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# The Anatomy of the South Carolina U.S.A. Coastal Sea Breeze 2019-2020

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## Abstract

The study presented herein is the analysis of Sodar based instrument measurements of air temperature, dew point, and vertical wind speed and direction, recorded at two South Carolina sites, Waties Island in North Myrtle Beach and in Sumter, and at three atmospheric ground stations. Two of the ground stations are National Weather Service stations near the Sodars and one is a Coastal Carolina University Sea-Econet, as a part of the National Oceanic & Atmospheric Administration, MESO program, weather-sensor site on the Coastal Carolina University campus in Conway South Carolina. Objectives of this study are to establish specific values of winds, land and sea temperatures, precipitation and dew points associated with the changes induced by passages of the Sea Breeze Front, and to examine differences in the station-to-station incarnation of the Sea Breeze circulation. Variability from station to station in the nature and timing of Sea Breeze Front passage is found to be a function of relative proximity to the coast with Sea Breeze Front passage occurring earliest at the North Myrtle Beach site (the station at the coast), then at Sumter (~100 km inland) and finally Aiken at >100 km inland. Satellite based estimates of the percentages of onshore penetration distances from the coast are depicted. Wind vectors and air temperatures associated with onsets and passages of the Sea Breeze display robust wind fields directed onshore perpendicular to the coastline. Kinematical descriptors of the Sea Breeze wind particle motions are presented and display coherent stable elliptical motions during the late summer to early fall but are absent during the winter.

## Keywords

Sea Breeze, Sea-Land Temperature Differences, Wind Sticks

## 1. Introduction

Generically, a Sea Breeze is a coastal wind generated by the differential heating of the land and the water ([1] [2]). When the land is at a higher temperature than the neighboring water, the air above it is heated and rises. The air at lower levels is replaced by cooler air advected from the adjacent ocean. Coastal temperatures are regularly impacted by sea breezes. If an offshore flow exists when a sea breeze forms, then there will be a region where the two opposing surface winds meet and are forced to ascend; this region is called a Sea Breeze Front ([3] [4]), a SBF. If there is enough moisture in the atmosphere, clouds and precipitation can form. Sea Breezes typically impact the land within some tens of kilometers of the coastline, a scale too small to be resolved in global models. They are consistently occurring phenomena that can result in the coastal climate being several degrees cooler in summer than nearby inland areas, as well as having higher levels of precipitation.

The Sea Breeze circulation of South Carolina (SC) on the southeast coast of the United States (U.S.A.) forms via relatively rapid differential heating across the land-sea surface interface. The resultant pressure gradient force (PGF) induces an onshore flow along the Marine Atmospheric Boundary Layer (MABL) from sea to the Land Atmospheric Boundary Layer (LABL) land surface and a return flow from land to sea higher in the atmosphere [5]. The Sea Breeze Front (SBF) is a reflection of this circulation, a boundary between the cool, moist, maritime air mass advancing landward and the warm, dry ambient air mass in place over inland SC areas (**Figure 1**). A recent study [5] shows that the SC circulation forms more often in the spring and summer months when the temperature difference between land and sea surfaces is greatest, though the circulation is observed [6] to exist in late winter transitioning into spring and into fall transitioning to winter as well.

Solar radiation penetrates SC coastal waters down several meters and slowly warms those upper ocean waters. In contrast, only the upper few centimeters of land are heated, and warming occurs rapidly in response to solar heating. Therefore, the land surface heats rapidly, warming the air near the surface and

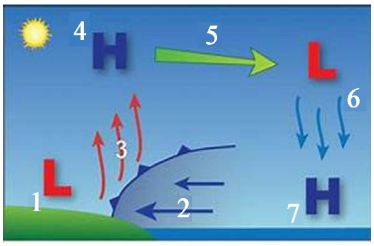



**Figure 1.** Conceptual schematic of the Sea Breeze on the SC coast. The numbers show the sequence of events. #1 is the Solar thermal heating of land. #2 the a-geostrophic onshore flow of marine air driven by the Pressure Gradient Force (PGF) in the MABL. #3 the upward rising air in the LABL driven upward by the incoming marine air wedging underneath. #4 the convective air mass that has cooled (#5, #6) thus completing the Sea Breeze Density Convective Cell.

decreasing its density. This causes the air to rise over the land, decreasing the atmospheric pressure near the surface relative to the pressure at the same altitude over the water surface. The rising air increases the pressure over the land relative to that above the water at altitudes of approximately 100 - 200 m. The air that rises over the land surface is replaced by cooler air from over the water surface. This air, in turn, is replaced by subsiding air from somewhat higher layers of the atmosphere over the water. Air from the higher-pressure zone several hundred meters above the surface then flows from over the land surface out over the water, and can complete a circular or cellular flow. Any general flow due to large-scale pressure systems will be superimposed on the Sea Breeze and may either reinforce or inhibit it. Ignoring the larger-scale influences, the strength of the Sea Breeze will generally be a function of the temperature excess of the air above the land surface over that above the water surface. This can be framed as an atmospheric density current from the MABL into the LABL. A density current in the atmosphere is in a state of balance between the PGF due to the density change across the front, and drag on the current due to turbulent stresses (principally a Kelvin-Helmholtz instability, at the head [4]. However, the sea breeze can also be influenced by the Coriolis acceleration f, over a timescale 1/f, and can be expected to turn with the Coriolis acceleration as the day progresses [2]. Sea breezes are quite sensitive to the larger-scale background atmospheric flow, and purportedly [6] will not develop if the ambient winds are strong. While sea breezes affect all coastlines to some degree, there are locations where the effect is larger, often because of the geometry of the coastline.

In general Sea Breeze winds blow onshore, nominally perpendicular to the coastline ([1] [2] [3] [4]), as shown schematically in **Figure 2** (left panel), so for SC, winds emanate from the east to south Earth quadrant (**Figure 2** (right panel)) which we will refer to herein, as the "Goldilocks Zone". Of course, with two Sodars and several NWS and MESO ground station observing sites, it is difficult to accurately confirm the relative angles of incoming events. **Figure 3** (left and right panels), from a previous study [7], indicates the extent to which Sea Breezes and associated fronts penetrate inland in the Southeastern United States (SEUS). In that study, NOAA GOES satellite imagery, from the NOAA National Center for Environmental Information site (https://www.ncei.noaa.gov/) and analyzed with Geographic Information System (GIS) software, determined the inland horizontal extent of the Sea Breeze circulation in the SEUS. In [3], inland penetration distances of 20 - 40 km were common, and occasionally the Sea Breeze front penetrated as far as 80 to 120 km, explaining the realization of the feature in Aiken, reported on in [5].

Since the specific heat of land is less than that of water, the land surface and the associated air at the lower levels of the atmosphere will heat faster than the water and the air over the water, creating temperature differentials on the order of 2˚C to 10˚C [4] in the spring and summer months. From the hypsometric relationship, the warmer air over the land surface will expand vertically, creating

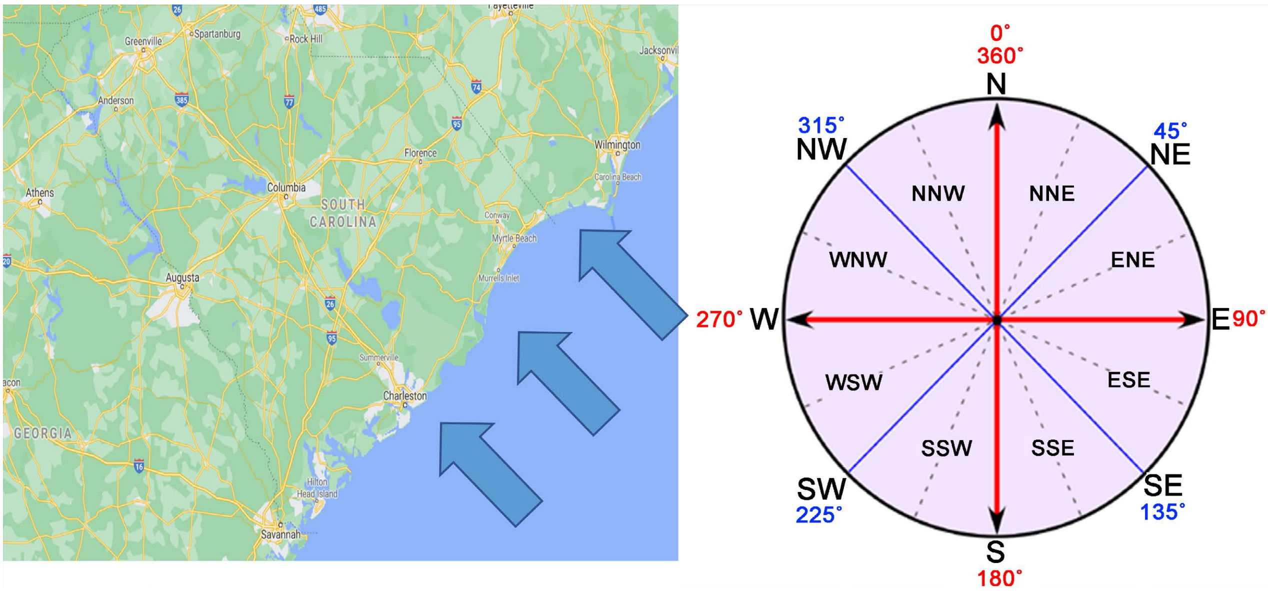



Figure 2. (left panel) shows the SC coast and the onshore Sea Breeze winds; (right panel) shows the 90˚ to 180˚ East to South Quadrant, the Goldilocks Zone.

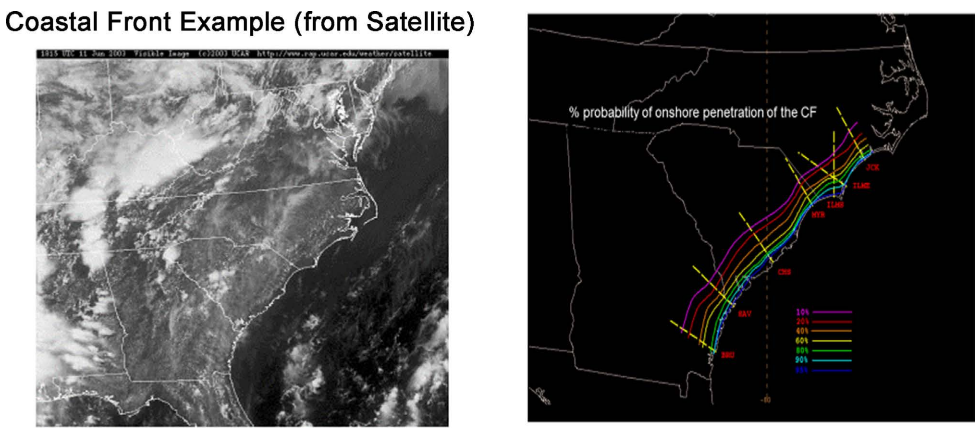



Figure 3. (left panel), NOAA GOES satellite image of the Sea Breeze Front in the SE US; (right panel), % of penetration of the Sea Breeze Front as documented in satellite imagery from 1995-2005 (both taken from [7]).

low pressure near the surface, and adjacent near-surface high pressure over the water, usually a pressure difference on the order of about 2 mb [7]. An onshore flow will develop along the landward-directed pressure gradient forming a frontal boundary separating the cool, moist MABL maritime air mass from the warmer, drier LABL air mass it displaces as it moves inland. Well above the surface, the vertical displacement of isobars results in the opposite configuration of pressure systems, with higher pressure onshore and lower pressure offshore. An insightful and comprehensive numerical model study of the balance of forces and thermodynamics was reported in [7], in which the study reflected upon the existing literature on the subject. The numerical model system applies herein.

The Sea Breeze circulation is typically about 1 km deep [4], although it thins to some degree closer to the advancing edge [8]. The complete circulation will continue as long as the differential land/water heating is maintained. It will also expand both inland and offshore, the extent of the expansion theoretically depending on the reinforcing or prohibitive effects of the synoptic wind regime and the magnitude of the land/water temperature difference. The Sea Breeze has been found to occur more frequently in the spring months when land surfaces are warming but the associated ocean waters are still relatively cool. Over inland areas, passage of the SBF typically results in a decrease in temperature, an increase in dew point or relative humidity, a shift in wind direction towards a surface onshore flow perpendicular to the coastline, and an increase in wind speed [7]. In [8], the statement is made that the shortness of the time scale during which the Sea Breeze forms and exists is not long enough to allow for the Coriolis force to build up a strong flow parallel to the pressure field isobars, and hence the flow is mainly perpendicular to the coastline. However, the theoretical development presented in [7], allows for the Coriolis force to be a part of the x (perpendicular to the coastline) and y (along the coastline) horizontal equations of motion and theoretical solutions with and without Earth rotation effects are presented.

In **Figure 4**, the details of the CCU SC observing network are presented. The Triton Sodar is at Waties Island in NMB, the CCU Campus ground station is in Conway and the Triton Sodar 123 is near Sumter. Python software was utilized to plot the data. Data included barometric pressure (in mbars), air temperature (in °F) and wind speeds (in meters/sec) and directions. Data were recorded every 10 minutes. With just over six-million observations, it was important to develop a quick way to sift through and find relevant data. The goal of using Python to plot data was to generate two-day graphs, which were manually analyzed, seeking to determine how the wind field, barometric pressure and air temperature changed during an apparent Sea Breeze event. In a complementary study [9], Sea Breeze events are "confirmed" via the combination of the temperature, pressure, dew point and wind fields. We also obtained data from the National Oceanic &

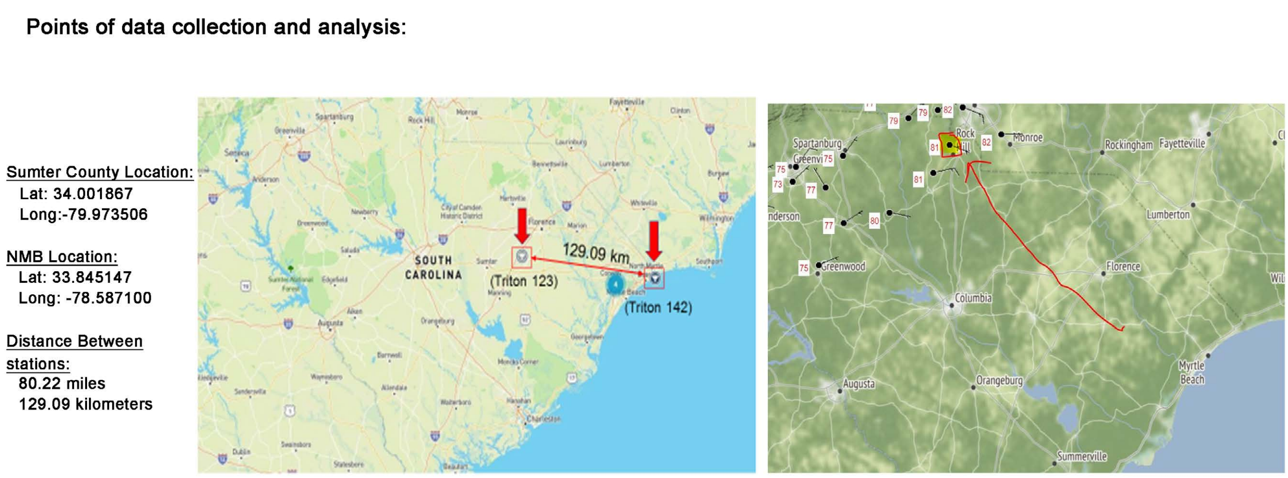



**Figure 4.** (left panel), CCU Sodar and NWS Ground Station data collection sites at NMB SC and Sumter SC; (right panel), NWS Ground station data from Rock Hill SC, ~240 km from NMB.

Atmospheric Administration (NOAA) National Weather Service (NWS) Station data from SC sites via: https://madis.noaa.gov/national_mesonet.shtml, in NMB, Sumter and Rock Hill SC.

We will now investigate kinematical, hodograph descriptors of the wind field over the record of continuous observations from the CCU Triton Sodar 142 located at NMB. Figure 5 left panel and Figure 5 right panel are presentations of the kinematic, hodograph descriptor plots of the horizontal components of the wind data collected. The decompositions reveal the axes orientations, the primary directions of particle motions for different bandwidths, the stability of and repeatability of the motions, and the coherency of the horizontally polarized +u (135˚ east of north), +v (45˚ east of north) components of motion of the time series of hourly wind data. In this decomposition, we employ the rotated u, v directions from the harvested data sets. As discussed in ([10] [11]) there are significant differences in the seasons of winter versus those in summer, so mashing them together would create a confusing picture. Therefore, we break the time

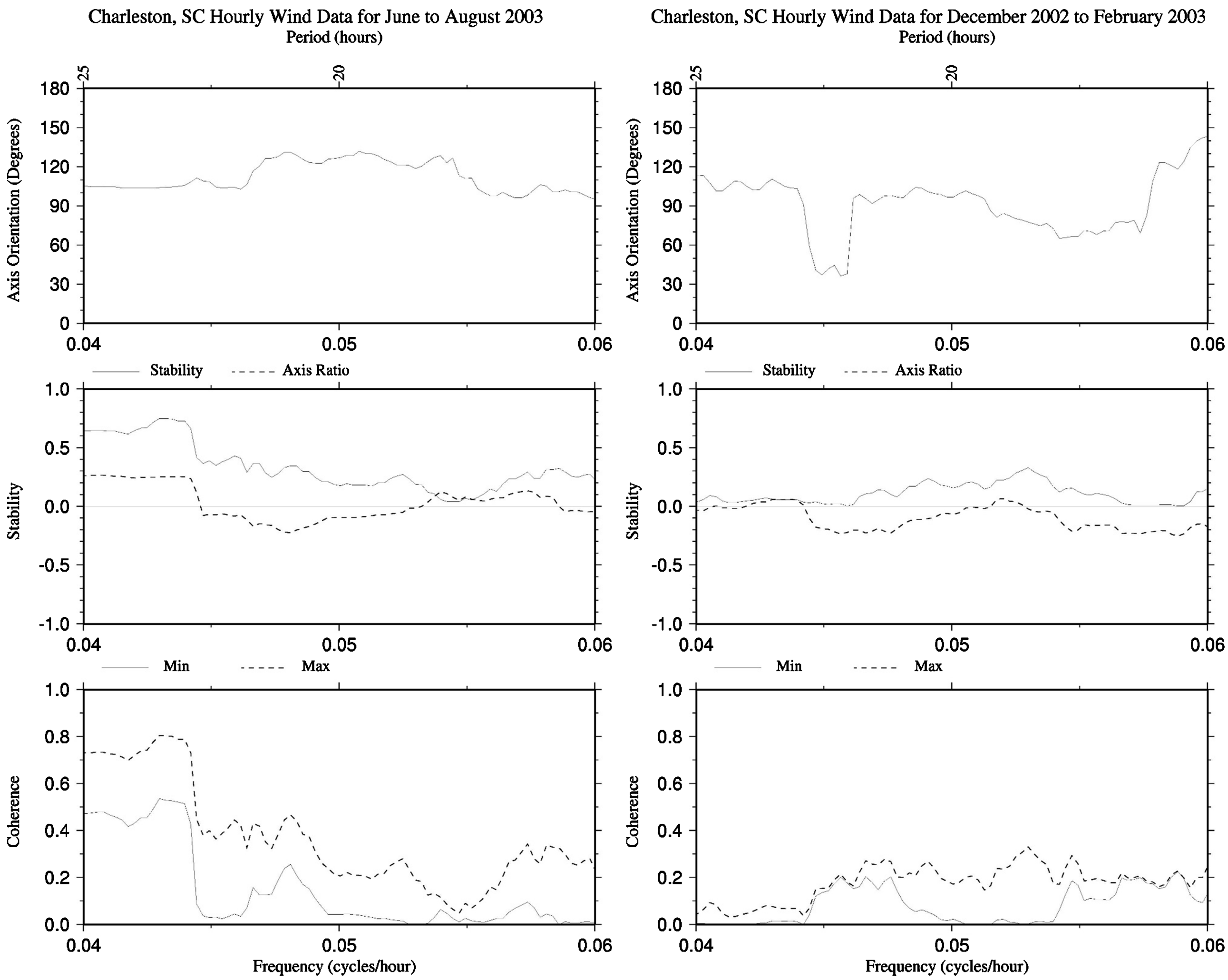



Figure 5. Kinematical descriptors of axis orientation, stability and coherency of (left panel) summertime period, versus (right panel) wintertime period, of the horizontal wind motions at the NMB Sodar site.

series up into winter and summer segments to better elucidate the descriptors. To do this we choose the summer period of June through August and the winter period of November-February. During the summer, June -August, motions (**Figure 4**, left panel) with periods less than 20 hours are not highly coherent. However, during that summer period, Sea Breeze particle motions, from 23 - 25 hours, are shown to be highly coherent with each other, and stable, elongated elliptically with a minor to major axis ratio of ~0.6, and nominally perpendicular to the coast at a persistent angle of ~115˚, so into the Goldilocks Zone. However, this is not the situation during the winter months (**Figure 4**, right panel), where the Sea Breeze displays low stability and low coherence in u, v particle motions; so is absent.

To identify the presence of a Sea Breeze at the CCU Sodars and/or National Weather Service (NWS) ground stations, an if-then methodology was employed. If there was a change in the wind field such that winds which blowing from any direction, began to blow into the Goldilocks Zone and persisted in that direction for the order of ~12 hours, then the queue went up. In addition, we focused on accompanying drops in atmospheric pressure and temperature and a rise in dew point, though the latter was not measured at the CCU Sodar sites. The manifestations of a Sea Breeze passage tended to occur mid to late afternoons and persist well into the evenings. Dew point time series are provided below via NWS and CCU MESO ground stations.

As seen in **Figure 6**, barometric pressure typically hovers near ~1013 mbar (14 pounds/inch$^2$, 6.35 kilograms/inch$^2$) but has slight deviations. Not surprisingly, due to the natural rising of temperature in the afternoon, there was a pattern of temperature peaking in the afternoon. However, Sea Breeze events were characterized by a drop in Air Temperature and a drop in Barometric Pressure as shown by two representative events (March 01 and August 12).

In determining the presence of a Sea Breeze and in documenting its passage

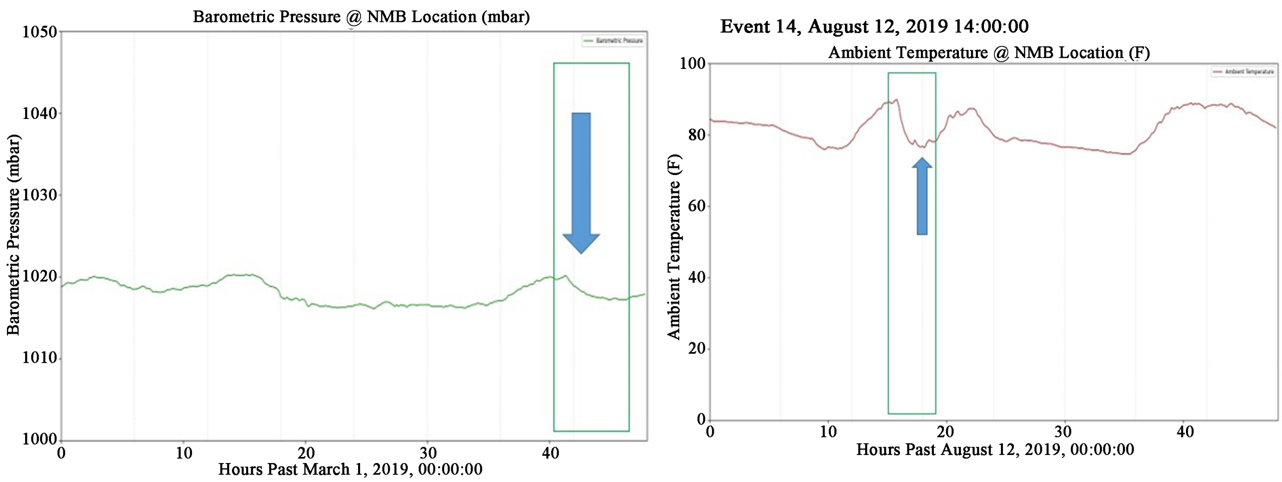
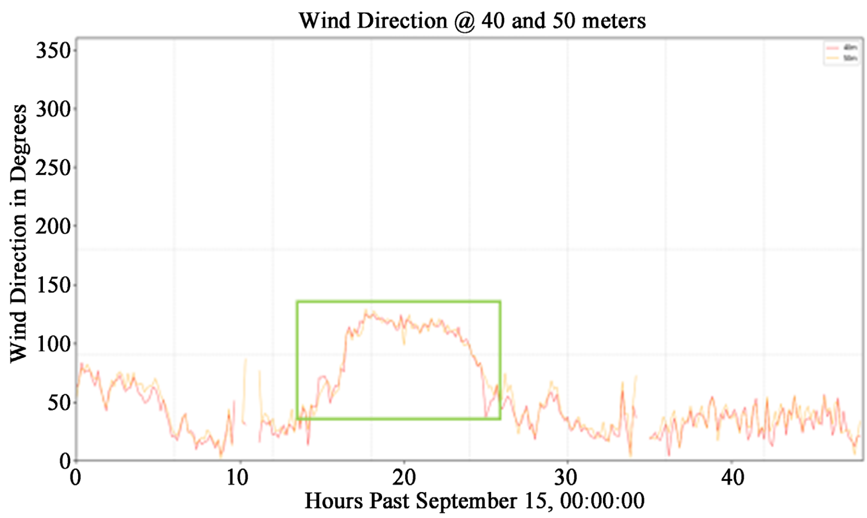



**Figure 6.** Representative examples of typical atmospheric pressure (left panel) for March 01 and air temperature (right panel) for August 14 changes during the passage of a typical Sea Breeze event. The Green Box represents the Sea Breeze event, and the Blue Arrow points towards the time-period over which the wind direction shifted into the Goldilocks zone. Vertical lines represent six-hour time blocks.

by one of the CCU observing sites, we focused first on the rapid rotation of wind vectors at height. We found that during the passage of a Sea Breeze, the winds blowing from any direction rapidly rotate into the zone of 90o to 180o, our designated Goldilocks Zone. Generally, the Sodar winds from 40 - 50 meters height showed the clearest characterization of the presence of the phenomenon (Figure 7, left panel). The wind vectors display a rapid rotation Figure 7, upper left of the right panel), an increase in turbulence from 0.2 to 0.9 m/s, Figure 7, upper right of the right panel), wind speed from 5 to 10 m/s (Figure 7, lower left of the right

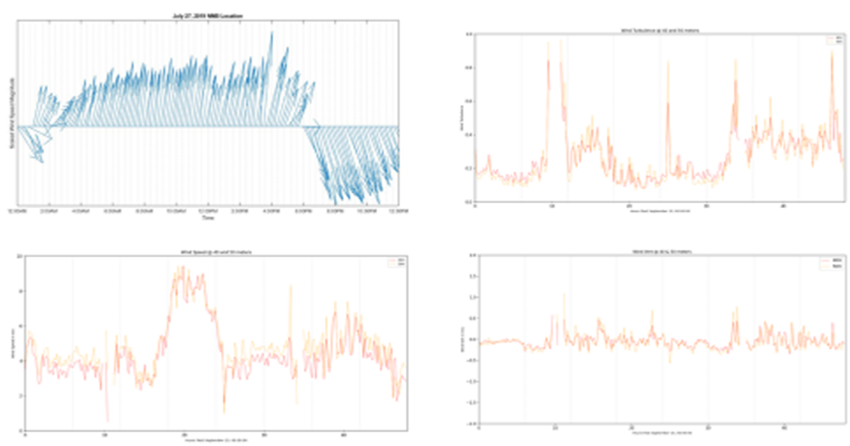
**A graphical representation of a prospective sea breeze event:**




As you can see, the wind direction takes a sharp and sudden shift from any direction into the 90-180 degree zone which we call the "Goldilocks Zone". This would be considered a prospective sea breeze event.

(left panel)

**The rest of the process:**



In order to move a prospective sea breeze event into the confirmation phase, other known variables including Wind Turbulence, Wind Vertical Velocity, and Wind Speed had to be compared to make sure there was a spike in speed and turbulence and a noticeable wind vertical velocity component. After this check, we moved into TCW and Radar images to confirm a sea breeze event

(right panel)

Figure 7. (left panel), the presence of the Sea Breeze in wind direction data from the CCU Sodar at height of 40 - 50 meters; (right panel), upper left are the wind vectors during a Sea Breeze passage, upper right is the increase in turbulence, lower left is the increase in wind speed and the lower right is the increase in vertical velocity.

panel) and vertical velocity from −0.2 m/s (downward) to +1.0 (upward) m/s (**Figure 7**, lower right of the right panel).

Using the above criteria, the following manifestations for Sea Breeze passages at the NMB and Sumter Sodar sites are presented in **Figure 8** (upper panel) and **Figure 8** (lower panel). There were 26 confirmed events at the two locations.

**Figure 9** (upper panel) displays the propagation of the Sea Breeze from NMB to Sumter, as depicted by the wind rotations into the Goldilocks Zone; NMB precedes Sumter. **Figure 9** (center panel) and **Figure 9** (lower panel) display additional Sea Breeze signatures at NMB; very consistent and persistent during the Summer months as ascertained in **Figure 4**, left panel, showing the strong stability of the Sea Breeze hodograph ellipses with their major axes oriented onshore-offshore. In this

Total events by month & category (NBM location):

| Month | Inconclusive | Not likely | Confirmed |
|---|---|---|---|
| January | 0 | 5 | 0 |
| February | 0 | 4 | 0 |
| March | 0 | 4 | 3 |
| April | 1 | 0 | 3 |
| May | 0 | 1 | 1 |
| June | 0 | 2 | 2 |
| July | 1 | 5 | 3 |
| August | 0 | 3 | 3 |
| September | 3 | 3 | 8 |
| October | 0 | 1 | 2 |
| November | 0 | 1 | 0 |
| December | 0 | 0 | 1 |

Again, there is a noticeable increase in confirmed events between the months of April-October.

And, as we will soon show, events that occurred at the NMB location were much more defined than their Sumter location counterparts.

There were 26 Confirmed Events @ North Myrtle Beach

The typical time of occurrence was around 2:30PM, much closer to the time we expected to see when originally researching sea breeze events. Now after compiling a list of days that had confirmed events at both locations, we were able to calculate the propagation speed of the event on each given day (as well as an average).

Total events by month & category (Sumter location):

| Month | Inconclusive | Not likely | Confirmed |
|---|---|---|---|
| January | 0 | 3 | 0 |
| February | 0 | 1 | 0 |
| March | 0 | 2 | 1 |
| April | 0 | 1 | 3 |
| May | 0 | 2 | 2 |
| June | 1 | 2 | 4 |
| July | 2 | 0 | 3 |
| August | 3 | 1 | 3 |
| September | 0 | 3 | 2 |
| October | 2 | 3 | 6 |
| November | 0 | 0 | 2 |
| December | 1 | 2 | 0 |

Of course, there is a possibility that a prospective event was misclassified, but based on the results we settled on, it can be noted (and confirmed) that the number of sea breeze events occurring decreases in the cooler months and increases in the hotter months, with November-March seeing noticeably less events that April-October.

There were 26 Confirmed Events @ Sumter

The typical time of occurrence was between 6PM and 12AM (even occurring into the early morning). This was surprising, considering we expected sea breeze events to occur in the afternoon. This led us to the question of 'How long is this coastal frontal system taking to propagate from the NMB location to the Sumter location?'
In order to answer this question, we looked for overlapping days of events.

**Figure 8.** (upper panel) NMB Total events by month; (lower panel) Sumter Total events by month.

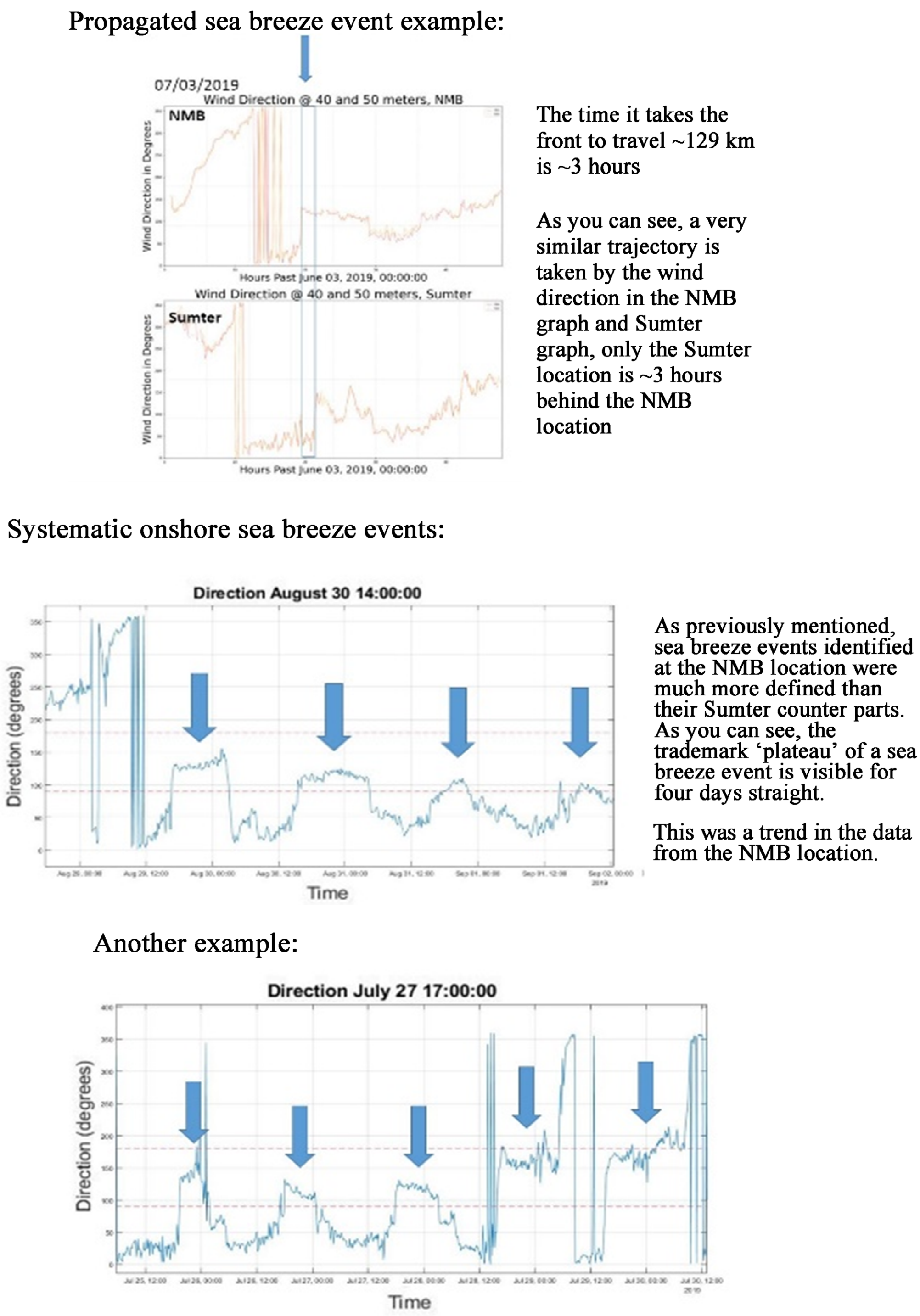



**Figure 9.** (upper panel) the NMB and Sumter manifestation of the Sea Breeze passage by wind rotations into the Goldilocks Zone; (central panel), Sea Breeze passages at NMB in late July; (lower panel), Sea Breeze passages in late August to early September.

realization, the feature passes by NMB about 3 hours prior than Sumter suggesting feature propagation speeds of 37 - 52 km/hour. Of course, Sumter is not directly inshore of NMB, as shown in Figure 5. Nonetheless, the feature is rapidly moving and highly convective as confirmed by the high relative wind speeds, turbulence generated and high ascending vertical velocities (**Figure 9**, left, center and right panels), respectively.

After examining the 26 confirmed sea breeze events from the NMB location, several characteristics were observed. The majority of sea breeze events occurred with an accompanying drop in atmospheric pressure and temperature and a rise in dew point. There did not seem to be specific pressures or temperatures or dew points associated with the onset of a Sea Breeze event. In **Figure 10**, a representative summary of a conventional Sea breeze event is described. This event occurred over the period of August 11-12, 2019. The Case demonstrates the cadre of Sea Breeze signatures; the movement of onshore winds into the Goldilocks Zone, the increase in wind speeds at height, the increases of vertical convection and turbulence, the drops in air temperature and pressure and the rise in dew point. The event moved into SC from the southwest past the Sumter site prior to NMB, different from the late July case shown in **Figure 9**.

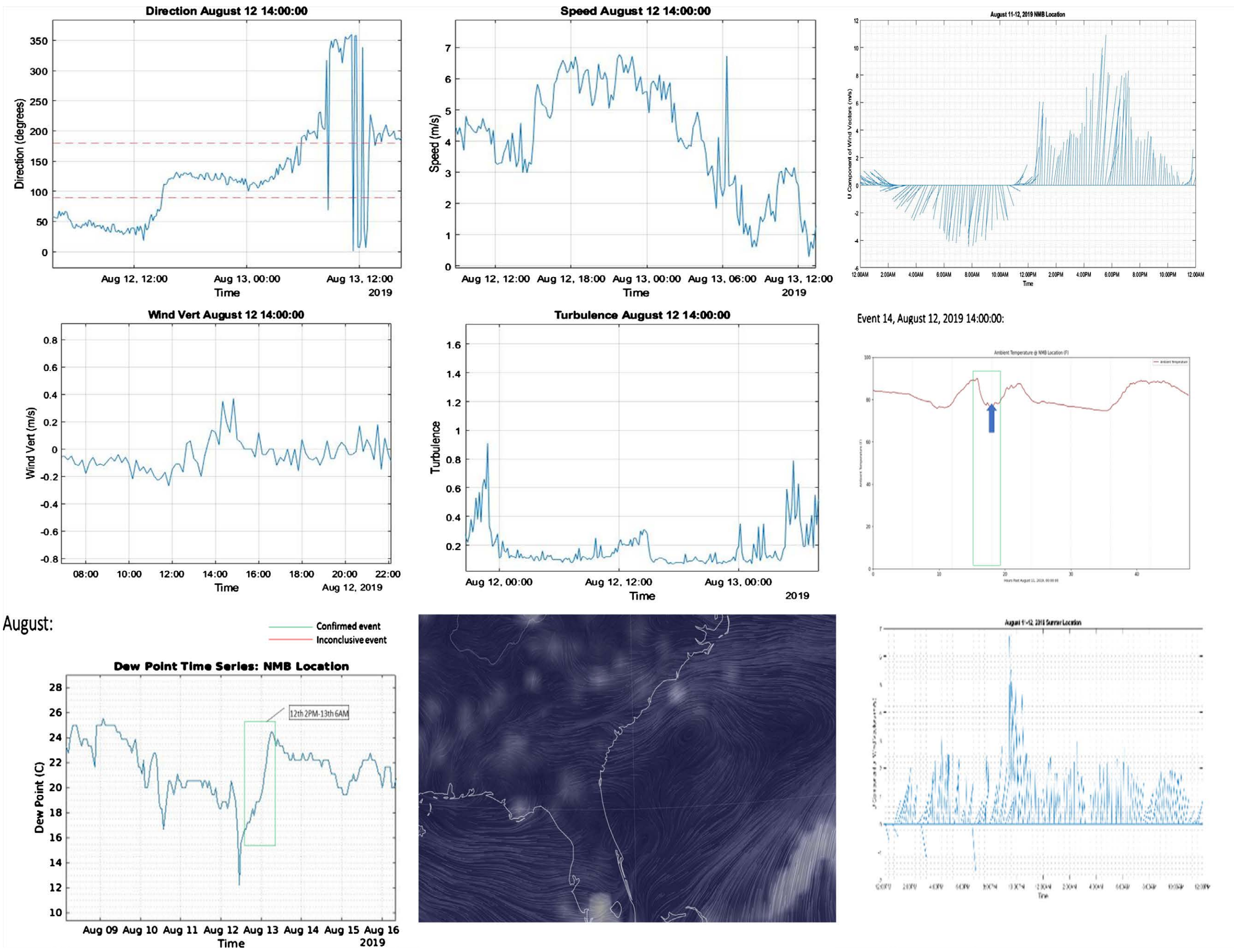



**Figure 10.** A Sea Breeze event at the NMB CCU Sodar site. Upper Left is the direction of winds into the Goldilocks Zone. Upper Center is the Wind Speed. Upper Right is the Wind Sticks. Middle Left is the Vertical Velocities. Middle Center is the Turbulence measurement. Middle Right indicates the Atmospheric Temperature drop as the Sea Breeze passes by the Sodar. Lower Left shows the rise in Dew Point. The Lower Center is a satellite image showing no large scale atmospheric system shading the Sea Breeze event. Lower Right is the wind sticks from the Sumter Sodar.

Given the CCU Sodars at NMB and Sumter, we considered additional sources of wind and atmospheric state variable data. The supplemental data display similar characteristics as shown in **Figure 11**. This suggests that additional realization of Sea Breeze passages can be harvested from the NWS network across SC. The sensors are at 7.93 m, so ~8 m above the ground. We now investigate a time series at NMB, one at Sumter and another well inland and upland at Rock Hill SC, ~240 km from Myrtle Beach. The plots are discussed below.

The realizations of Sea Breeze passages at the CCU NMB Sodar and the NWS KCRE sites, as recorded by wind directions and speeds are shown in **Figure 11**. The upper two panels display 7 events passing by the two sites during the period July 25-31 2019. The lower two panels cover the period 26 August-01 September but only 3 Sea Breeze events were present, from 29 August-01 September. The incursions into the Goldilocks Zone are entirely consistent from the NWS ~8 m height sensor to the CCU 40 m height observation. During these events, there was very little shear in the vertical as the winds at the lower level reach 6 m/s and those at the higher levels reach 8 m/s.

In **Figure 12** the stick plots of a Sea Breeze event, which occurred between 12 Noon and Midnight on August 12, as recorded at the CCU NMB Sodar (**Figure 10**, upper right panel) in and the NWS KCRE anemometer (**Figure 12** lower left panel), are presented, again display considerable coherency. In this case the speeds reach ~ 5 m/s at the 8 m lower level but up to 10 - 11 m/s at the 40 m upper level, so a measurement of ~0.17 m/s/m of vertical shear. In **Figure 11**, upper right panel, the wind directions are shown between the 8 m and 40 m levels. Clearly, they overlay. As the NWS measurements occur at twice the frequency of the CCU observations, twice as many wind sticks are plotted. This event is interesting for several reasons. We see in the lower left panel wind speeds are nominally 2 m/s higher at the higher altitude. In the lower right panel, the event is shown to have reached the NWS KUZA station in Rock Hill SC (**Figure 4** right panel) some 240 km from the NMB site. That is a significant inland penetration of the Sea Breeze Front.

In **Figure 13** the vertical attributes of the Sea Breeze are presented for the case study Sea Breeze event of August 11-12. The upper left panel shows the wind direction as a function of height, at the 100, 140 and 200 m levels, and shows a highly consistent direction. In the upper right panel wind speeds are shown to increase upward in the vertical, though unfortunately there were data dropouts. The wind turbulence as a function of height are shown in the lower left panel and during the presence of the Sea Breeze appear to be vertically coherent. Curiously, a significant precipitation event occurred as the Sea Breeze Front moved into and through the zone at NMB.

## 2. Discussion and Conclusions

We investigated the coastal Sea Breeze system on the SC coast by employing data collected using two CCU Sodars located at two SC sites, at the coast, Waties Island

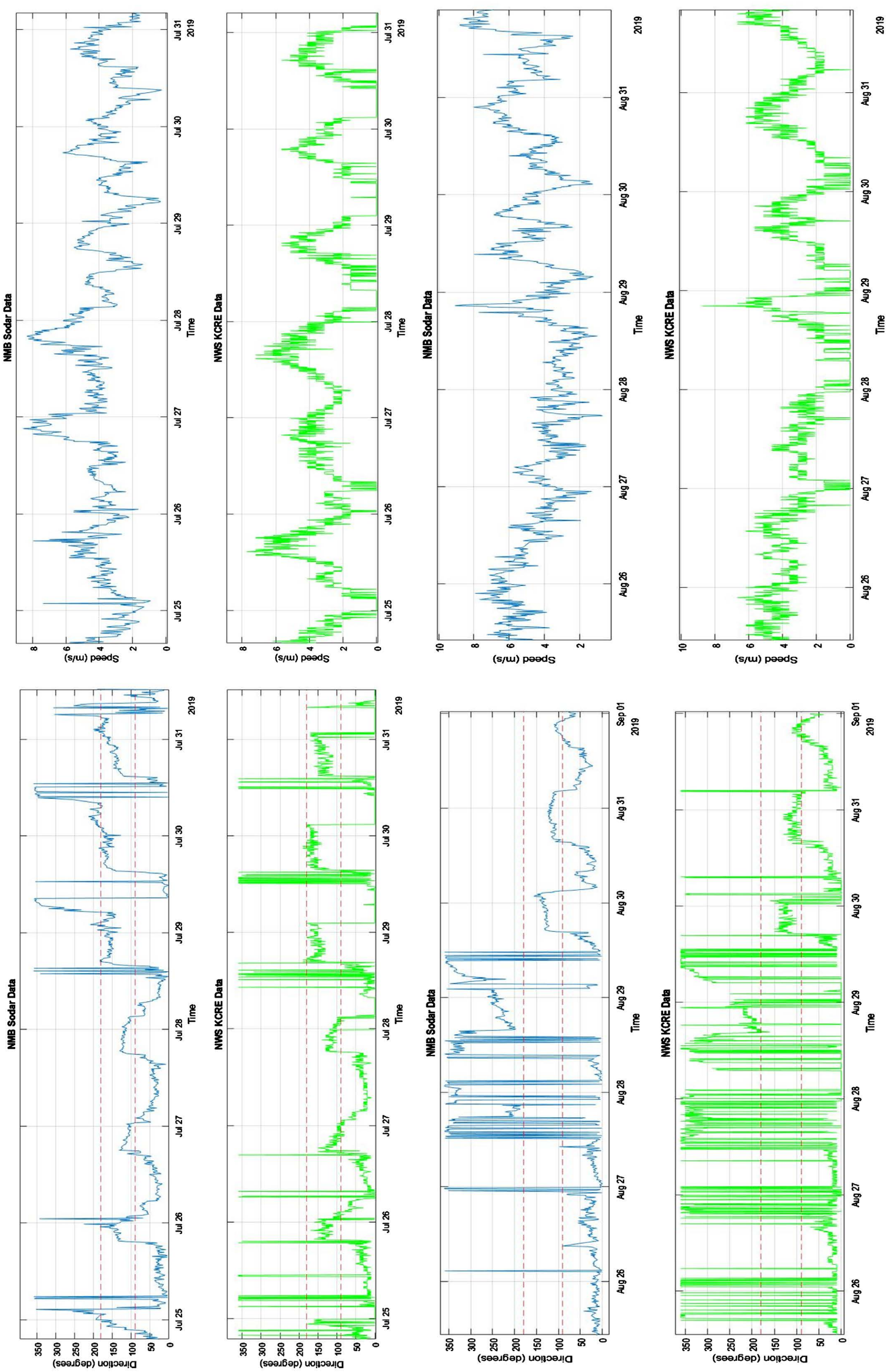



**Figure 11.** Realizations of Sea Breeze passages at the CCU NMB Sodar site and the NWS KCRE site as recorded by wind directions and speeds. The upper two panels display 7 events passing by the two sites during the period July 25-31 2019. The lower two panels cover the period 26 August-01 September but only 3 Sea Breeze events from 29 August-01 September.

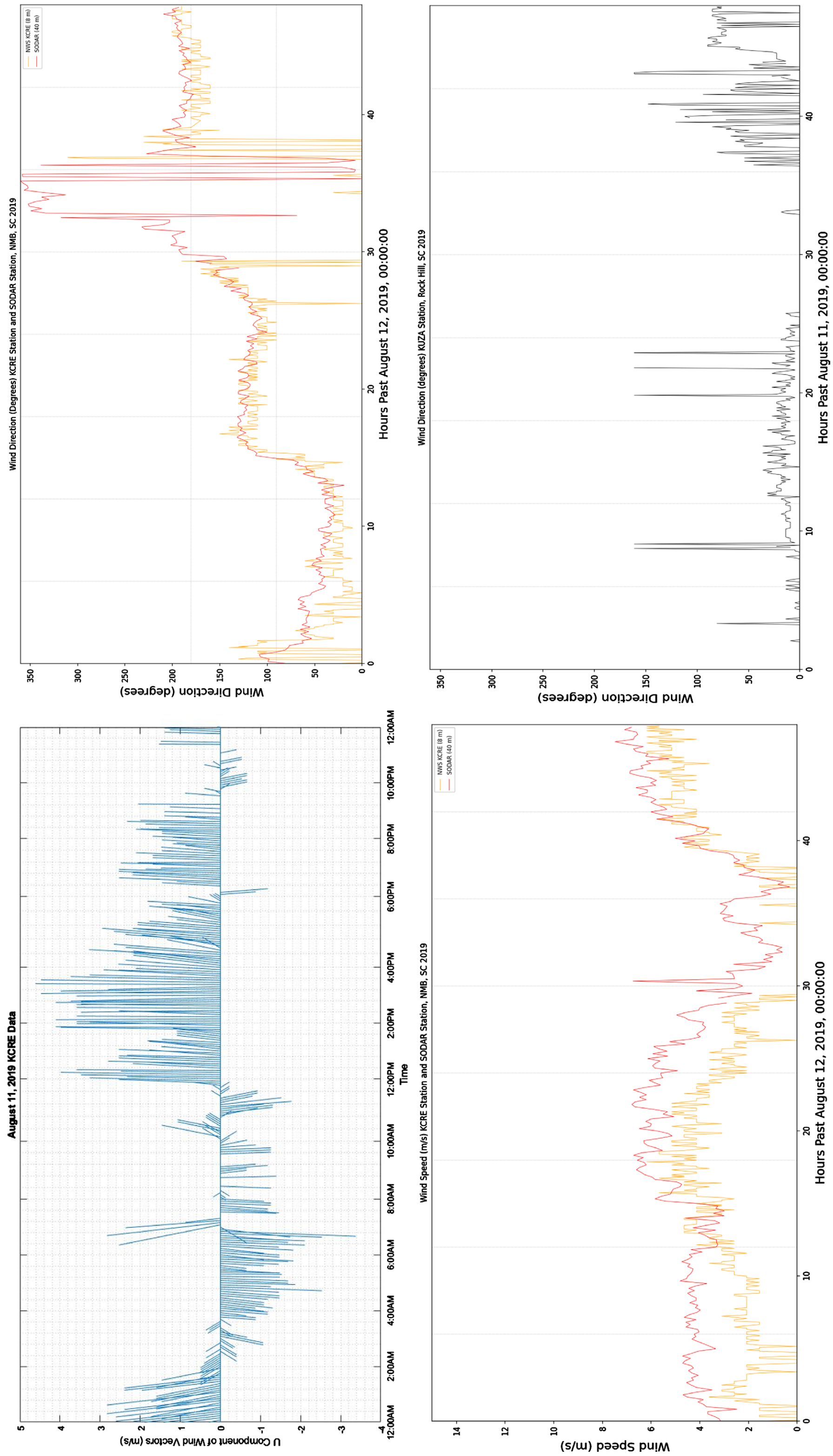


**Figure 12.** Lower left panel are the wind sticks at the NWS KCRE ground station. The upper left panel displays the wind directions at the NWS 8 m level vs the CCU 40 m level. The lower right panel shows the wind speeds at the 8 m vs 40 m levels. The upper right panel documents the penetration of the Sea Breeze from the SC coast at NMB 240 km inland to Rock Hill SC.

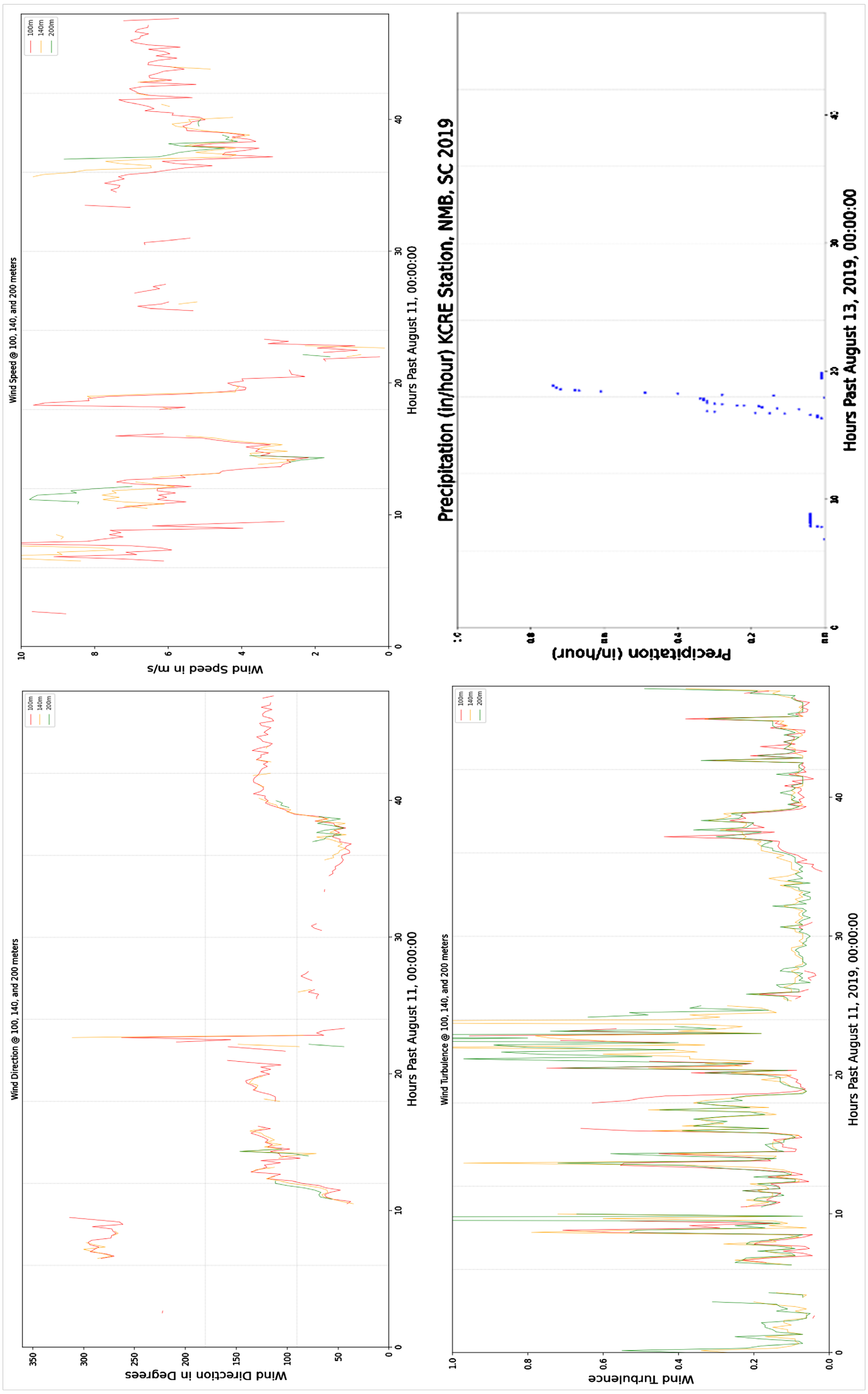



**Figure 13.** The vertical attributes of the Sea Breeze are presented for the case study Sea Breeze event of August 11-12. (lower left panel) shows the wind direction as a function of height, at the 100, 140 and 200 m levels, and shows a highly consistent direction. The (upper left panel) wind speeds increase upward in the vertical, with data dropouts. The wind turbulence as a function of height is shown (the lower right panel) and during the presence of the Sea Breeze is vertically coherent.

in North Myrtle Beach and inland near Sumter. Python software was utilized to plot the data. Data included atmospheric pressure and temperature and wind speeds and directions. Data were recorded every 10 minutes and in 2019 resulted in six-million observations.

The Sea Breeze was found to be far more prevalent during the late spring to early fall and hodograph, kinematical descriptors revealed horizontal plane onshore-offshore and alongshore particle motions, from 23 - 25 hours, which were highly coherent with each other, and stable, elongated elliptically with a minor to major axis ratio of ~0.6, and nominally perpendicular to the coast at a persistent angle of ~115˚ or perpendicular to the SC coastline. However, this was not the situation during the winter months, when the Sea Breeze displays low stability and low coherence in u, v particle motions; so is absent. A total of 26 Sea Breeze events were characterized by drops in atmospheric temperature and pressure and rises in dew point at the two stations. The Sea Breeze Front was found to propagate onshore with translation speeds on the order of 32 - 57 kms/hour. Evidence of the SBF reaching inland to Aiken SC, the location of the DOE Savannah River National Lab and to Rock Hill SC, 240 km from the coast, confirm the structural integrity and persistence of the system. Vertical shears of the wind fields were documented and are a subject of future studies. The economic value of the Sea Breeze to the state of SC is discussed in a study [12] and provides a different perspective on the natural phenomenon. Future studies of 2020 and 2021 data sets will investigate the climatology of the SC Sea Breeze system.

## Authors' Contributions

Pietrafesa-Bao-Gayes-Viner-Noble-Qian-Werth, conceived of this study. CCU students Mitchell and Burdette conducted the data reduction and constructed the Sodar data-based figures presented in the text.

## Data Availability Statement

The data used in this study are available from the U.S. Department of Energy Savannah River National Laboratory (stephern.noble@srnl.doe.gov) and from CCU (ptgayes@coastal.edu) and are available upon request at no cost for reproduction.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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