termed significant if the t test for the estimate of the slope was significant at α=0.05 level.

The percentile weather indicators were calculated by summing the number of days for which daily values exceed a time-of-year-dependent percentile. These percentiles are determined for each day of the year, using data from that day and 2 days on either side of it over the course of the base period. For easy comparison of indices across stations with records of various lengths, the thresholds were computed from a common base period, namely 1971–2000 for all stations. The 1971–2000 period was chosen as it is consistent with the WMO operational climatology base period (World Meteorological Organization 2010). The sample estimates of these indicators in the base years may not be reliable and there may be a discontinuity in the expected rates for the years on the boundaries of the base period (von Storch and Zwiers 1999). Therefore, the

RClimDex program was used to perform a bootstrapping procedure to provide cross-validation of these values (Zhang and Yang 2004). The bootstrapping makes the estimation of the threshold exceedance rate for both the in-base and out-of-base periods comparable (Zhang et al. 2005).

We calculated average decadal values for these indices for NYS as a whole by using the area-weighted average of indicator trends across the 10 NYS divisions for the years 1948 to 2008. Decadal trends (rate per decade) in all 26 indices were also calculated for each station that was judged to have data of adequate quality as detailed above. We calculated the proportion of stations with significant positive or negative trends for each indicator. Finally, the estimated decadal trends for each station were mapped using thematic maps to describe regional trends in temperature and precipitation extremes. All statistical analyses were done using SAS 9.2 (SAS Institute Inc., Cary, NC, USA) and R open-source software (R Foundation for Statistical Computing, Vienna, Austria). MapInfo 8.5.1(Pitney Bowes Business Insight, Troy, NY, USA) was used to map climate trends across NYS.

Results

State-wide temporal trends

The area-weighted average temporal trends across NYS from 1948 to 2008 for the indices of extreme weather are presented in Table 1. Most temperature indicators showed trends consistent with warming during the period of analysis. Among specific indicators, *warm nights* increased by +0.33 days/decade, while *frost days* decreased by 0.97 days/decade. The *diurnal temperature* decreased by 0.11°C per decade, while the *growing season length* increased by 1.66 days/decade. The precipitation indicators showed trends consistent with increasing intensity and duration precipitation events across the state. The *annual total precipitation* increased by 30.19 mm/decade and the *precipitation on very wet days* increased by 17.97 mm. *Number of heavy and very heavy precipitation days* increased by 0.99 and 0.62 days per decade, respectively. Similarly, *consecutive wet days* increased by 0.42 days and *consecutive dry days* decreased by 0.21 days, respectively.

Table 2 presents the annual, monthly, and seasonal trends in average weather indicators in NYS. There were no noteworthy trends in the average temperature across NYS except that the minimum temperature had a significant increasing trend in summer (0.05°C per decade). The average annual precipitation showed an increasing trend (+0.10 mm per decade). The summer and fall seasons showed significant increases (+0.13 and 0.16 mm per decade, respectively) and the months of September and October had the highest significant increasing trends. There were no significant trends in snowfall and snow depth across NYS from 1948 to 2008.

Indicator comparison

The analysis of extreme weather indicators presented in Fig. 1 is based on individual station data. Each indicator was assessed based on consistency in direction of a trend as well as

Table 2 New York State decadal trends in annual, monthly, and seasonal averages of meteorological factors (1948–2008)

	Maximum temperature (ºC)	Minimum temperature (ºC)	Total precipitation (mm)	Snow depth (mm)	Snowfall (mm)
Yearly	−0.02	0.04	0.10*	1.28	0.04
Monthly					
January	0.02	0.10	0.08	3.62	0.53
February	0.01	0.02	−0.05	2.97	0.05
March	0.17	0.02	0.04	3.45	0.05
April	0.06	−0.01	0.06	0.83	0.04
May	0.04	0.09	0.05	na	na
June	0.74	0.12	0.19*	na	na
July	0.12	0.07	0.16*	na	na
August	0.84	0.13	0.04	na	na
September	0.03	0.10	0.22*	na	na
October	−0.08	−0.08	0.23*	0.14	0.05
November	−0.30*	−0.02	0.04	0.55	−0.24
December	0.01	0.16	0.04	1.06	0.37
Seasonal					
Winter	0.06	0.09	0.03	2.54	0.32
Spring	0.09	0.03	0.05	na	na
Summer	−0.07	0.05*	0.13*	na	na
Fall	−0.10	−0.004	0.16*	na	na

na not applicable

*$p<0.05$ level

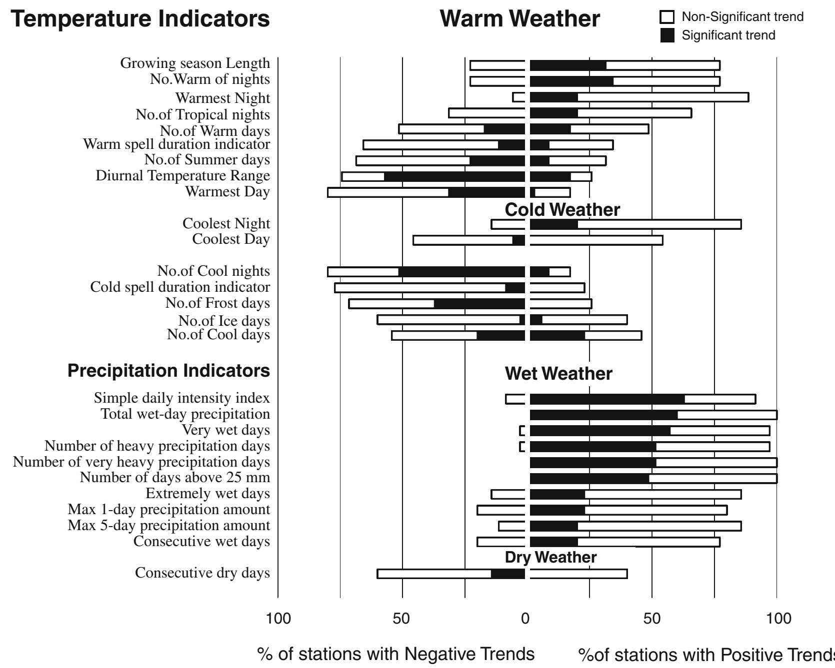

Fig. 1 Proportion of stations showing specific trends in extreme weather indicators in New York State: 1948–2008

proportion of significant trends across all stations. We used this information to identify the indicators that were most representative of climate trends across NYS. For example, 77% stations showed increase in *growing season length* with about 40% of these being significant trends. Similarly, 74% of stations showed a decrease in *diurnal variation* with 76% of those trends being statistically significant. Among indicators of temperature extremes, the majority of stations showed an upward trend in warm weather indicators. About 77% of all stations showed an increase in *warm nights*, with most of those being significant. More than half of stations showed upward trends in the *number of tropical nights* and temperature on the *warmest night of the month*. The only two indicators which did not show a consistent upward trend were *warm spell duration* and *warmest day* of the month. Consistent with warming over the period of study, most stations showed an upward trend in the temperature of the *coldest day* and *coldest night*. More than half of all stations showed downward trends in *cool days, ice days, frost days*, and *cool nights*. The strongest cold weather indicator was the *number of cool nights* with about 80% of stations showing significant negative trends, of which 64% were statistically significant. All of the precipitation indicators showed an upward trend in wetness across NYS. About 60% of stations showed significant upward trend in *annual total wet-day precipitation*. Similarly, 62% showed significant upward trend in *simple daily intensity index*. Finally, a total of 60% of stations showed a downward trend in *consecutive dry days*.

Regional trends

The trends in specific indices in New York weather divisions are shown in Table 3. The Great Lakes region as well as much of the eastern parts of the state including the Coastal region, Champlain Valley, Northern Plateau and, to some extent, the Hudson Valley region, show increasing trends in warm weather indicators especially *warm nights*. The same regions show a decreasing number of cold weather indicators most prominently in ice days. All regions showed increasing trends in precipitation indicators. The indicator with most significant trends was *total wet day precipitation* especially in the Coastal region, the Hudson Valley, Champlain Valley, the Great Lakes region, and the Eastern and Western Plateau regions. Albany showed some of the most consistent in temperature indicators with significant increases in *number of warm days*. The stations with the most consistent and extreme precipitation trends was Dannemor with the largest increase in *very heavy precipitation days*, *precipitation on very wet days* and *total wet day precipitation*.

Figure 2 presents decadal trends for stations showing significant trends in a few specific weather indicators. Series A presents maps for temperature indicators and series B for precipitation indicators. For the temperature indicators, the red hues represent warming and blue hues represent cooling over the period of study. Among warming indicators, *growing season length* increased for most stations and the majority of significant trends were seen in the Coastal region and the Great Lakes region (Fig. 3:A1.1). While a majority of stations in the eastern and western parts of NYS showed significant increases in *warm nights*, downward (non-significant) trends are observed in the Central Lakes and Western Plateau regions. The monthly *warmest night* showed highest increases in the Great Lakes and Northern Plateau regions. Series A2 shows trends in indicators of cold extremes. These maps show trends consistent with warming over most parts of New York. *Frost days*

Table 3 Trends in climate indicators per decade for individual stations in New York State (1948–2008)

Division	Stations	No. of warm nights/decade	Warmest night °C/decade	Coolest day °C/decade	Coolest night °C/decade	No. of cool days/decade	No. of ice days/decade	No. of heavy precipitation days/decade	No. of very heavy precipitation days/decade	Precipitation on very wet days mm/decade	Total wet-day precipitation mm/decade
Western Plateau	Alfred	**−0.5**	**−0.15**	**+0.24**	**−0.32**	+2.06	**−1.48**	+0.60	+0.33	−3.84	+5.11
	Allegany	**−0.22**	**−0.05**	**−0.65**	+1.26	**−6.89**	+3.63	+0.52	**+0.33**	+8.71	+13.24
	Angelica	−0.25	0	−0.22	+0.77	−3.06	+1.35	**+0.89**	+0.39	+7.88	**+34.99**
	Elmira	+0.28	+0.17	−0.28	**+0.66**	−3.18	**+1.95**	**+1.20**	**+0.55**	**+25.60**	**+31.04**
Eastern Plateau	Port Jerry	+0.3	+0.07	−0.28	**+0.50**	−1.05	+1.03	+0.66	+0.53	**+22.99**	+28.00
	Norwich	**+0.47**	+0.16	+0.40	−0.74	+1.73	−1.46	+0.36	+0.76	+28.32	+22.78
	Binghampton	+0.32	+0.05	+0.01	−0.03	−1.31	−0.40	**+0.98**	**+0.73**	**+16.87**	**+27.18**
	Cooperstown	+0.16	+0.15	−0.17	+0.34	−0.36	−0.35	**+1.49**	**+0.92**	**+20.97**	**+34.61**
Northern Plateau	Stillwater	**+0.74**	+0.12	−0.32	**+0.94**	−4.89	+1.32	+0.50	+0.29	+17.06	+25.81
	Lake Placid	**+0.71**	**+0.37**	+0.47	**−1.02**	−0.02	**−2.43**	+0.56	**+0.61**	**+24.30**	**+22.82**
	Tupper	−0.03	+0.04	−0.24	−0.08	+0.23	−0.44	+1.97	+0.98	+21.35	+49.75
	Indian Lake	**+1.02**	**+0.31**	−0.05	+0.40	−4.04	+0.98	−0.07	+0.14	+6.54	+2.14
	Wanakena	+0.34	+0.24	**−0.71**	**+0.44**	−0.55	−0.13	+0.25	+0.29	**+15.87**	+9.17
Coastal	Bridgehamton	+0.30	+0.15	+0.07	−0.49	+4.01	−0.51	+0.73	+0.61	**+32.89**	**+29.27**
	New York	**+0.49**	+0.18	+0.07	−0.22	−0.40	−0.48	+1.14	+1.22	+41.32	+59.20
	Setauket	−0.09	+0.01	−0.34	**−0.80**	+1.50	+0.14	+0.72	+0.23	+18.20	+20.67
Hudson Valley	Albany	**+0.64**	**+0.21**	**+0.18**	−0.13	**−0.72**	−1.22	+1.61	**+0.83**	+14.77	**+36.80**
	Dobbs Ferry	−0.10	+0.08	+0.18	**−0.59**	+1.24	−1.00	+0.28	+0.44	+19.96	+15.44
	Mohonk	**+0.55**	0.07	0.18	**−0.8**	5.38	−1.31	**+1.02**	**+0.86**	**+26.80**	**+33.66**
	Poughkeepsie	+0.50	0.19	0.1	−0.03	−0.45	−0.37	**+1.12**	**+1.17**	**+41.50**	**+52.17**
	WestPoint	**+0.85**	+0.40	+0.11	+0.28	−0.90	+0.22	+0.31	+0.44	+26.92	+21.25
Champlain Valley	Dannemor	+0.10	+0.28	−0.35	**+0.57**	−3.70	+1.20	**+3.23**	**+1.44**	**+25.89**	**+80.35**
St. Lawrence Valley	Canton	−0.03	+0.07	+0.09	+0.44	−1.80	+0.26	+0.51	+0.09	+4.28	+12.94
	Ogdensbu	**+0.93**	+0.14	−0.11	+0.91	−0.31	+1.17	+0.24	+0.09	+9.85	+31.72
	Lawrence	+0.40	**+0.53**	+0.29	−0.34	+1.01	−1.17	**+1.70**	**+0.69**	**+18.33**	**+47.06**
Great Lakes	Batavia	**+1.25**	**+0.60**	+0.15	**−0.59**	+0.80	−1.20	**+0.95**	**+0.76**	**+15.97**	**+25.35**
	Buffalo	+0.47	+0.17	+0.14	−0.17	−1.23	−0.78	+0.75	+0.31	**+10.74**	**+23.06**
	Fredonia	**+0.83**	0	−0.07	+0.14	−2.15	+0.15	**+0.86**	**+0.79**	**+22.45**	**+28.16**
	Oswego	**+0.34**	+0.04	+0.15	−1.02	+3.07	−0.68	+1.27	+0.53	+18.69	+45.82
	Rochester	+0.32	+0.14	+0.22	−0.12	−1.28	−0.49	+0.60	+0.45	**+14.89**	**+22.74**
	Watertown	+0.02	**+0.18**	+0.15	−0.30	+0.43	−0.80	+0.38	+0.24	+7.95	+20.49
Central Lakes	Dansville	+0.09	+0.10	−0.07	+0.41	−3.30	−0.08	**+1.36**	+0.45	+6.75	+11.18
	Ithaca	+0.28	+0.12	−0.10	+0.31	−1.19	+0.49	**+0.81**	**+0.64**	+9.05	**+23.11**
	Syracuse	+0.06	+0.13	+0.12	−0.19	−0.16	−0.59	+0.60	+0.45	+0.73	+11.58
	Hemlock	−0.16	+0.11	−0.12	+0.23	−1.31	+0.80	**+1.71**	**+0.53**	+10.48	**+37.61**

Bold values represent trends significant at α=0.05 level

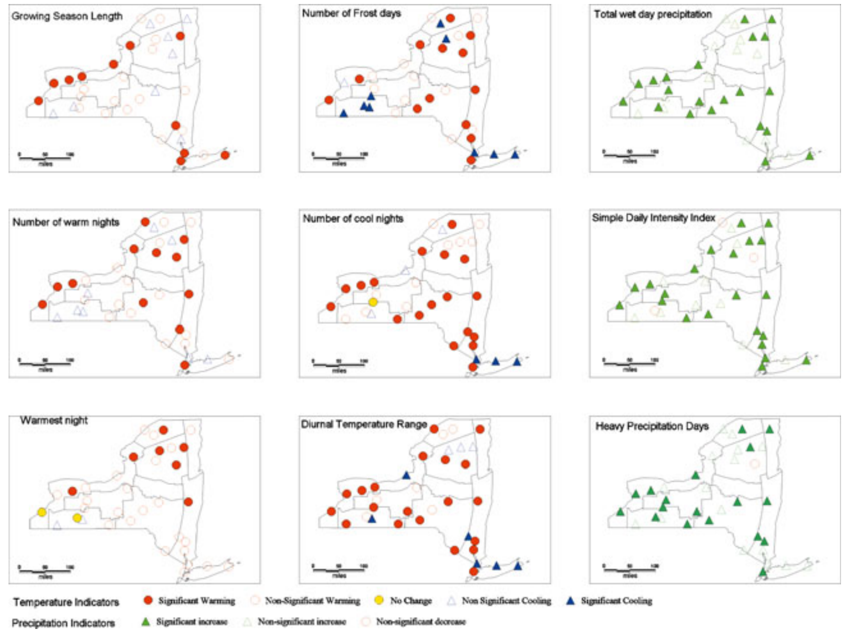

Fig. 2 Spatial distribution of trends in specific climate extreme indicators in New York State: 1948–2008

decreased significantly in most stations in the Great Lakes, Hudson Valley, and Eastern Plateau divisions. Similarly, *cool nights* showed downward trends most prominently in the Hudson Valley region, the Great Lakes, and the Eastern Plateau region, but the Coastal division showed an increase in *cool nights*. Most stations showed a decline in *diurnal temperature* except some stations in Western Plateau and Coastal divisions. Series B shows trends in precipitation indicators. In these maps, greener hues represent increasing wetness and orange hues represent drying over the period of study. *Total precipitation on wet days* increased significantly for most stations. The *simple daily intensity* also increased across most parts of New York as did the *number of heavy precipitation days*.

Discussion

This study suggests that NYS statewide temperature and precipitation have been increasing between 1948 and 2008. The highest increases in average temperature were seen in winter months and the average minimum temperature increased more than the maximum temperature. This is consistent with other reports from the region (Brown et al. 2010). All cold weather indicators except number of cold days showed warming trends which is consistent with greater warming during winter than summer seen in seasonal trends in the average maximum and minimum temperature as well. Extreme indicators based on minimum temperature showed more consistent warming trends than those based on maximum temperature. In addition, all of the precipitation indicators demonstrate trends consistent with increasing precipitation over time. The average trends in the indices are generally consistent in magnitude and direction with a recent study of climate trends in the whole of US northeast (Brown et al. 2010). For example, *cool nights* have decreased at rate of −0.5%/decade in our analyses which is consistent with their estimate for the US northeast. *Annual total precipitation* was reported to have increased by 18.7 mm/decade for the US northeast as compared to 30 mm/decade found in our analyses of NYS.

The most representative extreme weather indicators in NYS for warm weather are *growing season length* and *warm nights*. The most representative indicators during cold weather were a decline in *cool nights* and *frost days*. Most other temperature indicators are also consistent with the warming trend. In general, out of the 15 temperature indicators, 13 showed trends consistent with warming over the period of study. The only extreme indicators that showed significant trends in the majority of stations inconsistent with warming were two indicators based on maximum temperature (*warmest day of the month* and *warm spell duration*). This inconsistency has been reported in other studies of this region as well (Brown et al. 2010; DeGaetano and Allen 2002). It has been suggested that these decreases may be related to land use changes and resulting changes in surface hydrology (DeGaetano and Allen 2002; Mahmood et al. 2004). A recent study (Griffiths and Bradley 2007) examined trends from 1926 to 2000 for five temperature and five precipitation indicators in the entire Northeast and found upward trends in most stations for growing season length, a decreasing extreme temperature range but no clear pattern in the heat wave duration indicator. The precipitation indicators in our report all point towards increasingly wet conditions over time. The most representative indicators were *annual total wet day precipitation* and the *precipitation on wet days*. Previous studies have found mixed trends in precipitation in the US northeast (Brown et al. 2010; Griffiths and Bradley 2007).

On regional analyses, the most warming trends are seen for the most part in the Hudson Valley and Great Lakes regions of New York. The Great Lakes region had some of the greatest warming, while the Coastal and Western plateau regions of New York show less consistent trends. We also found higher trends in the Champlain Valley and Northern Plateau regions which have not been analyzed in previous studies. All of the precipitation indicators showed trends consistent with increasing precipitation in our study. The Hudson valley shows the most significant increases in precipitation.

Previous studies of climate trends in the US northeast region have used other periods of time for their analyses (1926–2000) which may be prone to inhomogeneities and some of the operational definitions for their indicators were slightly different from ours (Griffiths and Bradley 2007). We have attempted to use more recent data less prone to inhomogeneity due to station and instrument changes from the same source to estimate trends using standard methodology developed to compare climate change trends globally. We have used 26 separate indices to identify the most representative indicators for this region. The fixed threshold of 5°C used to define heat waves in previous studies may be too high in regions where the variability of daily temperature is low (Griffiths and Bradley 2007). Additionally, the heat wave duration index used in earlier reports (Griffiths and Bradley 2007) has a tendency to have too many zero values and may not be statistically robust (Kiktev et al. 2003). We have instead used the *warm spell duration index* which overcomes these problems.

Our paper is one of the first reports to use these standard indices to describe trends in climate extremes, across the state of New York, which has been identified as a sensitive area for climate change (Frumhoff et al. 2008). We used descriptive indices, developed by the Expert Team on Climate Change Detection and Indices of the World Climate Research Programme that refer to moderate extremes that typically occur several times every year (Tank et al. 2009). Such moderate extremes have more robust statistical properties than measures of extremes which are far enough into the tails of the distribution so as not to be observed during some years. The use of a 30-year base period (1971–2000) to calculate thresholds for weather variables as detailed above allows comparison across different stations with varying record lengths. We used a bootstrapping method to avoid inhomogeneities in threshold estimation. Finally, we have attempted to explore geographical differences in climate trends within NYS in more detail than previous reports.

In interpreting our results, it must be kept in mind that the urban heat island effect contributes to the higher extremes in urban areas and that while the USHCN stations represent the best long-term climate records available for the contiguous USA, no station is completely free of changes that could possibly affect its instrumental record. We used only 35 stations out of the 56 stations available in NYS as we selected stations with less than 10% data missing for the 60-year period from 1948 to 2008. Of these 35 stations, 18 had some changes in location (Appendix A2) which might affect trends over time. Low recording precision in temperature and precipitation data may result in some bias in calculation of threshold indices; however, the impact of this inhomogeneity is not expected to affect trend estimation (Zhang et al. 2009).

The various indices that were used in the study can be used to inform research in specific areas of climate change impacts, the most important being that on human health. An increased *number of warm days* and *warm nights* may adversely affect human health especially heat-related diagnoses. Increased *growing season length* may increase exposure to pollen, mold, and poison ivy which are major triggers of asthma and other allergic diseases (Beggs and Bambrick 2005). The increasingly milder climate (as evident in our analysis especially for *growing season length*) is believed to facilitate spread of Lyme disease which is an important health problem in New York State (Bacon et al. 2008) into higher altitudes (Brownstein et al. 2003). Increasing temperatures during April and November may prolong the questing periods of surviving ticks leading to increase in Lyme disease counts during those months. On the other hand, the lower number of *ice days* and *frost days* and higher *coldest day* temperatures may affect over-wintering of ticks leading to decreased tick survival. Incidence of food and waterborne illnesses are also predicted to increase with climate change especially with increasing heavy rainfall (Curriero et al. 2001; Hunter 2003). Since precipitation has been found to be an important predictor of food and waterborne outbreaks (Drayna et al. 2010; Thomas et al. 2006), the impact of precipitation indicators such as number of *heavy precipitation days* on these illnesses needs to be further explored. Further research is therefore needed to assess the impact of these rising climate change indicators on human health.

We have identified the Great Lakes and Hudson Valley regions maybe particularly sensitive to changes in extreme climate events. The geographical differences that have been so identified can be utilized to inform policy decisions regarding efforts to monitor and mitigate human health and economic impacts of climate change.

Conclusions

Our study has found that NYS in general showed trends consistent with warming and increasing precipitation from 1948 to 2008. There are regional differences in these trends and we have identified specific regions which maybe more vulnerable to this change in climate. We have also identified specific indicators which show the most consistent trends in all regions. Further research using these representative indicators may allow estimation of health impact of changing climate extremes.

Acknowledgments We thank Barbara Fletcher for her help in drafting of the manuscript. This research study was supported in part by grant #5U01EH000396-01 (NY) National Center for Environmental Health, Center for Disease Control and grant # 5U38EH000184-05 National Environmental Public Health Tracking Program, Centers for Disease Control and Prevention. The meteorological data were provided by the National Center for Atmospheric Research which is supported by grants from the National Science Foundation.

Appendix A1

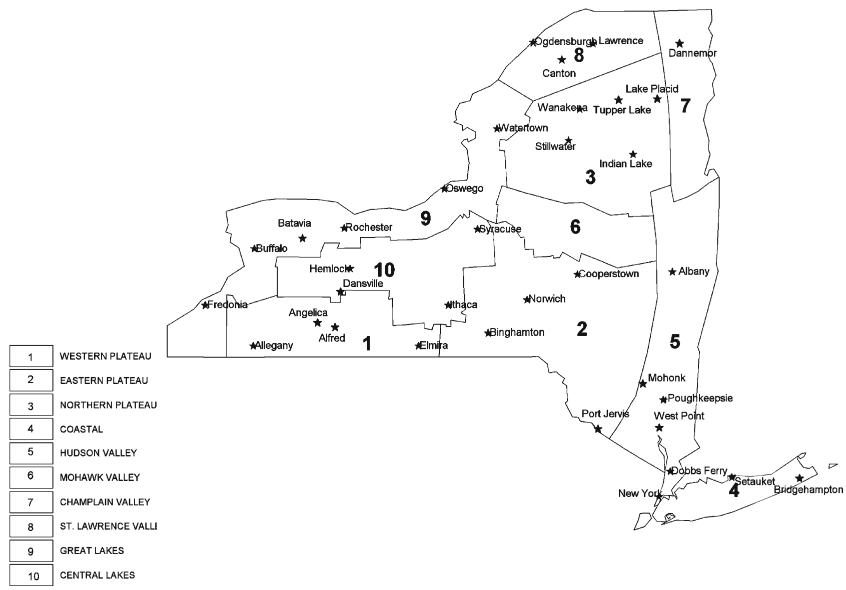

Fig. 3 Location of US Historical Climatology Network stations in New York State by climate division

Appendix A2

Table 4 Station changes for New York State by climate division (1948–2008)

Division	Stations	Station changes	Year	Location description
Western Plateau	Alfred	North/0.3 mi	1987	https://mi3.ncdc.noaa.gov/mi3qry/locationGrid.cfm?fid=20182&stnId=20182
	Allegany	None		https://mi3.ncdc.noaa.gov/mi3qry/locationGrid.cfm?fid=20114&stnId=20114
	Angelica	North/25 ft NE 0.3 mi	1989 1990	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20208&stnId=20208
		E 1 mi	1994	
	Elmira	NW/2.5/miles NW/2.2/miles	1986 2008	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20089&stnId=20089
Eastern Plateau	Port Jervis	NW/12/ft	1997	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19991&stnId=19991
	Norwich	SSE/1.2/miles	2008	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20279&stnId=20279
	Binghamton	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20155&stnId=20155
	Cooperstown	NW/1/miles	1999	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20339&stnId=20339
Northern Plateau	Stillwater	S/0.3/miles NE/480/ft	1986 1998	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=15346&stnId=15346
	Lake Placid	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20608&stnId=20608
	Tupper	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20604&stnId=20604
	Indian Lake	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20561&stnId=20561

Table 4 (continued)

Division	Stations	Station changes	Year	Location description
	Wanakena	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20602&stnId=20602
Coastal	Bridgehampton	N/0.1/miles	1985	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19940&stnId=19940
	New York	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19911&stnId=19911
	Setauket	W/120/ft	1992	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19943&stnId=19943
Hudson Valley	Albany	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20358&stnId=20358
	Dobbs Ferry	SE/1.5/miles	1989	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19953&stnId=19953
	Mohonk	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20026&stnId=20026
	Poughkeepsie	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20013&stnId=20013
	WestPoint	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=19989&stnId=19989
Champlain Valley	Dannemora	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20631&stnId=20631
St. Lawrence Valley	Canton	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20624&stnId=20624
	Ogdensburg	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20632&stnId=20632
	Lawrenceville	W/0.75/miles	1998	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20634&stnId=20634
		WNW/200/ft	2008	
Great Lakes	Batavia	xx/1/unknown units NE/2.6/miles	1955 1980	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20436&stnId=20436
		SW/2.6/miles	1982	
		E/1.8/miles	1983	
		N/2.8/miles	1994	
	Buffalo	W/0.5/miles NE/0.5/miles	1995 1997	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20409&stnId=20409
	Fredonia	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20252&stnId=20252
	Oswego	SW/12/ft N/0.25/miles	1986 1996	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20533&stnId=20533
	Rochester	N/1/miles S/0.8/miles	1989 1996	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20468&stnId=20468
	Watertown	NE/400/ft	1986	https://mi3.ncdc.noaa.gov//mi3qry/identityGrid.cfm?fid=20585
Central Lakes	Dansville	NW/0.9/miles	1987	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20293&stnId=20293
	Ithaca	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20262&stnId=20262
	Syracuse	S/0.1/miles	1984	https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=13507&stnId=13507
	Hemlock	None		https://mi3.ncdc.noaa.gov//mi3qry/locationGrid.cfm?fid=20366&stnId=20366

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