Climate Change and Hydrological Budget

DISSERTATION

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By

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Abstract

Climate change is not only increasing the Earth’s temperature but is also altering the hydrological cycle. This study aims to identify indicators of long term climate change in relation to hydrological cycle – changes in precipitation, pan evaporation, aridity index and to identify footprints of climate change in agricultural ecosystem– changes in thawing period, changes in freezing period of soil, changes in growing season, and air temperature. The data for precipitation, pan evaporation, and precipitation from metrological stations from 10 states (Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Florida, Arizona, New Mexico, and Texas) across a latitudinal gradient in the U.S. were analyzed for 20-80 years. Selection of the sites was based on the type of biome it represents, accuracy of data, length of the observation period, data availability online, and on the least missing data since the historical climate records have been archived for these stations. Precipitation was analyzed annually and for the warm season. Precipitation trends are increasing in some regions across U.S., such as Minnesota, Tennessee, Ohio, Oklahoma and Alabama while decreasing in others such as, for example Florida and Hawaii. In New Mexico, Arizona and Texas there is an increasing trend in long-term precipitation. However, in the last 20 years precipitation has been decreasing. The pan evaporation trends were analyzed for the summer season (May to September). Based on the trends, it is apparent that the pan evaporation has increased overtime in some regions across U.S. (i.e. Tennessee, Ohio, Florida, Hawaii and Alabama) but has also decreased
in others (i.e. Alaska, Arizona, New Mexico, Minnesota, Texas), assuming that there are no systematic error in the weather stations’ observations. The sites which showed an increase in mean annual temperature (MAT) are the ones in Alaska, Texas, Florida, New Mexico, Arizona and Hawaii. In contrast, sites which showed a decreasing trend in average temperature are in Minnesota, Alabama and Tennessee. The increase in minimum temperature has been much higher and prominent than the increase in maximum temperature. Fairhope (Alabama) is the only site in this study which showed a significant decreasing trend in minimum temperature. At all the other sites, the minimum temperature increased in the last few decades. The thermal or climatological growing season is the frost-free period between the last frost in spring to the first frost in autumn. The number of consecutive days with minimum temperature above 0°C can be assumed to be conducive for growth. The length of climatological growing season was studied for 5 sites in Ohio and one site each in Alaska and Minnesota. All five sites in the Midwestern state Ohio (Wooster, Coshocton, Circleville, Bellefontaine and Bowling Green) as well as the two sites in the northern states of Minnesota (Waseca) and Alaska (University Experiment Station) show an increasing trend in the length of growing season. The rate of increase varies amongst different sites, but they are all statistically significant. This means the frost-free period is getting longer, advancement of spring season and delay of autumn frost.
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Fields of Study

Major Field: Environmental Science
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Chapter 1
INTRODUCTION

The National Research Council Committee on America’s Climate Choices, in its fifth and final report to the United States Congress on climate change said (Science, May 2011):
“Climate change is occurring, is very likely caused primarily by the emission of greenhouse gases from human activities, and poses significant risks for a range of human and natural systems. Each additional ton of greenhouse gases emitted commits us to further change and greater risks.”

The concentration of the greenhouse gases (GHGs) determines the atmospheric capacity to trap solar heat, because these gases absorb heat and do not allow long-wave radiation to reflect back into the space. The mean surface temperature of the Earth is about 15°C and in the absence of the GHGs it would be -18°C (Peng, 1995). An increase in the GHG emissions is thus bringing about the phenomenon called “global warming”. Carbon (C) is being added into the atmosphere at a rate of 3.5 Pg/yr, the largest contribution being that of fossil fuel combustion and conversion of tropical forests to agricultural lands (Paustian et al., 2000). Globally the concentrations of CO₂, CH₄ and N₂O have increased significantly due to anthropological activities since 1750. While the increase in CO₂ emissions is attributed primarily to fossil fuel combustion and land use change, those of CH₄ and N₂O are mainly because of agriculture (IPCC, 2007). CO₂ is the most important
GHG because its relative contribution to the anthropogenic greenhouse effect is about 60%, and that of CH₄ and N₂O is 15% and 5%, respectively (Rodhe, 1990). Water vapor is also a powerful GHG and almost doubles the warming caused by CO₂, CH₄ and N₂O (Manabe and Wetherald, 1967; Raval and Ramanathan, 1989). 97% of water on this earth is present in oceans, 0.001% in the atmosphere and the rest is present in ice caps, snow and soil (Chahine, 1992).

Increase in temperature has significant impact on the hydrological cycle, especially in regions where the source of water supply is primarily melting snow or ice (Barnett et al., 2005). Globally, 35% of precipitation comes from ocean evaporation driven by winds and the remaining 65% comes from land evaporation (Chahine, 1992). The average US temperature has increased by ~ 1.1°C over the last 5 decades and the average precipitation has increased by 5% (NOAA, 2009). In the last 50 years, Alaska has experienced almost twice as much warming as the rest of the US. The mean annual temperature (MAT) has increased by ~1.8°C, while the increase in the winter temperatures has been even more significant, ~ 3.5°C (NOAA, 2009). Last 30 years in the Midwestern US were the wettest period in the past century. Fall precipitation is increasing but at the same time, frequency of summer and spring droughts is also increasing in the country (NOAA, 2009).

Agricultural response to climate change depends on the interaction between three factors: increase in temperature, change in water availability and increase in atmospheric CO₂ concentration. U.S. contributes 41% to global corn production and 38% to global soybeans production (Schlenker and Roberts, 2009). Even moderate increase in
temperature will decrease crop yields of *Triticum aestivum* (wheat), *Oryza sativa* (rice), *Zea mays* (maize), *Sorghum bicolor* (sorghum), *Gossypium spp.* (cotton) and *Arachis hypogaea* (peanuts) (Lobell and Field, 2007; Peng et al., 2004; Sinha and Swaminathan, 1991; Wheeler et al.). Crop yields increase with the initial increase in temperature, until it reaches their optimum temperature. Yields increase up to 29°C for corn, up to 30°C for soybeans and up to 32°C for cotton (Schlenker and Roberts, 2009). Any increase above this threshold temperature is very harmful for the crops. Increase in temperature accelerates crop development in wheat and rice, and this reduces the grain yield because there is less time for radiation to be intercepted in the vegetative phase (Conroy et al., 1994). Slope of the decline above the threshold is much steeper than the incline below it (Schlenker and Roberts, 2009). It has been widely reported that the increase in minimum temperature has been more significant than maximum temperature (Folland et al., 2002; Karl et al., 1993). Increase in minimum temperature is critical to the reproductive phase of growth. Increase in winter temperature causes dehardening of wheat crops during the vegetative stage. This reduces wheat crop immunity against subsequent extreme cold events (Rosenzweig and Tubiello, 1996). Higher minimum temperature also increases the plant respiration rate and hence reduces the amount of C sequestered during photosynthesis (Rosenzweig and Tubiello, 1996). Plants which have a low threshold temperature for growth will be negatively affected. Yields of fruits (such as apples and berries) that need long winter temperature will decline (NOAA, 2009). Increase in CO₂ concentration makes plants grow larger. For some plants, this results in lower N₂ and protein content and hence less nutrition (Conroy et al., 1994). If
temperature stays constant, increase in CO\textsubscript{2} concentration increases wheat yields by 20-35%. However, increase in temperature counteracts the beneficial effects of increased CO\textsubscript{2} concentration (Rosenzweig and Tubiello, 1996). Increased CO\textsubscript{2} concentration also increases photosynthesis and growth in C3 weeds, while it increases water use efficiency in both C3 and C4 weeds (Patterson, 1995; Patterson and Flint, 1990; Patterson et al., 1999). Tropical and sub-tropical varieties of weeds, currently present in southern US, will move northward (Patterson, 1995). It is reported that glyphosate, the most commonly used herbicide in the US, will not be as effective on weeds grown at increased CO\textsubscript{2} levels (Ziska and Teasdale, 2000; Ziska et al., 1999).

The growing season is getting longer for plants such as melon, okra, sweet potato whereas it is getting shorter for plants such as lettuce, broccoli, potato and spinach (NOAA, 2009). Adapting to climate change include changing planting dates to take advantage of longer growing season, changing crop varieties, and choosing the ones with higher tolerance to heat or drought.

The impacts of climate change on components of hydrological cycle are strongly evident. This project builds upon the available information, and assesses the footprints of climate change in agricultural ecosystem. The objectives and the hypothesis for the project “Climate Change and Hydrological Balance” are stated below.
OBJECTIVES:

1. To identify indicators of long term climate change in relation to hydrological cycle – changes in precipitation, pan evaporation, aridity index.
2. To identify footprints of climate change in agricultural ecosystem– changes in thawing period, changes in freezing period of soil, changes in growing season, and air temperature.

HYPOTHESIS:

1. Global climate change has increased average temperatures since 1910.
2. There is a net increase in the mean annual precipitation since 1950s.
3. Climate change has enhanced net evapo-transpiration.
4. There has been a change in the growing season.
References


Chapter 2

PRECIPITATION

Introduction

Increase in atmospheric concentration of greenhouse gases (GHGs) is causing global warming and abrupt climate change (IPCC 2007). The effects of climate change are multiple and vary across the planet. An important concern is the change in precipitation across the biomes. Increase in anthropogenic radiative forcing may increase the amount of atmospheric water vapor, which may destabilize the atmosphere and alter the precipitation regime (Kunkel 2003).

It is generally perceived that dry areas are reportedly getting drier and wet are getting wetter (Dore, 2005). For example, Karl and Knight (1998) reported a 10% increase in annual precipitation across U.S. while Groisman and Easterling (1994) reported only a 4% increase in annual precipitation in continental U.S. within the last century. During the early part of the 20th century, however, the precipitation either decreased or did not change significantly. Yet, it has increased significantly in the latter half of the 20th century (Bradley et al. 1987; Diaz and Quayle 1980; Klugman 1983). Total increase in precipitation is attributed to increase in its frequency and intensity (Karl and Knight 1998). A general trend of short duration of extreme precipitation indicates an increase in frequency of events between 1931 and 1996, especially in the southwestern U.S., across
the southern Great Plains, into the southern Great Lakes region and northeast (Kunkel et al. 1999). In contrast, a downward trend has been observed in the northwestern U.S. and Florida (Kunkel et al. 1999). These trends are in accord with the conclusions by IPCC (1996) that the hydrological cycle is likely to become more intense in warmer climates, which may lead to an increase in heavy rain events.

Establishing long term trends in precipitation across a large area can be difficult because of several inconsistencies in the instruments over such a long period of time (Lettenmaier et al. 1994). Major factors which can affect the precipitation include mean latitude, longitude, elevation, distance from the coast and slope aspect (Keim et al. 2005). The point precipitation measurements are also affected by the gauge undercatch bias, which is often larger in winter than in summer (Groisman and Legates 1994).

Changing climate has a strong impact in increasing the magnitude of flood damage in the U.S. in the latter part of the 20th century (Pielke Jr and Downton 2000). Economic losses by floods in the U.S. are second only to those by hurricanes amongst all natural hazards, averaging to $3 to $4 billion annually (Changnon and Hewings 2001). Increase in frequency of flooding in response to climate change is related to alteration in the precipitation regimes in the U.S. (Karl and Knight 1998). The changing patterns of precipitation also affect the production of food crops, which is one of the major global concerns in the 21st century (Dore 2005). Excessive precipitation can damage crops, and the costs of crop losses and agricultural damage are expected to increase significantly with the climate change (McCarthy 2001; Reilly et al. 2003; Rosenzweig et al. 2002).

Between 1990 and 2010, floods in Midwest, North Dakota, Red River and Mississippi
caused massive damages to crops resulting in a loss of billions of dollars, and also delayed planting (Rosenzweig et al. 2002). An increase in precipitation also increases soil wetness and risks of anaerobiosis, which makes plants more prone to diseases and insect infestation (Ashraf and Habib-ur-Rehman 1999). Farming operations, planting and harvesting, also get delayed because of inability to operate machinery due to excessive rains and poor trafficability. Rosenzweig et al. (2002) observed that the excessive soil moisture due to increase in precipitation may double the maize production losses by 2030 in the U.S.. Loss in yields by inundation of crops in the Midwest can also inflate food prices in the U.S. (Clemmitt 2009).

Water availability and quality are relevant issues nationally and internationally. Green water constitutes the rain water which percolates into the soil, is held in retention pores and is available for plant roots to absorb. In contrast, blue water is the water present in rivers, lakes and aquifers (Rockström et al. 2009). By 2050, 59% of global population will have scarcity of blue water and 36% will have a shortage of both green and blue water (Rockström et al. 2009). Large biomes which are responsible for the major ecosystem services depend on approximately 90% of green water or terrestrial vapor flow to the atmosphere (Rockström and Gordon 2001). It is important to identify technology of efficient ways to manage green water resources for lowering the risks of agricultural droughts and promoting global food security (Rockström et al. 2009).

It is in this context that the ecological and economic implications of changes in the hydrological cycle caused by climate change are extremely important and relevant. Thus, this chapter focuses on establishing any trends in precipitation across several states in the
United States. The overall goal is to establish any finger prints of climate change on the amount and distribution of annual and seasonal precipitation in diverse regions of the U.S.

**Data and Methodology**

Total annual precipitation for stations from 10 states – Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Florida, Arizona, New Mexico, and Texas was analyzed for 80-100 years. These sites were selected to represent diverse climates and eco-regions, such as boreal forests, tropical rainforests, temperate continental, humid subtropical and semi-arid climates. Selection of the stations was based on the accuracy of data, length of period, availability, and on the least missing data since the historical climate records have been archived for these stations. Precipitation trends were analyzed both on an annual basis and for the growing season. The growing season in this chapter is defined as the frost-free period.

The sites selected for the study were located in 11 states across a North-South gradient in U.S. – Waseca (Minnesota), Jackson (Tennessee), Fairhope (Alabama), Moore Haven Lock (Florida), Lihue (Hawaii), University Experiment Station (Alaska), Roosevelt and Barlett Dam (Arizona), San Jon and Caballo Dam (New Mexico), Anahuauc and Whitney Dam (Texas) and 5 stations in Ohio – Coshocton, Wooster, Circleville, Bowling Green and Bellefontaine (Figure 1 and 2). Data representing the precipitation measurements were collected from the National Climatic Data Center (www.ncdc.noaa.gov). These data were analyzed to establish trends in annual and seasonal precipitation for all different
stations. Regression analysis was performed by using MS Office Excel (2007) and StatTools 5.7. Confidence interval of 90% was used while calculating p value of the models. Growing season is the time between the last frost and the first frost of the year (Burkhead 1972). The period between May and October was used to categorize growing season data for all states.
### Table 1: Location and Description of the Sites

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude and Longitude</th>
<th>Height (m above sea level)</th>
<th>MAP(cm) Mean Annual Precipitation ± s.d.</th>
<th>Köppen Climate Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waseca, MN</td>
<td>44°04'N 93°32'W</td>
<td>351.4</td>
<td>78.97 ± 17.3</td>
<td>Humid Continental</td>
</tr>
<tr>
<td>Jackson, TN</td>
<td>35°37'N 88°51'W</td>
<td>121.9</td>
<td>129.78 ± 25.2</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Fairhope, AL</td>
<td>30°33'N 87°53'W</td>
<td>7.0</td>
<td>165.94 ± 33.2</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Moore Haven Lock, FL</td>
<td>26°50'N 81°05'W</td>
<td>10.7</td>
<td>122.43 ± 22.2</td>
<td>Tropical</td>
</tr>
<tr>
<td>Lihue, HI</td>
<td>21°59'N 159°20'W</td>
<td>30.5</td>
<td>103.42 ± 32.7</td>
<td>Tropical</td>
</tr>
<tr>
<td>University Exp Stn, AK</td>
<td>64°51'N 147°52'W</td>
<td>144.8</td>
<td>30.61 ± 7.6</td>
<td>Continental Subarctic</td>
</tr>
<tr>
<td>Coschocton, OH</td>
<td>40°22'N 81°47'W</td>
<td>347.5</td>
<td>94.21 ± 15.8</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>40°47'N 81°55'W</td>
<td>310.9</td>
<td>93.62 ± 15.5</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Bellefontaine, OH</td>
<td>40°21'N 83°46'W</td>
<td>361.2</td>
<td>92.06 ± 16.8</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Bowling Green, OH</td>
<td>41°23'N 83°37'W</td>
<td>205.7</td>
<td>82.56 ± 13.4</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Circleville, OH</td>
<td>39°37'N 82°57'W</td>
<td>205.1</td>
<td>99.32 ± 16.4</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Anahua, TX</td>
<td>29°47'N 94°38'W</td>
<td>7.3</td>
<td>133 ± 37</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Whitney Dam, TX</td>
<td>31°52'N 97°23'W</td>
<td>175</td>
<td>85.95 ± 21</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>San Jon, NM</td>
<td>35°07'N 103°20'W</td>
<td>1289.3</td>
<td>41.94 ± 13.4</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Caballo Dam, NM</td>
<td>32°54'N 107°19'W</td>
<td>1277.1</td>
<td>24.25 ± 9</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Roosevelt, AZ</td>
<td>33°40'N 111°09'W</td>
<td>672.1</td>
<td>140.77 ± 37.6</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Barlett Dam, AZ</td>
<td>33°49'N 111°39'W</td>
<td>502.9</td>
<td>34.79 ± 14.2</td>
<td>Semi-arid</td>
</tr>
</tbody>
</table>

Source: National Climatic Data Centre
Figure 1: Locations of sites used in the study
Results:

1. **University Experiment Station, Alaska** – This site was selected for the study because Alaska is situated in the northwest extremity of the North American continent and represents an arctic biome. Thus, it is important to analyze and compare the data from this site with those in the contiguous U.S.. No major significant changes were observed on an average in the amount of annual precipitation or that during the growing season. The annual precipitation showed a non-significant decreasing trend at the rate of 0.003 cm/year while the seasonal
precipitation increased at 0.01 cm/year (Fig. 3). The p values of 0.9 and 0.6 of the annual and the growing season trend, respectively, are not statistically significant.

![Graph of precipitation trends](image)

Figure 3: Trends in precipitation in University Exp Stn, AK from 1916-2010

2. **Waseca, Minnesota** – The annual precipitation in Waseca has increased over the last 95 years at the average rate of increase of 0.28 cm/year (Fig. 4). The trend during the growing season is similar to that of the annual precipitation trend, but the rate of increase is smaller. Thus, precipitation during the growing season increased at an average rate of 0.12 cm/year (Fig. 4), which is almost half the rate of increase on the annual basis. The p values for both the annual and the growing season trends are statistically significant (Fig 4).
3. **Ohio** – Several stations were selected within Ohio to establish any north-south gradients in precipitation.

i. **Coshocton**: Coshocton is located in east central Ohio (Fig. 5). Even though the National Climatic Data Centre has data dating back to only 1956 for this site, yet there is a clear trend for the precipitation records. The annual precipitation increased at an approximate rate of 0.25 cm/year (Fig. 5). The p value of 0.06 is statistically significant. The rate of increase in precipitation during the growing season is ~ 0.14 cm/year (Fig. 5). However, the p value for this model is 0.2, which is not statistically significant.
Figure 5: Trends in precipitation in Coshocton, OH from 1956-2010

ii. **Wooster** – Wooster is located in north eastern Ohio (Fig. 2) and the trend in precipitation is similar to that of Coshocton. The annual precipitation increased over the last 113 years (Fig. 6). The rate of increase in annual precipitation is ~ 0.14 cm/year, which is the same as the rate of increase during the growing season (Fig. 6). The p values for both the trends were statistically significant (Fig. 6).
iii. **Bellefontaine** – Bellefontaine is located in west central Ohio (Fig. 2). The precipitation records date back to 1895. Analysis of the data indicates some trends over the 115 years. The annual precipitation has increased at an average rate of ~ 0.1 cm/year (Fig. 7), and it has a significant p value of 0.02. The precipitation during the growing season increased by ~ 0.05 cm/year (Fig. 7) but the p value for the same is not statistically significant. These trends are not as prominent as for the sites in east central and north east Ohio.
iv. **Bowling Green** - Bowling Green is located in north west Ohio (Fig. 2). Similar to the Bellefontaine site, only minor changes are observed in precipitation in Bowling Green between 1895 and 2010 (Fig. 8). The rates of increase in precipitation are ~ 0.03 cm/year and ~ 0.04 cm/year annually and during the growing season, respectively. Both the trends have non-significant p values.
Figure 8: Trends in precipitation in Bowling Green, OH from 1895-2010

\[ y = 0.03x + 80.82 \quad \text{p} = 0.4 \]
\[ y = 0.04x + 44.76 \quad \text{p} = 0.16 \]

v. **Circleville** – Circleville is located in south central Ohio (Fig. 2). For the period between 1895 and 2010, there are only minor changes in the precipitation patterns and the p values for the trends are non-significant. There has been a minor decrease in the annual precipitation at an average rate of -0.018 cm/year (Fig. 9). In contrast, precipitation has increased during the growing season at an average rate of 0.03 cm/year (Fig. 9).
Figure 9: Trends in precipitation in Circleville, OH from 1896-2010

4. **Jackson, Tennessee** – This station is located far south of Waseca, MN (Fig. 1) but the precipitation trend over the last century is rather similar. The annual precipitation has increased between 1903 and 2010, at the average rate of 0.2 cm/year (Fig. 10) while the rate of increase during the growing season is ~ 0.14 cm/year (Fig. 10). The p values for both the models are significant.
5. Arizona – Precipitation patterns were analyzed for two stations from central Arizona.

i. Barlett Dam – Barlett Dam is located in Maricopa County in central Arizona (Fig. 1). There is no prominent trend in precipitation during the 61 year period between 1940 and 2010 and the p values are non-significant. The data in Fig. 11a show a slight increase in annual precipitation at the rate of ~ 0.12 cm/year. The precipitation during the growing season does not show any significant trend (Fig. 11). It is interesting to note that in the last two decades, however, the precipitation has decreased significantly (p value = 0.03) at the rate of ~ 1 cm/year and 0.5 cm/year annually and during the growing season, respectively (Fig. 12).
Figure 11: Trends in precipitation in Barlett Dam, AZ from 1940-2010

Figure 12: Trends in precipitation in Barlett Dam, AZ from 1990-2010
ii. Roosevelt, AZ – Roosevelt is also located in central Arizona (Fig. 1). The precipitation trends look similar to those in Barlett Dam, AZ but are not statistically significant. The average precipitation has decreased annually as well as during the growing season within 105 years. Between 1906 and 2010, the precipitation has decreased at the average rate of ~ 0.13 cm/year and 0.07 cm/year annually and during the growing season, respectively (Fig. 13). There has been a sharper decrease especially in the last two decades. Annual precipitation decreased significantly at the rate of ~ 1.54 cm/year while the seasonal precipitation decreased at the rate of ~ 0.3 cm/year (Fig. 13).

![Figure 13: Trends in precipitation in Roosevelt, AZ from 1906-2010](image-url)
6. New Mexico – Two sites from different parts of New Mexico were studied.

i. San Jon, New Mexico – San Jon is located in north eastern New Mexico. The data in Fig. 13a show that during the last 101 years annual precipitation has increased at ~ 0.05 cm/year. There is no clear trend in the growing season precipitation between 1910 and 2010 (Fig. 14). The p values for the 101 year period are not statistically significant. However, similar to Arizona a very sharp decreasing precipitation trend is observed in New Mexico since 1990. Precipitation has decreased at an average rate of ~ 0.45 cm/year between 1990 and 2010, both annually as well as during the growing season with significant p values.

![Figure 14: Trends in precipitation in San Jon, NM from 1910-2010](image-url)
ii. **Caballo Dam, New Mexico** - Caballo Dam is located in southwestern New Mexico (Fig. 1). Precipitation data were analyzed for a 71-year period between 1937 and 2007. An increasing trend was observed in the long-term data. The trend is statistically significant with the respective p values for the annual trend and the growing season – 0.05 and 0.06. The rate of increase in annual precipitation is ~ 0.12 cm/year (Fig. 15). However, the rate of increase in precipitation during the growing season is lower, ~ 0.8 cm/year (Fig. 15). Similar to the trends in other southern stations, the Caballo Dam site also shows a sharp decreasing trend in precipitation during the last two decades (Fig. 15). The rate of decrease in precipitation between 1990 and 2010 is ~ 0.5 cm/year for the annual and 0.31 cm/year for the seasonal precipitation. However, the trends in the last 20 years are not statistically significant.

![Figure 15: Trends in precipitation in Caballo Dam, NM from 1937-2010](image-url)
7. Texas – Several parts of Texas have experienced a severe drought during 2011. Thus, two stations were selected to analyze the long term and short term trends in precipitation.

i. Anahuac – Anahuac is located in eastern Texas. The precipitation records date back to 1910. A slight increasing trend in precipitation is observed over 101 years. Both the annual precipitation and that during the growing season have increased slightly at an average rate of ~ 0.1 cm/year between 1910 and 2010 (Fig. 16). However, during the last two decades, the annual precipitation has decreased at the rate of 0.95 cm/year, but the seasonal precipitation does not show any specific trend. None of the results at this site is statistically significant.

Figure 16: Trends in precipitation in Anahuac, TX from 1910-2010
ii. **Whitney Dam, Texas** – This site is located in central Texas. The trends in precipitation are similar to the station in eastern Texas. There is a small increasing trend in the precipitation within the last 61 years. The rate of increase in annual precipitation is ~ 0.18 cm/year (Fig. 17). Precipitation during the growing season does not show any statistically significant trend (Fig. 17).

![Figure 17: Trends in precipitation in Whitney Dam, TX from 1950-2010](image)

9. **Fairhope, Alabama** – The data in Fig. 18 show an overall increase in the annual precipitation in Fairhope, AL even though the rate of increase is not as high as that in Waseca, MN. Similarly, the rate of increase in the precipitation during the growing season is much smaller than the rate of increase in annual precipitation. Between 1920 and 2010 precipitation has increased at the rate of ~ 0.2 cm/year.
The increase is statistically significant. However, the rate of increase during the growing season is merely ~ 0.09 cm/year and is non-significant (Fig. 18).

Figure 18: Trends in precipitation in Fairhope, AL from 1920-2010

10. **Moore Haven Lock, Florida** – Rather than an increasing trend, annual precipitation in Moore Haven, FL and other southern sites in the U.S. indicate statistically significant declining trends. For example, the annual precipitation has decreased at Moore Haven Lock in Florida over the 88 year period between 1922 and 2010. Between 1922 and 2010, the annual precipitation has decreased at the rate of ~ 0.14 cm/year (Fig. 19). Furthermore, the rate of decline is even more during the growing season, at an average rate of 0.2 cm/year (Fig. 19).
11. **Lihue, Hawaii** – Hawaii was included in this study because it is located south west of the Continental U.S. and represents the tropical rainforest biome. It has a warm tropical climate, which differs from all other sites included in this study. However, the data availability for Lihue, HI is limited to 60 years from 1950 to 2010. Yet, there is a statistically significant declining trend in annual precipitation during the last 60 years. The rate of decrease in annual precipitation is approximately 0.44 cm/year (Fig. 20). However, the rate of decrease in precipitation during the growing season is relatively small and statistically non-significant, 0.07 cm/year (Fig. 20).
Discussion

This study shows no significant precipitation trend in the Alaskan site. However, an increasing trend is observed in sites located in Minnesota, Tennessee, and Alabama. In contrast, a decreasing trend is observed for sites in Florida and Hawaii. In Ohio, three sites show an increasing trend while two do not show any specific trend. In Texas, New Mexico and Arizona, an overall increasing trend is observed during the last century. However, in the past two decades, the precipitation has decreased, resulting in droughts. Stafford et al. (2000) reported an increase in total precipitation for 3 of the 4 seasons throughout most of Alaska in a 50 year period (1948-1998), while a slight decreasing trend was observed during the summer months. The present study is based on the 95-year precipitation records from the university experiment station located in Fairbanks. But neither the annual precipitation nor that during the growing season shows any specific
trends. There is a slight but non-significant decrease in annual precipitation and a non-significant increase in seasonal precipitation.

In contrast to the data of the present study for Minnesota, Baker (1962) reported a declining trend in both seasonal and annual precipitation between 1900 and 1958 in Minnesota for five stations studied across the state. Yet, the Waseca site located in southern Minnesota in the present study indicate an increasing trend in the long term precipitation between 1915 and 2010 both for annual as well as the amount received during the growing season.

In the present study, sites in east central and north eastern Ohio indicate an increasing trend in precipitation while the increase is not significant in the sites located in northwestern, south central and west central Ohio (Bellefontaine, Circleville and Bowling Green). Harstine (1991) studied the precipitation trends in Ohio between 1931 and 1980 and found precipitation to be the highest in southern and eastern Ohio and decreasing in northwestern Ohio.

The present study indicates a declining trend in the precipitation in Florida and the Caribbean region. The precipitation data from land-based sites indicate a similar declining trend in some regions (Coleman 1982; Kunkel et al. 1999; Neelin et al. 2006). The data from Moore Haven Lock located in southern Florida also indicate the declining trend. Annual precipitation has decreased between 1922 and 2010, and the rate of decrease in precipitation during the growing season is even higher.

In the Hawaiian Islands, records from stations along the windward coastal side of the island have shown a general decreasing trend in precipitation. In contrast an increasing
trend is reported along the southeast and northwestern side of the island (Doty 1982; Woodcock and Jones 1970). Precipitation data from 1951 to 2000 have been analyzed from more than 100 stations across four major islands in Hawaii. A declining trend in precipitation has been reported since 1980 (Diaz et al. 2005). In the present study, data from Lihue also show a similarly decreasing trend in rainfall from 1950 to 2010. However, the rate of decrease is less pronounced for the growing season than for annual precipitation.

For east central Texas, Harmel et al. (2003) reported that the precipitation increased over a 61 year period between 1939 and 1999. It was also reported that precipitation in most sites in southern and central Texas has increased historically between 1895 and 2006 (Nielsen-Gammon 2011). In the present study, both Anahuac and Whitney Dam sites located in eastern and western Texas, respectively, also indicate an increasing trend. However, during the last 20 years, precipitation has a definite decreasing trend.

An increasing trend of precipitation has been reported in most of Great Plains area, including stations located in south central, southwestern, northern and eastern Oklahoma between 1981 and 2001 (Garbrecht et al. 2004). It has been reported that dry areas in the U.S. are getting drier and wet areas are getting wetter (Dore 2005). The data analysis in the present study indicates that sites in the northern and midwestern states (Minnesota and Ohio) show an increasing trend in precipitation. The rate of increase is larger in the northern (MN, OH) than in the southern states of Tennessee and Alabama. The trend in annual precipitation is negative for some sites in southwestern and southeastern U.S. – Hawaii, Arizona and Florida. Precipitation in Alaska, located in extreme north western
U.S., does not show any definite trend. In New Mexico and Arizona, the precipitation in the last two decades is decreasing.

Several states in the southern U.S. have experienced severe drought during 2011 (CNN 2011). The rainfall received during 2011 has been extremely low in Texas, Florida, New Mexico, and Oklahoma. The present study shows a sharp decreasing trend in precipitation during the last two decades in Florida and New Mexico, corroborating the drought experienced in 2011. However, no decreasing trend is observed for sites located in Texas and Oklahoma. These observations are in agreement with the published literature (Garbrecht et al. 2004; Harmel et al. 2003; Nielsen-Gammon 2011). There are several other factors which may be responsible for severe droughts, such as increase in temperature, evaporation, and the changing pattern of oceanic currents (Fawcett et al. 2011; Seager et al. 2009). Rising demand for water resources due to increasing population is another factor responsible for the deficit (Manuel 2008). The results and findings of the present study can be used to develop guidelines for adapting agricultural, industrial, ecological and residential water management strategies in order to make the most efficient use of natural precipitation since surface and groundwater (blue water) supplies are also dependent on it. With the increasing population and the further increasing water demand in the midst of climate change, sustainable water resource management can play a crucial role in agricultural and industrial economies.
Conclusions

The data presented support the following conclusions:

1. Precipitation trends are increasing in some regions across U.S., such as Minnesota, Tennessee, Ohio, and Alabama while decreasing in others such as, for example Florida and Hawaii, based on their geographic location, climate and other factors.

2. In New Mexico, Arizona and Texas there is an increasing trend in long-term precipitation. However, in the last 20 years precipitation has been decreasing.

3. In Ohio, the data from north eastern and the east central regions indicate a larger increase in precipitation over the 20th century as compared to the western and the central parts.

4. In some cases the increase in precipitation is more pronounced on annual basis rather than during the growing season. In others, trends are almost the same. So, there can be a possible scenario where even though the total precipitation is increasing annually, the rate of increase during the growing season is rather small. Change in precipitation during the growing season is important to agricultural production.
Table 2: Summary of p values and significance for different sites (precipitation)

<table>
<thead>
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<th>Station</th>
<th>Trend</th>
<th>P values</th>
<th>Significant</th>
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</thead>
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References


(accessed August 08, 2011).


Köppen Climate Classification.

http://snow.cals.uidaho.edu/clim_map/koppen_usa_map.htm (accessed on August 14, 2011)


Chapter 3

PAN EVAPORATION

Introduction

A range of anthropogenic activities is disrupting the global carbon (C) cycle, leading to an increase in the global temperature over the 20th century by 0.6 ± 0.2°C at an average rate of increase of 0.17°C per decade since 1950 (IPCC, 2007; Lal, 2004). The increase in greenhouse gases (GHGs) in the atmosphere may not only increase the global temperature but also alter the hydrological cycle (Held and Soden, 2006). Evapotranspiration (ET) is that component of the hydrological cycle which is probably the most sensitive to climate change and its variability (Hobbs et al. 2001). As a result of global warming, there should be an increase in water vapor present in the lower troposphere (Held and Soden, 2006). Relative humidity can increase exponentially with an increase in temperature, especially at higher latitudes (Allen and Ingram, 2002). According to some climate models, for every degree Kelvin increase in Earth’s surface temperature, evaporation may increase by approximately 1 to 3% (Wentz at al., 2007). In the absence of any direct methods to measure evaporation from the earth's surface into the atmosphere, a simple but relatively old method of pan evaporation (PE) is widely used. The PE relates the evaporation from a pan of water to that from natural surfaces on earth such as a body of water (lake, river, ocean, reservoirs), plants and soil (Kahler and Brutsaert, 2006). Evaporation from these pans is thus assumed to simulate evaporation
from aquatic surfaces such as lakes and irrigated fields (Kahler and Brutsaert, 2006). The instrument used to measure PE is an open vessel containing water which is allowed to evaporate freely. The amount of evaporation from any given pan/vessel is easily measured. The slow rate of evaporation does not necessitate frequent measurement; and the measurements are typically taken once a day. The U.S weather bureau designated the pan as the official measurement instrument for estimating the PE (Kadel and Abbe, 1916). Other countries have widely used the pan for this purpose as well. The underlying principle behind this method is that evaporation is proportional to the surface area exposed. The pan is used to quantify evaporation using a measured surface area and quantity of water and the results may be extrapolated to estimate evaporation from larger water bodies or surfaces. Although this method is not intended for estimating actual evaporation in non-moist environments, it has been used for this purpose also. The results obtained have been inconclusive, primarily due to confusion about interpreting the data (Kahler and Brutsaert, 2006).

Interpretation of the PE data can lead to several contradictions. Some studies indicate a decreasing trend in PE across different geographic regions globally over the last 50 years including the conterminous United States and Russia (Peterson et al., 1995; Roderick et al., 2007); India (Chattopadhyay and Hulme, 1997); Venezuela (Quintana-Gomez, 1998), parts of Australia and New Zealand (Roderick and Farquhar, 2004, 2005), Thailand (Tebakari et al., 2005) and in most parts of China (Liu et al., 2004). The general consensus is to attribute decline in PE to a corresponding decrease in actual evaporation over the same period. The decrease in PE with climate change is attributed to decrease in
diurnal temperature range, an increase in cloud cover and changes in wind speed (Peterson et al., 1995; Karl et al., 1993; Burn and Hesch, 2007). However the general increase in the level of global precipitation over the same period (Bradley et al., 1987; Diaz and Quayle, 1980; Karl and Knight, 1998; Klugman, 1983), directly contrasts with this interpretation. Furthermore, estimates of actual evaporation over large areas obtained by water budget methods are in direct contrast to the conclusions based on the PE studies (Milly and Dunne, 2001; Walter et al., 2004). These studies computed annual evaporation by subtracting the river outflow (from a basin) from the annual precipitation. Yet, there are other reports of an increasing trend in actual evaporation with increase in temperature (Karl et al., 1996; Manabe, 1997; Walter et al., 2004). Szilagyi et al. (2001) also reported a 6% increase in evapo-transpiration during warm seasons in conterminous U.S. between 1949 and 1996.

Brutsaert and Parlange (1998) attributed this divergence between the PE and actual evaporation as a complementary relationship, and suggested that a decrease in PE could correspond to an increase in actual evaporation. This explanation is in accord with those of some studies (Golubev et al., 2001; Hobbins et al., 2004; Lawrimore and Peterson, 2000), but not so with others (Cohen et al., 2002; Ohmura and Wild, 2002; Roderick and Farquhar, 2002). Critics of the complimentary relationship theory argue that the decreasing PE is attributable to a decrease in solar irradiance, and thus indicates decreasing landscape evaporation. The complementary relationship between PE and evaporation from surrounding areas indicates a lack of consensus regarding the relationship between PE and actual evaporation (Kahler and Brutsaert, 2006). The
efficacy of this approach in estimating actual evaporation is limited, and is poorly understood.

A change in evaporation results in altering the amount of water vapor present in the atmosphere. An increase in water vapor has reportedly increased the warming by approximately 30% during the 1990s (Solomon et al., 2010). Flohn et al. (1992) reported that water vapor amplifies the greenhouse effect of CO$_2$ and other GHGs by a factor of about 5. An increase in air temperature can increase water retention in the troposphere. With the short residence time, the temperature gradient is insufficient to maintain a discrete water vapor influx prior to precipitation. Thus, a strong external forcing is needed for the initial increase in temperature so that the troposphere can sustain more water vapor. With the temperature remaining constant, there is no significant variation in the amount of water vapor in the troposphere (Hall and Manabe, 1999; Rind, 2006; Held and Soden, 2000; Dessler et al., 2008). However, a positive feedback loop starts when there is an external forcing leading to an increase in the temperature. Warmer air can hold more water vapor than cooler air. Increase in temperature would increase the evaporation as well, and also increase the water vapor concentration (Fig. 1). Being a GHG, increase in concentration of water vapor can trap infrared radiation and further increase the temperature (Hall and Manabe, 1999; Rind, 2006; Held and Soden, 2000; Dessler et al., 2008).
Figure 21: A schematic representation of positive feedback loop of water vapor

It is in this context that the ecological implications of changes in the hydrological cycle caused by climate change are extremely important and relevant. Thus, the objective of this chapter is to establish any trends in PE across a latitudinal gradient in the U.S. for an extended period. The overall goal is to establish any fingerprints of climate change on PE in diverse regions of the U.S.

**Data and Methodology**

The data on total PE from metrological stations from 10 states (Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Florida, Arizona, New Mexico, and Texas) were analyzed for 20-80 years. These sites were selected to represent diverse climates and eco-regions,
such as boreal forests, temperate rainforests, tropical, humid subtropical, and semi-arid climates. Selection of the sites was based on the continuity of data for an extended period, length of the observation period, data availability online, and on the least missing data since the historical climate records have been archived for these stations. The PE trends were analyzed for the summer season (i.e., May to September).

The Class-A evaporation pan is a cylindrical container, made of unpainted galvanized iron sheet or monel metal. It is usually 121 cm in diameter and 25 cm in depth. The pan is leveled at a site that is usually well-sodded and free from obstructions. It is filled with water to a depth of about 20 cm, and is refilled when the water level drops to 18 cm. Daily measurements are made of the water level. Evaporation is computed as the difference between observed water levels on two consecutive days. Daily measurements are corrected as necessary for rainfall (www.ncdc.noaa.gov).

The sites selected for the study were located in 10 states across a north-south latitudinal gradient in the U.S. – Waseca (Minnesota), Jackson (Tennessee), Fairhope (Alabama), Moore Haven Lock (Florida), Lihue (Hawaii), University Experiment Station (Alaska), Roosevelt and Barlett Dam (Arizona), Caballo Dam (New Mexico), Whitney Dam (Texas) and 2 sites in Ohio – Coshocton, and Wooster (Figure 3.1 and 3.2). Data representing the PE measurements were collected from the National Climatic Data Center (www.ncdc.noaa.gov). These data were analyzed to establish trends in warm season evaporation for all different sites. Regression analysis was performed by using MS Office Excel (2007) and StatTools 5.7. Confidence interval of 90% was used while calculating p value and the significance of the models.
<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude and Longitude</th>
<th>Data coverage</th>
<th>MAP(mm)</th>
<th>Köppen Climate Classification</th>
</tr>
</thead>
<tbody>
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<td>Waseca, MN</td>
<td>44°04'N 93°32'W</td>
<td>1964-2010</td>
<td>789.7</td>
<td>Humid Continental</td>
</tr>
<tr>
<td>Jackson, TN</td>
<td>35°37'N 88°51'W</td>
<td>1966-2010</td>
<td>1297.8</td>
<td>Temperate</td>
</tr>
<tr>
<td>Fairhope, AL</td>
<td>30°33'N 87°53'W</td>
<td>1935-2010</td>
<td>1659.4</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Moore Haven Lock, FL</td>
<td>26°50'N 81°05'W</td>
<td>1949-2010</td>
<td>1224.3</td>
<td>Tropical Monsoon</td>
</tr>
<tr>
<td>Lihue, HI</td>
<td>21°59'N 159°20'W</td>
<td>1956-2006</td>
<td>1034.2</td>
<td>Tropical Rainforest</td>
</tr>
<tr>
<td>University Exp Stn, AK</td>
<td>64°51'N 147°52'W</td>
<td>1950-1998</td>
<td>306.1</td>
<td>Continental Subarctic (Boreal)</td>
</tr>
<tr>
<td>Coshocton, OH</td>
<td>40°22'N 81°47'W</td>
<td>1955-2010</td>
<td>942.1</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>40°47'N 81°55'W</td>
<td>1979-2010</td>
<td>936.2</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Whitney Dam, TX</td>
<td>31°52'N 97°23'W</td>
<td>1955-2010</td>
<td>859.5</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Caballo Dam, NM</td>
<td>32°54'N 107°19'W</td>
<td>1950-2010</td>
<td>242.5</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Roosevelt, AZ</td>
<td>33°40'N 111°09'W</td>
<td>1962-2010</td>
<td>1407.7</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Barlett Dam, AZ</td>
<td>33°49'N 111°39'W</td>
<td>1964-2010</td>
<td>347.9</td>
<td>Semi-arid</td>
</tr>
</tbody>
</table>

Source: National Climatic Data Centre
Results

1. University Experiment Station, Alaska – This site was selected for the study because Alaska is situated in the northwest extremity of the North American continent, and represents continental subarctic biome/ boreal forests. Thus, it is important to analyze and compare the data from this site with those in the continental U.S. The site is located in Fairbanks, Alaska; approximately 320 km south of the Arctic Circle. The data are available from 1950 to 1998. The results indicate that PE decreased during the 48 year period from 1950 to 1998. The p value for the trend (0.0004) is statistically significant, and the rate of decrease is 0.25 cm/yr (Fig. 22). The drop in PE rate is pronounced between 1980 and 1990. Whereas the long term mean PE is 41cm, high PE of 55.7 cm and 54.5 cm were observed in 1957 and 1968, and low PE of 24.4 cm was recorded in 1981, 1982 and 1984 (Fig. 22). Incidentally, 1980s was also reported as the warmest decade in Fairbanks since 1920s (Wendler and Shulski, 2008).
Figure 22: Temporal changes in PE at the University Exp Stn, AK from 1950-1998

2. **Waseca, Minnesota** – The data are analyzed from 1964 to 2010. There exists only a slight trend of decrease in PE over the 46 years, at an average rate of decrease of ~0.11 cm/yr (Fig. 23). The p value of 0.3 is not statistically significant. The long-term mean PE is about 87 cm, and high PE of 127 cm and 110 cm were measured in 1988 and 1976, respectively. In contrast, low PE of 70 cm, 75 cm and 75 cm were observed in 2001, 1972 and 1993, respectively (Fig. 23). The data show that the PE increased between 1964 and 1985. However, after 1985 the PE decreased and remained in the same range. Overall, the analysis shows that PE in Waseca, MN in the last 46 years has had trends that were not strong enough to draw a valid conclusion about any climate induced changes in PE.
3. **Ohio** – The data on PE patterns were analyzed for two stations from Ohio, representing diverse ecological characteristics.

   i. **Coshocton** - Coshocton is located in east central Ohio. The PE data are analyzed for the 1956 to 2010 period, and no statistically significant trend is observed ($p = 0.3$). Nonetheless, there has been a slight increase at the rate of ~0.06 cm/yr (Fig. 24). The long term mean PE is 76 cm, with the high PE of 95.5 cm and 92.5 cm observed in 1999 and 1988, respectively. In contrast, low PE of 62.5 cm and 64 cm were measured in 2007 and 1990, respectively (Fig. 24). The highest and the lowest PE values were observed during the last
30 year period, which may indicate that the frequency of extreme events has increased.

![Graph showing temporal changes in PE at Coshocton, OH from 1956-2010.](image)

Figure 24: Temporal changes in PE at Coshocton, OH from 1956-2010

**ii. Wooster** - Wooster is located in north eastern Ohio and an increasing trend is observed in the PE over the last 30 years, with the significant rate of increase of 0.48 cm/yr (Fig. 25), \( p = 0.003 \). The highest PE values were observed in 2000 and 1991 – 107.5 cm and 98.65 cm, respectively, and the lowest PE values were measured in 1984 and 1989 – 71 and 72 cm, respectively (Fig. 25). The mean PE is 82.2 cm, which is higher than the mean PE value at Coshocton of 75.99 cm. The PE data availability in Wooster is only restricted to the last 30 years. However, the trend in the last 30 years is similar to that observed for Coshocton.
4. **Jackson, Tennessee** – The state of Tennessee, south of Ohio, has temperate climate (Table 3), and the data on PE are analyzed for the period between 1966 and 2010. Similar to Coshocton, Ohio, this site also does not have a strong trend over the time period, and the rate of change is rather small. The PE increased during the 44 year period, at an average rate of 0.08 cm/year (Fig. 26). The trend is not statistically significant under 90% confidence interval, and has a p value of 0.4. The long-term mean PE is 88.41 cm. Similar to Coshocton, the frequency of extreme events has increased since 1980.
5. Arizona – Trends in PE are analyzed for two stations from central Arizona.

i. Barlett Dam – The Barlett Dam is located in Maricopa County in central Arizona, and the data are analyzed from 1964 to 2010. Over the period, the PE declined at an approximate rate of 0.9 cm/yr (Fig. 27), and the p value of < 0.0001 is statistically significant. The long term mean PE is ~ 171 cm. The high PE of 220 cm and 212 cm were observed in 2004 and 2000, while low PE of 111 cm and 113 cm were observed in 2010 and 2005, respectively (Fig. 27). Extreme events in PE were observed during the last 15 years of the measurement period, when high and low values were observed during this period.
ii. Roosevelt, AZ – Roosevelt is also located in central Arizona, and the trend in PE over the measurement period of 1962 to 2010 is similar to that of the Barlett Dam. There exists an overall declining trend in PE over the last 48 years, with the rate of decrease of ~ 0.24 cm/yr (Fig. 28). The p value of 0.03 is statistically significant under 90% confidence interval. The long-term mean PE is 158 cm. However, the PE seems to have increased between 1992 and 2002 (Fig. 28). The highest PE values of 181 cm, 178 cm and 175 cm were measured in 2006, 2002 and 1981 respectively. The lowest PE values of 127 cm, 137 cm and 140 cm were measured in 1992, 2008 and 1995, respectively. Similar to the site of Barlett Dam, the high and low values at Roosevelt are also mostly observed from 1980-90 onward.
Figure 28: Temporal changes in PE at Roosevelt, AZ from 1962-2010

6. **Caballo Dam, New Mexico** - Caballo Dam is located in south western New Mexico. The PE records for 60 years between 1950 and 2010 indicate an overall declining trend and the rate of decrease is $\sim 0.3$ cm/yr, which is statistically significant with a p value of 0.08 (Fig. 29). The long-term mean PE is 156.5 cm and a high PE of 184 cm and 181 cm were observed in 1971, 1956 and 2003, respectively. In contrast, low PE of 115 cm and 116 cm were measured in 1979 and 1980, respectively. The period between 1980 and 1990 has particularly low values of observed PE.
7. Whitney Dam, Texas – This site in central Texas is characterized by humid subtropical climate (Table 3), and the PE data are analyzed for 55 years from 1955 to 2010. The data show a declining trend, with the average rate of decrease being ~ 0.3 cm/yr (Fig. 30). The p value of 0.004 is statistically significant under 90% confidence level. The long-term mean PE is 122.77 cm, with a high PE of 167 cm and 141 cm observed in 1956 and 1980 respectively. In contrast, low PE of 89 cm and 96.6 cm were observed in 2007 and 2003, respectively (Fig. 30).
8. **Fairhope, Alabama** – This site has the longest record for PE dating back to 1935. The data over 75 years show a consistently increasing trend between 1935 and 2010, with the rate of increase of ~0.15 cm/yr (Fig. 31), and statistically significant p of < 0.0001. Long-term mean PE is 73.25 cm, which is the second lowest amongst all the other sites studied. The high PE of 90.55 cm and 87.43 cm were observed in 1990 and 2000, respectively. In contrast, low PE of 61.5 cm and 61.7 cm were measured in 1975 and 1946, respectively (Fig. 31).
9. **Moore Haven Lock, Florida** – The PE data for this site are analyzed for the 61 year period between 1949 and 2010. Similar to the trends at Fairhope, the data from this site also show an increasing trend of PE over the 61 year period. The long-term mean PE is 93.41 cm, and the average rate of increase is ~ 0.13 cm/yr (Fig. 32), and the p value of 0.02 is statistically significant. The increase is more pronounced during the period between 1949 and 1985. The PE values decreased between 1985 and 2003 (Fig. 32), but high PE of 114 and 112 cm were measured in 2010 and 1980, and low PE of 78 cm, 80 cm and 80 cm were observed in 1976, 1999 and 1952, respectively (Fig. 32).
10. Lihue, Hawaii – The Hawaii site is included in this study because it is located south west of the Continental U.S. It has a warm tropical climate, which differs from all other sites included in this study. Like most of the other sites in southern US, this site also shows an increasing trend in PE and the rate of increase is 0.38 cm/yr (Fig. 33). The trend looks similar throughout the 49 year period, and the p value is statistically significant (p < 0.0001). The long-term mean PE is 124.5 cm. The highest PE values of 144 cm and 140 cm were recorded in 1984 and 1975, while the low PE of 96 cm and 100 cm were measured in 1959 and 1958, respectively (Fig. 33).
Discussion

The results presented in Figs. 22-33 are summarized in Table 4. The sites which show an increasing trend of PE are: Coshocton (OH), Wooster (OH), Jackson (TN), Fairhope (AL), Moore Haven Lock (FL), and Lihue (HI). In contrast, a decreasing trend in PE is observed for Moore Haven Lock, FL over two decades despite the overall increasing trend of PE. The sites which show a decreasing trend of PE are: University Experiment Station (AK), Waseca (MN), Barlett Dam (AZ), Roosevelt (AZ), Caballo Dam (NM), and Whitney Dam (TX). Also, extreme high and low values of PE were mostly observed during the last 20-30 years in Coshocton (OH), Jackson (TN), Barlett Dam (AZ) and Roosevelt (AZ).
The decreasing PE trend across U.S. as well as globally has been widely reported (Peterson et al., 1995; Roderick et al., 2007). Yet, there are some studies which show an increasing trend in PE (Purvis, 2000; Harmsen et al., 2004). For example, Purvis (2000) reported an increasing trend in PE in southern South Carolina. The increasing PE trends were also reported in some parts of Puerto Rico (Harmsen et al., 2004).

There may be several factors responsible for the site-specific trends. Decrease in the maximum temperature (diurnal temperature range) is related to the observed decrease in PE (Peterson et al., 1995; Thomas, 2000). The cloud cover is another factor which can influence PE, especially the low cloud cover. In general, PE is inversely proportional to the cloud cover (Karl et al., 1993; Peterson et al., 1995; Thomas, 2000), an increase in cloud cover reduces PE and vice versa. Moreover, an increase in air pollution and aerosol concentration reduces the incident sunlight and net loss of long wave irradiance from the surface at night time, which can decrease the PE (Dai and Trenberth, 1998; Roderick and Farquhar, 2002). Another climatic factor which can affect PE is the daily average wind speed (Rayner, 2007). However, the data on wind speed are needed on daily basis to understand the diurnal variations. All other factors remaining the same, a site with high winds would have a higher mean PE than that with fewer winds (Rayner, 2007).

There is another possible explanation. Brutsaert and Parlange (1998) have proposed that in water-limited environments, such as dry and non humid regions, PE is strongly related to the actual evaporation complementarily. The latter implies that the relationship is inversely proportional to one another. The amount of evaporation in a region depends on two factors - available surface moisture and the energy available to evaporate it. The
amount of evaporation for large uniform terrestrial surfaces with adequate moisture is limited by the energy available for evaporation. The potential evaporation is thus the maximum evaporation that can occur given the energy available. Thus, it is the available energy rather than the amount of moisture which is the limiting factor for evaporation. The actual evaporation is the same as the potential evaporation only when adequate moisture is available. Thus, the actual evaporation is less than potential evaporation in regions where surface moisture is inadequate. The resulting decrease in evaporation affects temperature, humidity and turbulence of surface air; the effect on net radiation is negligible. With other factors being similar and there is no overriding local effect, the excess energy (energy available - energy used for actual evaporation) is present as sensible heat flux. The potential evaporation is increased by the amount of energy released due to actual evaporation. The net energy budget thus stays balanced (Brutsaert, 1982; Lawrimore and Peterson, 2000). Lawrimore and Peterson (2000) suggested that PE and terrestrial evaporation may be inversely proportional throughout most areas of the U.S. That being the case, all sites in the present study which show decreasing PE actually have an increasing actual evaporation rate and vice-versa because of the complementary relationship.

Some scientists do not support this hypothesis, called the “pan evaporation paradox”. Ohmura and Wild (2002) showed through computer modeling that there was more evaporation in winter than in summer in both northern and southern hemispheres. A slight decrease in global evaporation was observed in a scenario when the atmospheric CO₂ concentration was doubled using the general circulation model (Wild et al., 1997).
Climate change has resulted in an increase in the areas of the world which are undergoing either drought or wetness or both (Dai et al., 1998). The land area in the U.S. experiencing excessive wetness has increased since 1970s (Karl et al., 1996). In the central U.S., large droughts like those of 1930s are predicted to occur once or twice in 100 years (Woodhouse and Overpeck, 1998). Extreme events are more vulnerable to the erratic changes in climate (Katz and Brown, 1992). Extreme events often result in loss of human life, damage to crop and agriculture and the economic costs associated with it (Karl and Easterling, 1999).

The data and the analysis presented in this chapter must be considered in view of some constraints. Notable among these are – missing historical data and the efficacy of PE data in a water-limited environment. Even though PE is not the perfect indicator of lake or ground evaporation, studying the trends can provide some insight into the changes in the hydrological cycle due to climate change and the pertaining impacts on environmental resources (Mmolawa, 2003). There are also some disadvantages of using PE for estimating the actual evaporation. Water surface reflects only 5-8% of solar radiation whereas plant surfaces reflect 20-25% of incoming solar radiation (Mmolawa, 2003). Unlike plants, evaporation pan offers no stomatal resistance to water loss. Furthermore, the wind profile over crop surface is different than that of a pan, which may affect the PE value. Moreover, evaporation pan may contain significant amount of heat inside, which may lead to equal amount of evaporation during day and night, whereas plants transpire only during the day (Mmolawa, 2003).
It is difficult to generalize the pan evaporation results geographically. However, as will be discussed in subsequent chapters, it is important to establish the cause-effect relationship among climatic factors (i.e. temperature) and the specific components of the hydrological cycle.

**Conclusions**

Results presented support the following conclusions:

5. Trends in PE indicate increase overtime in some regions across the U.S. (i.e. Tennessee, Ohio, Florida, Hawaii and Alabama) and the decrease in others (i.e. Alaska, Arizona, New Mexico, Minnesota, Texas). Such differences are attributed to the geographic location, climate and other site-specific factors.

6. In addition to the long-term response, there are specific changes in PE since 1990 or 2000. In Moore Haven Lock (FL), the long term trend is increasing but PE has decreased since 1990.

7. There are also more extreme events during the last few decades. Extreme high and low values of PE are mostly observed in the last 20-30 years at Coshocton (OH), Jackson (TN), Roosevelt (AZ) and Barlett Dam (AZ).

8. The published data provides contradictory views on the relationship between PE and actual evaporation. It is ambiguous whether the relationship is complimentary or not. Thus more research is needed to substantiate the complementarity hypothesis. Evaporation is one of the most integral components of the
hydrological cycle. Hence, it is extremely important to assess the impact of global warming on PE.

**Table 4: Summary of PE trends, p values and significance for different sites**

<table>
<thead>
<tr>
<th>Site, state</th>
<th>Mean PE (cm/yr)</th>
<th>Trend of PE</th>
<th>Rate of change (cm/yr)</th>
<th>p value</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>University Exp Stn., AK</td>
<td>41 ± 7.5</td>
<td>Decreased</td>
<td>-0.25</td>
<td>0.0004</td>
<td>✓</td>
</tr>
<tr>
<td>Waseca, MN</td>
<td>87 ± 10</td>
<td>Decreased</td>
<td>-0.11</td>
<td>0.3</td>
<td>×</td>
</tr>
<tr>
<td>Coshocton, OH</td>
<td>76 ± 7</td>
<td>Increased</td>
<td>0.06</td>
<td>0.3</td>
<td>×</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>82 ± 9</td>
<td>Increased</td>
<td>0.48</td>
<td>0.003</td>
<td>✓</td>
</tr>
<tr>
<td>Jackson, TN</td>
<td>88 ± 8</td>
<td>Increased</td>
<td>0.08</td>
<td>0.4</td>
<td>×</td>
</tr>
<tr>
<td>Barlett Dam, AZ</td>
<td>170 ± 22</td>
<td>Decreased</td>
<td>-0.90</td>
<td>&lt; 0.0001</td>
<td>✓</td>
</tr>
<tr>
<td>Roosevelt, AZ</td>
<td>158 ± 11</td>
<td>Decreased</td>
<td>-0.23</td>
<td>0.03</td>
<td>✓</td>
</tr>
<tr>
<td>Caballo Dam, NM</td>
<td>156 ± 16</td>
<td>Decreased</td>
<td>-0.21</td>
<td>0.08</td>
<td>✓</td>
</tr>
<tr>
<td>Whitney Dam, TX</td>
<td>123 ± 13</td>
<td>Decreased</td>
<td>-0.31</td>
<td>0.004</td>
<td>✓</td>
</tr>
<tr>
<td>Fairhope, AL</td>
<td>73 ± 6</td>
<td>Increased</td>
<td>0.15</td>
<td>&lt; 0.0001</td>
<td>✓</td>
</tr>
<tr>
<td>Moore Haven Lock, FL</td>
<td>93 ± 8</td>
<td>Increased</td>
<td>0.13</td>
<td>0.02</td>
<td>✓</td>
</tr>
<tr>
<td>Lihue, HI</td>
<td>124 ± 10</td>
<td>Increased</td>
<td>0.38</td>
<td>&lt; 0.0001</td>
<td>✓</td>
</tr>
</tbody>
</table>
References


Chapter 4
TEMPERATURE

Introduction

The mean surface temperature of the Earth is about 15°C and in the absence of the greenhouse gases (GHGs) it would be -18°C (Peng, 1995). “Global warming” is caused by anthropogenic acceleration of GHGs emissions (Tett et al., 1999). Huang et al. (2000) reconstructed temperature trends from borehole temperature and found that the magnitude of warming was higher in Northern Hemisphere with the cumulative change being 1.1K than in the southern hemisphere where the cumulative change was 0.8K over the past five centuries. The 20th century temperature change is 0.6K in Northern Hemisphere and 0.8K in the Southern Hemisphere (Huang et al., 2000). In the United States (U.S.), an increase in mean annual temperature (MAT) was observed mostly in northern and western parts while many stations in southern and eastern U.S. showed a decrease in MAT (Balling Jr and Idso, 1989; Lettenmaier et al., 1994). Lund et al. (2001) also reported an increasing trend in MAT across most of eastern and western coasts of the U.S. while decreasing trends were observed in south-east. Alternate periods of warming and cooling were reported in the 20th century – warming (1900-1940), cooling (1940-1965) and warming (1965-2000) (Hansen et al., 2001).
Since 1950, the minimum temperature has increased almost 2-3 times as much as the maximum temperature (Folland et al., 2002; Karl et al., 1993). Diurnal temperature range is the difference between mean monthly maximum and minimum temperatures (Karl et al., 1993). Hence, because of the trends in maximum and minimum temperature, the diurnal temperature range has been decreasing in many parts of the globe over past several decades (Braganza et al., 2004; Folland et al., 2002; Vose et al., 2005). Decrease in the diurnal temperature range is almost equal to the increase in mean annual temperature (Karl et al., 1993). There are several factors which affect the diurnal temperature range, such as land use change, cloud cover, soil moisture, precipitation and atmospheric circulation (Balling et al., 1998; Bonan, 2001; Braganza et al., 2004; Dai et al., 1999; Karl et al., 1993; Przybylak, 2000; Small et al., 2001). Urban population growth also has a significant impact on the regional temperature. Heat island effect can produce warming of as much as 0.1-0.3°C per decade (Balling Jr and Idso, 1989).

Land degradation has significant impact on temperature, especially the diurnal temperature range as well as on potential evapotranspiration (ET) (Balling et al., 1998). It was observed that conversion of forested lands to croplands in the U.S. decreased the temperature. The decrease was higher in maximum temperature than in minimum temperature (Bonan, 2001). Croplands of Midwestern U.S. show a decrease in maximum temperature compared to forest lands in the Northeast (Bonan, 2001). Hence, afforestation and reforestation are crucial causes of regional climate change (Bonan, 2001).
The decreasing diurnal temperature range is related to an increase in cloud cover and precipitation, which leads to an intensification of hydrological cycle. Dai et al. (1999) showed diurnal temperature range can be reduced by almost 25-50% because of cloud cover and secondary damping effects from soil moisture and precipitation. Atmospheric water vapor increases both the daytime as well as night time temperature. Clouds reduce the diurnal temperature range by decreasing surface solar radiation, while soil moisture increases diurnal temperature range by increasing daytime surface evaporative cooling (Dai et al., 1999).

Changes in temperature influence the amount of precipitation and evaporation. This chapter focuses on establishing any trends in temperature during the 20th century across several regions in the United States.

**Data and Methodology**

Total annual temperature for sites from 10 states – Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Florida, Arizona, New Mexico, and Texas was analyzed for 80-100 years. These sites were selected to represent diverse climates and eco-regions, such as boreal forests, tropical rainforests, temperate continental, humid subtropical and semi-arid climates. Selection of the sites was based on the accuracy of data, length of period, availability, and on the least missing data since the historical climate records have been archived for these sites. Mean annual temperature, mean maximum temperature and mean minimum temperatures were analyzed for all sites.
The sites selected for the study were located in 10 states across a North-South gradient in U.S. – Waseca (Minnesota), Jackson (Tennessee), Fairhope (Alabama), Moore Haven Lock (Florida), Lihue (Hawaii), University Experiment Station (Alaska), Barlett Dam (Arizona), Caballo Dam (New Mexico), Whitney Dam (Texas) and 5 sites in Ohio – Coshocton, Wooster, Circleville, Bowling Green and Bellefontaine. Data representing the temperature measurements was collected from the National Climatic Data Center (www.ncdc.noaa.gov). These data were analyzed to establish trends in maximum, minimum and mean annual temperature for all different sites. Regression analysis was performed by using MS Office Excel (2007) and StatTools 5.7. Confidence interval of 90% was used while calculating p value and the significance of the models.
### Table 5: Location and Description of the Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude and Longitude</th>
<th>Height (m above sea level)</th>
<th>Data coverage</th>
<th>MAT(°C) Mean Annual Temperature ± s.d.</th>
<th>Köppen Climate Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waseca, MN</td>
<td>44°04'N 93°32'W</td>
<td>351.4</td>
<td>1915-2010</td>
<td>6.94 ± 1.15</td>
<td>Humid Continental</td>
</tr>
<tr>
<td>Jackson, TN</td>
<td>35°37'N 88°51'W</td>
<td>121.9</td>
<td>1903-2010</td>
<td>15.5 ± 0.75</td>
<td>Temperate</td>
</tr>
<tr>
<td>Fairhope, AL</td>
<td>30°33'N 87°53'W</td>
<td>7.0</td>
<td>1930-2010</td>
<td>19.67 ± 0.57</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Moore Haven Lock, FL</td>
<td>26°50'N 81°05'W</td>
<td>10.7</td>
<td>1925-2010</td>
<td>22.2 ± 0.5</td>
<td>Tropical Monsoon</td>
</tr>
<tr>
<td>Lihue, HI</td>
<td>21°59'N 159°20'W</td>
<td>30.5</td>
<td>1950-2010</td>
<td>24.15 ± 0.45</td>
<td>Tropical Rainforest</td>
</tr>
<tr>
<td>University Exp Stn, AK</td>
<td>64°51'N 147°52'W</td>
<td>144.8</td>
<td>1905-2010</td>
<td>-2.57 ± 1.26</td>
<td>Continental Subarctic (Boreal)</td>
</tr>
<tr>
<td>Coshocton, OH</td>
<td>40°22'N 81°47'W</td>
<td>347.5</td>
<td>1957-2010</td>
<td>10.2 ± 0.9</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Wooster, OH</td>
<td>40°47'N 81°55'W</td>
<td>310.9</td>
<td>1897-2010</td>
<td>9.7 ± 0.74</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Bellefontaine, OH</td>
<td>40°21'N 83°46'W</td>
<td>361.2</td>
<td>1894-2010</td>
<td>10.3 ± 0.9</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Bowling Green, OH</td>
<td>41°23'N 83°37'W</td>
<td>205.7</td>
<td>1894-2010</td>
<td>10.1 ± 0.86</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Circleville, OH</td>
<td>39°37'N 82°57'W</td>
<td>205.1</td>
<td>1895-2010</td>
<td>11.9 ± 0.85</td>
<td>Hot summer continental temperate</td>
</tr>
<tr>
<td>Anahuac, TX</td>
<td>29°47'N 94°38'W</td>
<td>7.3</td>
<td>1932-2010</td>
<td>20.12 ± 0.67</td>
<td>Humid Subtropical</td>
</tr>
<tr>
<td>Caballo Dam, NM</td>
<td>32°54'N 107°19'W</td>
<td>1277.1</td>
<td>1937-2010</td>
<td>16.08 ± 0.67</td>
<td>Semi-arid</td>
</tr>
<tr>
<td>Barlett Dam, AZ</td>
<td>33°49'N 111°39'W</td>
<td>502.9</td>
<td>1941-2010</td>
<td>21.64 ± 0.76</td>
<td>Semi-arid</td>
</tr>
</tbody>
</table>

**Results**

1. **University Experiment Station, Alaska** – This site was selected for the study because Alaska is situated in the northwest extremity of the North American...
continent and represents an arctic biome. Thus, it is important to analyze and compare the data from this site with those in the continental U.S.. An increasing trend is observed in average temperature, maximum temperature and minimum temperature over the last 105 year period (Fig. 34). All p values are significant. MAT increased at the rate of 0.014 °C/ year. The increase in minimum temperature is much higher than the increase in maximum temperature. The maximum temperature increased at the rate of 0.001 °C/ year whereas the minimum temperature increased at the rate of ~0.02 °C/ year. The MAT is -2.57°C.

![Graph showing temperature changes](image)

Figure 34: Changes in temperature at University Exp Stn., AK from 1905-2010

2. **Waseca, Minnesota** – The MAT at Waseca has decreased slightly at the rate of $0.003^\circ$C/year, though this decrease is not statistically significant. The maximum
temperature has decreased at the rate of 0.01 °C/year (Fig. 35). The p value is 0.02, which is statistically significant. The minimum temperature has increased at the rate of 0.005 °C/year (Fig. 35) over the 95-year period. The MAT for this site is 6.94 °C. This pattern of increasing minimum temperature and decreasing maximum temperature results in a decreasing diurnal temperature range.

Figure 35: Changes in temperature at Waseca, MN from 1915-2010

3. **Ohio** – Several sites were selected within Ohio to establish any north-south gradients in precipitation.
i. **Coshocton**: Coshocton is located in east central Ohio (Fig. 2). Even though the National Climatic Data Centre has data dating back to only 1957 for this site, yet there is a clear trend for the temperature records. The MAT increased at an approximate rate of 0.03°C/year (Fig. 36). The p value is less than 0.0001 and highly significant. The average maximum and minimum temperatures also increased during this period at the rate of 0.03°C/year (Fig. 36). The mean annual temperature of Coshocton is 10.2°C.

![Figure 36: Changes in temperature at Coshocton, OH from 1957-2010](image)

ii. **Wooster** – The Wooster site is located in north eastern Ohio (Fig. 2) and the temperature records at this site go back to 1897. The trend in temperature is little different than that of Coshocton. The maximum
temperature decreased significantly at an average rate of 0.01°C/year while the minimum temperature increased significantly at the rate of 0.005°C/year (Fig. 37). The p values for both the trends are statistically significant. However, the MAT has decreased only slightly at the rate of 0.003°C/year and this trend is not significant under 90% confidence level. The MAT of this site is 9.7°C.

![Graph showing changes in temperature from 1897 to 2010 at Wooster, OH](image)

**Figure 37**: Changes in temperature at Wooster, OH from 1897-2010

### iii. Bellefontaine

Bellefontaine site is located in west central Ohio (Fig. 2). The temperature records date back to 1895. The MAT is 10.3°C. Unlike Coshocton and Wooster, analysis of the data indicates very weak trends in Bellefontaine over the 116 years. The maximum temperature decreased at
the rate of 0.003°C/year and the minimum temperature increased at the rate of 0.004°C/year (Fig. 38). The mean annual temperature does not show any statistically significant trend.

Figure 38: Changes in temperature at Bellefontaine, OH from 1894-2010

iv. **Bowling Green** - Bowling Green site is located in north west Ohio (Fig. 2). Similar to the Bellefontaine site, only minor changes are observed in temperature in Bowling Green between 1894 and 2010 (Fig. 39). The MAT at Bowling Green is 10.1°C. Between 1894 and 2010, the maximum temperature decreased slightly at the rate of 0.0031°C/year, whereas the minimum temperature increased significantly at the rate of 0.0074°C/year
Since the increase in minimum temperature is larger than the decrease in maximum temperature, the average annual temperature showed an increasing trend as well. However, the p value for the average annual temperature trend is not significant.

Figure 39: Changes in temperature at Bowling Green, OH from 1894-2010

Circleville – Circleville is located in south central Ohio (Fig. 2) and is the warmest site in Ohio compared to the other 3 sites discussed before. The mean annual temperature is 11.9°C. Like most other Ohio sites, there is a decreasing trend observed in the maximum temperature and an opposite trend in the minimum temperature (Fig. 40). The maximum temperature decreased at the rate of 0.008°C/year, whereas the minimum temperature
increased at the rate of 0.0042°C/year. Both the trends are statistically significant, with the p values of 0.005 and 0.08, respectively. However, the average temperature trend is not statistically significant and shows a slight decrease at the rate of 0.002°C/year (Fig. 40).

Figure 40: Changes in temperature at Circleville, OH from 1895-2010

4. **Jackson, Tennessee** – This site is located far south of Waseca, MN (Fig. 1) but the temperature trend over the last century is rather similar. The maximum temperature decreased, along with the average annual temperature and the minimum temperature increased on an average in the 107 year period (Fig. 41). The maximum temperature decreased significantly at the rate of 0.016°C/year, while the minimum temperature increased at the rate of 0.006°C/year (Fig. 41).
The p values for these were statistically significant. The overall average annual temperature decreased at a much smaller rate of 0.005°C/year, compared to the rate of decrease of maximum temperature. The mean annual temperature for this site is 15.5°C.

![Chart showing temperature trends with equations and p values](image)

Figure 41: Changes in temperature at Jackson, TN from 1903-2010

5. **Barlett Dam, Arizona** – Barlett Dam site is located in Maricopa County in central Arizona (Fig. 1). The temperature data are analyzed for a 70 year period and the trends look similar to those at Coshocton, OH. The data in Fig. 42 show an increase in maximum temperature, average temperature and minimum temperature. The maximum temperature increased at the rate of 0.026°C/year while the average annual temperature increased at a smaller rate of 0.0175°C/year (Fig. 42). The p values for
both the trends are less than 0.0001 and are statistically significant. The minimum temperature showed a small increase at the rate of 0.0088°C/year and is not statistically significant. Barlett Dam is the third warmest site in this study, after Lihue, HI and Moore Haven Lock, FL. The mean annual temperature is 21.64°C/year.

Figure 42: Changes in temperature at Barlett Dam, AZ from 1941-2010

6. **Caballo Dam, New Mexico** - Caballo Dam site is located in south western New Mexico (Fig. 1). Precipitation data were analyzed for 74-year period between 1937 and 2010. The MAT is 16.08°C. The maximum temperature increased at the rate of 0.01°C/year (Fig. 43). The p value is 0.01, which is statistically significant. The average annual temperature increased at the rate of 0.004°C/year, while the minimum
temperature decreased at the rate of 0.003°C/year. The p values for these trends are 0.3 and 0.4, which are not statistically significant under 90% confidence level (Fig. 43).

Figure 43: Changes in temperature at Caballo Dam, NM from 1937-2010

7. **Anahuac, Texas** – Anahuac site is located in eastern Texas. The temperature records date back to 1932. The MAT is 20.12°C. The average temperature has increased over the last 78 year period, at the rate of 0.001°C/ year (Fig. 44). The minimum temperature increased at the rate of 0.004°C/year whereas the maximum temperature decreased at the rate of approximately 0.001°C/year (Fig. 44). However, these trends are very weak and are not statistically significant.
Figure 44: Changes in temperature at Anahuac, TX from 1932-2010

8. **Fairhope, Alabama** – Fairhope is located at the extreme southern end of Alabama, very close to Gulf of Mexico. It is the only site in this study which shows a significant decreasing trend in maximum, minimum as well as average annual temperature. The MAT decreased at the rate of 0.008°C/year and the mean annual temperature is 19.67°C (Fig. 45). The maximum temperature decreased at the rate of 0.009°C/year, which is higher than the rate of decrease of minimum temperature, 0.007°C/year (Fig. 45). The p values for all trends are statistically significant.
9. **Moore Haven Lock, Florida** – Moore Haven Lock is located south of Florida. MAT observed is 22.2°C. The temperature trends look similar to those at Coshocton, Ohio. An increasing trend is observed in maximum, minimum and average annual temperature between 1925 and 2010 (Fig. 46). The average annual temperature increased by ~ 0.007°C/year, while the minimum temperature increased by a higher rate of 0.009°C/year (Fig. 46). The p value for both the trends is 0.001, which is highly significant statistically. The maximum temperature increased by a smaller rate of 0.004°C/year and the trend is statistically weak (Fig. 46).
Lihue, Hawaii — Hawaii was included in this study because it is located southwest of the Continental U.S. and represents the tropical rainforest biome. It has a warm tropical climate, which differs from all other sites included in this study. This is the warmest site analyzed in this study, with the MAT of 24.15°C. However, the data availability for Lihue, HI is limited to 60 years from 1950 to 2010. Yet, there is a statistically significant increasing trend in average annual temperature during the last 60 years. The average annual temperature increased by 0.01°C/year, with a p value of 0.0001 (Fig. 47). The rate of increase in minimum temperature is almost twice as much, at 0.02°C/year and is extremely significant statistically (p < 0.0001). Maximum temperature also shows a small increase at
the rate of 0.003°C/year. However, it is not statistically significant with a p value of 0.4 (Fig. 47).

Discussion and Conclusions

The results are summarized in Table 6. The sites which showed an increase in MAT are University Exp Stn (Alaska), Coshocton (Ohio), Bellefontaine (Ohio), Bowling Green (Ohio), Anahuac (Texas), Moore Haven Lock (Florida), Caballo Dam (New Mexico), Barlett Dam (Arizona) and Lihue (Hawaii). In contrast, sites which showed a decreasing trend in average temperature are Waseca (Minnesota), Wooster (Ohio), Circleville (Ohio), Fairhope (Alabama) and Jackson (Tennessee).
The increase in minimum temperature has been much higher and prominent than the increase in maximum temperature. Fairhope (Alabama) is the only site in this study which showed a significant decreasing trend in minimum temperature. At all the other sites, the minimum temperature increased in the last few decades. The maximum temperature trends vary among sites. The sites which have an increasing trend in maximum temperature are University Exp Stn (Alaska), Coshocton (Ohio), Moore Haven Lock (Florida), Barlett Dam (Arizona), Caballo Dam (New Mexico) and Lihue (Hawaii), whereas Waseca (Minnesota), Wooster (Ohio), Bellefontaine (Ohio), Circleville (Ohio), Anahuac (Texas) Fairhope (Alabama) and Jackson (Tennessee) showed a decreasing trend in maximum temperature.

Sites in Minnesota, Tennessee, Alabama and Ohio show a decreasing trend in average temperature. Ellsaesser (1986) reported that the average temperature over continental U.S. decreased by ~ 0.6°C in the 25 year period between 1960 and 1985. The South eastern U.S. reportedly cooled down and western U.S. warmed up between 1895 and 1977 (Diaz and Quayle, 1980). There is less number of regional state-based studies available in literature. Most temperature studies are global. Global warming of about 0.5°C-0.7°C is reported in the last century, with equal magnitude in both Northern as well as Southern Hemispheres (Hansen and Lebedeff, 1987). The largest increases in surface temperature over the Northern Hemisphere were observed in Alaska (Trenberth, 1990). Vinnikov et al. (1990) also reported an increase in MAT in both the hemispheres at an average rate of 0.5°C/century. In Northern Hemisphere, successive warming and cooling periods have been reported. Strong warming period was observed between 1880 and
1940, followed by a cooling period between 1940 and 1965 and a warming period after that (Hansen and Lebedeff, 1987; Jones and Kelly, 1983). Karl et al. (1995) also showed that the U.S. mean annual surface temperature has increased by ~ 0.3°C to 0.4°C during the last century. However, the recent temperature increase is accompanied by an increase in precipitation as well, unlike the dry 1930s (Karl et al., 1995).

There are several factors which affect the change in surface temperature, such as increase in GHGs, increase in seas surface temperature, and decrease in ozone in the stratosphere (Karoly, 1989).

The present study shows a significantly higher increase in minimum temperature than the maximum temperature at most sites. Increase in MAT is mainly because of a significant increase in temperature during winter and spring (Karl et al., 1995). Mean minimum temperature shows a better warming trend than mean maximum temperature. This is directly related to an increase in cloud cover over the last few decades (Karl et al., 1995).

Atmospheric-ocean interactions are also an important reason for the reported increase in surface temperature (Trenberth, 1990). Lower tropospheric temperature trends over the Pacific and Atlantic oceans are consistent with the changes in Northern Hemisphere sea surface temperature over the same period (Karoly, 1989).
Table 6 – Summary of temperature trends, p values and significance

<table>
<thead>
<tr>
<th>Sites</th>
<th>Temperature</th>
<th>Trend</th>
<th>P values</th>
<th>Significant</th>
<th>Rate of change (°C/yr)</th>
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References


Chapter 5

GROWING SEASON

Introduction

Climate change is altering the environment and affecting global natural resources and food security. The IPCC (2007) has stated that there has been an unequivocal warming in the past century and most of it is due to anthropological causes. Anthropogenic emissions of greenhouse gases (GHGs) increased by 70% between 1970 and 2004, and may increase by an additional 25% to 95% by 2030 (Rose and McCarl, 2008). Yet, the impacts of these emissions on agricultural systems and food security are not known. One amongst numerous effects of global warming is the change in the length of growing season. Growing season can be defined as the period between the bud burst and fall (EEA, 2004). The duration of this period is defined by temperature, precipitation and atmospheric CO$_2$ concentration. The temperature must be conducive to seed germination, seedling establishment and crop growth. Most of the physiological processes in plants require a temperature range of approximately 0°C to 40°C (Went, 1953). There is a threshold level of degree days in the temperate climate which is needed for seedling growth and development. In addition, there must be adequate soil moisture and oxygen in the seed zone to meet the water and oxygen demand for seedling growth (Loehwing, 1934; Veihmeyer and Hendrickson, 1950). Different plant species adapt differently to changes in the length of growing season induced by climate change. Though the growing
season is closely related to climate change, the knowledge and data currently available about the impact of a changing growing season on plants is inconclusive. Some potential effects of climate change can be summarized as follows –

1. **Warming Climate**: Native species might be replaced by invasives that thrive in higher temperatures and/or reduced soil moisture environments. Low winter temperatures are conducive to triggering bud bursting in some plants. An increase in winter temperature affects these plants (Chuine and Beaubien, 2001).

2. **Effect of increased length of growing season**: The response of growing season depends on species and the latitude.
   a. **Higher Latitudes** – Climate change might increase the length of the growing season, thereby decreasing the interval between the bud burst and leaf fall. This effect is especially noticeable in higher latitudes. There is a resultant increase in biomass in regions where plant growth has been limited by suboptimal temperature (EEA, 2004).
   b. **Lower Latitudes** - The amount of precipitation is the limiting factor for plant growth in lower latitudes. Warming climate exposes these regions to an increased degree of drought stress (EEA, 2004).
   c. **Effect on plant species composition** – Changes in the growing season due to climate change has wide ranging repercussions. Species with a low adaptive capacity are severely affected by changes in the length of growing season, causing a change in the species composition. Tree species that have commercial uses might not be available for forestry anymore, thereby creating
the need for changes in agriculture and forest management (Sykes et al., 1996; Parry, 2000). Nature conservation measures are also affected if protected plant species are endangered by climate change.

Ecosystem gross (GPP) and net primary productivity (NPP) depend on the length of growing season to a large extent (White et al., 1999). With an increase in temperature, timings of spring and summer species is likely to be progressively advanced (Sparks et al., 2000). Mean annual temperature and beginning of the growing season are highly correlated (Chmielewski and Rotzer, 2002; Fitter et al., 1995; Sparks et al., 2000; Wielgolaski, 1999).

In Northern high latitudes, an increase in temperature is often accompanied by an increase in plant growth during summer (Myneni et al., 1997). In Northern hemisphere, the atmospheric CO\textsubscript{2} concentration increases in winter and decreases in summer because of seasonal growth in terrestrial vegetation (Keeling et al., 1996). Annual amplitude of seasonal CO\textsubscript{2} cycle has increased since 1960s leading to an increase in growing season for crops and increased ecosystem uptake during spring and summer which stimulates photosynthesis (Keeling et al., 1996; Randerson et al., 1999). The increase in temperature due to climate change is causing an increased assimilation of CO\textsubscript{2} by terrestrial vegetation and the growing season is getting longer (Keeling et al., 1996). Growing season has already been extended in Europe by almost 11 days since 1960s (Menzel and Fabian, 1999). Because of the increase in the growing season, plant productivity has increased by almost 12\% (EEA, 2004). However, response to change in temperature is variable amongst different plant species (Fitter et al., 1995; Kramer, 1994).
Tucker et al. (2001) reported that at higher northern latitudes, growing season is starting earlier and is continued for longer period. Further, spring events (e.g., leaf unfolding) have advanced while fall events (e.g., leaf coloring) have been delayed (Menzel and Fabian, 1999). The diurnal temperature range has decreased in most parts of the world because the rate of increase in the minimum temperatures is higher than the rate of increase in the maximum temperature (Braganza et al., 2004; Folland et al., 2002; Karl et al., 1993; Vose et al., 2005). As a result, frost free periods in most mid and high latitude regions are increasing (Walther et al., 2002). For example, growing season has extended by 12 days in Japan since 1953 (Matsumoto et al., 2003). With every 1°C increase in mean annual temperature (MAT), length of the growing season can increase by 10 days in Japan (Matsumoto et al., 2003); 6 days at northern latitudes (Menzel and Fabian, 1999), and 12 days in Europe (Chmielewski and Rötzer, 2001). The growing season extended by 1.4 days/year between 1982 and 1993 in eastern China (Chen et al., 2005).

The definition of growing season used in this study is called thermal or climatological growing season, i.e. the frost-free period between the last frost in spring to the first frost in autumn (Burkhead, 1972). The number of consecutive days with minimum temperature above 0°C can be assumed to be conducive for plant growth. At higher latitudes, where the growing season is primarily temperature-limited, the frost-free period is a valid definition of the growing season (EEA, 2008). However, other factors (e.g., precipitation and evapotranspiration) must also be considered at lower latitudes (Linderholm, 2006). Therefore, climatological growing season is a good indicator to study the footprints of climate change because it provides a long spatial coverage of
meteorological stations in most states and there is availability of data going back to more than 100 years. Therefore, long-term changes in the length of growing season by the past climate change can be studied. However, the climatological growing season is a very broad definition and may not be the perfect indicator of actual biological growing season, which varies according to topography, latitude, species and a range of other regional and local differences in climate (Linderholm, 2006). Therefore, the objective of this chapter is to establish any trends in length of thermal or climatological growing season during the 20th century across several northern regions in the United States.

**Data and Methodology**

The threshold temperature for the growth of a plant varies, and the different phenological stages of growth depend upon the daily accumulation of growing degree units above the optimum temperature. The length of the climatological or thermal growing season depends on the last and first day of the threshold temperature above which plants grow. Thus, a 0°C threshold temperature was used in this study.

The temperature measurements are usually taken 2 m above the ground. The minimum temperature data were used directly to find the length of the growing season in each of the seven sites from the time these metrological stations were established. The last date of spring frost and the first date of autumn frost were also studied to establish trends in the last century.
Daily minimum temperature was studied for 5 sites in Ohio (i.e., Coshocton, Wooster, Circleville, Bowling Green and Bellefontaine) and one site each in Alaska (University Experiment Station) and Minnesota (Waseca). Selection of the sites was based on the accuracy of data, length of period of data availability, on the least missing data since the historical climate records have been archived for these stations and on the relevance of the concept of zero threshold temperature to the growing season. Data representing the temperature measurements were collected from the National Climatic Data Center (www.ncdc.noaa.gov). These data were used directly to calculate the length of growing season – the number of days between first and last snow. Regression analysis was performed by using MS Office Excel (2007) and StatTools 5.7. Confidence interval of 90% was used while calculating p value and the significance of the models.

**Results**

1. **Wooster, Ohio** – Wooster is located in the north eastern Ohio. The data show that the growing season has increased significantly between 1897 and 2010 (Fig. 48). The mean length of growing season is 152 ± 16 days, and the rate of increase is 1.6 days/decade (p = 0.0003). The increase in growing season has been especially prominent till 1990. In chapter – 4, it was shown that the minimum temperature in Wooster has increased significantly during the 20th century. Frost free periods in most mid and high latitude regions are increasing because of a sharper increase in the minimum than the maximum temperature (Walther et al., 2002). The data in Fig. 49 shows that the onset of spring events has advanced over the 20th century.
There has been a decrease in the last date of spring frost at the rate of 1.2 days/decade while there has been a delay in the first frost of autumn by about 0.4 days/decade (Fig. 49). The earlier onset of spring is statistically significant with a p value of 0.0004. However, the delay in onset of autumn is not statistically significant.

Figure 48: Changes in the length of growing season at Wooster, Ohio
2. **Coshocton, Ohio** – Coshocton is located in east central Ohio, and the temperature data are available since 1957. Analysis of the available data show that the length of the growing season has increased over the 53 year period from 1957 to 2010, at the mean rate of increase of 2.8 days/decade (Fig. 50). The p value is statistically significant, and the mean length of growing season is 177 ± 15 days. The minimum temperature at Coshocton, Ohio also increased during the same period of time (Chapter 4).

Since only 53 years of data are available for Coshocton, trends are not as strong as are for the other sites. Spring events were advanced and the autumn events delayed by 1.6 days/decade and 1.2 days/decade, respectively (Fig. 51). However, the trends are not statistically significant.
Figure 50: Changes in the length of growing season at Coshocton, Ohio

Figure 51: Changes in the frost dates of spring and autumn at Coshocton, Ohio
3. **Circleville, Ohio** – Circleville is located in south central Ohio, and the availability of data go back to 1895. The mean length of growing season between 1895 and 2010 is 171 ± 18 days. Analysis of the data show that the length of growing season increased at this site at the rate of 1.1 days/decade (Fig. 52). The p value of 0.02 is statistically significant under 90% confidence interval. The minimum temperature at Circleville during the 20th century also increased significantly (Chapter 4), and the trend of increase in growing season length is similar to those of other sites in Ohio.

The increase in growing season at Circleville is a result of early spring and longer fall seasons. Last date of spring frost advanced at the rate of by 0.4 days/decade, whereas first date of autumn frost was delayed by 0.8 days/decade (Fig. 53). However, Circleville is the only site in Ohio which shows a statistically non-significant trend in the early onset of spring but a very strong significant trend in the delay of the autumn frost.
Figure 52: Changes in the length of growing season at Circleville, Ohio

Figure 53: Changes in the frost dates of spring and autumn at Circleville, Ohio
4. **Bellefontaine, Ohio** – Bellefontaine is located in western central Ohio. Daily temperature data are available from 1894 to 2010. Analysis of the data from the 116 year period show that the length of climatological growing season has increased. However, the overall trend is rather noisy. For example, the average length of growing season did not increase significantly between 1955 and 1985. The mean length of growing season being 163 ± 18 days, the rate of increase has been 0.9 days/decade (Fig. 54). The minimum temperature during the same period also shows a weak trend at this site (Chapter 4).

Spring events advanced significantly, and the last frost of spring season advanced by almost 0.8 days/decade (p value = 0.02). However, there is no clear trend in the first frost of autumn pattern over the 116 year period (Fig. 55).

![Figure 54: Changes in the length of growing season at Bellefontaine, Ohio](image)

\[ y = 0.0963x + 156.89 \]
\[ p = 0.04 \]

**Mean = 163 ± 18**
Figure 55: Changes in the frost dates of spring and autumn at Bellefontaine, Ohio

5. **Bowling Green, Ohio** – Bowling Green is located in north western Ohio, and the temperature data for this site are available from 1894 to 2010. The mean length of growing season is 161 ± 19 days. The data of this site show the strongest trend amongst all five sites studied in Ohio. The length of growing season increased by approximately 3 days/decade (Fig. 56) and the p value is statistically significant, < 0.0001. Further, the minimum temperature at this site decreased significantly during the same time period (Chapter 4).

The strong increase in the growing season for the Bowling Green site is attributed to an early onset of spring as well as a delay in autumn seasons. The last frost of spring is advanced by almost 1.6 days/decade, whereas the first frost of autumn is
delayed by ~ 1.4 days/decade (Fig. 57). Both trends are statistically significant, with a p value < 0.0001.

Figure 56: Changes in the length of growing season at Bowling Green, Ohio

\[ y = 0.30x + 143.44 \]
\[ p < 0.0001 \]

Mean = 161 ± 19
6. **Waseca, Minnesota** – Minnesota is one of the northernmost states in the U.S., and the Waseca site is located in southern Minnesota. Temperature data for this site are available from 1915 to 2010. The mean length of growing season is 145 days. The growing season duration increased over the 96 year period, at the rate of 1.6 days/decade (Fig. 58). The p value for the trend is 0.01, and is statistically significant. The diurnal temperature range decreased in Waseca (Chapter 4), which also confirms that the growing season is getting longer.

The increase in growing season duration is primarily caused by an early spring. The last date of spring frost advanced significantly at the rate of 1.3 days/decade (Fig. 59), and the p value is 0.003. However, there is no clear trend in the first day of the autumn frost (Fig. 59).
Figure 58: Changes in the length of growing season at Waseca, Minnesota

Figure 59: Changes in the frost dates of spring and autumn at Waseca, Minnesota
7. **University Experiment Station, Alaska** – Alaska is located in northwest extreme of the US. The mean length of growing season is short, 93 ± 19 days. Temperature data are available for 105 years between 1905 and 2010. The length of growing season shows a strong increasing trend over the 106 year period, with the rate of increase of 2.2 days/decade (Fig. 60) and the significant p value of < 0.0001. These data and trend indicate that the frost-free period at this site in Alaska has increased over the century. Strongly significant and increasing trends are also observed in the minimum, maximum, and mean annual temperatures at this site (Chapter 4).

The increase in the length of growing season at the Alaska site is primarily caused by a delayed fall season, rather than an earlier spring season. The first date of autumn frost advanced significantly at the rate of ~ 1.8 days/decade with a p value of 0.0001 (Fig. 61). Last frost date of spring advanced by 0.5 days/decade. However, this trend is not statistically significant.
Figure 60: Changes in the length of growing season at Univ. Exp. Stn, Alaska

\[ y = 0.2286x + 81 \]
\[ p < 0.0001 \]

Mean = 93 ± 19

Figure 61: Changes in the frost dates of spring and autumn at Univ. Exp. Stn, Alaska

\[ y = 0.18x + 230.06 \]
\[ p = 0.0001 \]

\[ y = -0.05x + 149.06 \]
\[ p = 0.12 \]
Discussion and Conclusion

Trends in the growing season for all sites are summarized in Table 7. All five sites in Ohio (Wooster, Coshocton, Circleville, Bellefontaine and Bowling Green) as well as the two sites in the northern states of Minnesota (Waseca) and Alaska (University Experiment Station) show an increasing trend in the length of the growing season. The rate of increase varies amongst sites, but the increasing trends are all statistically significant. This means the frost-free period is getting longer because of the advancement of spring season and delay of the autumn frost. There has been a sharp advance in the dates for the last frost in spring at Wooster (Ohio), Bellefontaine (Ohio), Bowling Green (Ohio), Coshocton (Ohio), and Waseca (Minnesota). The delay in the first frost of autumn shows a significant trend only at Circleville (Ohio), Bowling Green (Ohio) and University Experiment Station (Alaska). So the increase in the length of growing season may be due to an early spring at some sites, delayed autumn at others and due to both reasons for the remaining sites.

The minimum temperature has shown a significant increasing trend over the 20th century at all these sites (Chapter 4). Advance of spring events, such as the first flowering of crops, is directly related to an increase in minimum temperature (Abu-Asab et al., 2001). The data presented are in agreement with most of the literature reviewed. Significant increase in the length of growing season has been observed through most of the Northern Hemisphere (Frich et al., 2002; Keeling et al., 1996; Randerson et al., 1999). Increase in the length of growing seasons has also been reported in Europe between 1890 and 1995 (Carter, 1998). Between 1951 and 2000, the growing season increased by 0.11-0.49
days/year in Germany (Menzel et al., 2003); by 0.5 days/year in Austria and Switzerland (Menzel et al., 2003), by 0.36 days/year in Estonia (Menzel et al., 2003); by 2.3 days/decade in northern China and by 1.3 days/decade in southern China (Song et al., 2010). In the US, length of growing season increased by almost 14 days in some parts of Minnesota between 1899 and 1982 (Skaggs and Baker, 1985), and increased by about 7 days in parts of Illinois between 1906 and 1997 (Robeson, 2002). In western Canada also, length of growing season increased along with early last frost in spring and later first autumn frost (Bootsma, 1994).

There are various implications of the change in the length of growing season. An elongation of growing season may increase long term carbon storage (Keeling et al., 1996; Linderholm, 2006; Menzel et al., 2003; Randerson et al., 1999; White et al., 1999). It may enable farmers to plant crops early, allowing the crops to reach complete maturity and may enable them to plant multiple crops (Robeson, 2002). Net ecosystem productivity is directly related to the dates of spring growth (White et al., 1999). Longer growing season maybe the reason for the accelerated tree growth in Europe (Menzel and Fabian, 1999). A longer growing season allows planting new crops which are very sensitive to frost in areas which were earlier limited by temperature conditions (EEA, 2008). The increase in the length of growing season can especially be useful for perennial crops but it may get counteracted by distribution and amount of precipitation (Song et al., 2010) and it can also lead to an increase in disease and pest damage (Patterson et al., 1999; Porter et al., 1991). The increase in temperature, which is responsible for increasing the length of growing season, is also increasing evapotranspiration which in
turn is increasing the drought stress which will affect the vegetation negatively, especially at lower elevation (EEA, 2004; Thornton et al., 2010). In Europe, boreal forests will benefit the most with almost 30% increase in growing season and almost no drought stress in the next 100 years; temperate vegetation will increase productivity from a 20% longer growing season but will have a 4% increase in drought stress; while southern Europe will suffer a 13% rise in drought increase and just a 8% increase in the length of growing season (EEA, 2004). However, these changes also exacerbate drought stress, pests and insects. Thus, to avail the benefits it brings to agriculture, management practices need to be adapted accordingly. These adaptations may include changes in the species grown, efficient and judicious use of irrigation and/or adaptation of the crop calendar (EEA, 2004).

In contrast, a decrease in the length of growing season may alter the planting dates for the crops and affect the crop yields because crops may not mature completely in the shorter growing period (Robeson, 2002). With a shorter growing season, there will be higher risk of frost damage from delayed spring frosts (EEA, 2004).

In Africa, crop yield response to climate change was found to be highly variable (Thornton et al., 2010). With an increase in temperature and changes in the amount and distribution of precipitation, crop yields increased at higher elevations and decreased at lower elevations (Thornton et al., 2010). During the last 60-80 years, crop yields have increased tremendously in all the sites studied in Ohio, where an increase in the length of growing season is observed. However, farm management practices have also changed
and the attribution of observed changes in phenology to climate change per se is difficult since there are so many other factors at play.

Table 7: Summary of trends in the length of growing season for the sites studied

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Site</th>
<th>Mean length of growing season</th>
<th>Trend</th>
<th>Rate of Increase (days/decade)</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wooster, Ohio</td>
<td>152 ± 16</td>
<td>Increasing</td>
<td>1.6</td>
<td>0.0003</td>
</tr>
<tr>
<td>2.</td>
<td>Coshocton, Ohio</td>
<td>177 ± 15</td>
<td>Increasing</td>
<td>2.8</td>
<td>0.03</td>
</tr>
<tr>
<td>3.</td>
<td>Circleville, Ohio</td>
<td>171 ± 18</td>
<td>Increasing</td>
<td>1.1</td>
<td>0.02</td>
</tr>
<tr>
<td>4.</td>
<td>Bellefontaine, Ohio</td>
<td>163 ± 18</td>
<td>Increasing</td>
<td>0.9</td>
<td>0.04</td>
</tr>
<tr>
<td>5.</td>
<td>Bowling Green, Ohio</td>
<td>161 ± 19</td>
<td>Increasing</td>
<td>3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>6.</td>
<td>Waseca, Minnesota</td>
<td>145 ± 17</td>
<td>Increasing</td>
<td>1.6</td>
<td>0.01</td>
</tr>
<tr>
<td>7.</td>
<td>Univ Exp Stn, Alaska</td>
<td>93 ± 19</td>
<td>Increasing</td>
<td>2.2</td>
<td>&lt; 0.0001</td>
</tr>
</tbody>
</table>
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Chapter 6

ARIDITY INDEX

Introduction

Climate change is resulting in an increase in global temperature, change in the distribution and amount of precipitation, rise in sea level, increase in the frequency of droughts and floods and change in the length of growing season (IPCC, 2007). These changes may have strong impacts on both irrigated and rain-fed agriculture around the globe, and also affect the soil organic matter (SOM) pool and the attendant alterations in soil quality.

Temperature has a significant influence on the production as well as the decomposition of SOM (Jenny, 1941). Rate of SOM decomposition increases with an increase in temperature, but the sensitivity of SOM decomposition to temperature decreases with progressive temperature increases. A 1°C increase in temperature may lead to a loss of over 10% of SOM in the world soils when the mean annual temperature (MAT) is 5°C. But if the MAT is 30°C, a 1°C increase in temperature may lead to only 3% of loss in the SOM (Kirschbaum, 1995). There exists a positive correlation between SOM and precipitation and a negative correlation between SOM and temperature (Jenny, 1941; Kirschbaum, 1995; Post et al., 1982; Shaver et al., 1992). Jenny (1941) explained the relationship between soil organic matter and temperature by this equation:

\[ N = C e^{-kT} \]
Where, \( N = \text{Total SOM} \);
\( T = \text{Temperature}; \) and
\( C \) and \( k \) = constants.

Further, the SOC concentration increases with an increase in atmospheric \( CO_2 \) concentration and it decreases with an increase in temperature (Kirschbaum, 1993). In warm climates, decomposition of SOM is accelerated (Jenni, 1941). For every 10°C decrease in temperature, the total soil \( N_2 \) and SOM increase 2-3 times, if the annual precipitation to evaporation ratio stays constant (Jenni, 1941). If an increase in temperature leads to a decrease in SOC, then carbon (C) would have to be oxidized to \( CO_2 \), thereby increasing the greenhouse gases (GHGs) concentration in the atmosphere, and starting a positive feedback loop (Jenkinson et al., 1991; Kirschbaum, 1993; Schimel et al., 1990). If global temperature increases by 0.03°C/year, 61Pg C from SOM will be added to the atmosphere as \( CO_2 \) in the next 60 years, which is \( \sim 19\% \) of the \( CO_2 \) which will be added due to fossil fuels over the same period of time (Jenkinson et al., 1991).

There is large disparity in the response of agricultural production to climate change between developed and developing countries (Rosenzweig and Parry, 1994). A relatively smaller increase in temperature is projected in the equatorial regions than at higher latitudes. Nonetheless, such a trend may not translate into any less severe agricultural effects (Kane et al., 1992). Evapotranspiration increases non-linearly with an increase in temperature. So, with every 1°C rise in temperature, there is higher potential of drought in warmer than in cooler regions. Also, cooler temperate regions may adapt to climate
change by switching to warm season crops, but a fewer options may be available in the tropics (Kane et al., 1992). Increases in temperature and precipitation in higher latitudes are expected to increase agricultural production in Northern parts of Soviet Union, Canada and Europe (Kane et al., 1992) and in most parts of Australia (Walker et al., 1989). But increase in temperature combined with aridity in middle latitudes can decrease agricultural production in US, western Europe and parts of Canada (Kane et al., 1992).

The US agriculture is highly capital-intensive which has the flexibility to adapt to climate variations, unlike labor intensive agriculture in most of the developing nations (Mendelsohn and Dinar, 1999).

Increase in temperature by climate change will increase the crop water demands and reduce the availability of fresh water supply (FAO, 2011). Rain-fed agriculture is practiced on 80% of global cropland area and 60% of global food output is generated by it (FAO, 2011). It is vulnerable to climate change, especially in arid and semi-arid regions. At higher latitudes and even in humid tropics, this form of agriculture is reliable and productive. But in mid-latitudes, rain-fed agriculture is less productive because of higher risks of droughts (FAO, 2011). By 2050, rain-fed cropland area is expected to increase by 27% and irrigated cropland area by 33% (Bruinsma, 2009). Expansion of rain-fed areas will exacerbate deforestation while that of irrigated area will aggravate the drought stress.

It is difficult to analyze the effect of any one component of the hydrological cycle on agricultural systems since most of the components are interdependent and the effects are inter-related. Moisture or aridity indices are widely used to integrate the variability and
effects of temperature and precipitation (Ayers et al., 1990; Baltas, 2007; Botzan et al., 1998; Feddema, 2005; Ives, 1949; Paltineanu et al., 2007). In order to quantify the effect, Lang (1920) proposed an index called “rain factor”, calculated as the ratio of annual precipitation (in mm) to the mean annual temperature (MAT in °C). Thus, it is also called P:T ratio, and climatic regions are grouped according to Lang’s Rain Factor as per Table 8 (Devi, 1992).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Lang’s Rain Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>0-40</td>
</tr>
<tr>
<td>Humid</td>
<td>40-160</td>
</tr>
<tr>
<td>Wet</td>
<td>&gt; 160</td>
</tr>
</tbody>
</table>

De Martonne (1926) modified this index and called it “De Martonne’s Index of Aridity” (Ia), which is the ratio between the mean annual precipitation and temperature plus 10°C. The method is related to the bio-physics of the plant-weather interaction. It is a simple empirical method and provides easy measurements which are consistent over time (Oury, 1965). The method is not limited to a particular agricultural area or a certain type of crop. Basic weather data are available in all agricultural districts in the U.S., and Ia can be computed for most regions (Oury, 1965). The purpose of this chapter is to see the impact of climate change on the aridity of the chosen sites over the last 80-100 years.
Data and Methodology

Total annual precipitation and MAT for sites from 10 states (i.e., Alaska, Minnesota, Ohio, Tennessee, Alabama, Hawaii, Florida, Arizona, New Mexico, and Texas) were used to calculate the De Martonne’s index of aridity” (Ia) for 80-100 years. Selection of the sites was based on the accuracy of data, length of period, availability, and on the least missing data since the historical climate records have been archived for these stations. The sites selected for the study were located in 10 states across a North-South gradient in U.S. – Waseca (Minnesota), Jackson (Tennessee), Fairhope (Alabama), Moore Haven Lock (Florida), Lihue (Hawaii), University Experiment Station (Alaska), Barlett Dam (Arizona), Caballo Dam (New Mexico), Whitney Dam (Texas) and 4 stations in Ohio – Coshocton, Wooster, Bowling Green and Bellefontaine. Data representing the temperature and precipitation measurements were collected from the National Climatic Data Center (www.ncdc.noaa.gov). The following formula was computed:

\[ I_a = \frac{P}{T+10}, \]

Ia = De Martonne’s index of aridity

P = Annual precipitation (in mm)

T = Mean Annual Temperature (in °C)

Climatic classification based on Ia values are given in Table 9


Table 9: De Martonne’s aridity index climatic classification: Adapted from Baltas (2007)

<table>
<thead>
<tr>
<th>Climate</th>
<th>Ia value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arid</td>
<td>Ia &lt; 10</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>10 ≤ Ia ≤ 20</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>20 ≤ Ia ≤ 24</td>
</tr>
<tr>
<td>Semi humid</td>
<td>24 ≤ Ia ≤ 28</td>
</tr>
<tr>
<td>Humid</td>
<td>28 ≤ Ia ≤ 35</td>
</tr>
<tr>
<td>Very humid</td>
<td>35 ≤ Ia ≤ 55</td>
</tr>
<tr>
<td>Extremely humid</td>
<td>Ia &gt; 55</td>
</tr>
</tbody>
</table>

These Ia values computed were analyzed to establish trends for all different sites. A decreasing Ia trend means that the region is getting more arid and vice-versa (Table 2).

The De Martonne’Aridity Factor is a modification of Lang’s factor in order to avoid any negative values. Regression analysis was performed by using MS Office Excel (2007) and StatTools 5.7. Confidence interval of 90% was used while calculating p value and the significance of the trends.

Results

1. University Experiment Station, Alaska – This site was selected for the study because Alaska is situated in the northwest extremity of the North American continent and represents an arctic biome. Thus, it is important to analyze and compare the data from this site with those in the continental U.S. A decreasing
trend is observed in Ia over the last 105 year period, which means that aridity has increased (Fig. 62). The rate of decrease is \( \sim 0.06/\text{yr} \). In the period between 1976 and 1990, very low Ia values are observed. However, the p value of 0.2 is not statistically significant under 90\% confidence interval. The mean value of Ia for this site is 41. The mean annual precipitation (MAP) has a decreasing trend, whereas MAT has increased at this site over the last century (Chapters 2 and 4). Hence the Ia has a modest increasing trend.

![Graph showing changes in Ia](image)

Figure 62: Changes in Ia at University Exp Stn., AK from 1916-2010

2. **Waseca, Minnesota** – Temperature and precipitation data were available since 1915. The Ia was computed for this period and a statistically significant increasing trend is observed (Fig. 63), with the p value of less than 0.0001. The
The rate of increase is 0.17/yr. This implies that the site is getting wetter over the last ~95 years. Several flooding events have occurred in Minnesota in the last couple of decades (Al Kean, 2011). The mean value of Ia for Waseca, MN is 46.88. The MAT has decreased, whereas the MAP values for this site have increased (Chapters 2 and 4) and hence the Ia values show an increasing trend.

Figure 63: Changes in index of aridity at Waseca, MN from 1915-2010

3. Ohio – Several stations were selected within Ohio to establish any north-south gradients in precipitation.

   i. Coshocton: Coshocton is located in east central Ohio. The National Climatic Data Centre has data dating back to only 1957 for this site. There is no
significant trend observed in $I_a$ over this period of time. Mean $I_a$ value is 46.75. The slight increasing trend is not statistically significant, with a $p$ value of 0.4 (Fig. 64). Both MAP and MAT values for this site have increased in the 53 year period (Chapters 2 and 4).

![Graph showing changes in index of aridity at Coshocton, OH from 1957-2010](image)

Figure 64: Changes in index of aridity at Coshocton, OH from 1957-2010

**ii. Wooster** – Wooster is located in north eastern Ohio and the temperature and precipitation records at this site go back to 1897. There is a strong increasing trend of $I_a$ over the 113 year period. The mean value of $I_a$ is 47.55. The increase is statistically significant, with a $p$ value of 0.0004 (Fig. 65). The aridity index is steadily increasing at the rate of 0.08/yr, which means the area is getting increasingly wetter with time. The MAP has increased, whereas MAT has decreased with time at Wooster (Chapters 2 and 4). Since the aridity
index is inversely proportional to temperature and directly proportional to the amount of rainfall, an increasing $I_a$ is attributed either to an increase in precipitation, decrease in temperature, or both (Botzan et al, 1998).

Figure 65: Changes in index of aridity at Wooster, OH from 1897-2010

iii. **Bellefontaine** – Bellefontaine is located in west central Ohio. The mean $I_a$ for this site is 45.42. There is an increasing trend of $I_a$ observed in the period between 1895 and 2010 (Fig. 66). The rate of increase is 0.05/yr. The $p$ value is 0.04, which is statistically significant. Like Wooster, an especially high $I_a$ trend is visible in the last two decades, implying more wetness. This site has showed an increasing trend of both MAP and MAT values (Chapters 2 and 4).
Increase in one factor can be more prominent than the other, causing a change in Ia values over time.

![Graph showing the changes in index of aridity at Bellefontaine, OH from 1894 to 2010.](image)

Figure 66: Changes in index of aridity at Bellefontaine, OH from 1894-2010

iv. **Bowling Green** - Bowling Green is located in north west Ohio. Similar to the Coshocton site, no specific trend in Ia is observed. The p value for the slight increasing trend is 0.58, which is very high and not significant statistically (Fig. 67). The mean value of Ia is 41.32, which is less than the other sites in Ohio. Except for one or two years, the aridity index has remained pretty constant in the period between 1894 and 2010. Increasing trends of both MAT and MAP have been observed at this site (Chapters 2 and 4).
4. **Jackson, Tennessee** – The mean Ia value for this site is pretty high, 51. The temperature and precipitation data are available from 1903 to 2010. Like the Ohio and Minnesota sites, the Jackson site also shows an increasing trend of Ia over the 107 year period. The long term rate of increase of Ia is 0.09/yr. The trend is statistically significant, with a p value of 0.03 (Fig. 68). On the basis of De Martonne’s index of aridity, this site has also become wetter on an average. An increasing trend of MAP was observed at this site, whereas a decreasing trend was observed in MAT (Chapters 2 and 4).
Figure 68: Changes in index of aridity at Jackson, TN from 1903-2010

5. **Barlett Dam, Arizona** — Barlett Dam is located in Maricopa County in central Arizona. Climatic data are available for the last 70 years. The mean Ia value for this period of time is 11, which categorizes this site as arid. An increasing trend of Ia is observed between 1941 and 2010 (Fig. 69). The p value is 0.2, which is not statistically significant. Very low values of Ia are observed in the last 15 years, making this area very prone to droughts. Increasing trends were observed in both MAT and MAP over the same period of time (Chapters 2 and 4).
6. **Caballo Dam, New Mexico** - Caballo Dam is located in southwestern New Mexico. Like the Arizona site, this site also has a very small mean Ia value of 9.3. This means the site is extremely arid. However, an increasing trend of Ia has been observed (Fig. 70). The rate of increase of Ia is 0.04/yr. The trend is statistically significant with a p value of 0.02. Increasing trends of MAP as well as MAT were observed at Caballo Dam in the period between 1937 and 2010 (Chapters 2 and 4). But perhaps, the increase in MAP is more prominent than the increase in MAT, and hence the Ia trend is increasing with time.
7. **Anahuac, Texas** – The Anahuac site is located in eastern Texas. Ia values were computed for the period between 1932 and 2010 and a very weak increasing trend is observed (Fig. 71). The p value is 0.22, not statistically significant. The mean Ia value is 44.38. Increasing trends of both MAP and MAT have been observed at this site, just like the sites in Arizona, New Mexico and Ohio (Chapters 2 and 4).
8. **Fairhope, Alabama** – Fairhope is located at the extreme southern end of Alabama, very close to Gulf of Mexico. Precipitation and temperature data are available from 1931 to 2010, which are used to calculate the aridity indices for this period. Like most other sites, this site also shows an increasing trend of Ia (Fig. 72). The long-term rate of increase of Ia is 0.09/yr. The p value is 0.1, which is statistically significant under 90% confidence interval. The mean Ia value for the 80 year period is 56.27, which is the highest amongst all sites included in this study. An increasing trend in MAP and a decreasing trend in MAT have been observed at Fairhope site between 1931 and 2010 (Chapters 2 and 4).
9. **Moore Haven Lock, Florida** – Moore Haven Lock is located south of Florida. It is the second warmest site in this study (Chapter 4). This site shows a weak decreasing trend of Ia between 1931 and 2010 (Fig. 73). The p value is 0.26, which is not statistically significant. The mean Ia value for this site is 37. MAP has been decreased, whereas MAT has increased with time at this site (Chapters 2 and 4). Hence the aridity indices have been decreasing, implying more aridity.
10. Lihue, Hawaii – Hawaii was included in this study because it is located south west of the Continental U.S. and represents the tropical rainforest biome. It has a warm tropical climate, which differs from all other sites included in this study. This is the warmest station analyzed in this study (Chapter 4). Ia values are computed for the last 60 years and a negative trend has been observed (Fig. 74). The rate of decrease of Ia is -0.14/yr. The p value of 0.04 is statistically significant under 90% confidence level. The mean Ia value for this site is 30.31. Like the Florida site, Lihue in Hawaii also showed a decreasing MAP trend and an increasing MAT trend in the chosen time period (Chapters 2 and 4). Because of the opposite trends in both the parameters, the Ia has decreased significantly.
Discussion and Conclusions

Results are summarized in Table 10. Three sites – University Experiment Station (AK), Moore Haven Lock (FL) and Lihue (HI) - show a decreasing trend of Ia, which implies that the aridity is increasing with time. The other sites – Waseca (MN), Coshocton (OH), Bellefontaine (OH), Wooster (OH), Bowling Green (OH), Fairhope (AL), Caballo Dam (NM), Barlett Dam (AZ), Anahuac (TX) and Jackson (TN) show a positive trend of Ia, which means that the wetness is increasing with time.

Grundstein (2009) used a different moisture index (modified Thornthwaite moisture index) to quantify climatic variability across U.S. but the results are in agreement with the findings of this study. Thornthwaite moisture index uses potential evapotranspiration and annual precipitation to classify regions (Grundstein, 2009):
MI = (P/PE−1), P<PE
MI = (1−PE/P), P≥PE
MI=0, P=PE=0,

Where, MI = Moisture Index,
P = Precipitation, and
PE = Potential Evaporation

Eastern U.S. is getting increasingly wetter, especially southern, north eastern and east north central mid-western regions (Grundstein, 2009). Wetness in south is driven primarily by an increase in precipitation but also by a decrease in temperature, hence potential evaporation (PE). In the eastern, north central and north eastern regions, temperature is also increasing but the increase in precipitation is far more and hence the wetness is increasing (Grundstein, 2009).

Based on the mean value of Ia, University Exp Stn (AK), Waseca (MN), Moore Haven Lock (FL), Jackson (TN), Anahuac (TX) and all sites in Ohio are classified as very humid regions. Barlett Dam (AZ) is semi-arid while Caballo Dam (NM) is arid. Fairhope (AL) is the wettest site and is categorized as extremely humid (Table 2). In Alabama, MAT has a decreasing trend (Chapter 3). Because of the decrease in temperature, PE decreases and reduces the climatic demand for moisture, thereby increasing wetness by 21% (Grundstein, 2009). There has been a 6% increase in areas classified as humid across the US (Grundstein, 2009). Such a trend may have an impact on agriculture, vegetation, and crops (Adams et al., 1990). Excess precipitation has also resulted in the huge losses due to crop damage in the US (Rosenzweig et al., 2002).
Global crop yields over the last 50 years have been increasing at an annualized rate of ~2% (Adams et al., 1998). The increasing trend is expected to continue during the foreseeable future even after accounting for the impact of climate change on crop yields. The increased yields are partly attributable to rapid advances and adoption of technology in agriculture. A plethora of costs are associated with the development and adoption of technical advancements in agriculture. These include research and development, cost of equipment required for implementing these new technologies at the farm level and investments in manpower (training to utilize advanced farming methods and equipment). Dealing with and mitigating the impact of climate change on agricultural production, adds to the cost burden of agricultural economies (Adams et al., 1998). Climate change can impose constraints on the adoption and efficacy of technical innovations in agriculture, since climate change can limit the availability of critical inputs such as water. Technical advancements in selective breeding and genetic engineering have greatly enhanced crop yields (Sinclair et al., 2004). High yielding varieties of staple crops such as *Triticum aestivum* (wheat), *Oryza sativa* (rice), *Zea mays* (maize) and *Sorghum bicolor* (sorghum) have helped boost the world's food supply. However the new high-yielding varieties of crops tend to be less resilient to climate change. The uncertainties imposed by climate change expose the farmers to additional risks and limits their ability to adopt newer technologies and higher yielding crop varieties (Alston et al., 1995). Farmers practicing subsistence farming are more risk averse and slower to adopt the higher yielding varieties in place of local varieties. The effect of climate change on agricultural yields depends on a multitude of interrelated
factors and feedback mechanisms. These interactive effects make it difficult to interpret the results universally. While studying the effects of climate change on agricultural yields, the following factors (and challenges) should be considered –

i. **Type of crop** - Climate change has varying effects on the yields of different crops. Different crops react differently to changes in climate influenced variables such as temperature (warming or cooling), precipitation (quantity and direction), CO$_2$ levels and nature of CO$_2$ fertilization. The effect of these factors cannot be studied in isolation. Increase in temperatures, while other factors remain unchanged, reduces crop yields while increase in precipitation in parallel with increased temperature mitigates the effect of decreased yields due to higher temperature (Lobell and Field, 2007; Peng et al., 2004). Increase in concentrations of CO$_2$ (as a consequence of climate change), results in a fertilization effect which improves yields (Kane et al., 1992).

ii. **Regional effects** - Different regions can experience varying degrees of change in yields depending on latitude. Low latitude areas with warmer climates and low rainfall (semi-arid) are the most vulnerable to climate change (Adams et al., 1998). Further, the climate change varyingly affects yields of a particular crop nationally and internationally. Climate change might favor certain regions or countries and adversely affect others that were conducive to a particular crop, thereby affecting the local and in some cases national economies.
iii. **Factors affecting economic consequences** - The overall economic effects of yield changes are contingent on the extent of adaptation and flexibility by farmers, consumers, government agencies and other institutions involved in the distribution and storage of produce. Consumption patterns are affected if consumers substitute a higher priced (due to climate change) crop with a more cost effective substitute. The economic response due to consumer's adaptive response can have widely ranging economic repercussions. The adaptive response can negatively impact one crop while positively impacting a substitute crop (Deschenes and Greenstone, 2007).

iv. **Lack of consensus** - Structural and spatial models yield diverging results about the economic impact of climate change on different crops. Though recent literature highlights the effect of adaptive response, other factors also contribute to the economic response to climate change. Structural and spatial models vary in their ability to account for fundamental biophysical relationships (CO₂ fertilization, yield response to climate change) and other resources such as soil quality and availability of moisture (Adams et al., 1995; Kaiser et al., 1993).

v. **Lack of standardization** - The task of enhancing structural models in order to assess adaptation responses is further compounded by a wide range (that is subjective in nature) of flat probability distributions different models use to imply climate change. In the absence of universally accepted levels of precipitation change and water availability, estimates at the farm level will
fluctuate excessively and will remain inaccurate. The lack of consensus about long term precipitation changes undermines the ability to detect climate changes over the long term. This exacerbates our inability to formulate an adaptive response and mitigate the effects of climate change by undermining research and development, education and training (Adams et al., 1998).

**vi. Effect on consumers versus producers and suppliers** – The fundamental laws of demand and supply affect consumers and suppliers of agricultural products impacted by climate change. Consumers are likely to suffer and bear the burden of higher prices due to short supply while the suppliers take advantage of inelastic demand and enjoy higher margins. Consumers in very wide geographic regions can be affected by climate change (and consequent price increase) while the effects on producers and suppliers tend to be more localized (Adams, 1989; Deschenes and Greenstone, 2007).

**vii. Limitations of regional (non-global) studies** - In today’s world no agricultural economy functions as an autonomous unit. Global economies and consequently agricultural entities rely on each other for trade, raw materials, technology and expertise. Regional and country specific studies about the impact of climate change on agricultural yields, fail to capture the global impact. A more comprehensive global approach (which evaluates regional responses in the light of global price and productivity trends) is required to quantify regional and national impact of climate change on agriculture (Adams et al., 1998).
<table>
<thead>
<tr>
<th>Sites</th>
<th>Mean Ia</th>
<th>Trend</th>
<th>Rate of change (per year)</th>
<th>p value</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waseca, MN (1915-2010)</td>
<td>46.88 ± 11.06</td>
<td>Increasing</td>
<td>0.17</td>
<td>&lt; 0.0001</td>
<td>✓</td>
</tr>
<tr>
<td>Jackson, TN (1903-2010)</td>
<td>51 ± 9.9</td>
<td>Increasing</td>
<td>0.09</td>
<td>0.03</td>
<td>✓</td>
</tr>
<tr>
<td>Fairhope, AL (1930-2010)</td>
<td>56.27 ± 11.2</td>
<td>Increasing</td>
<td>0.09</td>
<td>0.1</td>
<td>✓</td>
</tr>
<tr>
<td>Moore Haven Lock, FL (1925-2010)</td>
<td>37 ± 6.86</td>
<td>Decreasing</td>
<td>-0.04</td>
<td>0.26</td>
<td>✗</td>
</tr>
<tr>
<td>Lihue, HI (1950-2010)</td>
<td>30.31 ± 9.68</td>
<td>Decreasing</td>
<td>-0.14</td>
<td>0.04</td>
<td>✓</td>
</tr>
<tr>
<td>University Exp Stn, AK (1916-2010)</td>
<td>41.09 ± 13.34</td>
<td>Decreasing</td>
<td>-0.06</td>
<td>0.2</td>
<td>✗</td>
</tr>
<tr>
<td>Coshocton, OH (1957-2010)</td>
<td>46.75 ± 7.85</td>
<td>Increasing</td>
<td>0.06</td>
<td>0.4</td>
<td>✗</td>
</tr>
<tr>
<td>Wooster, OH (1897-2010)</td>
<td>47.55 ± 8</td>
<td>Increasing</td>
<td>0.08</td>
<td>0.0004</td>
<td>✓</td>
</tr>
<tr>
<td>Bellefontaine, OH (1894-2010)</td>
<td>45.42 ± 8.78</td>
<td>Increasing</td>
<td>0.05</td>
<td>0.04</td>
<td>✓</td>
</tr>
<tr>
<td>Bowling Green, OH (1894-2010)</td>
<td>41.32 ± 7.24</td>
<td>Increasing</td>
<td>0.01</td>
<td>0.58</td>
<td>✗</td>
</tr>
<tr>
<td>Anahuac, TX (1932-2010)</td>
<td>44.38 ± 12.38</td>
<td>Increasing</td>
<td>0.07</td>
<td>0.22</td>
<td>✗</td>
</tr>
<tr>
<td>Caballo Dam, NM (1937-2010)</td>
<td>9.3 ± 3.46</td>
<td>Increasing</td>
<td>0.04</td>
<td>0.02</td>
<td>✓</td>
</tr>
<tr>
<td>Barlett Dam, AZ (1941-2010)</td>
<td>11 ± 4.62</td>
<td>Increasing</td>
<td>0.03</td>
<td>0.2</td>
<td>✗</td>
</tr>
</tbody>
</table>
References


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Chapter 7

CONCLUSIONS

Based on the results discussed in chapters 1-6, the trends in different climatological parameters can be segregated according to the biomes that the sites belong to.

1. **Continental subarctic (Boreal)** – Example, **University Experiment Station, Alaska** – This site is located in Fairbanks. This is the only climatological station in interior Alaska with a consecutive record of metrological parameters for almost 80-90 years. It is located approximately at the center of a low-lying river valley at the intersection of the Chena and Tanana rivers (Wendler and Shulski, 2009). The interior Alaskan region is surrounded by the Alaska Range in the south and by the Brooks Range in the north so advection of moist air is hindered, resulting in low annual precipitation. The climate is continental sub-arctic, with relatively warm summers and very cold winters (Shulski and Wendler, 2007). The Fairbanks observational site has been relocated several times. However, the station always stayed in the bottom of the valley, where the temperatures are mostly uniform (Wendler and Shulski, 2009). This study shows that temperature is increasing; and precipitation and pan evaporation are decreasing since last 50-80 years.

2. **Humid continental** – Example, **Minnesota. Waseca** is located in southern Minnesota. On the Köppen climate classification, it falls under humid continental zone. It has long cold winters and short warm summers. The study shows that
since 1915 precipitation has been increasing, but pan evaporation and mean annual temperature are decreasing.

3. **Hot summer continental temperate** – Example, Ohio. Under this biome, winters are usually cold and summers are mild. Precipitation, pan evaporation as well as temperature show increasing trends.

4. **Humid subtropical** – Example, Tennessee, Alabama. The humid subtropical climate has warm, wet summers. The moist growing seasons and nutrient-rich soil make the humid subtropical areas some of the most fertile regions in the world. The study shows that the precipitation and pan evaporation have been increasing while mean annual temperature is decreasing in the last 50-100 years in such climatic regions.

5. **Tropical** – Example, Hawaii, Florida. According to Köppen climate classification, the whole of southern Florida is under tropical biome. The study site, Moore Haven Lock is located in south Florida. The island of Kauai is one of the oldest of the main Hawaiian Islands and it is a deeply eroded extinct volcano Mt. Waialeale. Lihue is located in the south eastern corner of Kauai Island. Lihue falls on the windward side of the island and receives an annual rainfall of approximately 100 cm. However, the slopes of Mt. Waialeale receive much more rainfall than Lihue. Lihue has tropical savanna climate with dry winters. Both the sites in Florida and Hawaii show similar trends in metrological factors - precipitation is decreasing while pan evaporation and mean annual temperature are increasing.
6. **Semi-arid** – Example, **New Mexico, Arizona, Texas**. Semi-arid regions receive low annual precipitation. The study shows that in the last 60-100 years these sites in semi-arid regions indicate an overall increasing trend in mean annual temperature and precipitation while a decreasing trend in pan evaporation. However, precipitation has been decreasing in the last 20 years.

This study focuses on the effects of climate change on hydrological budget on a regional level. The results may represent the trends in the entire biome that the site represents. Planning can play a crucial role in dealing with these inevitable effects of climate change. Based on the results summarized, the planning implications are discussed:

**Climate change impacts on city planning**

A key challenge in planning for climate change is the lack of collaboration between urban planning practices and scientific knowledge about the effect of climate change on city and regional planning. There is a gap between the two that needs to be bridged in order to make progress towards adaptation to climate change in urban areas. The need for research such as in this study to inform planning is pressing. There are many cities that have been historically built in low-lying areas which are prone to climate change induced rising sea-level, floods, and hurricanes, for example. One big challenge is how to make these cities adapt to such consequences of climate change. There is a dearth of planning research available on this issue (Pizarro et al., 2006).

Mitigation approach deals with curtailing the GHG emissions in order to prevent climate change while adaptation policies aim at dealing with the effects of climate change and
adapting in the best possible way (Pielke, 1998). Based on the findings of this study, where the change in metrological parameters over the last century is clearly evident, it can be concluded that adaptation responses must occupy a larger role in climate policy. There is also a need for regional policies based on the effect of climate change in that particular climatic biome in order to prioritize the most urgent adaptation policies on a local level and estimate the essential human and financial resources necessary. This will help cities to adapt rather than react when the problems arise (Mukheibir and Ziervogel, 2007).

This study shows that temperatures are increasing in continental subarctic, hot summer continental temperate, tropical and semi-arid climates. According to Pizzaro et al. (2006), in many parts of the world most homes are built for coping with mild climate, and are unable to cope with the rising heat in summer. As a result, most cities across the world are facing energy shortage. Pizzaro et al. (2006) suggest that urban systems should be designed so that they can withstand future severe conditions imposed by climate change. Planners should develop long term projected climate change scenarios to design future settlements.

Land use changes take place because of urbanization and development of rural areas. Open land and vegetation get replaced by buildings, roads and other urban infrastructure. This leads to an increase in impervious surfaces. These changes result in air temperatures being several degrees warmer in cities than the suburbs around and hence formation of “urban heat island” (EPA, 2012). Urban heat island has adverse effects on human health, hydrological cycle, and biodiversity and energy consumption. Urban green infrastructure,
on the other hand, can be useful in adapting to climate change by regulating temperature, and absorbing runoff water. “Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments” (EPA, 2012). The effects of climate change in urban areas, as discussed in this study, will not be felt by just the human population but also by the infrastructure. And thus, urban green infrastructure can be useful in addressing some of the effects of climate change such as reduction of water runoff and lowering the surrounding temperature by evaporative cooling and shading. The maximum surface temperature varies with the proportion of green cover. More highly built up areas have higher temperatures than well vegetated ones. Adding 10% green cover to highly built up areas lowers the temperature significantly (Gill et al., 2007), by the cooling effect of evapo-transpiration. Hence, vegetation cover is an important tool in reducing temperatures, and providing ancillary benefits (e.g., C sequestration).

Maintaining the vegetation cover may require irrigation in some cases, which can exacerbate the water demand. The study shows that precipitation has been decreasing in continental subarctic and tropical areas, and also in semi-arid climates in the recent years. In this context, trees are more useful in cooling the surroundings than grasses during event of a drought because of the shading effect. Water retention can be increased by using green roofs on buildings and by increasing pervious surfaces by increasing the soil organic matter (SOM) content, which can also improve the quality of water (Lorenz and Lal, 2012). Gill et al. (2007) observed that adding 10% green cover will reduce the
surface runoff by as much as 14%. If droughts become more frequent, effective water restrictions may be imposed through regulation and pricing (Rosenzweig et al., 2007). This study shows that precipitation has been increasing in humid continental, hot summer continental temperate, and humid subtropical climates. Also, the frequency of extreme events has increased. Drainage systems can adapt to excessive precipitation by reducing the rate of storm water input, increasing depression storage, and by disconnecting impervious surfaces (Waters et al., 2003). Planners can also utilize rainfall intensity duration frequency (IDF) curves to design drainage structures in such areas (Rosenzweig et al., 2007). To prevent droughts and inundation, urban development should be avoided in ground water protection areas, flood prone areas and high inundation areas (Leeuwen and Koomen, 2012).

High density development is crucial to mitigation strategies by reducing the car travel and preserving energy consumed by buildings (hence low GHGs emission). On the other hand, adaptation policies advocate high ceiling buildings with a lot of ventilation between the neighboring buildings in order to cope with rising temperatures. However, wide-spaced buildings reduce the density (Hamin and Gurran, 2009). Thus, planners need to assess the pros and cons of both situations and develop strategies to satisfy both goals with least compromises and multiple benefits. Buildings with moderate density and low transit C emissions maximize the natural cooling potential. Open spaces required for storm water management and species migration, need to be carefully planned so that its benefits are fully exploited and the resulting reduction in density is minimized (Hamin and Gurran, 2009). Development of a sustainable green landscape requires reduction of
hidden C costs; use of natural resources within urban ecosystems judiciously; increase of effective rooting depth of plants and grasses grown in urban agriculture, and elimination the risk of contamination by heavy metals, such as lead (Lal, 2012).

Climate Change Action Plans

Sites for this study were selected in 10 different states. As discussed above, it is important to take measures to prepare for the impacts of inevitable climate change. There are some state governments which have taken the initiatives for the same. Table 1 shows which of these states have a climate change action plan already in place.

Table 11: State Climate Change Action Plan

<table>
<thead>
<tr>
<th>State</th>
<th>Climate Change Action Plan</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Alaska</td>
<td>Yes</td>
<td>2009</td>
</tr>
<tr>
<td>2. Minnesota</td>
<td>Yes</td>
<td>2008</td>
</tr>
<tr>
<td>3. Ohio</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>4. Tennessee</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>5. Arizona</td>
<td>Yes</td>
<td>2006</td>
</tr>
<tr>
<td>6. New Mexico</td>
<td>Yes</td>
<td>2006</td>
</tr>
<tr>
<td>7. Texas</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>8. Alabama</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>10. Hawaii</td>
<td>No</td>
<td>-</td>
</tr>
</tbody>
</table>
Alaska – In August 2009, 32 policy recommendations were published by the Alaska Climate Change Strategy’s Mitigation Advisory Group in order to reduce GHG emissions (EPA, 2012). The highlights were as follow:

- Update the state’s knowledge base about the actual and anticipated effects of climatic warming in the foreseeable future.
- Prepare the communities in Alaska to deal with the anticipated impacts of climate change by formulating a set of applicable measures and policies.
- Direct Alaska’s participation in efforts to address the causes and effects of climate change on a regional and national level.

The Adaptation technical work groups focus their efforts on determining ways to address present and future impacts of climate change on:

1. public infrastructure,
2. health and culture,
3. natural systems, and
4. economic activities.

The Mitigation technical work groups have been assembled in diverse greenhouse gas mitigation action categories including the following -

1. oil and gas,
2. energy supply and demand,
3. transportation and land use,
4. forestry, agriculture, waste, and

5. cross-cutting issues.

Thawing permafrost is associated with well documented and often dramatic effects which include the effect on the foundations of buildings and on roads. (Larsen et al. 2008). The thawing of frozen ground tends to destabilize buildings, roads, bridges, pipelines and other structures resulting in substantial infrastructure maintenance costs. The contamination risk is elevated in the case of waste water lagoons. Surrounding areas can be severely contaminated, if the impermeable barrier for a sewage lagoon is breached. Erratic freeze and thaw cycles cause the soil in the previously frozen ground to shift. The soil shifts stress structures resulting in increased failure rates and a consequent increase in operating and maintenance costs. Transportation infrastructure and underground pipelines are highly susceptible to disruption by thawing ground. Building infrastructure and architectural techniques should incorporate new techniques to mitigate the effect of global warming on structures (EPA, 2012).

Public infrastructure has only a limited capacity to adapt. The rigid and fixed nature of most public infrastructure (roads, runways, bridges, buildings) leave little (if any) room to alter parameters such as alignment, elevation or structural foundation to better withstand coastal erosion or floods. In the rare situations when modifications to adapt the structure are technically feasible, the cost is usually prohibitive. Updated design and construction techniques enhance the adaptive capacity of new infrastructure to withstand climatic change (EPA, 2012).
Wide scale construction of new infrastructure better adapted to withstand climate change requires a multi-pronged, coordinated approach; site selection, planning, design and building techniques are all critical elements that need to be evaluated in parallel. Building codes and standards need to be updated to accurately reflect the required enhancements. Systematic feedback and performance reviews based on carefully selected metrics need to be integrated into the key elements of public infrastructure – funding, development, construction and operations (EPA, 2012).

The study shows that the MAT and the annual precipitation are increasing in the Alaska site while the pan evaporation is decreasing. The climate change action plan for the state does focus on the adaptation strategies resulting in thawing permafrost due to increasing temperature.

**Minnesota** – The Minnesota Climate Change Advisory Group’s final report was issued in April 2008, and it includes recommendations to the governor for reducing the state’s GHG emissions (EPA, 2012). Some recommended measures are briefly outlined below:

State building codes were amended to specify minimum energy efficiency standards for new developments and for existing buildings under renovation. These amendments will yield long term GHG emissions reductions, given the long life of modern buildings. Building energy codes specify minimum energy efficiency requirements for new buildings or for existing buildings undergoing a renovation. Given the long lifetime of most buildings, amending state building codes will include minimum energy efficiency requirements and periodically update energy efficiency codes to cause long-term GHG
emission reductions. As a result of the high energy efficiency requirements required by code since 2000, Minnesota leads the nation in producing energy-efficient one- and two-family homes. Although the new residential code will not significantly increase the efficiency of one- and two-family residential buildings, its applicability will be broadened to include townhouses and, by doing so, will increase their energy efficiency (EPA, 2012).

Approximately 85% of Minnesota’s population lives in an area where the Minnesota State Building Code (including the energy code) has been adopted and enforced. Of Minnesota’s 87 counties, 39 have adopted the Minnesota State Building Code. While the Minnesota State Building Code is not enforced statewide, homebuilders who are licensed by the state are required to build code-compliant homes, regardless of location (EPA, 2012).

The study shows that precipitation is increasing significantly in the Minnesota site, while MAT and PE have been decreasing. It is recommended that city and urban planners should include ways to store the excessive rainwater which may be used for other purposes throughout the year (such as toilet flushing).

Arizona – In August, 2006, 49 policy recommendations to address and reduce GHG emissions were made in the Governor’s Climate Change Advisory Group’s action plan. The governor is advised to develop a state climate change adaption strategy in conjunction with steps undertaken to reduce GHG emissions in Arizona. The strategy should identify and outline a response to the potential impacts of climate change on the
state (EPA, 2012). Arizona should adopt and strive to achieve the following GHG reduction targets statewide:

- Lower GHG emissions to 2000 levels by 2020, and
- Lower GHG emissions to 50% below 2000 GHG levels by 2040.

Housing and commercial developments should be moved to location efficient sites such as brown fields and infill parcels, in an attempt to minimize commuting and consequently GHG emissions. Shifting residential and commercial developments from location inefficient sites (such as greenfields) to location efficient sites can drastically reduce overall travel and the per capita C footprint. Brownfields (abandoned or underutilized commercial or industrial properties) offer significant potential for redevelopment. The full utilization of brown fields is impeded by the uncertainties, risks (environmental liability) and high costs (investigation and clean up). A wide range of properties comprise brownfields – former industrial developments, abandoned gas stations, vacant warehouses and former dry cleaning facilities. In addition to the environmental benefits (GHG reduction), brown field redevelopment has a positive economic and social impact on local communities and government. Brownfield redevelopment tends to boost local communities by creating jobs, and revitalizing neighborhoods. Revitalization of neighborhoods via brownfield redevelopment creates jobs, increases revenues (property and sales tax), contains urban sprawl and reduces potential health risks (EPA, 2012).

*Transit-oriented development:* Strategically locating residential and commercial developments close to public transit encourages the use of lower emitting modes of
transport (walking, biking). Mixed use developments play an important role since they enable consumers to meet daily needs around transit stops and reduce use of personal vehicles.

* **Smart growth:** The state should promote planning, modeling and regulatory tools conducive to location efficient growth. Smart growth permits multiple transport options accessible by pedestrians and bikers and mixed (range of housing options) land use. The state funded investments should be focused on smart growth communities with a view to encouraging smart growth over growth in areas that require more extensive daily commutes and have fewer transportation options/modes.

* **Targeted open space protection:** Conservation and protection of State lands and other open spaces is vital. The state should undertake measures to conserve open spaces and to develop and improve local (neighborhood, community, regional) parks in order to promote location efficient growth (EPA, 2012).

**New Mexico** - The Climate Change Advisory Group finished its final report on December 1, 2006. The report includes a GHG inventory and 69 policy recommendations. The target is to reduce New Mexico's emissions to 2000 levels by 2012, 10% below 2000 levels by 2020, and 75% below 2000 levels by 2050. New Mexico also recommends Building Code policies similar to the ones in Minnesota (EPA, 2012). The study shows that both Arizona and New Mexico sites show an increase in MAT and annual precipitation, whereas PE shows a decrease over the years. Adaptation strategies to adapt to the rising temperatures are essential.
Florida – Florida is especially vulnerable to the rise in sea level and extreme weather because of its low lying topography and sub-tropical geographical location. On October 17, 2008, Florida Governor’s Action Team on Energy and Climate Change published a report recommending that Florida should join a regional cap-and-trade system. The policy recommendations aim to acquire 20% of the state electricity from renewable sources by 2020, and hence reduce power usage by encouraging energy efficiency. The report estimates that the reforms would reduce GHG emissions by 34% by 2025 and save $28 billion from 2009 to 2025 (EPA, 2012). The study shows that annual precipitation has been decreasing while PE and MAT have been increasing in the southern Florida site over the last century. Adaptation strategies should focus on how to make the infrastructure adapt to the rising temperature and how to minimize the loss of water through evaporation.

The climate change action plans undertaken by the governments focus primarily on mitigation and not so much on adaptation. There is an acute need for a two pronged approach: mitigation and adaptation strategies need to be pursued in parallel. While mitigation strategies are vital to reduce GHG emissions, the importance of adaptation strategies cannot be undermined. In order to be effective, adaption plans need to be carefully formulated in accordance with the impact of climate change on a particular area/region. The pro-active role of local governments and authorities is vital in formulating policies that are most effective in adapting to climate change. The strategies have to be customized based on the data analysis and trends of different metrological factors pertaining to the region.
Protection adopted a holistic long term strategy while planning the city water supply, sewer, wastewater treatment and other urban infrastructure (Rosenzweig et al., 2007). Other urban areas can benefit greatly by following a similar adaptation strategy. There is a need for more local studies similar to this to determine the regional footprints of climate change on the hydrological budget. The findings can be used as an effective tool to develop efficient adaptation strategies. Additional studies focusing on changes in runoff, percolation and actual evapo-transpiration can provide useful information to local planners.
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