**P2.8 An Observational and Modeled Examination of the Seaward Expansion of a Sea Breeze Circulation**

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1. INTRODUCTION

The Navy's JSLSCAD Experiment was completed during July of 2004 off of Virginia Beach Virginia. The successful experiment involved the release of tracer gases 30 to 50 km offshore during weakly forced synoptic conditions. The primary focus of the experiment was to improve knowledge of ducting within the boundary layer and its relationship to radar performance. As an aside, a wealth of meteorological data, along with mesocale model output was collected during the one week duration of the experiment. These data, along with WeatherFlow's coastal mesonet provide the data required to examine sea breeze circulations during the period. In particular, little observational data is routinely available when examining the spatial extent of sea breeze. The JSLSCAD data set provides some much needed insight into the seaward behavior of such events.

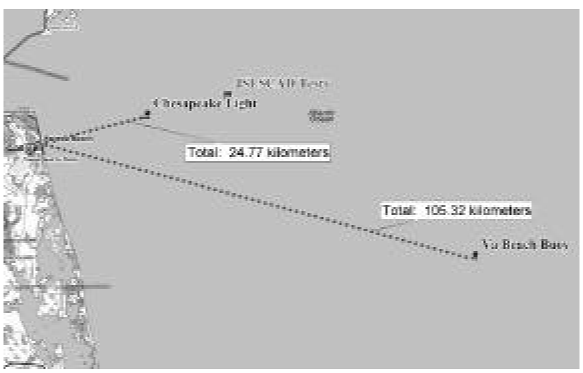


**Figure 1**

2.1 EXPERIMENT SYNOPTIC SYNOPSIS

The experiment period commenced on Monday the 19th with a short period rather void of any driving synoptic feature as a trough just east of the forecast region simply dissolved, thus allowing sea breezes to crop out through the afternoon hours. Then Tuesday through Wednesday afternoon was primarily dominated by weak high pressure that filled just north of the area Monday evening, then drifted slowly south and east and off the Atlantic coast by Wednesday evening and into Thursday.

2.2 EXPERIMENT MESOSCALE SYNOPSIS

As a result, the flavor of the sea breeze signal for the first three days is highlighted by large directional shifts by stations located in the coastal zone. The onshore flow with a progressive veer as speeds increase to a late afternoon maxima is quite typical. The veering pattern itself is caused by the coriolis effect. Other factors that influence the amount of veering include coastal orientation/complexity and orographic influences. The delicate balance between weak prevailing synoptic flow and sea breeze tendencies differs enough Monday through Wednesday that the duration of the sea breeze and its spatial behavior varies widely each day. The synoptics, albeit weak , spatially limit sea breezes on Tuesday to the immediate coast, with temporarily short durations of only an hour or two. Sea Breeze behavior on Monday is classic with extensive veering and some speed acceleration during the late afternoon, but the fact that prevailing flow is from the northeast direction, hinders one from determining the actual onset of the sea breeze mechanism. That is, this day does not experience an abrupt directional shift at the onset of the sea breeze. Therefore, Wednesday, with a discrete sea breeze signal at onset, is the optimum case to examine the inland versus seaward spatial build, and duration. Finally, by Thursday, the sea breeze signal is detected more from speed acceleration during the later afternoon hours. Since high pressure offshore (fair weather) is often the synoptic set-up in which east coast sea breezes occur most frequently, Thursday is examined in detail too despite the fact that the directional component is much less evident.
Figures 1 through 4 contain a depiction of a colorized sequence of station plots representing the behavior of the wind during the pm hours. The “ROYGBIV” sequence equates to successive hours from 1 pm to 8 pm with Red representing 1 pm and ending with Violet at 8 pm. Figures 1 through 3 indicate that for many of the sites in proximity of the coast, significant veering over the course of the afternoon occurs. Station plots exhibiting the wind shift and veer pattern yield the appearance of a rainbow star pattern.
Station plots in Figure four have a significantly different appearance. There is little spread in the wind direction over the course of the afternoon. The two main wind behavior characteristics that reveal a sea breeze signal, are the accelerated speeds, peaking during the late afternoon hours, and the overall spatial directional shift between more of a predominant SW flow inland to one of

a more SSE to SE direction for sites in proximity to Atlantic Ocean coastal waters.

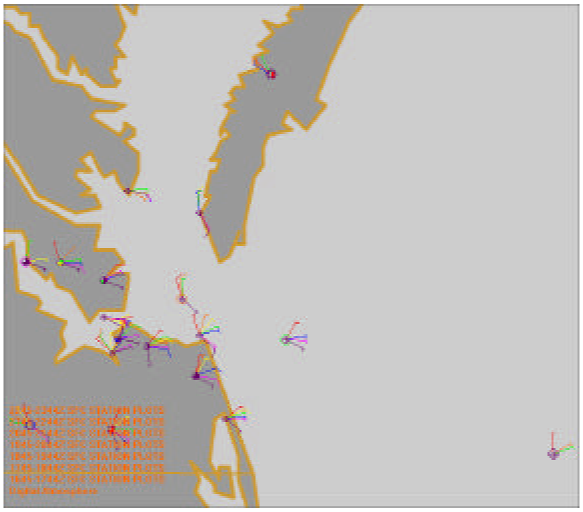

**Figure 2** ***July 19th***

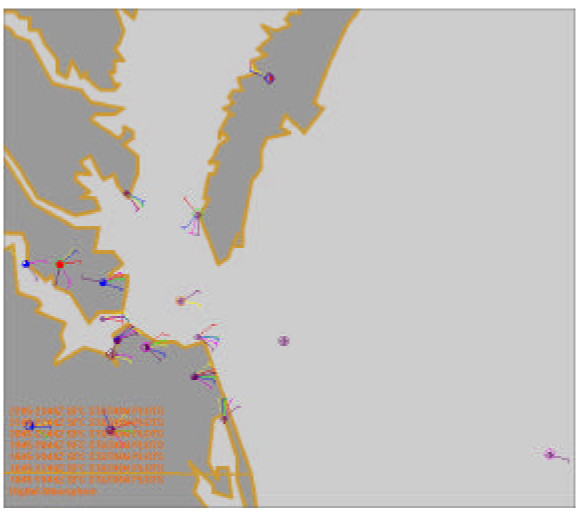

**Figure 3** ***July 20th***

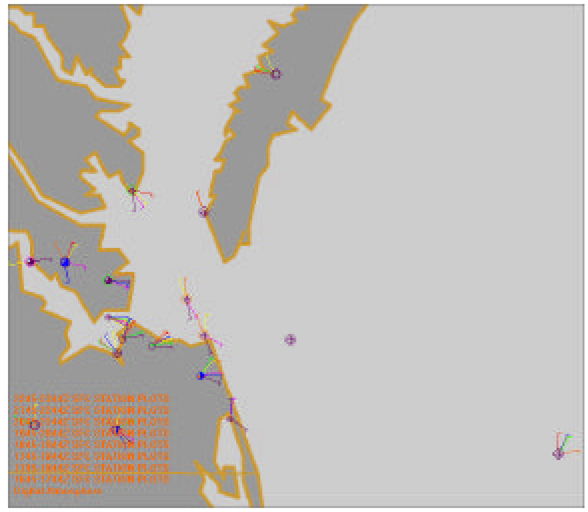

**Figure 4** ***July 21st***

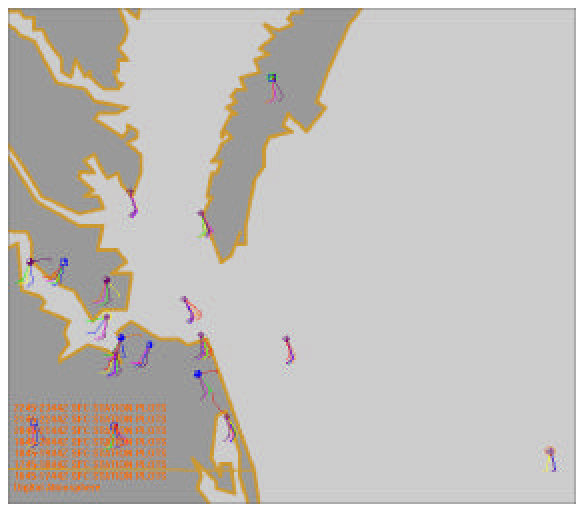

**Figure 5** ***July 22nd***

Figure 6, time series plot at Cape Henry, yields a more telling view of the speed acceleration during the late afternoon on the 22nd. Speeds, red line with lull/gust range in yellow, ramp up and hover near 17 knots from 2:30 through about 6:30 pm LST before declining into the evening hours. Meanwhile, directions flip from SW during the late morning hours to east at the onset of the sea breeze, then veer southeast and finally south by the evening hours when speeds drop.

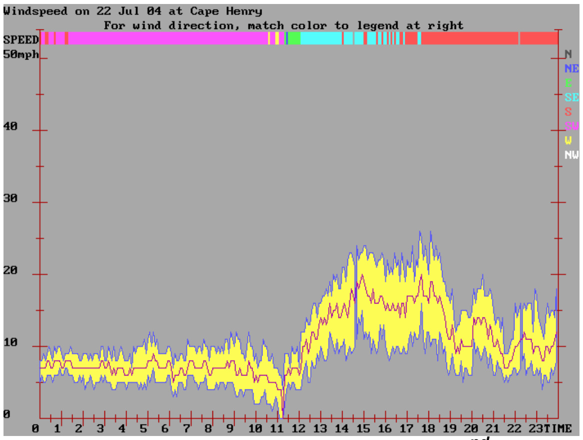


**Figure 6 *Cape Henry VA, July 22nd***

2.3.1 JULY 21ST ANALYSIS

The 21st sea breeze is revealed more in the form a significant wind direction shifts during the pm hours. Classic sea breeze behavior commences with an initial onshore component, orthogonal to the local shoreline. The 3 dimensional circulation is shallow, a few 10's of meters, yielding an offshore component just aloft. As the breeze matures, it's lateral extent increases, both inland and offshore with speeds increasing, especially along the immediate coast. The depth of the circulation deepens, often from 10's of meters to well over 100. Finally, in the northern hemisphere, veering occurs due to the Coriolis Effect. This affect, especially along coastal ocean waters, can be quite dramatic with directions veering to the extent that by evening hours, winds often have a primary component parallel to the coast. The 21st is quite typical, in that there is some, albeit weak, prevailing synoptic flow. Late morning, mid-day flow is light mix of varying northerly winds.

**Table 1 July 21st Wind Directions by Hour**

| LST | CPK | NTU | HEN | CHLV2 | 44014 |
|---|---|---|---|---|---|
| offset | +:20 | -:04 | ---- | --- | --- |
| 1 | 000 | 030 | 341 | 025 | 360 |
| 2 | 330 | 040 | 347 | 017 | 080 |
| 3 | 010 | 040 | 011 | 341 | 028 |
| 4 | 060 | 030 | 046 | 000 | 031 |
| 5 | 150 | 090 | 090 | 044 | 025 |
| 6 | 120 | 080 | 131 | 146 | 017 |
| 7 | 130 | 110 | 151 | 145 | 035 |
| 8 | 130 | 150 | 193 | 142 | 042 |
| 9 | 000 | 170 | 203 | 153 | 044 |
| 10 | 000 | 180 | 205 | 167 | 094 |
| 11 | 000 | 200 | 225 | 190 | 116 |

The sea breeze "force" must overcome this prevailing flow, and does so, first at the immediate shoreline, WeatherFlow site at Cape Henry at 4pm (wind shift of 44 degrees). Inland site Chesapeake (CPK) also experiences a dramatic shift of 90 degrees between 3 and 4 pm, but the observation is not taken until 20 minutes past the hour.
The shift occurs at other inland site, Ocean Naval Air Station, and the offshore site about 12 miles from the shoreline, Chesapeake Light within the next hour. The sites all then continue some sort of slow veer, or semi-stationary southeast flow until the wind either goes to calm

**Table 2 July 21st Wind Speed by Hour**

| LST | CPK | NTU | HEN | CHLV2 | 44014 |
|---|---|---|---|---|---|
| 1 | 0 | 7 | 6 | 2 | 4 |
| 2 | 5 | 9 | 5 | 2 | 4 |
| 3 | 3 | 7 | 5 | 1 | 4 |
| 4 | 4 | 6 | 2 | 0 | 4 |
| 5 | 4 | 7 | 4 | 0 | 3 |
| 6 | 6 | 6 | 6 | 1 | 2 |
| 7 | 3 | 6 | 6 | 2 | 2 |
| 8 | 3 | 3 | 6 | 3 | 2 |
| 9 | 0 | 3 | 6 | 4 | 2 |
| 10 | 0 | 3 | 6 | 4 | 2 |
| 11 | 0 | 4 | 7 | 3 | 1 |

Inland at CPK, or continues a veers to the south at the other sites. Only Cape Henry does not experience at drop in speeds. The lingering question, does the sea breeze veer expand seaward to the Virginia Beach Buoy (C-MAN station 44014) which is located about 60 miles offshore? There is no increase in wind speeds through the duration of the afternoon and into the evening, but winds due shift 50 degrees to the east, then east-southeast between 9 and 10 pm LST, too late to be the direct influence of a sea breeze, but the decaying event near-shore could propagate eastward, although with high pressure moving offshore synoptic gradient is also in a transition stage with a veering pattern too.

2.3.2 JULY 22ND ANALYSIS

The 22nd also displays some directional evidence of a sea breeze, but the prevailing flow is more from the south, so the dramatic 40 plus degree shifts are not seen. On this day, the sea breeze is exhibited by a backing then veering pattern as the peak heating of the afternoon generates a local onshore component. The local onshore, then veering, east to southeast sea breeze behavior is reflected through vector addition with prevailing southerly flow to yield the directional pattern revealed by the shaded cells in table 3.

**Table 3 July 22nd Wind Direction by Hour**

| LST | CPK | NTU | HEN | CHLV2 | 44014 |
|---|---|---|---|---|---|
| offset | +:20 | -:04 | ---- | --- | --- |
| 1 | 160 | VRB | 154 | 170 | 200 |
| 2 | 200 | 150 | 169 | 152 | 200 |
| 3 | 190 | 140 | 171 | 164 | 190 |
| 4 | 190 | 140 | 168 | 161 | 167 |
| 5 | 170 | 150 | 171 | 159 | 165 |
| 6 | 150 | 150 | 169 | 162 | 167 |
| 7 | 150 | 160 | 181 | 164 | 169 |
| 8 | 150 | 150 | 176 | 166 | 170 |
| 9 | 160 | 150 | 179 | 163 | 169 |
| 10 | 190 | 170 | 194 | 175 | 160 |
| 11 | 180 | 190 | 211 | 182 | 164 |

Like the previous day, this event begins first along the immediate shoreline, and then works its way both inland and seaward. The sea breeze signature with respect to wind speed is more dramatic than on the previous day. Once again, the jump in wind speeds commences first right at the immediate shoreline, then with time the increase is seen both inland and out to sea. In this case, Oceana Naval Air Station also jumps by 5 knots about an hour later. The increase in

| LST | CPK | NTU | HEN | CHLV2 | 44014 |
|---|---|---|---|---|---|
| 1 | 7 | 6 | 13 | 5 | 2 |
| 2 | 7 | 10 | 14 | 8 | 2 |
| 3 | 6 | 9 | 18 | 8 | 3 |
| 4 | 8 | 14 | 16 | 8 | 3 |
| 5 | 6 | 11 | 17 | 9 | 4 |
| 6 | 6 | 10 | 16 | 10 | 5 |
| 7 | 3 | 11 | 11 | 11 | 6 |
| 8 | 5 | 8 | 10 | 11 | 6 |
| 9 | 4 | 8 | 10 | 11 | 6 |
| 10 | 5 | 8 | 10 | 10 | 5 |
| 11 | 7 | 7 | 8 | 9 | 6 |

**Table 4 July 22nd Wind Speed by Hour**

speeds penetrate further inland and are seen at Chesapeake, but the jump is only two knots and commences on a downward trend just an hour later. Oceana also drops 3 knots after only one hour, but then hovers in the low teens until between 7 and 8 pm LST.
Meanwhile the increase is also seen out to sea but it is more subtle, oozing upward over a several hour span, then dropping off just slightly by the late evening hours. Warm oceanic waters are able to keep the near-surface region a few degrees warmer after dusk, also the case along the immediate shoreline. Conversely, further inland, winds due not completely fall to calm, but fall more appreciably than over water.

3.0 MODEL ANALYSES

An optimum objective method to determine how well a model is able to capture the sea breeze feature is a difficult endeavor. If a model is to correctly predict a sea breeze but is incorrect in the timing the onset, may yield a higher error than a forecast for no sea breeze at all. For example, if a model calls for a wind shift at 1pm from west to east with constant speed of 5 knots But the shift does not occur until 2 pm.

$$WVD = \sqrt{(U_{model} - U_{obs})2 + (V_{model} - O_{obs})2}$$

The 1 pm wind vector difference (WVD) for the incorrectly timed hour is 10. In contrast, a forecast for continued west winds yields a lower error for west winds of any observed magnitude of speed greater than 15 knots.

3.1 NCEP ETA

For the NCEP 12 km ETA, Table 5 reveals WVD values for four of the 5 locations previously discussed for both the 21st and 22nd. The darker shaded data/site combos are examples of events wind relatively low wind speeds, but rather high errors. The aforementioned example would yield this type of result. That is, an ill-timed onset of a sea breeze. Conversely, the lightly grayed date/site combo highlights an event that is windier, yet a lower error. Oceana exhibited a more gradual wind shit not too far off from that which was experienced due to the synoptic veering pattern as weak high pressure drifted off of the coast.

**Table 5 Wind Vector Differences**

| Date | Site | avg speed | wvd rmse |
|---|---|---|---|
| 7/21 | Chesapeake Light | 4.7 | 11.7 |
| 7/21 | Va. Beach Buoy | 5.8 | 12.8 |
| 7/21 | Cape Henry | 2.8 | 11.1 |
| 7/21 | Oceana | 6.7 | 4.1 |
| 7/22 | Chesapeake Light | 9.9 | 11.7 |
| 7/22 | Va. Beach Buoy | 4.1 | 9.4 |
| 7/22 | Cape Henry | 8.9 | 9.3 |
| 7/22 | Oceana | 5.8 | 13.1 |

4.0 CONCLUSIONS

The sea breeze event takes on many different faces in both wind speed and direction. Local coastal orientation, water temperatures, and even tidal cycle are examples of non-meteorological factors than may govern sea breeze behavior. Meteorologically, a sea breeze is an example of a meso-scale feature. In reality, meso-scale features are embedded in prevailing synoptics. The sea breeze exhibits most clarity when prevailing synoptics are weak, but the mechanical process is basically present along at least the immediate coastline with a the presence of a thermally induced pressure differential across the land/sea interface. The JSLSCAD Experiment provided the data for a well-documented daily sequence of varying sea breezes that displays the day-to-day variability that makes the sea breeze event one of the most documented examples of a mesoscale weather feature, but yet still so elusive to forecast with a high degree of accuracy.