A Measurement Based Analysis of the Hydrokinetic Energy in the Gulf Stream

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ABSTRACT

This study uses ocean current measurements made off the East Coast of the US to evaluate the ocean current based electricity production potential in the Gulf Stream. Drifter data from the World Ocean Circulation Experiment are used to map the energy density from South Florida to North Carolina, showing that the most energy dense areas exist off the east coast of Central Florida. Bottom and vessel mounted ADCP measurements are used to conduct a more detailed study near 26°N and 27°N respectively. These results quantify the energy profiles in these regions suggesting that 54% more energy dense currents are available at 27°N than at 26°N.

KEY WORDS: Resource, assessment, hydrokinetic, ocean, energy, Gulf Stream.

INTRODUCTION

The world demand for electric power is increasing every day, due to the economic and population growth of humanity. The International Energy Agency (IEA) released a study predicting that the world demand for energy will increase by 37% by 2040 (IEA, 2014). To satisfy this need for increased power production both traditional and renewable forms of energy are being pursued. The western boundaries of the world's ocean offer renewable energy (VanZwieten *et al.*, 2013). The power density at a depth of 50 m is shown in Figure 1 calculated using the Hybrid Coordinate Ocean Model (HYCOM) (VanZwieten *et al.*, 2013). While HYCOM numerical model has shown to be significantly under predicting the average energy density in several areas (VanZwieten *et al.*, 2014), it is still valuable for visualizing regions contain ocean current resource.

To produce electricity from ocean currents, devices that can convert the hydrokinetic power in these currents to electrical power are being developed and tested (DOE, 2015). It has been calculated that on average about 19GW of electrical power generation is technically feasible from ocean currents located in US waters off the east coast of the United States (Georgia Tech., 2013). This is equivalent to 4.07% of the 467.24 GW of electricity consumed in the U.S. during the year of 2014 (EIA, 2015). The US electricity need is expected to grow. In the year of 2013 the total electricity consumption was 3.836 billion kWh, and it is predicted to increase to 4.797 billion kWh in 2040 (EIA, 2015).

This paper focuses on providing a purely measurement based analysis of the ocean current resources of US east coast, with a focus on SE

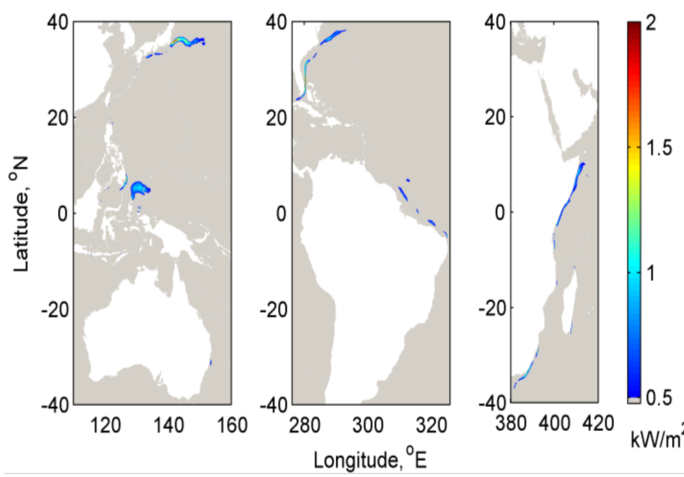

Figure 1: HYCOM-calculated area with Time-averaged power densities greater than 0.5kW/m^2 at 50 m depth (2009-2011) for the western boundary of the Pacific (left), Atlantic (center), and Indian (right) oceans.

Florida. Ocean current velocities measured by drifters that are part of the World Ocean Circulation Experiment (WOCE) are used to map the energy density of surface currents from South Florida to North Carolina. After this, ADCP data are used to assess the energy potential at approximately the northern and southern ends of the primary area being considered for ocean current energy extraction off Florida. Vessel mounted ADCP measurements are used to assess the ocean current resource throughout the water column at 27°N with bottom mounted ADCP data being used to assess the resource near 26°N between Florida's East Coast and the Bahama Islands (Figure 7).

SEA SURFACE CURRENT ENERGY

To explore and collect ocean sea surface data a global network of drifters was deployed as part of the WOCE. These data have been collected since 1990 and are publically available on the Fisheries and Oceans Canada website (Fisheries and Oceans Canada, 2015).

Drifter Data

Drifter data collected by the WOCE include the following sea surface characteristics along the drifter's path: temperature, latitude, longitude, east component of current, north component of current, and the year, month, day, hour and minute at which the specific data was gathered. The Surface Velocity Program (SVP) drifters used in this study are made up of a spherical surface buoy that maintain their shape even in high-shear flow. Data from two sizes of SVP drifters are available; the original size weighs 45 kg and the 'mini' size weighs 20 kg. The SVP drifters contain 4 to 5 packs of 7 to 9 alkaline D-cell batteries, a transmitter, a thermistor, a submergence sensor or a tether sensor to verify the presence of the drogue. The average life of a SVP drifter is 400 days, which is typically limited by battery life. Additionally, drifters sometimes lose their drogue shoot or are picked up by fishermen (Lumpkin *et al.*, 2010).

These drifters utilize the satellite based system called ARGOS to identify the drifters' location. SVP drifters transmit periodic messages every 90 to 200 seconds (the transmission of each message takes less than one second), with the position of the drifter computed based on the Doppler Effect (CLS, 2014). The drifter location is calculated by ARGOS using one of the following two methods: 1) The Least Square Analysis or (2) The Kalman Filtering Method.

In case the satellite receives four or more messages from the transmitter, the Least Square Analysis begins. First the platform (drifter) position is initially estimated by computing the 1st and 2nd message collected through a single satellite pass. From these two messages, two cones with the terrestrial radius plus the height of the transmitter gives two possible locations. The location with minimal residual error is chosen. However, if only a single transmission is received a Kalman Filtering Method is utilized that accounts for the platform dynamics. This filter first predicts the platform position based on the previous position and a movement model and then estimates error using frequency measurements acquired during the satellite pass (CLS, 2011). The Global Drifter Program is responsible for the availability of the collected drifter data.

This study utilized each year of data that was publicly available on the WOCE database, those from 1990-2011 (Fisheries and Ocean Canada, 2015). Drifter data utilized in this study include latitude, longitude, and near surface current velocity; which are available at six hour increments. The six hour time intervals stem from the raw data being interpolated to uniform six hours intervals through the interpolation procedure known as Kriging (Fisheries and Ocean Canada, 2015). This methodology was applied as detailed by Hansen and Poulain (1995) for the 1-dimensional time series data including latitude, longitude, surface current velocity and sea surface temperature. Drifter location (latitude and longitude) is calculated according to

$$x_0^* = \sum_{i=1}^{n} w_i\, x_i \ , \quad (1)$$

where x_i are the values observed by the WOCE and w_i is a weighting factor calculated to minimize the mean-square difference between the true values and their estimates at the interpolation points.

The error associated with this approach is quantified using the Kriging variance (σ_k^2), which is calculated according to:

$$\sigma_k^2 \ = \ \sum_{i=1}^{n} w_i S_{0i} + \ \lambda \ , \quad (2)$$

where S_{0i} is the structure function for error-free data for the interpolation point (x_0) relative to the observed value (x_i), and λ is a constrain of a Lagrange multiplier, this constrain assures that the estimated values are unbiased in the mean, that is,

$$\langle(x_0 - \ x_0^*)\rangle. \quad (3)$$

Data Processing

The data processing techniques in these sections utilizes the publically available drifter data presented in the previous section as inputs, including: the location (latitude and longitude) and velocity (north and east vector components). These are used to calculate the Kinetic Energy Flux (KEF) at the sea surface for each data point according to:

$$\mathrm{P} \ = \tfrac{1}{2}\rho\left[\dot{\mathrm{N}}^2 + \dot{\mathrm{E}}^2\right]^{1.5} , \quad (4)$$

where P is the kinetic energy flux, ρ is the density of seawater (1030 kg/m^3), $\dot{\mathrm{N}}$ is the north component current velocity, and $\dot{\mathrm{E}}$ is the east component of the current velocity.

To calculate the average kinetic energy flux these data are averaged based on measured location into a rectangular grid. This grid is fixed to increments of latitude and longitude according to:

$$Lat(\mathrm{i}) = Lat_{min} + i \cdot \delta Lat|_{i=0}^{N-1} \ , \quad (5)$$

$$Lon(\mathrm{j}) = Lon_{min} + j \cdot \delta Lon|_{j=0}^{M-1} \ , \quad (6)$$

where i is the latitude block number, $Lat(i)$ is the latitude block, Lat_{min} is the minimum latitude considered, δLat is the utilized latitude step size, j is the longitude block number, $Lon(i)$ is the longitude block, Lon_{min} is the minimum longitude being considered, and δLon is the utilized longitude step size. The average power in each block defined by each latitude/longitude combination above is calculated using the following logic:

$\delta^{ij}(k) = 1$ of both of the following are true: (7)

$$|Lat(k) - Lat(i)| < \frac{\delta Lat}{2}$$

$$|Lon(k) - Lon(j)| < \frac{\delta Lon}{2}$$

$\delta^{ij}(k) = 0$ otherwise,

and then

$$P_{avg}(i,j) = \frac{\sum_{k=1}^{K} P(k)\delta^{ij}(k)}{\sum_{k=1}^{K} \delta^{ij}(k)} \ , \quad (8)$$

where k is a counter that sequentially calls all K available data points and $P_{avg}(i,j)$ is set to zero if no data points are available in the evaluated block.

For the calculations in this paper the following values were selected:

$Lat_{min} = 25$, $\delta Lat = 0.4$, $N = 31$, Lon_{min} = -83, δLon = 0.15, M = 61. The corresponding latitude range is therefore from 25°N to 37°N and the longitude range is from -83°E to -72°E. These values were selected to span the area off the east coast of the US from Southeast Florida through North Carolina.

Results

Utilizing the data processing approach described above the average KEF density is mapped off the SE coast of the US (Figure 2). In this figure the white areas represent land that includes the Southeast US and Bahama islands. It is noted that approximately 50 drifter measurements utilized in each grid block to calculate the average water velocity results in somewhat noise results, two contour lines represent depths of 200 m and 500 m; it is interesting to observe that the areas of maximum kinetic energy flux are located approximately along the 500 m contour off Florida and Georgia, but primarily slightly offshore from the 500 m contour off South and North Carolina. Figure 2 suggests that the most energy dense currents exist between latitudes about of 26°12' N to 31°48' N along Florida's East coast where average KEF are greater than 2.0 kW/m^2. Figure 2 also indicates that an average KEF greater than 2.0 kW/m^2 exists off Cape Hatteras, North Carolina, at latitudes ranging from 35°00' N to 36°12' N.

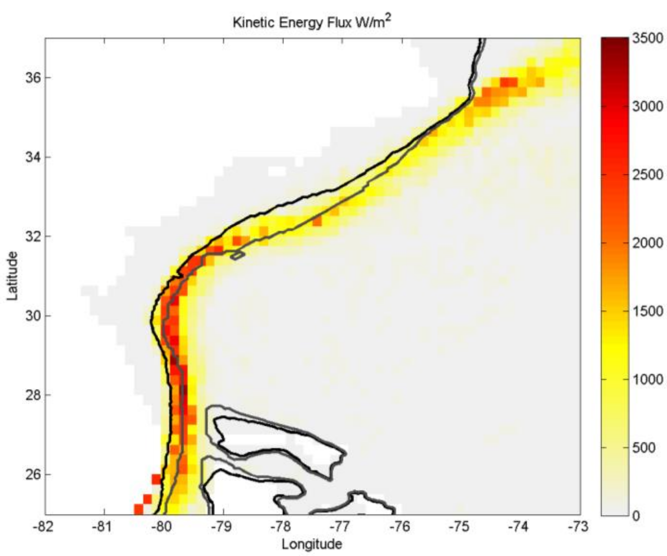

Figure 2: Average KEF calculated from drifter data in W/m^2. Contour lines are at 200m and 500m water depth.

Along the entire U.S. Southeast coast there is a flow of kinetic energy varying between 1.0 kW/m^2 and 3.5 kW/m^2. Off Florida's coast, for analysis purpose, two areas are highlighted for containing an average KEF that exceeds 3.0 kW/m^2. One site is located at 27°48' N and 79°45' W, approximately 65 km from offshore in about 400 m of water (Figure 3-Left). The second site is located farther north at 29°24' N and 79°54' W, which is approximately 115 km offshore Flagler Beach in about 600 m of water (Figure 3-Right).

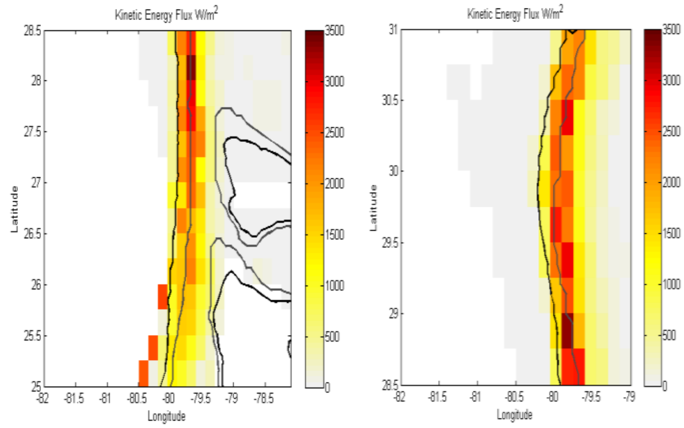

Figure 3: Sites where the average KEF calculated from drifter measurements exceeds 3.0 kW/m^2. Contour lines are at 200m and 500m water depth.

When evaluating potential deployment locations it is important to consider the velocity range at potential sites, in addition to the average available energy, for designing devices and mooring systems. For this reason the maximum measured current (Figure 4-Left) and minimum measured current (Figure 4-Right) are presented. These results show that the highest measured surface current velocity in this region reached 3 m/s. These also show areas where the minimum currents were not measured to drop below 0.8 m/s. Each data block has in average 50 data points and therefore it is very likely that some extreme events were missed in this analysis. At Cape Hatteras surface current velocities also reaches 3.0 m/s by an ADCP resource characterization of the Gulf Stream (Muglia, 2014).

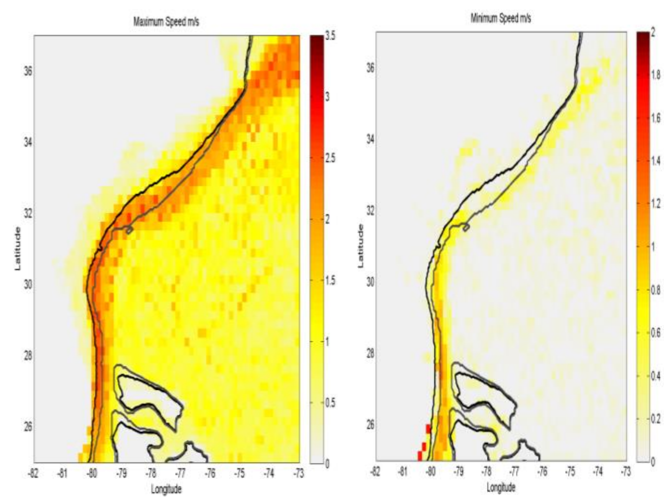

Figure 4: Maximum (Left) and Minimum (Right) current speeds in m/s measured by the drifter network. Contour lines are at 200m and 500m water depth.

27°N ENERGY ANALYSIS

Ocean current energy resource estimates at 27°N are based on vessel mounted Acoustic Doppler Current Profiler (ADCP) data. These data are utilized to map the temporally averaged kinetic energy flux density along this transect as a function of longitude and depth for ocean current based electricity production applications. A total of 35 data sets are utilized for this project that were collected, between August 20, 2002 and January 12, 2015 along a transect line of 27° N at longitudes from approximately 79°0' W to 80°0' W. In each ADCP data were available at a depth of 50m, with data also available at depth of 30 m in 29 out of 35 of the data sets. These transects were conducted by the National Oceanic & Atmospheric Administration (NOAA) Atlantic Oceanographic & Meteorological Laboratory (AOML), as part of a study focused on characterizing the Florida Current transport (NOAA AOML, 2013) and are publically available

Vessel Mounted ADCP Data

The vessel mounted ADCP data were collected from the research vessel Walton Smith, which gathered data along a 27°N transect line crossing the Florida Straits. This vessel was equipped with two ADCPs during most of these transects, a 75 kHz instrument for collecting data spanning almost the entire water column and 600 kHz instrument for collecting higher resolution measurements in the upper water column. The measurements collected from both instruments were provided at averaging times of 5 minutes, at depth intervals varying from 2 to 10 m. These vertical bin sizes are calculated from measurement bin sizes of 16 m for the 75 kHz instrument and 1 m for the 600 kHz instrument. The vessel's motion was removed from these measurements using directional GPS and a gyro compass measurements.

The post processing conducted before public release used the University of Hawaii's CODAS 3 program. It is utilized together with UHDAS, which is a system written at the University of Hawaii to collect data from the ADCP and use the CODAS processing to build sets of data of averaged ocean velocities for each ADCP (University of Hawaii, 2015). No attempt has been made to quantify the impact of potentially making these measurements during different tidal phases or irregularly sampled environmental conditions may have in the calculated results.

Data Processing

The data sets are distributed with the following data type: longitude, latitude, depth, and water velocity. Each data set was first manually reduced to data collected along the 27°N transect line.. Water velocity data are then used to calculate the kinetic energy flux density using (3). These data are re-ordered so that they sequentially increase with longitude and then linearly interpolated is used calculated kinetic energy flux at fixed grid points that are a function of longitude and depth, with depth varying from 0m to 700m and longitude from -79.9° to -79.2°E.

Each data set is then used to create a kinetic energy flux profile; similar to Figure 5 except for a single transect. Data sets with gaps greater than approximately 0.025° of longitude did not cover the region in Figure 5 within the 1.5 kW/m^2 contour, or showed un-natural looking discontinuities were excluded from this analysis. After excluding the data sets that did not meet this criteria the remaining data were averaged for each grid point to calculate the average KEF. For the analysis that included data only below a depth of 50 m 35 data sets met these criteria and for the analysis that included only data below a depth of 30 m 29 data sets met this criteria.

Results

This section presents the average energy profile for 27°N that is based on the vessel mounted ADCP transects conducted by NOAA/AMOL. Figure 5 shows the average KEF calculated from the ADCP data collected during 35 separate transects. The presented measurements span a depth range from 50-650 m and covers longitudes from 79.2° to 79.9°W. For water depth of 50 m the most energy dense current at this latitude was calculated to occur at a longitude of 79°47'W, with a value of 3.0 kW/m^2. This location is 29 km from shore where the total water depth is 390 m.

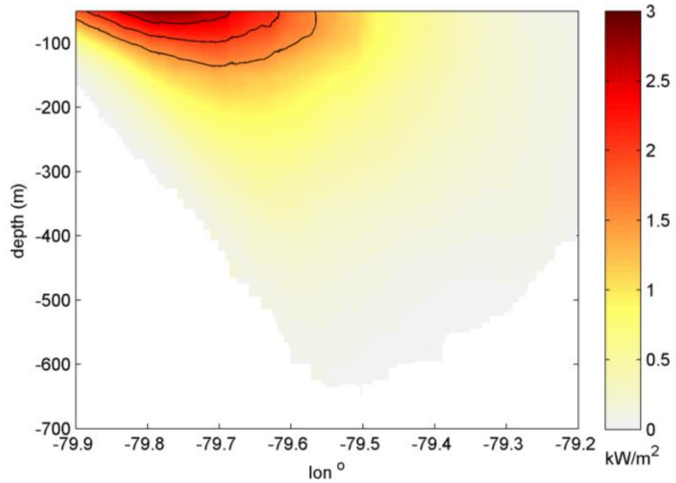

Figure 5: Average KEF measured by the vessel mounted ADCP calculated over 35 transects. Color scale units are in kW/m^2 and contour lines are drawn at 1.5, 2.0 and 2.5kW/m^2.

To evaluate the energy gains higher in the water column the average KEF was calculated separately from the 29 transects where ADCP data are available at both 30 m and 50 m of water depth (Figure 6). At the longitude where the most energy dense currents were predicted from the 35 transects at a depth of 50 m 79°47'W,, the increase in average power from a depth of 50 m to a depth of 30 m is 9%. Based on this average energy shear it can be estimated that at 30 m depth the average KEF is approximately 3.3 kW/m^2.

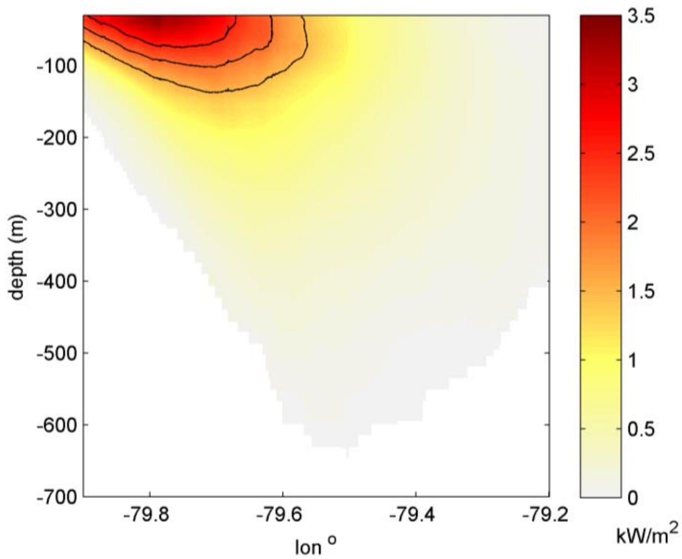

Figure 6: Average KEF measured during 29 ADCP transects where data are available at both 30 m and 50 m water depth. Color scale units are in kW/m^2 and contour lines are drawn at 1.5, 2.0, and 2.5kW/m^2.

26°4'N ENERGY ANALYSIS

This analysis utilizes bottom mounted ADCP data measured by the Southeast National Marine Renewable Energy Center (SNMREC) near 26°4'N to calculate energy statistics for four distinct longitudes. Statistics used for this study are calculated using data that have been previously published (most recently – VanZwieten *et al.*, 2015) and more recent measurements.

Bottom Mounted ADCP Data

During 2009-2015 ADCPs were deployed near four primary longitudes in the Florida Straits near a latitude of 26°4'N. The locations of the measurements are indicated in Figure 7 with an "x" placed on each deployment location. The deployments that are considered a single location for the conducted analysis also indicated. These locations were selected to approximately measure from the western edge of the current to its core. These locations are identified in this paper as locations L1-L4, with L1 being further from shore and L4 being closest to shore. Data utilized from these four site include those at the following locations, total water depths and date ranges:

- L4 (26°04'N; 79°55'W; 260 m) 1191 days of data including: Feb. 27, 2009-Mar. 20, 2009; Aug. 23, 2011-Nov. 16, 2011; Nov. 16, 2011-Apr. 3 2012; May 22, 2012–Dec. 17, 2012; and May 27, 2013-June 2, 2015.
- L3 382 days of data including: May 22, 2012-June 27, 2012 (26°4.3'N; 79°52.5'W; 290 m); May 26, 2013-May 5, 2014 (26°1.2'N; 79°52.8'W; 290 m); and May 27, 2013-April 29, 2014 (26°7.8'N; 79°52.8'W; 290 m).
- L2 (26°04'N) 1082 days of data including: Feb. 27, 2009-Mar. 25, 2010 (79°50.5'W; 340 m); Nov. 16, 2011-Apr. 6, 2012 (79°51'W; 320 m); May 22, 2012-Dec. 17, 2012 (79°51'W; 320 m); and May 24, 2013-April 29, 2014 (79°51'W; 320 m).
- L1 (26°04'N; 79°45'W; 640 m) 294 days of data spanning: Feb. 27, 2009-Dec. 10, 2009.

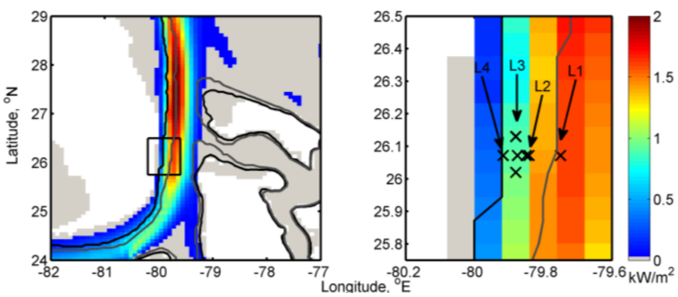

Figure 7: Locations of bottom mounted ADCPs used in this study (represented as "x") and buoy groups of nearly constant longitude indicated by text areas plotted atop HYCOM-based average KEF (kW/m^2) to show relative proximity to the resource. Contour lines are included at 250 m and 500 m isobaths and the Figure on the Right is a subset of the Figure on the Left.

Data Processing

The bottom mounted ADCP data utilized in this study were pre-processed to remove potentially erroneous data. This included removing data that did not meet the following criteria: pressure data corresponded to expected deployment depth, average bin depth was calculated to be more than 5 m, correlation of three or more bins exceeded 64 counts, "percent good" for all four beams exceeded 50%, echo intensity did not increase by 30 counts between bins at an increasing distance from the transducer, and vertical current speed gradients did not increase by more than 0.4 m/s. Vertical bins where at least 75% of the ensembles passed these filtering thresholds were utilized.

Since the vertical bin depths between ADCP data sets are not identical, each was linearly interpolated to a vertical grid with 1 m spacing (rather than its pre-set sampling bin height). To correlate these new vertical bins with absolute locations in the water column, mean sea surface height is determined for each ADCP data set and used to identify the most complete 1 m bin nearest the depth location. Then, statistical information is calculated only at the 1 m depth intervals common to all of the deployments at a specific site.

The average KEF presented from bottom mounted ADCP measurements was calculated using (3) and current velocity statistics were directly calculated from the measurements after accounting for the different utilized sampling rates. Additionally, for location L3 two ADCP's were simultaneously deployed at slightly different latitudes and therefore the current speed and KEF from these two ADCPs were averaged before combining with additional data sets to calculate the mean speed and KEF statistics.

Results

This section presents KEF and flow statistics as a function of depth for the four evaluated ADCP longitudes where measurements were made near latitude 26°4.3'N. Figure 8-Top presents the average KEF for these latitudes, showing that it increases with distance from shore until the second deepest location for a depth of 50 m. For a depth of 50 m the KEF was 1.58, 2.09, 2.20, and 2.14 kW/m^2 respectively. This shows that by moving further from shore, beyond the second shallowest location, does not significantly change the average KEF. Figure 8-Bottom shows the standard deviation of the KEF at these locations. For a depth of 50 m the standard deviation has a maximum value at the second shallowest location, with a significant decrease at the deepest location. Corresponding values for a depth of 50 m are 1.28, 1.34, 1.29, and 0.97 kW/m^2 respectively. This highlights the fact that while mean available power in this region does not significantly increase with distance from shore the capacity factor of installed devices and the ability to generate base load power from these ocean currents does.

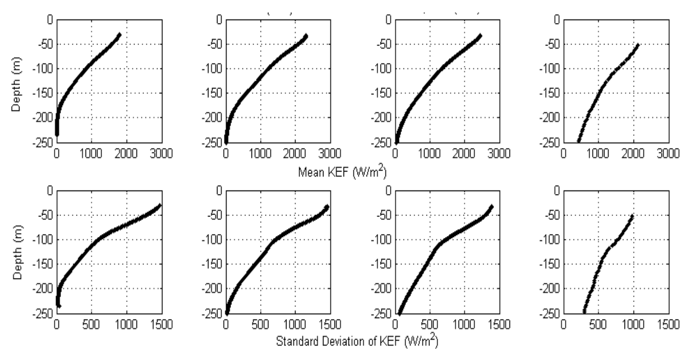

Figure 8: Mean and standard deviation of the KEF calculated at 26°4' N using bottom mounted ADCP data. These plots represent deployments grouped as L4-L1 moving from left to right to be consistent with Figure 7.

The minimum, mean and maximum flow speeds measured at the four evaluated locations are presented in Figure 9. These figures show that at the shallower 3 locations flow speeds near 0 m/s can occur over the entire water column. However, at the location furthest from shore flow speed below 0.8 m/s were not measured. The greatest maximum measured flow speeds were measured at the two middle locations with values approaching 3.0 m/s at the second shallowest location. These flow speeds were measured during an event that occurred on July 22 and 23 of 2013, a date on which measurements from the deepest locations are not available. Excluding this event maximum current speeds slightly decrease with distance from shore over the measurement location, consistent with earlier results presented by VanZwieten *et al.*, 2014).

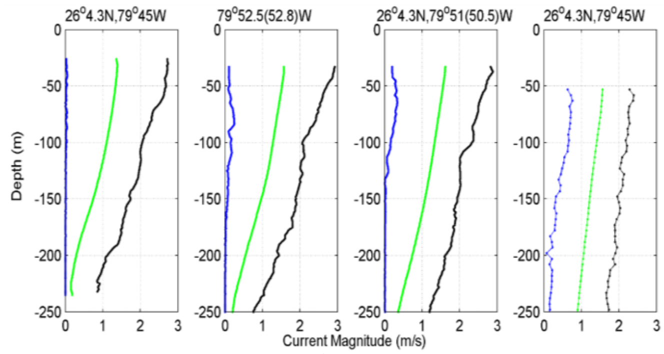

Figure 9: Minimum, mean, and maximum flow speeds measured by the bottom mounted ADCPs near 26°4' N.

CONCLUSIONS

This study utilized three types of ocean current measurements: drifter data, vessel mounted ADCP data, and bottom mounted ADCP data to evaluate the ocean current resource off the Eastern United States. The drifter data based analysis provides information on the location and magnitude of the ocean current resource off the entire US east coast, but with considerable noise due to the relative scarcity of the measurements. Vessel mounted ADCP transect data provide average energy statistics for a single latitude; clearly defining the relationship between depth, distance from shore and average energy density. Bottom mounted ADCPs provide data valuable for a more thorough statistical analysis than the other two data sets at specific locations, including the variability of the resource and estimates of extreme current events.

The drifter measurements highlighted resources with average kinetic energy densities off Florida above 3.0 kW/m^2 and off North Carolina above 2.0 kW/m^2. Off Florida the most energy dense longitudes approximately follow the 500 m depth contour, with much of the energy located between the 200 m and 500 m depth contours. However, off North Carolina most of the ocean current energy is located offshore from the 500 m contour. ADCP measurements off SE Florida collected in a region targeted for ocean current turbine developers (between 26°4'N and 27°N) show a temporally averaged KEF at 26°4'N of 2.2 kW/m^2 for a depth of 50 m, and 3.0 kW/m^2 at 27°N for this same depth. This highlights the importance of latitudinal turbine location. For 27°N it has been shown that the energy at a water depth of 30 m is approximately 9% greater than at a depth of 50 m, 3.3 kW/m^2 instead of 3.0 kW/m^2, highlighting the importance of keeping ocean current turbines in relatively close proximity to the sea surface. The bottom mounted ADCP measurements were able to capture an extreme current event where current speeds were measured at 3.0 m/s, and provide a basis for evaluating site specific capacity factors. These data suggest that at 26°4'N average energy densities only vary slightly with relative location to the Gulf Stream core, but that near the core of the Gulf Stream energy production will be much more consistent.

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