# Gulf Stream Marine Hydrokinetic Energy Resource Characterization off Cape Hatteras, North Carolina

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The Gulf Stream off North Carolina has current velocities that approach 3 m/s and an average volume transport between 65 (Johns et al 1995) and 90 Sv (1 Sv =1 x $10^6$ $m^3/s$) (Hogg 1991) off of Cape Hatteras, making it the most abundant MHK (Marine Hydrokinetic Energy) resource for the state. Gulf Stream transport increases from about 33.5 Sv through the Florida Straits to a maximum of about 150 Sv off of Nova Scotia (Richardson 1985, Halkin and Rossby 1985). A downstream long-shore pressure gradient exists that may contribute to the increase in flow (Fofonoff 1981), or is perhaps a dynamic outcome of the increase.

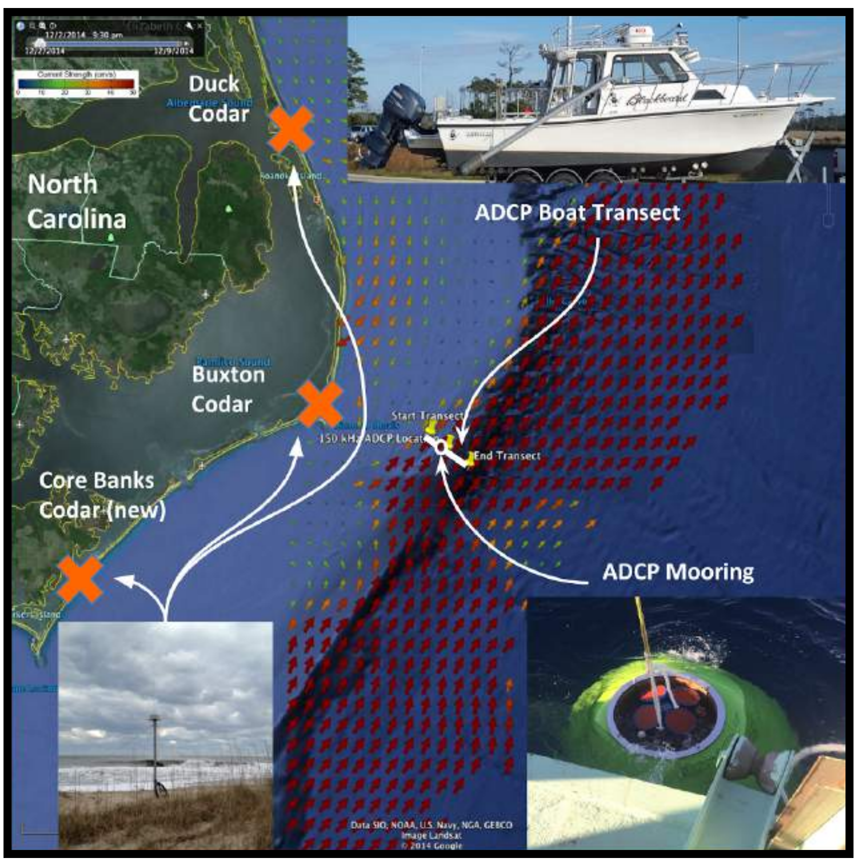


Figure 1: *The map indicates the location of the three types of observing systems used to make current measurements. Orange 'X' marks are the locations of the 3 land-based HF radars used to measure surface currents shown in the background vector field. The yellow push pins denote the beginning of the boat transect, moored ADCP location, and end of the boat transect respectively.*

Resource availability at a specific location depends primarily on the variability in Gulf Stream position, which is least offshore of Cape Hatteras after the stream exits the Florida Straits (Miller 1994). Proximity to land, high current velocities, and relatively shallow waters abutting a steep shelf slope that places vorticity constraints on Gulf Stream position variability make this an optimal location to quantify the MHK energy resource for NC.

Three different types of observations inform the Gulf Stream MHK estimates (Figure 1). A 150 kHz ADCP (Acoustic Doppler Current Profiler) located on the 230m isobath since August of 2013 off the coast of Cape Hatteras continues to provide current measurements over nearly the entire water column every 10 minutes with 4 meter resolution. A 300 kHz vessel mounted ADCP measures currents along a cross isobath transect in the top 100 meters of the water column. The transect extends from inshore at the 100 m isobath, offshore across the mooring location to the 1000m isobath.

The vessel current measurements provide an estimate of resource variability with water depth, and will soon be extended across the Gulf Stream jet. The 5 MHz Codar HF radars measure surface currents in the top 3m of the water column with 6 square km resolution. The radar surface current measurements provide essential consistent hourly estimates of Gulf Stream position.

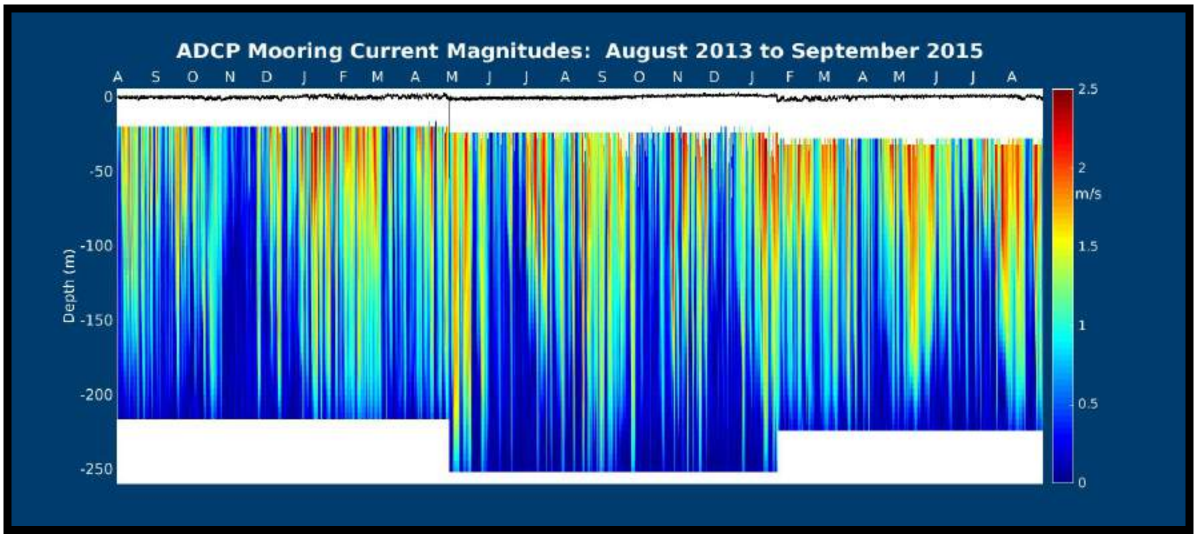


**Figure 2:** ***Current magnitudes above the moored ADCP location from August 2013 to September 2015.***

Two years (Figure 2) of continuous current measurements beginning in August of 2013 from the 150 kHz ADCP at anticipated optimal location (35.1393° N, 75.1056° W) based on aforementioned practical constraints for energy extraction quantify the available energy resource and its variability at the mooring location, and establish the skill of a Mid Atlantic Bight and South Atlantic Bight Regional Ocean Modeling System (MAB/SAB ROMS) in predicting the available MHK energy there.

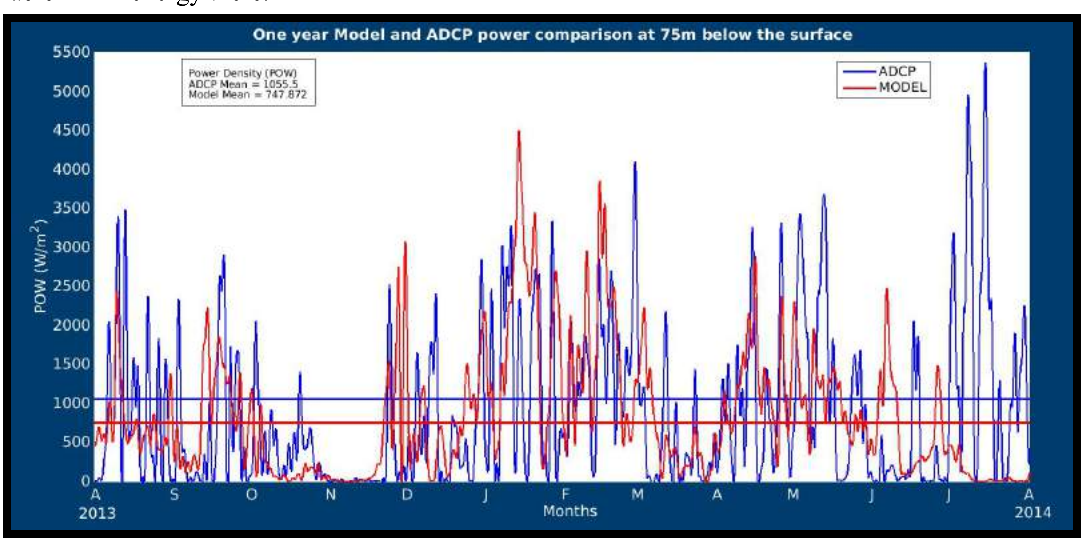


**Figure 3:** ***The model power density (red) and mooring observed power density (blue) at an assumed hub depth of 75m over a period of one year, with corresponding averages for each over the time period***

The MAB/SAB ROMS is a free surface, terrain-following, primitive-equation ocean model. Model horizontal resolution is 2km. The model is nested in the HYCOM/NCODA 1/12 degree global data assimilative model, with M2 tidal forcing derived from ADCIRC (Gong et al. 2015). Presently, model comparisons have been made with the moored ADCP measurements only. The model slightly underestimates long-term observed average power densities derived from the current magnitudes at an assumed 75-meter hub depth (Figure 3), and does not capture all of the higher frequency fluctuations seen in the observations, possibly due to the interpolated bathymetry of the model that levels the actual steepness of the shelf slope in the ADCP area. Comparisons between the model and moored ADCP currents, and power density during the first year of observations demonstrate significant intraannual variability. Annual current magnitude and direction averages over the same time period also demonstrate slightly higher variability in the observations, with higher inshore more northerly currents than the model (Figure 3).

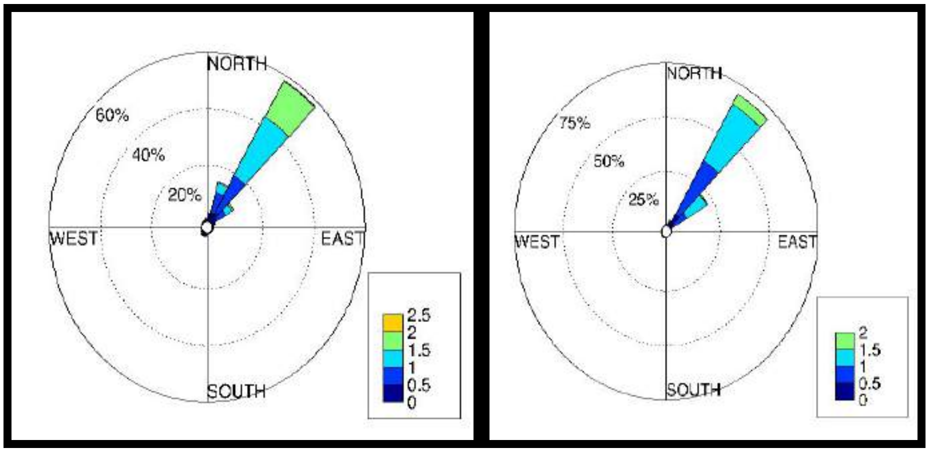


*Figure 4: Current roses for observed (left) and modeled (right) currents averaged from August 2013 until August 2014 at 75m below the surface.*

Shipboard 300 kHz ADCP cross-stream transects and hourly surface currents measurements off Cape Hatteras from a network of land based HF (high frequency) radars further inform MHK power estimates and variability. Model comparisons and assimilation capabilities are currently being developed for vessel measurements.

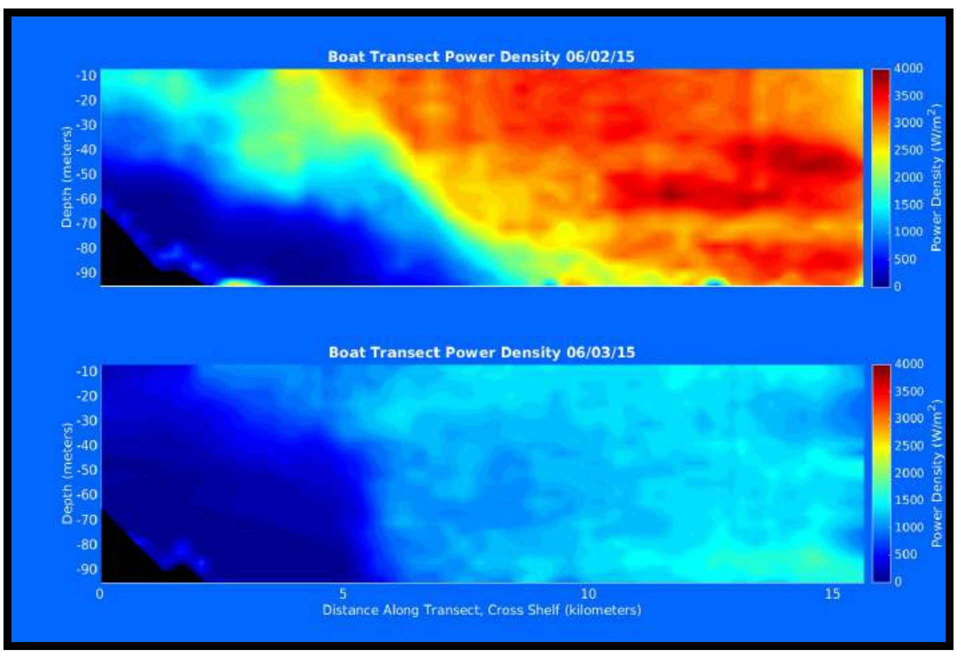


*Figure 5: Power density estimates derived directly from vessel current measurements in the top 100m of the water column on two consecutive days, with distance along transect coinciding with the 100m isobath at 0 km, and proceeding offshore to the 1000m isobath at 15 km.*

Cross-stream transects made from the vessel measure currents in the top 100m of the water column with 4m resolution from the 100m isobath to the 1000 m isobath (Figure 1). The vessel transect is approximately cross stream within the Gulf Stream cyclonic shear zone. Large variability in power density along the transect has been measured in time periods as short as 24 hours (Figure 5).

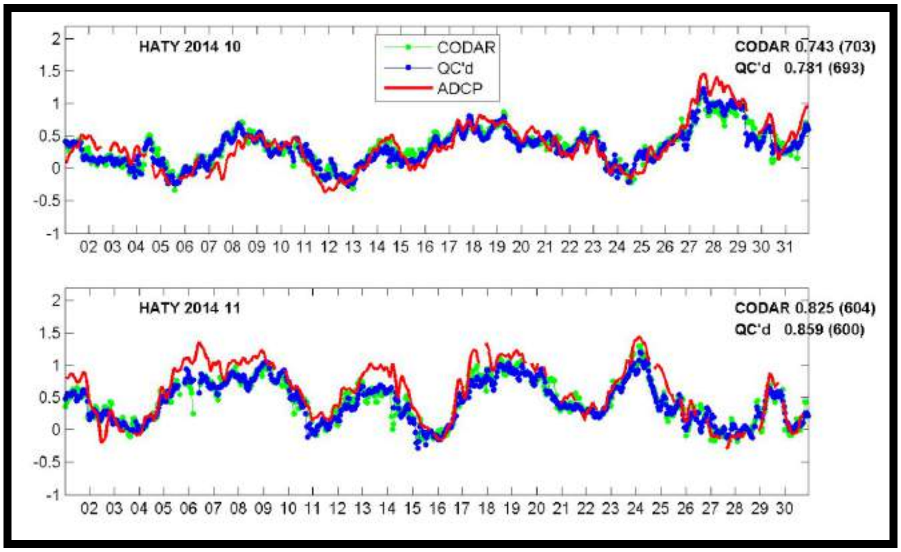


**Figure 6: Comparison of the current magnitudes for the top measurement bin of the moored ADCP and the HF radar measurements for October and November of 2014. Radar vendor software produced currents are green, our QC software currents are blue, and ADCP currents 40m below the surface are in red.**

The land based HF radars provide essential consistent hourly information about the location of the Gulf Stream. Consistent high frequency estimates of Gulf Stream location are essential because the variability in MHK resource at a given location depends primarily on the stream position There are known problems with the radar surface current measurement quality controls, and several site specific challenges related to quantifying uncertainty in radar measurements (Liu et al. 2010). Significant effort has been made to improve the quality of the radar surface current measurements off of Cape Hatteras, beginning with improvements to the radial (relative to the radar) surface current measurements made from individual radars (figure 7). The radar surface currents in the top 2-3 meters compare favorably to the top bin, 40m below the surface, of the ADCP current measurements within the radar footprint . Our quality control processing further improves the ADCP comparison from the radar vendor software produced currents (figure 6).

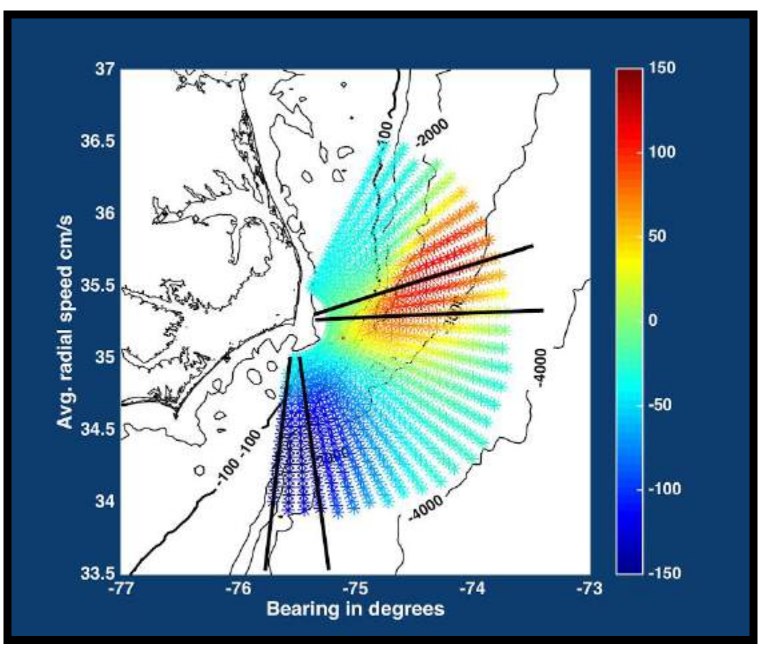


**Figure 7: Hatteras HF radar map showing averaged radial current velocity magnitudes for October and November of 2014. Black lines indicate chosen bearings for Gulf Stream location analysis.**

Using these improved quality controlled currents, a method to determine the location of the landward Gulf Stream edge using the maximum shear and maximum velocity of the radar surface currents is being developed. Using an individual radar, 4 bearings are chosen that consistently lie within the radar's Gulf Stream coverage over a chosen time period for analysis - October and November of 2014 are shown(Figure 7). At each of the four selected bearings, an hourly estimate of the location of the Gulf Stream cyclonic shear zone is made by selecting the largest change in radial current over all ranges, and the largest radial current speed.

To evaluate the efficacy of this method, comparisons are made with landward Gulf Stream edge estimates from available satellite SST (sea surface temperature) images. High quality SST images, those not impeded by significant cloud cover, are green, moderately good images are yellow, and poor images are red (figure 8).

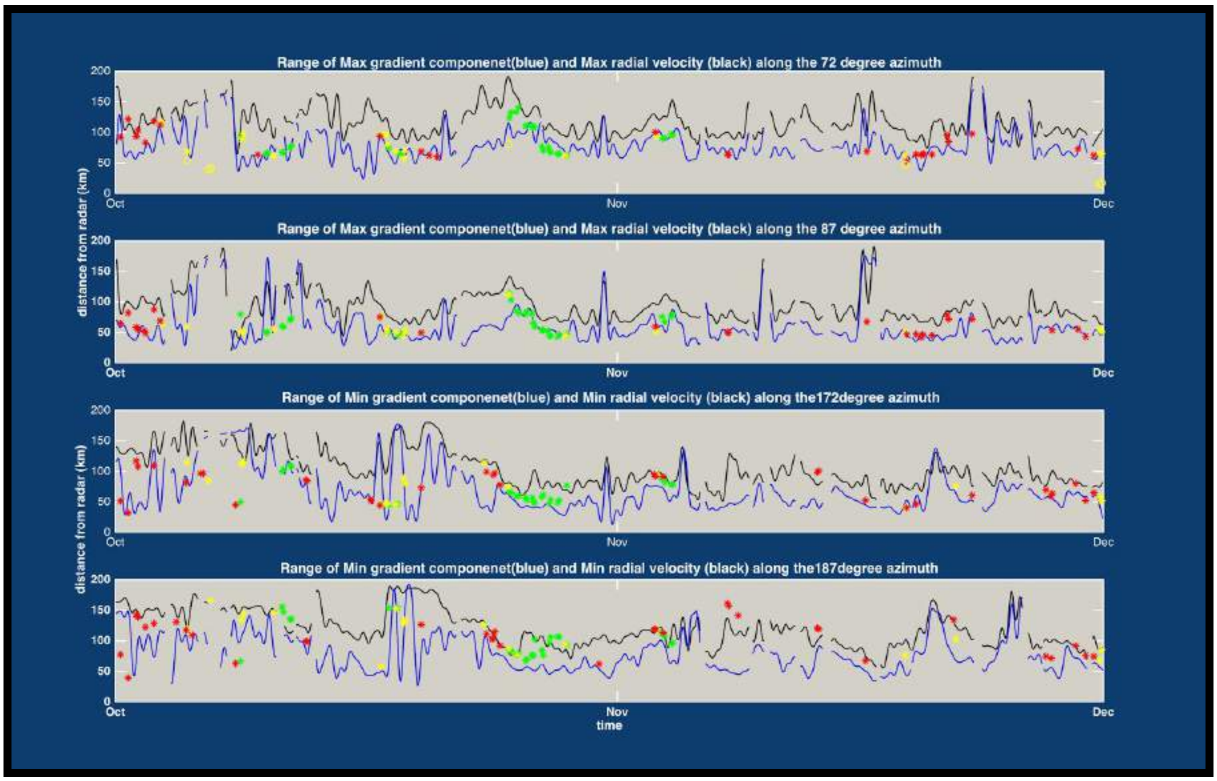


**Figure 8:** ***Method to determine the Gulf Stream distance from the Buxton radar installation along four bearings with consistent GS coverage: distances from the radar to the maximum shear in the measured surface currents (blue) and maximum surface currents (black) provides a consistent hourly estimate of Gulf Stream location variability that is compared to available SST estimates of GS edge. SST images are ranked from 'green' for good, to 'red' for poor images.***

Presently, our group has made three years of observations from a moored ADCP, shipboard ADCP transects, and from land based coastal ocean radars. Using these observations, we have begun to quantify the skill of a regional MAB/SAB ROMS model in making MHK energy estimates of the Gulf Stream for NC. We have also demonstrated improved quality control of surface current measurements from a NC HF radar network, and have begun to evaluate a novel method of observing hourly Gulf Stream variability off of NC using the radars. Future work will include further comparisons between observations, and observation assimilation into the MAB/SAB ROMS model.

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