Gulf Stream marine hydrokinetic energy resource characterization off Cape Hatteras, North Carolina USA

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Abstract **-**The Gulf Stream off North Carolina (NC), USA has current velocities that approach 2 ms^{-1} and average volume transports of 90 Sv (1 Sv= 10^6 m^3s^{-1}) off of Cape Hatteras, making it the most abundant MHK (Marine Hydrokinetic Energy) resource for the state. Resource availability at a specified location depends primarily on the variability in Gulf Stream position, which is least offshore of Cape Hatteras after the stream exits the Florida Straits. Proximity to land and high current velocities in relatively shallow waters on the shelf slope make this an optimal location to quantify the MHK energy resource for NC. Multi-years of consistent current measurements beginning in August of 2013 from a moored 150 kHz ADCP at an optimal location for energy extraction quantify the available energy resource and its variability, and establish the skill of a regional ocean circulation model in predicting the MHK energy resource. The model agrees well with long term observed current averages and weekly to monthly fluctuations in the currents. Comparisons between the model and ADCP observed currents, and power density demonstrate the significant inter-annual variability in the Gulf Stream power density.

Keywords- Gulf Stream, marine hydrokinetic energy, North Carolina, U.S.A.

I. Introduction

The ocean offers significant potential for electrical power generation from strong ocean currents. Wise use of such renewable ocean energy can effectively and economically fulfill part of our regional energy needs, reduce national dependence on non-renewable energy sources, and help create jobs and economic opportunities. The Gulf Stream off North Carolina has current velocities that approach 2 ms^{-1} and average volume transports of 90 Sv (1 Sv= 10^6 m^3s^{-1}) off of Cape Hatteras, making it the most abundant MHK (Marine Hydrokinetic Energy) resource for the state [1]. Resource availability at a specified location depends primarily on the variability in Gulf Stream position, which is least offshore of Cape Hatteras after the stream exits the Florida Straits. Proximity to land and high current velocities in relatively shallow waters on the shelf slope make this an optimal location to quantify the MHK energy resource for NC.

Our efforts are to develop an Integrated Observing-Modeling Prediction and Assessment System to support ocean hydrokinetic energy assessment off North Carolina. We are producing the best available quantitative descriptions of numerous aspects of the ocean environment that relate to power generation in the Gulf Stream along the NC continental slope and outer continental shelf. In addition to calculating the power levels in the Stream, we continue gathering information that will be helpful in engineering design, environmental assessment, and developing an improved understanding of the character and causes of the current variability in this region. This last topic will be especially valuable in model predictions that are necessary for emplacement and operations of submarine power generating machinery.

Ultimately, we will use this well-calibrated model to estimate energy flux along a cross-isobath transect that crosses the moored ADCP deployment site east of Cape Hatteras. Using that, available power estimates for various depths on that transect will be made, in order to provide a resource estimate that is corroborated by observations made in that location. Our findings will provide critical information about energy at other locations as well, and about variability and predictability of the Gulf Stream current.

II. Results

To date, our team has made substantial progress in developing a combined modeling-observational prediction system to guide the optimal development of ocean energy extraction from the Gulf Stream off the coast of North Carolina. Model development was conducted at NC State [2, 3]. To inform the model, the UNC Coastal Studies Institute expanded upon regional oceanographic observations to provide crucial Acoustic Doppler

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Current Profiler (ADCP) data to validate and refine a high-resolution ocean circulation model. This ocean model filled data gaps and provided temporally- and spatially-continuous, four-dimensional (*x*, *y*, *z*, *t*) circulation fields, which supported the analysis of the Gulf Stream's energy generation potential (including the magnitude of energy available and its variations in time and from location to location) that UNC-CH have focused on.

The modeling system that we have been developing for ocean current and power estimation continued to be improved. UNC-CSI has made important and useful new current measurements, and we have used these measurements for improved and extend-in-time model validations and power generation estimations. The value of these new observations can hardly be overestimated. They are crucial in knowing what the real-world hydrokinetic energy resource is in the Gulf Stream off North Carolina. A similar sentiment applies to the capability of the ocean circulation model, which provides power generation information over a larger geographical region and longer time frame than do the direct current observations.

The area of interest is shown in Figure 1. The green arrows are average current velocities at 75 meters below the surface for 2014, computed by the NCSU circulation model for several stations (yellow dots) along each of three cross-isobath transects. The blue cot has both model-computed and ADCP-measured current vectors, which overlie so well they cannot easily be distinguished from each other. The jet-like flow of the Gulf Stream is apparent.

Figure 2 shows the current speed at 75 meters measured by the ADCP and computed by the model for all of 2014. The ADCP annual-average speed is 1.03 m s^{-1}, which is close to the model's annual-average speed of 1.09 m s^{-1} (6% greater than the ADCP average speed). Although these averages are relatively close to each other, it is apparent that the speed fluctuations in the two time series that have several-day periods (due primarily to Gulf Stream meanders) are not in phase and are of generally differing amplitudes.

More slowly varying speed fluctuations, with periods longer than 21 days, also occur. These are due to large-scale, lateral shifts in the Gulf Stream's path. The speed changes at the ADCP site can be seen when the shorter-period fluctuations are filtered out of the time series. Figure 3 shows a comparison between the ADCP-observed and modeled speeds with fluctuation periods greater than 21 days. This comparison is quite good, with essentially every significant fluctuation appearing in both time series. Even so, some of the peaks in the ADCP and model speeds coincide but are of different magnitudes in amplitude, while other shared peaks in the ADCP and model speeds are comparable in magnitude but somewhat out of phase with each other. We are presently investigating the causes for the model-ADCP differences in amplitudes and phases between these longer period fluctuations (Figure 3), as well as the differences in the speed variations caused by the Gulf Stream meanders (Figure 2).

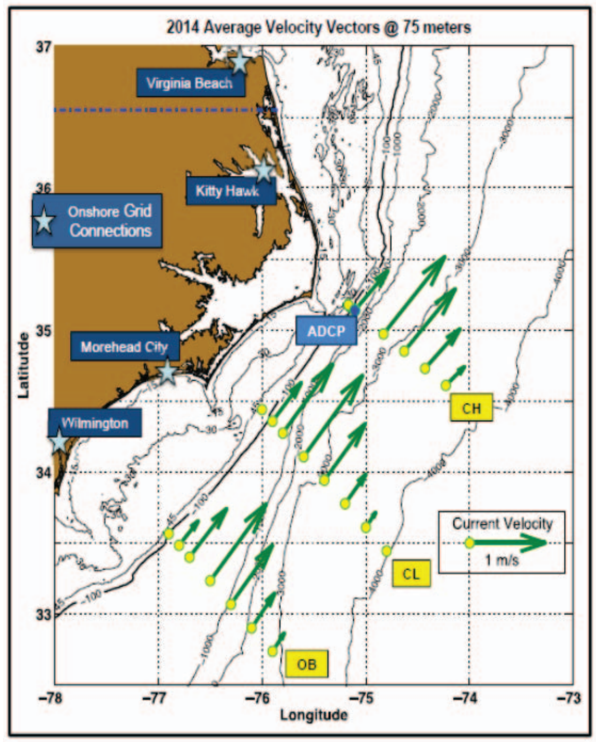


Figure 1. Average current velocities at 75 m during 2014 (green arrows). Stations along three cross-isobath transects (from north to south: Cape Hatteras, Cape Lookout, Onslow Bay) are shown by yellow dots. Both model and ADCP-observed velocity vectors are shown at the blue dot. Black contour lines are isobaths (meters), with the 100 m isobath in bold. The four blue stars show the locations of the cities Virginia Beach, Kitty Hawk, Morehead City, and Wilmington, which are present locations where onshore connections can be made to the power grid.

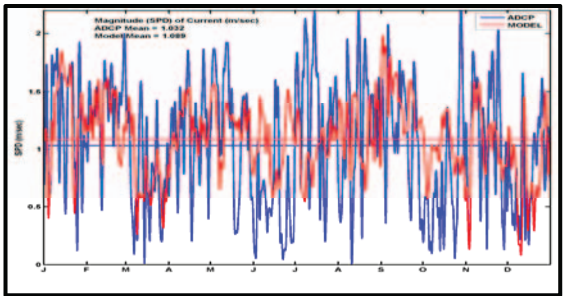


Figure 2. Time series of the current speed at 75 m for 2014. Model speeds are shown in red and moored ADCP speeds in blue. The red horizontal bar shows the model speed average of 1.03 m s^{-1}, and the blue bar shows the ADCP average speed of 1.09 m s^{-1}.

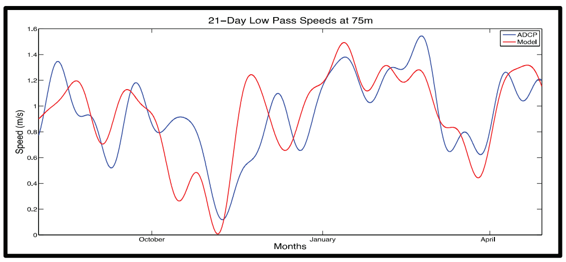


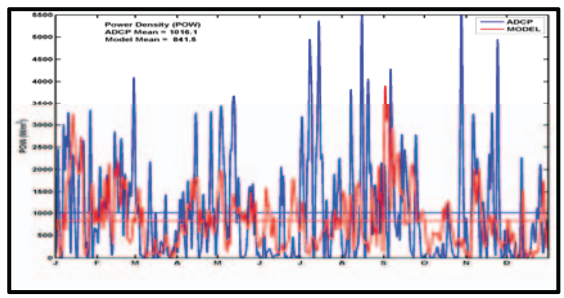
Figure 3. Current speed time series from the moored ADCP and from the model. The time period is from August 1, 2013 through April 28, 2014 at 75 meters below the surface. The ADCP is the blue time series and the model is the red. A 21-day low-pass filter has been applied to the speeds to remove fluctuations with periods of three weeks and shorter. Some of the peaks in the ADCP and model coincide but are of different magnitudes in amplitude, while other shared peaks in the ADCP and model are comparable in magnitude but somewhat out of phase with each other.

The power in an ocean current is usually and usefully reported in terms of power density, POW, which is computed from the current speed, S, as follows:

$$\mathrm{POW} = \frac{1}{2}\rho S^3$$

where ρ is the density of the ocean water (around 1,025 kg m^{-3} for near-surface Gulf Stream water). POW has units of W m^{-2}. It is apparent from this equation that POW at 75 meters below the surface at the ADCP site will vary with time, since the speed varies at that level as we have shown above. Time series of POW computed from the ADCP-observed speed and the model-computed speed during 2014 are shown in Figure 4. POW varies significantly due to Gulf Stream meanders (fluctuation periods around a week) and also due to Gulf Stream path shifts (fluctuation periods longer than 21 days). Meander-related POW fluctuations can be seen throughout the year. Clear examples of path-shift-related POW fluctuations can be seen in March and in October, when the power density was quite low for most of each of those months.

The actual power that is extracted from the site with a moored submarine turbine-driven generator will depend on the efficiency of the turbine /generator /mooring design and the design of the turbine array, if there is more than one turbine installed in the ocean. Published studies suggest that around 40% of the power in the ocean current is the maximum that is reasonable to expect.



III.

Figure 4. Time series of power density (POW) at 75 meters below the surface at the moored ADCP site for 2014, computed from moored ADCP data and from model computed currents. Model POW is shown in red and moored ADCP POW is in blue. The red horizontal bar shows the model's annual-average power density of 842 W m^{-2}, and the blue bar shows the ADCP's annual-average power density of 1016 W m^{-2}.

III. Summary

Substantial progress in developing a combined modeling-observational prediction system to guide the optimal development of ocean energy extraction from the Gulf Stream off the coast of North Carolina has been mad. Our research findings and observational and modeling products feed directly to another research that focuses on the economical assessment of utility-scale investment in ocean current energy off North Carolina. Together, we provide key scientific justifications and feasibility analyses for the State to make decisions about economic development related to renewable ocean energy.

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