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Supplementary Information

Influence of Climate Change and Meteorological Factors on Houston's Air Pollution: Ozone a Case Study. *Atmosphere* 2015, *6*, 623-640

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1. Monthly Averaged Ozone *vs*. Temperature

Based on the data from four meteorological sites and four ozone sites along the north-south direction in the Houston area, we plotted the monthly averaged ground-level ozone mixing ratios and monthly averaged air temperature for all sites. Figure S1 shows the trends of the two factors at Aldine over the recent two decades.

In Figure S1, the slope for the trend-line of ozone is 2.1e−010 ± 1.6e−009 and 1.3e−009 ± 1.7e−009 for the air temperature. Both of the two numbers are small, which shows there is no significant trend for both monthly averaged ground-level ozone and air temperature factors along the past 24 years at the Aldine site. The correlation coefficient between the two factors is 0.51 and the p value < 0.005, barely passing the significant test. In summary, monthly averaged air temperature is positively related to the monthly averaged ground-level ozone-mixing ratio, along the past two decades, at the Aldine site, there is no significant trend for the two factors.

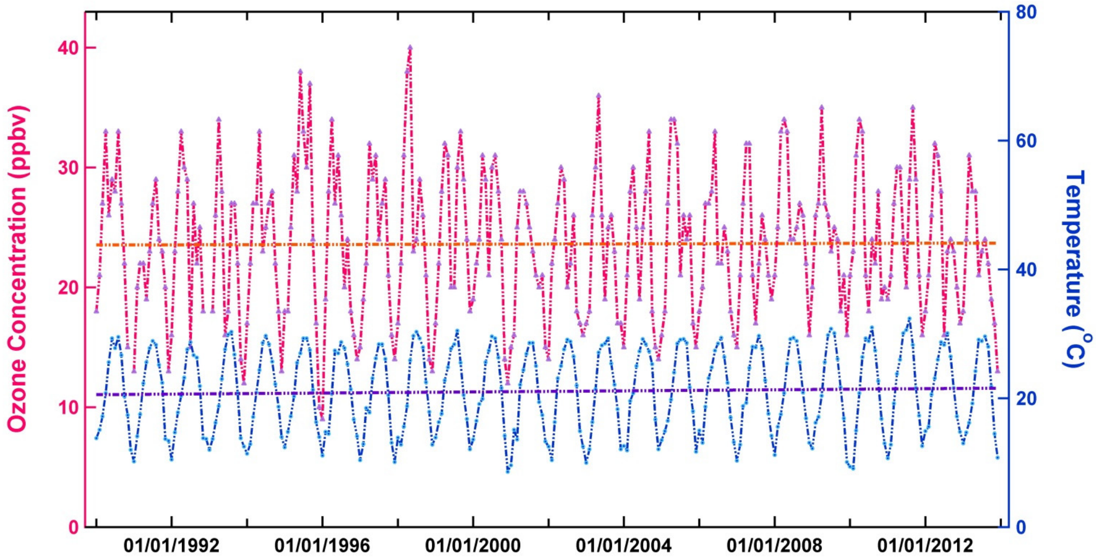


Figure S1. Monthly Averaged Ground-Level Ozone Mixing Ratio *vs*. Temperature data at the Aldine site.

For the Clinton site, the same two factors, the slope for the monthly averaged ozone mixing ratio trend-line is 3.4e−009 ± 1.7e−009 and 1.5e−009 ± 1.6e−009 for the monthly averaged air temperature. The correlation coefficient between them is 0.42 and p value < 0.005. It passes the significant test. During 1990–2013, the monthly averaged ground-level ozone mixing ratio increased by 3 ppbv with the slope number of 3.4e−009 ± 1.7e−009. The monthly averaged air temperature data did not show significant trend. The factors are positively related with each other, which probably means that the temperature is a positive contributor for the production of surface ozone on a long-time period.

The Clinton site is located of the downwind of Houston ship-channel area where over 400 petrochemical facilities are located. According to previous studies, the refinery processes may produce ozone precursors which can increase the ground-level ozone concentration in atmosphere.

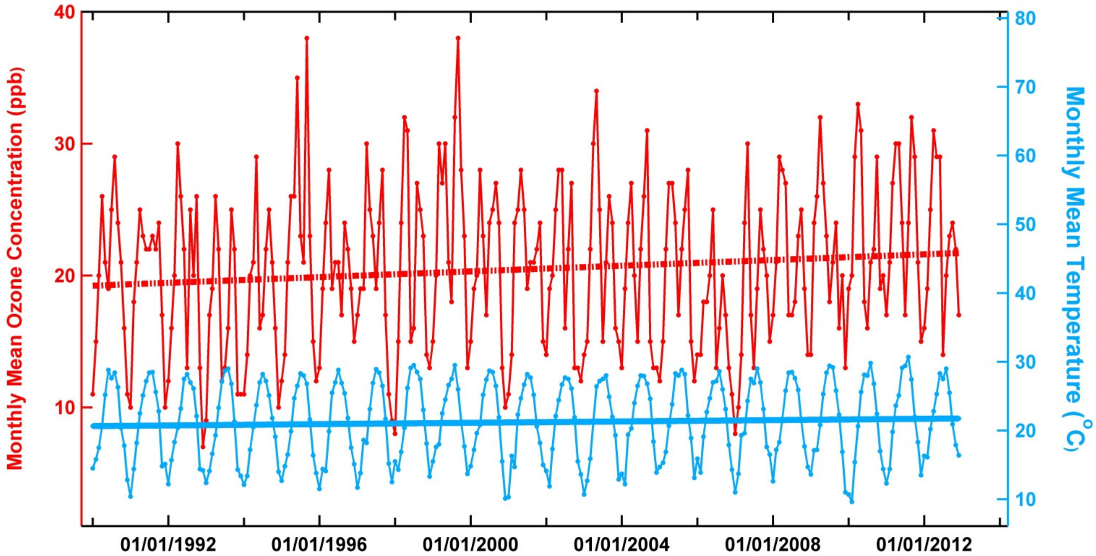


Figure S2. Monthly Averaged Ground-Level Ozone Mixing Ratio *vs*. Temperature data at the Clinton site.

2. Annual Exceedance Days *vs*. Annual Southerly Flow Hours

The relationship between number of exceedance days and hours of southerly flow per year is depicted in Figure S3 (Galveston) and Figure S4 (Northwest Harris). The anti-correlation between these two parameters is striking, and shows that the length of time per year Houston is under the influence of southerly flow has more than doubled from 1990 to 2013. The correlation coefficient between annually southerly flow hours and annually number of exceedance days of 1-hour averaged (8-hour averaged) in Galveston site are −0.51 (−0.59), for Northwest Harris site are −0.58 (−0.51). All of them pass the significant test. The slope of the linear regression line for 1-h exceedance days at Galveston is −0.4 exceedances year^{-1} and −0.5 exceedances year^{-1} at Northwest Harris. Conversely, the slope for Galveston is +78.5 southerly h year^{-1} and +62.0 southerly h year^{-1} for Northwest Harris.

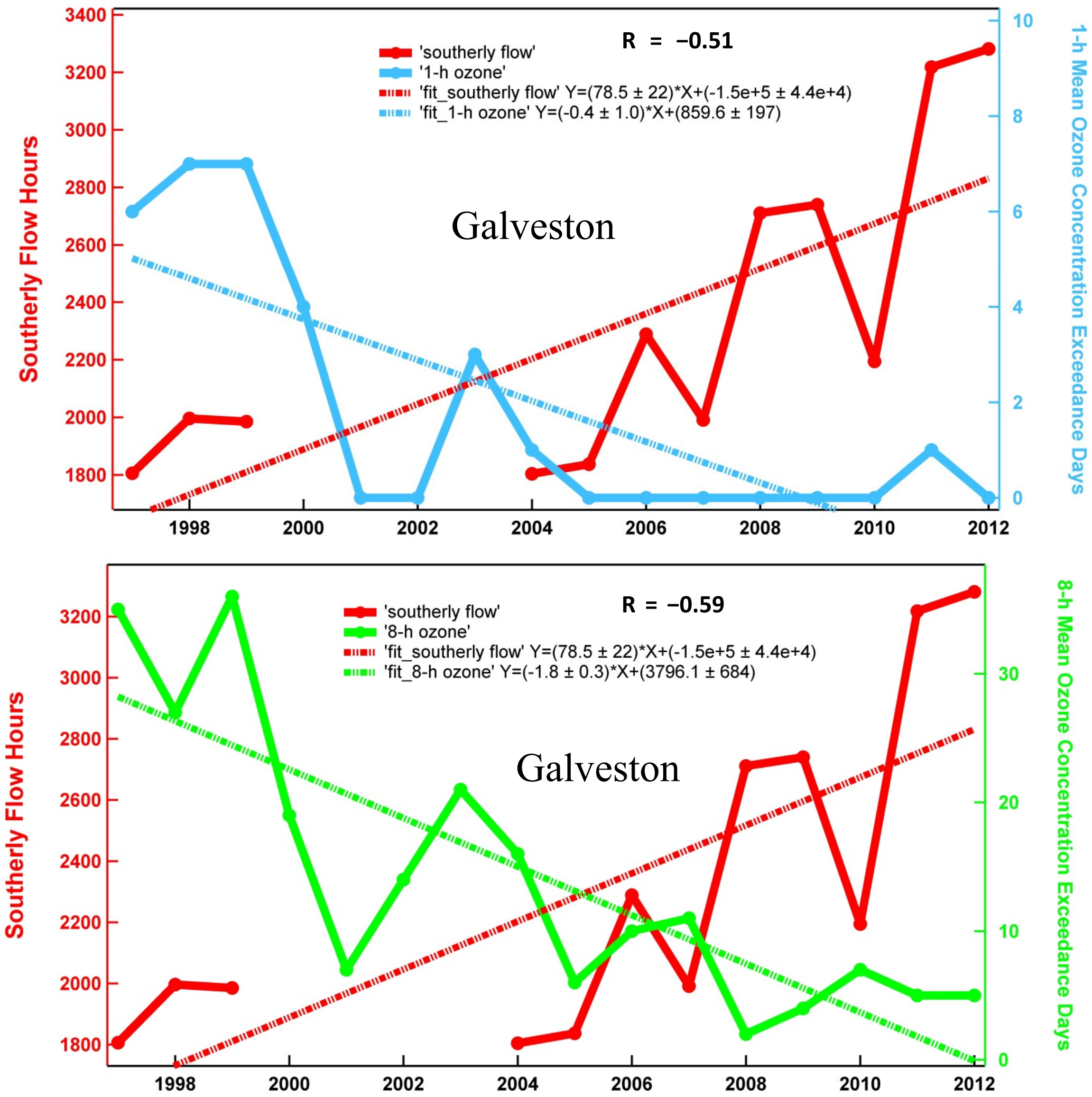


Figure S3. 1-h and 8-h exceedance days as a function of annual southerly flow hours per year at the Galveston site.

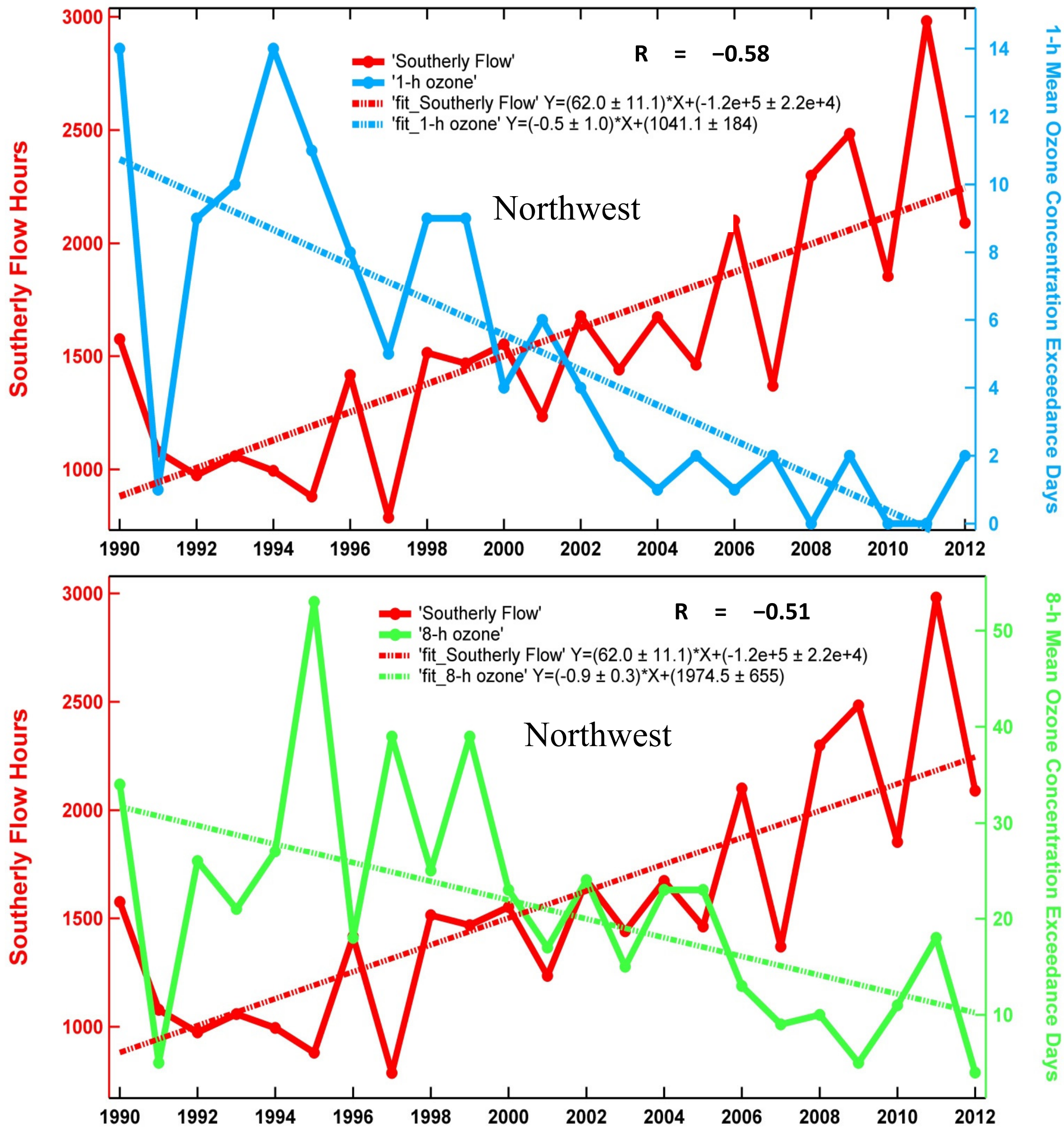


Figure S4. 1-h and 8-h exceedance days as a function of annual southerly flow hours per year at the Northwest Harris site.

3. The Frequency of Southerly Flow

For the Northwest Harris site, during March–October (Figure S5), Figure S5a is the total southerly flow hours for all research months between the two periods, 1995–1996 and 2010–2011. Especially in August, it increased by a factor of three, in March, April, June and September, the total southerly flow hours increased by a factor of two. Figure S5b is the total southerly flow days, in June, August, September and October which increased by a factor of 0.5. For the average daily southerly flow hours, Figure S5c is for period I, during 1995 and 1996 and Figure S5d is for period II, during 2010 and 2011. Contrasting Figure S5c and S5d, the daily southerly flow hours increase in each month during March to October, especially in April June and August, increasing by a factor of two.

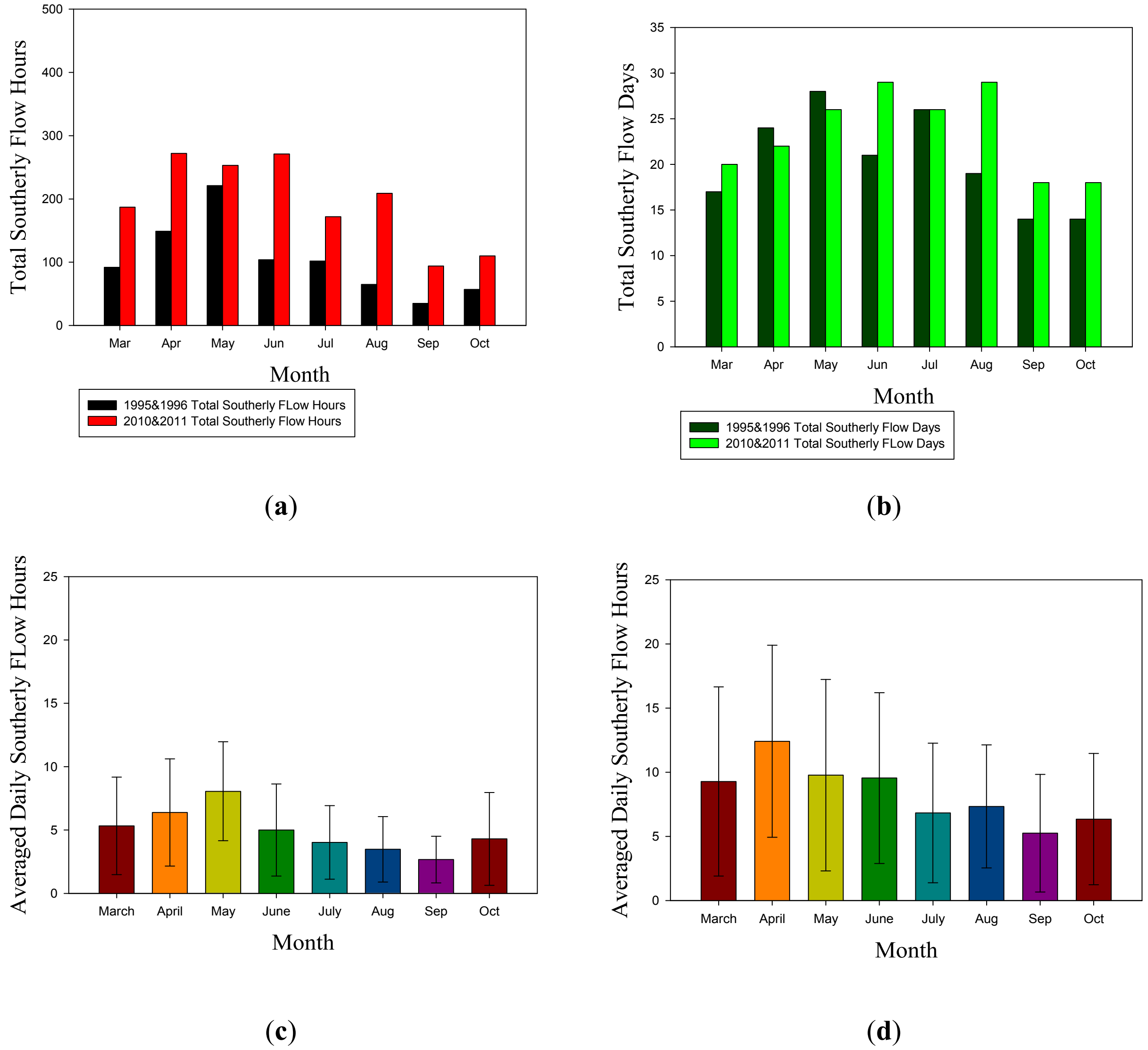
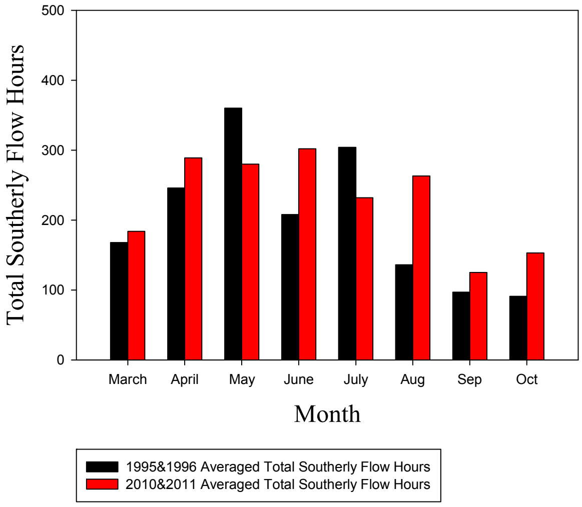
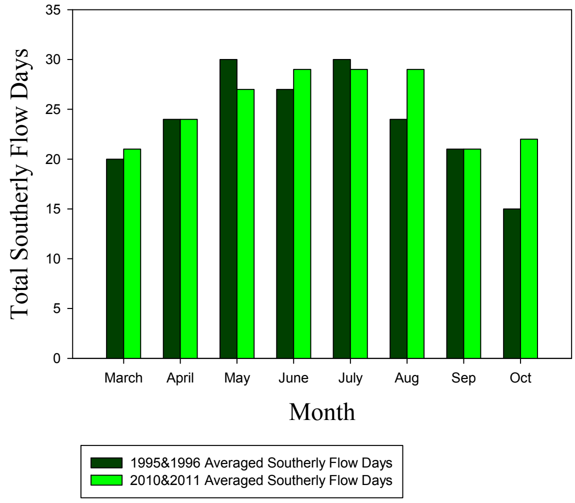


Figure S5. Days with southerly flow at the Northwest Harris site.

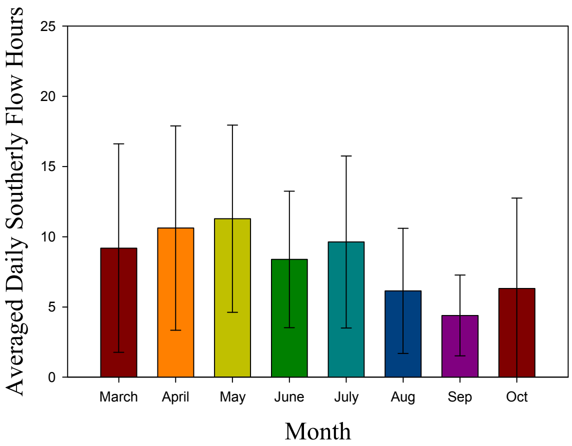
For the Clinton site during March–October, Figure S6a shows the total southerly flow hours increase in all research months between the two periods, 1995–1996 and 2010–2011. In August it increased by a factor of two. Figure S6b shows the total southerly flow days, in August and October where it increased by a factor of 0.3. For the average daily southerly flow hours, Figure S6c shows for period I, during 1995 and 1996 and Figure S6d shows for period II, during 2010 and 2011. After contrasting Figure panels S6c and S6d, the daily southerly flow hours increased in each month during March to October, however, it is not as significant as the other three sites. We propose that the reason is probably because the location of Clinton site, which is located downwind direction of Houston Ship-channel area. Over 400 petrochemical and refinery facilities are based there with significant emissions.



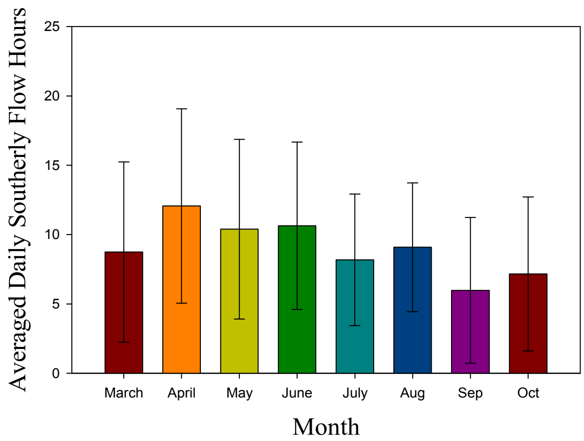
(a)



(b)



(c)



(d)

Figure S6. Days with southerly flow at the Clinton site.

4. Wind Rose Graphs

For Clinton site the rose of 1990–1994 shows that general wind directions were from the south (25%), east and north (40%). Wind speeds were generally between 4–6 m/s (62%). During 1995–1999 and 2000–2004, major wind directions shifted to the south and southeast. The highest wind speed (8–10 m/s) occurred from the northerly direction.

During the period 2005–2009, major wind directions were distributed among 160°–195° (32%), which is southerly wind. Wind speeds were in the range of 6–8 m/s (34%). The frequency and wind speed of the southerly flow increased in contrast to the previous three time intervals. The last interval of 2010–2013, 42% of the wind directions are during 160°–195°. The strength of the sea breeze system was intensified.

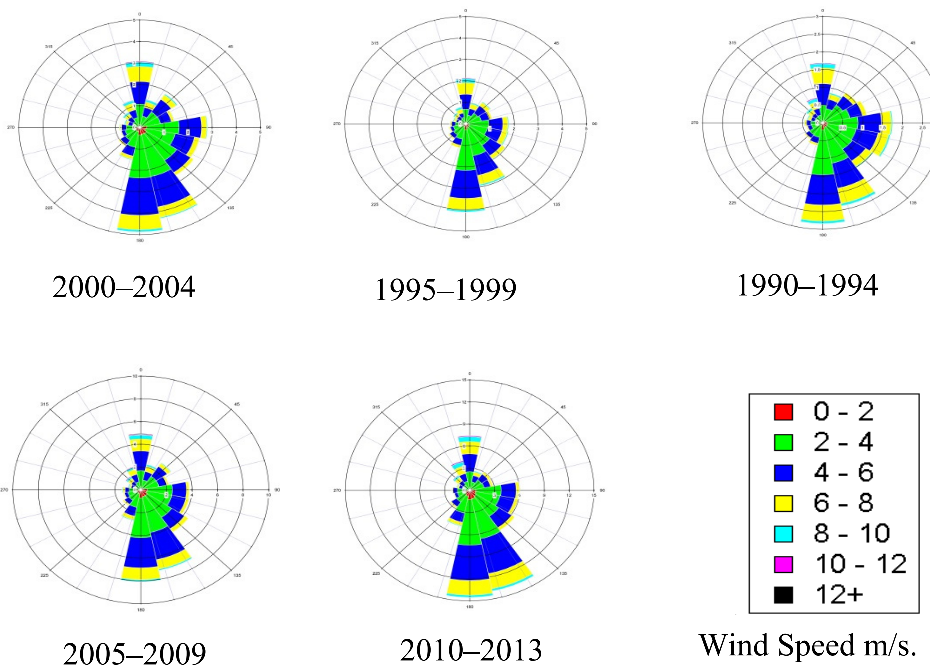


Figure S7. Wind speed and direction as a function of time in Clinton.

To the Northwest Harris site, in the rose graph of 1990–1994, general wind directions were from the north (25%), and south (35%). Wind speeds were generally between 4–6 m/s (50%). During 1995–1999 and 2000–2004, the frequency of northerly flow increased. During the period 2005–2009, major wind directions were distributed among 160°–195° (40%), which is southerly wind. Wind speeds were in the range of 6–8 m/s (30%) and 10% of the wind speed increase to the range of 8–10 m/s. The frequency and wind speed of the southerly flow increased in contrast to the previous three time intervals. The last interval of 2010–2013, 50% of the wind directions are between 130°–195°. Specifically, for the directions from 160°–180° degrees, the strength of the sea breeze system was intensified.

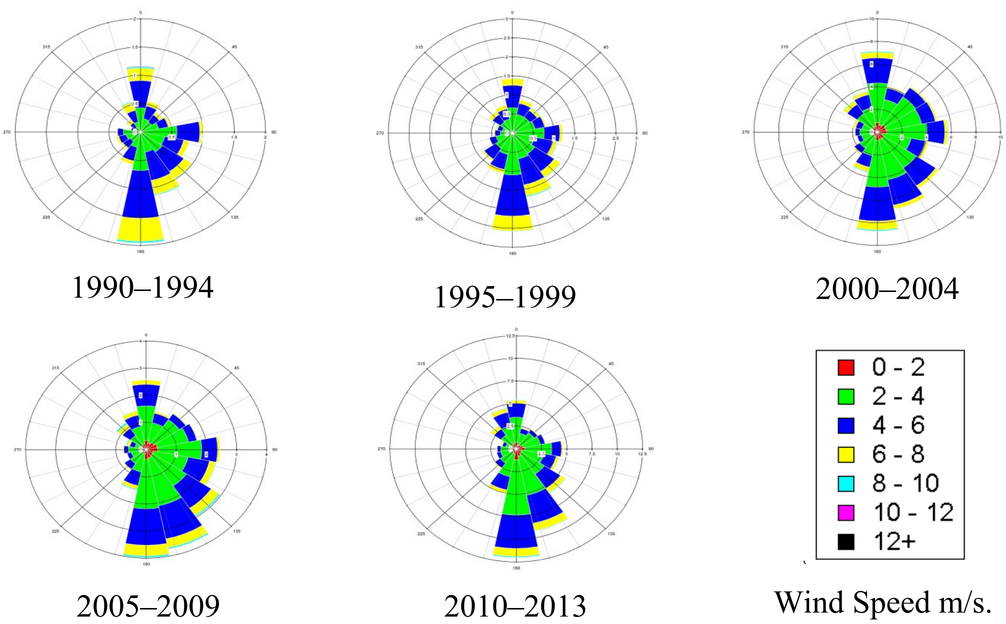


Figure S8. Wind speed and direction as a function of time in Northwest Harris.

For the Galveston site the rose for 1990–1994, general wind directions were from the south and southeast (60%). Wind speeds were generally between 6–8 m/s (65%). During 1995–1999 and 2000–2004, northerly flow increased. During the period 2005–2009, major wind directions were distributed among 90°–195° (32%), which is southerly wind. Wind speeds were in the range of 6–8 m/s (40%). The last interval of 2010–2013, 60% of the wind directions are between 130°–195°. Specifically, for the directions from 160°–180° degrees, 30% of the wind speeds were distributed among 6–10 m/s with 12% being in excess of 10 m/s. In summary, the strength of the sea breeze system was intensified. After contrasting with the other three sites, southerly flow wind speed was the highest.

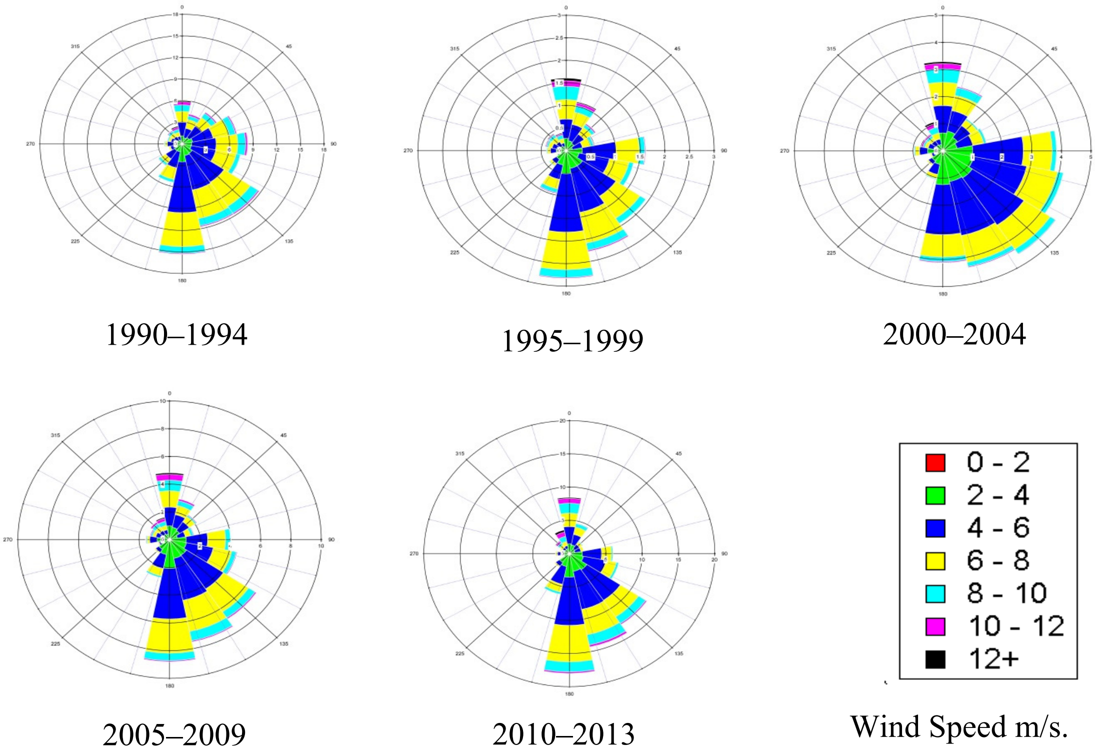


Figure S9. Wind speed and direction as a function of time in Galveston.

5. LST–SST Temperature Difference

We investigated the long-term sea surface temperature (SST) using data from two buoy sites located at the western Gulf of Mexico operated by NOAA National Data Buoy Center, The buoys are located at 27°54′25″ N and 95°21′10″ W and 26°5′29″ N and 93°45′29″ W. From March 1990 to October 2013, we used monthly averaged land and sea surface temperatures in our analysis. Because the heat capacity of water is greater than that of soil, when temperature increases, the temperature growth over land is faster than that in the ocean. We know that the southerly flow mainly occurs from March to October, so again we used this time period. In order to investigate how temperature difference between land and ocean trends in long-term period (recent two decades) in Houston area, we choose May and June as the sample months. We subtracted sea surface temperature data from land surface temperature data, Figure S10 shows the relationship. The slope of temperature difference for May is 0.46, and 0.34 for June. The temperature differences trend increased in both months. In May it increased from −1 °C to 9 °C and in June, it increased from −1 °C to 6 °C, significantly.

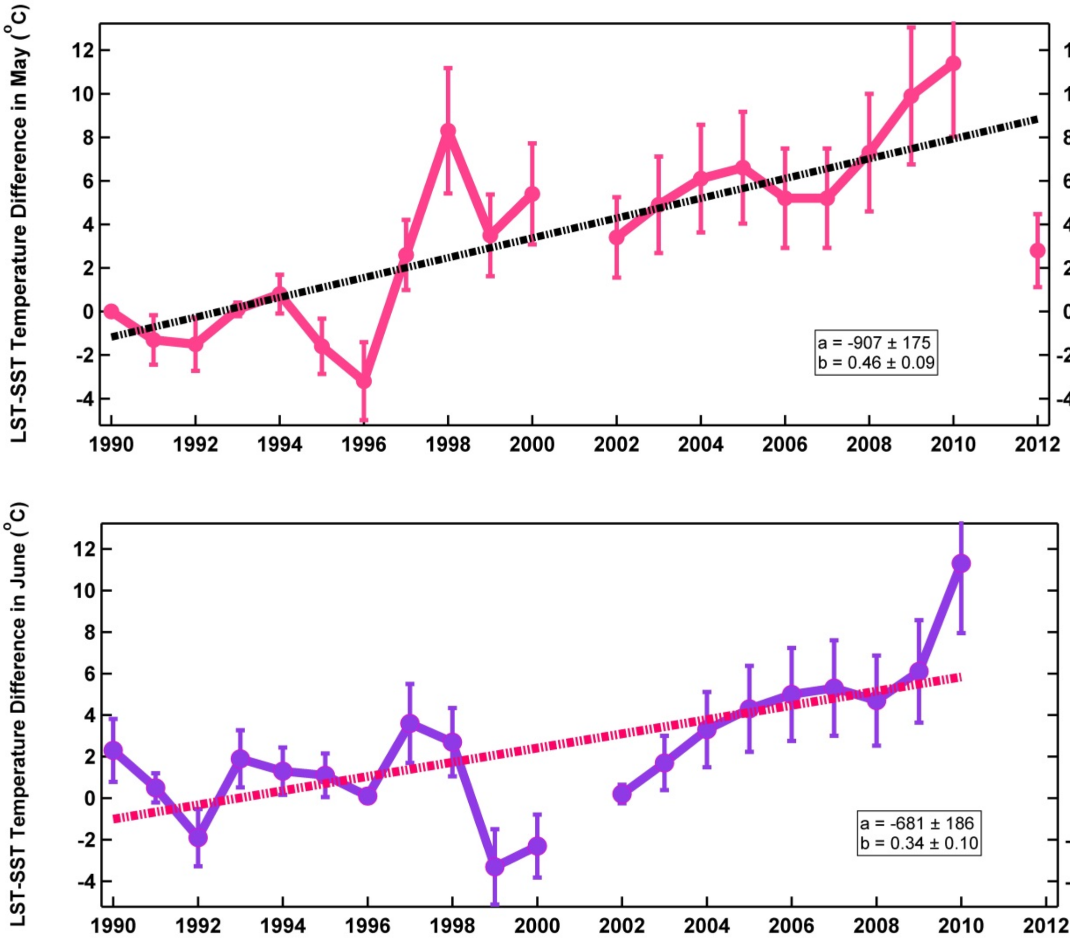


Figure S10. LST–SST temperature difference in May (**top**) and June (**bottom**).