OBSERVATIONS OF SEA-BREEZE FRONTS ALONG THE HOUSTON GULF COAST

A Thesis Presented to

the Faculty of the Department of Earth and Atmospheric Science

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Michele Kocen

December 2013

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ABSTRACT:

Observations of sea breeze fronts along the Houston Gulf Coast were used to correlate meteorological conditions with remote sensing observations. The aim of this study was to find patterns in cloud and weather parameters during the progression and development of the sea-breeze front as it relates to the Houston geographical conditions. Houston sea-breeze is affected by both the Gulf of Mexico and Galveston Bay waters. Often the sea-breeze produces convective single-cell rain showers. By observing patterns in the sea-breeze the goal was to better predict whether the sea breeze will produce rain showers. Specific parameters obtained included wind direction and speed, air pressure, air temperature, dew point, and relative humidity, as well as sea surface temperature. Geostationary Operational Environmental Satellite (GOES) and Weather Surveillance Radar (WSR-88D) Doppler data were used for cloud patterns and verification of rain showers. Two years (2011 and 2012) with distinctly different conditions were chosen for this study. 2011 was considered a drought year for Houston and 2012 was more of a normal climate year. Data were collected for four months of each year (June-September) based on highest probability of having a sea-breeze event. Radar and satellite data was reviewed first for possible sea-breeze days, single-cell rain shower days, and to eliminate visible rain that was caused by synoptic events. Sea-breeze days were then confirmed by looking at the meteorological conditions at various sites around the Houston area. The monthly recognizable days varied from 2 to 16. On average only 2 days a month had both single-cell rain showers and recognizable sea breeze conditions. The sea breeze

could not be shown to be the cause of the showers. Overall this study provides a month by month climatology of all recognizable sea-breeze days in the Houston area.

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1.0 INTRODUCTION

The definition of a sea-breeze line is well known. The sea-breeze front is generally a movement of air on a smaller scale than a front. A typical cold front is a synoptic scale phenomenon and can extend 1000-2000 km, whereas a mesoscale sea-breeze front occurs along or inland of the coast up to 150 km. The sea breeze is caused by a difference in surface temperature between the land and an adjoining body of water. The temperature difference creates a gradient causing the air movement. The direction of the air movement is onshore from the cooler water to the warmer land (Figure 1) As the land warms it warms the air at the surface. The air over the land is warmer so less dense. The land-based air begins to rise. This rising warm air creates low pressure over the land. The colder denser air from the water acts as a cold front and is pulled inland to replace the warm air at the surface. At the leading edge of the front the air is lifted and cooled. At this point clouds develop and rain can form. With the water being cooler than the land lower pressure develops aloft over the water. Since air moves from high to low pressure, the colder denser air aloft is then carried back aloft over the water. The clouds are not carried back with the air because the air on the back side of the circulation is sinking. As the sinking air gets closer to the surface it becomes part of the sea breeze again and closes the circulation cell.

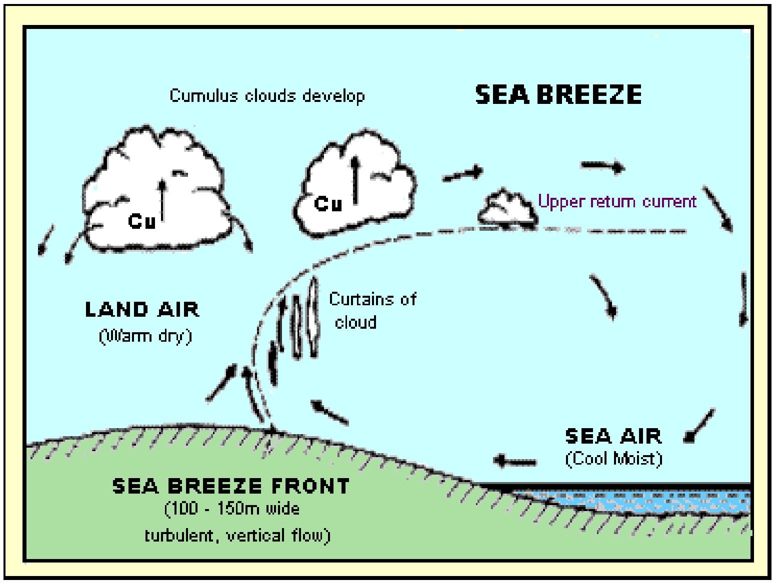

Figure 1 Pictorial View of Sea Breeze (www.bom.gov.au)

In the case of Houston the bodies of water include both the Gulf of Mexico and the Galveston Bay/Houston Ship Channel. Galveston Bay creates what is known as a bay breeze. Due to the proximity of the bay to the gulf coast both have to be considered when studying the effects for Houston. As the sea-breeze front progresses inland from the Galveston coast it may interacts with the front caused by the bay. This progression most times leads to a line or lines of clouds that line up parallel to the coast. During the progression of the sea-breeze front, the convective line of the sea breeze may trigger clouds that generate brief periods of rain showers. These showers may be “spotty” or along the whole front. The strength of these showers may also vary.

Previous sea-breeze studies in the Houston area have observed the transport of pollution due to the front. Past work that involved the effects of the Houston sea and bay breeze were part of the Texas Air Quality Studies (TexAQS) in 2000 and (TexAQS II) in 2006. Both air quality studies involved specifically ozone (O_3) concentrations. Banta et al. (2005) showed that the timing and location of the sea breeze could affect the concentration of O_3. Darby (2005) focused on area wind clusters. Some of the clusters were caused by the Gulf breeze. As result of TexAQS II, Day et al. (2009) and Tucker et al. (2010) looked at daytime and nighttime boundary layer winds. Both of these studies (Tucker et al., 2010; Day et al., 2009) made apparent the clock-like diurnal cycle of the land/sea-breeze winds. During the diurnal cycle the wind changes direction like the rotation of a clock. During the land breeze, usually at night, the wind flows from the land to the water. As the land heats up during the day the wind rotates to reverse direction from the water to the land. Langford et al. (2010) studied how convection moves ground O_3 up to the free troposphere. One source of this convection could be due to the sea breeze.

The most relevant previous study was performed on the Florida coast. In 1991 Wakimoto and Atkins performed an extensive sea-breeze study on the coast of Florida. Their study was part of CaPE (Convective and Precipitation Electrification Experiment). During this study Wakimoto and Atkins (1994) were trying to predict the organization of the cloud formations along the sea-breeze front. Their study included both on-shore and off-shore sea-breeze flows. The results of their study showed that the clouds tended to contain horizontal convective rolls that are parallel to the coast with on-shore surface wind flow and perpendicular to the coast with off shore flow.

The interaction of the sea breeze with the horizontal convective rolls (HCR) can lead to the uplift needed to generate clouds capable of initiating rain (Daily and Fovell, 1999). The HCR are tube-like rotations that are formed by surface heating. The HCRs form where there is vertical wind shear and align with the mean wind. The moist air in the sea breeze is lifted and condensed as it cools to form rain showers.

Figure 2 shows how the cloud line of the sea-breeze front interacts with the HCR to create the cumulus uplift. In another study Fovell (2004) showed that not only was lift needed, but another spark like a gravity wave to intensify the convection.

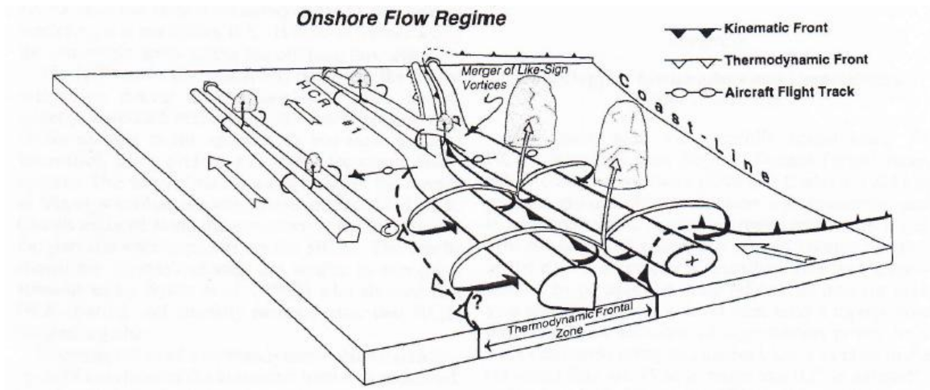

Figure 2 Sea-Breeze Interaction with Horizontal Convective Rolls (HCR) with Onshore Ambient Flow Low level wind is designated by the white arrows. the horizontal vorticity vectors associated with the roll are also shown (Atkins and Wakimoto, 1995)

In Part II of the CaPE study, Atkins and Wakimoto (1995) further studied how HCRs interacted with the sea-breeze front. With onshore ambient flow the HCR merges with the sea-breeze front to intensify updraft and increase cloud formation. Figure 2 shows an example of the parallel HCR merging with the sea-breeze front. Parallel HCR have opposite directions of rotation. Boundary layer shear and kinetic energy can be found between the HCRs. The amount of kinetic energy is proportional to the amount of shear (Atkins and Watkimoto, 1994). Atkins and Watkimoto (1994) also found that as the sea-breeze front came in contact with a HCR with a like-sign vortices or rotation, then the front was intensified due to the merging process.

Also in the Florida area Case et al. (2005) performed a 7 year climatological study (Feb. 1995 to Jan. 2002) of the land breezes. They used similar instrumentation to the Atkins/Wakimoto study and included analysis of wind direction and wind speed in relation to days that had land breeze effects. It was also studied whether there was a difference in the land breeze, if it was preceded or followed by a sea-breeze event. Part of study was broken up into two sections to look at how temperature changes were affected by surface stability. October through May were considered minimal convective months because the surface layer is more stable during this time. June through September were listed as peak convective months due to the greater instability of the surface layer. A similar instability is likely to exist in Houston over the same months.

Planchon (2006) and Li (2009) showed that remote sensing could be used to detect sea breeze. Using the Geostationary Operational Environmental Satellite (GOES) visible color differences, Planchon (2006) could tell if the clouds were generated due to a synoptic condition or were part of the sea breeze. Planchon (2006) studied the north-eastern Brazilian coast while Li (2009) studied the North Carolina coast. A similar technique would be used as an initial observation for determining Houston sea breeze. Li (2009) used both Polar Orbiting Environmental Satellite (POES) and GOES to observe the cloud lines along the coast. GOES was found to be better. GOES is capable of a 15 minute temporal resolution as compared to only a 6 hour resolution for the POES. Li (2009) found through surface analysis that sea breeze was not always visible from the satellite because of natural high humidity and clouds in the area.

Roberts (2003) used the GOES and the Weather Surveillance Radar-1988 Doppler (WSR-88D) in pattern recognition for cumulus clouds over different forms of storm initiation. Roberts (2003) showed HCR could be seen on radar as linear reflective thin lines. Storm development was seen at intersections of gust fronts and HCR. A similar outcome may be seen as the sea-breeze front interacts with the HCR on a smaller scale. A sea-breeze front is not as strong as a gust front.

The study for this thesis only concentrated on the timing and meteorological conditions of the sea-breeze front. Land breeze was not considered. The goal of the study was to see if the changes in surface meteorological parameters, at various locations throughout the Houston area, due to sea breeze. Changes in parameters such as temperature, dew point and wind speed/direction are likely candidates to describe convective rain development. Personal observations had shown that convective single-cell rain showers occur around the city. The study also aimed to see if some of these showers would occur at the intersection of the Galveston Bay breeze and sea breeze. The convergence of the two fronts should increase the uplift needed to create rain showers. The results will show that the location of the single-cell rain showers could not be proven to correspond to this intersection.

At a minimum, this study provided characteristics of the sea breeze as it passed through ground sites around the Houston area. Data for this study were limited to existing sites around the city and the meteorological parameters those sites had available. Another limitation is that rain showers did not always occur near one of these sites. For this study only ground-based sites were considered. The vertical component of the sea breeze was not reviewed.

Two years were chosen for the study. Data were gathered for the months June through September for 2011 and 2012. These months were chosen since they are the peak convective months. Year 2011 was a major drought year for the Houston area and year 2012 was considered climatologically a standard year. Table 1 shows the Houston

Intercontinental Airport (KIAH) climate normals and summaries for the months of interest (National Weather Service Houston/Galveston Office, 2013). The National Climatic Data Center (NCDC) distributes quality controlled local climatology data for 1600 location in the United States. The KIAH site is a quality controlled location Houston weather. NCDC produces and distributes the National Oceanic and Atmospheric Administration (NOAA) products for the 30 year average climatological conditions (Arguez, 2012). The latest 30 year cycle is 1981 - 2010. The NOAA products are referred to as Normals. KIAH is one of the reporting stations used for the products. Precipitation is available on a daily, monthly, seasonal, and annual basis. Table 1 contains the NOAA precipitation Normals for the months of interest and the annual rate. As Table 1 shows, the 2011 year end rain total was only half of the climatological normal. For the month of August 2011 there was only 2.3 mm of rain. According to Nielson-Gammon (2011) the 12-month rainfall total for October 2010 through September 2011 was 63.8 mm less than the previous record set in 1956. The two years for this study were expected to have different conditions generated by the passage of the sea-breeze front.

		Jun	Jul	Aug	Sep	Annual
Rain Totals (mm)	Normal*	150.6	96.3	95.5	104.7	1264.2
	Standard deviation**	4.45	2.89	2.6	3.0	10.6
	2011	23.4	75.7	2.3	32.5	624.1
	2012	126.2	119.6	98.6	51.3	1074.9
Mean Temp (°C)	Normal*	28.0	29.1	29.2	26.6	21.0
	2011	30.1	30.6	32.4	28.3	22.1
	2012	28.7	28.3	30.1	26.5	22.3
Avg High (°C)	Normal*	33.0	34.3	34.7	32.1	26.5
	2011	36.3	36.1	38.9	35.3	28.1
	2012	34.2	32.7	35.2	32.1	27.8
Avg Low (°C)	Normal*	22.9	23.9	23.8	21.0	15.6
	2011	23.8	25.2	25.9	21.2	16.2
	2012	23.2	23.9	24.9	20.9	16.7

* based on the average of the 30 year period 1981-2010
** Calculated from data received from National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/)

Table 1 Houston Intercontinental Airport Climatology Comparison (National Weather Service, 2013)

2.0 METHODS

Data was gathered from all sources (see section 2.1.1) for each of the four months (June-September) for each year (2011 and 2012). Pre-processing of the data was needed to ensure similar units for time and the meteorological parameters like temperature, wind speed and pressure. Coordinated Universal Time (UTC) was used for all data. Data were observed between 12:00 UTC and 24:00 UTC which corresponded to 7am Central Daylight Time (CDT) to 7pm CDT. Table 2 contains both the standard NOAA operational and System International (SI) meteorological units that were chosen for each measurement. Data was pre-processed and analyzed using NOAA operational units and Fahrenheit for temperature. The majority of the original data used Fahrenheit. Then the data converted to SI units for inclusion in this paper.

Parameter	Unit	Parameter	Unit
Time	UTC	Wind Direction (WD)	Degrees (deg)
Temperature (temp)	Fahrenheit (F) Centigrade (C)	Wind Speed (WS)	Knots (kts) meters/second (m/s)
Barometric Pressure (press)	millibars (mb) hecto Pascal (hPa)	Precipitation (precip)	Inches (in) millimeters (mm)
Relative Humidity (RH)	Percent (%)		

Table 2 Parameter Units - When two units are present data processing units are listed first then SI units

2.1 Locations

Houston is located in Harris County in Southeast Texas. Locations were constrained to the counties surrounding Houston and the Galveston Bay Figure 3.

Figure 3 Houston Area Counties Used for Study (http://www.travelnotes.org/ustravel/texas/images/houston-galveston-area.gif)

Locations within the shaded counties in Figure 3 were chosen based on the hypothesis of this study, which would show that rain showers might be found at the intersection of the bay and sea-breeze fronts. Many of the sites were within expected progression, inland and parallel to the coast, of both fronts. Locations were also chosen based on expected parameter availability. At a minimum a site needed air temperature and wind direction. In addition having dew point or relative humidity was preferred. Section 2.1.2 goes into further detail on the location parameters. Figure 4 contains a map of the locations chosen.

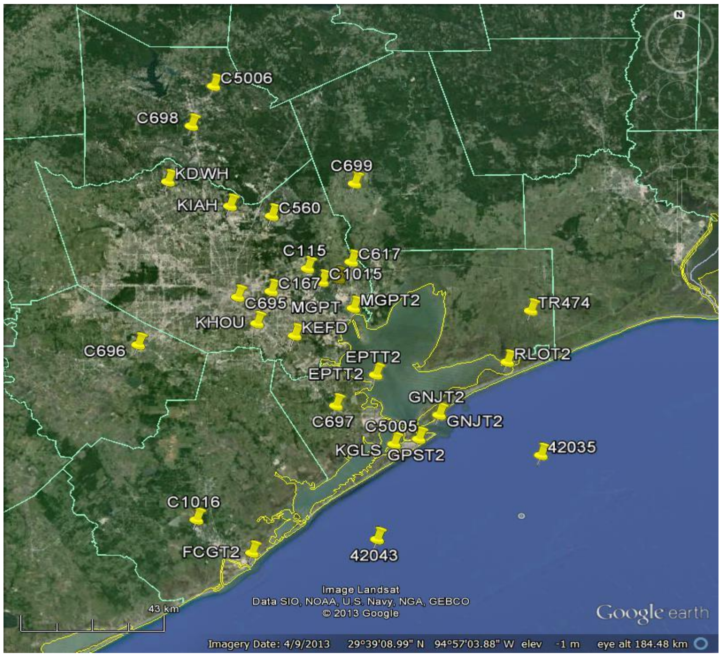

Figure 4 Data Locations - (complete site names can be found in Table 3)

After data were collected, a number of these sites were found to have a substantial amount of missing or invalid data. These sites were eliminated. Other sites were eliminated due to the low frequency of data. Plotted data showed that the average time it took for the sea breeze to pass through a site was approximately 30 minutes. Based on this time, a site needed data at a temporal resolution of at least 15 minutes to be able to determine sea-breeze start and stop time. The start and stop time refers to the time that the sea breeze arrived and exited the site. Elimination of sites did not occur until data was pre-processed and plotted. Figure 5 shows the final sites that were used for analysis. A detailed description of the sites and the data found at each site can be found in sections 2.1.1 and 2.1.2.

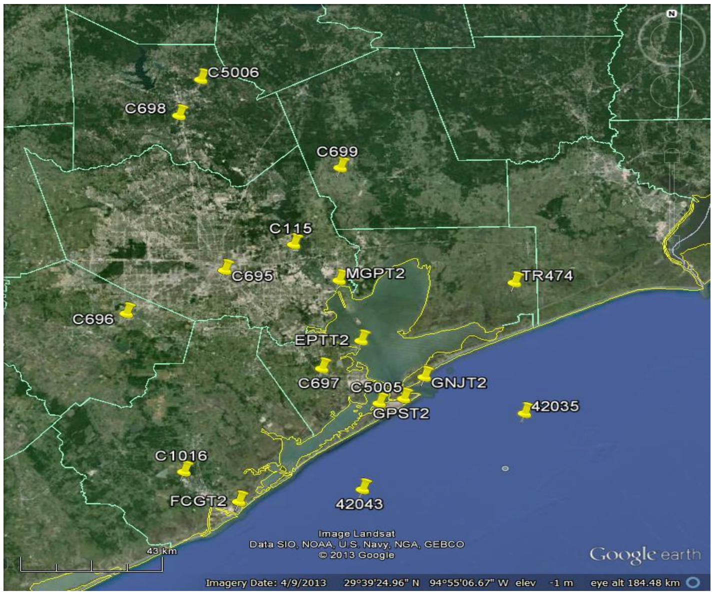

Figure 5 Final Data Sites - (complete site names can be found in Table 3)

2.1.1 Sources

Ground sources for historical data were obtained from the Texas Commission on Environmental Quality (TCEQ) (http://www.tceq.state.tx.us/), MesoWest (http://mesowest.utah.edu/), and National Data Buoy Center (NDBC) (http://www.ndbc.noaa.gov/) websites. Geostationary Operational Environmental Satellite (GOES) data were obtained from the Comprehensive Large Array data Stewardship System (CLASS) database system at http://www.nsof.class.noaa.gov. Houston/Galveston (HGX). Doppler radar data were obtained from the National Climatic Data Center (NCDC) at http://www.ncdc.noaa.gov/oa/radar/radardata.html.

GOES data was acquired once every 30 minutes or hour when satellite was in full disc scan. Houston is located at 29.76° N and 95.38° W. Only CONUS data located between longitude -91.5 and -98.13 degrees and latitude 27.52 and 31.39 degrees were requested to encompass the area and save on file size. From Sept 5-10, 2012 GOES 13 failed and no data were available. By September 24, 2012 GOES 14 had replaced GOES 13.

All available radar level II data were requested. Level II data provided the highest resolution reflectivity data to be able to better locate the single-cell rain showers. Depending on the radar mode data temporal resolution was different. For example if the radar was in Clear Air mode, then data were available every 10 minutes. If the radar was in Shallow Precipitation mode, the data were available every 5-6 minutes and in the Convection mode every 4.5-5 minutes.

Sites were requested from multiple sources such as NDBC and MesoWest, when available, to lower the chance of missing data. After data preparation (Section 2.1.2) it was found that the MesoWest data was only saved hourly. Also MesoWest airport data did not even contain hourly data for many parameters. Table contains the list of the sites shown in Figure 4 and their data sources.

Site Abbreviation	Site Name	Latitude	Longitude	Source	Height (MSL)
42035	East Galveston	29.232	-94.413	NDBC	Buoy
42043	GA52	29.982	-94.919	NDBC	Buoy
EPTT2	Eagle Point	29.48	-94.918	NDBC	10m
FCGT2	Freeport	29.943	-95.303	NDBC	6.7m
GNJT2	North Jetty	29.357	-94.723	NDBC	9m
RLOT2	Rollover Pass/Bolivar	29.515	94.513	NDBC	10.7m
MGPT2	Morgan Point	29.682	-94.985	NDBC	9m
GPST2	Pleasure Pier	29.285	94.788	NDBC	7m
EPTT2	Eagle Point	29.48	-94.918	MesoWest	NA

(MSL) - Mean Sea Level, (NA) - Not Available, (UH) - University of Houston, (TCEQ)- Texas Commission on Environmental Quality

Table 3 Sites and Data Sources (continued on next page)

Site Abbreviation	Site Name	Latitude	Longitude	Source	Height (MSL)
GNJT2	Galveston Bay Entrance	29.357	-94.725	MesoWest	NA
KDWH	Hooks Airport	30.068	-95.556	MesoWest	4.6m
KEFD	Ellington Field	29.6	-95.167	MesoWest	10m
KGLS	Galveston Shoals Field	29.270	-94.864	MesoWest	2.1m
KHOU	Hobby Airport	29.638	-95.283	MesoWest	14m
KIAH	Bush Intercontinental Airport	29.993	-95.364	MesoWest	29m
MGPT2	Morgan Point	29.682	-94.985	MesoWest	NA
TR474	Anahuac	29.670	-94.438	MesoWest	1.5m
CAMS 560	Atasocita	29.962	-95.235	TCEQ	12m
CAMS 148	Baytown	29.771	-95.031	TCEQ	6m
CAMS 115	Channelview	29.803	-95.126	TCEQ	6m
CAMS 697	UH Coastal Center	29.388	-95.041	TCEQ	5m
CAMS 5006	KCXO Conroe Airport	30.357	-95.414	TCEQ	61m
CAMS 167	Galena Park	29.734	-95.238	TCEQ	6m
CAMS 5005	Galveston Airport	29.270	-94.864	TCEQ	0m
CAMS 698	UH Jones Forest	30.236	-95.483	TCEQ	56m
CAMS 1016	Lake Jackson	29.044	-95.473	TCEQ	0m
CAMS 1015 /A165	Lynchberg Ferry	29.762	-95.081	TCEQ	0m
CAMS 695	UH Moody Tower	29.718	-95.341	TCEQ	18m
CAMS 696	UH Sugarland	29.574	-95.650	TCEQ	23m
CAMS 617	Wallisville Rd	29.821	-94.99	TCEQ	12m
CAMS 699	UH West Liberty	30.058	-94.978	TCEQ	24m

(MSL) - Mean Sea Level, (NA) - Not Available, (UH) - University of Houston, (TCEQ)- Texas Commission on Environmental Quality

Table 3 Sites and Data Sources (continued)

2.1.2 Data Preparation

Data acquired from each site were sorted into daily comma-delimited files based on UTC. Each location had to be analyzed as to what data were listed as available and the units for the data. Some locations did not have a dew point measurement but had relative humidity so the dew point could be calculated. Macros were created using the WaveMetrics IGOR plotting program. These macros were used to perform the unit conversion, if needed, and plot each available parameter vs. time. Table in Appendix A shows parameters and default units for each site. As stated earlier the data were originally converted to units listed in Table 2 then only post-processed to SI units for the purpose of presenting in this paper. If a site did not have enough valid data, in terms of frequency and parameters as discussed in section 2.1, it was eliminated.

2.2 Classification of Bay/Sea-Breeze Day

To classify what would be considered as a sea-breeze day, the first thing was to eliminate obvious synoptic events. Unidata's Integrated Data Viewer (IDV) software (Murray et al., 2003) was used to view the GOES and HGX radar data. Only the GOES visible band data was used due to software constraints. For the HGX data only 0.5 degree elevation reflectivity was used since sea breeze is a surface layer based event.

Satellite data were reviewed for each day. A whole day could be viewed at once and put in motion to note direction of cloud movement. Figure 6 shows an example of a synoptic system. The thick clouds with bright white spots in Figure 6 show high cumulus clouds symbolic of heavy rain showers. Days similar to this were validated by radar then eliminated as possible sea-breeze days.

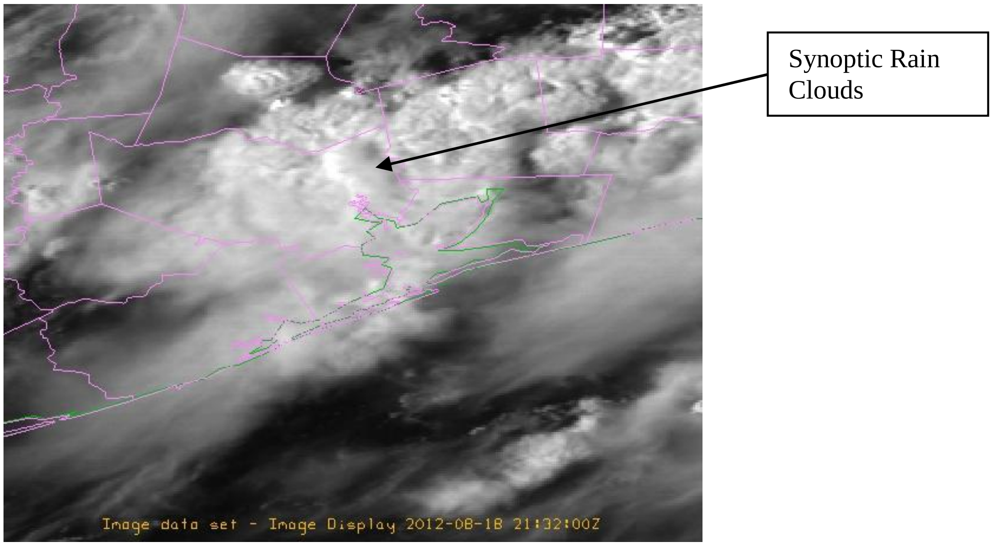

Figure 6 Non-Sea Breeze Example GOES Visible Band Synoptic Rain 08/18/12

Figure 7 shows potential sea breeze as seen from the GOES satellite. The coastal line of isolated small cumulus clouds as seen by the bright white color (Figure 7) that bends around the bay was a common signature (Planchon, et al, 2006) of potential sea breeze. Another signature in Figure 7 was the cloudless air on the coastal side. Notes were taken each day for direction of clouds or systems that may be entering the Houston area.

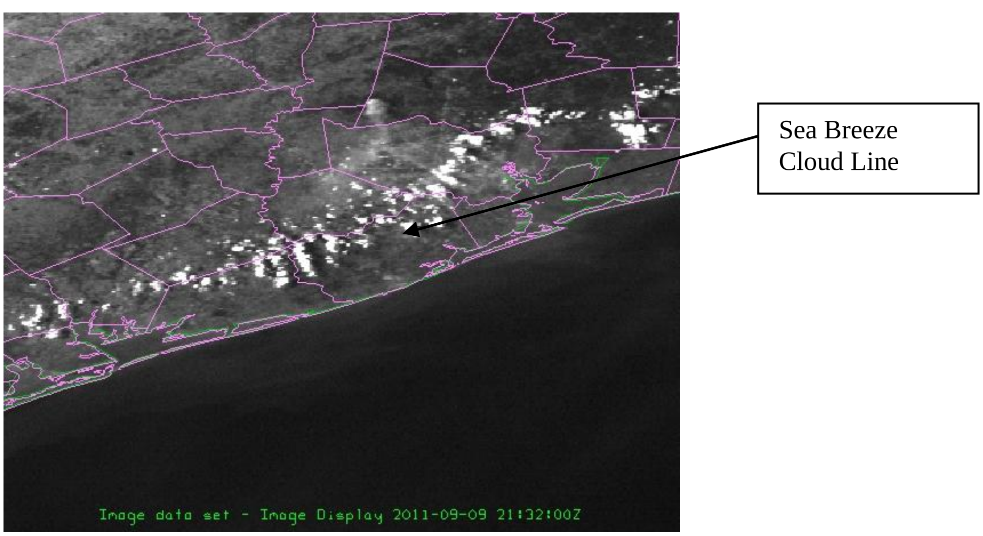

Figure 7 GOES Visible Band Potential Sea Breeze 09/09/11

Next HGX radar data were evaluated for each day. Synoptic rain days were very obvious and eliminated from further study. The radar files could be viewed in 30-60 minute increments to note direction of motion and intensity of the rain. Figure 8 shows an example of a synoptic rain day. The red and orange colors show areas of high reflectivity meaning strong rain showers. The level of strong storms in the area and the fact that the rain clouds were coming in from off-shore and toward Louisiana showed that this was not a good case to evaluate sea breeze. Observing the radar data in motion indicated a center of circulation off-shore in the Gulf of Mexico. Sea breeze may have been present but would be difficult to recognize in the meteorological data as synoptic processes would have strongly overlapped in the area. Figure 8 corresponds to the GOES satellite picture in Figure 6 confirming the rain in the clouds. Days showing similar features as in this example were not used for the study.

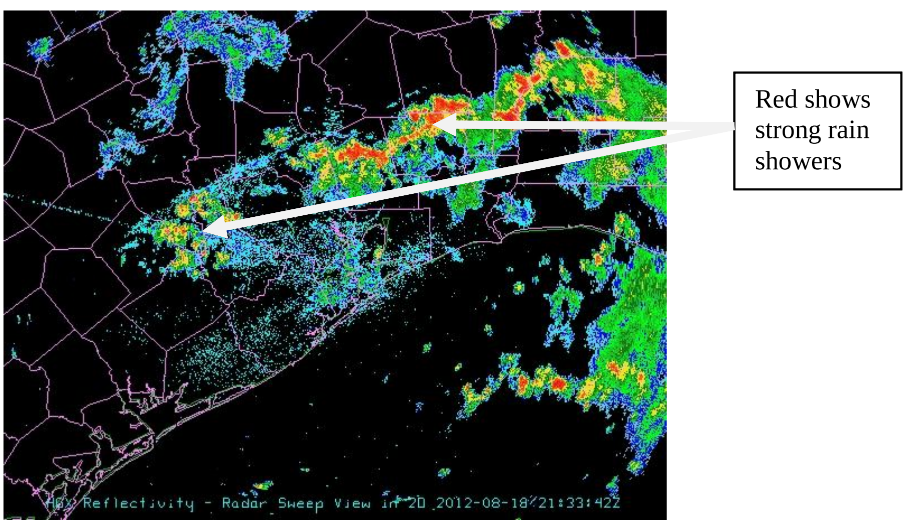

Figure 8 HGX Radar Showing Synoptic Generated Rain 8/18/12

Sometimes the bay/sea-breeze front appeared clearly on the radar (Figure 9). As seen in the figure the blue line with the light green within that runs parallel to the coast and bay is representative of a frontal line (Roberts and Rutledge, 2003). In motion this line moved from the water inland the same direction as an expected sea breeze. Figure 9 is the radar picture that corresponds to the GOES picture in Figure 7. Here the time stamp on the picture was noted, to compare with the ground meteorological data timing of the sea breeze. The ground data would later confirm whether this line was sea-breeze generated. Anytime the radar showed one of these lines, plotted ground data at the sites were used to obtain meteorological characteristic details. These details would confirm whether or not the line was generated by sea breeze.

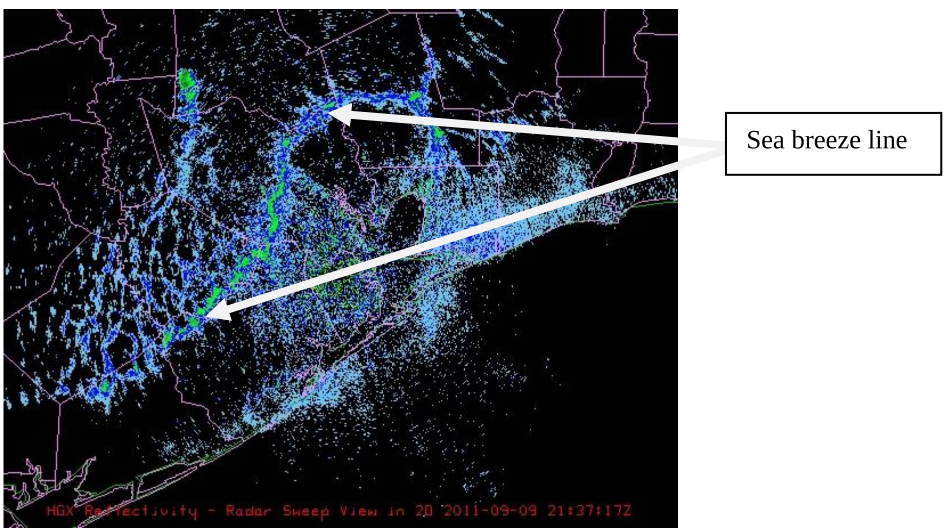

Figure 9 HGX Radar (filtered to 10 dbz minimum) Showing Bay/Sea-Breeze Line 09/09/11

The radar also revealed where and when showers occurred. Time and approximate location of the rain shower was noted for further inspection using the ground meteorological data from a site near the location of the shower was analyzed. The

Unidata IDV software showed the time stamp of the data on the bottom of the window. The latitude and longitude could be found by placing the cursor over the cell. Figure 10 contains an example of a single cell rain shower as noted by the red spot at the arrow.

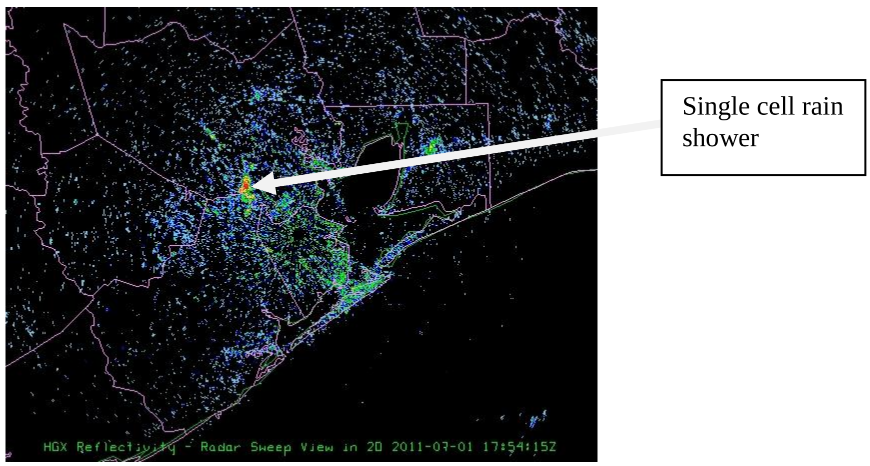

Figure 10 HGX Radar Showing Single-cell Shower 07/01/11

The radar could also show if a single cell shower produced outflow causing subsequent rain showers to develop. These outflow times were noted to help in analyzing the ground meteorological data. Cells caused by outflow were not directly caused by the sea breeze. Figure 11 contains an example of an outflow boundary as seen by the radar. Outflow can be seen by the blue line that surrounds the rain cell. Another cell can be seen forming on the outflow line. Even though the outflow cell could be a secondary effect of the sea breeze it was not considered as part of the rain evaluation results found in section 3.3.

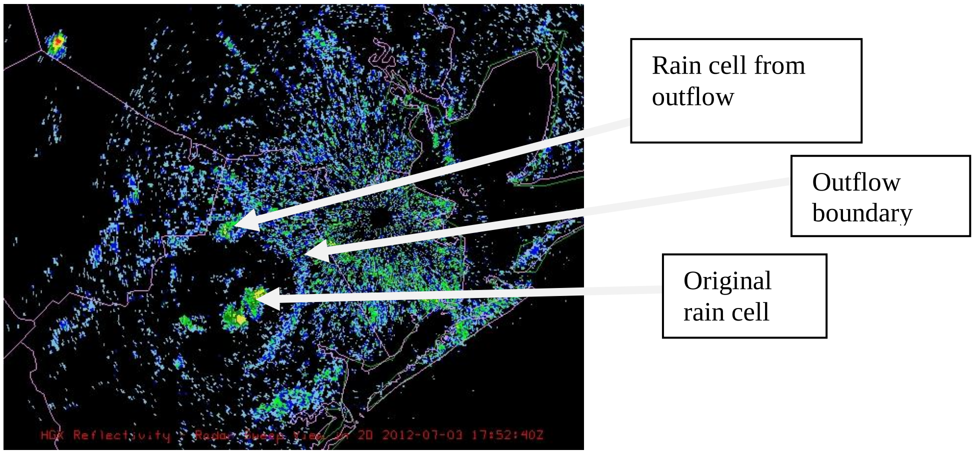

Figure 11 HGX Radar Showing Single-cell Rain Shower with Visible Outflow 07/03/11

Finally the plots for each site were examined on each day that wasn't completely eliminated based on the radar or satellite data. Sites that had dew point as an available measurement were analyzed first. Plots that showed an increase of dew point temperature and decrease of air temperature during daylight hours were considered possible bay/sea-breeze days. Other methods were used for sites that did not contain dew point. Figure 12 through Figure 14 contain examples of sites that showed evidence of sea/bay-breeze passage.

In Figure 12, the green dew point line shows a sharp increase around 20:00 UTC, while at the same time the red air temperature line is decreasing (noted by arrows). The temperature change along with the wind direction shift to the southeast was a good indicator of a sea-breeze front passage. The time span that encompassed the air and dew point temperature changes were considered the start and stop times of the sea-breeze frontal passage for the particular site.

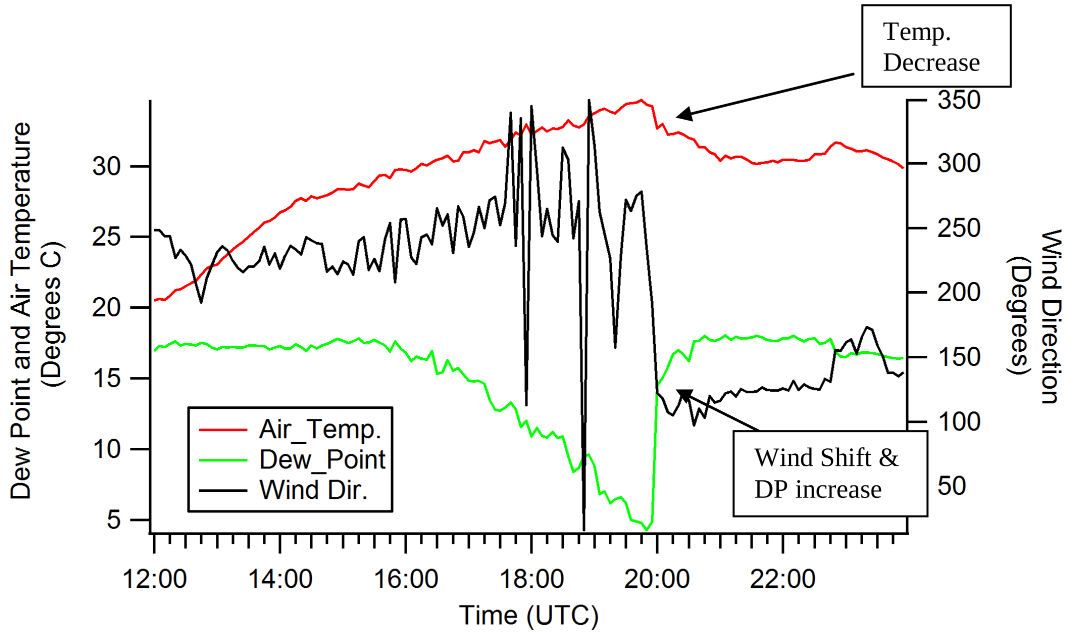

Figure 12 Channelview 09/10/11 Sea Breeze based on Dew Point (DP) Increase, Air Temperature (Temp.) Decrease and Wind Direction (Dir.) Change

When analyzing coastal sites where dew point was not available, just temperature and wind direction were used. If the air temperature decreased with a wind direction shift to a direction that originated over the water, it was considered to be due to the bay or sea breeze. Figure 13 contains an example of a site meeting the air temperature and wind direction criteria. At 20:30 UTC, the red air temperature line was decreasing, as indicated by the arrow, while the wind direction was from the southeast. The blue line on the plot is the water surface temperature. Water surface temperature was noted, when available, at the time of the sea-breeze passage.

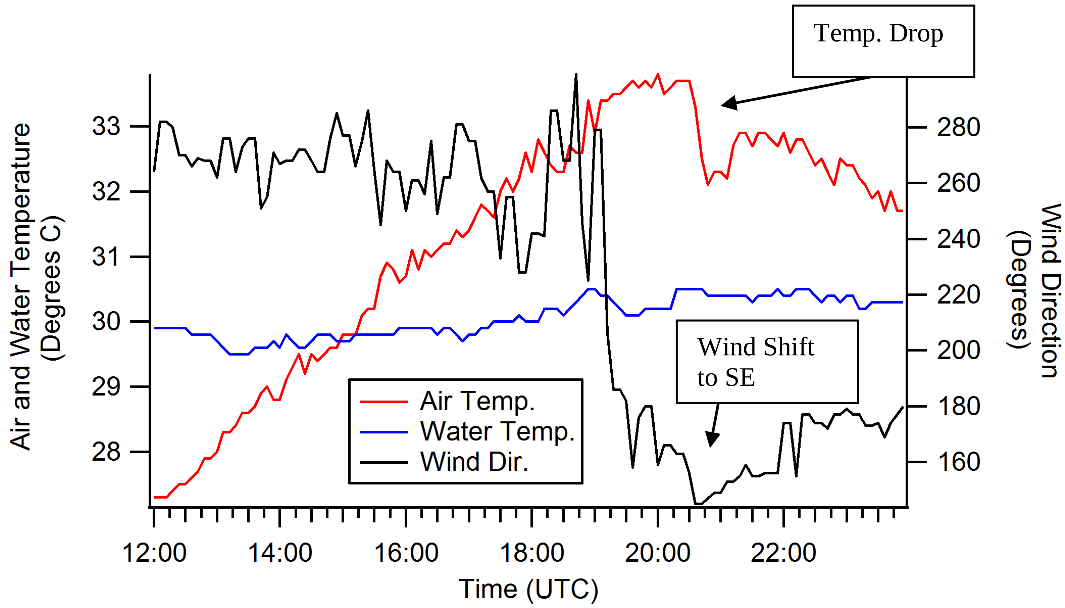

Figure 13 Morgan Point 07/31/12 Sea Breeze based on Air Temperature (Temp.) Decrease and Wind Direction (Dir.) Change . Water Temperature (Temp.) is also Shown.

Distinguishing bay breeze from sea breeze was done, if possible, based on site location and wind direction. Due to timing of the frontal passages some sites contained both bay and sea-breeze events that were very distinct. Figure 14 contains an example of the two events seen at one site. At approximately 19:30 UTC the air temperature (red line) decreases. A second temperature decrease can be seen at 21:30 UTC. At the same two times the green dew point line increases. Also the black wind direction line shifts to east-southeast then to south. Based on the wind shift, the bay breeze reached this site first followed immediately by the sea-breeze front.

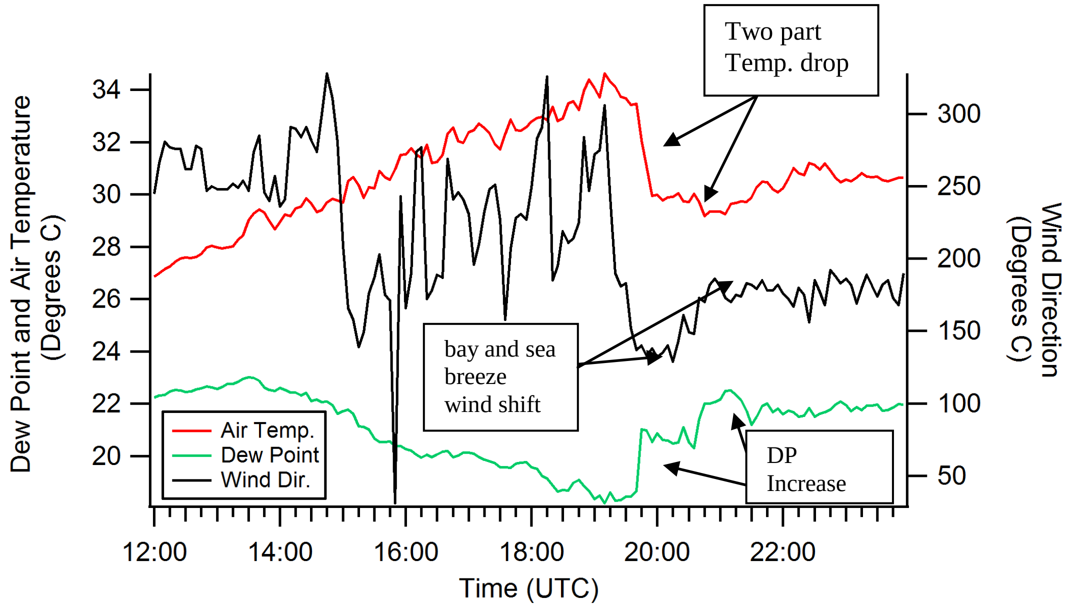

Figure 14 University of Houston Moody Tower 08/08/12 Separate Indications of Both Bay and Sea Breeze. Air Temperature (Temp.) decrease in two places with corresponding Dew Point (DP) increases and different Wind Directions (Dir.)

2.3 Recording Data

Spreadsheets were created to log the meteorological parameters at each site that met the criteria from section 2.2 during sea/bay-breeze events. When a day had a site that met the criteria it was considered what will be referred to as a recordable day. The available parameters shown in Table were recorded based on the start and stop times of the sea breeze as it passed by each site. If a site had both events, separate line items were given to that site.

Table 4 contains an example of how start and stop values were determined. Based on the plotted meteorological data demonstrated in Figure 12 through Figure 14 for each site, estimated time of sea-breeze passage was found. The meteorological data from the site were analyzed around that time to find the exact time of sea-breeze passage, based on criteria in section 2.2. Sometimes the time of air temperature decrease and dew point increase were not at the exact same time, so the start and stop of the sea breeze encompassed the complete time span. The time span was based on which parameter (temperature or dew point) had the earliest start time and which parameter had the latest stop time. This procedure for obtaining meteorological data was performed for each site where sea breeze could be found. This study used ground site level data to define the start time of the sea breeze passed based on where the temperature started to decrease first. Sometimes this start time corresponded to the maximum diurnal temperature for the day at that site but sometimes the start time occurred after the maximum. For each site, day and month calculations were made based on the recorded data available as shown in Appendix A Table 20. The following sections describe the methodology of these calculations.

Date	Time (UTC)	Wind Speed (m/s)	Wind Direction (degrees)	Wind Gust (m/s)	Air Temp. (deg C)	Dew Point (deg C)	Relative Humidity (%)
9/10/2011	19:35:00	2.1	263.3	5.5	34.4	5.0	15.7
9/10/2011	19:40:00	2.9	275.1	5.3	34.5	4.9	15.5
9/10/2011	19:45:00	2.9	278.3	4.7	34.7	4.8	15.2
9/10/2011	19:50:00	2.2	235.2	4.4	34.3	4.3	15.0
9/10/2011	19:55:00	3.7	191.2	6.6	34.2	4.8	20.0
9/10/2011	20:00:00	4.3	122.1	5.9	32.7	14.5	34.1
9/10/2011	20:05:00	4.6	117.9	8.1	33.0	15.1	34.0
9/10/2011	20:10:00	5.6	107.3	8.2	32.2	15.8	38.1
9/10/2011	20:15:00	4.8	105.0	6.9	32.3	16.7	39.1
9/10/2011	20:20:00	5.3	112.3	7.8	32.4	17.0	39.8
9/10/2011	20:25:00	5.4	123.8	7.8	32.2	16.7	38.9
9/10/2011	20:30:00	6.0	116.4	8.6	32.0	16.2	39.3

Table 4 Site Example (Channelview) of Meteorological Parameters Logged at Site During Sea-Breeze Passage. This table is just a portion of the complete .csv file for one site. The Time (UTC) column represents the time stamp of the data. The grey boxes in this column are the start and stop time of the sea-breeze passage for this site .Grey cells in the other columns represent the data recorded for the start and stop times of the parameters

2.3.1 Site Calculations Based on Recorded Data

For each site it was desired to see how much the meteorological parameters changed as the sea-breeze front passed. To calculate, for example, how much the temperature decreased or dew point increased at a given site, the difference between the values recorded at the start time and stop time of the sea breeze at the site was calculated for each parameter. Only a single site value was recorded for atmospheric pressure and surface water temperature during the time of the sea-breeze event. Neither of these parameters had any noticeable change during sea-breeze passage at the site. Pressure changed over the course of the day but not as the sea breeze passed the site. Constant pressure is due to sea breeze being an air density-driven event and not having an effect on air pressure. The changes in temperature, dew point, and relative humidity were calculated to see if there was any consistency as to the amount of change generated by the sea-breeze passage. The differences in wind direction, wind speed, and wind gust were calculated to explore whether the sea breeze occurred as the wind was changing directions or after.

2.3.2 Daily Calculations Based on Site Recorded Data

Each recordable day would have at least two sites in which sea-breeze passage was included in the spreadsheet. Basic daily calculations were generated for each recorded parameter using all the sites for that day. Maximums, minimums, and averages were calculated for each meteorological parameter and the changes in the parameters for each day. Maximum and minimum of the start time parameter would show the earliest and latest time for that day in which sea breeze was recorded. Average for the time parameter in this case would not be useful. In contrast, the maximum, minimum, and average of the time change (difference between start and stop time), would show the time variation for the sea breeze to pass by individual sites that day. For the meteorological parameters the maximum, minimum and average was used to see if there were similar patterns at the sites for that day as the sea breeze passed through the site. Accordingly, maximum, minimum and averages were calculated for the site specific differences of the meteorological parameters between the start and stop time of the sea breeze at that given site, as discussed in section 2.3.1. For the meteorological parameters the maximum, minimum, and averages of the change in, for example, temperature and dew point, was used for a day-to-day comparison of recordable sea-breeze days. The number of sites each day that contained recordable data was also determined. A condensed version of a daily spreadsheet can be seen in Appendix B Figure 31

.

2.3.3 Monthly Calculations Based Daily on Recorded Data

Once all the daily maximum, minimum, and average values were calculated, monthly maximum, minimum, and averages were calculated. To generate the monthly value each daily maximum, minimum, and average value of the individual parameters and the differences of the parameters for the month were consolidated onto another spreadsheet. For the monthly calculations, instead of counting the number of sites per day which contained recordable data, now the number of days per month that had sites containing recordable data was counted. Calculating the monthly maximum, minimum, and average was done to show if any monthly variation in the meteorological parameters existed as the sea breeze passed the sites.

2.4 Analysis

The goal of this study was to determine the climatology of a Houston sea-breeze event. Along with the climatology, the study set out to prove or disprove that the single-cell rain showers are associated with the sea breeze and/or Galveston Bay breeze contain similar characteristics. The data created in the spreadsheets were analyzed to compare day-to-day and month-to-month similarities as well as differences. Additional comparisons were made to see if differences in daily surface water temperature showed any signs of affecting the timing of the sea/bay breeze. Using the location of the last site, based on time, which showed indications of sea breeze an approximate inland distance, was inferred. These distances were noted both daily and monthly. Section 3.0 contains the results of the comparisons.

3.0 RESULTS

Similarities and differences were found between the two years analyzed. For most months the drought year 2011 had more recordable days of sea breeze. Recognition of a sea-breeze event that involved noting an increase in moisture (dew point) was easier to determine because the initial air was drier than near normal years. For example looking at the GOES satellite data for August 2011, many of the days had no clouds at all. Clouds would be visible only when sea breeze was present. Figure 7 is a good example of one of the sea-breeze only cloud days. Monthly recordable days can be seen in Figure 15. This figure confirms that August 2011, the driest month based on Table 1, had the most recordable sea-breeze days. Also the drought year had fewer days eliminated due to synoptic events. All data presented in this section only include meteorological values collected from recordable days. Additional sea breeze may have been noted from the radar or satellite observations. These additional days could not be verified with the ground meteorological data. To be a recordable day data values had to be observable from data at one of the ground sites.

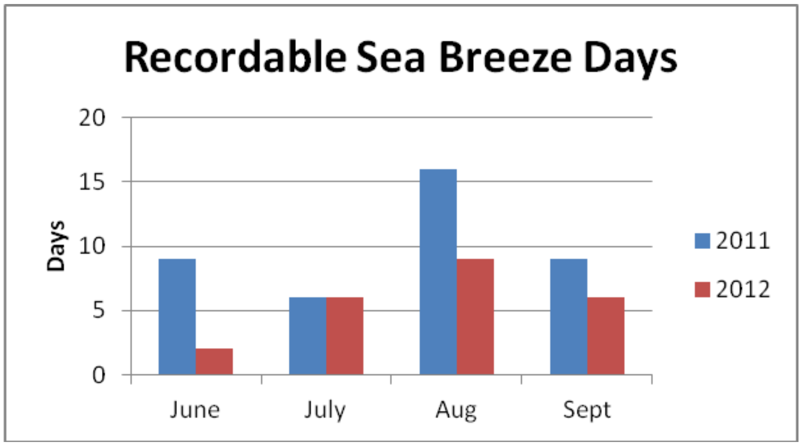

Figure 15 Recordable Sea-Breeze Days per Month

Radar data showed which days had small cell rain showers. These days were compared to the recordable sea-breeze days. Figure 16 shows how many days with small showers per month overlapped with the recordable sea-breeze days. These overlap days would be used to determine if there was any difference between a sea-breeze day with and without rain.

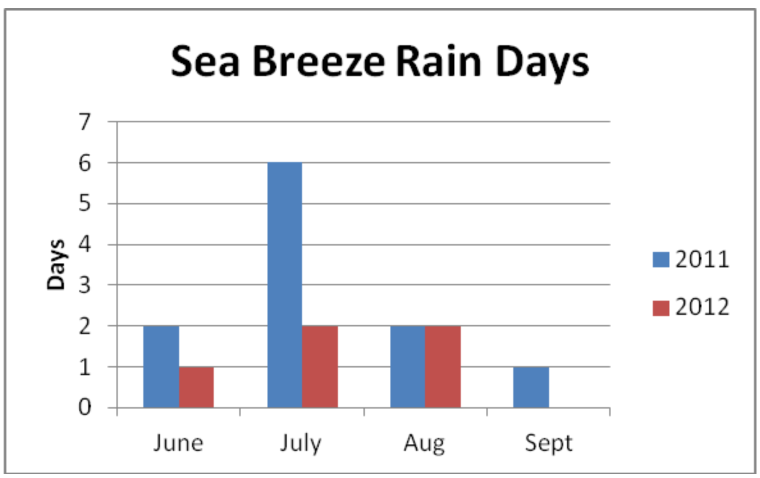

Figure 16 **Monthly Sea-Breeze Days with Single-Cell Rain Showers**

Figure 16 shows rain days as seen by the HGX radar. On some of these days the rain actually occurred over one of the sites that had a rain gauge. Houston Intercontinental Airport (KIAH) was used as the reporting station for the historical climatological reference of rain in Houston. The sea-breeze showers in the two years of this study did not occur near the airport so officially for the Houston climatological record no sea-breeze induced rain was measured. As shown earlier, sea-breeze generated rain can form in single cells that are very localized. Daily rain data was acquired from NOAA NCDC data located on a NOAA Southern Region Headquarters web page (http://www.srh.noaa.gov/images/hgx/climate/lcd/IAH/). Table 5 contains specific sea-breeze rain days with the sites that showed a precipitation measurement. As seen in Table 5, KIAH did not pick up any of these sea-breeze showers. Based on the table it can be concluded that many sea-breeze rain showers that were measured at sites used by this study were so isolated that they are unaccounted for in daily officially reported Houston measurements.

<table>
<tr><th>Date</th><th>Site</th><th>Site Rain (mm)</th><th>Site Monthly (mm)</th><th>KIAH Rain (mm)</th><th>KIAH Monthly Total (mm)</th></tr>
<tr><td>06/28/11</td><td>UHCC</td><td>5.6</td><td>6.1</td><td>0.0</td><td>23.4</td></tr>
<tr><td>07/01/11</td><td>KHOU</td><td>5.1</td><td>83.1</td><td>0.0</td><td>75.7</td></tr>
<tr><td>08/13/11</td><td>UHMT</td><td>0.8</td><td>16.3</td><td>0.0</td><td>2.3</td></tr>
<tr><td>07/16/12</td><td>UHCC</td><td>3.6</td><td>7.6</td><td>T *</td><td rowspan="2">119.6</td></tr>
<tr><td>07/22/12</td><td>Anahuac</td><td>3.6</td><td>281.2</td><td>0.8</td></tr>
<tr><td>08/04/12</td><td>UHMT</td><td>0.2</td><td>35.1</td><td>0.0</td><td>98.6</td></tr>
</table>

*** Trace**
University of Houston Coastal Center (UHCC), Houston William P. Hobby Airport (KHOU), University of Houston Moody Tower (UHMT)

Table 5 Example Rainfall Amounts for Sea-Breeze Rain Days Compared to Official Recorded Rain Total

3.1 Timing

The sea breeze was not always detectable at the coast. On many days the Galveston coastal sites (North Jetty or Galveston Airport/KGLS) showed a continuous south to southeast wind direction even overnight so the moisture content of the air was constant. In these cases the first site, as determined by the criteria mentioned in section 2.2, to detect the sea breeze may be the University of Houston Coastal Center (UHCC). Occasionally the first site was further down the coast at Freeport or Lake Jackson. When the first site was on the Bay or further inland then the bay breeze may have been the only front present. The impacts due to merging of both the sea breeze and bay breeze made it difficult to measure total distance inland. The sea-breeze front would start out parallel to the coast (slight NE/SW slant) northward. Then as the bay breeze interacted with the sea breeze the front was sometimes pushed or bent in a northwest direction around the bay.

Figure 17 shows the location of the sea breeze as seen with the GOES satellite. A trace was done of the sea-breeze edge for ease of recognition. The distinct bend in the line on the right side due to the bay breeze can also be seen.

Figure 17 Trace of Sea-Breeze line Overlaid with GOES Satellite Picture 08/08/2011 at 21:32Z. Red line is the trace of the sea-breeze location.

Figure 18 contains an isochronal example of sea-breeze passage for one day (08/13/11). On this particular day, the sea breeze progressed for approximately 6 hours from onshore time until it was undistinguishable. The red lines were generated by tracing the edge of the cloud line as seen in Figure 17 using the GOES satellite data for that day. Time stamps for the lines represent the time of the GOES data. Note that the 21:32Z and 22:32Z lines have a slight bend on the right side. This bend is caused by the bay breeze. The distance between the first red line along the coast and the last red line inland is different at various points on the lines.

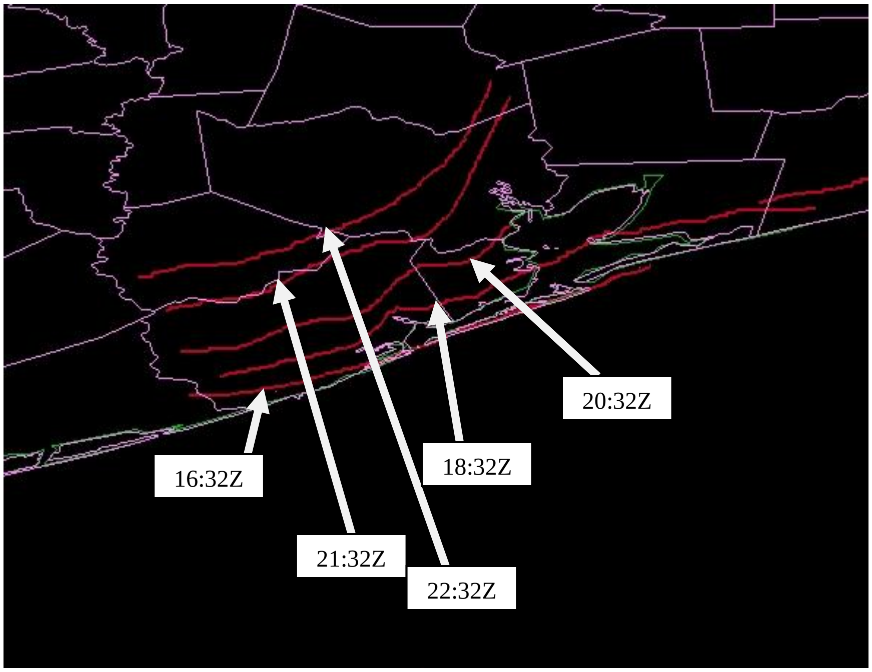

Figure 18 Isochronal Representation of Sea-Breeze Passage 08/03/2011

Table 6 through Table 13 were generated for each month showing the first site based on time where sea-breeze criteria was recognizable and the last site again based on time, for each recordable day. As shown by the tables sometimes the first site to have recognizable sea breeze was not on the coast but slightly inland. The tables also contain average wind direction (WD) and wind speed (WS) for the day to see if there was any correlation between duration of the sea-breeze front and wind direction and wind speed. Pure bay breeze cases were confirmed when the wind direction was from the east to east-southeast. The data showed a variation for wind speed and the duration of the sea-breeze front. Sometimes the higher wind speed cause the sea breeze to progress quicker but other times it allowed the sea breeze to progress farther. Most of the time the sea breeze progressed for 3-5 hours from start to finish.

June 2011

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
6/5/11	Freeport	1600	UHCC	2100	05:00	156	4.0
6/11/11	UHCC	1620	Channelview / West Liberty	2000	03:40	125	4.5
6/13/11	UHCC	1530	West Liberty	2040	05:10	149	5.8
6/14/11	Channel-view	1920	West Liberty	2130	02:10	145	5.4
6/15/11	UHCC	1535	Channelview	2020	04:45	163	5.5
6/16/11	UHCC	1745	West Liberty	1815	00:30	161*	6.9
6/28/11	Galena Park	1745	UHMT	1755	00:10	97 **	3.7
6/29/11	KGLS	1600	UHCC	1605	00:05	109	3.1

*** UHCC was sea-breeze based. and West Liberty bay breeze. no sites detectable in between**
**** Both sites were bay breeze only. Short distance between two sites.**
Site names found in Table , Wind Direction (WD), Wind Speed (WS)
Table 6 June 2011 Daily Sea-Breeze Duration

July 2011

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
7/1/11	Lake Jackson	1400	Conroe Airport	1950	05:50	142	3.3
7/2/11	KGLS	1630	UHMT	2020	03:50	160	4.4
7/3/11	Freeport	1624	Channelview	2105	04:41	157	3.8
7/4/11	UHCC	2015	KIAH	2053	00:38	135	5.6
7/7/11	KGLS	1600	Channelview	1935	03:35	150	4.0
7/8/11	UHCC	1700	UHMT	2030	03:30	139	6.2

Site names found in Table , Wind Direction (WD), Wind Speed (WS)
Table 7 July 2011 Daily Sea-Breeze Duration

August 2011

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
8/1/11	Freeport	1600	UHSL	2200	06:00	167	4.3
8/2/11	KGLS	1645	UHSL	2240	05:55	184	5.1
8/3/11*	KGLS	1635	UHMT	2230	05:55	163	4.3
8/4/11	KGLS	1610	UHMT	2100	04:50	158	4.7
8/5/11	KGLS	1615	West Liberty	2000	03:45	141	4.6
8/6/11	North Jetty	1530	Jones Forest	2200	06:30	149	3.4
8/7/11	Channelview	1830	UHMT	1920	00:50	123	5.9
8/8/11	Lynchberg Ferry	1845	UHMT	2125	02:40	129	6.3
8/11/11	Eagle Point	1830	Conroe Airport	2125	02:55	154	5.9
8/13/11	KGLS	1750	Conroe Airport	2250	05:00	196	5.9
8/15/11	KGLS	1640	UHMT	2040	04:00	139	4.6
8/16/11	Eagle Point	1636	UHMT	2030	03:54	121	5.2
8/19/11	North Jetty	1712	UHMT	2210	04:58	152	5.1
8/27/11	North Jetty	1824	UHCC	2030	02:06	150	4.7
8/28/11	Freeport	1618	UHCC	2055	04:37	140	4.3
8/29/11	KGLS	2125	UHCC	2145	00:20	159	4.8

***Date used for the Isochronal example in Figure 18**
Site names found in Table , Wind Direction (WD), Wind Speed (WS)
Table 8 August 2011 Daily Sea-Breeze Duration

Sept 2011

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
9/8/11	North Jetty	1930	Eagle Point	2212	02:42	127	5.0
9/9/11	North Jetty	1518	UHSL	2240	07:22	147	5.4
9/10/11	North Jetty	1512	UHSL	2310	07:58	154	5.3
9/11/11	North Jetty	1518	UHSL	2210	06:52	156	5.4
9/12/11	North Jetty	1518	UHMT	2230	07:12	152	5.2
9/13/11	North Jetty	1612	UHSL	2220	06:08	151	5.8
9/14/11	Morgan Point	1800	UHCC	1930	01:30	172	4.8
9/20/11	North Jetty	1630	UHSL	2230	06:00	139	4.9
9/24/11	UHCC	1855	West Liberty	2215	03:20	148	5.8

Site names found in Table , Wind Direction (WD), Wind Speed (WS)

Table 9 September 2011 Daily Sea-Breeze Duration

June 2012

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
6/5/21	North Jetty	1706	UHSL	2240	5:34	143	2.5
6/10/12	North Jetty	1612	UHMT	2050	4:38	167	5.2

Site names found in Table , Wind Direction (WD), Wind Speed (WS)

Table 10 June 2012 Daily Sea-Breeze Duration

July 2012

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
7/6/12	North Jetty	1436	West Liberty	2035	5:59	177	4.8
7/16/12	Lake Jackson	1425	UHSL	1800	3:35	161	3.7
7/22/12	Eagle Point	1824	Channelview	2105	2:41	140	4.8
7/30/12	Freeport	1530	West Liberty	2255	7:25	147	4.4
7/31/12	KGLS	1630	West Liberty	2215	5:45	145	4.5

Site names found in Table , Wind Direction (WD), Wind Speed (WS)

Table 11 July 2012 Daily Sea-Breeze Duration

August 2012

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
8/1/12	KGLS	1655	UHMT	2130	4:35	186	4.8
8/4/12	KHOU	1753	UHMT	2000	2:07	163	5.4
8/7/12	Freeport	1542	Morgan Point	1748	2:06	140	2.7
8/8/12	UHCC	1450	West Liberty	2100	6:10	139	5.2
8/9/12	UHCC	1810	UHSL	2130	3:20	185	5.5
8/10/12	North Jetty	1748	Eagle Point	1936	1:48	197	7.7
8/11/12	Eagle Point	1724	UHCC	1855	1:31	151	3.2
8/13/12	Eagle Point	1824	UHMT	2135	3:11	189	3.9
8/14/12	KGLS	1630	West Liberty	2215	5:45	181	6.4

Site names found in Table , Wind Direction (WD), Wind Speed (WS)

Table 12 August 2012 Daily Sea-Breeze Duration

Sept 2012

Date	Start Site	Time Start Site	End Site	Time End Site	Duration (hh:mm)	Average WD (deg)	Average WS (m/s)
9/2/12	North Jetty	1442	Channelview	2255	8:13	164	3.9
9/3/12	Eagle Point	1800	West Liberty	2210	4:10	149	4.4
9/4/12	Eagle Point	1818	West Liberty	2255	4:37	165	3.9
9/5/12	Eagle Point	1754	West Liberty	2200	4:06	135	4.8
9/6/12	North Jetty	1754	West Liberty	2245	4:51	169	4.3
9/7/12	KGLS	1655	UHMT	2235	5:40	141	4.0

Site names found in Table , Wind Direction (WD), Wind Speed (WS)

Table 13 September 2012 Daily Sea-Breeze Duration

A single site evaluation was also created. Table 14 contains the monthly average start time for the sea-breeze passage at the University of Houston Coastal Center (UHCC). This site had recordable data for most of the recordable sea-breeze days. The timing of the sea-breeze passage at UHCC is consistent within about 2 hours.

Year	June Start Time (UTC)	July Start Time (UTC)	August Start Time (UTC)	September Start Time (UTC)
2011	18:10	17:44	19:04	18:18
2012	18:27	19:26	18:42	18:41

Table 14 Average Monthly Start Time of the Sea-Breeze Passage at the University of Houston Coastal Center

3.2 Meteorological Variation

Meteorological parameters were compared, both monthly and yearly, to document what, if any, difference existed between the two years.

3.2.1 Temperature

Since sea breeze is generated by differences in land and sea surface temperature, monthly variation of temperature differences were also analyzed. Water surface temperature was generally warmer during 2011 than during 2012. In September 2011 water surface temperature and air temperature was cooler than that of 2012. The reason for the cooler temperature was not able to be found. According to the National Weather Service Houston/Galveston Climate Summary for 2012 (National Weather Service, 10/17/12) the monthly average ambient air temperature for June through September for the Houston area was warmer in 2011 than 2012. Yet the data averaged from the recordable sea-breeze days for September showed the opposite result. Figure 19 and Figure 20 show the monthly air and water surface temperatures for each year. The values shown in Figure 19 and Figure 20 were derived by generating a daily average from all the sites with recordable sea-breeze data. Then the daily values were averaged to obtain the monthly value. The air and water surface temperature chosen was the value at the start of the sea breeze.

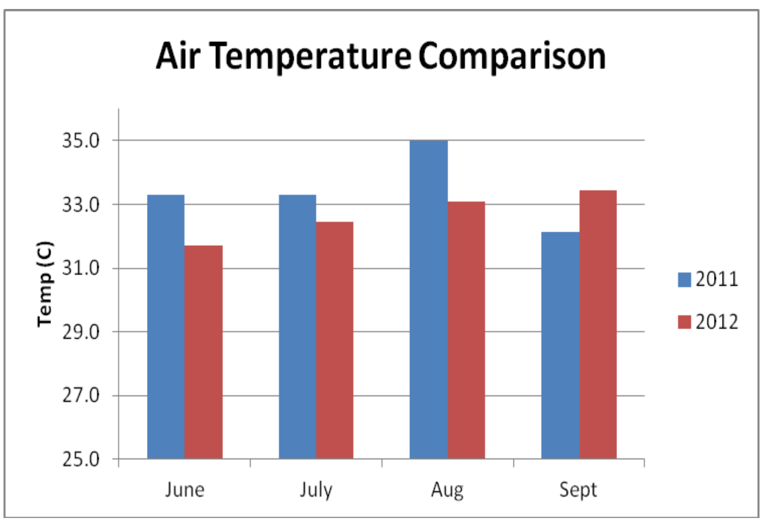

Figure 19 Average Recordable Day Monthly Air Temperature (Temp)

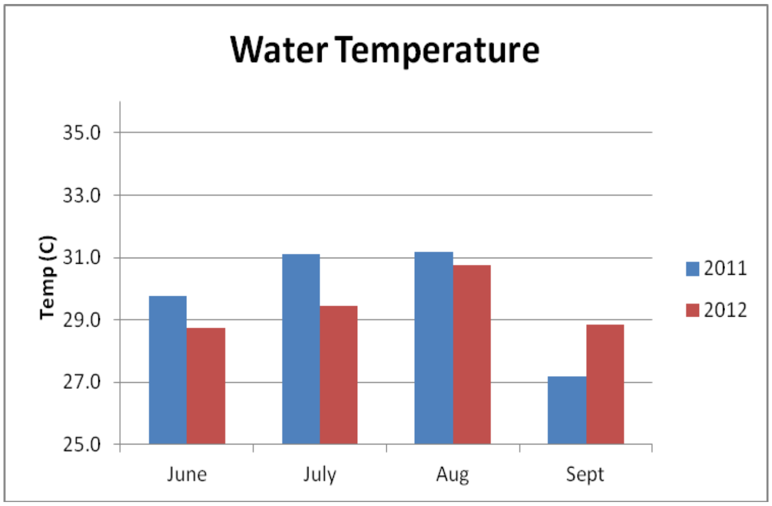

Figure 20 Average Recordable Day Monthly Water Surface Temperature (Temp)

Next a comparison was made for each year showing the monthly average air temperature from all sites with recordable sea-breeze data, at the start and stop of sea-breeze passage and water surface temperature from sites where available. The monthly average was generated daily by averaging the air temperature at the start and stop time of the sea breeze for each recordable site. The daily averages were then averaged to find a monthly average. Figure 21 shows a difference of about 1-2 ºC between start (blue line) and stop (red line) temperature in 2011 due to the sea breeze. In addition, the temperature signature more closely followed that of the water temperature. For 2012 the air temperature difference (space between red and blue line) due to the sea breeze was larger than 2011 and did not seem to be correlated as well to the water surface temperature (Figure 22).

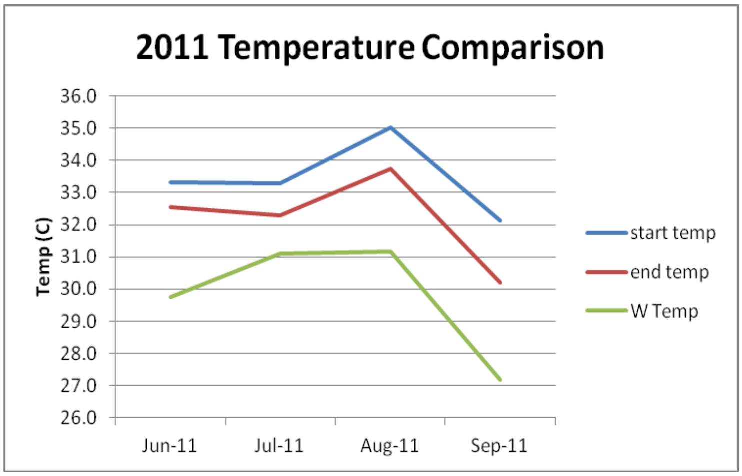

Figure 21 2011 Average Air and Water Temperature Difference. Recordable average monthly air temperature of the start and end time of the sea breeze as it passed through each site with the average monthly water temperature

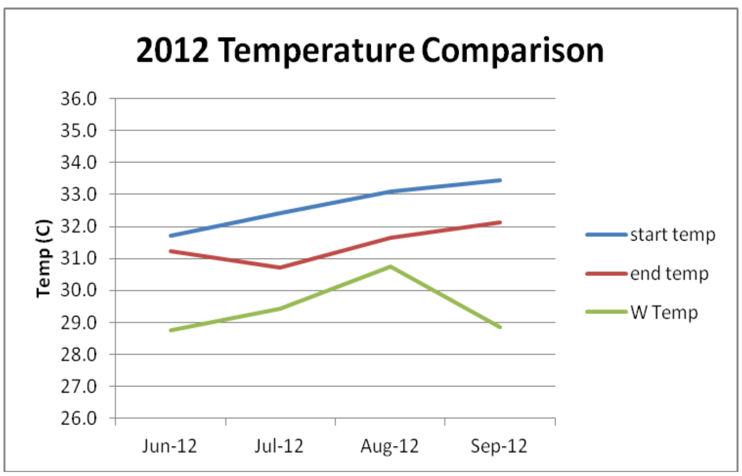

Figure 22 2012 Average Air and Water Temperature Difference. Recordable average monthly air temperature of the start and end time of the sea breeze as it passed through each site with the average monthly water temperature

3.2.2 Meteorological Parameter Change

Changes in meteorological parameters were compared each for each month of each year. Parameter changes were calculated for each site. A parameter change consisted of calculating the difference between the value at the start time and the stop time of the sea-breeze event. Statistics were generated from these calculated differences using all the sites with data on the recordable sea-breeze days. Then all the days for each month were grouped together to generate the monthly statistics. For each parameter the maximum, minimum and average changes are included in Table 15, Table 16, and Table 17. No monthly pattern or difference was found between years. Monthly averages were actually very similar. A negative value represents a decrease from start to end of the sea-breeze event. As an example that the years 2011 and 2012 were similar, the average dew point change between start and stop time of sea-breeze event were plotted for each year (Figure 23). Since the dew point is a prime parameter used to recognize sea breeze it can be deduced that drought does impact the sea breeze. August and September change in dew point was 1-4 ºC larger in 2011 than 2012.

Month	**Duration (hh:mm)**	**AirTemp Change (deg C)**	**DP Change (deg C)**	**RH Change (%)**	**Wind Speed Change (m/s)**	**Wind Gust Change (m/s)**
Jun-11	00:29	-0.8	2.3	7.1	0.8	0.5
Jul-11	00:32	-1.0	1.9	6.9	2.6	2.5
Aug-11	00:37	-1.3	3.3	10.8	2.2	1.8
Sep-11	00:35	-1.9	7.4	18.5	2.9	2.1
Jun-12	00:42	-0.5	2.1	8.8	1.5	-8.7
Jul-12	00:36	-1.7	2.2	13.6	1.8	1.9
Aug-12	00:37	-1.4	1.9	11.7	2.2	1.5
Sep-12	00:32	-1.3	3.1	13.3	-5.3	2.0

Table 15 Average Monthly Parameter Change at Sites During Sea-Breeze Passage

Month	Duration (hh:mm)	AirTemp Change (deg C)	DP Change (deg C)	RH Change (%)	Wind Speed Change (m/s)	Wind Gust Change (m/s)
Jun-11	01:05	1.0	5.7	17.1	4.1	3.3
Jul-11	03:00	1.8	6.1	22.0	9.3	15.0
Aug-11	01:50	2.5	6.7	33.9	7.0	6.2
Sep-11	01:06	0.1	17.3	42.4	10.7	5.2
Jun-12	02:00	0.8	3.9	20.2	3.4	-1.7
Jul-12	03:12	0.7	5.7	25.0	7.6	6.0
Aug-12	01:24	0.2	4.5	41.4	6.3	5.4
Sep-12	01:00	-0.4	6.1	22.4	2.9	5.1

Table 16 Maximum Monthly Parameter Change at Sites During Sea-Breeze Passage

Month	Duration (hh:mm)	AirTemp Change (deg C)	DP Change (deg C)	RH Change (%)	Wind Speed Change (m/s)	Wind Gust Change (m/s)
Jun-11	00:05	-2.9	0.2	-1.4	-3.3	-5.9
Jul-11	00:05	-5.0	-0.8	-2.0	-4.2	-5.8
Aug-11	00:10	-5.3	0.1	-1.0	-4.2	-5.4
Sep-11	00:15	-4.5	2.8	5.6	-1.2	-1.3
Jun-12	00:05	-2.3	-0.8	-2.6	-2.1	-12.9
Jul-12	00:18	-5.1	0.2	1.7	-1.7	-5.7
Aug-12	00:10	-3.7	-19.2	1.5	-3.5	-3.3
Sep-12	00:18	-2.5	1.3	4.7	-10.8	0.5

Table 17 Minimum Monthly Parameter Change at Sites During Sea-Breeze Passage

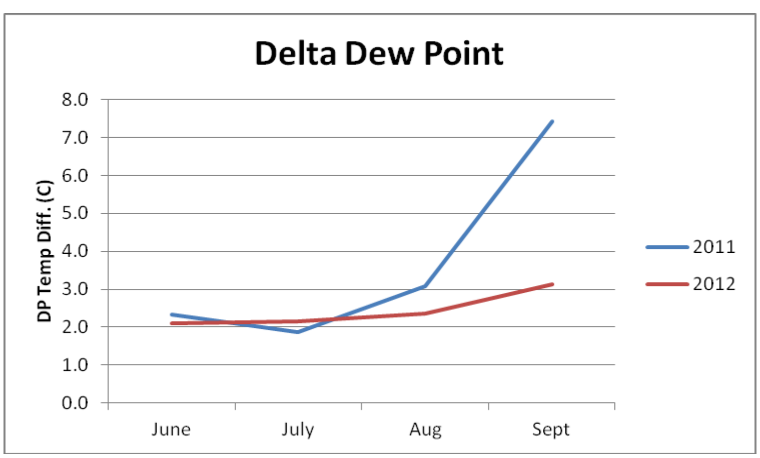

Figure 23 Monthly Average Dew Point Change of Recordable Sites

3.2.3 Wind direction

For each recordable sea-breeze day the final sea-breeze wind direction was averaged. Each day per month was plotted to identify what wind direction predominated the sea breeze. As expected the southeast wind direction was the most common. Southeast is the direction perpendicular to the coast. The range of data for 2011 was from east-southeast (ESE) to south-southwest (SSW). The range for 2012 was southeast (SE) to south-southwest (SSW).

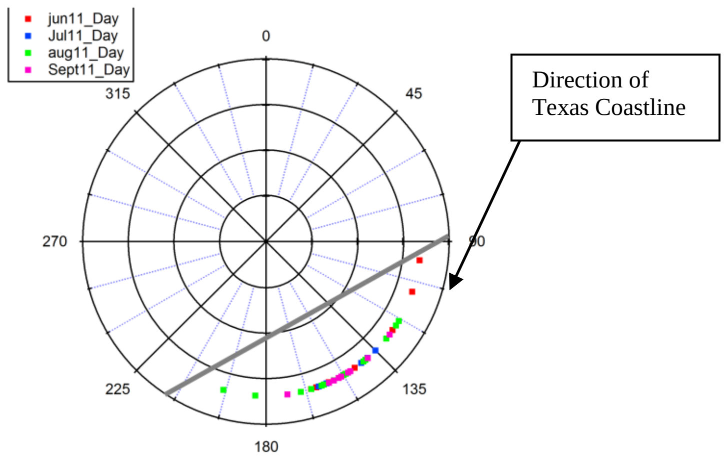

Figure 24 2011 Monthly Average Wind Direction

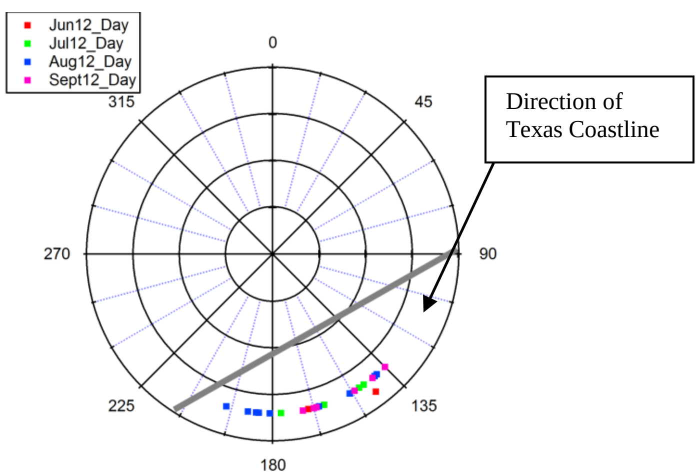

Figure 25 2012 Monthly Average Wind Direction

There was also a monthly variation of the wind direction at the start of the sea-breeze event as compared to the end of the event. The previous plots (Figure 24 and Figure 25) showed only the average end direction. Table 18 shows the monthly average starting and ending direction as well as the amount of change of the wind direction. A negative value represents a counter-clockwise change in wind direction. Table 18 shows that for June in both years the wind direction from the start to end of the sea-breeze passage did not vary. All the other three months showed a counter clockwise shift in direction.

Month	**Start WD (degrees)**	**End WD (degrees)**	**D WD (degrees)**
Jun-11	137	138	1
Jul-11	172	147	-25
Aug-11	176	151	-25
Sep-11	180	150	-30
Jun-12	153	155	2
Jul-12	177	154	-23
Aug-12	207	169	-38
Sep-12	203	154	-49

Table 18 Monthly Wind Direction (WD) and Delta Wind Direction (D WD)

When the wind was from the southwest, i.e. parallel to the coast, a particular cloud pattern was noticed on the GOES satellite (Figure 26) and the HGX radar (Figure 27) to occur all day. No sea breeze was seen for days when the clouds had this pattern.

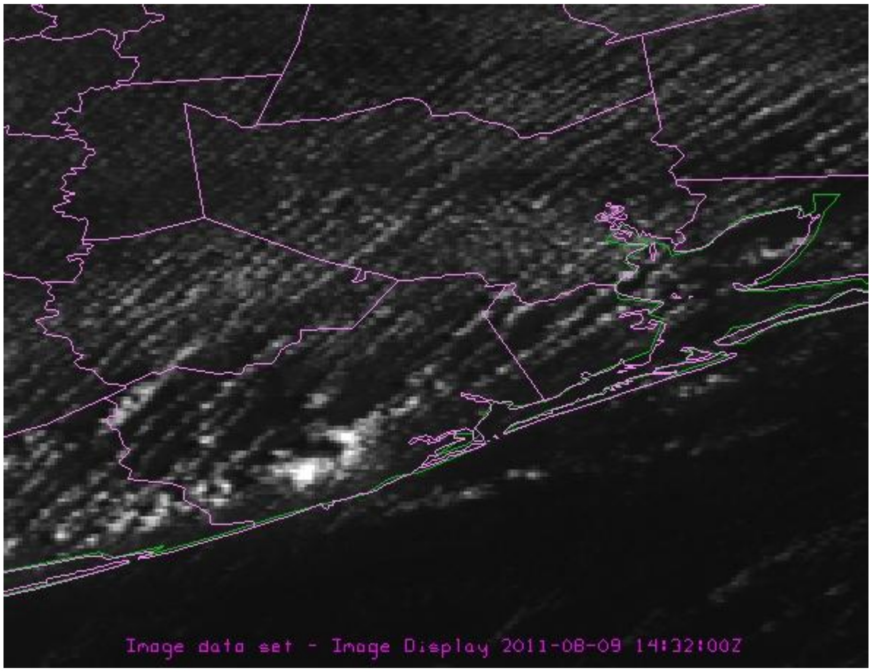

Figure 26 GOES Satellite Southwest Wind

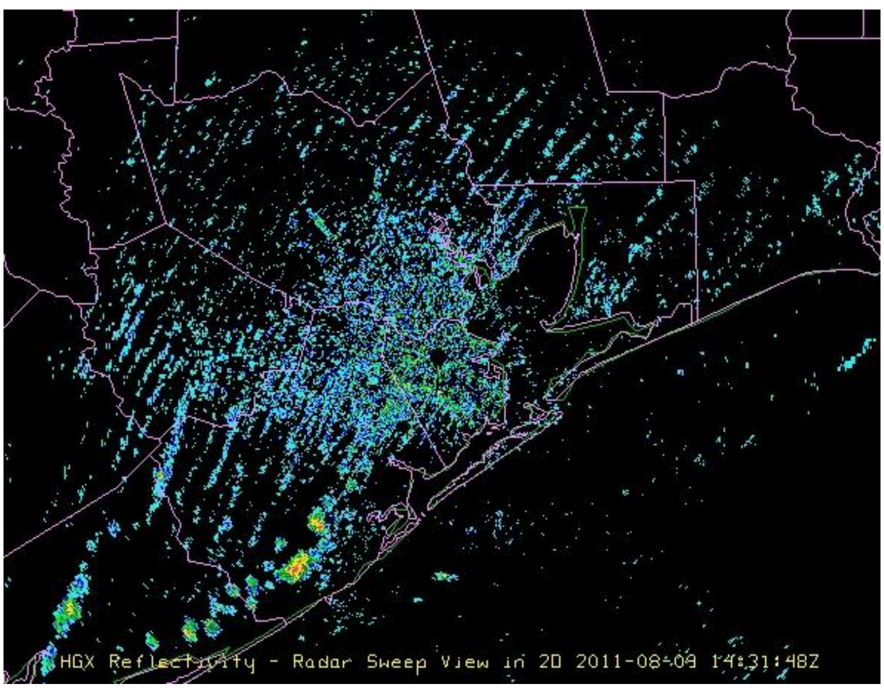

Figure 27 HGX Radar Southwest Wind

3.3 Rain Days Evaluation

HGX radar pictures and the daily spreadsheets as in Figure 31 Appendix B were used to study the days that had single-cell rain showers and sea breeze. Screen dumps of the radar would show location and time of the rain shower. The screen dumps contained county lines which were used to identify approximate location of the rain shower. The IDV software used to generate the screen dumps also provided the latitude and longitude of the cell by placing the computer cursor over the location. Figure 28 is an example of a single cell that was not considered because the cell was out ahead of the sea-breeze line. Figure 29 and Figure 30 show cells that may have been generated by the sea breeze, because they correspond to times and locations of sites that detected rain.

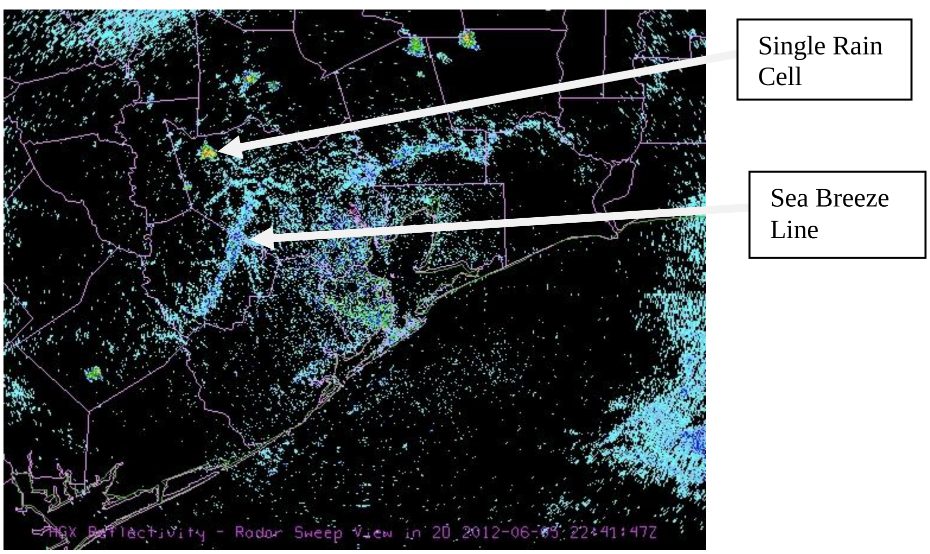

Figure 28 Single Cell ahead of sea-breeze line 06/05/11 22:41Z

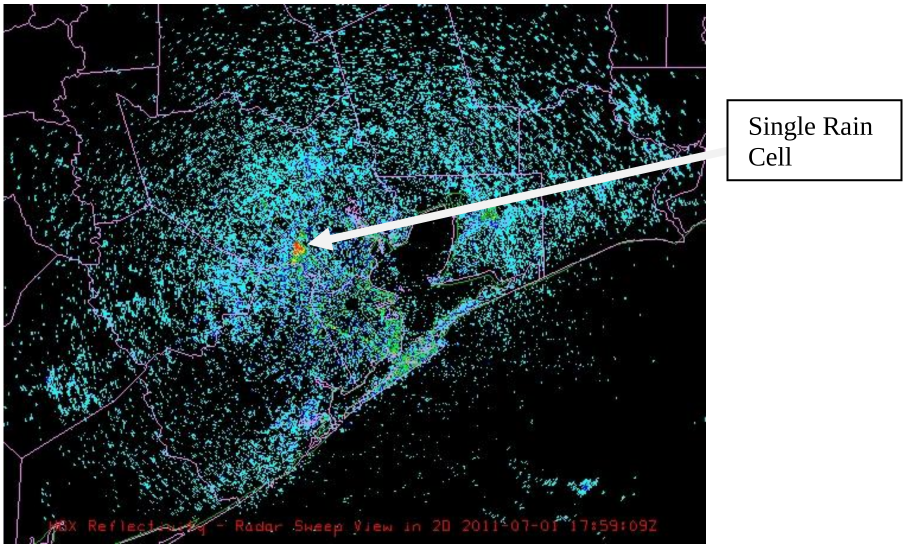

Figure 29 Single cell at William P. Hobby Airport 07/01/11 17:59Z

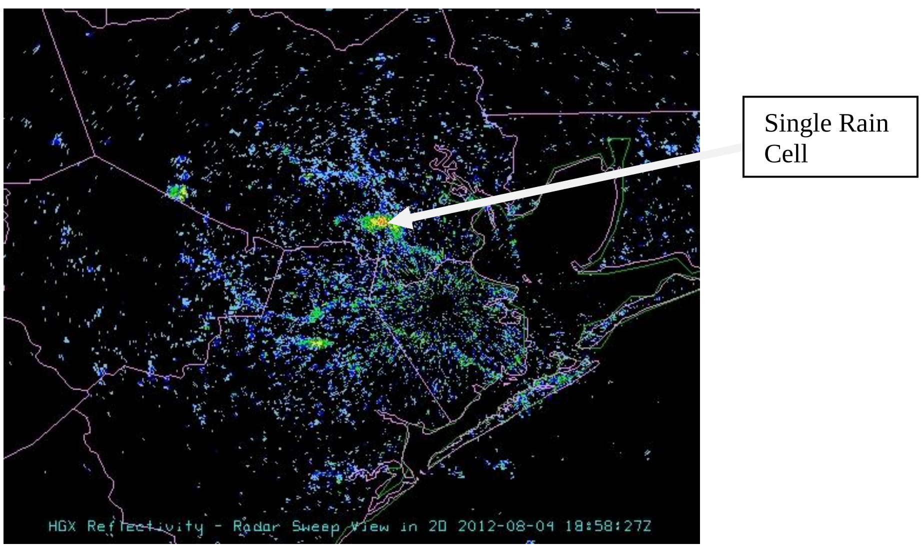

Figure 30 Single cell at William P. Hobby Airport 08/04/12 18:58Z

The time and location of the cell were compared to the sea-breeze timing and data gathered from the ground sites. If a site near the rain shower had sea or bay breeze passage, the data from that site were placed in another spreadsheet. On some days the rain showers were present, but site data near the shower were not available. The goal was to try and demonstrate that rain showers occurred during or close to the time of the sea-breeze passage for the site. The data from the sites were compared to see if there were any similarities, such as amount of temperature decrease, dew point increase or wind direction/speed change, that could be used to correlate or predict if a rain shower was going to occur with the sea breeze.

Table 21 in Appendix C contains locations and times where rain cells were located, based on the HGX radar. These cells were recorded only for sea-breeze days and the closest corresponding site that had data available. If a site could not be matched with location and time it was only matched by time. When a site had a precipitation measurement it was also noted on the table. If multiple cells were located at the same time the individual latitudes and longitudes of each cell were noted. On 6/28/11 the University of Houston Coastal Center (CAMS 697) measured some precipitation but this could not be found on the radar. This site is very close to the radar site so sometimes the rain may have been below detectable radar elevation level.

Date	Delta** time (hh:mm)	Delta** Temp (C)	Delta** DP (C)	Delta** WS (m/s)	Delta** Gust (m/s)	Delta** WD
6/11/2011	00:01*	-1.4	1.7	-0.7	0	-96
6/11/2011	00:13	-0.3	2.9	4.1	0	-50
6/28/2011	00:25	-0.3	1.4	0.7	0	56
7/1/2011	00:06	-4.8	0.3	1.7	8	-20
7/2/2011	01:33	-0.4	1.8	2.4	0	-76
7/3/2011	00:47	-0.8	2.5	0.5	2.8	80
7/4/2011	00:07	-0.4	0.9	2.2	0	4
7/7/2011	01:39	-2.7	4.1	4.8	0	-43
7/8/2011	00:08*	-2.0	3.8	5.3	0	-110
8/6/2011	00:00	-3.2	2.7	-4.2	0	27
8/13/2011	00:09*	-4.0	2.8	7.0	0	-78
8/13/2011	00:37	-5.3	2.7	4.7	0	-54
8/13/2011	00:27	-1.0	3.3	2.5	6.4	26
7/6/2012	00:08	-5.0	1.9	3.2	0	-4
8/4/2012	01:05	-1.1	1.2	-3.5	0	-10
8/4/2012	00:33	-2.1	1.9	4.6	0	-11
8/4/2012	01:02*	-2.8	2.2	4.6	0	-9
8/8/2012	00:11*	-3.1	2.7	6.3	0	-57
8/8/2012	00:41*	-2.9	2.8	0.8	-3.7	73
Average	00:31	-2.3	2.3	2.5	0.7	-19
Maximum	01:39	-0.3	4.1	7.0	8.0	80
Minimum	00:00	-5.3	0.3	-4.2	-3.7	-110
Std Dev	00:30	1.6	1.0	3.1	2.5	55

***Time of sea-breeze passage after detected rain shower,**
****Delta refers to the change of the parameter between the time of the rain shower and the start of the sea breeze**

Table 19 Differences of Meteorological Parameters at Rain Sites The grey lines in each of the tables represent those days in which the rain was verified by a precipitation measurement at the site.

As it is shown in Table 19, no correlation could be found between the data closest to the rain showers. In the case of most of the parameters, the standard deviation was as large as the average, showing that there was a large variation in the data. Dew point was one of the better parameters showing only 1.0 ºC of standard deviation. Air temperature only had 1.6 ºC of standard deviation. It was interesting to see that the average drop in temperature was equal to the average increase in dew point. The average sea-breeze rain shower occurred within 30 minutes either before or after passage at the site. There are a couple of explanations for the rain showers that were an hour or more from the start of the sea breeze-passage at the site. First, the timing of the sea breeze passage near the cell would be better represented if there was a site closer. Occasionally there were no sites near the cell so a site that was as close as possible was picked. Second, the cell could have been created by another source other than the sea-breeze passage.

4.0 CONCLUSION/SUMMARY

The goal of this study was to document the characteristics of the Houston sea breeze and Galveston Bay breeze for two different climatological years. Along with the characteristics the study set out to prove or disapprove that the single-cell rain showers are associated with the sea breeze and/or Galveston Bay breeze. In terms of climatology 2011 was a drought year and 2012 was considered normal. The number of recordable sea-breeze days was found to be higher in 2011. Recognition of a sea-breeze event that involved an increase in moisture (dew point) was easier to determine in 2011 data because the initial air was drier than normal years. Also, the drought year had fewer days eliminated due to synoptic rain events.

Meteorological parameters also showed some difference between the two years. The daily temperatures for both the ambient air and the water surface were higher during the drought year. The difference between the water surface and air temperature was lower for the drought year versus the normal year. The drier air in 2011 showed that the dew point temperature increase during sea-breeze passage was larger than a normal year. As expected the wind direction was found to be close to perpendicular to the coast in both years to produce recognizable sea breeze. Patterns in the Doppler radar and GOES satellite visible band could occasionally be used to find a sea-breeze day, but verification was still needed with ground data.

For sea breeze, the single-cell rain showers showed no pattern as to location or climatology of meteorological parameters. Some showers were shown to be associated with the sea breeze while others were not. There was no evidence that the sea breeze-related showers were at the intersection of the bay and sea breeze. More years of data may be needed to verify this phenomenon. Single cell rain showers can be created by vertical uplift of warm air as produced during sea-breeze circulation. Based on this study there must be other mesoscale sources of uplift. One of these other sources could be due to the urban heat island effect. This heating could create a surface temperature difference between the city of Houston and the outlying areas causing a circulation similar to the sea breeze. This study only focused surface conditions related to the sea breeze. The vertical component relating to the rising air as part of the sea-breeze circulation was not evaluated.

5.0 FUTURE WORK

This study should be continued by evaluating the vertical component of the air movement. The velocity measurement from the Doppler radar could be one tool for the evaluation. Also, profiler or balloon data could be very useful. Other data that could be used are synoptic weather charts to note exactly where high pressure and low pressure systems may be relative to the Houston area, as well as fronts. Synoptic passages were noted by radar and satellite but ground weather charts would have provided actual timing and location of synoptic systems. Two years was a minimum to evaluate. More years should be evaluated to better validate the statistics.

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7.0 Appendix A

Param.**	Air Temp	Dew Point	Water Temp.	Press.	Rel. Humid.	Wind Speed	Wind Dir.	Wind Gust	Precip.
NOAA Units	°F	°F	°F	mb	%	kts	deg	kts	in
SI Units	°C	°C	°C	hPa	%	m/s	deg	m/s	mm
East Galveston	°C	°C	°C	hPa		m/s	deg	m/s	
42043	°C	°C	°C	hPa		m/s	deg	m/s	
Atascocita	°F	°F *			%	mph	deg	mph	
Baytown	°F					mph	deg	mph	
Channelview	°F	°F			%	mph	deg	mph	
UHCC	°F	°F *		mb	%	mph	deg		in
KCXO	°F	°F			%	mph	deg	mph	in
EPTT2	°F		°F	inHg		kts	deg	kts	
Eagle Point	°C	°C	°C	hPa		m/s	deg	m/s	
Freeport	°C	°C	°C	hPa		m/s	deg	m/s	
Galena Park	°F					mph	deg	mph	
Galveston Airport	°F	°F			%	mph	deg	mph	in
GNJT2	°F		°F	inHg		kts	deg	kts	
North Jetty	°C	°C	°C	hPa		m/s	deg	m/s	
Pleasure Pier	°C	°C	°C	hPa		m/s	deg	m/s	
UHJF	°F	°F *		mb	%	mph	deg		in
KDWH	°F	°F		inHg	%	kts	deg	kts	in
KEFD	°F	°F		inHg	%	kts	deg	kts	
KGLS	°F	°F		inHg	%	kts	deg	kts	in
KHOU	°F	°F		inHg	%	kts	deg	kts	in
KIAH	°F	°F		inHg	%	kts	kts	kts	in
Lake Jackson	°F					mph	deg	mph	
Lynchberg ferry	°F					mph	deg	mph	
MGPT2	°F		°F			kts	deg	kts	
Morgan Point	°C	°C	°C	hPa		m/s	deg	m/s	

*Dew point was calculated in Fahrenheit units based on air temperature and relative humidity.
**Centigrade (C), Fahrenheit (F), hecto Pascal (hPa), inches of Mercury (inHg), miles per hour (mph), Meters per second (m/s), Millimeters (mm), kts (knots), deg (degrees), in (inches)

Table 20 Site Parameters and reported units. The top row shows the units that were used for the plots. Grey fields contain data for each site that was found to be missing or invalid (continued on next page)

Param.**	**Air Temp**	**Dew Point**	**Water Temp.**	**Press.**	**Rel. Humid.**	**Wind Speed**	**Wind Dir.**	**Wind Gust**	**Precip.**
UHMT	°F	°F *		mb	%	mph	deg		in
RLOT2	°C	°C	°C	hPa		m/s	deg	m/s	
UHSL	°F	°F *		mb	%	mph	deg		in
TR474	°F	°F	°F		%	kts	deg	kts	in
Wallisville Rd	°F					mph	deg	mph	
West Liberty	°F	°F *		mb	%	mph	deg		in

*Dew point was calculated in Fahrenheit units based on air temperature and relative humidity.
**Centigrade (C), Fahrenheit (F), hecto Pascal (hPa), inches of Mercury (inHg), miles per hour (mph), Meters per second (m/s), Millimeters (mm), kts (knots), deg (degrees), in (inches)

Table 20 Site Parameters and reported units. The top row shows the units that were used for the plots. Grey fields contain data for each site that was found to be missing or invalid (continued)

8.0 Appendix B *

Site Abbrev	Site Name	start time	end time	start temp	end temp	start DP	end DP	start RH	end RH	start P	start WD	end WD
CAMS 5005	Galveston Airport	16:55	17:30	91.6	92	76	78.6	60.1	65.1		226	193.5
GNJT2	North Jetty	16:54	17:30	86.72	85.46					1014.5	236	220
CAMS 697	UH Coastal Center	20:00	20:35	93.1	91.5	71.3	76.7	49.4	59	1014	238	203
CAMS 695	UH Moody Tower	21:30	21:40	95.5	92.7	62.8	65.7	34.41	41.2	1007.5	226	181
CAMS 115	Channelview	21:25	22:00	96.3	94.4	68	73.2	40.5	49.8		191.6	132.3
	Max	21:30	22:00	96.3	94.4	76	78.6	60.1	65.1	1014.5	238	220
	Min	16:54	17:30	86.72	85.46	62.8	65.7	34.41	41.2	1007.5	191.6	132.3
	Average	19:20	19:51	92.64	91.21	69.53	73.55	46.10	53.78	1012.00	223.52	185.96
	Count	5	5	5	5	4	4	4	4	3	5	5

Site Abbrev	Site Name	start WS	end WS	start Gust	end Gust	W Temp	Precip	D time	Dtemp	D DP	D RH	D WS	D Gust	D WD
CAMS 5005	Galveston Airport	8.8	12.2	14	17			00:35	0.4	2.6	5	3.400	3	-32.5
GNJT2	North Jetty	7.7	11.8	8.7	13.2	85		00:36	-1.26	0	0	4.100	4.5	-16
CAMS 697	UH Coastal Center	4.4	5.7					00:35	-1.6	5.4	9.6	1.300	0	-35
CAMS 695	UH Moody Tower	0.1	7.5					00:10	-2.8	2.9	6.79	7.400	0	-45
CAMS 115	Channelview	4.4	9.8	6.5	14.1			00:35	-1.9	5.2	9.3	5.400	7.6	-59.3
	Max	8.8	12.2	14	17	85	0	00:36	0.4	5.4	9.6	7.4	7.6	-16
	Min	0.1	5.7	6.5	13.2	85	0	00:10	-2.8	2.6	5	1.3	3	-59.3
	Average	5.08	9.40	9.73	14.77	85.00		00:30	-1.43	4.03	7.67	4.32	5.03	-37.56
	Count	5	5	3	3	1	0	5	5	4	4	5	3	5

***Note: all units in figure are NOAA Operational and not SI**

Figure 31 Condensed Spreadsheet Example

9.0 Appendix C

Date	Time of rain	Cell Loc.(s) (lat, long) (º)	Site	Site Lat (º)	Site Long (º)	Time SB Start	Time SB End	Rain at site (mm)	Comment
6/11/11	16:19	29.5, -95.1	CAMS 697	29.4	-95.0	16:20	17:10		
6/11/11	17:33	29.4, -95.0 29.4, -95.4	CAMS 695	29.7	-95.3	17:20	17:50		
6/28/11	Not on Radar		CAMS 697	29.4	-95.0	19:05	19:30	5.6	
7/1/11	17:59	29.7, -95.3	KHOU	29.6	-95.3	17:53	18:01	5.1	
7/2/11	19:08	29.4, -95.2	CAMS 697	29.4	-95.0	17:35	17:55		
7/3/11	19:42	29.9, -95.0	CAMS 115	29.8	-95.1	18:55	19:40		
7/4/11	21:07	29.6, -95.5	CAMS 695	29.6	-95.6	21:00	21:20		
7/7/11	21:59	29.6, -95.2 29.7, -95.2 29.9, -95.2	CAMS 695	29.7	-95.3	20:20	20:50		
7/8/11	19:28	29.5, -95.0	KEFD	29.6	-95.2	19:36	19:50		
8/6/11	21:30	29.5, -95.7	CAMS 696	29.6	-95.6	21:30	22:05		
8/13/11	18:09	29.5, -95.0 29.3, -95.4	CAMS 115	29.8	-95.1	18:00	18:35		not near cell but at same time
8/13/11	20:02	29.5, -95.1 29.6, -95.5 29.7, -95.3	CAMS696 CAMS 695	29.6 29.7	-95.6 -95.3	19: 25 19:35	20:05 20:05	0.8	
7/6/12	20:23	29.5, -95.7 29.7, -95.4	CAMS 696	29.6	-95.6	20:15	20:40		
8/4/12	18:58	29.6, -95.2	KHOU CAMS 695 CAMS 695	29.6 29.7 29.7	-95.3 -95.3 -95.3	17:53 18:252 0:00	18:53 19:00 20:35	0.3 0.2	
8/8/12	19:09	29.3, -95.4 29.5, -95.2 29.7, -95.4 29.7, -95.2	CAMS 695 CAMS 115	29.7 29.8	-95.3 -95.1	19:20 19:50	19:50 20:35		

All Times in UTC, mm (millimeters)

Table 21 Sea-Breeze (SB) and Rain Cell Locations

Date	Start Temp. (°C)	End Temp. (°C)	Start DP* (°C)	End DP* (°C)	Start WD* (deg)	End WD* (deg)	Start WS* (m/s)	End WS* (m/s)
6/11/2011	30.0	28.6	22.8	24.6	131	35	3.3	2.7
6/11/2011	31.9	31.6	16.3	19.2	193	143	0.9	5.0
6/28/2011	32.2	31.9	21.6	23.0	75	131	4.6	5.3
7/1/2011	32.8	28.0	22.9	23.2	130	110	5.4	7.1
7/2/2011	33.6	33.2	21.6	23.4	248	172	0.2	2.6
7/3/2011	36.8	36.0	16.4	18.9	86	166	2.7	3.1
7/4/2011	35.4	34.9	16.6	17.5	138	142	1.2	3.4
7/7/2011	35.1	32.3	16.5	20.6	214	171	1.3	6.1
7/8/2011	37.0	35.0	22.2	26.0	210	100	1.8	7.1
8/6/2011	35.5	32.3	20.4	23.1	153	180	5.7	1.5
8/13/2011	35.7	31.7	18.8	21.6	234	156	0.2	7.2
8/13/2011	36.9	31.6	19.0	21.7	206	152	1.2	5.9
8/13/2011	36.5	35.5	19.3	22.6	107	133	1.9	4.3
7/6/2012	33.7	28.7	19.5	21.4	192	188	1.7	5.0
8/4/2012	33.3	32.2	24.3	25.4	200	190	3.5	
8/4/2012	34.0	31.9	19.2	21.1	202	191	0.2	4.8
8/4/2012	33.5	30.7	19.7	21.9	152	143	3.3	7.9
8/8/2012	34.1	31.1	18.3	20.9	190	133	1.7	8.0
8/8/2012	34.9	32.0	20.4	23.3	147	220	2.3	3.1
Average	34.4	32.1	19.8	22.1	169	150	2.3	5.0
Maximum	37.0	36.0	24.3	26.0	248	220	5.7	8.0
Minimum	30.0	28.0	16.3	17.5	75	35	0.2	1.5
Std Dev	1.9	2.2	2.4	2.2	49	41	1.7	2.0

***Dew Point (DP), Wind Direction (WD), Wind Speed (WS)**

Table 22 Meteorological Parameters of Sites Closest to Rain Showers