A Study of Climate Change and Its Impacts on Food Security in the Continental United States

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Abstract

Global climate changes and climate variability are impacting agriculture and food security. The increasing frequency and magnitude of extreme weather events including drought, flood, heat and cold waves, pose potentially disastrous consequences for agriculture and food security. In this research report, three major efforts are focused on: 1) to integrate climate and agricultural data of the continental United States for study of climate change and its impacts on food security; 2) to analyze climate change of the continental USA using ground observations from thousands of weather stations over the past 100 years; and, 3) to study the impacts of climate extremes events on food security, using the US Corn Belt region for a case study. The agro-climate database was established based over 100 year daily climate data from NOAA/NCDC and over 100 year country-level yield data of 14 major crop types from USDA/NASS; the temporal trend and spatial patterns of climate change and variability were investigated based on the daily precipitation, maximum temperature (TMAX) and minimum temperature (TMIN) and diurnal temperature range (DTR) of the continental United States over the past one hundred years. As a case study of climate change and variation impacting food security, an integration of county-level yield data from the NASS Quick Stats database and precipitation data from the NCDC GHCN-Daily database for over 400 counties was done in the United States Corn Belt based NASA MODIS satellite remote sensing Vegetation Health Index (VHI) measurements for studying corn yields in non-drought year of 2002 and the drought year of 2012. The temporal trend and spatial patterns of climate change and variability pose potentially disastrous consequences for agriculture and food security. This approach for integrated analysis of massive data sets from various sources discovered the quantitative linkage between climate extreme events and crop yield, which is critical accurate assessment of climate impacts on food security. These approaches not only can be used for global climate change and its impacts assessment on food security and but also can be used to establish the foundation for early warming system for global food security.

Keywords: Climate Change, Food Security, Agriculture, Drought, Drought, Temperature, Precipitation, Corn Belt, Remote Sensing, Impact Assessment, and Agro-climate Database

1. Introduction

Climate change involves complex interactions and changing likelihoods of diverse impacts (IPCC, 2014). In recent decades, changes and variations in climate impacting global agriculture sustainability and food security has been an important concern for our Earth family. Based on my summer internship in the Global Environment and Natural Resources Institute (GENRI), George Mason University, I was luck having the opportunity for working on analysis of climate change and assessment of climate impacts on agriculture under the supervision by my research mentor.

1.1 Climate Change of the United States

Temperature and precipitation are essential elements for climate change study. Daily mean temperature is generally used as a universal measurement for climate change study. However, mean temperature alone is not enough to reflect the complicated variations of climate. In fact, trends in mean surface temperature are often due to changes in daily maximum and minimum temperatures (Sun et al., 2006). So, daily maximum and minimum temperatures, as well as diurnal temperature range (DTR) are also important indicators for climate change (Karl et al., 2004; Karl et al., 2004). DTR has steadily decreased throughout the United States (Karl et al., 1991), which can be attributed to the increase in mean daily temperature and a steady daily maximum temperature (Karl et al. 1991). Karl et al. studied cloudy and clear sky conditions and their impacts on diurnal temperature range (Karl et al., 1987). They found a significant decrease in diurnal temperature range over time during cloudy days. Many other additional factors that affect in diurnal temperature range including land use/ land cover changes (Gallo et al., 1996), irrigation (Karl et al., 1988), station moves, desertification, and other climatic effects (Karl et al., 1993). Urbanization, also, has been extensively investigated in many papers (Karl et al., 1988; Landsberg, 1981; Wang et al., 2012). It was found that as the population of an urban center increases, the diurnal temperature range would shift in an asymmetrical manner (Karl et al., 1991). Despite these confounding variables, many studies have been conducted on diurnal temperature range study. A variety of data and methods have been used. Most studies utilized station observations and analyzed the trends of diurnal temperature range on global level (Karl et al., 2004; Easterling et al., 1997; Leathers et al., 1998). Karl et al. studied the decreasing diurnal temperature range in the United States and Canada (Karl et al., 1991). Sun et al. used satellites measurements to evaluate the diurnal temperature range (Sun et al., 2006). Park and Joh used climate models to predict diurnal temperature range changes (Park and Joh, 2005). These studies have analyzed the diurnal temperature range in the United States, but many of these studies used limited number of station observations, or covered limited historical period, it is necessary to analyze climate data of the United States with more weather stations and longer temporal period.

In this study, climate change and variation over the continental United States since 1911 through spatial and temporal analysis of observations from thousands of stations over the continental United States. The United States was separated into 4 regions where the trends of each region were analyzed as well as the United States as a whole. The four regions were analyzed through their four seasons as well as their yearly averages. DTR, as well as daily maximum temperature (TMAX) and minimum temperature (TMIN) are not only analyzed for region to region differences, but also, season to season differences.

1.2 Impacts of Climate Change on Food Security

As rapid population growth and climate change present far-reaching threats to food security, it has become vital to understanding the impact of extreme weather events on agricultural productivity. Climate models predict drastic changes in water availability due to the combination of precipitation and temperature changes. Although localized effects may be difficult to predict, the overall severity and extent of drought is projected to increase. These extreme weather events are likely to cause major crop losses, which will have drastic political, economic, and humanitarian consequences (Jones et al. 1986; Taylor et al., 2013). Assessing and responding to these crises require a deep understanding of how drought impacts agricultural yield (Rosenzweig et al. 2001]. Currently, corn is the major food crop in much of sub-Saharan Africa, Southeast Asia, and Latin America, while in the United States it is the major cash crop for the Midwestern Corn Belt and is essential to the production of fuel and livestock (Nuss et al. 2010). While plant breeding and genetic engineering have been used to improve the drought-tolerance of corn, drought during critical development periods still has serious consequences (Cattivelli et al. 2008). This vulnerability was demonstrated as recently as 2012, when severe summer drought over much of the United States Midwest crippled corn yields and drove prices to record highs (Mallya et al. 2013). Many studies have been conducted to quantify the effect of drought on corn yields. By controlling watering regimes to simulate drought and comparing the characteristics of different corn varieties, experiments have profiled the effect of water stress throughout corn growth and development. These studies indicate that adequate moisture is crucial during the silking stage, when water stress can delay development of silks (which receive pollen for fertilization) and prevent kernel formation (Claassen et al. 1970; Grant et al. 1989; Bolanos et al. 1996). Water stress after this stage, when plants direct resources towards kernel development, can also severely reduce yield (Claassen et al. 1970; Grant et al. 1989).

Estimating corn yields using real agricultural data also offers important insights. Existing methods include sophisticated models which account for factors including plant physiology, soil characteristics, and even economic factors (Jones et al. 1986; Kaufmann et al. 1997). While these approaches give excellent results for small regions where parameters such as soil type, variety, or planting date are known, the large number of parameters limits their applicability when detailed data are not available. Other approaches have used climate data and historical yield to fit a model, but this has generally been limited to individual pilot fields, a few counties, or state-level average data (Meyer et al. 1993; Nielsen et al. 2010; Prasad et al. 2006).

This study addressed these issues by integrating historical precipitation data from the National Climatic Data Center's GHCN-Daily (Global Historical Climatology Network) database (Menne et al. 2012) and yield data from the National Agricultural Statistics Service (NASS) (NASS, Quick Stats 2.0. http://www.nass.usda.gov/Quick_Stats/) at the county level in order to access and quantify the impact of precipitation on corn yield over a large area of United States Corn Belt during two different years. Thus, this study provides a broadly-applicable view of the impacts of drought for the diverse soil, climate, and cultivation conditions over the study area.

1.3 The US Corn Belt

In the United States, corn it is the major cash crop for the Corn Belt and is essential to the production of fuel and livestock (Nuss et al. 2010). The Corn Belt includes Iowa, Illinois, Indiana, and parts of Michigan, Ohio, Nebraska, Minnesota and Missouri (Hart, 1986). Although a large percentage of corn in the Corn Belt grows for export outside the region, corn is also produced for raising livestock, another basic farm enterprise in the Corn Belt. Figure 1 is the map of major corn producing areas from the USDA World Agricultural Outlook Board (WAOB), based on averaged county-level corn production data from year 2006 to 2010 (http://www.usda.gov/oce/weather/pubs/Other/MWCACP/Graphs/USA/US_Corn.pdf). In this study, five major corn-producing states in the US Corn Belt were chosen for this study: Iowa, Illinois, Indiana, Ohio, and Minnesota, containing a total of 434 counties. Eastern Nebraska is also a major corn producer, but much of its corn crop is irrigated using readily available water from the Ogallala Aquifer (Dennehy et al. 2002). Thus, data from Nebraska was excluded to reduce confounding factor of irrigation. Meanwhile, counties in the five selected states all have low irrigation rates, and thus it is appropriate to compare their responses to climate extreme events.

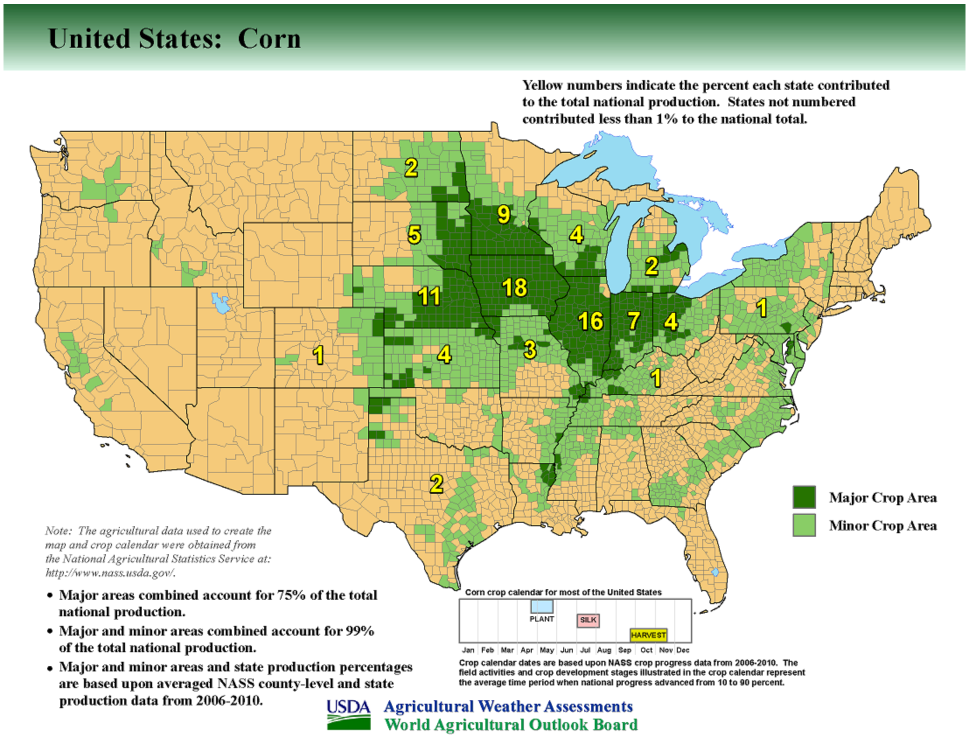

Figure 1. Major corn areas of the continental United States (from http://www.usda.gov/oce/weather/pubs/Other/MWCACP/Graphs/USA/US_Corn.pdf).

1.4 Objectives

This study addressed the analysis of climate change and extreme events with historical data records, and assessment of climate impacts on crop yield through case study in US Corn Belt. There are three objectives for this project.

1) To integrate climate and agricultural data of the continental USA and establish a database for study of climate change and its impacts on food security;
2) To analyze climate change of the continental USA using ground observations from thousands of weather stations over the past 100 years;
3) To study the impacts of climate extremes events on food security, using the US Corn Belt region for a case study.

2. Data and Methods

2.1 Data Sets

2.1.1 The NOAA NCDC's GHCN (Global Historical Climatology Network)-Daily Data

The Global Historical Climatology Network Daily contains records from over 75,000 stations around the world. Maximum and minimum air temperature, snowfall, snow depth, and daily precipitation are primary variables provided by these stations (Menne et al., 2012). The data is comprised of daily climate records from numerous sources that have been integrated to a plethora of quality assurance reviews (Menne et al., 2012). The Global Historical Climatology Network Daily contains the most complete collection of United States daily climate summaries available, even provides some of the earliest observations available for the United States.

For this project, over 20 Giga-bytes of GHCN-Daily data were downloaded from NOAA NCDC's website http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/.

2.1.2 The USDA's National Agricultural Statistics Service (NASS) Agricultural Data

County-level yield data for the region was obtained from the NASS Quick Stats 2.0 database [15, http://www.nass.usda.gov/Data_and_Statistics/index.asp], using records from annual NASS surveys. NASS provides comprehensive data sets and statistics of crop planting area, yield, production, etc. at county and state levels. For this project, field crop data of the continental USA since 1940 were downloaded from NASS.

2.1.3 The NASA EOS's MODIS Remote Sensing Measurements

MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the NASA's Terra and Aqua satellites (http://modis.gsfc.nasa.gov/about/). Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days at nominal spatial resolutions of 250m (band 1-2), 500m (band 3-7) and 1km (band 8-36) at nadir. Many data products derived from MODIS measurements describe features of the land that can be used for studies of crop status at various scales. For this project, Terra MODIS surface reflectance and MODIS land surface temperature datasets from year 2000 to 2012 were obtained from NASA Distributed Active Archive Centers (DAAC) to produce Vegetation Health Index (VHI) using GENRI's remote sensing data processing tools.

2.1.4 U.S. Drought Monitor (USDM) Data

The U.S. Drought Monitor, established in 1999, is a weekly map of drought conditions that is produced jointly by the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln (http://droughtmonitor.unl.edu/Home.aspx). USDM incorporates information from multiple sources to monitor drought development and severity. In this study, USDM data for year 2012 were collected for case study.

2.2 Data Processing and Analysis Methods

2.2.1 Spatial and temporal processing of climate data

Daily DTR data was obtained by subtracting daily minimum temperature from daily maximum temperature at each station. Then, spatial and temporal averages of daily minimum temperature, maximum temperature, DTR, and precipitation were conducted get regional, annual and seasonal mean. To investigate spatial variations, regions were separated with longitude and latitude. The northern and southern regions were separated at 40° latitude, and the eastern and western portions were separated at the -100° longitude. The four regions are North West Region (NWR), North East Region (NER), South West Region (SWR), and South East Region (SER). Regional mean maximum temperature, regional mean minimum temperature, regional mean DTR, and regional precipitation are the average of corresponding daily observations at stations within the specified spatial area, i.e.

$$TMAX_{region} = \frac{1}{N}\sum_{j} TMAX_j$$

$$TMIN_{region} = \frac{1}{N}\sum_{j} TMIN_j$$

$$DTR_{region} = \tfrac{1}{N}\textstyle\sum_j DTR_j \ ,$$

$$PRCP_{region} = \frac{1}{N}\sum_j PRCP_j \ ,$$

where N is the number of stations over the specified region, $TMAX_j$, $TMIN_j$, DTR_j, and $PRCP_j$ are daily maximum temperature, minimum temperature, DTR, and precipitation for the No. j station of the study region, respectively. Monthly mean was calculated by averaging these data for each month. Annual mean was obtained through yearly average of monthly data. And similarly, seasonal mean was obtained by averaging data over specified season.

2.2.2 Integrated database and online visualization

In order to investigate the impacts of climate on food security, it is essential to obtain both climate data and crop data at consistent spatial and temporal scales. In this study, climate data from discrete weather stations were averaged to county level as described in the section 2.2.1, at the same scale as crop data from NASS. All these county level data were stored into a MySQL database on GENRI server to facilitate the search and retrieval of climate and crop data for counties. A simple web interface was developed using PHP script language and MySQL database for quick view of time series of climate data, the URL is: http://wamis.gmu.edu/agroclim/ .

2.2.3 Trend analysis of climate data and crop data

Matlab statistics toolbox was used to identify the trends of monthly, seasonal, and annual trends of mean maximum temperature, minimum temperature, diurnal temperature range. For crop yield data, Matlab statistics toolbox was also used to analyze the trend of crop yield from 1940s.

2.2.4 Generation of Vegetation Health Index (VHI) from MODIS data

Vegetation Health Index (VHI) (Kogan, 1995) is an efficient index to estimate vegetation water stress from space. VHI can be derived from Normalized Difference Vegetation Index (NDVI) and surface temperature. In this study, Matlab tools developed by GENRI were used to produce NDVI from MODIS surface reflectance data products first, then generate VHI by combining MODIS surface temperature data and NDVI. Maps of VHI can illustrate the status of crops, and demonstrate the impacts of climate extreme events on crop visually.

2.2.5 Regression analysis of climate data and corn yield

To assess the impacts of climate extremes on food security, the 2012 drought over Corn Belt was investigated for case study by integrating climate data and crop information.

Corn yields varied locally throughout the study region, likely due to factors such as cultivation practice (planting conditions, fertilizer usage, etc.) and local geographic variation (soil type, climate, etc.). In order to reduce the confounding effect of these variables, the yield anomaly was used as the response variable. The expected yield was calculated by fitting a least-square linear regression line to yield time series data from 1960 to the year preceding the target year (1960 – 2011). For this time period, increases in yield seemed to follow a linear pattern, justifying the use of this method to calculate expected yield. The yield anomaly was calculated as the percent difference between the projected and observed values.

Total precipitation was calculated for each 8-week interval within the two study years. When measurements were missing, the mean of available precipitation data multiplied by the period length was used if more than half of the values were available; otherwise the county was excluded.

Regression analysis was used to fit observed yield anomaly to average precipitation, but examination of the data revealed that the relationship between precipitation and yield, while monotonically increasing, was non-linear. Transforming precipitation by taking its base-10 logarithm produced linear relationship between the predictor and response variables (as evident in Figure 4), with no clear pattern in the residuals and relatively constant variance around the trend line. Thus, it is appropriate to apply methods that assume a linear relationship with a normally distributed, homoscedastic error term to the data.

3. Results and Analysis

3.1 Integrated Database

AgroClim database is an integrated database of climate data for agricultural study at county level in the United States. The database is based on observations of US climatology network. Currently, the database contains daily precipitation, daily maximum temperature, and daily minimum temperature at county-level, as well as yearly crop information (planting area, yield, production, etc.). In this project, a simple web interface was developed using PHP script language and MySQL database for quick view of time series of climate data from http://wamis.gmu.edu/agroclim/. Figure 2 shows an example of online visualization from the website, illustrating the time series of daily maximum temperature of the Blackford county, Indiana, from 2003 to 2012.

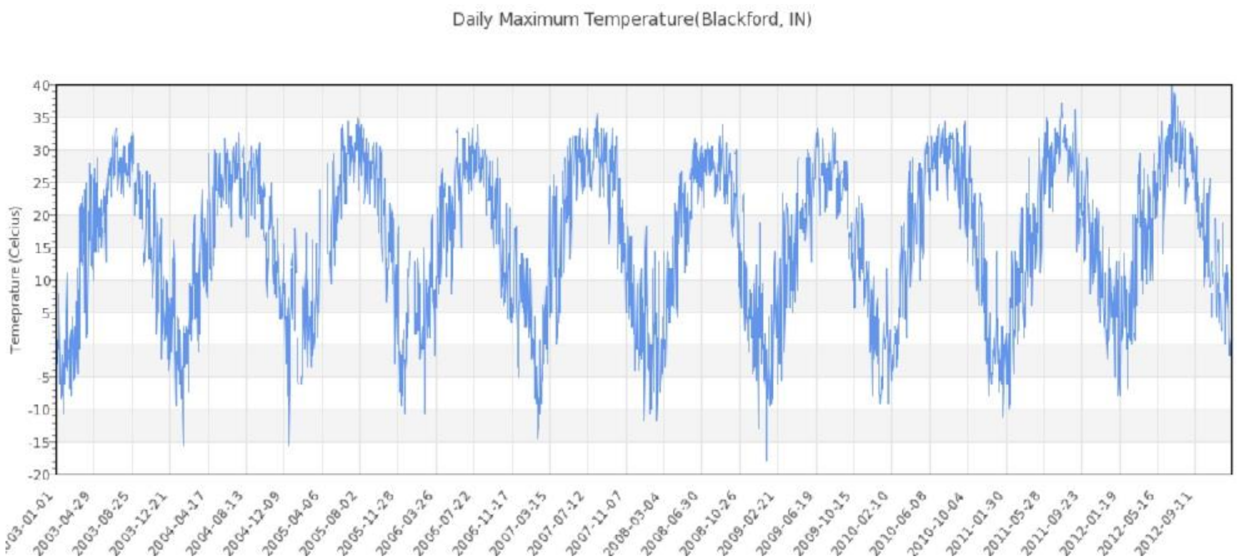

Figure 2. Example of web-based visualization of climate data at county level.

3.2 Climate Change of the Continental USA

In this study, significant trends of maximum temperature, and minimum temperature, diurnal air temperature range, of the continental USA from year 1911 to 2012 were found, and the spatial and seasonal variations of temperature change were analyzed. These results were already published on a peer-reviewed journal (Qu et al. 2014).

3.2.1 Annual temperature change of the continental USA

Fig. 3 illustrates the yearly average diurnal air temperature range, maximum air temperature, and minimum air temperature of the continental USA from year 1911 to 2012. The annual mean maximum air temperature has a slightly increasing trend at 0.002848 ˚C /year, but the annual mean minimum air temperature is rising at a much faster rate, 0.007506 ˚C /year. And, a steadily decreasing trend of DTR can be identified statistically, with a slope of -0.004658˚C /year. The significantly increasing trend of mean minimum temperature contributes to the decrease of mean DTR. Especially, during recent decades, the decreasing trend is more significant. Since 1991, the yearly mean DTR are usually below 13.5˚C.

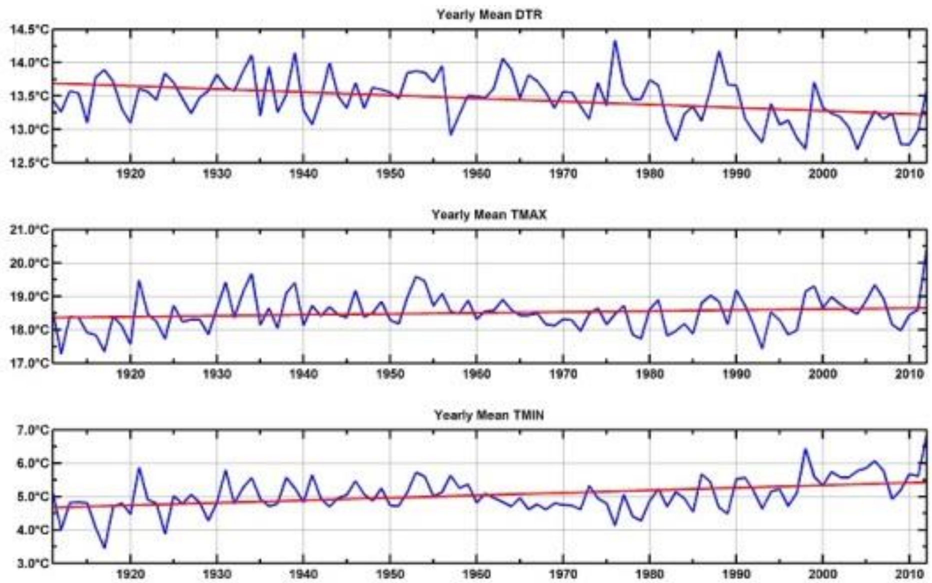

Figure 3. Yearly average diurnal air temperature range (DTR), maximum air temperature, and minimum temperature of the continental USA.

3.2.2 Seasonal temperature change of the continental USA

Trends of seasonal DTR, TMAX and TMIN were summarized in table 1. Obviously, TMAX and TMIN have different seasonal behaviors, and DTR change demonstrates clear seasonal patterns. DTR has decreasing trend in all the 4 seasons, with the highest decrease rate in summer, and the lowest decrease rate in winter. In summer, TMAX has a slightly decreasing trend, but TMIN shows the highest increasing rate among the 4 seasons, so DTR demonstrates the most significantly decreasing trend, at the rate of -0.010594 ˚C /year. In winter, both TMAX and TMIN demonstrate significantly increasing trend, however, the rates are close, so DTR shows relatively stable change comparing to other seasons.

Table 1. Trends of seasonal average daily maximum temperature (TMAX), minimum temperature (TMIN), and diurnal air temperature range (DTR) (unit: ˚C /year) of the continental USA.

Variable\Season	Spring	Summer	Fall	Winter
TMAX	0.007170	-0.000701	-0.000761	0.007740
TMIN	0.009669	0.009893	0.004355	0.008576
DTR	-0.002499	-0.010594	-0.005116	-0.000837

3.2.3 Regional temperature change of the continental USA

Climate elements, especially temperature and precipitation, usually vary both spatially and temporally. Table 2 shows the TMAX, TMIN, and DTR trends of the 4 regions mentioned above. All the four regions show increasing trend of yearly average minimum air temperature, especially the Northwest region, where the yearly average minimum temperature has a trend at 0.005847 ˚C/year. But time series of yearly average maximum temperature shows remarkable differences in trend between eastern and western regions, the Southwest and Northwest regions demonstrate increasing trend, while the Southeast and Northeast show decreasing trend. Obviously, regional DTR differences are quite significant. The western regions usually have much higher DTR than the eastern regions. All the four regions show decreasing trend of DTR over the past 100 years. The Southwest region has most rapid DTR decreasing rate at -0.007462˚C/year, while the Southeast region has the slowest DTR decreasing rate at -0.004661˚C/year.

Table 2. Trends of yearly average daily maximum air temperature (TMAX), minimum air temperature (TMIN), and diurnal air temperature range (DTR) (unit: ˚C /year) of the four regions.

Variable\Region	Northeast	Northwest	Southeast	Southwest
TMAX	-0.005425	0.001080	-0.001874	0.006946
TMIN	0.001503	0.005847	0.002787	0.014408
DTR	-0.006928	-0.004767	-0.004661	-0.007462

3.3 Climate Change and Extreme Events of the US Corn Belt

As demonstrated in previous sections, the climate is changing with significant trends. And, along with the trends, fluctuations associated with extreme climate and weather events are also need to be identified and investigated. For case study, 5 major corn production states in US Corn Belt were investigated. Figure 4, 5, and 6 shows the anomalies of Iowa, Illinois, Indiana, Minnesota and Ohio. During the corn silking period in 2012, extreme high temperature and low precipitation occurred in most of the areas, except for Minnesota.

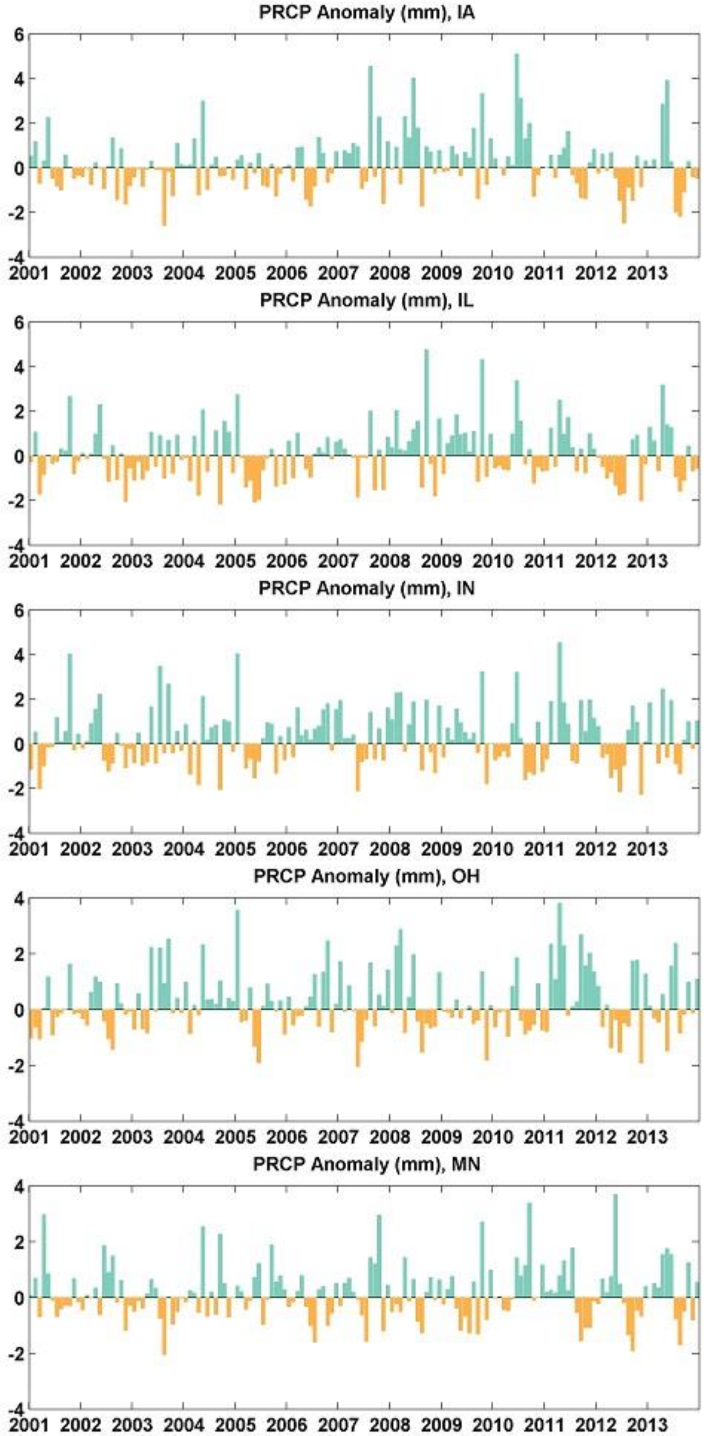

Figure 4. Precipitation anomalies of the selected 5 states from year 2001 to 2013.

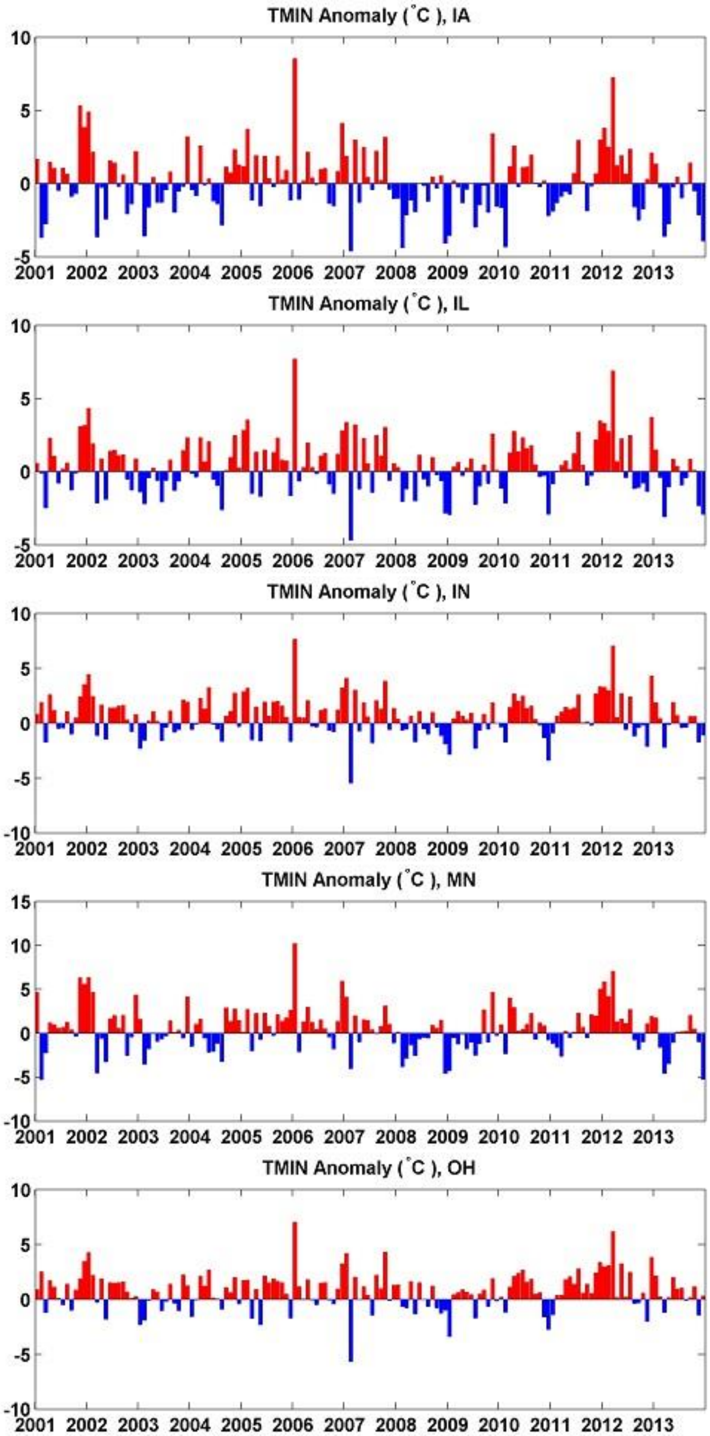

Figure 5. Anomalies of mean minimum temperature of the selected 5 states from year 2001 to 2013.

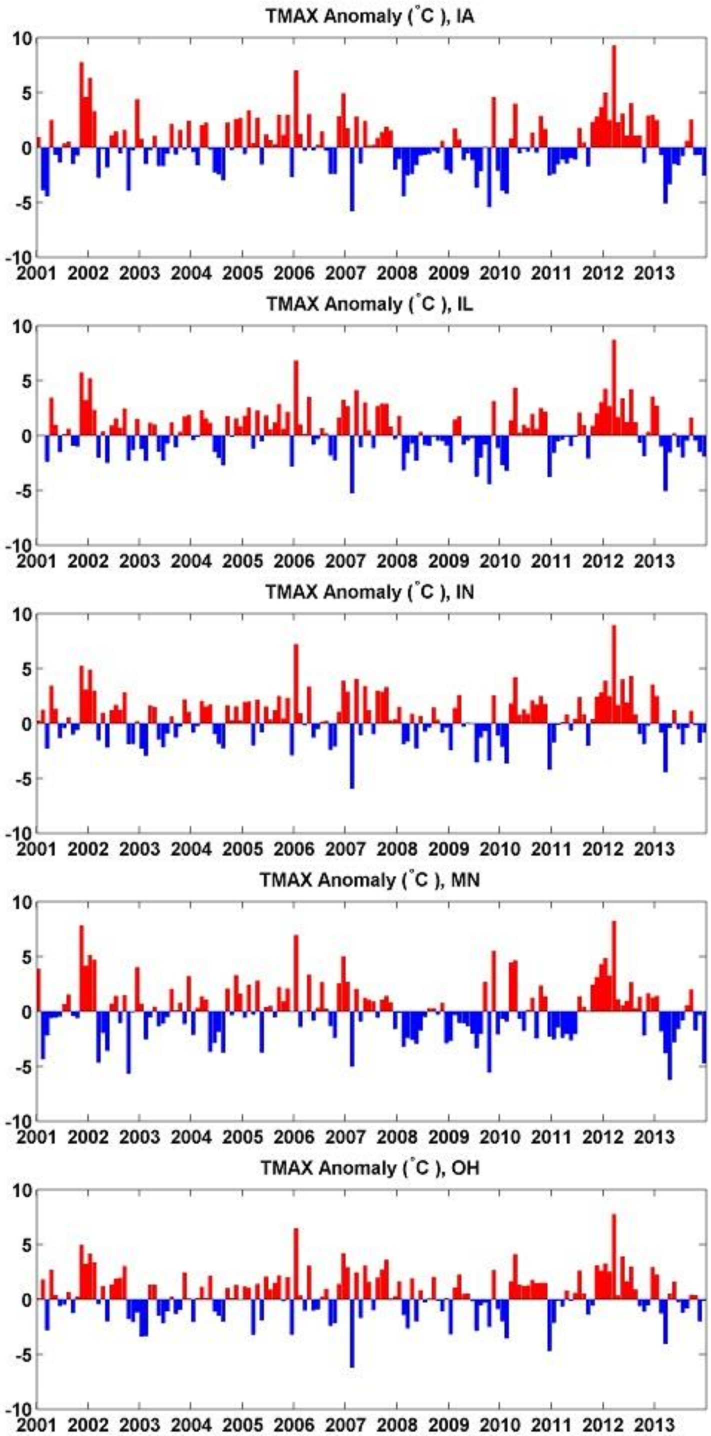

Figure 6. Anomalies of mean maximum temperature of the selected 5 states from year 2001 to 2013.

Figure 7 shows the USDM drought severity in mid-July, 2012, moderate to severe drought extended over most of the Corn Belt, which is consistent with the results of anomalies of temperature and precipitation.

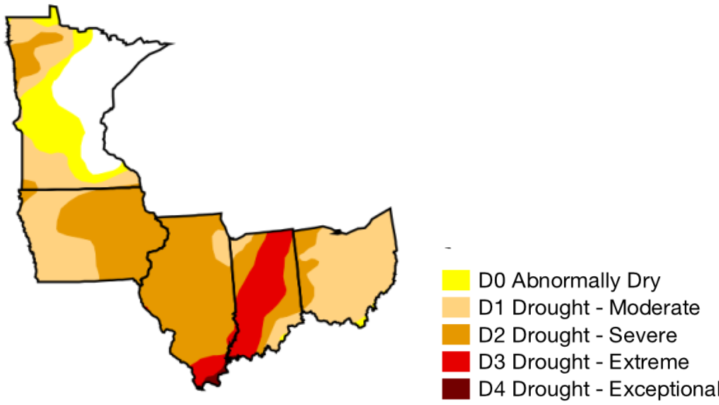

Figure 7. Drought conditions over the study area in mid-July 2012. Data was obtained from the U.S. Drought Monitor (http://droughtmonitor.unl.edu). In 2012, moderate to severe drought extended over most of the Corn Belt.

3.4 Impacts of Drought on Corn Yield

Previous studies have concluded that water stress during the silking impedes fertilization and greatly reduces corn yields (Claassen et al. 1970; Grant et al. 1989; Bolanos et al. 1996). NASS data for the year 2012 (Table 3) indicate that silking generally occurs in July for the Corn Belt study region. Figure 8 shows satellite remote sensing results of vegetation health status in July 2011 and 2012. Compared with July 2011, VHI is significantly low in July 2012, the spatial pattern is consistent with the drought severity map in figure 7.

Table 3. Approximate silking dates for the five study states. Dates and represent the first week at which more than half of the crop had reached the silking stage according to NASS Quick Stats data.

State	2012	
	Week	Date
Illinois	27	July 8
Indiana	27	July 8
Iowa	28	July 15
Minnesota	28	July 15
Ohio	28	July 15

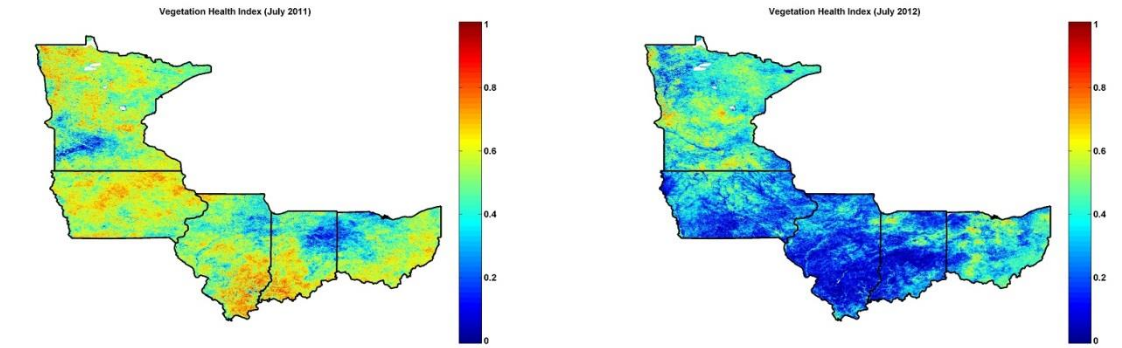

Figure 8. MODIS Vegetation Health Index in July 2011 and 2012 illustrates the significant impact of 2012 drought on crop growth.

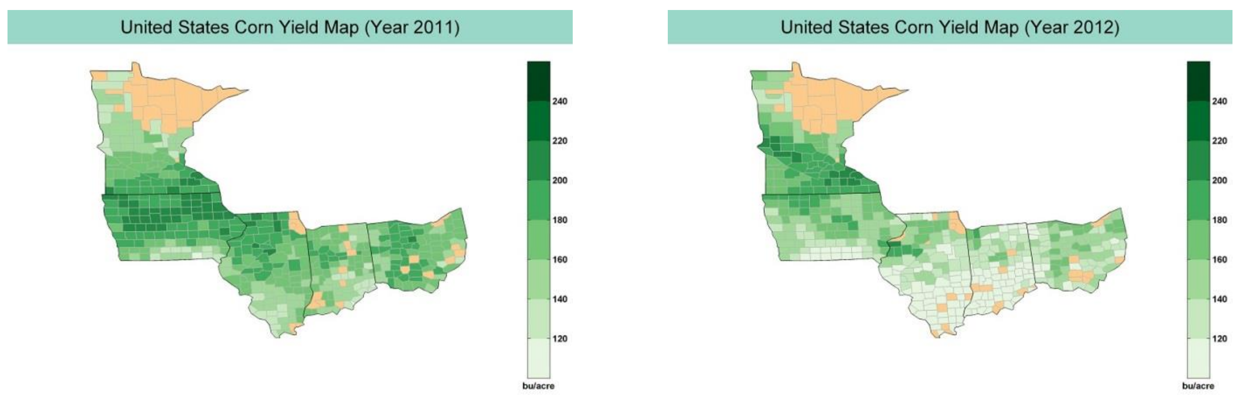

Figure 9. Corn yield map for the selected study area in 2011 and 2012.

Figure 9 shows corn yield maps of year 2011 and 2012. Figure 10 shows cron yield change from 2011 to 2012. We can see signifcant decrease of corn yield in 2012 in Iowa, Illinois, Indiana, and Ohio, which the state Minnesota is fine in 2012. The corn yield change map is also consistent with the VHI image of July 2012 (figure 8), and USDM drought severity map (figure 7).

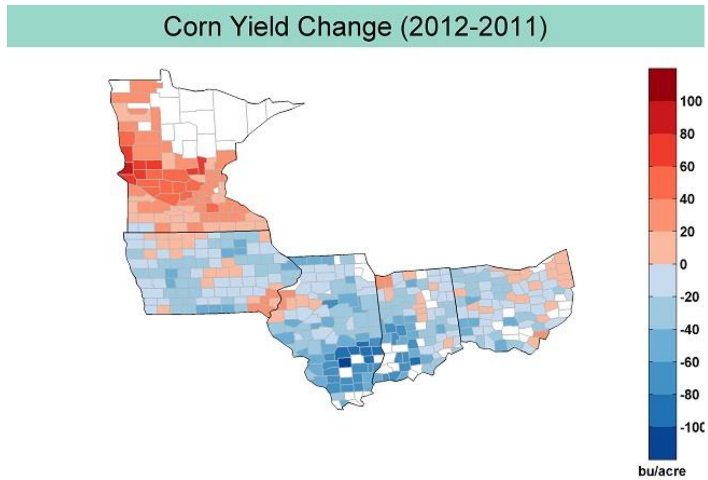

Figure 10. Crop yield change from 2011 to 2012 shows significant decrease of corn yield in most of the selected study area.

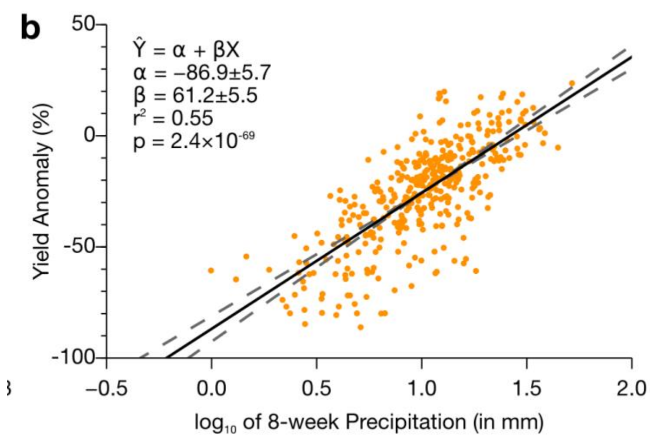

Figure 11. Least-squares regression lines for yield anomaly using transformed precipitation (in the period of maximum correlation).

Least-squares linear regression with the transformed precipitation as the predictor variable was used to estimate the impact of low precipitation on yield (Figure 11). The 95% confidence interval for the regression line is shown with dashed lines. In 2012, using the log10 of total precipitation over the period May 6 – June 30, a slope of 61.2±5.7 was obtained, with $r^2 = 0.55$ and a highly-significant p-value of 2.4×10-69. Sufficient data was available for 389 counties.

In year 2012, the slope of the regression lines was highly significantly different from 0 (with p-values approaching 0). According to the r2 values, variation in the log10-transformed precipitation during each period of maximum correlation explained about 55% variation in yield anomaly in 2012. For this model, the regression slope β has a simple interpretation as a linear decrease in yield associated with each ten-fold decrease in precipitation. For 2012, a 61% yield decrease was associated with each ten-fold decrease in precipitation, or equivalently, an 18% yield decrease was observed for every two-fold precipitation decrease.

4. Conclusions and Discussions

As the climate is changing significantly, it is critical to analyze the trends of climate change, investigate extreme weather and climate events, and assess their impacts on agriculture. This project conducted massive data processing and integrated analysis of climate data from NOAA NCDC, satellite remote sensing data from NASA EOS mission, and crop data from USDA NASS. The main results from on my research project are:

- An integrated climate and agricultural database was established to store historical climate and crop data records at county level. And, a web-based interface was developed for data search and visualization.
- Trends of temperature changes (maximum temperature, minimum temperature, and diurnal temperature range) of the continental USA were found, and the spatial and temporal patterns were analyzed.
- The 2012 climate event (drought) over the Corn Belt was characterized and analyzed through anomaly analysis of temperature and precipitation.
- The impacts of drought on corn yield were analyzed quantitatively through regression analysis with precipitation data over corn silking period. For 2012, around 61% yield decrease was associated with each ten-fold decrease in precipitation, or equivalently, an 18% yield decrease was observed for every two-fold precipitation decrease.

The proposed approaches for integrated analysis of massive data sets from various sources discovered the quantitative linkage between climate extreme events and crop yield, which is critical accurate assessment of climate impacts on food security. These approaches not only can be used for global climate change and its impacts assessment on food security and but also can be used to establish the foundation for early warming system for global food security.

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