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Trend Detection in Annual Temperature & Precipitation using the Mann Kendall Test – A Case Study to Assess Climate Change on Select States in the Northeastern United States

Neha Karmeshu

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Abstract

The impact of climate change on annual air temperature and precipitation has received a great deal of attention by scholars worldwide. Many studies have been conducted to illustrate that changes in annual temperature and precipitation are becoming evident on a global scale. This study focuses on detecting trends in annual temperature and precipitation for the nine states in the Northeastern United States. For this study, the widely used modified Mann-Kendall test was run at 5% significance level on time series data for each of the nine states for the time period, 1900 to 2011. The resultant Mann- Kendall test statistic (S) indicates how strong the trend in temperature and precipitation is and whether it is increasing or decreasing. For temperature, all the states indicate statistically significant increasing trends, except for Pennsylvania and Maine that do not indicate statistically significant trends. In the case of precipitation, the states of New Hampshire and Maine do not show statistically significant results, while the other states show statistically significant increasing trends. On the contrary, linear trend line plotting indicates increasing trend in temperature for all nine northeastern states in the range of 0.00006 to 0.02 °F/yr, while a US EPA study demonstrates that the US average temperature rise is 1.3°F/century. [1] For precipitation, the linear trend line indicates a decreasing trend for Maine, while the other eight states have an increasing trend that ranges from 0.03 to 0.13 mm/yr.

Trend Detection in Annual Temperature & Precipitation using the Mann Kendall Test – A Case Study to Assess Climate Change on Select States in the Northeastern United States

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Acknowledgement

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I would like to dedicate this thesis to my family and friends who have always supported me in my endeavors and have had an unfaltering confidence in my abilities and skills.

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Abstract

The impact of climate change on annual air temperature and precipitation has received a great deal of attention by scholars worldwide. Many studies have been conducted to illustrate that changes in annual temperature and precipitation are becoming evident on a global scale. This study focuses on detecting trends in annual temperature and precipitation for the nine states in the Northeastern United States. For this study, the widely used modified Mann-Kendall test was run at 5% significance level on time series data for each of the nine states for the time period, 1900 to 2011. The resultant Mann-Kendall test statistic (S) indicates how strong the trend in temperature and precipitation is and whether it is increasing or decreasing. For temperature, all the states indicate statistically significant increasing trends, except for Pennsylvania and Maine that do not indicate statistically significant trends. In the case of precipitation, the states of New Hampshire and Maine do not show statistically significant results, while the other states show statistically significant increasing trends. On the contrary, linear trend line plotting indicates increasing trend in temperature for all nine northeastern states in the range of 0.00006 to 0.02 °F/yr, while a US EPA study demonstrates that the US average temperature rise is 1.3°F/century. [1] For precipitation, the linear trend line indicates a decreasing trend for Maine, while the other eight states have an increasing trend that ranges from 0.03 to 0.13 mm/yr.

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1. Introduction

Scientific evidence shows that climate change has begun to manifest itself, globally, in the form of increased downpours and storms, rising temperature and sea level, retreating glaciers, etc. Using data from the National Oce1anic and Atmospheric Administration's National Climatic Data Center (NCDC), a US EPA study [1] identifies the global and U.S. temperature patterns from 1901 to the present. This report states that the global average surface temperature has risen at an average rate of 0.13°F per decade (or 1.3°F per century) since 1901. The study indicates that the rate of warming for the lower 48 states in the U.S. has been similar to that of the global rate, since 1901. However, the study indicates that, since the late 1970’s, the United States has warmed at nearly twice the global rate. The average global warming in the late 1970’s was 0.35° to 0.51°F per decade. In fact, most of the temperatures increase in the United States was seen in the North, the West, and Alaska saw, while some parts of the South experienced little change. [1] Therefore, warming has not been uniform across the United States (Figure 1).

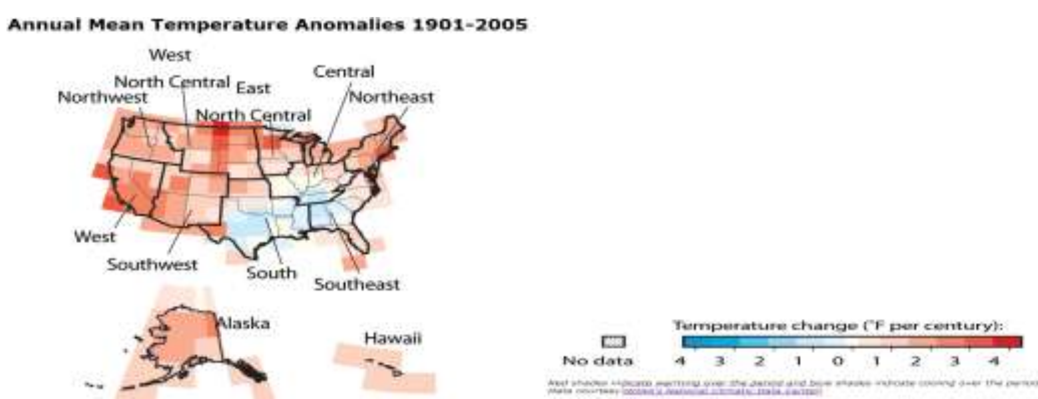


Figure 1. Annual Mean Temperature Trend in The US from 1901-2005. [1]

In a similar study done by the US EPA on U.S. and global precipitation patterns from 1901 to the present, the report suggests that global precipitation has increased at an average rate of 1.9% per century, while precipitation in the lower 48 states has increased at a rate of 6.4% per century. [2] According to the study, there has been a regional variability in the annual precipitation in the United States (Figure 2), some parts of the US experienced greater increases in precipitation, while parts of southwest and Hawaii experienced a decrease.

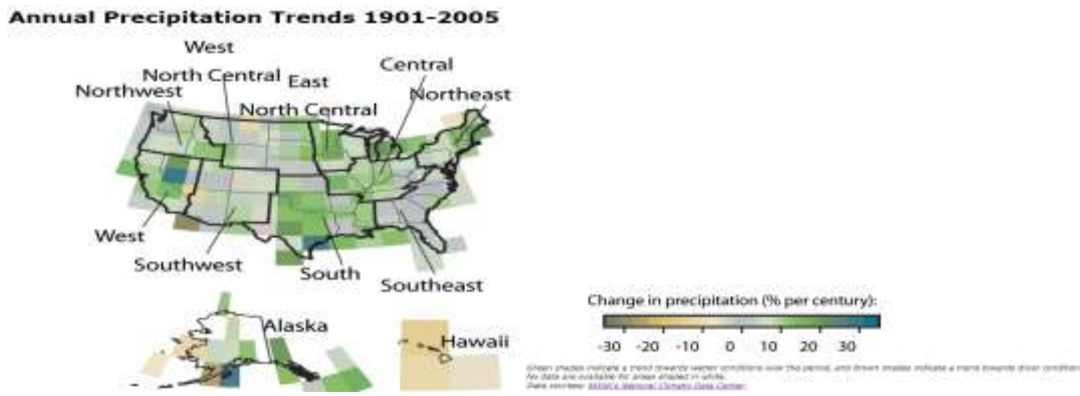


Figure 2: Annual Precipitation Trend in the US from 1901-2005. [2]

Temperature and precipitation are fundamental components of climate and changes in their pattern can effect human health, ecosystems, plants, and animals.[3] An increase in temperature can result in heat wave incidents and cause illness and death in susceptible populations. In addition, temperature changes can cause a shift in animal and plant species. [1] Similar changes in precipitation forms and its timing can have widespread effect on the availability of water and can cause a shift in animal and plant species.[2] Increases in precipitation trends can also result in an increase in the frequency of floods and could thereby impact water quality. On the other hand, a decrease in precipitation trend could imply an increase in instances of drought. The two variables, temperature and precipitaion, are also interconnected. An increase in Earth's temperature leads to more evaporation and cloud formation to occur, which in turn, increases precipitation. [4]

This study focuses on trend detection in annual precipitation and temperature for the Northeastern US, an area encompassing the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania. The Northeast region is taken as a case study herein, since it not only consists of densely populated coastal cities, but is also a prime destination for winter recreation. An analysis of vagaries in the two important climate parameters – temperature and precipitation - provides interesting insights on how they might influence tourism and flood insurance in this region. [21] The study was conducted to assess the effect of climate change for nine states on a regional scale and not at the local level. The time period under consideration is 1900-2011.

2. Data Sources and Methodology

2.1 Data Sources

The 12-month accumulation data on precipitation was obtained for nine states, including Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center. [18] The data used for this study is for the time period: 1900-2011 and was measured in inches.

Similarly, the 12-month average temperature data was obtained from the NCDC's database [19] for all nine states over the same time period as precipitation. The temperaturehe data was in Fahrenheit.

2.2 Methodology

Mann Kendall test is a statistical test widely used for the analysis of trend in climatologic [9] and in hydrologic time series [6]. There are two advantages of using this test. First, it is a non parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to inhomogeneous time series [4]. Any data reported as non-detects are included by assigning them a common value that is smaller than the smallest measured value in the data set [7]. According to this test, the null hypothesis H_0 assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis H_1, which assumes that there is a trend. [3]

The computational procedure for the Mann Kendall test considers the time series of n data points and T_i and T_j as two subsets of data where i = 1,2,3,…, n-1 and j = i+1, i+2, i+3, …, n. The data values are evaluated as an ordered time series. Each data value is compared with all subsequent data values. If a data value from a later time period is higher than a data value from an earlier time period, the statistic *S* is incremented by 1. On the other hand, if the data value from a later time period is lower than a data value sampled earlier, *S* is decremented by 1. The net result of all such increments and decrements yields the final value of *S* [5].

The Mann-Kendall S Statistic is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\,(T_j - T_i)$$

$$Sign\left(T_j - T_i\right) = \begin{cases} 1 \; if \; T_j - T_i > 0 \\ 0 \; if \; T_j - T_i = 0 \\ -1 \; if \; T_j - T_i < 0 \end{cases}$$

where T_j and T_i are the annual values in years j and i, j > i, respectively. [10]

If n < 10, the value of |S| is compared directly to the theoretical distribution of S derived by Mann and Kendall. The two tailed test is used. At certain probability level H_0 is rejected in favor of H_1 if the absolute value of S equals or exceeds a specified value $S_{\alpha/2,}$where $S_{\alpha/2}$ is the smallest S which has the probability less than α/2 to appear in case of no trend. A positive (negative) value of S indicates an upward (downward) trend. [5] For n ≥ 10, the statistic *S* is approximately normally distributed with the mean and variance as follows:

$E(S) = 0$

The variance (σ^2) for the S-statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i (i)(i-1)(2i+5)}{18}$$

in which t_i denotes the number of ties to extent i. The summation term in the numerator is used only if the data series contains tied values. The standard test statistic Z_s is calculated as follows:

$$Z_S = \begin{cases} \frac{S-1}{\sigma} \, for \, S > 0 \\ 0 \, for \, S = 0 \\ \frac{S+1}{\sigma} \, for \, S < 0 \end{cases}$$

The test statistic Z_s is used a measure of significance of trend. In fact, this test statistic is used to test the null hypothesis, $H_{0.}$ If | Z_s| is greater than $Z_{\alpha/2}$, where α represents the chosen significance level (eg: 5% with Z $_{0.025}$ = 1.96) then the null hypothesis is invalid implying that the trend is significant. [10]

Another statistic obtained on running the Mann-Kendall test is Kendall's tau, which is a measure of correlation and therefore measures the strength of the relationship between the two variables. Kendall's tau, like Spearman's rank correlation, is carried out on the ranks of the data. That is, for each variable separately, the values are put in order and numbered, 1 for the lowest value, 2 for the next lowest and so on. In common with other measures of correlation, Kendall's tau will take values between ±1 and +1, with a positive correlation indicating that the ranks of both variables increase together whilst a negative correlation indicates that as the rank of one variable increases, the other decreases. [7]

In time series analysis it is essential to consider autocorrelation or serial correlation, defined as the correlation of a variable with itself over successive time intervals, prior to testing for trends. Autocorrelation increases the chances of detecting significant trends even if they are absent and vice versa. In order to consider the effect of autocorrelation, Hamed and Rao (1998) suggest a modified Mann-Kendall test, which calculates the autocorrelation between the ranks of the data after removing the apparent trend. The adjusted variance is given by:

$$Var\,[S] = \frac{1}{18}[N(N-1)(2N+5)]\frac{N}{NS^*}$$

Where $\frac{N}{NS^*} = 1 + \frac{2}{N(N-1)(N-2)}\sum_{i=1}^{p}(N-i)(N-i-1)(N-i-2)p_s(i)$

N is the number of observations in the sample, NS* is the effective number of observations to account for autocorrelation in the data, p_s (i) is the autocorrelation between ranks of the observations for lag i, and p is the maximum time lag under consideration. [8]

Software used for performing the statistical Mann-Kendall test is Addinsoft's XLSTAT 2012. The null hypothesis is tested at 95% confidence level for both, temperature and precipitation data for the nine states. In addition, to compare the results obtained from the Mann-Kendall test, linear trend lines are plotted for each state using Microsoft Excel 2007.

2.3 Sources of Error

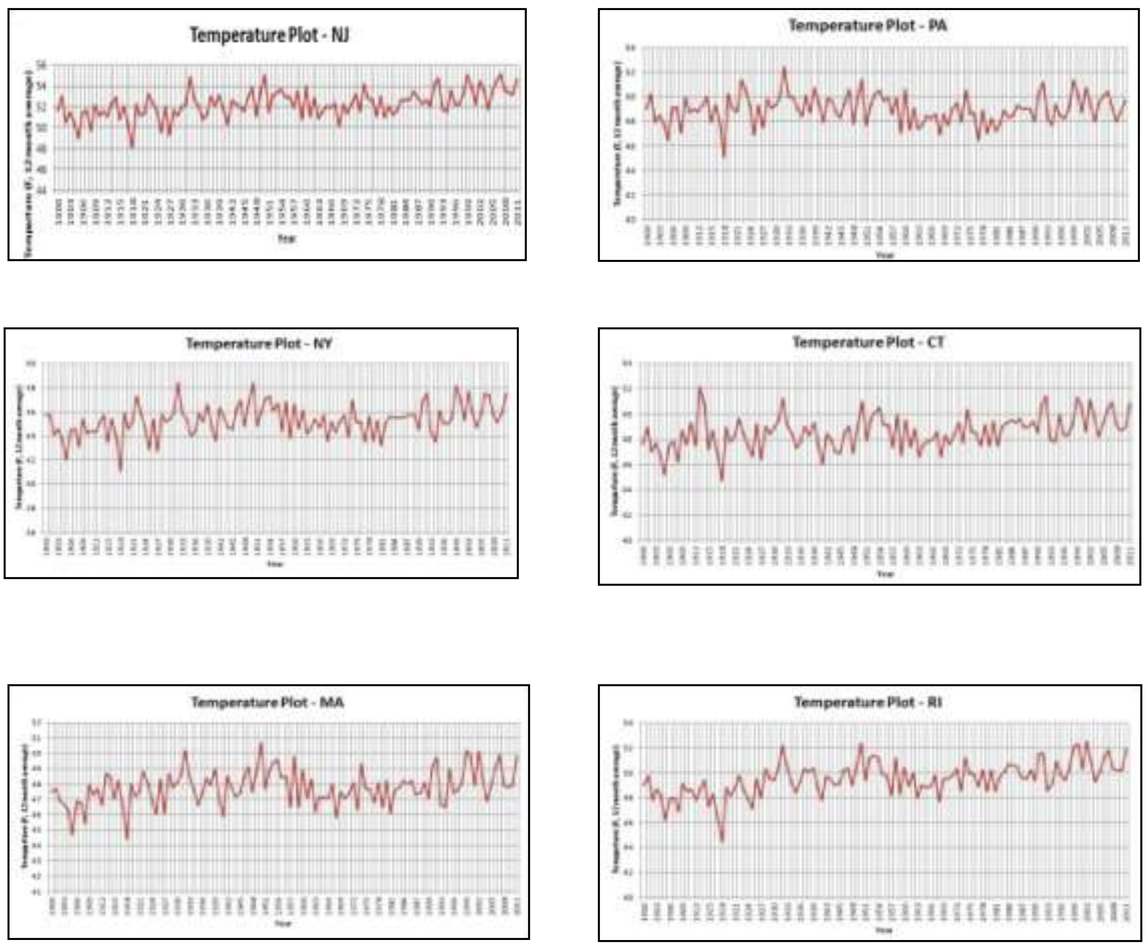
No information is available about the number of precipitation gauges and temperature sensors used in each state to record precipitation and temperature data. Also, the exact location of these gauges and sensors is unknown. The lack of uniformity in precipitation gauges and temperature sensors can influence the quality of recorded data.

National Climatic Data Center Website also mentions that due to problems in data transmission by each station location, errors might be observed in the data. Though quality control is performed, but a 100% correction rate is not possible. [20]

3. Results

3.1. Temperature

Figure 3 are the graphs for the 12-month average temperature observations for each of the nine states - New Jersey (NJ), Pennsylvania (PA), New York (NY), Connecticut (CT), Massachusetts (MA), Rhode Island (RI), Vermont (VT), New Hampshire (NH), and Maine (ME) for the timeperiod, 1900-2011.



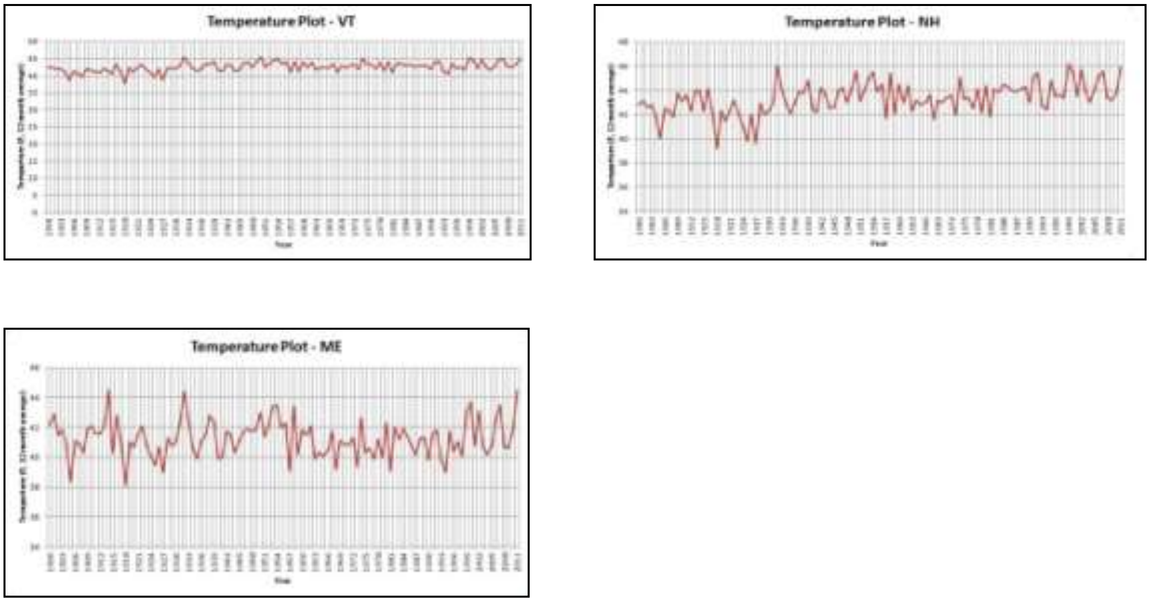


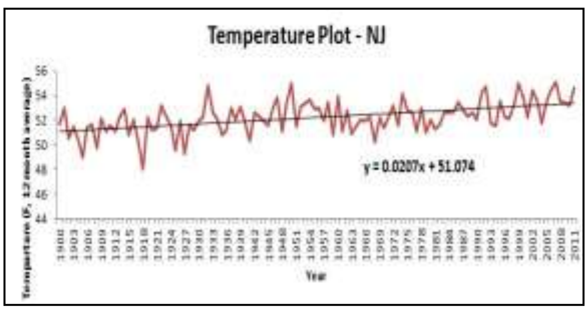
Figure 3: 12-month average temperature for each of the Northeast states

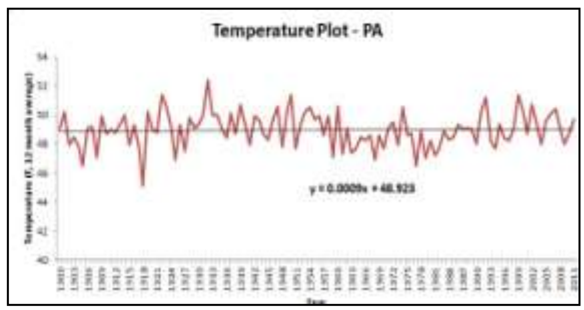
On running the Mann-Kendall test on temperature data, the following results in Table 1 were obtained for the nine states. If the p value is less than the significance level α (alpha) = 0.05, H_0 is rejected. Rejecting H_0 indicates that there is a trend in the time series, while accepting H_0 indicates no trend was detected. On rejecting the null hypothesis, the result is said to be statistically significant. Table 1 indicates that the Null Hypothesis was accepted for only 2 states, Maine and Pennsylvania.

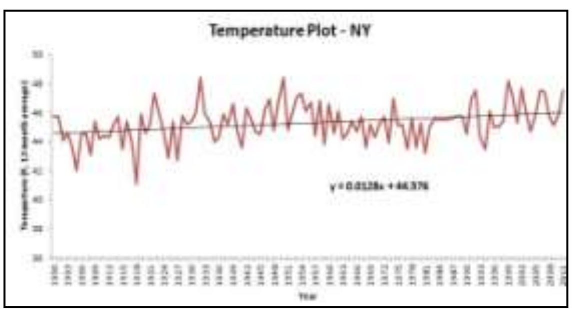
States	Mann Kendall Test					
	Mann-Kendall Statistic (S)	Kendall's Tau	Var (S)	p-value (two tailed test)	alpha	Test Interpretation
NJ	2177	0.354	157943.667	< 0.0001	0.05	Reject H0
PA	39	0.006	157925.667	0.924	0.05	Accept H0
NY	1290	0.210	157938.000	0.001	0.05	Reject H0
CT	1673	0.272	157955.667	< 0.0001	0.05	Reject H0
MA	1095	0.178	157975.000	0.006	0.05	Reject H0
RI	2412	0.392	157949.333	< 0.0001	0.05	Reject H0
VT	1769	0.288	157955.667	< 0.0001	0.05	Reject H0
NH	1984	0.323	157892.667	< 0.0001	0.05	Reject H0
ME	-178	-0.029	157964.000	0.656	0.05	Accept H0

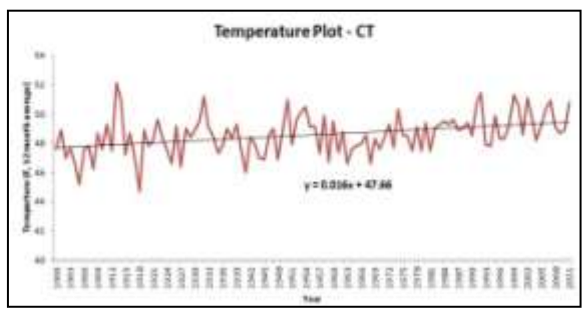
Table 1: Results of the Mann-Kendall test for temperature data for the Northeastern states.

On plotting the linear trend line for the Northeast states, the following results in Figure 4 were obtained.









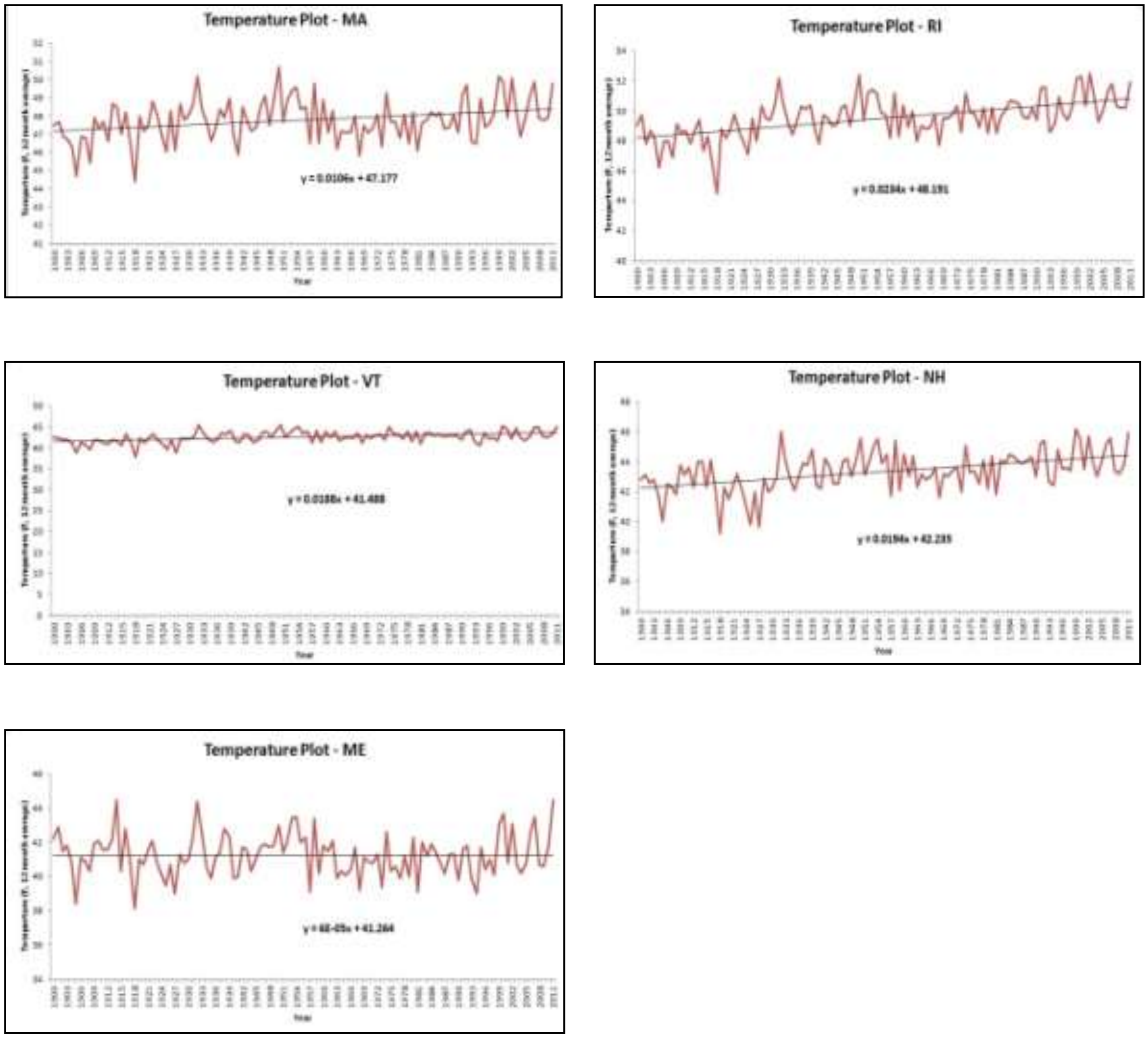
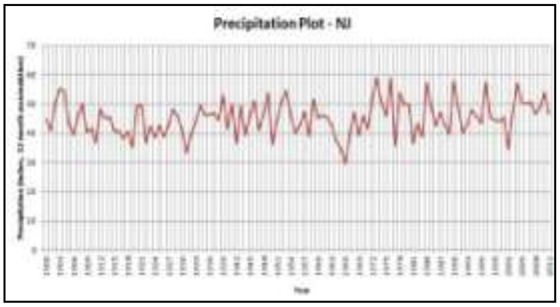
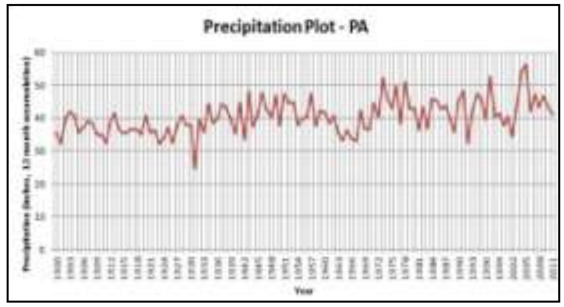


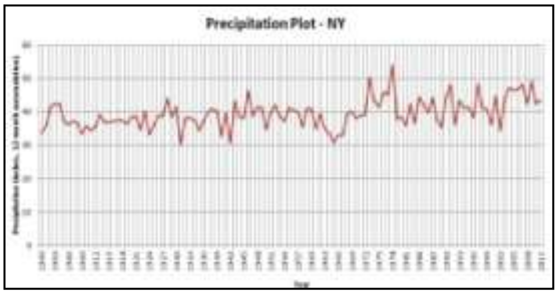
Figure 4: Linear trend line corresponding to temperature data for each of the Northeast states

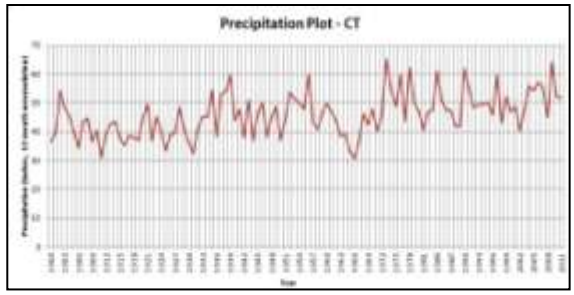
3.2 Precipitation

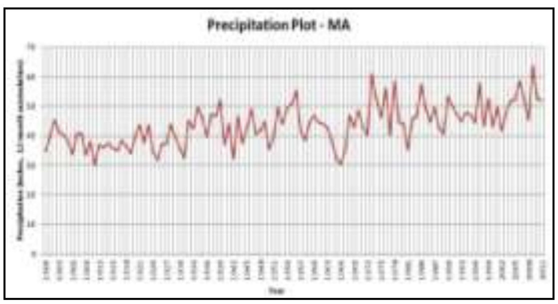
Figure 5 are the graphs for 12-month precipitation accumulation observations for each of the nine states - New Jersey (NJ), Pennsylvania (PA), New York (NY), Connecticut (CT), Massachusetts (MA), Rhode Island (RI), Vermont (VT), New Hampshire (NH), and Maine (ME) for the timeperiod, 1900-2011.

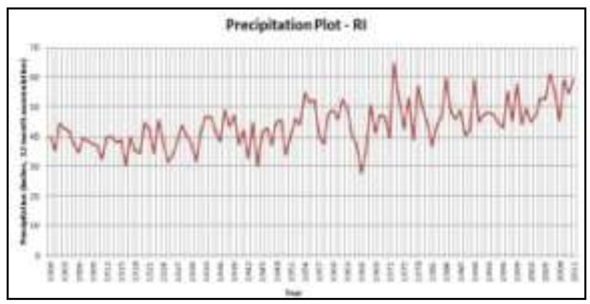

Precipitation Plot - NJ


Precipitation Plot - PA
Year

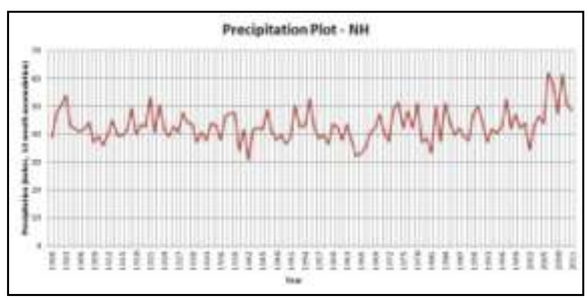

Precipitation Plot - NY


Precipitation Plot - CT


Precipitation Plot - MA


Precipitation Plot - RI


Precipitation Plot - VT


Precipitation Plot - NH

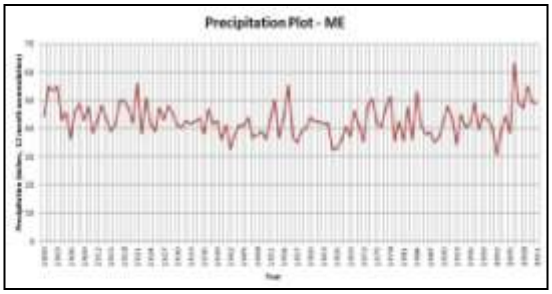


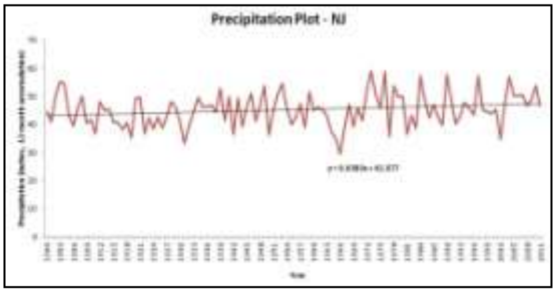
Figure 5: 12-month precipitation accumulation for each of the Northeast states

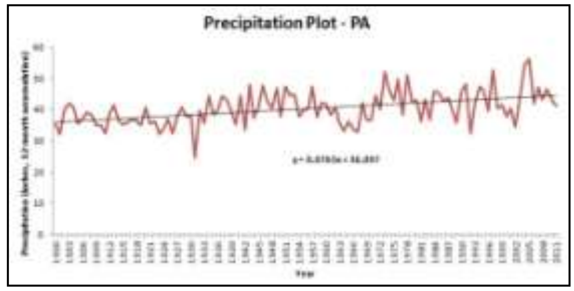
On running the Mann-Kendall test on precipitation data, the following results in Table 2 were obtained for the nine states. If the p value is less than the significance level α (alpha) = 0.05, H_0 is rejected. Rejecting H_0 indicates that there is a trend in the time series, while accepting H_0 indicates no trend was detected. On rejecting the null hypothesis, the result is said to be statistically significant. For this test, the Null Hypothesis was accepted for only 2 states, New Hampshire and Maine.

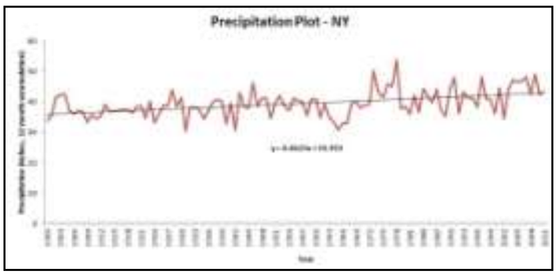
States	Mann Kendall Test					
	Mann-Kendall Statistic (S)	Kendall's Tau	Var (S)	p-value (two tailed test)	alpha	Test Interpretation
NJ	898	0.144	158160.667	0.024	0.05	Reject H0
PA	1970	0.317	158156.667	< 0.0001	0.05	Reject H0
NY	2010	0.324	158156.667	< 0.0001	0.05	Reject H0
CT	2130	0.343	158158.000	< 0.0001	0.05	Reject H0
MA	2670	0.430	158160.667	< 0.0001	0.05	Reject H0
RI	2671	0.430	158157.667	< 0.0001	0.05	Reject H0
VT	792	0.127	158160.667	0.047	0.05	Reject H0
NH	576	0.093	158162.667	0.148	0.05	Accept H0
ME	-621	-0.100	158161.667	0.119	0.05	Accept H0

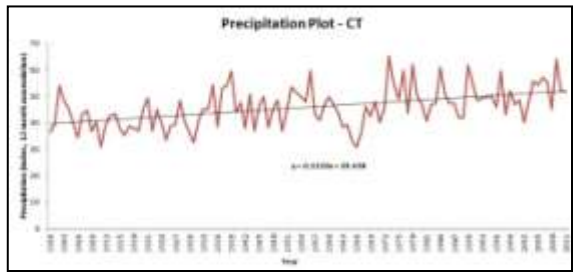
Table 2: Results of the Mann-Kendall test for precipitation data for the Northeastern states.

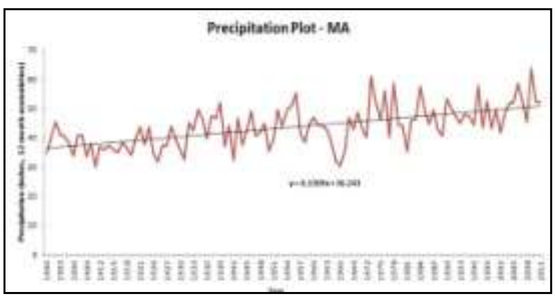
Plotting of linear trend lines for the Northeast states is seen in Figure 6.

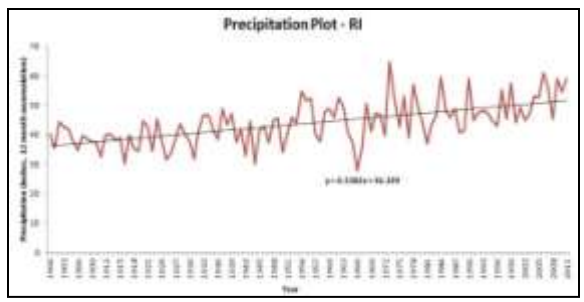


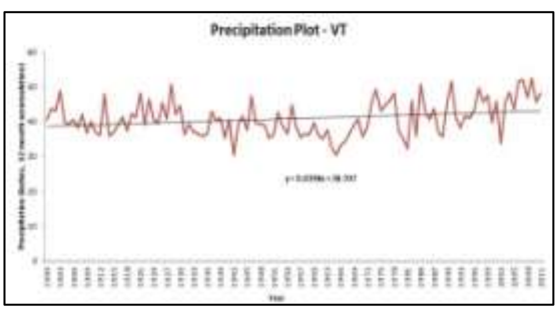


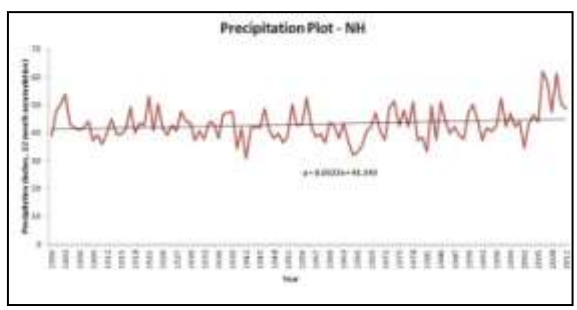












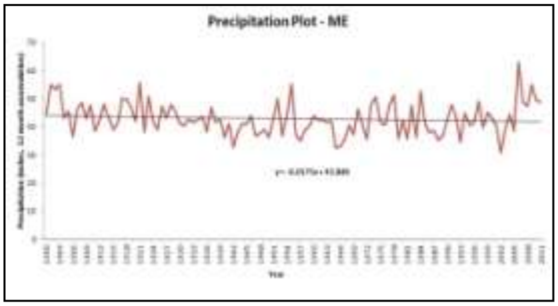


Figure 6: Linear trend line corresponding to precipitation data for each of the Northeast states

4. Discussion

4.1 Precipitation

The Mann-Kendall test (MK) gives interesting insight about annual temperature and precipitation data for the Northeast United States. The MK test Statistic (S) indicates that there is an increasing precipitation trend for the states of New Jersey, Pennsylvania, New York, Connecticut, Massachusetts, Rhode Island, and Vermont. The S statistic, however, is not very strong for New Jersey and Vermont implying that the trend is not as strong compared to the other states. However, the MK test result is different for New Hampshire and Maine, since the null hypothesis H0 is accepted for both. This means that there is no trend is seen for these two states.

On further analyzing the S statistic for the nine states, it becomes evident that there is conformity in magnitude of the statistic when a latitudinal factor is taken into consideration (Figure 7). That is, for the states of Pennsylvania, New York, and Connecticut, the S statistic is near 2000, while for Massachusetts and Rhode Island, the statistic is nearly 2600. Also, for Vermont and New Hampshire, the statistics are small in magnitude, but are similar to some extent. The only two states that stand apart are Maine and New Jersey.

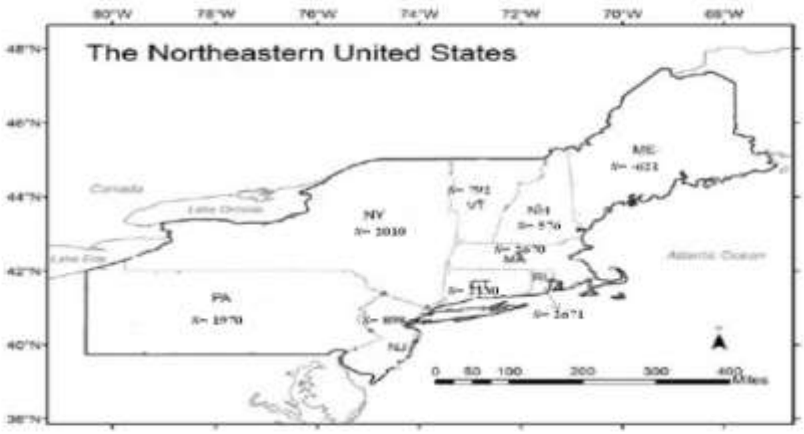


Figure 7: S Statistic for precipitation for the nine states on a latitude map of Northeast U.S. [22]

Again, on fitting the linear trend line, it is observed that trend is increasing for all the northeast states, except for Maine. For Maine, the trend apparently is decreasing. The slope of the trend line is not very large in magnitude for all the states, but it is positive. On taking latitudinal factors into consideration, states fall in groups having similar slope magnitude. For example, Pennsylvania and New York have slopes around 0.0600, while Massachusetts, Connecticut and Rhode Island have slopes in the range of 0.1100 to 0.1400.

Based on the above results, it is of immense importance to discuss the ecological, economic, and social impacts that could result if increasing precipitation trends continue in these states in the future. For coastal areas, in particular, vulnerability to hurricanes, tropical storms, and coastal storms arising from Nor'easters already exists and therefore, coastal insurance is of prime importance. The vulnerability to storms might further be aggravated if extreme rainfall episodes continue in the future and consequently result in inland and coastal flooding. Institutional changes, coastal regulation, and management goals have to be, therefore, adapted in a timely manner.[12] The areas most vulnerable to shoreline erosion are portions of Cape Cod, Long Island, and most of coastal New Jersey.[14] Increased precipitation can influence the water quality and possibly result in the outbreak of waterborne diseases due to sewage overflows (in case of combined sewers) and/or ineffectiveness of wastewater treatment systems to handle increased load. Excess rainfall could also lead to soil saturation as well as to runoff and soil erosion problems. [14]

On the other hand, Maine experienced a decreasing precipitation trend during the 101 year time period of this study and if this trend continues in the future then it could have repercussions in the sustainability of surface water resources and groundwater recharge. [13]

4.2 Temperature

For the temperature data, the MK test shows that there is an increasing trend for New Jersey, New York, Massachusetts, Connecticut, Rhode Island, New Hampshire, and Vermont. The MK test is statistically significant for all the states, except Pennsylvania and Maine. For both of these states, therefore, null hypothesis H0 is accepted and thereby implying that no trend can be seen in the data. The S statistic obtained for temperature data does not show any similarity among the states on a latitudinal basis (Figure 8).

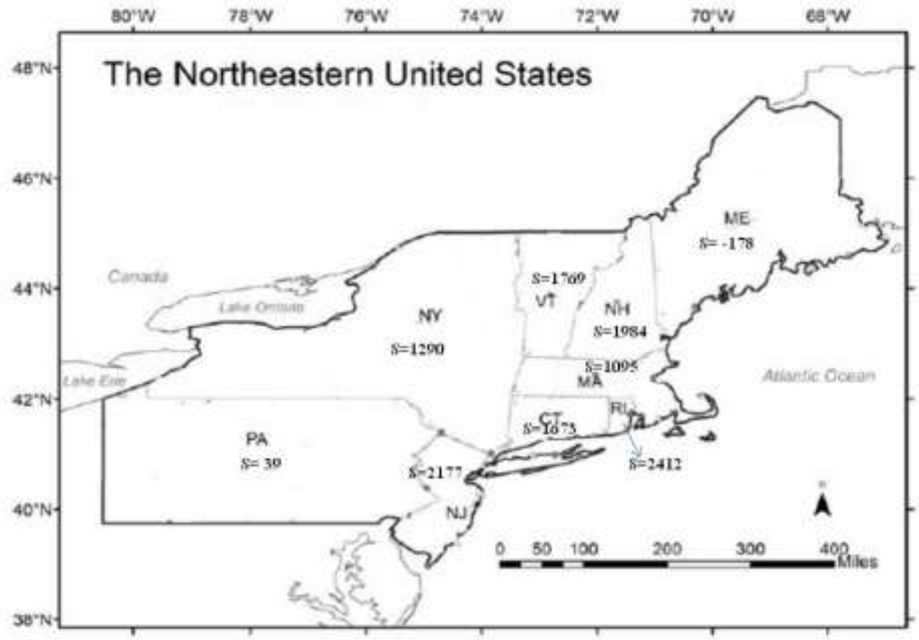


Figure 8: S Statistic for temperature for the nine states on a latitude map for Northeast U.S. [22]

A fitting of linear trend lines shows that there is an increasing temperature trend for all nine states, although slopes are small in magnitude.

If temperature shows an increasing trend for the states in 101 years time period, it becomes essential to understand how this may also affect ecosystems and human life if such a trend continues. Change in a temperature - pattern can lead to a shift in species habitat for forests and insects. [11] Also, the rise in temperature can result in intense heat waves that could be challenging for aging and other vulnerable populations. [11] The winter recreation industry is one such industry that might be considerably impacted by the temperature rise. Over the past two decades, due to reduced snowfall, ski resorts have invested heavily in snowmaking technology, however, the snowmobiling industry, which relies mostly on natural snowfall finds this technology unfeasible for adaptation. [12]

Another industry that can be affected by high temperature is the dairy industry. Heat stress can cause decline in milk production and reproduction rate, since cows are sensitive to heat above 72°F. Also, an increase in transpiration increases the chances of rainfall and diminishes the chances of snowfall. This could also influence groundwater recharge triggered by reduction in summer and fall streams. [12]

It is important to mention here that the states, including New Jersey, New York, Massachusetts, Connecticut, Rhode Island, and Vermont show increasing trends for both, temperature and precipitation for the time period, 1900-2011. One of the reasons that such a phenomenon of increase in temperature and precipitation could occur together is because an increase in temperature increases the capacity of the atmosphere to hold water which in turn increases the amount of precipitation. [13]

Another possible reason behind such a phenomenon could be changes in the presence of the jet stream, which is a narrow band of strong winds in the upper atmosphere that blows west to east, but often shifts to the north and south. The strength of these winds increases as the temperature difference between two locations increases and therefore, the regions around 30° N/S and 50°-60° N/S are the regions where these winds are the strongest. [15] Research suggests that global warming could cause jet streams to rise in altitude and shift to the poles. [16] In a study conducted at the Carnegie Institution over a 23 year span (1979-2008), scientists have determined that jet streams in both hemispheres have risen in altitude and shifted toward the poles. This could have implications for the frequency and intensity of future storms, including hurricanes in the northeast. As jet streams move away from the sub tropical zone, where the hurricanes are formed, and because their development is inhibited by the jet streams, the storm paths are likely to become more powerful and shift northward. [17]

5. Conclusion

In general, there was conformity in the results obtained from the Mann-Kendall test and the linear trend line for the nine northeast states for the 101year time period. The linear trend line shows that there is an increase in precipitation for all nine states. For temperature, the trend line indicates that it is increasing for all the states except for Maine, where the temperature is decreasing. The Mann Kendall test, on the other hand, demonstrates that in the case of precipitation, no trend is noticeable for the states of New Hampshire and Maine; however, an increasing trend is seen for the rest of the six states. For the temperature data, the Mann Kendall test indicates that no trend exists for Pennsylvania and Maine, and an increasing trend is observed for the remaining six states.

It is critical to understand here that these estimates should be analyzed from a global perspective and no conclusions should be drawn for the local level. In other words, the trend in temperature and precipitation seen for each state could imply that the changes are more pronounced for certain locations and less for others, or the changes in temperature and precipitation patterns could be affected seasonally.

The study, therefore, offers remarkable insights and new perspective for policy makers and planners in helping them take proactive measures in the context of climate change. Timely measures and institutional changes can certainly help in reducing the irreparable damages that can be caused by climate change, since the trends in 101 year precipitation and temperature data do not deny climate change is occurring.

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