An observational, stability-based estimate of 80 m wind speed offshore of North Carolina – seasonal patterns

H. Seim, S. Haines
Dept. of Marine Sciences
University of North Carolina at Chapel Hill
Chapel Hill, NC, USA
hseim@email.unc.edu

N. Thomas
Dept. of Atmos. And Ocean. Sci.
University of Maryland
College Park, MD, USA
npthomas@umd.edu

Abstract—Winds at 80 m elevation have been estimated with a stability-based height adjustment scheme to study the feasibility of utility-scale wind energy offshore of North Carolina. Data sources are the daily ASCAT 10 m wind field as measured by the METOP-A satellite, the North American Regional Reanalysis (NARR) estimates of near-surface atmospheric temperature, pressure and humidity and the National Climate Data Center's optimally-interpolated Advanced Very High Resolution Radiometer (AVHRR-OI) sea surface temperature (SST). The study focuses on the 2008-2012 time period. The COARE V3.0 algorithm is used to provide the stability-based height adjustment scheme. Data from six buoys have been used to establish validity of the remotely-sensed and modeled fields.

A variety of results were produced, including long-term average wind speeds, wind power density and capacity factor at hub height, and a monthly climatology of these quantities. In this note the focus is on seasonal variations utilizing the monthly climatologies. Using the climatologies the largest differences between the neutral and stability-based schemes occur in winter and spring when and where stable atmospheric conditions are most common. There is a significant difference in the annual variation of atmospheric stability north and south of Cape Hatteras. Only the inner shelf region is prone to stable conditions during winter and spring south of Cape Hatteras, whereas the full width of the shelf is prone to stable conditions from fall into early summer north of Cape Hatteras. Where stable conditions occur the stability-based 80 m wind speeds are 2-3 m/s greater than 80 m neutral wind speeds, and where unstable conditions occur the stability-based 80 m wind speeds are 0.5-1 m/s less than the 80 m neutral wind speeds. The result is a pattern in the 80 m stability-based winds with notably greater speeds near the coastline than expected from a neutral height adjustment.

Keywords—coastal meteorology; atmospheric stability; renewable energy

I. Introduction

Offshore wind resource assessments over the continental shelf off North Carolina, e.g. [1] have suggested that tens of gigawatts of power generation potential exist for offshore wind farms. An initial assessment undertaken by the University of North Carolina at Chapel Hill took advantage of a variety of in-situ historical observations and employed simple height adjustment schemes (a power law and log-layer formulation) to estimate turbine height winds and power potential [2, 3]. Subsequent work [4] has investigated a variety of more sophisticated height adjustment schemes and established that L3 daily 10 m satellite Advanced Scatterometer (DASCAT) winds [5] estimated by the ASCAT program (2008-present) are consistent with buoy-based winds over the area of interest. Most recently a stability-based height adjustment scheme was applied to the DASCAT winds and evaluated to provide a spatially-explicit estimate of the wind resource at typical turbine hub height for the entire Exclusive Economic Zone offshore of North Carolina [6].

Motivation for the re-examination came from recognition of the influence that oceanic conditions offshore of North Carolina have on the lower atmosphere there and the ongoing lease process by the US federal government. This study area includes the Gulf Stream, which during most times of the year exhibits a strong ocean thermal front that has been documented to influence the low-level (10 m) mesoscale wind field [7], leading to increased low-level winds where SST is elevated. There is also a persistent area of cooler water over the continental shelf and slope just inshore of the Gulf Stream, where stable atmospheric conditions are common during part of the year. The juxtaposition of these two areas clearly influences the 10 m wind field and can be expected to impact hub height winds as well. These conditions present a challenge for implementing a stability-based height adjustment that can capture correctly the strong horizontal variations that characterize the area offshore of North Carolina. The sign and strength of the change in wind speed relative to neutral atmospheric conditions, as well as its variation along- and across-shore and over time, is documented in [6].

In this note we build on the work in [6]. We first discuss a methodological issue related to the interpretation of the 10 m DASCAT winds. The results section presents monthly climatologies to demonstrate the strong seasonal variations.

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II. METHODS

A. Height adjustment

Monin-Obukhov Similarity (MOS) scaling, modified to apply over the oceans, adequately represents the variations in surface fluxes and wind shear in a number of settings, e.g. [8]. It is a simple way to account for variations in atmospheric stability at low elevations over the ocean. A commonly available implementation of MOS, the Coupled Ocean-Atmospheric Response Experiment bulk algorithm (COARE V3.0, Fairall et al., 2003) was used. The wind speed is adjusted using

$$u(z_{new}) = u_r + \left(\frac{u_*}{k}\right)\left(\ln\left(\frac{z_{new}}{z_r}\right) - \left(\frac{z_{new}}{L}\right) + \left(\frac{z_r}{L}\right)\right)$$

where $u(z_{new})$ represents estimated wind speed at turbine height z_{new}, u_r is the wind speed at the reference height z_r (10 m for the DASCAT winds), k is Von Karman's constant, u_* is the friction velocity, □ is an empirically determined function, and L is the Obukhov length. A neutral height-adjusted wind, formed assuming neutral stratication in the atmosphere, is used for comparison. Further details are available in [6].

An unusual finding in [6] was that the DASCAT winds at 10 m were more consistent with actual (stability-corrected) buoy winds, rather than equivalent neutral 10 m winds. The formulation above applies when used with actual 10 m winds; the last term in parantheses on the right-hand side is dropped when neutral 10 m wind are used for u_r. We explore below the impact of both interpretations of the DASCAT winds on the 80 m estimates.

B. Data Sources

In addition to the 10 m DASCAT winds, gridded at 25 m resolution and available daily, information on surface ocean and atmosphere properties are needed to use the COARE algorithm. The North American Regional Reanalysis (NARR) product from the National Centers for Environmental Prediction [9] was available for the time period of interest and largely compatible in spatial resolution (roughly 32 km) with the DASCAT winds. NARR provides surface air temperature (SAT), relative humidity and barometric pressure. In-situ observations in the study area are available from six National Data Buoy Center (NDBC) buoys offshore of North Carolina over the time period 2008-2012. The sea surface temperature (SST) from NARR was found to be biased; the 25-km resolution National Climate Data Center optimally-interpolated Advanced Very High Resolution Radiometer (AVHRR-OI, [10]) was found to best represent SST along the NC coast relative to buoy-based observations. Fig. 1 shows the locations of the buoys and place names used to describe the results. Accuracy of individual buoy observations are presented at http://www.ndbc.noaa.gov/rsa.shtml. For the long time averages formed as part of this study the standard error, given as the standard deviation divided by the square root of the number of independent data points, is used to establish uncertainty.

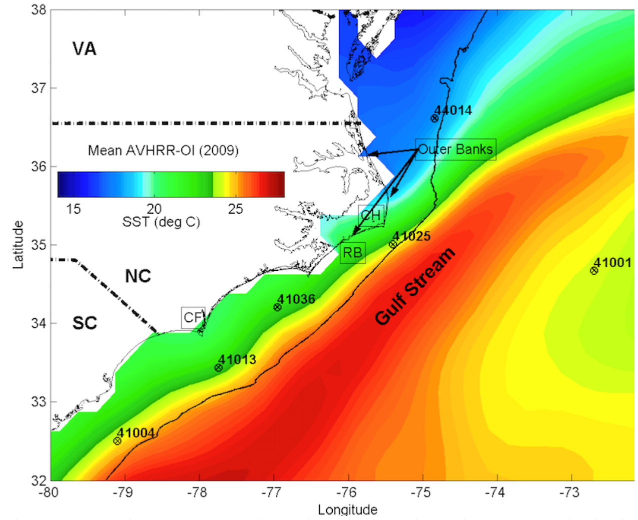

Fig. 1 - Annual average SST; buoy locations and numbers; 100 m isobath (black line); and feature names.

III. RESULTS

A. Height adjustment

We first examine how the interpretation of the DASCAT winds, as either actual or neutral 10 m winds, impacts the comparison of height-adjusted winds. Buoy observations are used to estimate 80 m winds and compared with satellite winds adjusted to 80 m in Table 1. Either interpretation of satellite winds compare favorably with the buoy winds but one additional site is significantly different than zero when DASCAT winds are assumed to be equivalent neutral winds. None of the differences exceed 1 m/s. It is clear that the last term in the height-adjustment scheme is relatively small compared to the other correction terms. We choose to interpret the DASCAT wind as actual winds due to the smaller discrepencies with the buoy-based estimates.

B. Seasonal variations

We next examine the spatial structure of the height-adjusted winds for different seasons. Each represents an average formed over 2008-2012 using all daily estimates in the given month. For each season the 10 m DASCAT wind, average SST-SAT, 80 m wind assuming neutral stability, and 80 m wind using the stability-based height adjustment are shown.

In winter, using February as an example, 10 m wind speeds offshore are strong, increasing from south to north and exceeding 10 m/s over the Gulf Stream in the northeast portion of the coverage area (Fig. 2). Wind speed decreases significantly approaching the coastline, to about 7 m/s except in the area surrounding Cape Hatteras where wind speed is above 8 m/s. Higher wind speeds over the continental shelf along the central North Carolina coastline are common and likley reflect the reduction in surface roughness due to the presence of the large sounds behind the barrier islands. The pattern of the 80 m neutral wind speeds is identical to that of the 10 m wind speeds but are everywhere increased, to 8 m/s or more nearshore and in excess of 12 m/s offshore. To examine atmospheric stability effects we first review the SST-SAT field. It is dominated by a

Table 1 - Comparison of 80 m winds formed with buoy observations and formed from combining 10 DASCAT winds with AVHRR-OI SST and NARR atmospheric data. The difference is formed as buoy – satellite wind, with standard error. Zero is shown is the standard error exceeds the difference.

Station	Mean Difference (buoy-sat_neutral)	Mean Difference (buoy-sat_actual)
41001	0	0
41004	0.34±0.21	0
41013	0	-0.29±0.22
41025	0.52±0.31	0
44014	-0.76±0.31	-0.70±0.30
41036	-0.34±0.28	-0.53±0.27

region of strongly positive values, peaking at 9 °C directly east of Cape Hatteras over the Gulf Stream. The difference decreases rapidly towards the coastline and is negative north and south of Cape Hatteras over the inner shelf. Offshore of the Gulf Stream values decrease but remain positive at 1-2 °C. The 80 m stability-adjusted winds differ significantly from the 80 m neutral winds. Offshore where SST-SAT is positive the wind speeds are reduced by 0.5-1 m/s. The greatest change is near the coastline, where wind speeds increase by 2-3 m/s, corresponding to locations where SST-SAT is negative. The overall result is a more uniform wind speed at 80 m in the stability-adjusted representation, with peak values near the shoreline and over the Gulf Stream and a slight minimum separating them.

In spring, using May as an example, 10 m wind speeds decrease relative to winter, the offshore maximum being less than 9 m/s and falling below 6 m/s near the coastline, but the spatial pattern is similar to that in winter (Fig. 3). Height adjustment to 80 m with the neutral scheme increases the speeds by about 1 m/s. The SST-SAT field exhibits less extreme values, reaching +4 °C over the Gulf Stream, and falling to zero further offshore. Negative SST-SAT still occurs along parts of the coastline. South of Cape Hatteras it is weakly negative (-1- 0 °C). Over the continental shelf north of Cape Hatteras the minimum is close to -3 °C and has shifted away from the coastline and is centered over the continental shelf. Stability-based 80 m wind speeds are maximum over the minimum in SST-SAT, on the shelf north of Cape Hatteras. The stability-based wind speeds are similar in structure to the neutral 80 m winds offshore but of reduced magnitude, and south of Cape Hatteras mirror offshore winds in the nearshore, rather than decreasing in speed as seen in the neutral 80 m wind speed field.

In summer, using August as an example, 10 m wind speeds are at an annual minimum, being everywhere less than 6.5 m/s

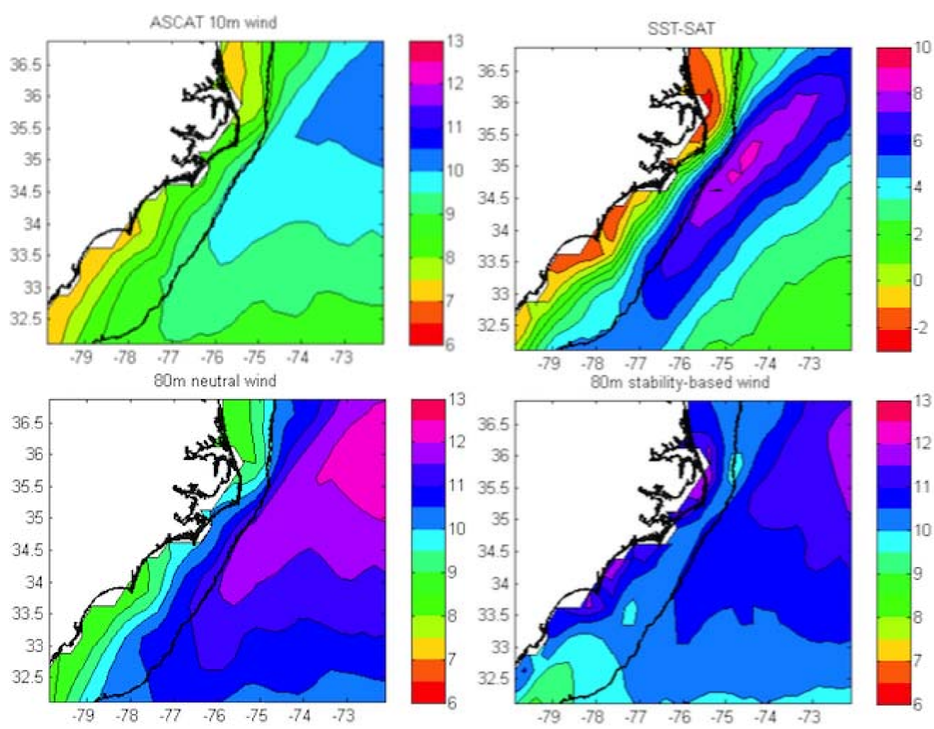

Figure 2. February climatology of (top left) 10 m DASCT wind speed, (top right) average SST-SAT, (bottom left) neutral 80 m wind speed and (bottom right) stability-based 80 m wind speed. The black line marks the 100 m isobath. Speeds are in m/s and temperatures in °C.

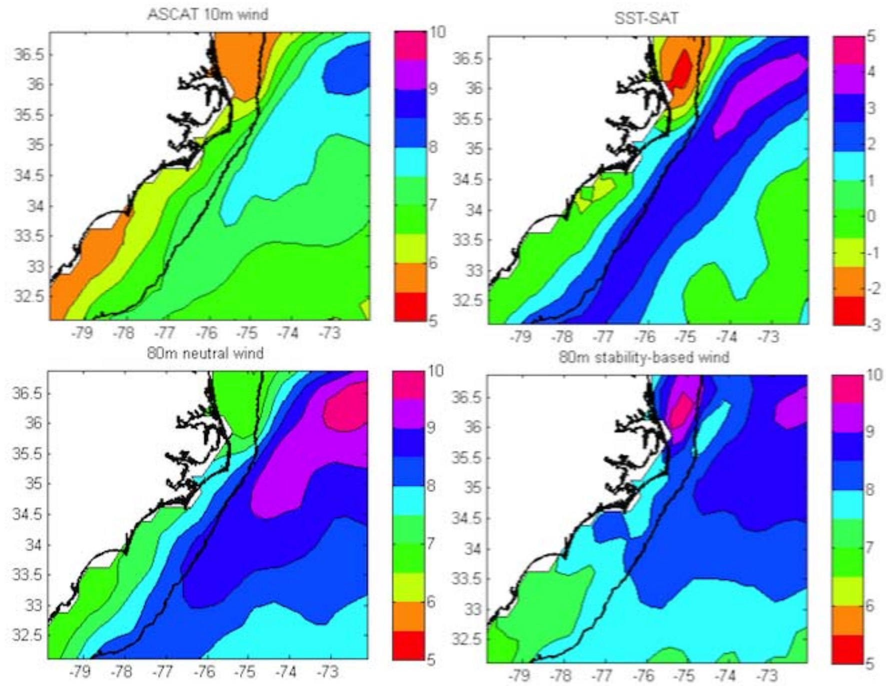

Figure 3. May climatology of (top left) 10 m DASCT wind speed, (top right) average SST-SAT, (bottom left) neutral 80 m wind speed and (bottom right) stability-based 80 m wind speed. The black line marks the 100 m isobath. Speeds are in m/s and temperatures in °C.

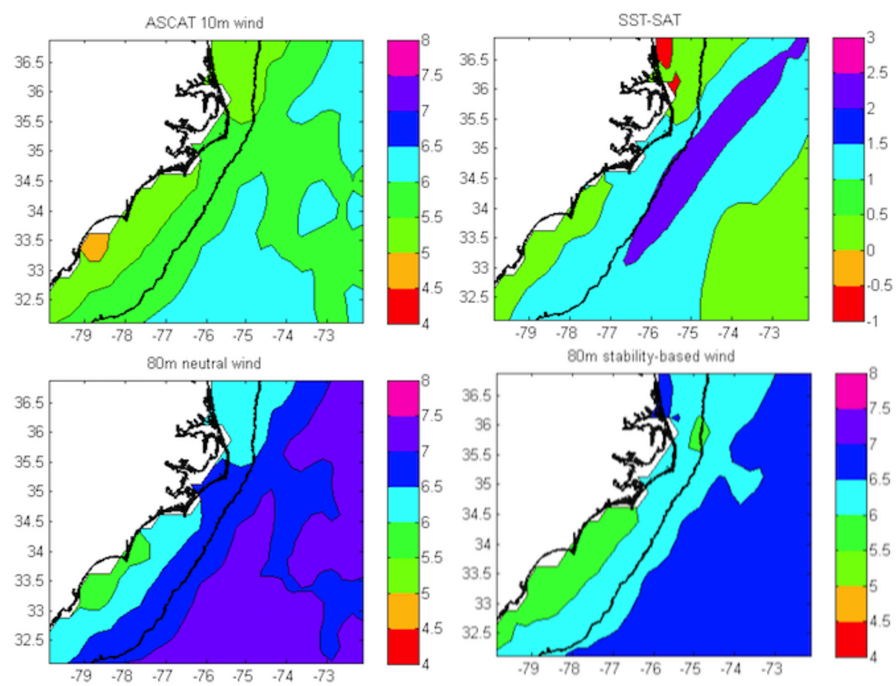

Figure 4. August climatology of (top left) 10 m DASCT wind speed, (top right) average SST-SAT, (bottom left) neutral 80 m wind speed and (bottom right) stability-based 80 m wind speed. The black line marks the 100 m isobath. Speeds are in m/s and temperatures in °C.

(Fig. 4). Wind speeds near the coastline are about 5 m/s except around Cape Hatteras where they are somewhat larger at 5.5 m/s. Neutral 80 m wind speeds are roughly 1 m/s greater. Extremes in the SST-SAT field are at a minimum as well, being about 2 °C over the Gulf Stream, falling to near zero along the coastline south of Cape Hatteras and being slightly negative along the coastline north of Cape Hatteras. The stability-based 80 m wind speed is similar to but about 0.5 m/s lower than the neutral 80 m except north of Cape Hatteras where it is about 1 m/s greater.

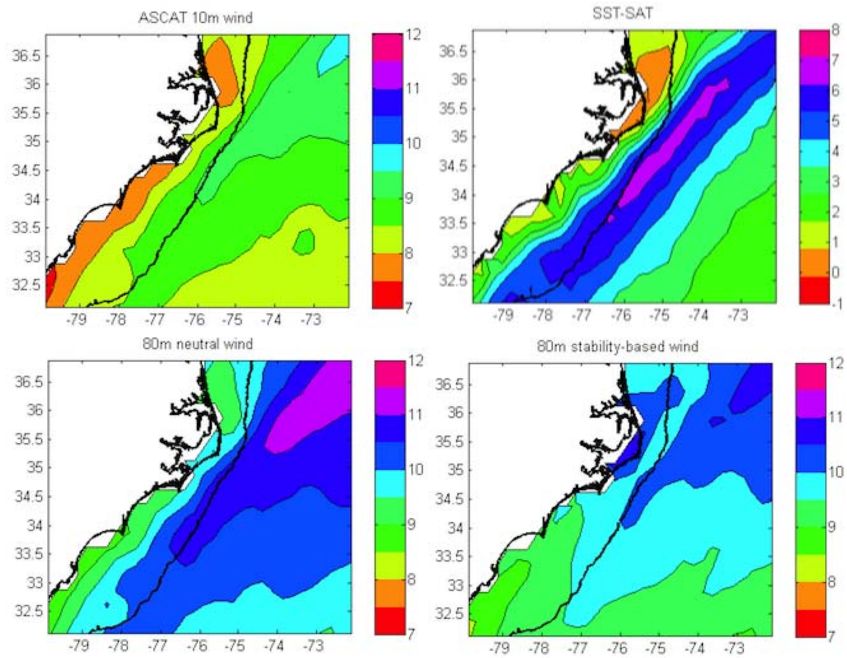

Figure 5. November climatology of (top left) 10 m DASCT wind speed, (top right) average SST-SAT, (bottom left) neutral 80 m wind speed and (bottom right) stability-based 80 m wind speed. The black line marks the 100 m isobath. Speeds are in m/s and temperatures in °C.

In fall, using November as an example, wind speeds increase significantly and are greater than 9 m/s over the Gulf Stream and 7-8.5 m/s near the coastline. Neutral 80 m wind speeds are 1-1.5 m/s greater. The SST-SAT field has an elongated maximum above the Gulf Stream of up to 7 °C and decreases abruptly towards the coastline, being slightly negative only north of Cape Hatteras. The stability-based 80 m wind speeds increase from south to north and do not decrease towards the coastline, unlike the neutral 80 m wind field.

IV. DISCUSSION

Limitations of the MOS theory in this setting are discussed in [6]. As has been recently documented in [8], the theory is expected to be an accurate representation of hub height winds when the atmosphere is unstable, neutral, or weakly stable. Less clear is its applicability during strongly stratified conditions, increasing uncertainty in the wind speed estimate under these conditions. However, there is value in identifying when and where wind speeds may differ significantly from estimates based on an assumed neutral atmosphere. As is clear from the results, stable conditions lead to significant increases in 80 m wind speed estimate relative to neutral conditions.

How best to interpret satellite winds for these kinds of resource studies is debatable. Assessed against MOS theory-based 80 m from buoys it appears that an interpretation as actual winds produces somewhat better agreement. In [6] it was found that the 10 m winds were rather clearly more consistent with actual buoy winds, but it is unclear if the cause is soley due to stability.

There is a clear seasonal cycle to the wind speeds and air-sea temperature differences offshore of the North Carolina coastline. Strongest winds occur during winter and are only slightly less during fall. A distinct minimum occurs during summer. Extremes in SST-SAT also follow this timing, being greatest in winter, though still large in fall and spring, and a minimum in summer. The location of the largest values of SST-SAT is always the Gulf Stream, where they can be as large as 9 °C. Minima in SST-SAT occur near the coastline north and south of Cape Hatteras over the inner shelf. Local air-sea heat transfer, which will produce the greatest change in water temperatures where the ocean depths are least, is the probable reason for the occurrence of minimum SST and greatest stability adjacent to the coastline during fall and winter.

The most persistent region of stable conditions is in the area north of Cape Hatteras. Southward oceanic flow over the continental shelf delivers cool water to this area year-round [11], helping maintain the negative SST-SAT. These cool waters turn offshore at Cape Hatteras and restrict the influence to the area north of Cape Hatteras. The advective influence, rather than just local air-sea heat transfer, likely explains the difference in the spatial extent of stable conditions north and south of Cape Hatteras.

In all seasons stable conditions lead to increased stability-based 80 m wind speeds relative to neutral 80 m wind speeds. Because stable conditions occur where the 10 m winds are least, the net result is a more uniform wind field in the cross-shore direction. In some seasons the nearshore minimum becomes a local maximum, and overall the spatial pattern of the wind field in the stability-based estimate is quite different from the 10 m wind field.

The increased wind speeds in the stability-based 80 m wind field suggest that prior estimates of the wind resource available to conventional wind farms may have been under-estimated. The area in Figs. 2-5 inshore of the 100 m isobath is shallow enough to support development, and is also the area where the two 80 m wind speed estimates differ the most. Particularly for the area north of Cape Hatteras the stability-based winds shift from being a regional minimum to a local maximum.

V. SUMMARY

A stability-based estimate of the 80 m wind speeds offshore of North Carolina has been developed. Daily satellite winds at 10 m measured by the ASCAT sensor were adjusted to 80 m height using MOS theory, atmospheric conditions from NARR and SST from AVHRR-OI. A estimate of the 80 m wind speed assuming neutral stability was formed as a reference. Atmospheric stability is found to vary widely, in space and time. Unstable conditions persist over the Gulf Stream year-round but SST-SAT varies from 2-9 °C. Stable conditions occur near the coastline but have a differing character north and south of Cape Hatteras. Stable conditions are persistent north of Cape Hatteras and occur across the continental shelf, whereas south of Cape Hatteras stable conditions occur only near the coastline during winter and spring.

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