INVESTIGATIONS OF ATMOSPHERIC AND PLANT PHYSIOLOGICAL EFFECTS ALONG AN URBAN-TO-RURAL GRADIENT IN THE HOUSTON METROPOLITAN AREA COMPARING 2011 TO 2012

A Thesis

by

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ABSTRACT

This project hypothesizes that changes in climate resulting from urbanization can serve as a proxy for the changes expected from climate change, and therefore, future climate change effects on the biosphere can be estimated by comparing urban trees to rural trees. To study this, an urban-to-rural gradient was set up starting near downtown Houston, TX, and extending north approximately 90 km. Three weather stations were erected along this gradient to continually monitor weather. Photosynthesis rates of oak trees near each weather station were measured on periodic field trips throughout the growing season.

Comparisons of temperature, rainfall, carbon dioxide, and ozone concentrations indicate that urbanization is a possible but imperfect proxy for climate change. Considering only two years of photosynthesis measurements, the long term effects of climate change are difficult to distinguish from short term effects, such as rain, and seasonal term effects, such as drought. However, observations hold promise that further measurements may lead to more conclusive results.

NOMENCLATURE

CO_2	Carbon Dioxide
H_2O	Water
VOC	Volatile Organic Compound
JDHS	Jefferson Davis High School (located in downtown Houston)
SHNF	Sam Houston National Forest

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1. INTRODUCTION

It has long been known that changing atmospheric conditions alter carbon assimilation rates [Farquhar 1980], and that plants' secondary metabolism, which is a source of volatile organic compounds (VOCs) to the atmosphere [Rasmussen 1972], may in turn be altered directly and indirectly [Kesselmeier 1998]. These interactions create a feedback loop that potentially can have a large impact on how we understand climate change, but the magnitude of that impact remains uncertain [Booth 2012]. Essentially, there are two ways to study this problem. First, using controlled environments, by analyzing how different plants respond to different stressors such as drought, increased temperature, and higher levels of carbon dioxide and ozone. Second, via using a climate change proxy, something that incorporates all or most of the changes that are expected to result from climate change, to analyze how plants adapted to that particular environment. Unless individual stressors dominate effects spatially or temporally, this second method lacks the ability to tease out how these stressors are affecting plants, but it does allow for a big picture view of what can be expected as the climate continues to change.

This study is of the second type. The Houston metropolitan area and the regional climate change it creates as a result of urbanization were examined to determine if they could serve as an acceptable climate change proxy. Simultaneously, measurements were taken on select oak trees to catalogue changes that resulted from the urban environment. For comparison, two other sites, one suburban and one rural, were similarly monitored.

Selected results of the first two years of the project, which is scheduled to run for five years, are presented here.

2. METHODS

2.1 Sites

Three sites, their locations shown in figure 1, were selected based on criteria that matched the project and research goals. Namely the sites needed to:

Figure 1: Map of Weather Station Locations

Jefferson Davis High School (JDHS) is in downtown Houston, The Woodlands is a forested suburban community approximately 45 km north of JDHS, and Sam Houston National Forest (SHNF) is 45 km further north. Galveston Bay is visible in the lower right.

1. Be located along a gradient from an urban area to a rural area but have a similar background climate so that the degree of urbanization is the primary difference between the locations.
2. Have similar species of trees in close proximity to the weather station in order for comparison of photosynthesis measurements taken at each site.
3. Be accessible to nearby schools to facilitate educational involvement for high school and junior high school science students.

The urban site is located at Jefferson Davis High School (JDHS) north of downtown Houston, TX. The site is inside the inner loop and is 1.6 km west of highway 59, 1.3 km east of I-45, 1.8 km north of Hwy 90/I-10, and 36 km west-northwest of Galveston Bay. The weather station is located next to the school football field and tennis courts and directly borders a residential neighborhood composed mainly of low- to middle-income single family houses, but light commercial and industrial areas can also be found within a few blocks [Park et al., 2011].

The suburban site is located at Jane McCullough Junior High in The Woodlands, TX approximately 45 km NNW of the urban site and 4.4 km west of I-45. The Woodlands (officially “The Woodlands Township”) is a master-planned community started in 1974 and currently covering 115 km^2 with a population of over 100,000 residents and a median household income over $100,000 [US Census Bureau 2012]. As the name indicates, The Woodlands is a heavily wooded area. According to their official website, "the Woodlands philosophy even encourages ‘natural yards’ with less grass and more forest" [The Woodlands Township 2014]. The weather station is located behind the school in an area characteristic of the natural landscape philosophy. The immediate neighborhood is low density residential.

The rural site is located at the Sam Houston National Forest ranger station approximately 42 kilometers north of the suburban site and 4 km west of I-45. One of four national forests in Texas, Sam Houston National Forest covers 650 km^2. However, it is largely fractured and commonly described as "urban forest" (Salinas 2004).

2.2 Weather Stations

Three weather stations from Onset Computer Corp. (Bourne, MA) were set up to continually record weather conditions at each of the three sites. Each station was equipped with a HOBO® U30 Data Logger, solar panel, and sensors to monitor

Table 1: Weather Station Instrumentation

Sensor	Range	Accuracy
S-BPB Barometric	660 to 1070 hPa	±3.0 hPa at 25°C, ±5.0 hPa over all operating temperatures
Photosynthetically Active Radiation	0 to 2500 $\mu mol/m^2/s$, 400 to 700 nm wavelengths	±5 $\mu mol/m^2/s$, or ±5%, whichever is greater.
Rain Gauge	0 to 12.7 cm/hr	±1% at up to 20 mm/hr
Leaf Wetness	0 to 100%	Repeatability 5%
Temperature/RH	-40°C to 75°C 0 to 100%	±0.21°C from 0°C to 50°C ±2.5% from 10% to 90%
Soil Moisture	0 to 0.550 m^3/m^3	±0.031 m^3/m^3 from 0°C to 50°C
Wind Speed	0 to 45 m/s	±1.1 m/s or ±4%, whichever is greater
Wind Direction	0° to 355°, 5° dead band	±5°
Model 202 Ozone Monitor	1.5 ppb to 250 ppm	1.5 ppb or 2%, whichever is greater
GMP343 Carbon Dioxide Probe	0 to 1000 ppm	±3 ppm + 1% of reading

Figure 2: Pictures of Weather Stations
From left to right, the weather station locations are JDHS, The Woodlands, and SHNF.

weather conditions. Data was logged every minute, and later averaged to 15 minute periods. Additionally, each station was supplemented with a 2B Technologies model 202 ozone analyzer and a Vaisala GMP 343 carbon dioxide probe. Table 1 shows the full list of sensors and their specifications. Figures 2a-b show each station at its site.

Prior to deployment, the weather stations were set up next to each other outside the laboratory on the roof of Eller O&M Building at Texas A&M University to collect data for three weeks. The measurements were compared to ensure precision.

Comparisons of pressure, temperature and relative humidity readings between the towers returned r^2 (determination coefficient) values greater than 0.99 and ozone comparisons returned values greater than 0.98. The carbon dioxide probes for The Woodlands and Sam Houston National Forest likewise returned a comparison r^2 value greater than 0.98; however the comparison of the Jefferson Davis High School probe

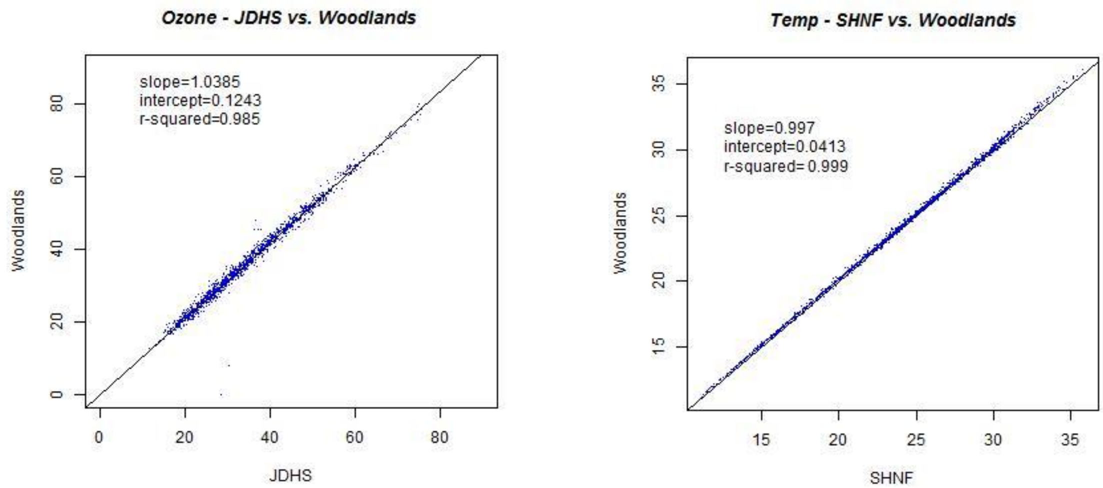

Figure 3: Examples of Instrument Inter-Calibration Checks

with the other two gave r^2 values greater than 0.90. Figure 3 shows two examples of the comparisons done. The Sam Houston National Forest weather station was the first to begin operations on March 17, 2011. This was followed by The Woodlands station on March 18, 2011 and the downtown Houston station on March 22, 2011.

Carbon dioxide probes were calibrated for the first time in November 2011 and have been calibrated roughly monthly since then. As the testing prior to deployment indicated, the carbon dioxide probe in Houston tended to have the most trouble staying calibrated and was found to at times drift several ppm between calibrations. Eventually it was decided to substitute carbon dioxide measurements from the Houston weather station with carbon dioxide measurements being taken as part of another project just 0.6 km away.

Ozone analyzers were zeroed one to two times per month since the start of the project and its Teflon PTFE inlet filters (Sartorius AG, Goettingen, Germany) replaced each time the analyzers were zeroed. They were returned to the laboratory and cleaned or returned to the manufacturer for repair as needed, which has happened approximately annually.

Only a few corrections were needed for the data after it had been collected. Weather data was spot-checked to ensure that no power spikes or outages caused the instruments to turn off. Drift in the ozone and carbon dioxide analyzers were linearly corrected between each calibration. All data was converted to 15-minute averages from the 1-minute averages recorded by the data logger before any analysis was done.

Temperatures at SHNF were corrected for the measurement height difference because the sensor was installed at 5 m above ground level while the other sites measured at 2 m above ground level. No correction was made for the 95 m change in elevation between JDHS and SHNF because part of the experiment was to analyze how trees were impacted by temperature experienced, so while a correction for height above ground level is necessary, a correction for altitude is not. Regardless of whether an elevation correction is applied, it would not significantly impact the conclusions that are made because it would only emphasize that a sea breeze is the controlling factor in keeping JDHS temperatures cool during summer afternoons. The gradients observed at other times were all larger than an elevation correction, which would therefore not alter the analysis. Carbon dioxide measurements were adjusted to account for changes in pressure and temperature. Separately pressure was converted to sea level pressure.

2.3 CIRAS-II Photosynthesis System

The CIRAS-II is a user-friendly, portable photosynthesis measurement system. It combines four infrared gas analyzers with carbon dioxide and water vapor absorbent columns to accurately control concentrations in a leaf cuvette. The leaf cuvette itself clamps onto a leaf and isolates a 2.5 cm^2 area of the leaf exposing it to accurately controlled gas flows and light from an array of photodiode lamps. After a period of time sufficient to allow the leaf clamped into the cuvette to acclimate to the cuvette environment, measurements of gas exchange of the leaf allow for calculations of photosynthesis and transpiration rates. The instrument records measurements every 10 seconds, but only data from the final minute of measurements, after the exposed leaf area had 5 to 7 minutes to acclimate and readings were steady, are used in the analysis.

Each field site was visited roughly every 1 to 2 weeks during the sampling season between May and October each year. At each site, a selection of trees was chosen that would be revisited during each trip to the site. Trees were selected based on species, relative age, orientation, and accessibility. A species misidentification occurred early in the project and was unfortunately only discovered during the second year. The "post oak" (*Quercus stellata*) at the downtown Houston site was actually an overcup oak (*Quercus lyrata*). This prevents direct comparison of those measurements with post oak measurements at other sites, but measurements done on other tree species can still be compared between the sites, and the overcup oak measurements can be used to analyze trends that occurred at the downtown Houston site. Other tree species sampled included water oak (*Quercus nigra*), southern red oak (*Quercus falcata*), and American sweetgum (*Liquidambar styraciflua*). Not all of these measurements are presented in this thesis.

All data processing and analysis was done in R and Microsoft Excel. R is a computer language and environment used for statistical analysis and graphic production. It is free software developed as a GNU project and available for download online [R Core Team 2012]. Statistical analyses done include student t-tests, analysis of variance, and linear regression, all of which are functions built into R.

3. EVALUATION OF URBAN CLIMATE VS. CLIMATE CHANGE

3.1 Introduction

The first part of this project, which must be completed before knowing how to interpret photosynthesis measurement results, is an evaluation of the quality of the chosen locations, specifically with regard to how well the chosen urban-to-rural gradient reflects the expected changes that are predicted to result from global climate change. This will be done in steps; first an examination of literature and IPCC reports is necessary to determine effects expected from climate change. Then, the experiment's data will be analyzed to determine if changes along the urban-to-rural gradient are similar to the expected changes resulting from climate change. Then the collected photosynthesis data can be interpreted both in terms of the effects of urbanization and the effects of climate change.

3.1.1 Expected Changes from Climate Change

Global climate change observed over the last 50 years is very likely not caused by natural forcings [IPCC 2007]. Carbon dioxide, CO_2, emitted by the burning of fossil fuels and as a result of deforestation, represents the largest anthropogenic contribution to climate change [IPCC 2007]. The warming that results from anthropogenic greenhouse gas emissions leads to several feedbacks that also increase atmospheric carbon dioxide concentrations such as thawing of permafrost and increasing respiration rates. Background carbon dioxide concentrations have increased from 270 ppm in pre-industrial times to 391 ppm in 2005 [IPCC 2007], reaching 399.77 ppm during May

2013 at the Mauna Loa NOAA ESRL observing station [Tans 2014]. Concentrations are expected to continue increasing at increasing rates until major policy changes are made.

Increased atmospheric carbon dioxide concentrations have a direct effect on global temperatures. Anthropogenic emission scenarios, along with natural feedbacks, lead to estimated temperature increases between 1.8°C and 4°C, but possibly as high as 6.4°C during this century [IPCC 2007]. Depending on the emissions scenario, the fastest rate of increase will occur during the middle to late part of the century, and only a 0.15°C to 0.3°C increase per decade for the near-term projections [IPCC 2007]. But these are global estimates, and warming will be neither spatially nor temporally uniform. Warming is projected to be more extreme in polar regions than in tropical regions [IPCC 2007]. Additionally, studies have found that for a given location, the frequency of extreme heat events will increase as the frequency of extreme cold events decreases [IPCC 2007]. On even smaller time scales, it has been observed that night time minimum temperatures during the 20th century increased more than day time maximum temperatures resulting in an overall decrease in the diurnal temperature range (DTR) [IPCC 2007, Zhou 2009]. Projections indicate regional variability in diurnal temperature range will be closely anti-correlated with cloud cover [IPCC 2007].

Projected changes in precipitation are also variable at regional scales. In general, increases in precipitation can be expected in the high latitudes while decreases can be expected in the subtropics [IPCC 2007]. Additionally, as a result of higher temperatures and thus the capacity for higher atmospheric water vapor concentrations, the frequency of heavy precipitation events is expected to increase [IPCC 2007].

3.1.2 Expected Effects of Urbanization

Compared to global climate change, urbanization affects climate on a relatively local scale; however the magnitude of its effects can be just as strong. One of the most studied aspects of urbanization is the urban heat island, UHI, effect. It describes the phenomenon of urban areas being warmer, sometimes several degrees warmer, than their surrounding countryside. This effect results from a number of different causes including:

- City canyon effect, in which large vertical surfaces of tall buildings make it more difficult for longwave radiation to escape, thus decreasing longwave albedo,
- Lowered evapotranspiration due to reduced vegetation amounts,
- Increased heat storage due to construction materials with high heat capacities,
- Direct, anthropogenic heat emissions from buildings and vehicles, and
- Some urban surfaces (e.g. pavement, roofs) being darker than undeveloped surfaces, such as bare soil or grassland, resulting in lower shortwave albedo. [U.S. EPA 2008].

Like climate change, the temperature increases that result from urban heat islands are not spatially or temporally uniform. Rather, the strongest effects are seen during the winter and at night such that the diurnal temperature range is decreased as a result of the heat island [U.S. EPA 2008]. There is also some indication that urban heat islands can increase precipitation 30-60 km downwind of cities [Kanda 2007]; however it was concluded that more observations would be necessary before determining the urban effect on precipitation [Kanda 2007].

Further studies have established that in addition to heat islands, urban areas can also form islands of elevated carbon dioxide [George 2007, Weissert 2014]. While carbon dioxide is a long lived gas and can be described as having near uniform background levels across the globe, which will continue to increase as anthropogenic emissions continue, proximity to emission sources can cause elevated concentrations on a regional scale. In addition to regionally increased concentrations, another study has shown that urban canopy structure in combination with a stable night time boundary layer can cause carbon dioxide build-up in excess of the surrounding areas [Moriwaki 2005].

Urban areas are also frequently noted for their pollution plume, which is an area of increased atmospheric pollution, notably ozone (Trainer et al., 1995; Schade et al., 2011), downwind of city sources. Ozone is considered a secondary pollutant, meaning that it is formed by a series of chemical reactions that begin with primary pollutants. The ozone formation pathway is [Sharkey 2007]:

$$VOC + \bullet OH + O2 \rightarrow RO2 + H2O \qquad [R1]$$

$$RO2 + NO \rightarrow RO + NO2 \qquad [R2]$$

$$RO + O2 \rightarrow R`CHO + HO2\bullet \qquad [R3]$$

$$HO2\bullet + NO \rightarrow NO2 + \bullet OH \qquad [R4]$$

$$2(NO2 + hv + O2 \rightarrow NO + O3) \qquad [R5]$$

This reaction series takes a few hours, so peak ozone concentrations are often found downwind of cities. One study done near Birmingham, AL found ozone concentrations highest 40 km downwind of the city center [Trainer 1995].

3.2 Results – Comparison of Urban and Rural Climate

Two years of data collection showed two different climatologies affected by a unique Houston area climate dominated by its proximity to the Gulf of Mexico, and highly variable based on synoptic weather conditions. To illustrate this, this thesis will present both climatic means and analytical case studies.

3.2.1 Means

3.2.1.1 Temperature

Average temperatures for the three sites are shown in figure 4. JDHS was warmer than both of the other two sites during both years. 2011 was characterized by a record setting summer. Both June and August 2011 were the warmest Junes and Augusts on record, and April through September were all in the top ten [HGX Webmaster 2013]. Daytime temperatures during the summer were at least 2.5°C warmer in 2011 than in 2012 at all three sites. The urban heat island effect is very clearly observed as the downtown Houston site consistently 1-3°C warmer than the rural site with the exception of daytime summer temperatures. The Houston UHI effect is further illustrated in figures 5 and 6, which show spatially extrapolated temperature data from this project's three weather stations alongside TCEQ (Texas Commission on Environmental Quality) and NCDC (National Climatic Data Center) station temperature data. In figure 5 (winter morning), the UHI effect is very evident, and while the Gulf of Mexico is the warmest feature on the map, downtown Houston, Galveston, and the other urban and suburban areas are significantly warmer than the rural sites.

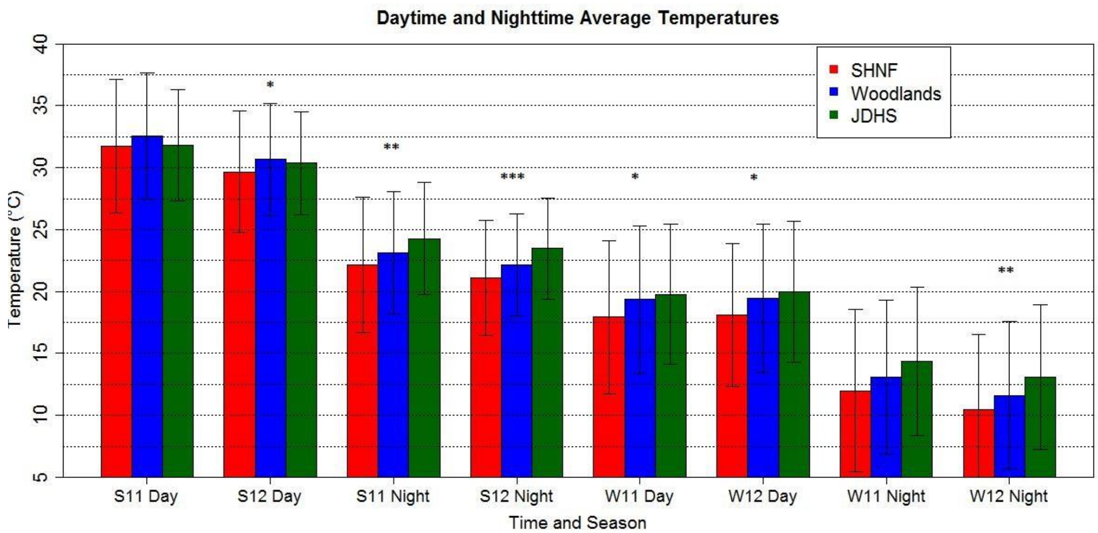

Figure 4**:** Mean Temperatures at Weather Stations

Mean temperatures and standard deviations from each site for summer (JJA) and winter (DJF), day (12PM to 6PM LDT) and night (1AM to 6AM LST). Asterisks represent the significance of the difference between the highest and lowest temperature. * = 0.1; ** = 0.05; *** = 0.01.

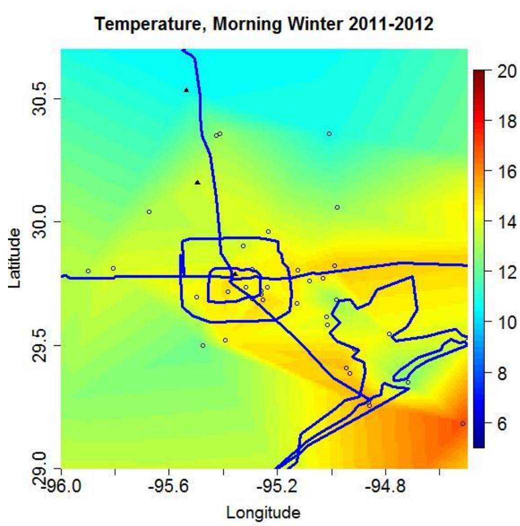

Figure 6: Spatial Temperature Patterns, Winter Morning

Average morning (10AM – 12PM LST) winter temperatures. Project weather stations represented by triangles, TCEQ represented by circles, and NCDC sites represented by x's.

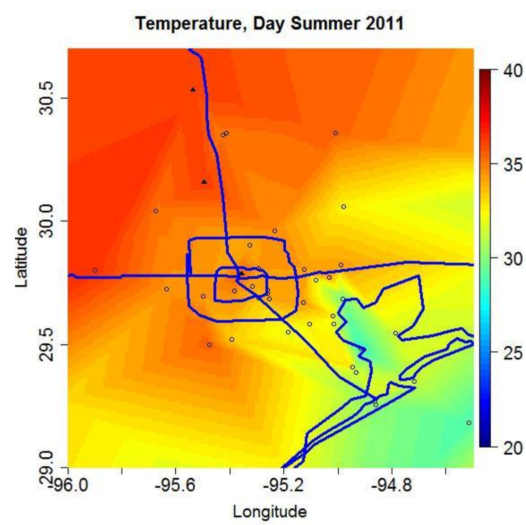

Figure 5: Spatial Temperature Pattern, Summer Day

Average daytime (12PM – 6PM LST) winter temperatures.

In comparison, figure 6 (summer day) shows The Woodlands and Sam Houston National Forest as slightly warmer than Houston, driven by an afternoon sea/bay breeze that is present on most days during the summer. Figure 7 shows the average diurnal cycle of temperature at each site. Of note is that the maximum daytime temperature in Houston is reached earlier in the day than at either The Woodlands or Sam Houston National Forest. A previous study has found a similar phenomenon of sea surface temperatures and sea breezes affecting urban heat islands and potentially rainfall during the summer [Oda 2009]. As the Gulf of Mexico/Galveston sea/bay breeze front moves inland, it causes a significant temperature drop at the JDHS site during passage, which usually happens just before the expected daytime maximum temperature, thus affecting daytime averages under southerly wind directions dominant during summer.

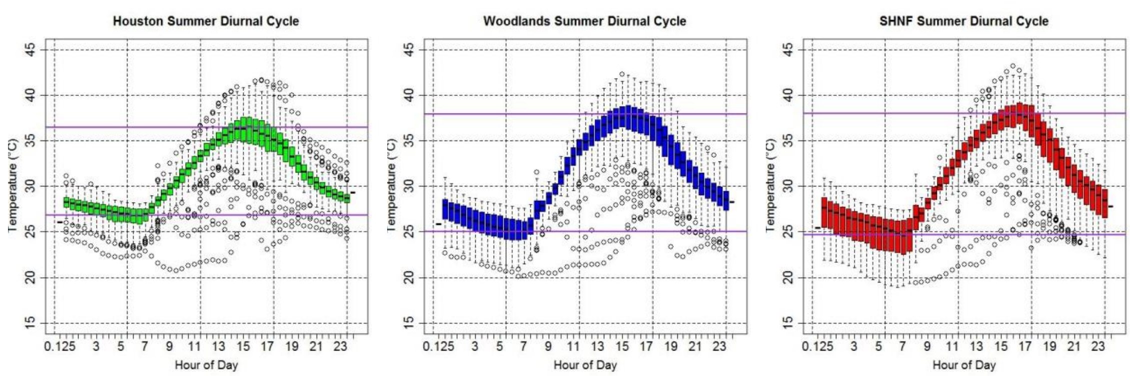

Figure 7: Average Diurnal Cycle

Average diurnal cycle (in LST) made by averaging temperatures every half hour during the 2011 summer. Horizontal lines indicate the average high and low temperatures.

3.2.1.2 Precipitation (Frequency and Intensity)

There were approximately half as many days experiencing rain in 2011 than in 2012, but in both cases, the rural location had more rainy days than either the suburban or urban sites (figure 8a). The rural site also received significantly more precipitation than the other two sites during 2011 (figure 8b), and on average received 14.1 mm of rain per rainy day compared to 11.1 mm and 10.2 mm for the suburban and urban sites. However, this pattern does not hold true for 2012. The SHNF rainfall data for 2012 is likely wrong since NCDC sites in Conroe and Huntsville both received more than twice the amount of precipitation that the SHNF site measured, and increases in soil water content following rain events indicated that much more rain fell than was recorded by the rain gauge. Using changes in soil water content from 2011 as a local metric (r^2 of 0.69) for estimating rainfall in 2012, the rainfall at SHNF would amount to 1453 mm (±320 mm). Figure 9a-b shows the SHNF regression and a comparison with a similar regression analysis for the Woodlands site. The result is on par with measurements from the two closest NCDC sites in Conroe and Huntsville, which showed increases from 806 mm to 1168 mm and 673 mm to 1053 mm from 2011 to 2012, respectively.

However, even though SHNF received more rain than either of the other two sites, average rainfall intensity and maximum intensity in SHNF was different. Calculating rainfall intensity as the amount of rainfall per day [IPCC 2007], we found that SHNF rainfall intensity was lower than either of the other sites during 2011 (figure 10). JDHS saw an average intensity of 10.4 mm/day in 2011 while SHNF saw an average intensity of only 8.1 mm/day. Figure 11 illustrates that rain in SHNF was dominated by days with intensity below 1.6 mm/day while JDHS and the Woodlands had median rainfall intensities at 3.3 and 5.5 mm/day, respectively.

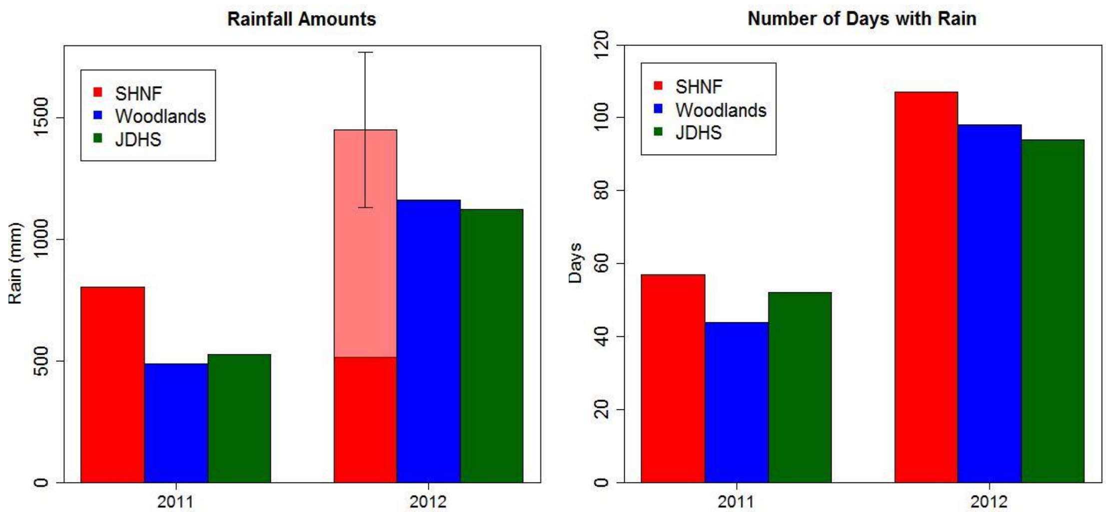

Figure 8: Rainfall Amounts and Frequency

Number of days with rain and the amount of rain measured at each site during 2011 and 2012.

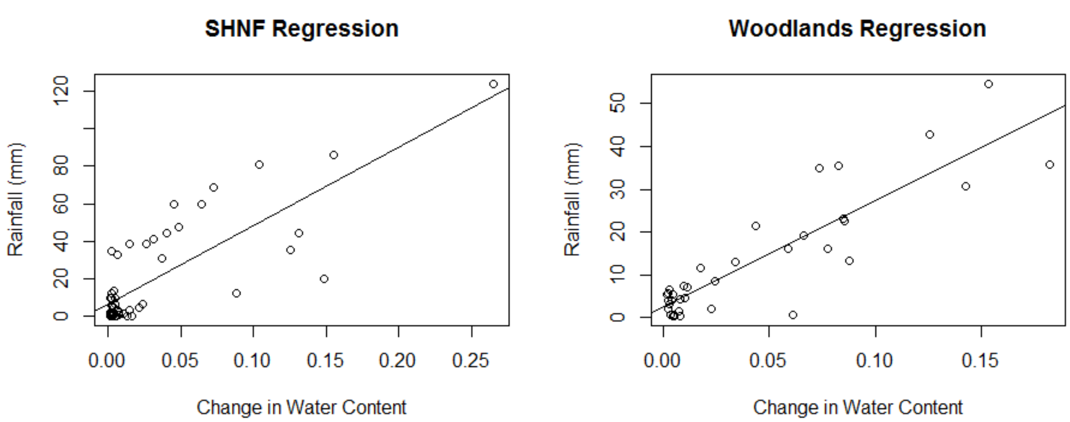

Figure 9: Comparison of Regression used for SHNF Precipitation Estimation

The SHNF regression had an r-squared of 0.69 while the Woodlands regression had an r-squared of 0.78. For both regressions, rainfall amounts 0.2 mm and below were ignored.

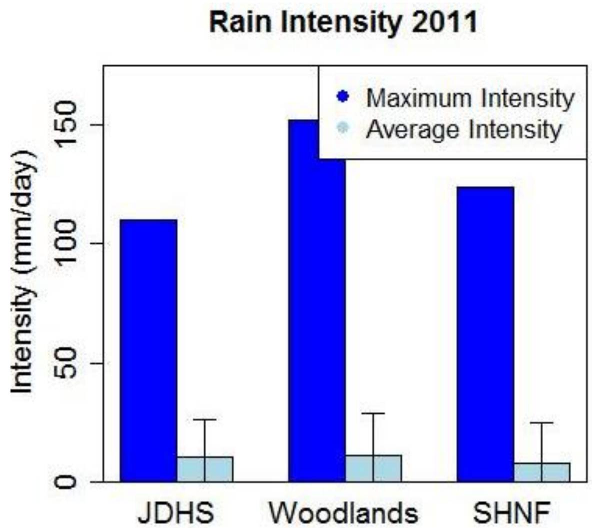

Figure 10: Rainfall Intensity 2011

Average rainfall intensity for JDHS was 10.3 ±15.5 mm/day, for the Woodlands it was 11.1 ±17.7mm/day, for SHNF it was 8.1±17.3 mm/day. Maximum rainfall intensity for JDHS was 110 mm/day, for the Woodlands it was 152 mm/day, and for SHNF it was 124 mm/day

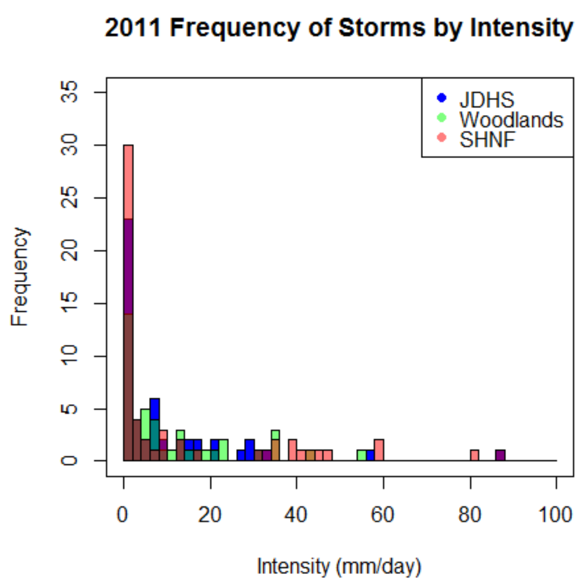

Figure 11: Frequency of Storms by Intensity

Note that the overlay of colors indicates an occurrence at multiple sites, so rain occurring at all three sites appears as a brown bar (blue + green + red).

3.2.1.3 Carbon Dioxide

Daytime carbon dioxide concentrations during both years were higher in downtown Houston than at either the suburban or rural sites (figure 12). However the opposite tended to be true for night time observations with carbon dioxide concentrations usually being significantly lower in Houston than at the other two locations. This is likely the result of the urban heat island effect, which typically leads to higher nocturnal boundary layers [Pal 2012], which combined with less vegetation reducing plant respiration lowers CO_2 in Houston compared to the other two sites. It appears that although nighttime temperatures are higher in Houston, this effect is overridden by the fact that impervious areas, typically varying between 30 and 90% of surface in urban areas, strongly reduce the amount of emitting soil and plant surfaces. Although anthropogenic emissions may be expected to compensate for the lack of vegetation respiration, most anthropogenic emissions (e.g. from car traffic) occur during daytime, and human respiration does not compensate for lack of plant respiration either.

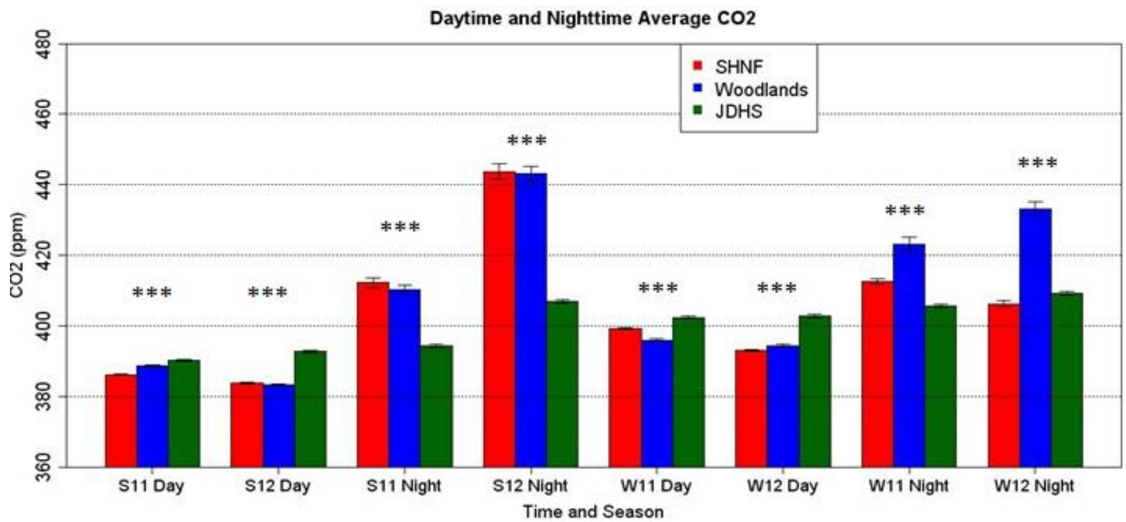

Figure 12: Mean CO_2 Concentrations at Weather Stations

Asterisks represent the significance of the difference between the highest and lowest temperature. * = 0.1; ** = 0.05; *** = 0.01.

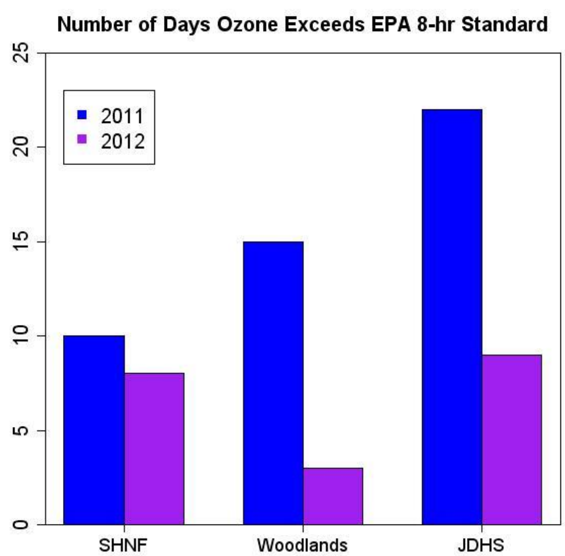

Figure 13: Number of Days with Ozone Exceedances

Number of days each year that ozone concentrations exceeded the EPA 8-hour standard at each weather station.

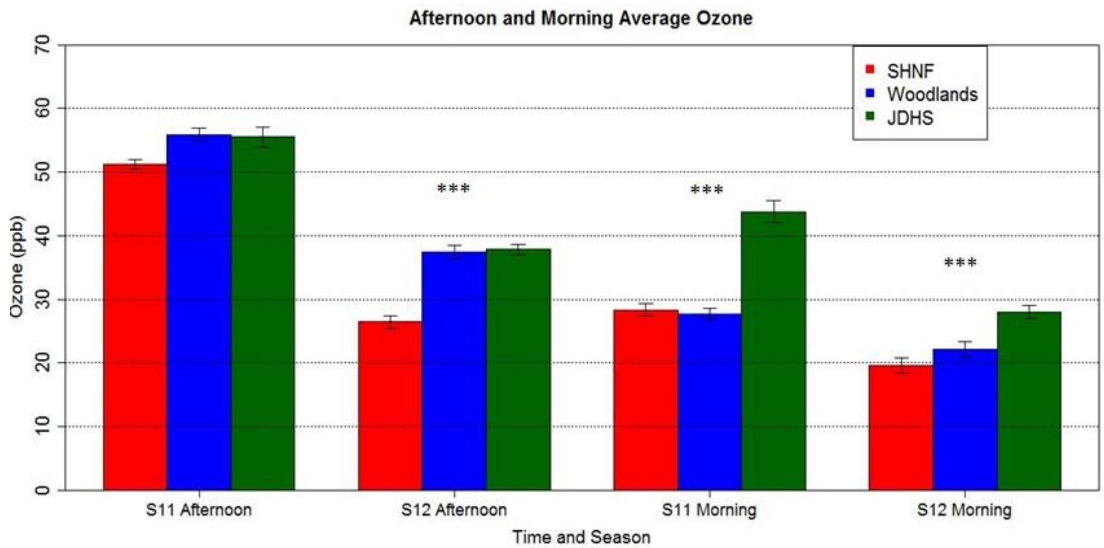

Figure 14: Mean Ozone Concentrations at Weather Stations

Ozone concentrations measured at each site during the summer mornings (10AM to 12PM LST) and afternoons (3PM to 8PM LST).

3.2.1.4 Ozone

Ozone is an EPA regulated pollutant under the National Ambient Air Quality Standards (NAAQS) with the current limit set at an 8-hour average of 0.075 ppm (strictly, referring to the 4^{th} highest value using a 3-year time-series, the so-called “design-value”). Figure 13 shows the number of days that each site exceeded the EPA standard during each year, and figure 14 shows the average summer time ozone concentrations. From figure 14, it is clear that summer time afternoon ozone concentrations during 2011 were much higher at all locations than during 2012. This can also be inferred from figure 13, at least for The Woodlands and downtown Houston, which both saw large decreases in the number of days they violated the EPA 8-hour standard from 2011 to 2012. However the Sam Houston National Forest site did not show a similarly large change.

Figure 15 shows two ozone indices, w126 and AOT40. Both are designed for the purpose of quantifying the effect ozone has on agricultural crops. The w126 is a weighted index such that higher ozone concentrations have a larger effect than lower concentrations [U.S. EPA 2010]. The weighting formula used is:

$$Daily\ Index = \sum_{i=8am}^{7\ pm} [O_{3i}] \times \left(\frac{1}{1 + (4403\ \times\ e^{-126\times[O_{3i}]}}\right)$$

where brackets denote concentration. The index is designed to reflect ozone's increasing and non-linear detrimental effects on photosynthetically active plants. EPA suggested in 2010 (U.S. EPA 2010) to sum daily index values over three months as the appropriate measure for rural ozone exposure during the vegetative season. The older AOT40 index looks only at ozone concentrations over 40 ppb, but all concentrations are weighted the same so long as they are above the 40 ppb cutoff [U.S. EPA 2006]. Calculating the AOT40 index is done by:

$$AOT40 = \sum([O_3] - 40) \times time$$

where only ozone concentrations over 40 ppb are used. When ozone concentrations exceed 40 ppb only marginally, there is not much difference between the two indices, but they each tell a different story when comparing their values in the light of peak ozone concentrations. The three-month sums at JDHS during both years reached a peak during October. The AOT40 index reached 18 ppm·h in 2011 and decreased 66% to 6.2 ppm·h in 2012. On the other hand, w126 reached 23.5 ppm·h in 2011 and decreased

70% to 7.1 ppm·h in 2012. This is largely because the highest ozone concentration during the August to October period of 2012 was 92 ppb. During the same months in 2011, this concentration was exceeded on 19 days. Such very high concentrations in 2011 are weighted much more heavily on the w126 index than on the AOT40 index, and thus the w126 index emphasizes the difference between the two years.

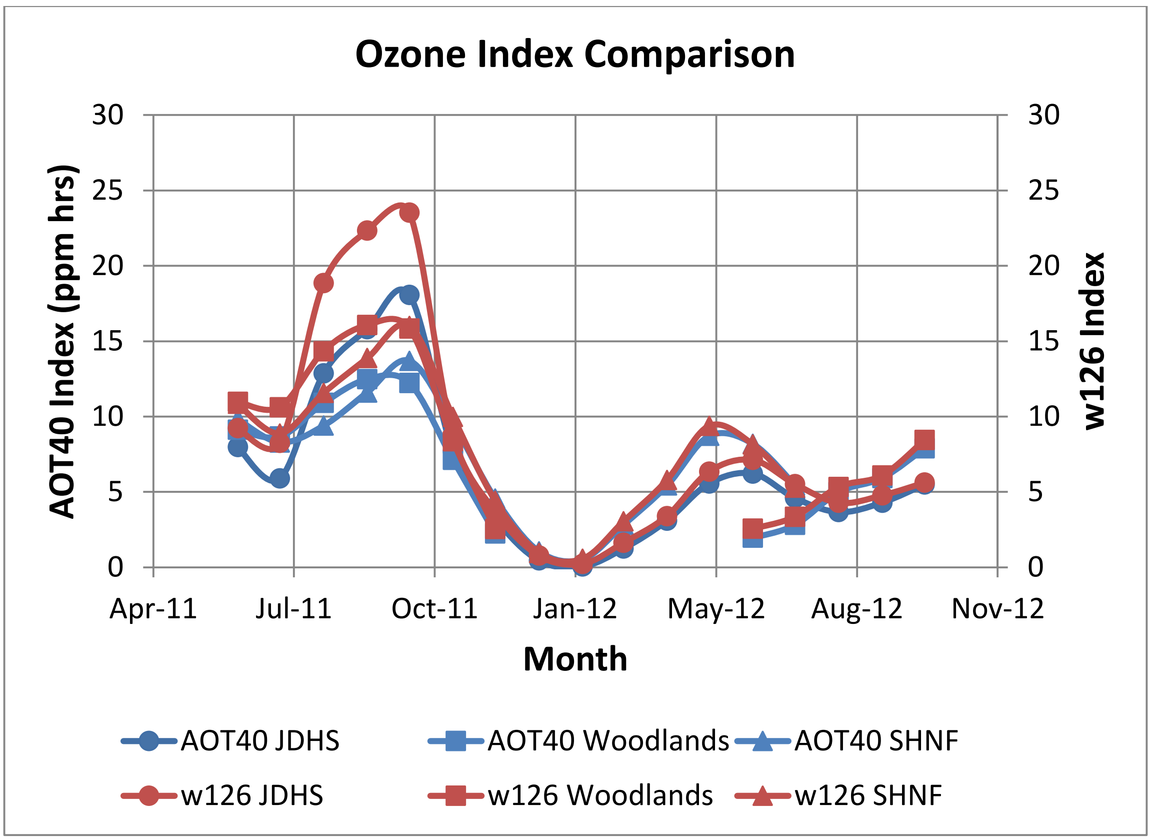

Figure 15: Ozone Index Comparison

Two common ozone indices, AOT40 and w126, are compared. Both are designed with the purpose of examining the impact ozone can have on agricultural crops and other plants.

3.2.2 Case Study - High Ozone

The days of August 12, 2011 (doy 224) through August 31, 2011 (doy 243) provided an excellent opportunity to examine the potential effects of high ozone on the field-grown oaks studied. During this three week period, the ozone meters recorded ozone levels in excess of the EPA standard at Houston on 16 days, at The Woodlands on 7 days, and at SHNF on 4 days. However, on the final two days of this period (242 and 243), Houston concentrations stayed much lower than concentrations in The Woodlands and SHNF. The reason for this was evaluated via NOAA Hysplit back trajectories, surface weather maps, and surface ozone concentration time series. Back trajectories were calculated using the NAM (North American Mesoscale Forecast System), 12 km gridded meteorological input data. August 26, 2011 (figure 16) illustrates a low wind speed condition where winds in Houston were coming from Houston and transporting pollutants downwind to the other two experimental sites. The initial concentration increase in Houston is likely caused by mixing after the nocturnal boundary layer broke up, and concentrations continued to increase throughout the day as a result of emissions and low wind speeds. Downwind of Houston, there were comparable morning increases in ozone, but afternoon increases are noticeably offset by the amount of time needed for the Houston plume to reach those sites; the increase in Woodlands occurred at ~1900 LST and the increase in SHNF approximately two hours later.

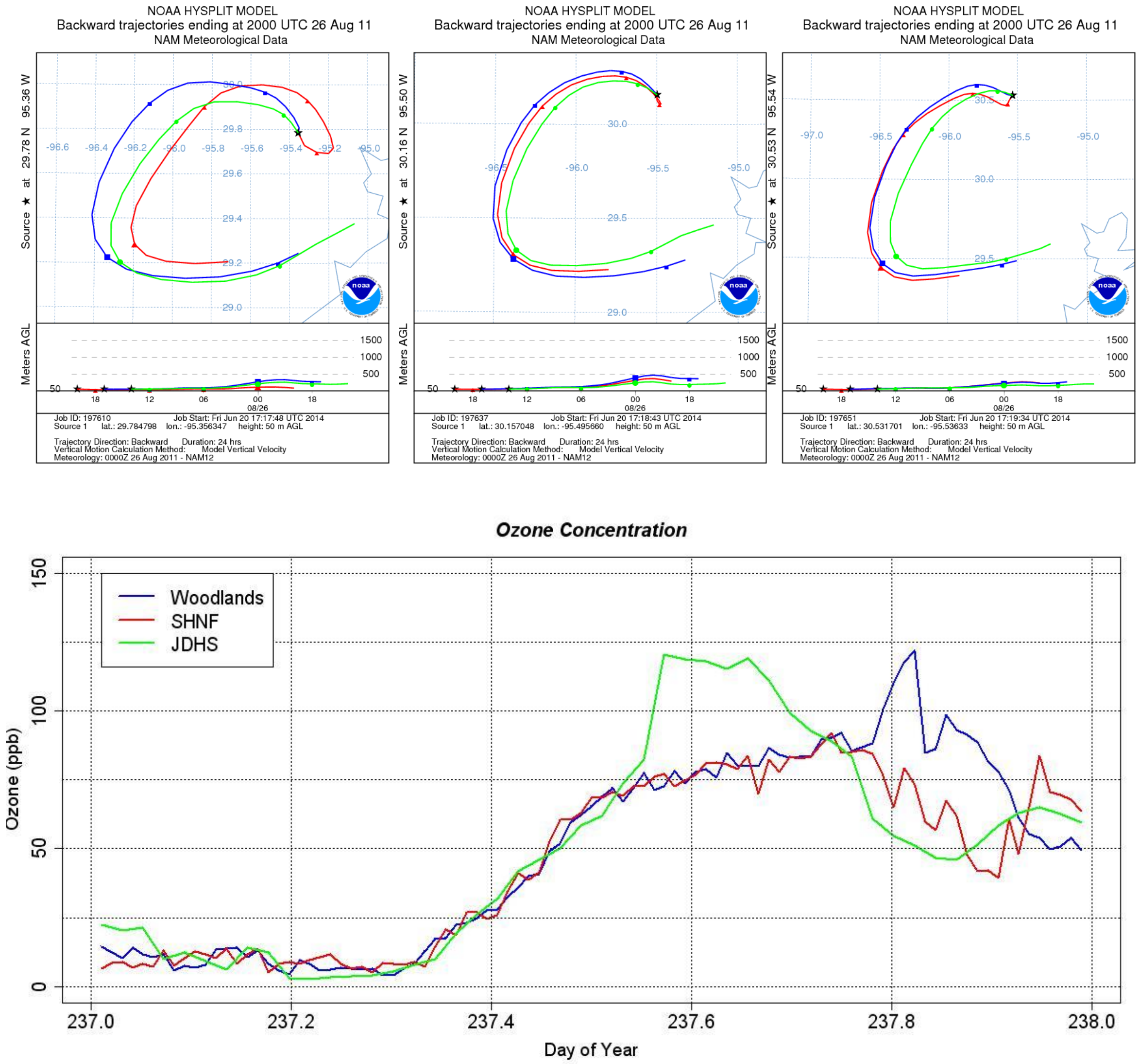

Figure 16: High Ozone Case Study, August 26, 2011

Winds were slow throughout the day (green, blue then red ending at 1400, 1700, 2000 LST), as indicated by the points along each trajectory indicating 1800, 1200, 0600, 0000 LST. At all times, however, winds originated in Houston, before rotating clockwise to their destination. The plot of vertical height indicates subsidence.

Three days later, a weak stationary front had developed in the experiment area (figure 17). This meant the establishment of a continental air mass on its northeast side. For the region, this type of air mass typically has higher than normal background ozone concentrations. Therefore, when the nocturnal boundary layer broke up over SHNF and The Woodlands, mixing of surface air with the free troposphere dramatically increased surface ozone concentrations even faster than the concentration increased in downtown Houston (figure 18). Wind speeds were also faster on August 31, 2011 preventing JDHS ozone concentrations from getting as high as they did on August 26.

By September 1, 2011, all three sites were seeing rapidly increasing ozone concentrations in the morning when the nocturnal boundary layer disintegrated (figure 19). However, winds shifted over the course of the day, so air reaching the Woodlands and SHNF largely missed Houston, and so ozone concentrations did not reach as high as they had on August 29 because fewer ozone formation precursors (NO_x and VOCs) were advected towards the more rural sites.

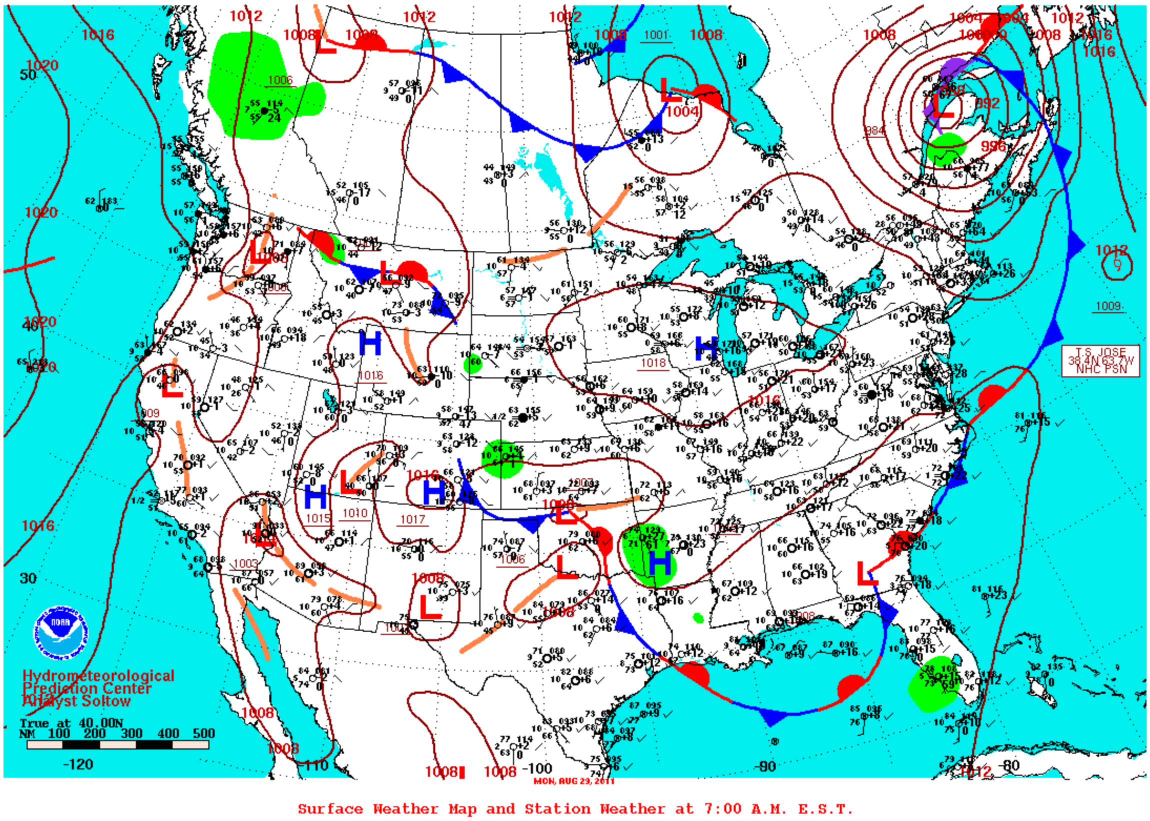

Figure 17: Surface weather conditions for August 29, 2011 [NOAA 2014].

A stationary front is located in the experiment area, which would have higher than normal background ozone concentrations for the area.

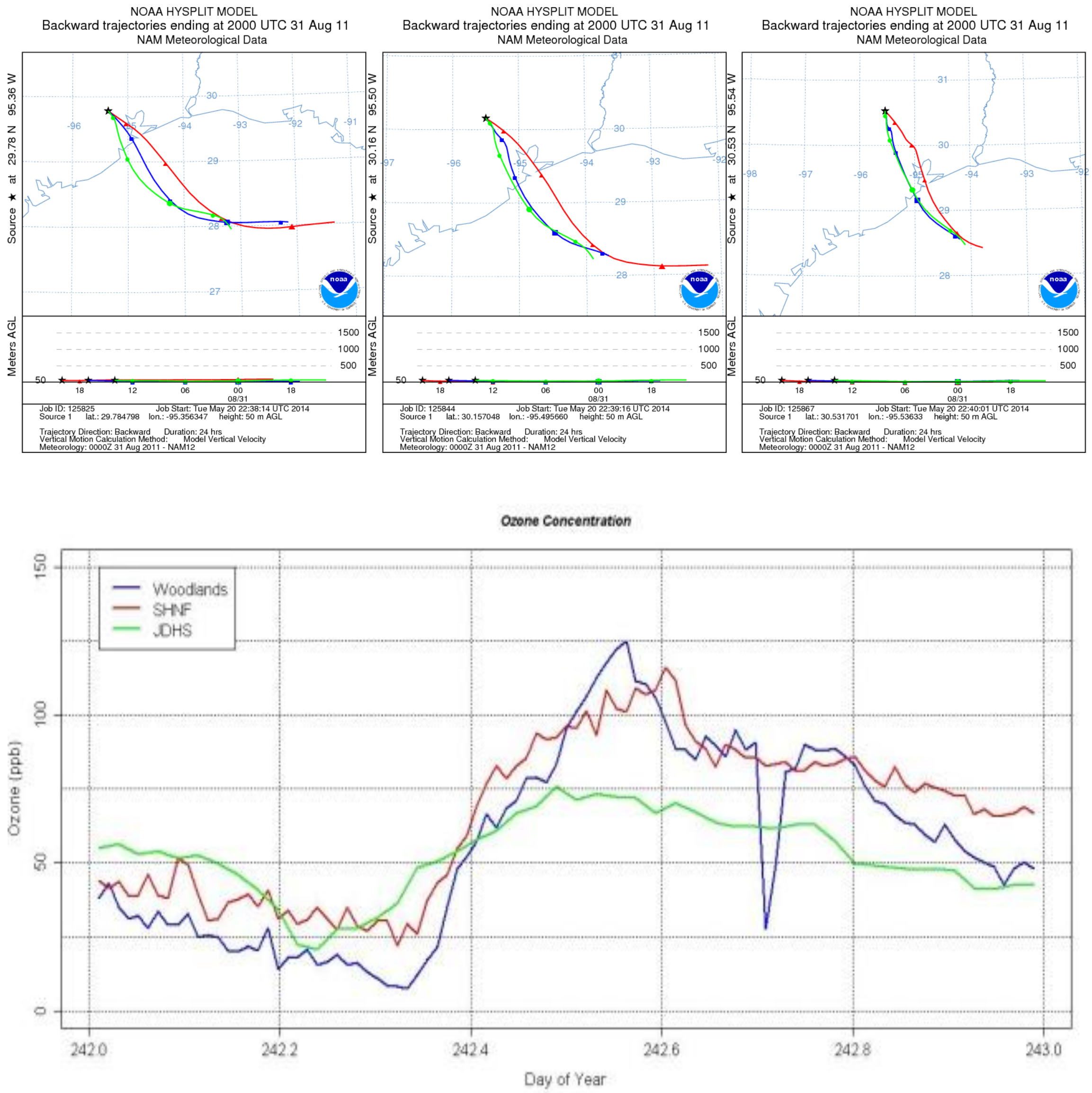

Figure 18: High Ozone Case Study, August 31, 2011

Early winds are slightly faster on this day than on August 26, 2011, and still increase throughout the day. Trajectories are originating from the Gulf of Mexico.

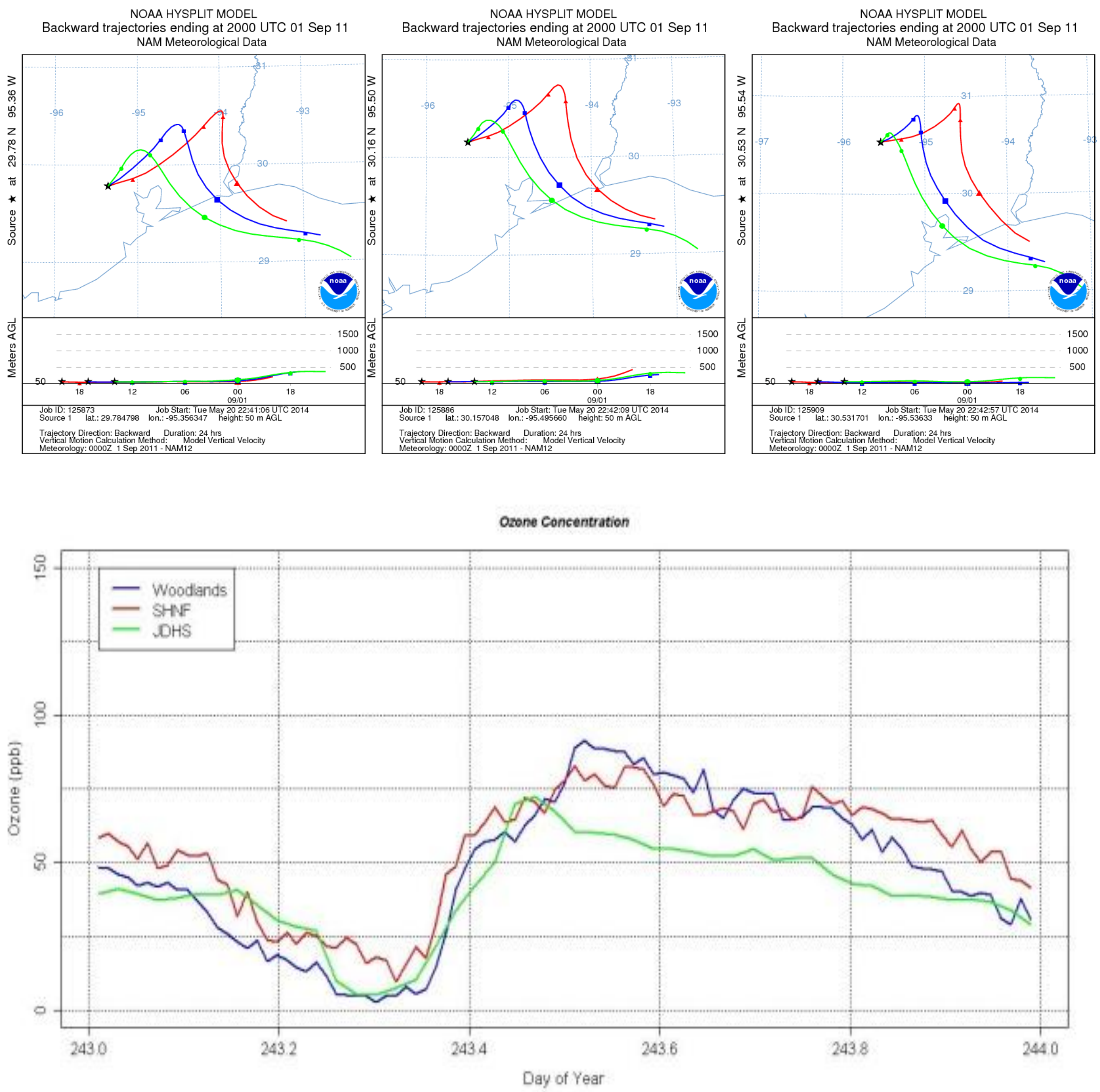

Figure 19: High Ozone Case Study, September 1, 2011

Morning wind speeds are significantly higher than on the previous two case study dates and are generally coming out of the east.

Under significant wind speeds reinforced by a summer synoptic meteorological setup, ozone values in Houston typically remain lower due to constant advection of low ozone level Gulf of Mexico air masses. However, ozone builds up as the air advects north of Houston, with speed and direction dictating where the afternoon ozone maximum materializes. Thus, even though the region north of Houston produces few ozone precursors, it is affected by high ozone in Houston's urban pollutant plume under typical summer southerly air flows, particularly when wind speeds are relatively low.

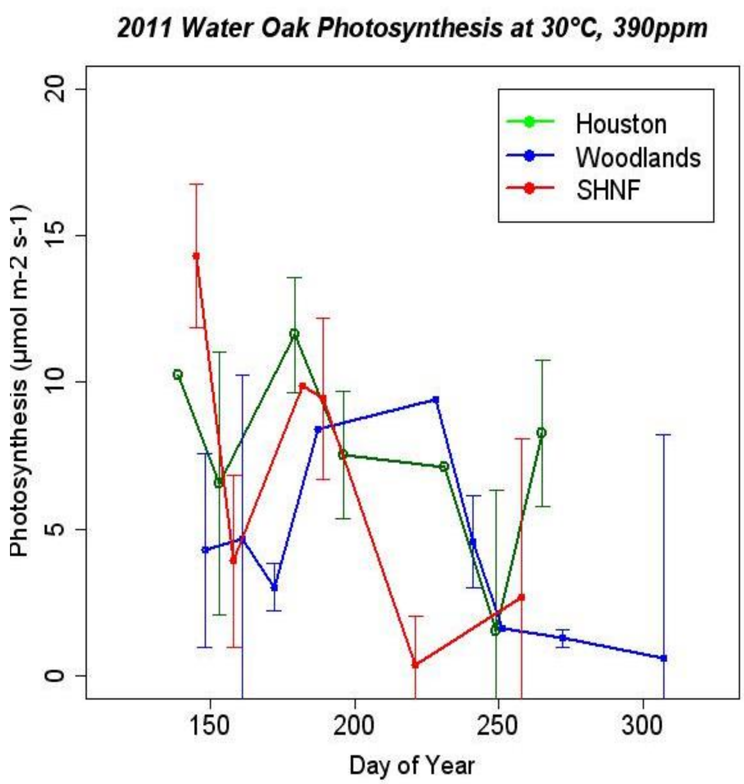

Figure 20: Water Oak Photosynthesis Rates at Standard Conditions

Standard water oak photosynthesis measurements were made at 30°C and 390 ppm CO_2.

It appears likely that several factors, high temperatures, low soil moistures and high ozone may have led to the dramatic decrease in water oak photosynthesis rates in Houston and the Woodlands (figure 20). The SHNF water oak photosynthesis rate was already very low, so it is hard to tell how it was further affected by this period. Regardless, the trend was mirrored in the post oak photosynthesis rates at The Woodlands and SHNF, though it was not as strong as in the water oaks (figure 21).

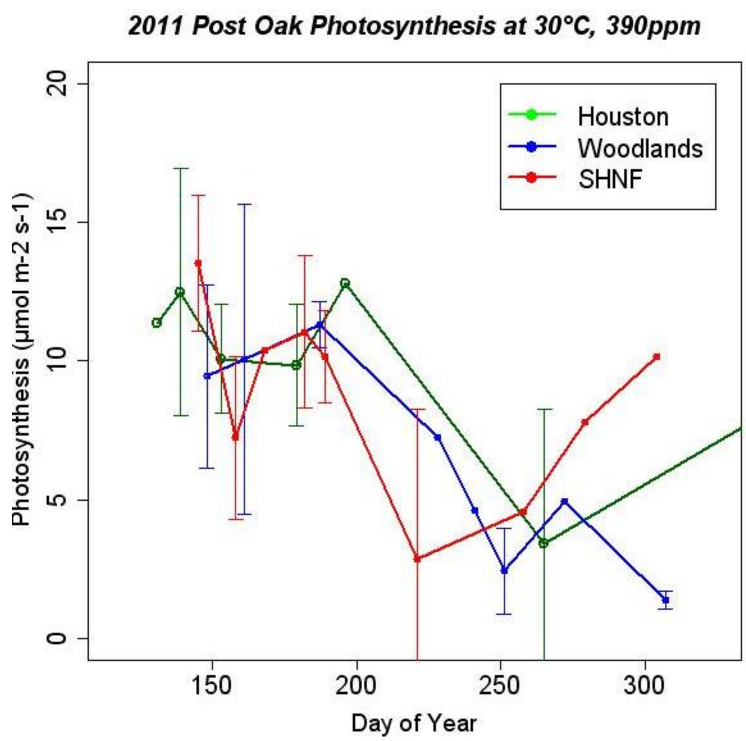

Figure 21: Post Oak Photosynthesis Rates at Standard Conditions

Standard water oak photosynthesis measurements were made at 30°C and 390 ppm

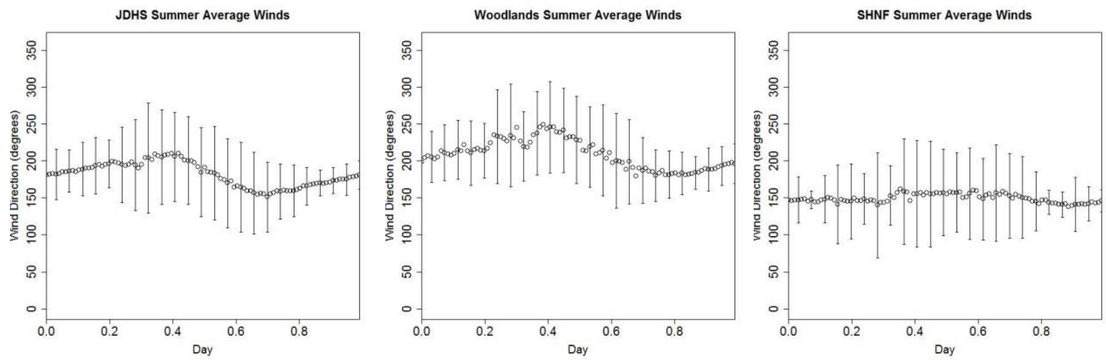

Figure 22: Average Diurnal Wind Directions

Wind directions were averaged every 15 minutes for each day in JJA 2011. Error bars are spaced every hour and represent the standard deviation for the 15-minute interval. Wind speeds below 0.2 m/s are not included.

3.2.3 Case Studies - Winds from Different Directions

3.2.3.1 Case Study - Winds from Different Directions: SE

Wind direction and speed plays a significant role in the day to day weather and air quality in the Houston area. Winds most often come from the south or south east, from the Gulf of Mexico. Average wind directions for each site over the course of summer 2011 are shown in figure 22. The wind directions for all three sites on June 11, 2011 are shown in figure 23. For much of the day, winds were coming out of the SSE at all three sites, but still closely mirrored the average wind directions from figure 22. NOAA Hysplit model back trajectories (figure 24) show that the air mass was coming straight off the Gulf of Mexico. Figure 25 shows the temperature development for the day which closely mirrored the summer 2011 average diurnal cycle (figure 7). The temperature at JDHS reached a maximum earlier in the day than either Woodlands or SHNF, and begins cooling in the early afternoon because of a sea/bay breeze (figure 25).

Ozone concentrations (figure 26) were lower in Houston than at either of the downwind sites.

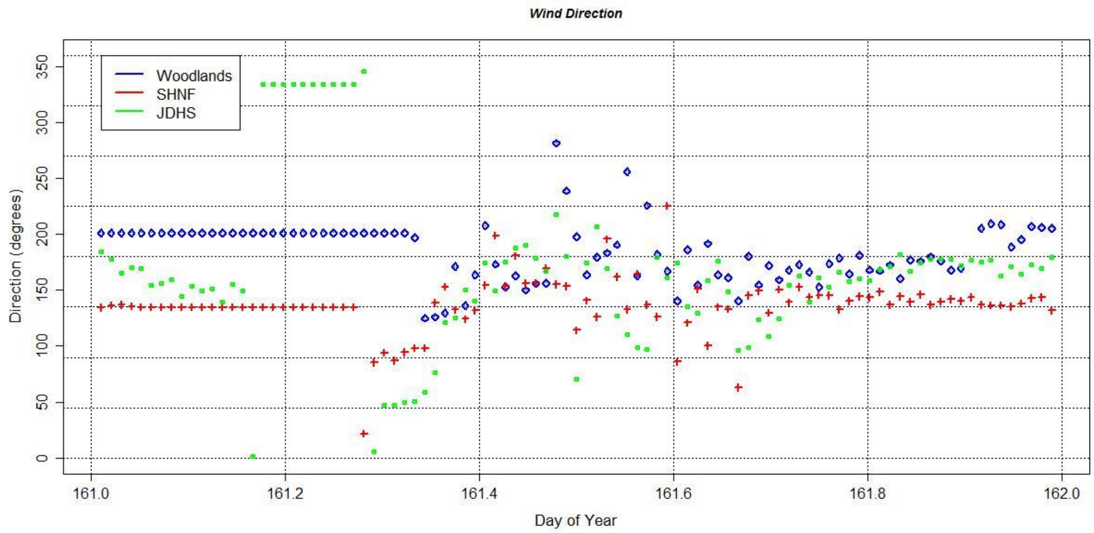

Figure 23: Case Study June 11, 2011 - Wind Direction

(Unchanging wind direction indicates calm conditions.)

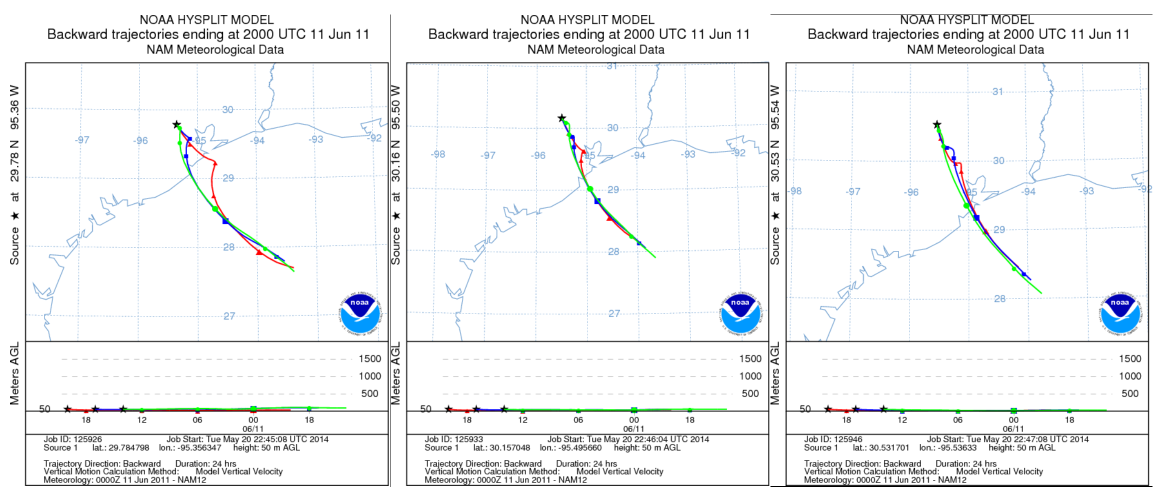

Figure 24: Case Study June 11, 2011 - NOAA Hysplit Back Trajectories.

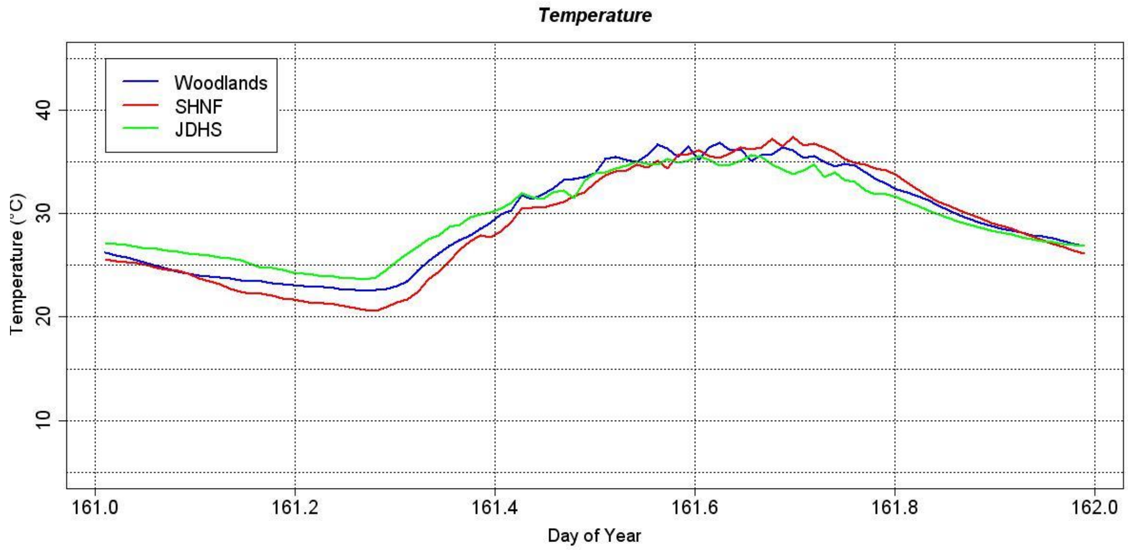

Figure 25: Case Study June 11, 2011 - Temperature

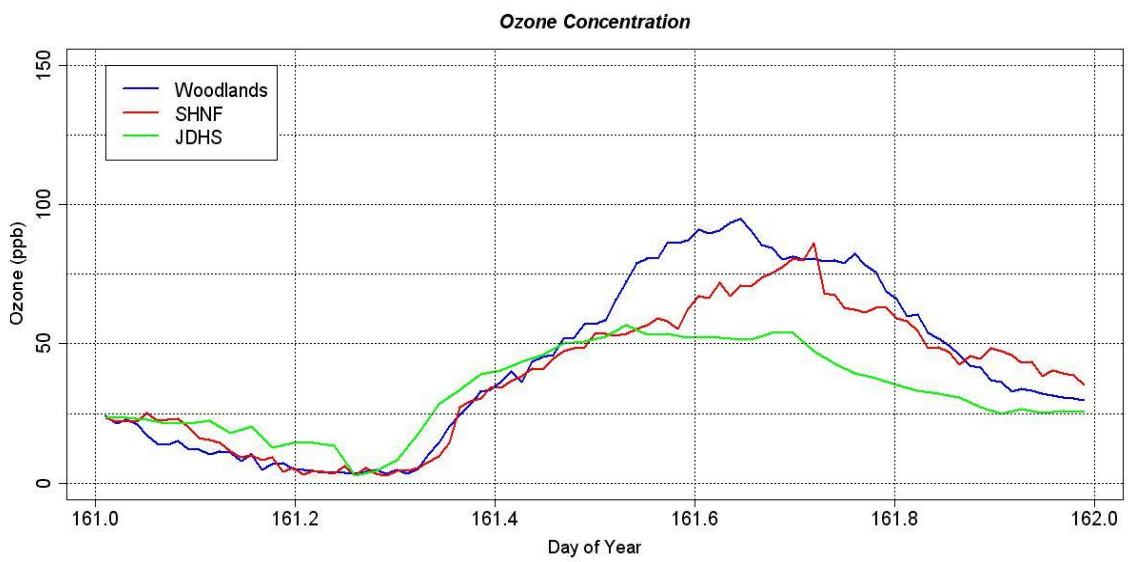

Figure 26: Case Study June 11, 2011 - Ozone Concentrations

3.2.3.2 Case Study 2 - Winds from Different Directions: NW

A very different wind pattern occurred on doy 325 (figure 27). Winds shifted from the SE in the morning to NNW in the afternoon at all locations consecutively as a cold front passed through (figure 28); temperature (figure 29) was higher in Houston throughout the day, and ozone concentrations (figure 30) were low. In Houston, the lowest ozone concentration occurred just after noon. Cold fronts typically occur during the late fall and winter, and rarely during the summer. Since this was a fall time cold front with cloudy and rainy skies, the replacing air mass, which seemingly did not originate in high ozone precursor emissions areas (Figure 28), was not elevated in ozone, and hardly any additional ozone formation occurred as a result of local formation in the afternoon following the frontal passage (Figure 29).

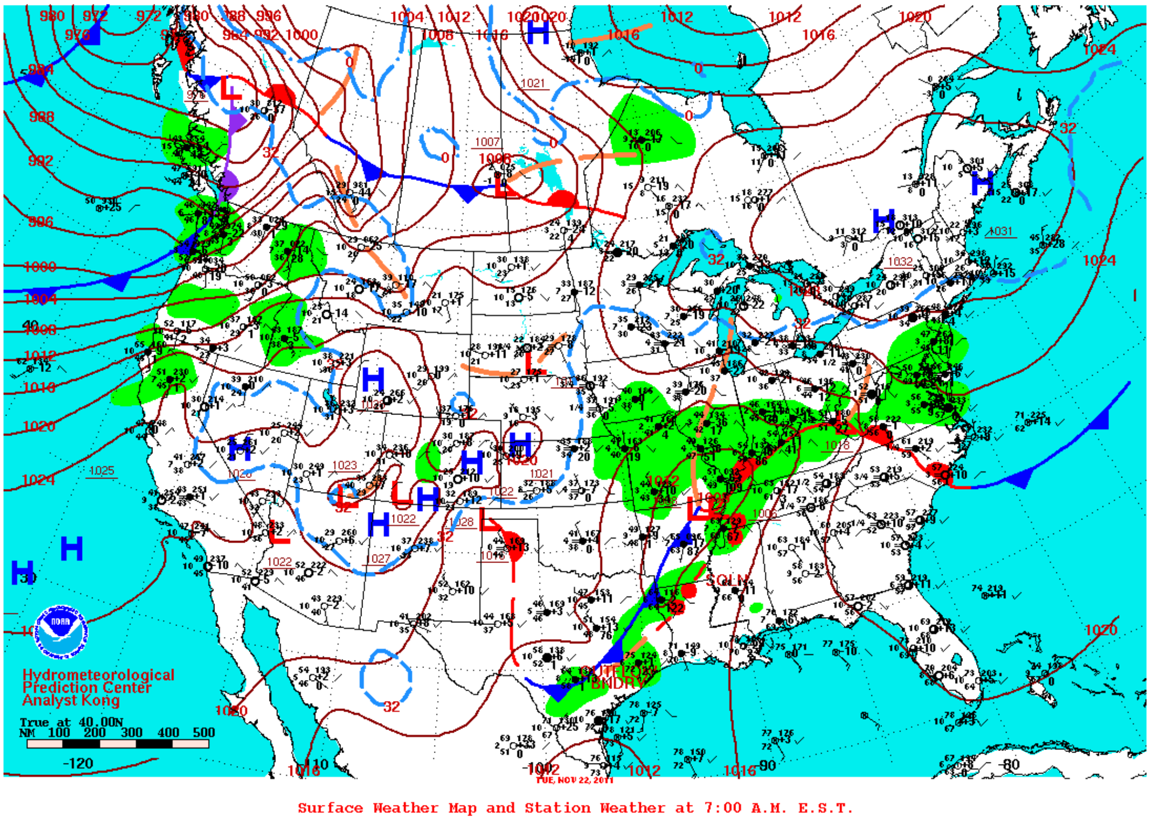

Figure 27: Surface Weather Map November 22, 2011

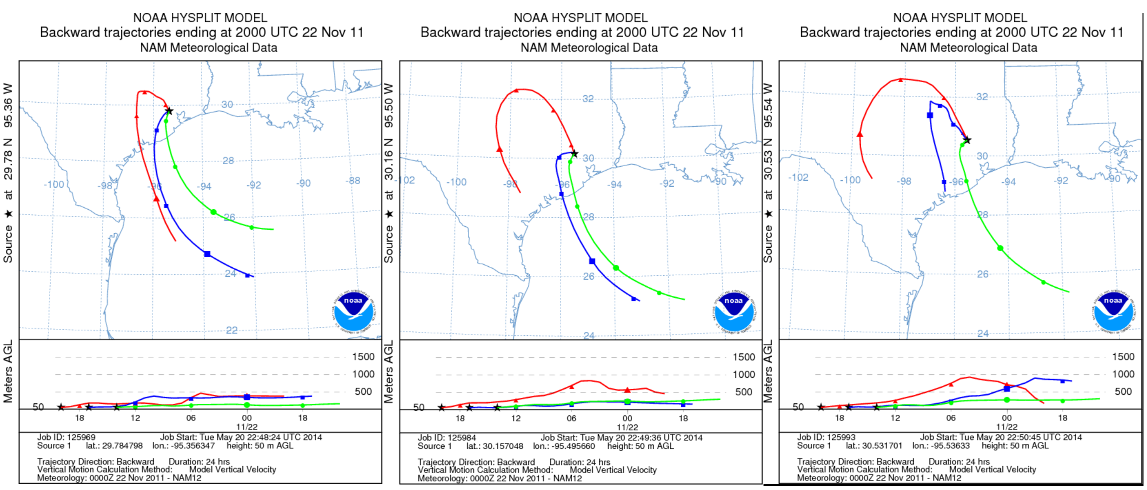

Figure 28: Case Study November 22, 2011 - NOAA Hysplit Back Trajectories

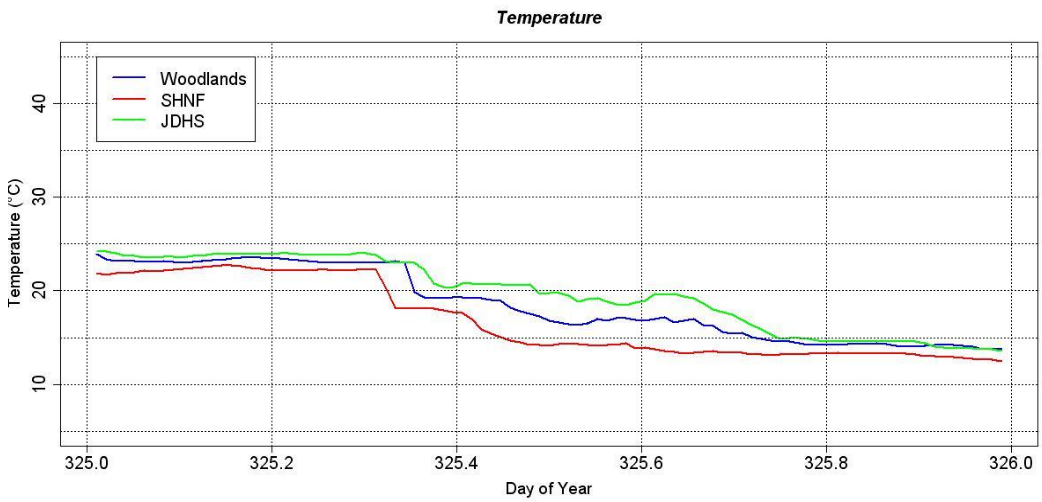

Figure 29: Case Study November 22, 2011 - Temperature

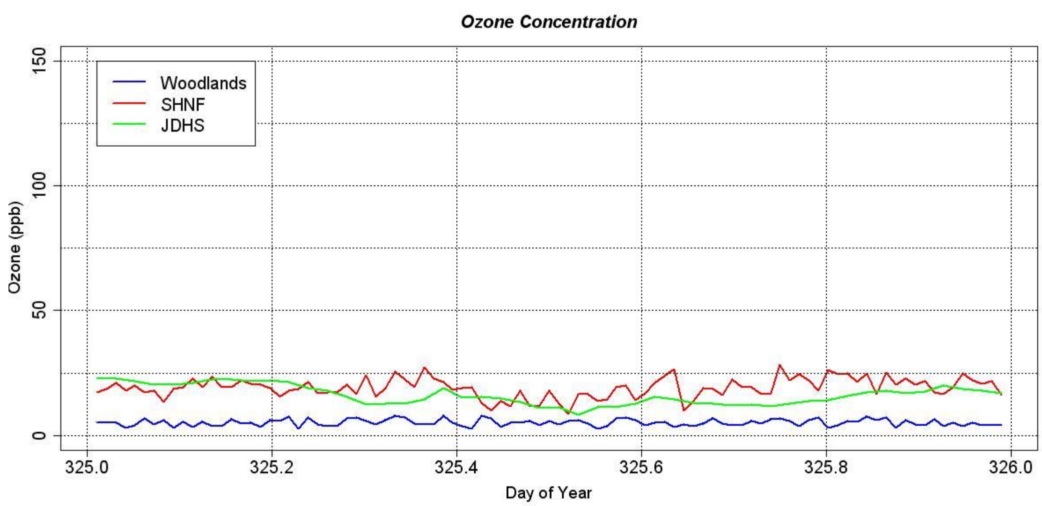

Figure 30: Case Study November 22, 2011 - Ozone Concentration

3.2.3.3 Case Study 3 - Winds from Different Directions: SW

The third meteorological situation is one where winds are from the SSW. Ultimately, they still originate in the Gulf of Mexico, but the air mass travels over significantly more land before reaching the Houston area (figure 31). This is a middle

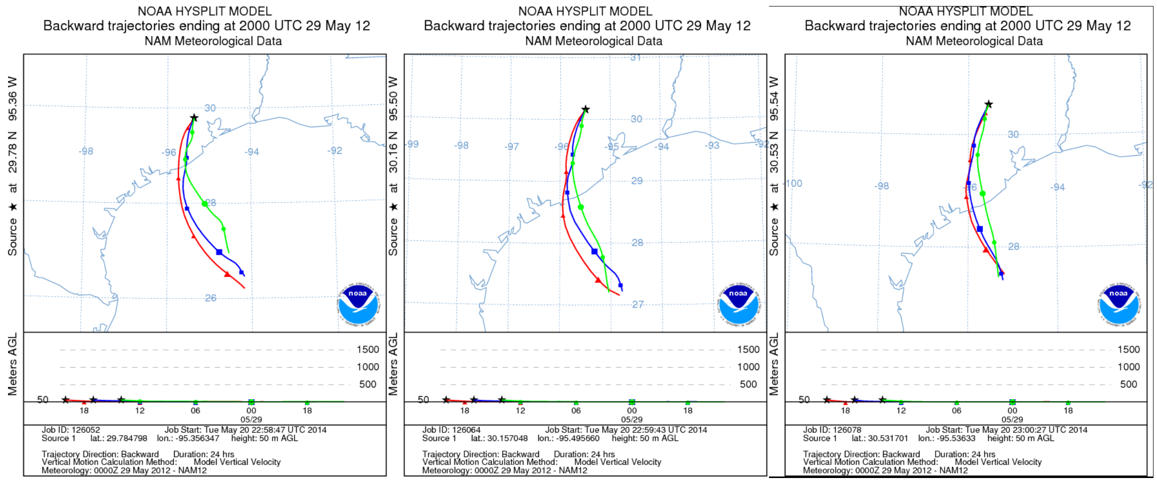

Figure 31: Case Study May 29, 2012 - NOAA Hysplit Back Trajectories

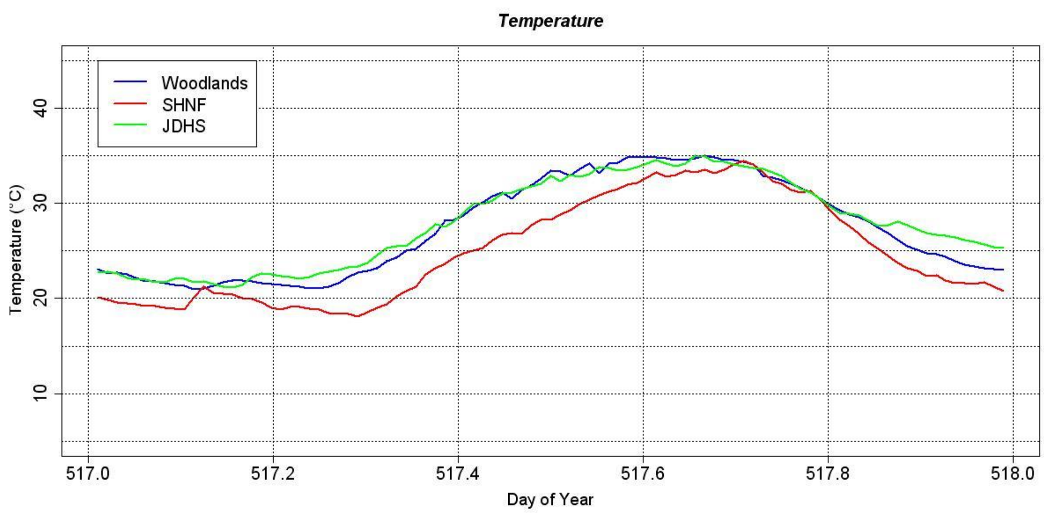

Figure 32: Case Study May 29, 2012 - Temperature

ground situation in many aspects. The temperature in Houston is very close to the temperature in The Woodlands indicating that the usual cooling that results from a sea breeze is having a reduced effect (figure 32). Ozone concentrations in Houston approached 100 ppb, and SHNF ozone peaked at 80 ppb, lower than concentrations in Houston, but still elevated (figure 33). In both cases, the air mass advected over areas

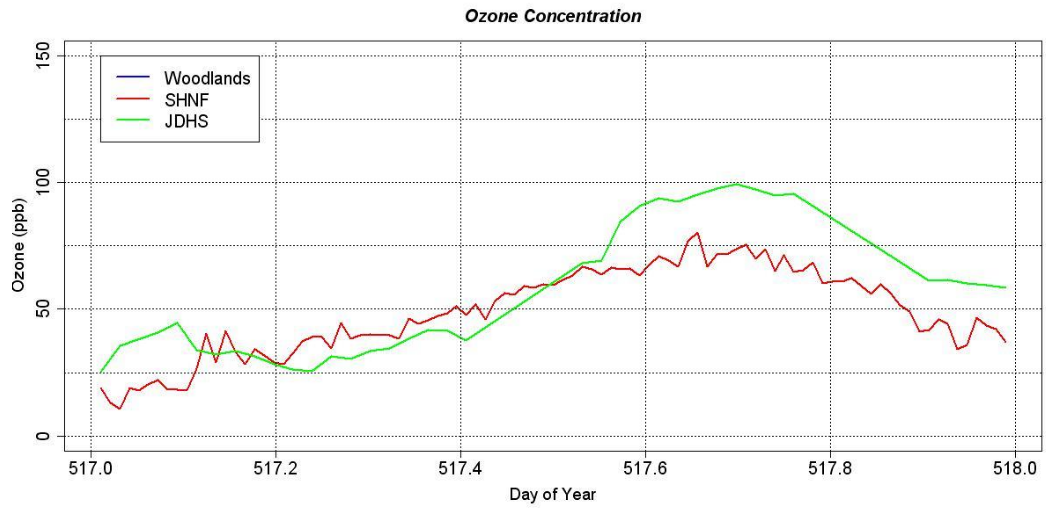

Figure 33: Case Study May 29, 2012 - Ozone Concentrations

with fewer ozone precursor emissions, but likely more in the case of Houston than in the case of SHNF. A small amount of rain on the previous day, coupled with evaporative cooling as there were no clouds on this day, is likely the reason SHNF remained cooler than normal compared to the other two site, which did not receive rain.

3.3 Discussion

Table 2 shows a summary of the expected effects of climate change compared to the observed effects of Houston urbanization. First, daytime concentrations of carbon dioxide were higher in Houston than at the other two sites. This was not the case for night time concentrations, but since the night time concentrations are largely dependent on local weather patterns and vegetation density, whereas daytime concentrations better reflect background CO_2 concentrations, the daytime concentrations are better suited for comparison with climate change effects. Therefore, this observation supports the hypothesis that urbanization can be used as a proxy for climate change.

Temperature in the urban environment was higher at the urban site than at the rural site, 1.5°C in 2011 and 2.1°C in 2012 (table 2). However, unlike the predicted climate change scenarios, warming as a result of Houston's urban heat island occurs dominantly during nights and in winter, with daytime summer temperatures on average slightly cooler than the rural environment in 2011 due to the regional sea breeze. Thus, the comparison to the effect of climate change is not ideal.

Table 2: Expected Climate Change vs. Urban Climate Change

Summary of expected changes resulting from climate change and observed differences between Houston (urban) and Sam Houston National Forest (rural).

Climate Factor	Expected Change from Climate Change (from IPCC 4th Assessment Report, 2007)	Observed Effect in Houston vs SHNF
Carbon Dioxide	Concentrations are expected to increase to between 425 and 454 ppm based on emission scenario by 2030.	Daytime summer concentrations are 4 to 9 ppm higher in Houston compared to SHNF.
Temperature	Global Average temperatures are expected to warm between +0.64 and +0.65 °C between 2011 and 2030.	1 to 3 °C warmer than surrounding countryside, except during summer daytimes when it is 0-1 °C cooler.
Tropospheric Ozone	Ozone concentrations are expected to increase, but increases are highly dependent on location and policies implemented to control them. An increase of 3.7 ppb is expected in the eastern part of the United States by 2050, with higher increases in urban areas.	During ozone season, average concentrations are 4 to 15 ppb higher in Houston than in SHNF depending on time of day.
Rain	Overall rainfall is projected to decrease by 20% in the southwestern United States, but there is a large amount of uncertainty in this projection, especially for the much wetter (mesic) east Texas location, which could become wetter instead of dryer. Individual precipitation events are expected to become more intense.	SHNF had 5 more days of rain in 2011 and 13 more days in 2012, increases of 8 to 14% over Houston. For actual rainfall, SHNF received 276 mm more rain than Houston in 2011 and an estimated 366 mm more in 2012, a difference of 34 to 52% compared to Houston.

The third major change expected from climate change is in precipitation. In 2011, Houston received 52% less rain and experienced fewer days with rain than Sam Houston National Forest. Similarly, in 2012, Houston received an extrapolated 34% less rain than SHNF. Climate change predictions are for 20% less precipitation in dryer areas such as the US-SW, so the differences observed here parallel the prediction that large parts of the subtropics will become more drought-prone. According to the IPCC reports, high intensity precipitation events are also expected to increase. This was also observed in the comparison between Houston and SHNF. Average rainfall intensity at JDHS was almost double the rainfall intensity at the SHNF site. In terms of using urbanization in Houston as a proxy for climate change, these data suggest that the changes in rainfall may parallel climate change predictions more closely than other factors.

4. CHANGES IN PHOTOSYNTHESIS

4.1 Background

The largest fluxes of the contemporary global carbon cycle are the absorption of CO_2 by plants through photosynthesis and emission through plant respiration and decay. These fluxes are strongly influenced by climate variables such as light availability, carbon dioxide concentration, and temperature. But, surprisingly little research has been done to incorporate uncertainties in the global carbon cycle into global climate change models. A 2011 publication by Booth et al. (2012) found that "the spread of CO_2 concentrations arising from land carbon cycle uncertainties is greater than the full spread of future SRES [Special Report on Emissions Scenarios] concentration scenarios when carbon cycle uncertainties are neglected." The authors further concluded that the largest variables in this uncertainty were the plant physiological responses to increased CO_2, and temperature dependencies of photosynthesis.

4.1.1 Effects of Temperature

Temperature is one of the largest factors affecting photosynthesis and growth. All plants have a broad "optimum temperature" range for photosynthesis. Below this temperature, increases in temperature will bring the biological reactants closer to the activation energy needed for chemical reactions associated with photosynthesis to proceed [Jones 1992]. However temperature increases above the optimum temperature will lead to decreases in photosynthesis for a variety of reasons, but mainly due the exponential increase in autotrophic respiration with temperature, and ultimately due to induced harm to the enzymes that catalyze photosynthetic reactions. The optimum temperature for photosynthesis is different between species largely as a result of differences in thermal stability of chloroplast membranes and the ability of photosystem II to withstand temperature stresses [Jones, 1992]. Optimum temperature can also vary even between different plants of the same species as a result of their adaptations to a particular climate. Kattge and Knorr [2007] in a reanalysis of 36 species demonstrated how temperatures during the previous month of growth affect the two main factors governing photosynthesis rates and optimum temperature. They found that moderate acclimation is enough to double photosynthesis at 40°C if plants had been grown at 25°C rather than 17°C.

4.1.2 Effects of Carbon Dioxide

Increasing atmospheric CO_2 will affect plants in several different ways. C4 plants (examples include maize and sorghum) and CAM plants (mostly cacti) will not be strongly affected by increases in atmospheric CO_2, whereas C3 plants (most plants and all trees) will likely increase carbon assimilation and growth. This is due to differences in C3 vs. C4 photosynthesis systems. Where C3 plants use the enzyme RUBISCO [Ribulose-1,5-bisphosphate carboxylase oxygenase] to uptake and photosynthesize CO_2, C4 plants use PEP Carboxylase to uptake CO_2 and deliver it to RUBISCO, and CAM plants store CO_2 as an acid until it can be released for photosynthesis. But not all C3 plants will see equal benefits from increased CO_2 concentrations. For instance, Hunt et al. [1991] found that growth rate increases varied from 5% to 46% among C3 plants in response to doubling CO_2. In general, increased CO_2 abundance can only be beneficial to plants when other growth factors, such as water and nutrients, are of sufficient supply.

Increased CO_2 may also help plants better withstand drought conditions; with higher CO_2 concentrations, leaf stomata do not need to open as much, thus decreasing transpiration through the leaf and increasing plant water use efficiency [Jones 1992]. Further research has indicated that this effect may be disproportionately in favor of evergreens due to the structure of needles versus leaves, allowing an evergreen to have even greater water use efficiency [Niinemets 2010]. Another study done on Norwegian Spruce trees found that trees grown in higher CO_2 environments had longer "memories." That is, after being exposed to drought-like conditions, plants grown in a higher CO_2 environment retained increased activity of catalase and guaiacol peroxidase (antioxidative enzymes) longer than plants grown at ambient CO_2 [Schwanz 1996]. In the presence of both increased ozone and CO_2, the results were even more pronounced.

4.1.3 Effects of Ozone

Ozone is a relatively well studied stressors for plants. Two different effects have been observed in plant interactions with ozone. The first is necrosis, or the death, of leaves. The second is chlorosis, which is a condition whereby leaves produce reduced amounts of chlorophyll. These effects are observed when plants are exposed to acutely high levels of ozone and light [Heath 1988]. In addition, lower levels of ozone can inhibit photosynthesis, reducing overall carbon fixation, and possibly lessening overall productivity (yield for crops) of the plant [Heath 1994]. Several possible mechanisms could cause this reduction. One proposed by Heath [1994] is that ozone interactions within leaf cells could result in the injury of leaf stomata, causing them to close prematurely thus reducing CO_2 uptake. This hypothesis found support in a study on the effect of ozone on rice yields, which noted elevated ozone levels led to decreased stomatal conductivity and transpiration, and ultimately led to lower rice yields [Peng 2013]. Another proposed mechanism is that ozone interactions with the leaf will cause it to produce toxins, such as peroxides, that damage chlorophyll structures in the leaf [Heath 1994]. Peroxide production, in turn, generally increases plant antioxidant production.

4.1.4 Interactive Effects

None of the above effects are completely independent or additive. Combinations of elevated carbon dioxide, ozone, temperature, and drought stress can lead to unexpected changes in plant physiology and photosynthesis. For example, a study on aspen showed that, while elevated ozone will always cause decreases in photosynthesis, the negative effects of elevated ozone can be amplified by the presence of elevated carbon dioxide [Noormets 2009]. A separate study on Norwegian spruce trees measured the antioxidant content of needles and found that after drought stress, trees grown at elevated CO_2 maintained higher antioxidant levels longer than trees grown at ambient CO_2. This effect was further increased by the presence of elevated ozone [Schwanz 1996]. A study examining the effects of all possible combinations of stressors would have to be very extensive, and until that happens, generalizations will be necessary. This

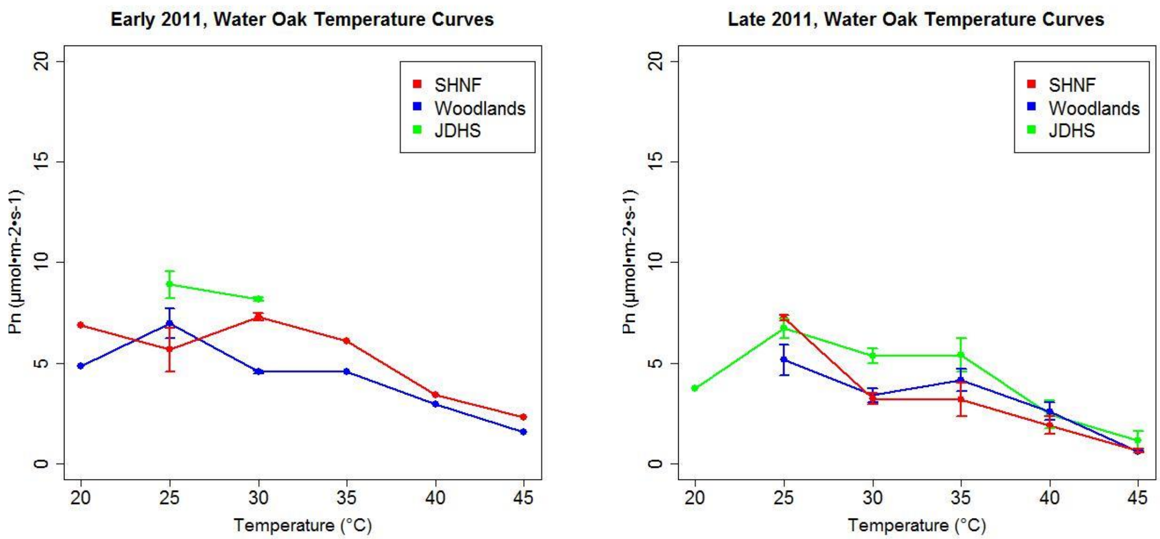

Figure 34: Early vs. Late Season Water Oak Temperature Curves

Average temperature curves for 2011, divided into early and late year. Error bars represent standard error. No error bars on a point indicates it represents only one data point.

is especially true for our project where the studied plants are located outdoors in uncontrolled environments.

4.2 Results

4.2.1 Water Oaks

Water oaks were present at all three sites and were tested throughout 2011. Temperature curves for early and late 2011 water oaks are shown in figure 34. The measurement season is divided at August 6, a date which falls in the middle of the climatically warmest time of the year in Houston. On this day, the average high temperature (1981-2010) is 35°C [HGX Webmaster 2013]. As discussed in section 3.2.1, 2011 was a year characterized by little rainfall and high temperatures. As shown in

Figure 34, photosynthesis was generally higher at 25°C during both times of the year at Houston and The Woodlands sites although differences were insignificant for Houston early in the season. The SHNF water oak showed photosynthesis rates broadly peak at 30°C early in the year shifting to higher photosynthesis rates at 25° later in the year. Overall, photosynthesis rates decreased at most temperatures between the early and late growing season. At 30°C in the Houston water oak, rates decreased from 8.2 μmol m^{-2} s^{-1} to 5.3 μmol m^{-2} s^{-1}, and at SHNF, they decreased from 7.3 μmol m^{-2} s^{-1} to 3.2 μmol m^{-2} s^{-1}. Considering the 25°C and 30°C measurements (because significantly more data was collected at those temperatures), SHNF water oak – compared to the other sites – saw the smallest decrease in photosynthesis from early 2011 to late 2011, an average change of -1.3 μmol m^{-2} s^{-1}, a 20% decrease, at 25° and 30°C. Water oaks were affected by water stress sooner than the post oaks, but also had quicker recovery after periods of rain.

4.2.2 Post Oaks[1]

Post oaks provided a different challenge. After the first year of data collection, the decision was made to focus on post oaks during the second year and use them to do comparisons between years. Unfortunately towards the end of 2012, it was realized that the tree identified as a post oak (*Quercus stellata*) in Houston was an overcup oak (*Quercus lyrata*). This data is still used to compare 2011 to 2012 in Houston, but the comparison cannot be directly done between Houston and the other two sites.

[1] See text

The Houston overcup oak did not do well in 2011 (figure 35): from early to late growing season, its carbon assimilation dropped by 8.4 µmol m^{-2} s^{-1} or 71%. At 35° and 40°C the percentage drop was even larger. And as with the water oaks, there was no clear indication of a temperature acclimation of photosynthesis during the course of 2011. In early 2012 (figure 36), the overcup oak had a clear optimum temperature around 30°C. In contrast to 2011, late 2012 photosynthesis at 30° was only down 7%, and at 35° and 40°C, within the error bars, photosynthesis was unchanged.

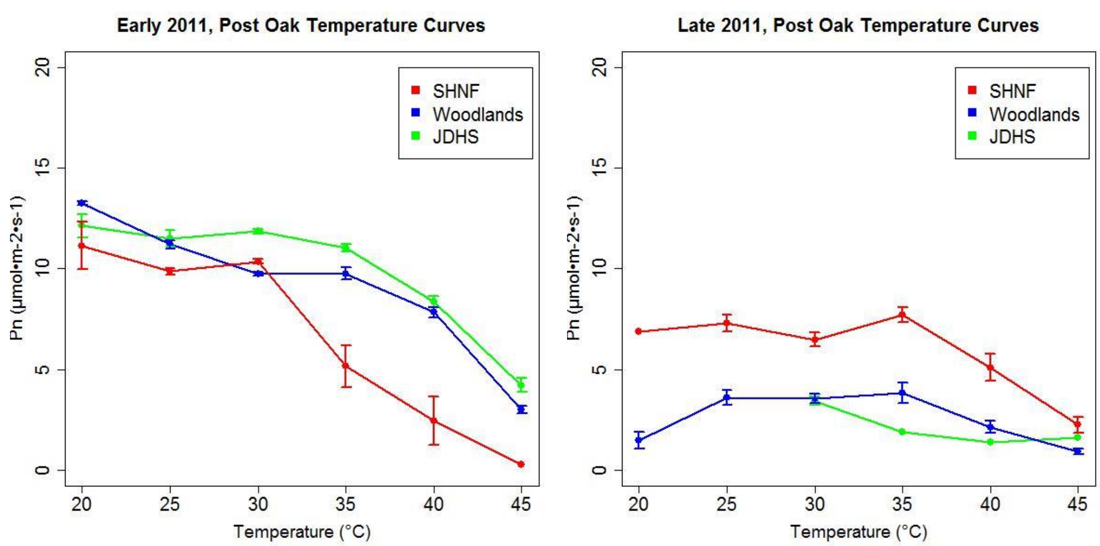

Figure 35: Early vs. Late 2011 Season Post Oak* Temperature Curves

Average temperature curves for 2011, divided into early and late year. Error bars represent standard error. No error bars on a point indicates it represents only one data point. Again, the tree representing Houston here was an overcup oak.

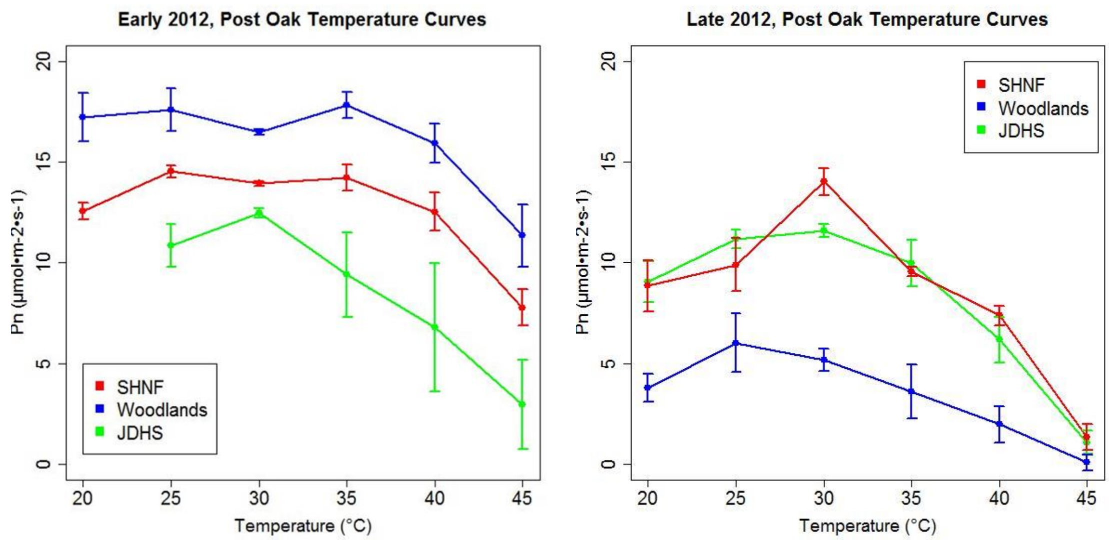

Figure 36: Early vs. Late 2012 Season Post Oak* Temperature Curves

Post oaks at The Woodlands and SHNF did show signs of acclimation. In early 2011, both the trees in The Woodlands and SHNF had the highest photosynthesis rates at 20°C. However by late season, while carbon assimilation overall had decreased, temperature curves showed that photosynthesis rates were not strongly affected by temperature between 25 and 35°C, with photosynthesis rates at 35° being slightly higher than at the lower temperatures. This indicates the post oaks adjusted their photosynthesis optima to higher temperatures. At the start of 2012, while overall photosynthesis had again increased, the overall pattern of the curves resembled the pattern seen at the end of 2011. By the end of 2012, both curves had surprisingly reverted back to the expected curve shape with peaks at 25° and 30°C. However, only the post oak in The Woodlands showed much lower overall photosynthesis rates compared to early season measurements, possibly a result of lower soil moistures at this site.

4.3 Discussion

In comparing the water oak and post oak data for 2011, it appears that the drought did not have as large an effect on the water oaks as it did on the post oaks at SHNF and The Woodlands. However, this is somewhat deceiving. Analysis showed that the water oaks had the largest photosynthesis response to rain events, indicating that they were also fastest to react to a lack of rain early in 2011 resulting in low photosynthesis rates and therefore relatively small changes in photosynthesis rates between early and late 2011. The effects of the drought in 2011 took longer to affect the post oaks in SHNF and the Woodlands, and even the overcup oak at JDHS. Therefore large changes in photosynthesis rates appear between early 2011 and late 2011.

Interannual changes in the post oaks at SHNF and The Woodlands are especially interesting. While overall photosynthesis rates increased from late 2011 to early 2012, the shape of the temperature curve, and the relatively high photosynthesis rates at 35 °C persisted from late 2011 to early 2012. By the end of 2012, temperature curves had reverted back to having a peak photosynthesis rate at 25 and 30 °C, similar to the situation observed in early 2011. More data would need to be collected to confirm whether this is a general trend, but this seems to indicate the post oaks could have a longer "memory" than currently thought.

The overcup oak, though closely related to post oaks, did not exhibit a similar behavior. While the overcup oak photosynthesis rates were higher early in 2011 compared to the post oaks at the other two sites, and higher than the water oak located in Houston, by the end of 2011 its photosynthesis had dropped lower than that of either post oaks or water oaks, suggesting a stronger response of this species to the drought conditions, possibly for reasons of its growth between two impervious areas within a meter of its stem, limiting soil water infiltration.

In terms of location, between the water oaks in 2011, the Houston location fared marginally better than the water oaks at the other two sites. During late 2011, the water oaks at The Woodlands and SHNF, within error bars, had approximately the same photosynthesis rates above 30°C. This is in contrast to the post oaks in The Woodlands and SHNF. During both 2011 and 2012, at almost every temperature level, the post oak in The Woodlands exhibited higher photosynthesis rates than the one in SHNF in the early part of the growing season. This completely reversed in the latter half of both years when the SHNF post oak displayed higher photosynthesis rates at every temperature. Future measurements are designed to confirm this tendency, and to eliminate that other factors, such as the chosen tree, its location, or leaf location on the tree affected this result.

5. CONCLUSIONS

In terms of the study objectives, first using the shift in climate from a rural area to an urban area as a proxy for climate change was only somewhat useful in our setup. Table 2 lists the factors examined, which include temperature, total rainfall and rainfall intensity, and carbon dioxide and ozone concentrations. The expected shifts resulting from global climate change, and the observed shifts from downtown Houston to Sam Houston National Forest match imperfectly. While increases in temperature are expected from global climate change, Houston exhibited lower daytime temperatures than Sam Houston National Forest during both summer 2011 and summer 2012, however, largely driven by the regional sea/bay breeze. Nevertheless, temperature increases during the winter and nights are roughly on par with what is expected from climate change over the next 50 to 100 years. Carbon dioxide increases in Houston, present only during the daytime, are less than half of the lower end of predicted carbon dioxide increases over the same 50 to 100 years. Ozone was highly variable, but in general, concentrations were higher in Houston than Sam Houston National Forest, which agrees with climate change predictions. Perhaps the best match was found regarding precipitation. Regionally, precipitation is expected to decrease while the intensity of precipitation is expected to increase. Both of these were mirrored in Houston, which had lower precipitation overall and higher intensity than Sam Houston National Forest.

Few conclusions can be made regarding the second goal of this project, namely that differences in oak tree photosynthesis rates can be attributed to urbanization, and therefore indicate what may result from climate change. Differences in temperature and rainfall between downtown Houston and Sam Houston National Forest were smaller than interannual changes between 2011 and 2012. Without more data, this fact makes it difficult to separate the effects of the drought from the effects of the urban or rural environment. However, the observation of the effect of high ozone on photosynthesis rates in the case study, and the observation of post oak acclimation between late 2011 and early 2012 suggest that more definitive conclusions could be made with more data.

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