The impact of Drought on Leaf Area Index (LAI) over Texas

GISWR 2012 Fall Term Project

Ling Huang

Abstract

Drought is predicted to occur more frequently over Texas in the future. The understanding of how air quality will be affected by drought is far from satisfactory. One pathway that drought could affect air quality—ozone concentrations in this case—is through the ozone formation process. Leaf Area Index (LAI) is a critical parameter controlling the biogenic emission, which is directly related to ozone formation. This project utilizes ArcGIS as a tool to investigate how LAI is affected by drought by comparing LAI distributions over Texas between a wet year (2010) and a drought year (2011). MODIS LAI data is post-processed by ArcGIS and various ArcGIS tools are involved in producing the results. By looking at the LAI ratio distributions, it is concluded that drought could cause substantial decrease of LAI, especially in central Texas. East and west Texas sees much smaller impact. In July, nearly 90% of Texas sees at least moderate impact and over 50% areas are significantly affected by drought. This substantial decrease of LAI has been demonstrated to cause much decrease of biogenic emissions estimated by land surface model. However, further researches need to be done in order to evaluate the overall impact of drought on ozone concentrations.

Key words: Drought, Leaf Area Index, Biogenic Emissions, Ozone

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1. Backgrounds and Motivation

1.1 Drought and ozone concentration

Over the past 50 years, the frequency of droughts has increased coincidentally with rising temperature in much of the Southeast and large parts of the West in U.S. (US Global Change Research Program, 2009). Meanwhile, most climate models suggest that these droughts will become more severe as climate changes in response to increased concentrations of greenhouse gases and other radiative forcing species in the atmosphere (IPCC, 2007). Figure 1 shows the predicted summer and fall precipitation in North American in response to global climate change by 2080-2090. In southern U.S., for example Texas, are predicted to see substantially reduced precipitation during these seasons, particularly in summer when air quality is of greatest concern (US Global Change Research Program, 2009).

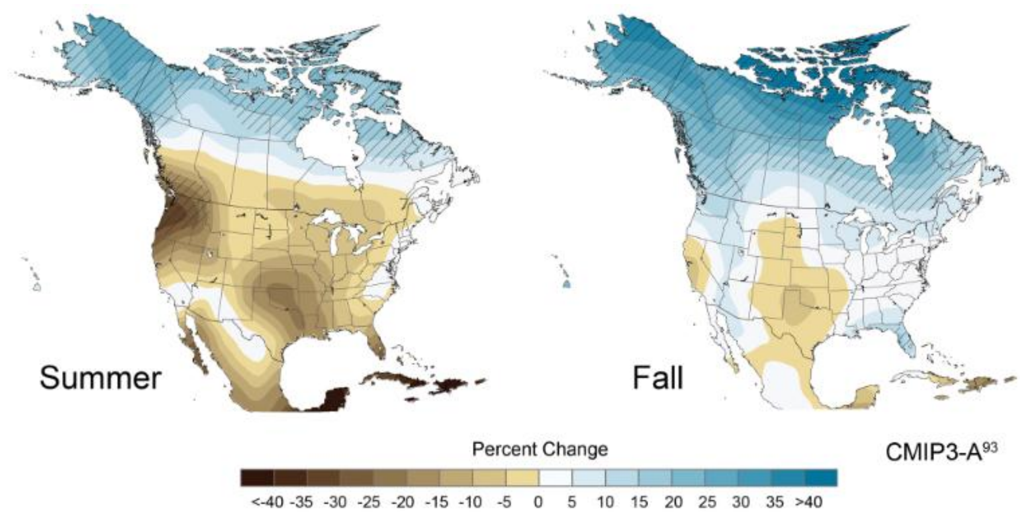

Figure 1 Projected future changes in precipitation relative to the recent past as simulated by 15 climate models. The simulations are for late this century, under a higher emissions scenario. (US Global Change Research Program, 2009)

Air pollution is the combined result of high emissions and unfavorable weather. How air quality, for instance, tropospheric ozone concentrations would respond to drought and the associated reduced summer and fall precipitation is quite complex. Previous studies have identified large numbers of meteorological candidates that would potentially correlate with ozone concentrations, for example, temperature, wind speed, mixing depth, and so on (Wise and Comrie, 2005; Solberg *et al*., 2003; Jacob and Winner, 2009).

One primary way that drought would affect tropospheric ozone concentration is by impacting the biogenic emission, which is key parameter in ozone formation process. Tropospheric ozone is formed from the oxidation of volatile organic compounds (VOCs) by hydroxyl radical when NO_x is present (Arya, 1999). Figure 2 is reproduced from Arya (1999), which shows the schematic of ozone formation. When VOC is absent (Figure 2a), nitrogen dioxide (NO_2) is photodissociated into nitric oxide (NO) and an excited state of oxygen $O(^3P)$. Ozone is produced from the reaction between the excited oxygen atom and a diatomic oxygen molecule. Subsequently, this ozone will be consumed by reaction with NO and convert back to NO_2 and O_2, which closes the cycle. There is no net ozone accumulation under this so-called photostationary state. However, in the presence of VOCs (Figure 2b), the photostationary equilibrium is disturbed. Since NO is more readily converted into NO_2 by reactions involving VOCs without consuming O_3, the net result is the accumulation of ozone.

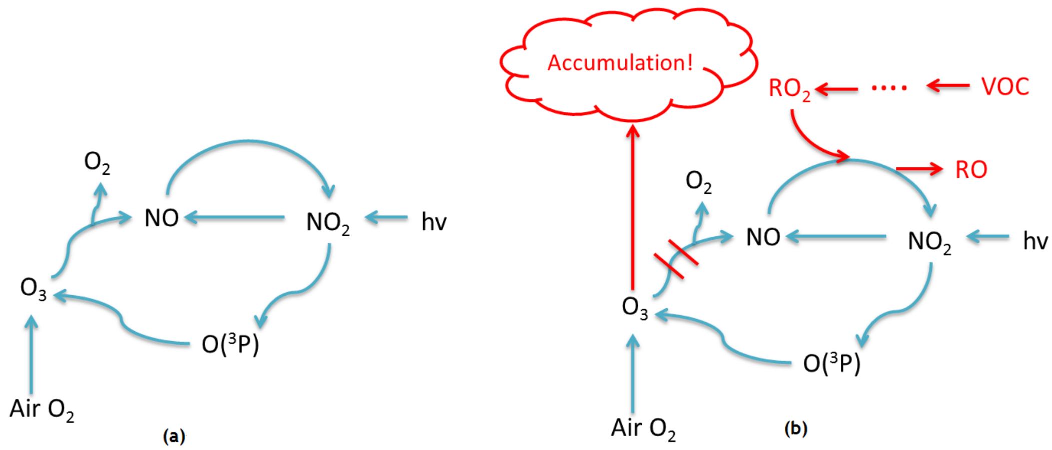

Figure 2 A schematic of ozone formation in the polluted troposphere: (a) The photostationary state in the absence of VOCs; (b) ozone accumulation in the presence of VOCs. (Ayra, 1999)

Ozone formation can be either VOC-limited or NO_x-limited, depending on the land use/land cover of the specific area. Usually urban areas are VOC-limited, while rural areas are mostly NO_x-limited. Therefore, when NO_x is sufficiently present, the availability of VOCs controls the amount of ozone that will be formed. VOCs can be either from anthropogenic sources or from nature, mainly vegetation. Liao *et al*. estimated the total VOCs that were emitted from vegetation, i.e. biogenic VOCs (BVOCs), are four times higher than VOC emissions from anthropogenic sources in United States. Previous studies have found that biogenic emissions are not much affected by mild drought but decrease significantly during prolonged drought (Lavoir *et al*., 2009; Pacifico *et al*., 2009; Pegoraro *et al*., 2004). The decrease of biogenic emissions caused by drought is closely related to the Leaf Area Index (LAI), which will be described in the following section.

1.2 Leaf Area Index

Leaf Area Index (LAI), usually defined as one half the total leaf area per unit ground area, is a critical parameter controlling many biological and physical processes associated with vegetation (Running, 1990; Bonan, 1995). LAI is also a key input variable to biogenic emissions models, for example, GloBEIS (Global Biosphere Emissions and Interactions System) and MEGAN (Model of Emissions of Gases and Aerosols from Nature). For both cases, the value of LAI is directly correlated to the amount of biogenic emissions. Both models consider the impact of drought by taking accounting an activity factor which represents the emission change caused by reduced soil moisture. However, in addition to the soil moisture change, the change of LAI during drought would cause the most direct and significant change of biogenic emissions, and would subsequently lead to substantial change of tropospheric ozone production, especially in VOC-limited regions.

Both *in-situ* and remote sensing techniques are available for estimating LAI. As a result of time and work-consuming nature, *in-situ* techniques are incapable of providing LAI estimation over large and continuous areas (Cohen *et al*., 2003; Jonckheere *et al*., 2004). On the contrary, satellite remote sensing provides a unique way to estimate the LAI distribution over large areas. Therefore, abundant researches have been done focusing on LAI retrieval from remote sensing data. Common LAI products from remote sensing include NASA MODIS (Moderate Resolution Imaging Spectroradiometer), NASA/NOAA AVHRR (Advanced Very-High Resolution Radiometer), ESA GLOBCARBON and etc.

1.3 Motivation

Year 2011 is the worst one year drought in Texas history. The impacts of this severe drought on air quality are unknown. This project is motivated to determine the impact of the 2011 drought on the LAI distribution over Texas, which provides the base of how biogenic emissions and subsequent ozone production would be affected by drought. By comparing the LAI distribution of the 2010 season (relatively wet) and the 2011 season (extreme drought) over Texas, the impact of drought on LAI will be evaluated.

2. Data and Method

2.1 MODIS LAI data

As mentioned above, various satellite-derived LAI data products are available. Numerous studies have been done to compare and validate various LAI products against observations (Weiss *et al*., 2007; Garrigues *et al*., 2008; etc.). However, there is no single product that is dominantly better than the rest. For this project, MODIS LAI product is chosen because (1) MODIS LAI has a high spatial resolution (1000m) and a high temporal resolution (8-day); (2) constant efforts have been applied to improve the quality of MODIS LAI product with the fifth version available; (3) easy and free to download. Three sets of MODIS LAI product is available: MYD15A2 (based on Terra sensor), MOD15A2 (Aqua sensor) and MCD15A2 (combined). The product based on both sensors (MCD15A2) is used in this project. The following section describes the detailed steps to process the LAI data.

2.2 Data process

The 8-day averaged LAI raw data is downloaded from NASA/Reverb website[1] between May 1st and September 30th for year 2010 and year 2011. The raw data is in HDF-EOS format and contains six layers, with layer 2 (Lai_1km) and layer 3 (FparLai_QC) are of importance in this project. The "Lai_1km" layer contains the LAI value for each grid and the "FparLai_QC" contains the quality control information of the LAI product. HDF files with multiple layers cannot be imported and converted to raster files by ArcGIS directly. Therefore, another tool "MRT" (MODIS Reprojection Tool[2]) is used to extract the LAI and QC layers into separate HDF files that can be used by ArcGIS directly.

The following steps as well as tools are taken to post-process the raw LAI data:

(1) Mosaic. Global raw LAI data is divided into 36x18 tiles. The "Mosaic" tool is used to combine the five tiles covering Texas into one raster. This step is done for both the LAI layer and the QC layer.

(2) Reclassify. After a single LAI raster covering Texas is created, the "Reclassify" tool is used to set the fill values of LAI layer (249-255) to "NoData" value. The fill values represent land cover types including snow, urban, barren or unclassified area. The values need to be set as "NoData" value otherwise the final LAI data would be incorrect.

[1] http://reverb.echo.nasa.gov/
[2] https://lpdaac.usgs.gov/tools/modis_reprojection_tool

(3) Create QC mask. After a single QC raster covering Texas is created in Step (1), a quality control mask is built. QC value is in 8-bit format and the last three bit No. indicates whether the corresponding LAI data is good or not. For example, “000” suggests the best result possible and “100” indicates pixels where values cannot be retrieved. In this project, only pixels with “100” are discarded. In order to create such a quality control mask, a “Mod” tool is used to calculate the value of the last three bit No. in the QC raster. The constant used in “Mod” is 8, since the last **three** numbers are of interest. The result QC mask contains 0, 1, 2, 3, 4 and “NoData”.

(4) Apply QC mask. After a QC mask is created, a “Raster Calculator” is used to exclude the pixels that have QC mask value equal to 4 and leave the other values.

(5) Reproject. Since the raw LAI data is in Sinusoidal projection, the “ProjectRaster” tool is applied to convert the LAI raster to NAD83.

(6) Extract by Mask. The mosaic LAI raster covers not only Texas but also the surrounding areas. The “Extract by Mask” tool is used to extract only the LAI within Texas. The Texas boundary shapefile is downloaded from National Atlas[3].

(7) Scale. The raw LAI value has a scale factor of 0.1. Therefore, the “Raster Calculator” is used to apply this scale factor to LAI raster. This step is the final step of generating a LAI distribution over Texas.

In order to post-process the raw data automatically, a model is built in ArcGIS as shown in Figure 3. A python script is written to process all the raw LAI data using the model. The final raster is the LAI distribution map over Texas with a time resolution of 8 days from May to September for year 2010 and year 2011.

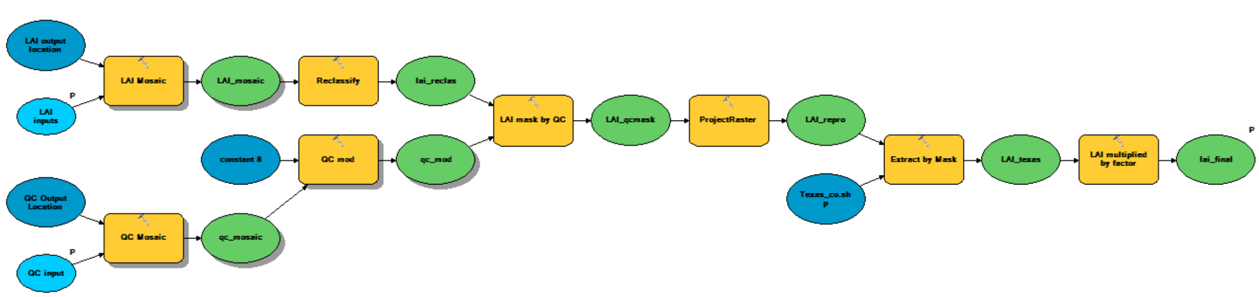

Figure 3 Schematic of LAI post-process model in ArcGIS

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[3] http://nationalatlas.gov/index.html

3. Results

3.1 General LAI distributions over Texas

Figure 4 shows the LAI distribution over Texas on May 1st in 2010 and 2011. By looking at the two LAI distribution maps, there is a clear increase of LAI as it goes from the desert in west Texas to the evergreen deciduous trees in east Texas. This increasing trend of LAI from west to east is consistent with the annual precipitation and temperature trend of Texas. Figure 5 shows the annual precipitation and annual temperature distribution of Texas from 1981 to 2010 (Water for Texas 2012 State Water Plan[4]). There is also a clear increase trend for both precipitation and temperature from west to east Texas. The combination of temperature and precipitation determines the land cover type and therefore the LAI values. Generally, high temperature and high precipitation lead to high LAI values. There are several big white blocks in the LAI distribution map where the LAI values are zero. Those places are metropolitan areas, like Dallas-Fort Worth, Houston, Austin and San Antonito. The other white blocks represent water bodies, where LAI values are also zero.

Comparing the LAI distribution on the same day between a wet year (2010) and a drought year (2011), a significant decrease of LAI is observed, especially in central Texas. This decrease of LAI caused by drought is not much seen in both east Texas, where the LAI values are very high and west Texas, where the LAI values are already very low. The following sections are dedicated to examine this decrease of LAI from a more quantitative way both statistically and geographically.

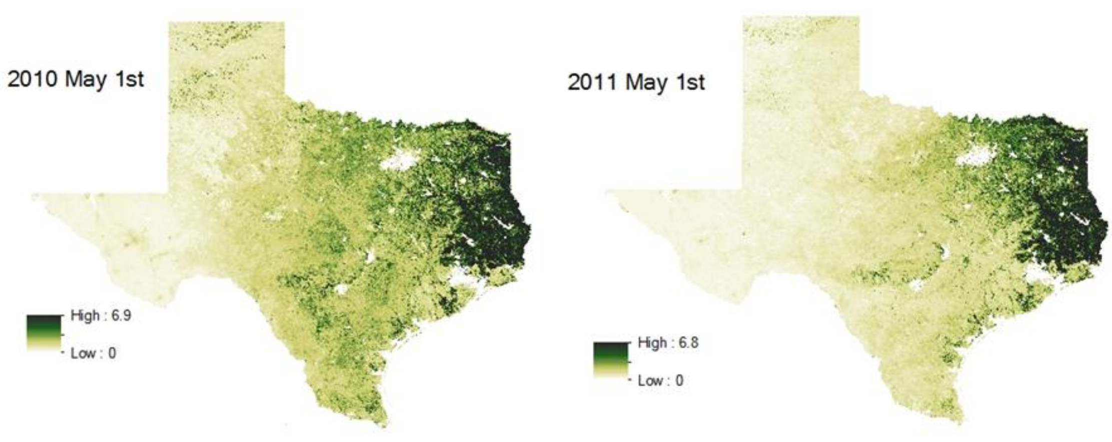

Figure 4 LAI distribution over Texas on May 1st 2010 (left) and May 1st 2011 (right)

[4] http://www.twdb.state.tx.us/publications/state_water_plan/2012/04.pdf

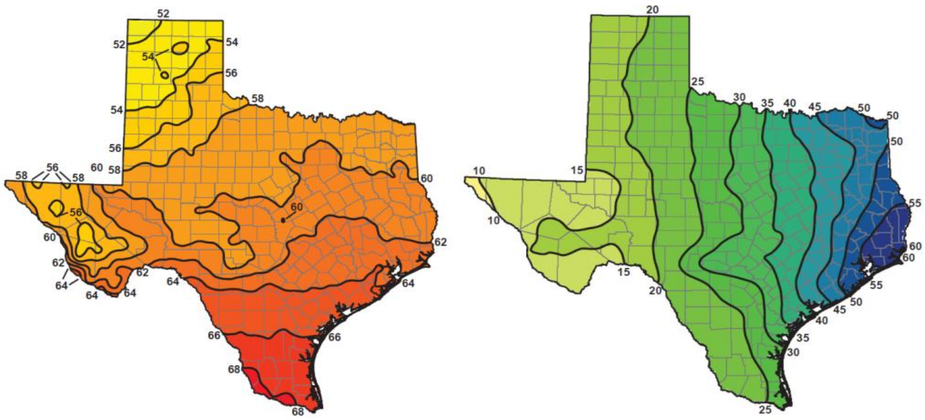

Figure 5 Average annual temperature (left, in degrees Fahrenheit) and precipitation (right, in inches) for 1981 to 2010. (source: Water for Texas 2012 State Water Plan)

3.2 Statistics of LAI change caused by drought

Figure 6 shows the probability density function of LAI distributions on May 1st 2010 (upper) and 2011 (lower). In both cases, most of the LAI values are between 0 to 2, with small pikes between 6 and 7. When the two functions are shown in the same plot (Figure 7), there is a clear shifting from larger LAI values in the wet year to smaller LAI values in the drought year.

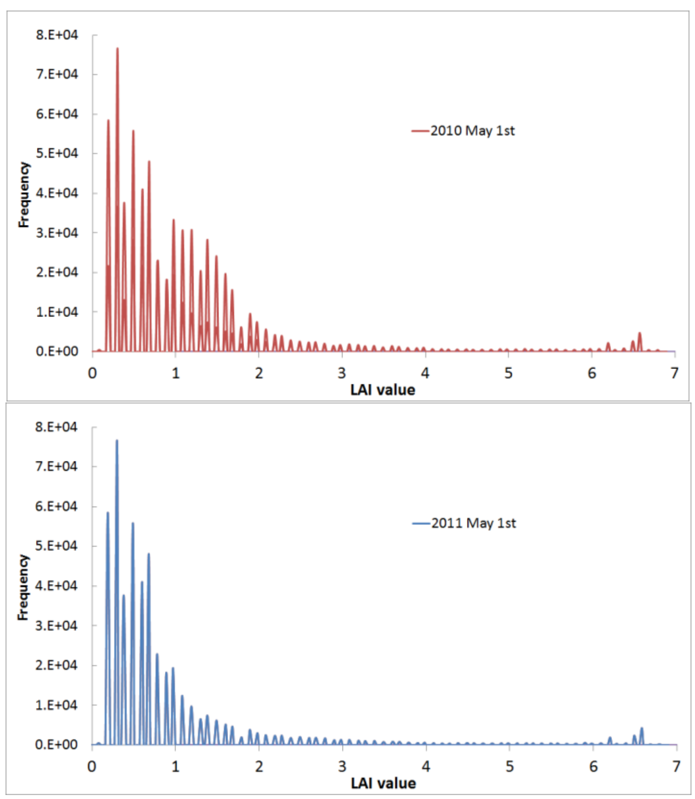

Figure 6 Probability density functions of LAI distribution on May 1st 2010 (upper) and 2011 (lower)

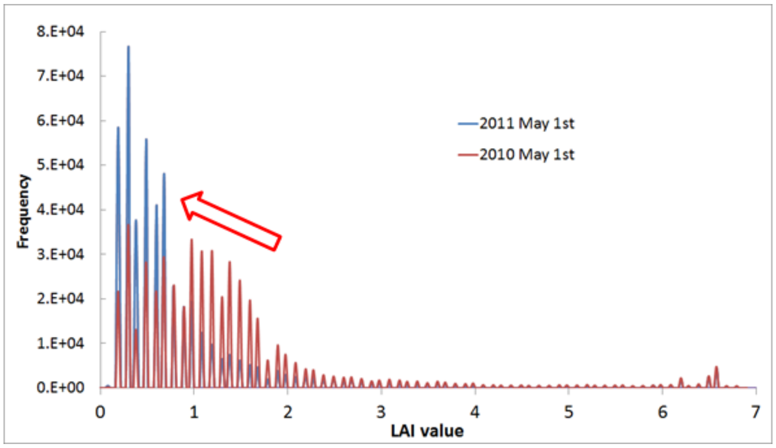

Figure 7 Comparison of probability density functions between wet year and drought year

3.3 Change of LAI distribution

A most powerful capability of ArcGIS is that it enables viewing changes geographically. The monthly ratio of LAI distribution between the drought year (2011) and the wet year (2010) is calculated as the drought LAI divided by the wet LAI using the "Raster Calculator" tool in ArcGIS. This LAI ratio indicates how much the impact of drought on LAI decrease is. The range of LAI ratio is divided into four classes that represent the significance of drought impact (Table 1). Ratio that is greater 0.75 indicates no impact of drought is seen; ratio between 0.5 and 0.75 means at least moderate impact; ratio between 0.25 and 0.5 suggests significant impact and ratio less than 0.25 indicates extreme impact. Since the MODIS LAI data is based on every 8 days, monthly LAI distribution is generated by averaging the LAI values within the month.

Table 1 Classification of drought impact based on LAI ratios

LAI Ratio (calculated as LAI_2011 / LAI_2011)	Classification of Drought Impact	Color
> 0.75	No impact	Green
0.5 – 0.75	Moderate impact	Orange
0.25 – 0.5	Significant impact	Red
0 – 0.25	Extreme impact	Purple

Figure 8 shows the LAI ratio distribution or the impact of drought for May. Figure 8a-8d shows the distribution of the individual impact class and Figure 8e shows the combined results. The green color representing no impact of drought covers most of the west and east of Texas. There are large areas with at least moderate impact covering most of the central Texas, indicated by orange and red color. Only small regions see extreme impact of drought (purple color) and most of them are located in the panhandle area. Figure 8e shows that there seems to be a trend of increasing impact of drought as going more towards the central Texas. This result is expected. For east Texas, it is ever-green deciduous trees with high LAI values (Figure 4), indicating that the impact of drought is well buffered by the high LAI values. For west Texas, it is desert with already very low LAI values (Figure 4); therefore the impact of drought is unable to cause further decrease of LAI. On the contrary, central Texas, considered as a transition zone from the very dry west to the very wet east, sees the most impact of drought and therefore, is more vulnerable to drought.

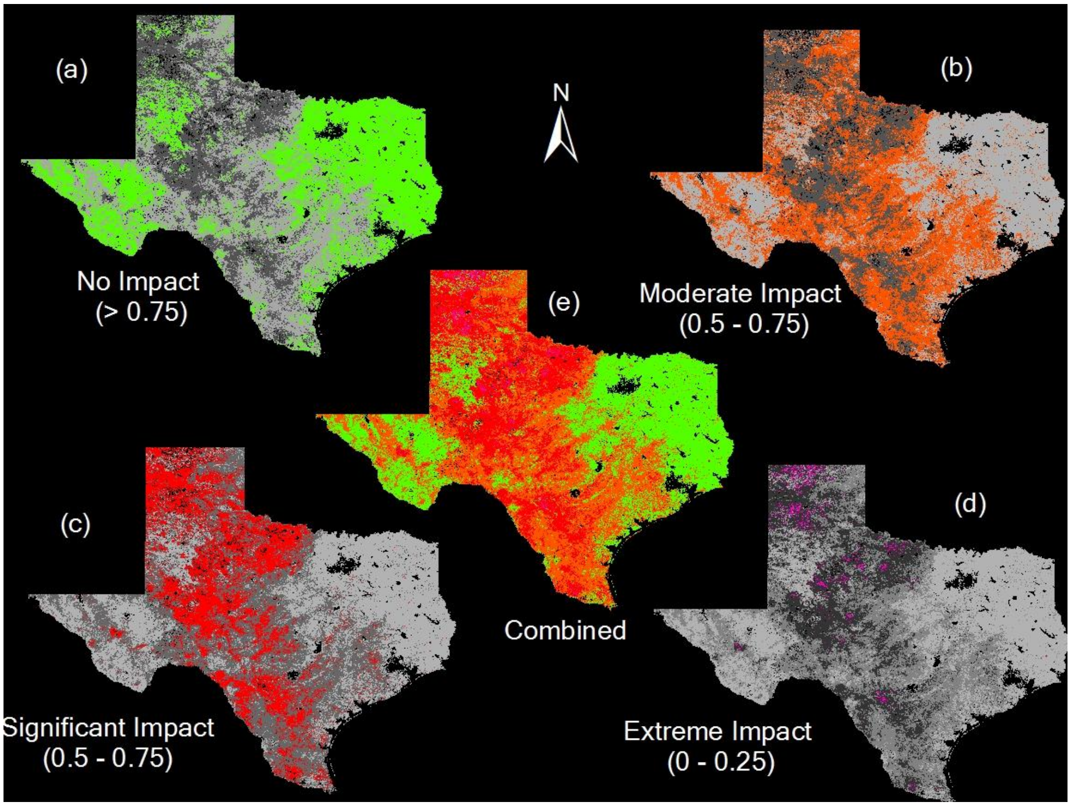

Figure 8 LAI ratio distributions for May

Figure 9 shows the LAI ratio distributions from May to September. There is a clear expanding of the impact of drought from May to September, indicated by the more orange and red color. It is worthy to note that in July, the impact of drought seems to reach a peak and then in August and September, the impact of drought seems to draw back a little bit. In August and September, the temperature is very high. As a result, plants close their stomata in order to reduce evapotranspiration. At the same time, the uptake of CO_2 through the stomata is also reduced leading to less photosynthesis and less new leaf biomass production. Therefore, the LAI reaches maximum in July and will decrease in August and September as the result of continuing increasing temperature. The natural decrease of LAI in August and September causes the drawback of the impact of drought. But still, most of Texas sees at least moderate impact of drought in summer season.

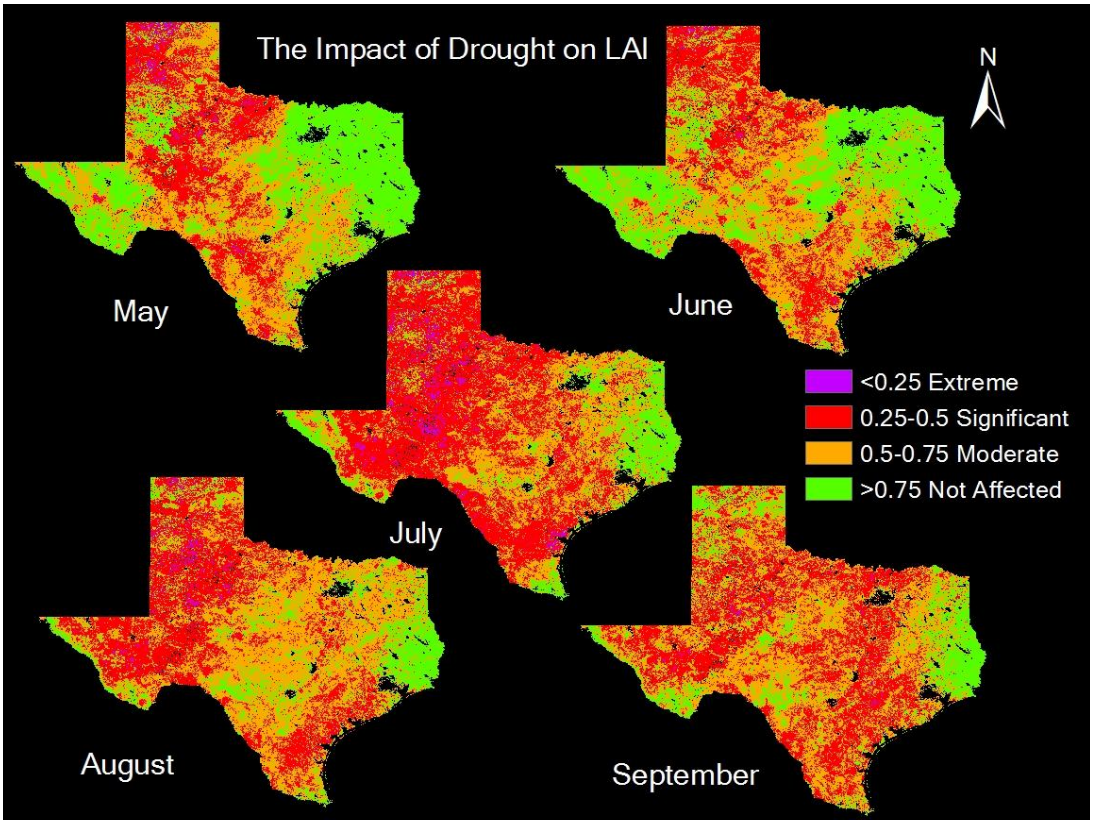

Figure 9 LAI ratio distributions for May to September

Figure 10 shows the percent of area that experience different level of drought impact. The color scale is consistent with the above figures. For example, in May, about 37% of Texas sees no impact of drought; 63% of Texas sees at least moderate impact of drought; only about 1% areas sees extreme impact. It is more obvious to see the expanding impact of drought from May to September by looking at this figure. In July, nearly 90% of Texas experiences at least moderate impact of drought and about half Texas has been significantly impacted by drought. The combination of Figure 9 and Figure 10 enables to delineate the impact of drought both quantitatively and geographically.

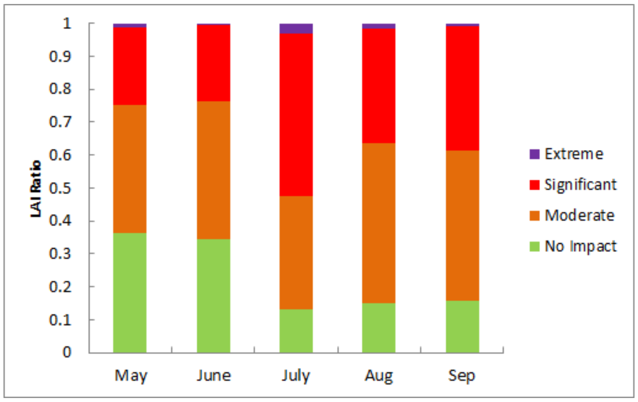

Figure 10 Percent of areas for different levels of drought impact

3.5 Climate Division

The National Climatic Data Center divides Texas into 10 climate divisions (Figure 11), which present regions with similar characteristics such as vegetation, temperature, humidity, rainfall, and seasonal weather changes. The descriptions of each climate division are shown in Table 2.

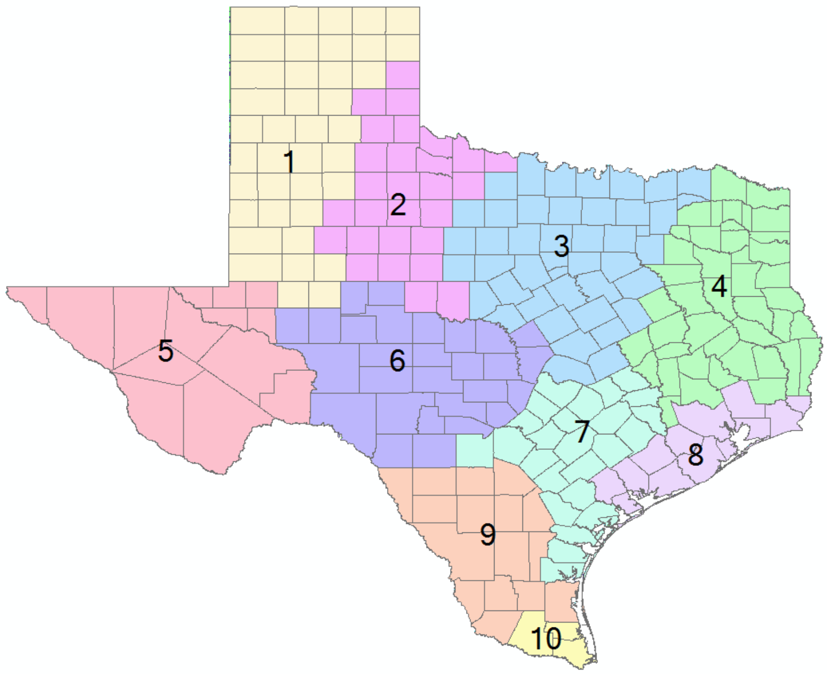

Figure 11 Climate divisions of Texas

Table 2 Descriptions of climate divisions of Texas

Division No.	Name	Description
1	High Plains	Continental steppe or semi-arid savanna
2	Low Rolling Plains	Sub-tropical steppe or semi-arid savanna
3	Cross Timbers	Sub-tropical sub-humid mixed savanna and woodlands
4	Piney Woods	Sub-tropical humid mixed evergreen-deciduous forestland
5	Trans-Pecos	Except for the slightly wetter high desert mountainous areas, sub-tropical arid desert
6	Edwards Plateau	Sub-tropical steppe or semi-arid brushland and savanna
7	Post Oak Savanna	Sub-tropical sub-humid mixed prairie, savanna and woodlands
8	Gulf Coast Plains	Sub-tropical humid marine prairies and marshes
9	South Texas Plains	Sub-tropical steppe or semi-arid shrubland
10	Lower Rio Grande Valley	Sub-tropical sub-humid marine

In order investigate the impact of drought on LAI distribution based on climate divisions, the "Zonal Statistics as Table" tool in ArcGIS is used to generated the LAI ratio for each climate division and each month. Figure 12 shows the averaged LAI ratio for each climate division from May to September. Again, color scale is consistent with green representing no impact and red indicating significant impact.

From Figure 12, it is clear that climate divisions that locate in central Texas are more affected by drought, e.g. division No.1, 2, 6, 7 and 9. These five divisions are all characterized either as a "sub-arid" savanna or "sub-humid" savanna. Again, these results demonstrate that central Texas as a transition zone from arid to humid is more vulnerable to drought.

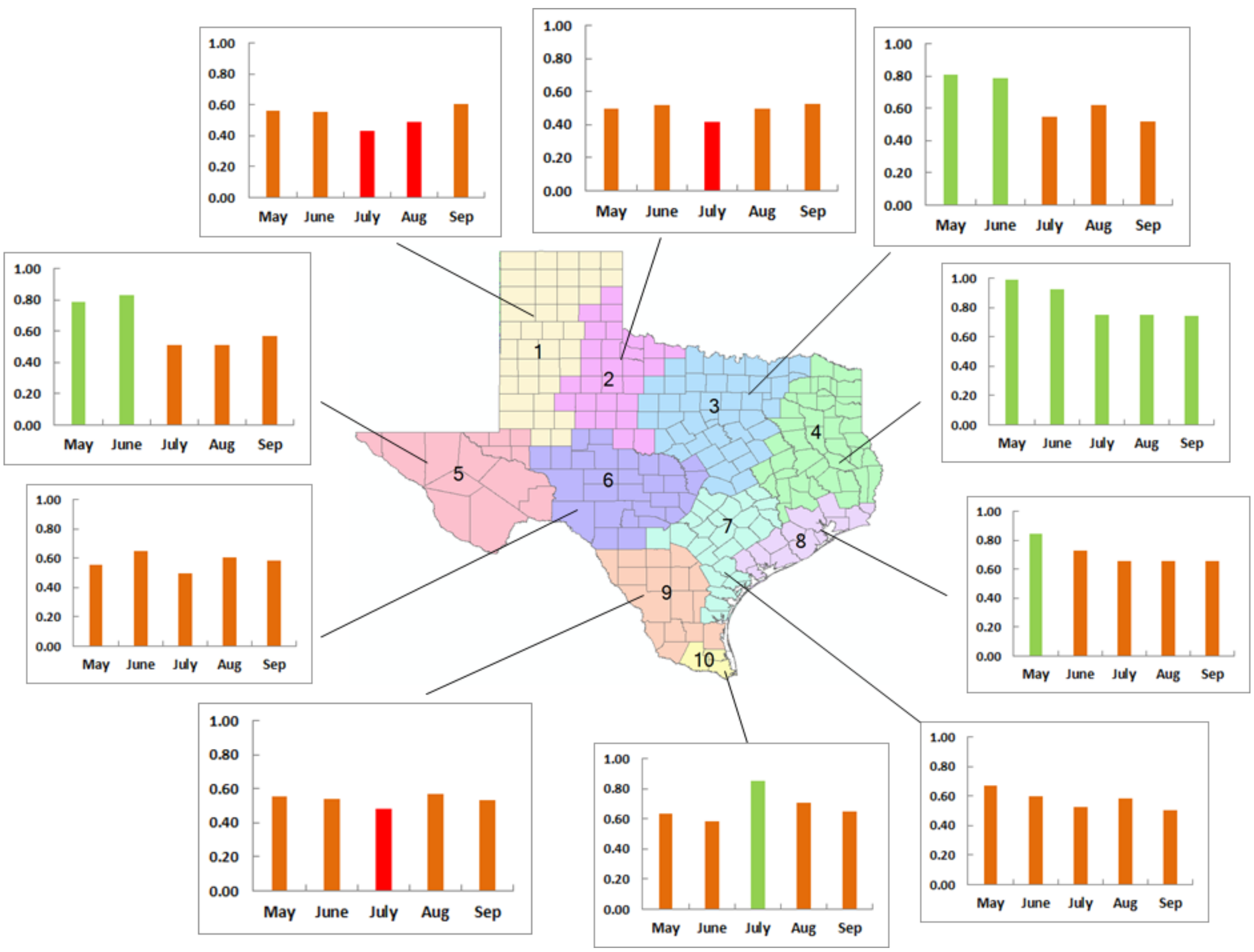

Figure 12 Average LAI ratio based on climate divisions of Texas

3.6 Change of Biogenic Emissions

In the previous sections, the results have demonstrated that the LAI distribution can be significantly affected by drought, especially in central Texas. But how this impact on LAI results the change of biogenic emissions? The results presented in the following are actually from another course project which employed a land surface model to simulate the impact of drought on biogenic emissions due the change of LAI.

The land surface model used is Community Land Model version 4 (CLM4.0), which is the land component of the Community Earth System Model (CESM). CLM simulates the exchanges of water, carbon, energy and momentum between land surfaces and atmosphere through a wide range of ground and canopy biogeophysical processes (Levis *et al*., 2003). For the other course project, two simulations were conducted with CLM4.0 by using two sets of LAI dataset: control simulation uses prescribed LAI dataset representing a normal year; experiment simulation uses adjusted LAI dataset which represents a drought year. By comparing the estimated biogenic emissions between the two simulations, the impact of drought on biogenic emissions can be examined. Isoprene is quantitatively the most important type of biogenic VOCs (Fehsenfeld *et al*., 1992; Guenther *et al*., 2006). Therefore, in that project, only isoprene emissions were compared.

Figure 13 shows the LAI ratio and isoprene ration in May and July. It can be seen that the decrease of LAI in central Texas (left figures) causes decrease of isoprene emissions (right figures) in similar geographical locations. The decrease of isoprene emission can be as much as 34% in May and 45% in July.

This decrease of isoprene emission by drought has important indication. Ozone formation can be either VOC-limited when NO_x is sufficiently present or NO_x-limited when VOCs is abundant. Usually in urban areas, ozone formation is VOC-limited, in which case, the availability of VOCs controls the ozone formation processes. Therefore, the substantial decrease of biogenic emission, i.e. isoprene emission, caused by drought is expected to result substantial reduction of ozone formation, which is a positive impact of drought on improving air quality. However, drought can affect air quality in other ways. For example, the removal of tropospheric ozone is by dry deposition onto vegetation. During drought, plants close their stomata in order to reduce evapotranspiration. The stomatal resistance increases which results less removal of ozone in the atmosphere. This would lead to high ozone concentrations and is considered as a negative impact of drought on air quality. In order to understand the overall impact of drought on air quality, further studies need to be done by incorporating all the potential pathways that drought can affect air quality.

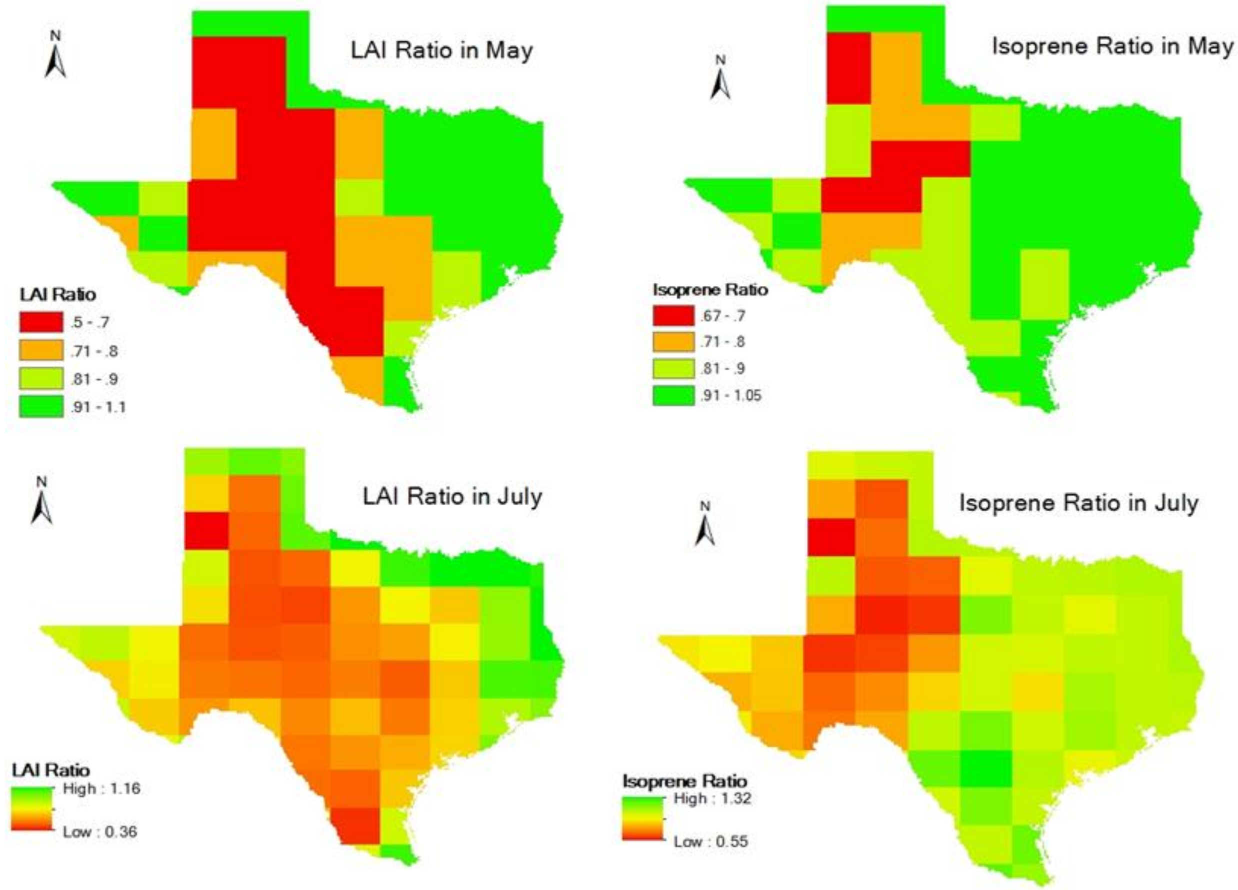

Figure 13 LAI ratio and isoprene ratio simulated by CLM4.0 in May and July

4. Conclusion

LAI is a key parameter in estimating biogenic emissions, which subsequently controls ozone formation process. One major way that drought can affect tropospheric ozone concentrations is though the change of LAI during drought. This project aims to investigate the impact of drought on LAI distribution over Texas during summer seasons, when air quality is of greatest concern. MODIS LAI data from May to September for a wet year (2010) and a drought year (2011) is downloaded and post-processed by ArcGIS. A model is built in ArcGIS in order to process batches of raw LAI data. The final LAI distributions are compared between the two years both statistically and geographically. The major conclusions of this project are summarized as following:

(1) LAI is a key parameter in biogenic emissions estimation, which controls the downstream ozone formation process. The decrease of LAI caused by drought can lead to substantial decrease of isoprene emissions.
(2) The LAI distribution of Texas is consistently with the annual precipitation and temperature distribution. LAI increases from the dry west to the wet east Texas. High LAI is the results of high precipitation and high temperature.
(3) LAI can be much affect by drought. In July 2011, nearly 90% of Texas is at least moderately affected by drought and over 50% areas were significantly affected.
(4) Compared to the very dry west and the very wet east Texas, central Texas, as a transition zone, is much more vulnerable to drought.
(5) ArcGIS is an excellent tool to view the impact of drought geographically.

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