THE IMPACT OF COASTAL DEVELOPMENT ON THE DELAWARE BAY/SEA BREEZE

1.5 COASTAL ATMOSPHERIC/OCEANIC PROCESSES AND URBAN EFFECTS

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1. Introduction

The Sea Breeze phenomenon occurs routinely along the coasts of nearly every major land mass, ranging from the poles to the equator (Miller, 2003). It is a circulation pattern that is thermally driven by uneven heating between land and ocean surfaces. Resulting pressure differences cause cool marine air near the surface to move inland. Sea breeze fronts can develop at any point after sunrise and can persist for hours after sunset. The thickness of the moving marine air mass associated with the sea breeze is typically between a few hundred meters and one kilometer (Barry and Chorley, 1992) (Venkatesan, 2009). Strong offshore winds from synoptic and mesoscale sources can block or dismantle a sea breeze front.

The area for this investigation includes the southern half of Delaware with a focus on the coastline along the Delaware Bay and the Atlantic Ocean. The terrain over this region is extremely flat and moderately underdeveloped. There are no major cities in the region but there are several coastal cities including Lewes, Rehoboth Beach, Bethany Beach, and Fenwick Island. These coastal resort towns are expected to undergo significant growth in the next ten years (OSPC). This will undoubtedly have the effect of increasing the urbanization in the region which will change the land surface properties associated with heat flux, radiation absorption, and surface temperatures.

There are many reasons why a sea breeze is important to those living along the coast. The passage of a sea breeze front has a cooling effect which often moderates summer heat and can influence tourism (Papanastasiou, 2009). This is especially important to commercial businesses along Delaware's coastline whose tourist season occurs when sea breezes are most abundant. Additionally, air pollutants such as ozone can get transported in a sea breeze circulation and can affect a location's air quality. Within a sea breeze circulation, wind speeds can be relatively higher and this could be a benefit to offshore wind farms. Characterization of Delaware's sea/bay breezes can help to determine their impact on the local climate, such as overall impact on rainfall. This is important since much of southern Delaware consists of farmland. Understanding the low-level winds in this area will be useful in understanding how conditions may change in the future as local land-use and the global climate continue to change.

To assist in the analysis of the Delaware Bay/Sea breeze the Weather Research and Forecasting Model Version 3.1.1 (WRF) is employed. WRF is a mesoscale model with a non-hydrostatic option that is essential for studying small scale phenomena. The NOAH land surface model incorporates four layers of soil moisture. In NOAH there is an urban canopy option that allows for the incorporation of building geometry on wind flow and thermal properties. This potentially allows for increased accuracy in surface fluxes and heat transport, both of which are crucial to sea breeze development and progression (Kusaka et al, 2001).

2. Data and Analysis Methods

The effects from the passage of a sea breeze front are relatively predictable and easy to understand. The cool moist air is expected to bring with it a drop in temperature and will increase the dew point if the prevailing conditions are dry. Otherwise, the dew point may be unaffected or even drop if the prevailing conditions are extremely moist. The magnitude of wind coming from the coast is expected to moderately increase. Along the Delaware coastline this is typically represented by a shift in winds from the west to the east.

There are many factors that make the detection of a sea breeze front difficult to recognize. A sea breeze front can often be superimposed onto coast parallel synoptic winds. Along the Delaware coastline these winds can add noise in the horizontal component along with advecting cold or warm air. Synoptic winds can vary significantly in direction and strength during the day. Convective winds develop during hot summer days and add another dimension of complexity. Backdoor cold fronts show very similar frontal characteristics as a sea breeze front and they are very difficult to differentiate at the mesoscale level. Thunderstorm outflows can often destroy a sea breeze, make it stronger, or shift its direction.

There are many tools available to detect a sea breeze. Synoptic maps illustrate if conditions are favorable for sea breeze development along the coast. They show strong lower level winds and precipitation, both of which hinder sea breeze development. Radar is the most useful tool for visualizing the location of a sea breeze front. Dry-air mode can detect the fronts based on differences in reflectivity between the air masses (Fig. 1). One limitation of analyzing sea breeze fronts with radar presents itself when the radar is in precipitation mode which is significantly less sensitive than dry-air mode. Radar data gives no insight into the temperature and wind gradients that may be present. This study employs twelve meteorological stations from the Delaware Environmental Observing System (Fig. 2). Several are located within a few kilometers of the coastline and two are located within a few hundred feet. Some stations are located over thirty kilometers from the coastline and are rarely impacted by the sea breeze and when they are it is weak and occurs in the late evening hours. These stations give insight into the synoptic winds and how they vary throughout the day. All these stations record values every five minute for temperature, relative humidity, wind speed, and wind direction. The biggest limitation is that some stations have problems with wind shadowing. For example, one station located on the boardwalk in Bethany Beach is positioned near large buildings on its western side which decrease the magnitude of west winds that reach it. Despite this limitation, the model is able to detect the occurrence of most sea breezes and is not removed from the analysis.

A crucial part of this study was to develop a program that detects the passage of sea breeze front through a station automatically. This study looks at up to four summers of data for twelve stations. The program avoids judgmental biases involved in eyeballing a sea breeze. For each day of the study the program searches through every five minute interval between 6 AM and 8 PM. Thirty minute (7-value) averages are used to smooth out the data. After the program runs through the entire timeframe it then assigns a category to each station for each day. Several categories and their necessary conditions are shown in Figure 3. Before the program assigns a category it searches for missing data throughout the day. If there is enough missing data then the day is invalid and not analyzed. The first category is assigned to a day that shows all the classic signs of a sea breeze. The second category looks for a sea breeze front that may pass through with or without a significant reduction in temperature but a noticeable increase in dew point. The third category looks for a wind direction change from west to east without any significant temperature or dew point changes. The fourth category looks for a shift in wind direction to the south along with a dew point increase. This could be evidence of a late day sea breeze that has been affected by the Coriolis force. It also could be the result of a sea breeze front coming from southern Maryland where the coastline has a larger southern component. The fifth and sixth categories respectively search for dominant and persistent east and west winds. A condition was also set to look for a sea breeze reversal. This was used within the Classical Sea Breeze Category. The condition looked for a reversal in winds from onshore to offshore along with a reduction of the temperature gradient between the coastal and inland station. This is because this category has the most well defined changes associated with it. Finally the seventh category is composed of the remaining samples and is associated with variable winds. The coastal station looked at is the one on the boardwalk at Bethany Beach, DE. The station in Laurel, DE was used as a reference station to measure the synoptic winds in the region where there is no significant effect from the sea breeze during the daytime and early evening hours.

WRF runs were done on a monthly basis between 2002 and 2008 for the months of June, July, and August. They were run in non-hydrostatic mode with three nests. The smallest nest with the highest resolution is centered over the Delaware Bay and has a resolution of two kilometers. The model is run with a time step of just under two minutes. The model was forced with synoptic data from the North American Regional Reanalysis Model every three hours.

An aim of this research study is to modify the land surface in the WRF model to represent the increasing urbanization that is occurring in Delaware, especially along the coastline. This will allow WRF to simulate how the changes might affect the regional climate and the sea breeze circulation. The first step in this modification process was to conduct a sensitivity study to observe how the model responds to moderate changes in albedo and other surface properties. Thus far, WRF was run twice for one month (July 2002) with an increase and decrease in albedo of 0.05 over all non-water areas. Eventually, runs will be done over many years with land modifications that represent predicted changes in Delaware over the next twenty years.

3. Results and Analysis

3.1. Observation Analysis

Observation data is available for twelve DEOS stations for the year 2008. The classic sea breeze is the strongest evidence that a sea breeze front passed through the region. The three stations that boarder the Atlantic Ocean had the highest frequency of this category with 37, 60, and 67% respectively. The station with 37% (DBNG) is located approximately a mile away from the coast. This explains the large drop off in frequency. This drop off continues with distance from the coast. DSJR is away from the Atlantic Ocean but boarders the Delaware Bay. The dew breeze category has similar shifts with distance from the coast. However, for this category, there is a significant increase in frequency associated with DSJR's proximity from the Delaware Bay. The east/west split category is an attempt to represent a sea breeze that doesn't show strong drop offs in temperature or dew point. This could occur early in the day with a developing sea breeze or in the evening with a weakening sea breeze. Again the frequency is affected negatively with distance from the Atlantic Ocean. Using all three categories, one can say that a sea breeze occurs near the Atlantic coastline between 60 and 80% of the time. This drops off to approximately 10 to 30% with stations that are between 15 and 35 kilometers from the Atlantic Ocean. Stations further inland experienced sea breezes only a handful of times during the study. DSJR is the exception, seeing a sea breeze 31% of the time and being 43 kilometers from the border between the Delaware Bay and the Atlantic Ocean.

Non sea breeze days with dominant west winds occurred only 7 to 14% of the time near the Atlantic Ocean but 40 to 70% at other stations. Non sea breeze days with dominant east winds showed no such distinction with values between 9 and 16% for all stations. Non sea breeze days with variable winds showed a bias against the bay and ocean. Those stations showed the variable wind condition 0 to 11% of the time while the inland stations showed this condition approximately 8 to 23% of the time.

3.2. WRF Analysis

There have been many studies employing WRF to study the effects of the sea breeze (Case et al., 2008). WRF has been run for June, July, and August for the years 2002 to 2008. Output data is saved every hour during the run. As expected, WRF is fully capable of simulating a sea breeze circulation along the Delaware Coastline (Fig. 4). In the example shown on July 13th 2008, a well-developed sea breeze circulation is present along the coastline. Along the Atlantic Ocean coastline, the front has propagated inland approximately ten to fifteen kilometers while over the Delaware Bay coastline there is less propagation. Winds are coming from the east-southeast at approximately four meters per second.

As a precursor to changing the landscape in WRF, a sensitivity analysis will be employed first to investigate how the sea breeze and synoptic conditions respond to land surface properties. A change in albedo was an easy and meaningful property to change. Two runs were performed in addition to the control run for July 2002. The two perturbed runs altered the albedo by 0.05 in both directions for every land point. The albedo of water points were left unchanged since they would not be directly affected by any urbanization in the future.

The sea surface temperatures used are based on NARR climatological averages with a large resolution. As shown in Figure 5, there is very small temperature variation between the Delaware Bay and the Atlantic Ocean. However, this is not generally true. A more complete picture of the SST's is shown using satellite data (Fig. 6). Upwelling is common along the Atlantic coastline and especially at the mouth of the Delaware Bay. This can lead to local SST differences of over 5*C. This will soon be incorporated into the model and modest differences in sea breeze formation and propagation is expected.

4. Conclusions

The sea breeze circulation is a prominent feature along coastal Delaware. The front typically develops in the early morning hours. Most of the time the front remains near the coast. This is a balance between the temperature gradient and the synoptic offshore winds. These regions can often experience a sea breeze front passing through and retreating several times during the day. Sometimes, the front can migrate landward over thirty kilometers. During the evening hours the temperature gradient caused by the front shrinks to zero.

Overall WRF closely simulates a developing sea breeze front. It predicts the frequency, propagation, and timing that compare well with the observation data. However, on occasion, WRF can significantly overestimate or underestimate the magnitude of the sea breeze. This could be a result of the input SST data represented in WRF. This also may be a limitation of the NARR. Data is being forced with a resolution of approximately 40 by 40 kilometers which may make it difficult to precisely simulate synoptic temperatures and wind fields.

There are a few unrealistic results from the WRF model. The inaccuracy with the SST input field is one issue that has already begun to be addressed. Another issue is that the NOAH land surface model appears to underestimate the soil moisture content with time. There is an exponential decay in soil moisture with a daily cycle superimposed on top of it. On average, by the end of the month the soil moisture is cut in half. To alleviate this situation as well as study its effects, the WRF runs may be reduced in duration and concatenated or ensemble averaged.

The long term goal of this project is to simulate the effect of urbanization on the sea breeze. Sensitivity studies are currently being run which investigate WRF's response to changes in surface properties. Eventually, this may lead to a modification of WRF's representation of the land surface based on a changing population and the urbanization that comes along with it.

5. Acknowledgments

I would like to thank my advisor Dr. Dana Veron. She designed the framework of this project and has guided me through many hours of data analysis. I would also like to thank, Dr. Daniel Leathers who has helped me immensely with the DEOS network and Dr. Neil Barton, Justin Gilchrist and Matthieu de Maillard for their advice and direct help with my research.

6. References

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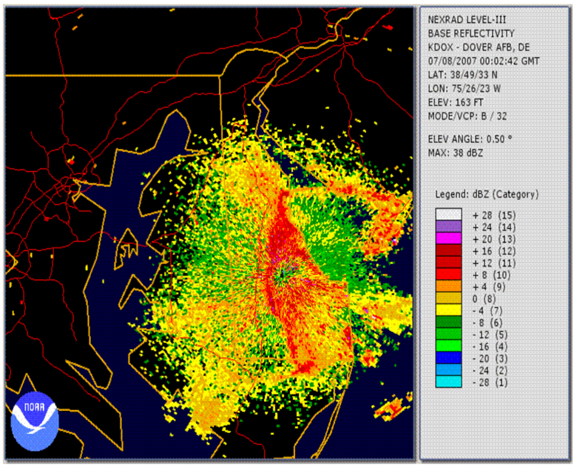
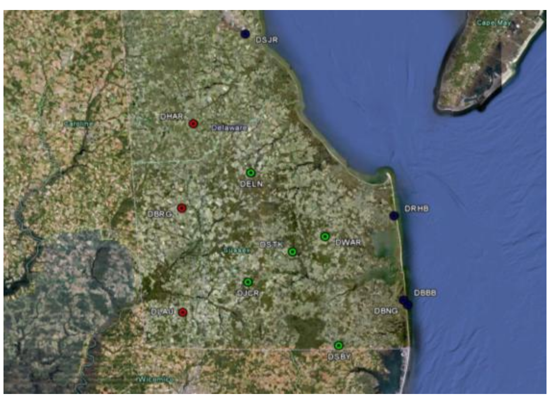
7. Illustrations and Tables

Figure 1: Radar Depiction of a Sea Breeze Front



This image is a recompilation of data from the NCDC. The sea breeze front is shown as the dark orange line that represents high reflectivity. The front has propagated inland over Delaware. Part of the front appears to be traveling up the Delaware Bay.

Figure 2: DEOS Stations

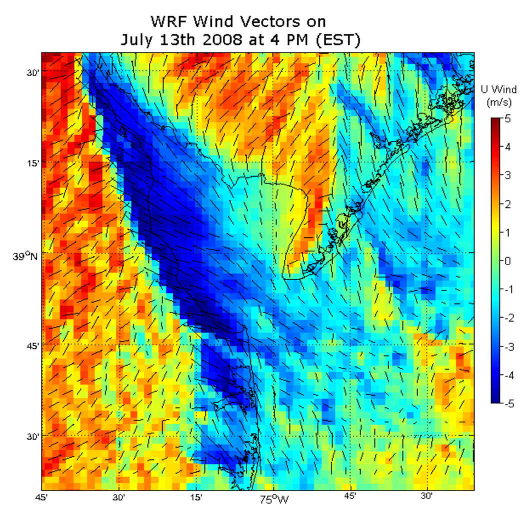


The twelve stations from the Delaware Environmental Observing System are shown. They are divided into coastal (blue), inland (green), and reference (red) stations.

Figure 3: Category Determination for Each Station

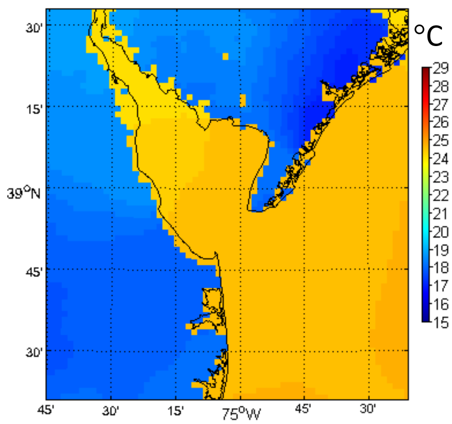
CATEGORY	COASTAL WIND	COASTAL WIND (-1hr)	INLAND TEMP – COASTAL TEMP	Δ COASTAL TEMP (-1hr) - Δ INLAND TEMP (-1hr)	INLAND WIND	Δ Dew (-1hr)
1. Classic Sea Breeze	East & >1m/s	West or (East & <1m/s)	>1.0°C	>2.0°C	West or (East & <1m/s)	N/A
2. Dew Sea Breeze	East & >1m/s	West or (East & <1m/s)	N/A	N/A	West or (East & <1m/s)	>1.0°C
3. East/West Split	East & >1m/s	N/A	>2.0°C	N/A	West or (East & <1m/s)	N/A
4. South Feature	150° - 210° & >1m/s	N/A	N/A	N/A	N/A	>2.0°C
5. East Dominant	>80% East					
6. West Dominant	>80% West					
7. Variable	<80%East & <80% West					

Figure 4: WRF Depiction of a Sea Breeze



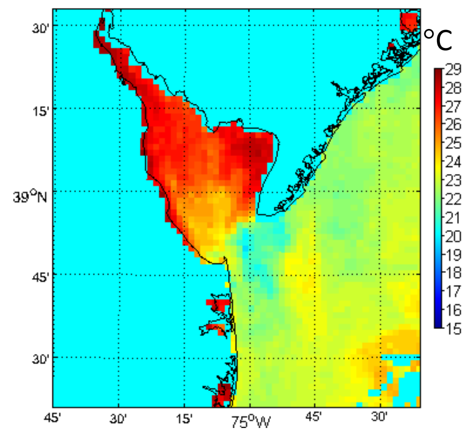
The red color represents a strong westerly 10m wind component which the blue color represents the east component. A sea breeze is depicted along the Delaware Bay and Atlantic coastline. Also depicted is a sea breeze along the coastline of New Jersey.

Figure 5: NARR SST Average



In this format there is very little variation in sea surface temperature between the Delaware Bay and the Atlantic Ocean. This is unrealistic based on satellite and observation records.

Figure 6: Satellite Instantaneous SST



The depicted satellite data clearly shows the warm sea surface temperatures up the Delaware Bay. This is primarlly because of the bay's shallow batheometery. At the mouth of the bay there is a large area of semipresistant upwelling. These features lead to a large temperature gradiant through the Delaware Bay.