Observation and regional model based Gulf Stream marine hydrokinetic energy resource estimates for North Carolina

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Abstract— **North Carolina and Florida are likely the only two states on the US east coast that have practical access to energy extraction from the Gulf Stream. After leaving the Florida Straits, the Gulf Stream in the region offshore of Cape Hatteras, NC exhibits the least variability in position of any location on the east coast, while simultaneously being closest to land. Gulf Stream current speeds exceed 2 m/s. These important characteristics have made this area the focus of observations and regional model estimates to quantify the hydrokinetic energy that may be available from the Gulf Stream for the state of North Carolina.**

Three types of observations to quantify the energy resource off NC began in 2013. A 150 kHz Acoustic Doppler Current Profiler (ADCP) was moored on the 225 isobath at the location estimated to be best for energy extraction, and recovered after two consecutive nine- and ten-month deployments, respectively. Another ADCP was moored in nearly the same location to continue observations, and will be retrieved in August 2015. Currents from the first deployment averaged 1.15 m/s, and the power density was 779 W/m^2 at a depth of 30m over the 9-month duration. Significant variability in current speed, and thus power, occurred over the deployment period. Additionally, current measurements from a vessel mounted 300 kHz ADCP were made from water depths of 100m to 1000 m on a cross-isobath transect that passed over the location of the ADCP mooring. Currents measured from the vessel compare favorably with those from the moored 150 kHz ADCP in both magnitude and direction, and provide valuable information about the spatial variability of the current and its dependence on depth.

In 2013, a coastal ocean radar (Codar) was added to an existing radar network that had been measuring ocean surface currents for more than a decade in the region to expand coverage over the entire study area. The radar current measurements provide consistent spatial and temporal coverage throughout the Gulf Stream cyclonic shear zone, and are being used to measure the variability in Gulf Stream position off of Cape Hatteras, NC.

One method being developed using measurements from individual radars assumes the landward Gulf Stream front lies along selected maxima in the radial current shears chosen for consistency over the time period sampled, and magnitude. The locations where the Gulf Stream first enters and exits the radar coverage area are apparent in the large radial speeds measured by the radar, and the width and variability of the Gulf Stream cyclonic shear zone is estimated using maxima in velocity and velocity shears.

Favorable comparisons between the three current observations will provide confidence that power estimates can be extrapolated from the radar surface currents alone over long time periods when ADCP information may not be available.

Finally, observations are being compared with a regional specific Mid-Atlantic Bight and South Atlantic Bight (MABSAB) Model. Moored ADCP current measurements compared favorably with the model, demonstrating the skill of the model for power estimates in this area. Averaged current measurements 30 m below the surface from the ADCP mooring made between August 2013 – April 2014 and model estimates at the same location were nearly identical, both having average current speeds of 1.15 m/s. The model is more conservative than the observations with respect to higher frequency fluctuations in speed and direction.

I. INTRODUCTION

The Gulf Stream presents an abundant hydrokinetic energy resource for the state of North Carolina. Only off of Cape Hatteras, NC, and through the Florida Straits, does the Gulf Stream exhibit limited variability in position (Miller 1994), and close proximity to land to make it a practical location for energy extraction. Gulf Stream transport off Cape Hatteras is 90 Sverdrups (1 Sverdrup = 10^6 m^3/s) (Hogg 1991) and currents frequently exceed 2 m/s. These important characteristics have made Cape Hatteras the focus of a combined observation and modeling effort to quantify the hydrokinetic energy resource and its variability off of North Carolina. This work summarizes and expands upon the paper presented by Muglia et al. 2015.

Three different observing methods were implemented to measure the hydrokinetic energy resource and its variability, and to evaluate the skill of a MAB/SAB (Mid Atlantic Bight/South Atlantic Bight) ROM (Regional Ocean Model): a 150 kHz ADCP mooring, 300 kHz ADCP cross-isobath boat transects, and land based HF radar surface current measurements.

A 150 kHz moored ADCP was deployed at 35.14N and 75.11W for 9 months beginning in August 2013 in a water depth of 230m, an optimal location based on practical constraints. The first ADCP was recovered in May 2014, and a second was deployed 7 km northeast of it at a depth of 265 meters (figure 1)

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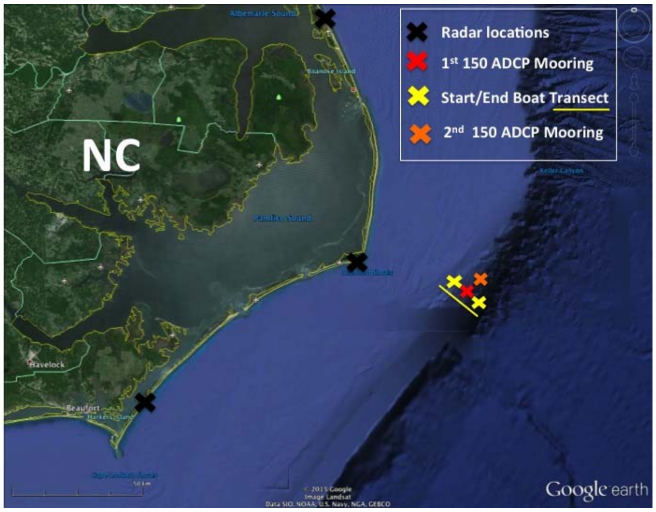

Figure 1: Map of study focus area off Cape Hatteras, NC with three observation types: 150 kHz ADCP mooring, cross isobaths boat transect, and HF radar locations.

The unintentional difference in location resulted from challenging ocean conditions during the second deployment. Measurements made by both ADCP's over one month when they were simultaneously deployed demonstrated that the current speeds co-varied similarly at both locations (figure 2). The second was recovered, and a third ADCP was deployed in January 2015 at the same location as the first. The third will be recovered and replaced in August 2015.

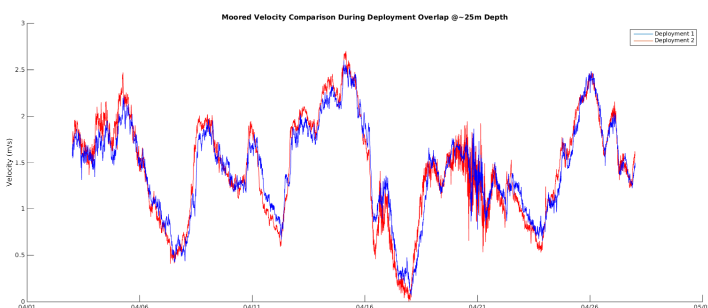

Figure 2: Current magnitudes 25m below the surface in April 2014 from both ADCP deployments one (blue) and two (red).

The ADCP measures currents over most of the water column above the instrument, from about 8 m above the seabed to 25 m below the surface every 10 minutes with a vertical resolution of 4 m. The standard deviation of the measurements is 2 cm/s. This observing method provides a consistent long-term estimate of the energy resource and its variability from the stream at one location.

A 300 kHz ADCP was installed on a small vessel to make cross-stream transects from the 100 – 1000m isobaths (figure 3).

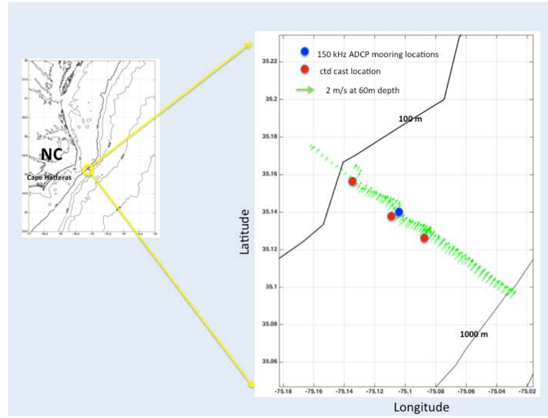

Figure 3: Boat ADCP transect with 50m depth current vectors, locations of ADCP mooring, and ctd cast locations

Transects consist of an offshore and onshore leg, and are repeated along the same line which passes over the moored ADCP location, as often as weather allows. At this time, ten small vessel 300 kHz ADCP transects have been made. Transects proceed from inshore across the 100m isobath, over the moored 150 kHz ADCP location, offshore to the 1000m isobath, and back in a cross-stream direction (figure 3). Measurements are made from 7.5m to 100 m below the surface with 4m resolution every two minutes, with average velocity errors 0.22 m/s over all measurement depths. The vessel transects provide a snapshot in time of current variability with depth within the Gulf Stream cyclonic shear zone, and provide valuable information about the spatial variability of the current and its dependence on depth.

Land based HF radar observations provide consistent hourly surface current measurements in near real time. A 5 MHz radar from Codar Ocean Sensors was added to the existing radar network in the Core Banks of NC at the beginning of this study, in November 2013, to expand consistent surface current measurements over the study area. The radar surface current measurements provide long-term high frequency estimates of the variability in Gulf Stream position not previously available with other observing techniques.

II. Observations

A. 150 kHz ADCP Mooring Current Measurements

Although Gulf Stream transport has been observed to vary annually (Baringer and Larsen 2001), seasonally, and with higher frequency (Shott et al. 1988, Halkin and Rossby 1985), the primary cause of variability in available energy from the current at a given location is due to variability in position of the stream. This variability is apparent in the current measurements made by the ADCP moorings, viewed in long-stream and cross-stream coordinates (figures 4 and 5). Long/cross stream directions were estimated by averaging currents over depth and time during the deployment period. Current measurements were then rotated into the along and cross-stream coordinate system. Along stream currents approach 3 m/s at the mooring location.

Currents from the first deployment averaged 1.15 m/s, and the power density was 779 W/m^2 at a depth of 30 m over the 9-month duration. The currents exemplify high frequency variability caused by Gulf Stream meanders that occur over periods from 3-8 days typical of downstream meander propagation (Savidge 2004) (figure 4).

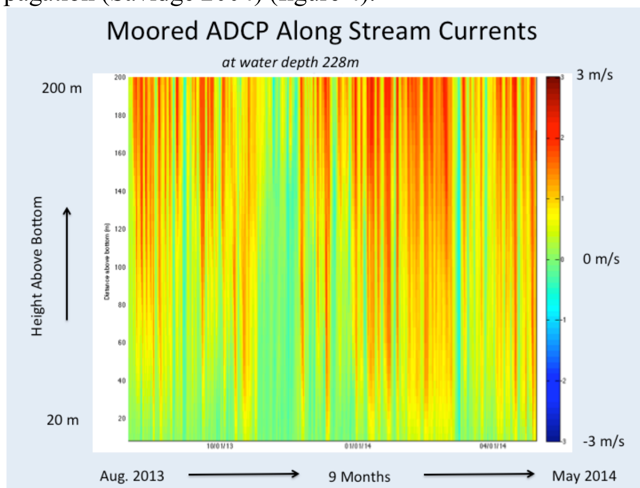

Figure 4: Along-stream moored ADCP current speeds.

Reversals in current direction caused by frequently shed Gulf Stream filaments along the shelf slope, and counter current flows of shelf water when the stream is offshore of the mooring and beneath stream flow, were also apparent during the deployment period. These phenomena, combined with infrequent but significant cross-stream currents (figure 5) approaching 1 m/s present challenges to those considering mooring and turbine design.

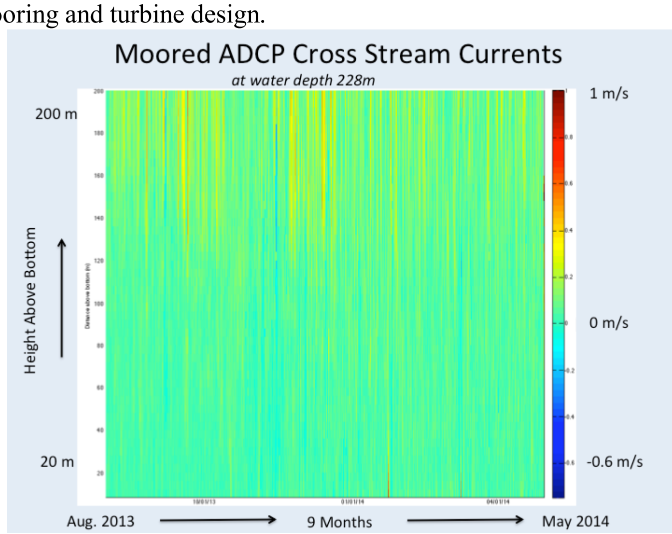

Figure 5: Cross-stream moored ADCP current speeds.

B. 300 kHz ADCP Boat Transects

Currents observed by the boat ADCP provide important information about the variability of the MHK energy resource with depth, and inform those involved in mooring and turbine design of the of the vertical and horizontal shears present in the water column (figure 6).

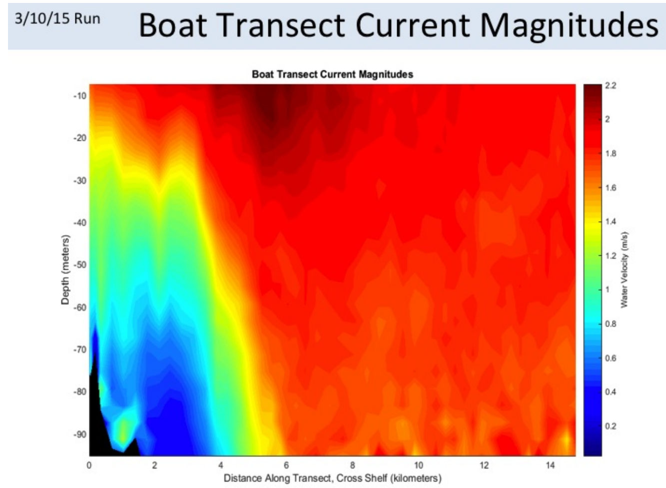

Figure 6: Currents speeds measured from the cross isobath vessel ADCP transect on 3/10/15 vary significantly with depth along the transect line that begins in less than 100m of water and extends to the 1000m isobath 15 km offshore. Black shading in the bottom left corner is the ocean bottom.

Boat transects made on consecutive days in May of 2015 fortuitously measured the high frequency Gulf Stream variability that can occur here within 24 hours (figure 7).

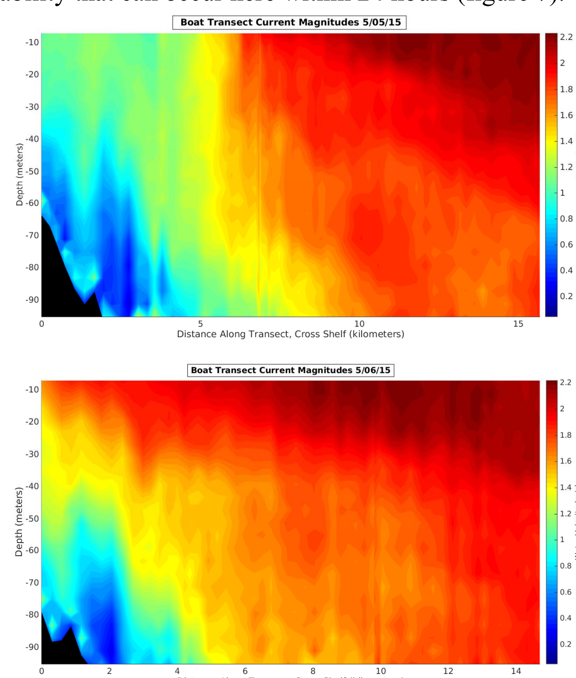

Figure 7: Consecutive days of current measurements along the boat transect show a shift in Gulf Stream position over the 24 hour period.

Further examination of the difference in U (east) and V (north) components of the current on both days suggests the difference in current magnitude is caused by an onshore shift in

Gulf Stream position rather than a change in the stream's orientation (figure 8 left panels). The difference in magnitude, and thus power density (equation 1) caused by this shift in position is significant (figure 8 right panels). The power density is given as half the density of seawater (ρ), 1025 kg/m^3, multiplied by the velocity cubed.

$$\text{Power Density} = \tfrac{1}{2}\,\rho\,V^3 \qquad (1)$$

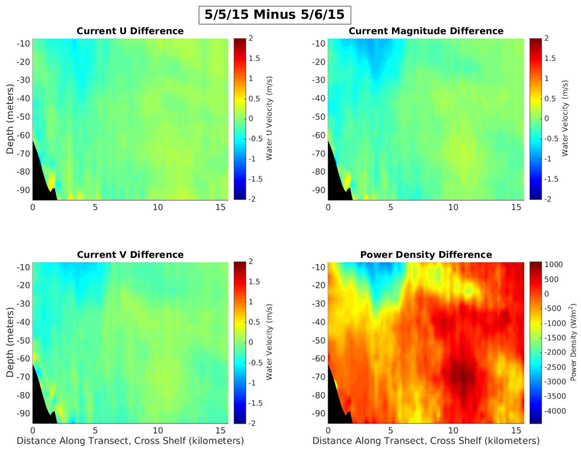

Figure 8: Difference between current measurements along the boat transect on consecutive days in U (east), V (north), magnitude, and power density.

C. HF Radar Surface Currents

A decade of coastal ocean radar surface current observations of the Gulf Stream off Cape Hatteras, NC have been collected that offer to provide key new insights into the temporal and spatial variability of the Gulf Stream position in this region. Historically, Gulf Stream variability in this area has been difficult to quantify because of the challenge involved in obtaining observations of consistent spatial and temporal resolution over long time periods.

The 5MHz radars that comprise the radar network in this area make hourly surface current measurements, in the top 2-3m of the water column, across the entire cyclonic shear zone on the landward edge of the Gulf Stream (figure). The radar provides more consistent observations of the Gulf Stream location over space and time than satellite Sea Surface Temperatures (SST's) because the radar estimations are not limited by cloud cover, observing frequency, and low temperature gradients between inshore water and the Gulf Stream typical in the summertime south of Cape Hatteras. There are limitations to the radar, however; drawbacks include the 6 km resolution, as compared to Advanced Very High Resolution Radiometer (AVHRR) satellite SST's that have 1.09 km resolution (http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html), and site specific challenges related to quantifying uncertainty in the radar measurements (Liu et al. 2010).

There are known quality control problems with the radar current measurements that are being addressed concurrently with the development of our Gulf Stream radar estimates. Despite these challenges, this data set is being analyzed by developing the algorithms so that the quality-controlled data can immediately improve estimations when available. Because of these limitations, a method to investigate Gulf Stream position variability using individual radars is being developed that focuses only on those regions of relatively consistent high quality measurements.

A single Codar measures the radial component of the ocean surface current relative to the radar in the top 2-3m of the water column. Radial currents are produced every hour. Each radial current vector is a three hour average, with the spatial resolution decreasing as a function of range from the radar. Each vector is a spatial average over an annulus bounded by a 5.85 km range difference, and five degree bearing separation. The radar range varies from 100 to 200 km. Range variation is due to environmental factors such as ionospheric interference from the radar signal reflection off the ionosphere, nonlocal interference, and variation in the ocean wave field reflecting the radar signal.

The Gulf Stream is apparent in the radial current coverage area in two zones (figure 8). The Gulf Stream enters from the south of the coverage area where it appears in the large negative current speeds moving toward the radar. The Gulf Stream exits the radar coverage to the northeast in the area of large positive radial current speeds. Between these two zones where the Gulf Stream is perpendicular to the radar signal, the radar cannot provide a good approximation of Gulf Stream location. This method determines the location of the shoreward edge of the Gulf Stream, and width of the cyclonic shear zone at two bearings from each radar site. Two bearings are selected: one from the region of coverage where the large negative current speeds indicate the Gulf Stream enters the radar coverage, the other from the region of large positive speeds where it exits (figure 1). Bearings are chosen within these two regions based on large radial velocities and consistency in coverage over the sampling period.

Along each bearing, the Gulf Stream landward edge location is estimated to be at the maximum gradient component of the averaged radial speeds (v_r), determined by taking the maximum of the absolute value of the derivative of the averaged speed with respect to range at a given bearing (Θ) (Eq.2), and inshore of the maximum radial current on that bearing.

$$G_r(\Theta) = |(\partial v_r/\partial r)|_{max} \qquad (2)$$

The maximum radial current is assumed to be the center of the Gulf Stream jet, and the distance between the maximum shear along that bearing and the maximum current speed is the determined width of the Gulf Stream cyclonic shear zone.

The four bearings (figure 9) used for estimating the Gulf Stream position are selected by averaging the radial speed over all ranges at each azimuth, and choosing two bearings where the maximum and minimum values occur most frequently over the sampling period and two more that are 15 degrees in the offshore direction from each. The latter two bearings were recently added to the algorithm to develop a method to determine Gulf Stream orientation.

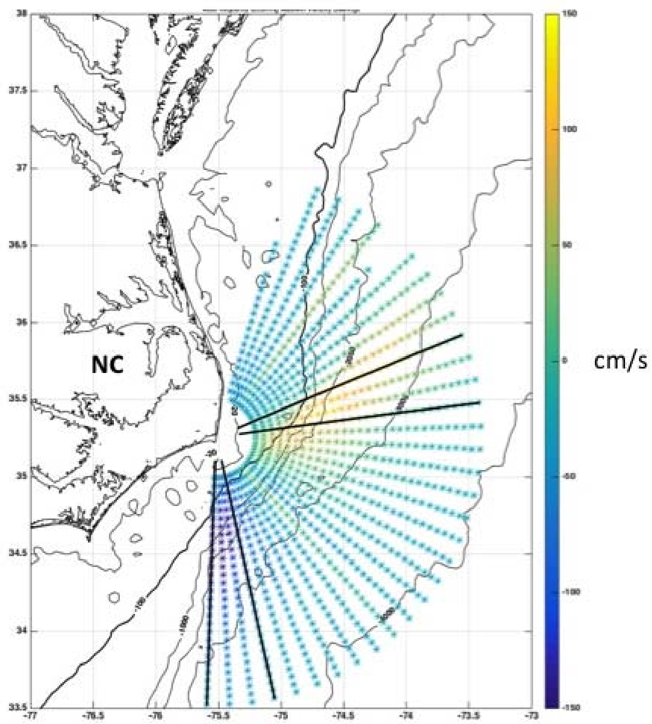

Figure 9: Averaged radial speeds from the Buxton, NC Codar from February 2014 with chosen 67 and 182 degree Gulf Stream analysis bearings in black. By convention, negative (cool) speeds are toward the radar and positive (hot) speeds are away.

The variability in distance to the gradient component and maximum (minimum) radial velocities appear correlated in this preliminary analysis. The average estimates of the cyclonic shear zone width from this method are 30.6 km along the 67-degree bearing, and 31.2 km along the 182-degree bearing (figure 10). Results from the Buxton, NC Codar system are highlighted here, but the algorithms are developed to also be applicable to the radial currents from the recently deployed radar on the Core Banks of North Carolina.

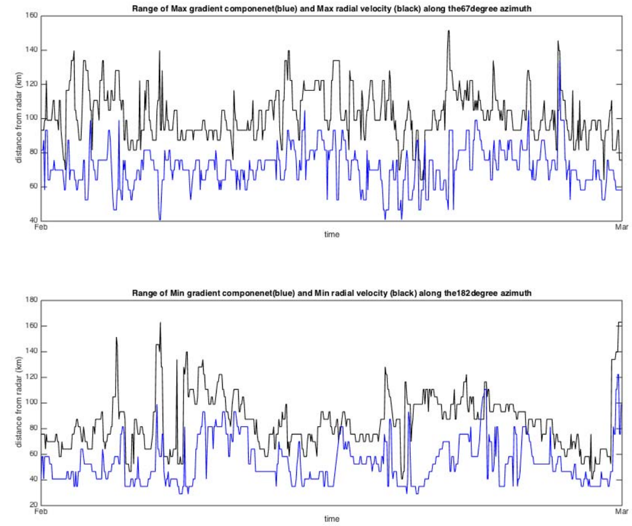

Figure 10: February 2014 maximim (minimum) gradient component distances from the radar are in black, and radial velocity maximum distances are in blue on the top (bottom) panel over the time period sampled.

The lower temporal limit of Gulf Stream position variability that can be resolved by the radar measurements is not yet clear, and requires further comparison with other methods that estimate Gulf Stream position.

The utility in determination of the edge with the radar lies in the nearly continuous temporal coverage, permitting assessment of front variability on time scales from hours to years, and the ability of the radar to detect the Gulf Stream landward edge when heavy cloud cover obstructs satellite imaging, or warmer inshore water temperatures render SST edge delineation inconclusive.

III. Preliminary Results and Model Comparisons

To date, model comparisons have been made with the first 9-month moored ADCP current measurements, and preliminary comparisons have been made between the model current estimates and boat transects observations.

Model and observed averaged current magnitudes from the ADCP mooring 75 m below the surface are nearly identical, both 0.94 m/s (figure 11).

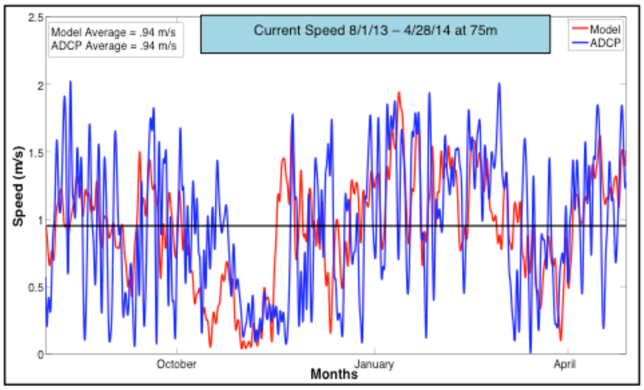

Figure 11: Model (red) and ADCP (blue) current speed comparisons at a depth of 75m over 9 months. Black line is the average for both over the time period.

Similar comparisons between the two at other depths over the time period also agree well. At 30 m below the surface for example, both average 1.15 m/s. The model speeds are slightly more conservative than the observations, thus the model underestimates the power density (1) at a given depth.

Preliminary comparisons between model current magnitude estimates and boat transect observations demonstrate the models' skill in predicting the approximate location of the stream. As with comparisons with moored ADCP currents, the model slightly underestimates the currents when compared with the boat observations (figure 12). Some of the difference between model and boat transects may be attributed to the models relatively coarse spatial resolution in both the water column and the local bathymetry.

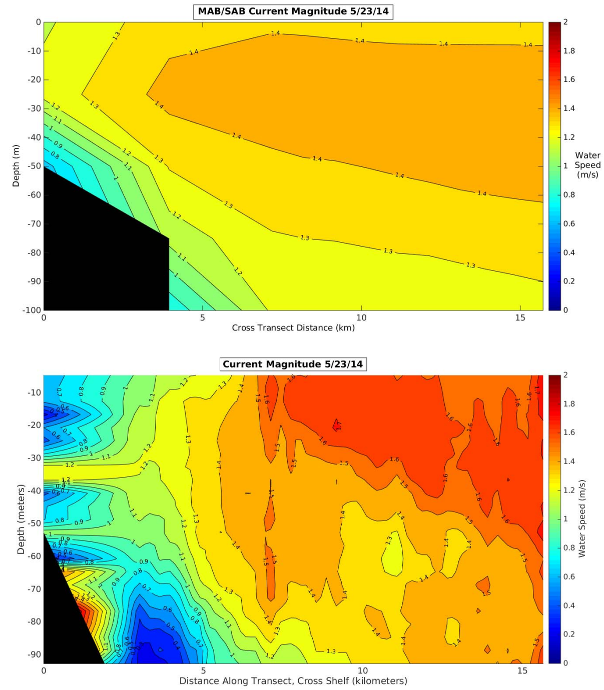

Figure 12: Model (top) and boat transect observations (bottom) current magnitude comparisons.

Although the model fails to capture the high frequency variability in magnitude and direction of the observations, favorable long-term average comparisons of the power density provide confidence in long-term model average power densities. Thus, the model was used to predict power density along three different cross-stream transects (figure 13), and over times when observations were not available (figure 14).

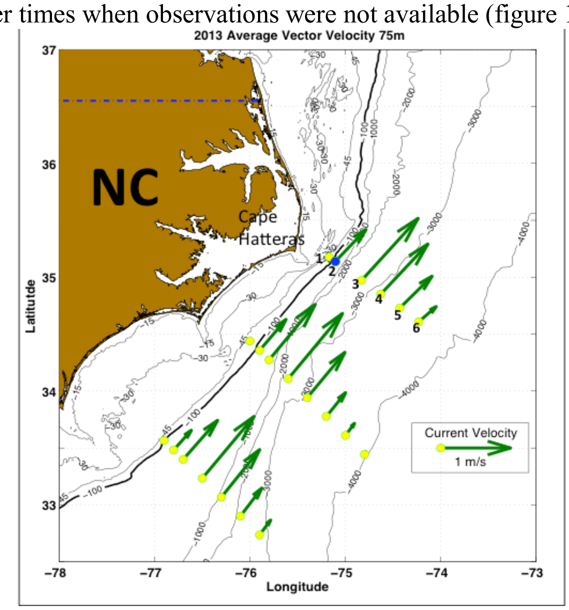

Figure 3: MAB/SAB averaged annual current speeds for 2013 along three different cross-stream transects 75m below the surface. Points are numbered along the northern 'CH' transect where model outputs were compared with available observations. Point 2 (blue) is the location of the ADCP mooring.

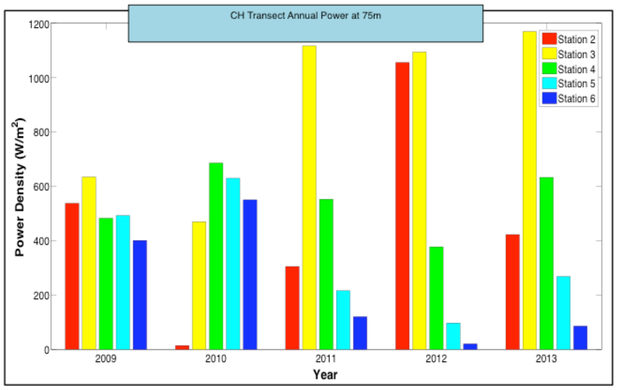

Figure 14: 5 years of power density model estimates at different locations along the northern most 'CH' transect in figure 11.

The model demonstrates large inter-annual variability, with power densities that vary by up to four times from year to year (figure 14).

The second ADCP mooring, deployed 7 km to the north east of the first and in water 35 meters deeper on 04/04/14 and recovered on 01/21/15, has provided long term current speeds and power densities not yet compared with model estimates. High frequency variability in the current speed and directions, counter flows, and long-term averages were similar to the first (figure 15).

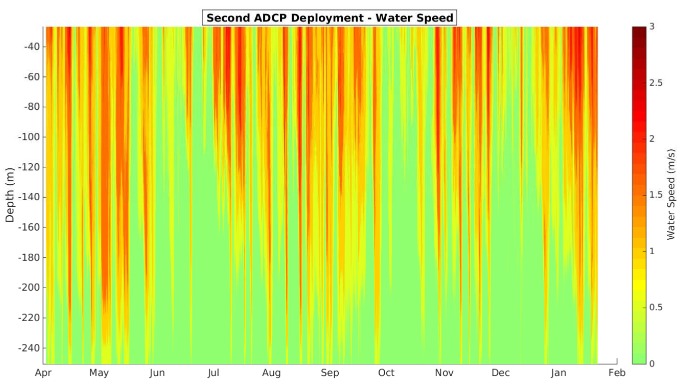

Figure 15: Current magnitudes from the second ADCP deployment over a period of ~9 months.

Averages over the entire deployment are:

Depth 30m: Avg. Velocity = 1.2349 m/s
Avg. Power Density = 1625.6 W/m^2

Depth 50m: Avg. Velocity = 1.1658 m/s
Avg. Power Density = 1400.8 W/m^2

Depth 75m: Avg. Velocity = 1.0552 m/s
Avg. Power Density = 1109.1 W/m^2

IV. Future Efforts

Several efforts to improve and expand model estimates and observations of the Gulf Stream MHK energy resource are ongoing. Boat transects will be expanded in 2015/2016 to include the entire Gulf Stream jet to depths of 400m below the surface, rather than just the top 100m within the cyclonic shear zone. Moored ADCP observations are continuing at the same location, providing better estimates of longer-term variability.

Radar estimates of variability in stream position are being compared with ADCP measurements from this work, as well as other frontal estimates like Navy Gulf Stream Frontal Charts available bi-daily (http://www.opc.ncep.noaa.gov/sst/NavyFeatures.shtml) to estimate accuracy. Quality control efforts are beginning to provide better surface current measurements and eliminate spurious vectors from consideration. Favorable comparisons between radar surface currents and ADCP observations will demonstrate the ability to infer the available resource based on surface current observations alone, based on the remarkably consistent Gulf Stream structure at a given latitude (Halkin and Rossby 1985).

Efforts to assimilate all of the observations into the MABSAB model are beginning this year. The model will also add the ability to make Gulf Stream forecasts.

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