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EVALUATION OF HYCOM AS A TOOL FOR OCEAN CURRENT ENERGY ASSESSMENT

James H. VanZwieten[a,b], Imke Meyer[c], Gabriel M. Alsenas[b]

[a]Corresponding author: jvanzwi@fau.edu
[b]Southeast National Marine Renewable Energy Center, Florida Atlantic University, Boca Raton, FL, USA
[c]Centre for Renewable and Sustainable Energy Studies, Stellenbosch University, Stellenbosch, South Africa

ABSTRACT

This paper provides a global ocean circulation model based world-wide assessment of two flow characteristics and presents a direct comparison between model based predictions and *in situ* measurements in two regions. Four years (2009-2012) of HYbrid Coordinate Ocean Model (HYCOM)-generated data were used to estimate the average kinetic energy flux and flow direction variability in eight regions with time-averaged power density of at least 500 W/m^2. A direct comparison was then made between model calculated flow statistics those calculated from Acoustic Doppler Current Profiler data in both South Africa and the Southeast United States. Included analysis and discussion is intended to provide model predictions of the ocean current resource and assess the accuracy that can be expected when this model is used for making these predictions. This paper focuses on model predicted kinetic energy flux, flow speeds, and current direction variability, as these are important to the development and installation of OCT devices.

INTRODUCTION

Energy in the world's oceans is found in either kinetic (i.e. waves, tides, or currents) or potential (i.e. thermal or salinity gradients) forms, and all are being investigated to generate useful electric power. This paper focuses specifically on ocean current energy, the kinetic energy available in large-scale open-ocean geostrophic surface currents. These ocean currents generally exhibit strongest flow near the ocean's surface [1] and have been studied for over a century as a potential source for generating electric power. Region-specific ocean current resource characterization studies have been performed for the Gulf Stream in the United States [2, 3, 4, 5, 6], the Agulhas Current off the coast of South Africa [7, 8, 9] and the Kuroshio Current near Japan and Taiwan [10]. Because interest in these currents has evolved closer to commercial development in recent years, there is a need to identify a tool which could be used to pre-select potential energy generation sites. This tool would not replace *in situ* data collection, but would allow for more strategic selection of locations to measure.

Such a tool should minimally describe the magnitude and temporal variability of average kinetic energy flux per unit area (KEF) available in each of the world's oceans, as was recently presented [1]. In this previous study, KEF was evaluated using HYCOM model data. In addition, water depth and distances from shore for areas with averaged KEF greater than 500 kW/m^2 were quantified. However, the variability of the magnitude and direction of the ocean current velocity (important for system design and control) was not evaluated. Additionally, if measurements were available to evaluate model confidence, such a tool's utility could be quantified.

The research presented here expands the previous analysis [1] by investigating HYCOM flow direction variability for the previously identified major currents and provides a comparison between model-based data and direct Acoustic Doppler Current Profiler (ADCP) measurements collected off Florida, U.S.A. and South African coasts. We provide a brief overview of HYCOM, data processing approaches used, and a global overview of the ocean current resource. Then, HYCOM results and ADCP measurements are compared in Southeast United States and South African regions so that model performance can be quantified.

HYCOM

The numerical prediction presented in this paper and those presented in the preceding global assessment [1] were generated by the global HYbrid Coordinate Ocean Model (HYCOM) [11,12]. In this paper versions 90.6, 90.8, and 90.9 are utilized. This model is a 3-dimensional, ocean prediction simulator with a 1/12° resolution. This resolution corresponds to approximately 8 km spacing in the longitudinal direction and 9.25 km in the latitudinal direction for 30° North or South latitudes. HYCOM incorporates data assimilation to produce, via a 5-day hindcast/forecast scheme, global datasets with daily snapshots of eastward and northward velocities, salinity, sea-surface height, and ocean temperature. One of the notable features of HYCOM is its vertical coordinate schemes. HYCOM utilizes an isopycnal structure for deep ocean modeling, constant depth or pressure schemes for mixed layer modeling, a terrain-following coordinate approach for coastal regions, and level coordinates for very shallow regions.

This study selected the publically available once-daily HYCOM data sets from the period 1 January 2009 – 31 December 2012 for ocean current feature investigations. These dates were chosen to ensure water velocity estimates were derived from the most recent HYCOM versions and to benefit from other update improvements. Complete consecutive years were chosen to remove seasonal biases from the HYCOM based statistics presented in Global Research Summary section of this paper.

For comparison studies between ADCP and HYCOM model data presented in the HYCOM vs. ADCP Comparison section of this paper, the period between 1 November 2008 and 31 December 2012 was selected for the reasons indicated earlier as well as ensuring that available measured data sets overlap with model results. All HYCOM datasets, including the ones used for this study, are publicly available through the community web site at http://www.hycom.org.

DATA PROCESSING

Statistics used for this study include those related to the available energy in the flow for power production analyses (prior results [1]) and flow speed/direction for mooring and force analyses (new results). The following section also includes a discussion about how model data and offshore measurements were combined using interpolation techniques.

Statistical Derivations

This paper presents KEF to help quantify the available power in a flow. While the KEF does not independently imply the total energy that can be extracted from an ocean current, it does provide significant insight into the energy that can be extracted by either a single ocean current turbine (OCT) or a small array of turbines. The KEF available to a turbine (unit area perpendicular to a flow) is calculated using:

$$P = \frac{1}{2}\rho V^3, \qquad (1)$$

where P is kinetic energy flux, ρ is the density of seawater, and V is free-stream current magnitude. To evaluate a more practical amount of extractable power for a particular turbine technology (or small array which extracts only a small fraction of the energy in the flow), the product of the KEF and a power coefficient can be used to estimate the extractable power per unit area swept by a turbine exposed to a flow. This paper examines both the mean and standard deviation of P.

Since ocean current turbines may be installed with compliant mooring systems, the variability of flow direction is evaluated in this study. The standard deviation and the percentage of time that flow reversals occur at various locations is presented. The mean flow direction is defined in this paper as:

$$\bar{\Psi} = tan^{-1}\left(\frac{\bar{V}_E}{\sqrt{\bar{V}_N + \bar{V}_E} + \bar{V}_N}\right), \qquad (2)$$

where $\tan^{-1}$ is the inverse tangent function, $\overline{()}$ indicates the mean, V_E is the eastward component of velocity, and V_N is the northward component of velocity. The standard deviation of flow direction, Ψ_{std}, for a single location is then calculated from:

$$\psi_{std} = \sqrt{\overline{((\Psi - \bar{\Psi})|_{-\pi}^{\pi})^2}}, \qquad (3)$$

where $(\,)|_{-\pi}^{\pi}$ indicates that the angle is unwrapped to its equivalent radial value between $-\pi$ and π and Ψ is the flow direction vector. In this paper a current reversal is defined as a current that is flowing in a direction that is more than $\pi/2$ radians (90°) from $\bar{\Psi}$. This fractional relationship is calculated from:

$$\frac{\sum_{i=1}^{N}|\Psi_i-\bar{\Psi}|>\pi}{N}, \quad (4)$$

where $|\,|$ indicates the absolute value and $()_i$ indicates an element within a vector.

Data Filtering and Interpolation

To calculate flow characteristics at a HYCOM model grid point, the equations in the proceeding section are sufficient. However, because available measurements are not co-located with HYCOM grid point locations, bi-linear interpolation is used to convert data to common spatial reference locations.

HYCOM data has fixed depth intervals and a latitude/longitude spacing of 1/12°. In the method selected to resolve data locations for this study, HYCOM statistics are first calculated at each HYCOM grid point over the dates that correlate with adjacent ADCP data. Once statistical calculations are available at four HYCOM grid points surrounding an ADCP location, the resulting statistical values are then bi-linearly interpolated to the ADCP location. This approach was selected to avoid contamination from spatial averaging of velocity values before calculations are performed.

Since 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 being compared to HYCOM. Then, the statistical investigation being conducted is calculated only at the 1 m depth intervals common to all of the deployments at a specific site.

Multiple ADCP data sets were available for every deployment location (besides 26°4.3'N 79°45'W). Data from South African deployments were provided by Eskom Holdings Limited and was delivered pre-windowed (some bins were removed from the sea surface and from the instrument's blanking distance). U.S. ADCP data were provided by the Southeast National Marine Renewable Energy Center, with no windowing or QA/QC.

U.S. ADCP data required pre-processing before analysis for this study, which 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 meters, 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.

GLOBAL RESOURCE SUMMARY

An extensive global ocean current energy resource assessment based upon HYCOM results was presented in [1]. However, the average hydrokinetic energy density on a global scale is re-presented here (except at a shallower depth and using a longer HYCOM data set) as a review (Figure 1), as well as a global look at flow reversals not discussed in the previous work (Figure 2). To assemble candidate global grid points into regions (currents), an evaluation depth of 20 m was selected as a shallowest "hub height" for ocean current turbines. Deeper depths will likely be used for large turbines, or where vessel traffic and/or large surface waves are important. However, this relatively shallow depth was chosen so that shallow water sites (such as those being considered off South Africa's coast) were not excluded.

To more easily represent global currents, grid points were grouped into eight regions with the largest potential, presented graphically in Figures 1 and 2. In these figures (and many of those following), land and freshwater areas are shaded white, while areas with less than a 0.5 kW/m^2 temporally averaged KEF at a depth of 20 m are shaded grey. At a depth of 20 meters, 1,064,600 km^2 of the world's sea surface exhibits an available time-averaged KEF greater than 0.5kW/m^2. Of that area, 14% (150,640 km^2) is more energy dense than 1.0 kW/m^2, 1.8% (19,231 km^2) greater than 1.5 kW/m^2, and 0.03% (369 km^2) greater than 2.0 kW/m^2. This, of course, suggests that turbines designed with greater efficiency at slower flow speeds will be compatible with more regions. The maximum KEF off Japan is 2.15 kW/m^2 (41°33'N, 140°52.8'E), the Southeast United States is 2.03 kW/m^2 (27°05.4'N, 79°45.6'W), and South Africa is 1.83 kW/m^2 (28°47.2'S, 32°28.8'E).

The frequency of current reversals (Figure 2) will be important to the design of mooring systems. Off the Southeast U.S. coast, no current reversals were indicated over 31% of the region's area with KEF greater than 0.5 kW/m^2. Much smaller areas with energy densities above this threshold were also identified not to contain reversals off Japan, Somalia, Brazil, and Madagascar.

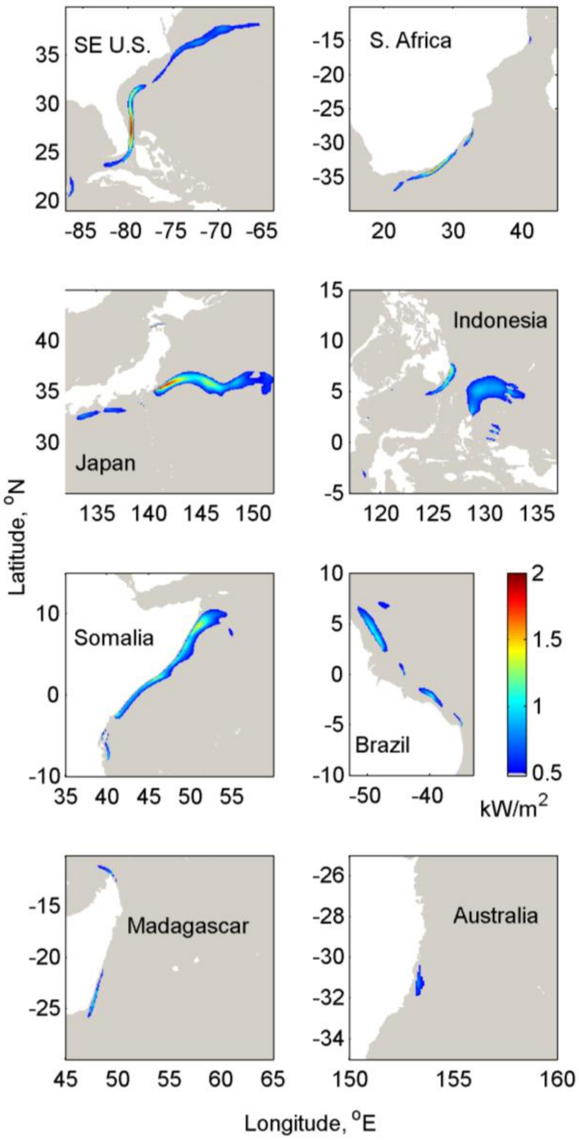

Figure 1: Eight regions with concentrated time-averaged kinetic energy flux in excess of 0.5 kW/m^2 between 2009 and 2012 at a depth of 20 m.

HYCOM VS. ADCP COMPARISON

The goal of this study is to quantify the performance of HYCOM as a useful ocean current energy assessment tool. Although HYCOM incorporates assimilated *in situ* data, its grid scaling and global resolution may not sufficiently describe the parameters useful for local energy assessment. Therefore, ADCP measurements are compared with results obtained from HYCOM in two regions (of the eight defined in [1]), the Southeast U.S. and South Africa. Three metrics are evaluated for each zone for comparison: KEF, current speed, and occurrence of current direction reversals.

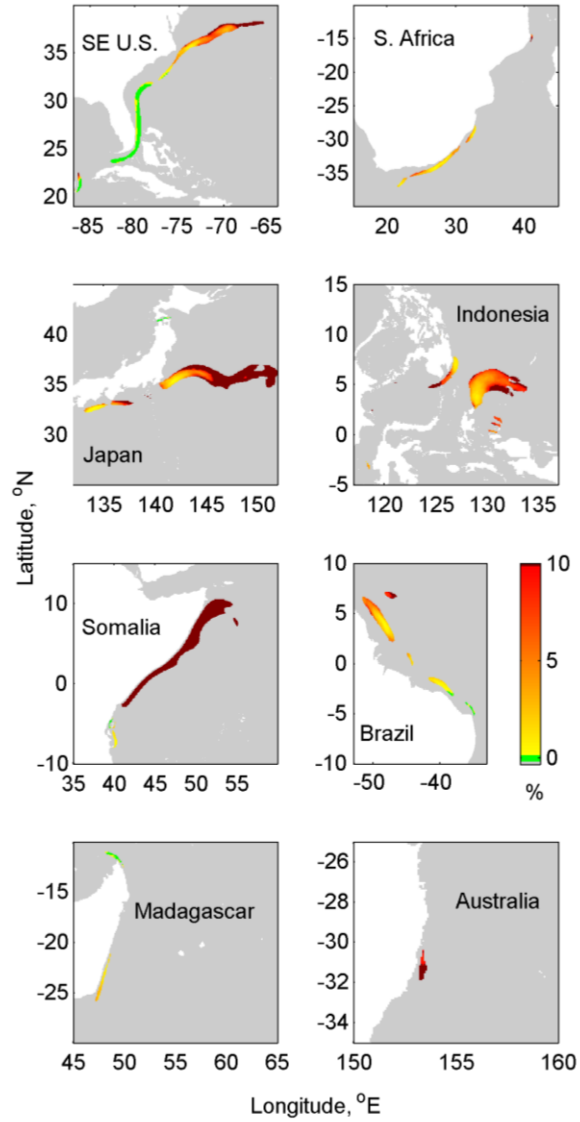

Figure 2: Percentage of time that flow reversals exist as calculated by HYCOM at a depth of 20 m. Dates utilized include those from 2009 to 2012.

Southeast U.S.

The Gulf Stream represents the ocean current energy resource available to the Southeast U.S. Although most energy dense in the Florida Straits, over all, the Gulf Stream has been estimated to possess up to 44 GW of theoretically extractable energy [13]. HYCOM predicts the greatest KEF in the Gulf Stream at 27.090N, -79.760E and at a depth of 20 m, of 2.03 kW/m^2. HYCOM also predicted that no current reversals occurred during 2009-2012 near its core (Figure 3). However, it has been documented that there are 10-30 km cyclonic spin-off eddies that travel along its western edge approximately weekly [14]. These eddies can cause current reversals in shallower locations (closer to shore) [15].

During 2009-2012 ADCPs were deployed in three locations in the Florida Straits (indicated in Figure 3 with an "x"). The ADCPs were moored in an east-west configuration at the same latitude (26°4.3'N), approximately perpendicular to the shoreline. The locations were selected to approximately measure from the western edge of the current and at its core. At the shallowest and most inshore location, (B3, 79°55'W longitude) ADCP data was available from 455 days including: Feb. 27, 2009-Mar. 20, 2009; Aug. 23, 2011-Nov. 16, 2011; Nov. 16, 2011-Apr. 3 2012; and May 22, 2012–Dec. 17, 2012. At the center location (B2, 79°51'W and 79°50.5'W longitude) ADCP data was available from 742 days including Feb. 27, 2009-Mar. 25, 2010; Nov. 16, 2011-Apr. 6, 2012; and May 22, 2012-Dec. 17, 2012. Finally, at the westernmost location (B1, 79°45'W longitude) ADCP data was available from 294 days spanning Feb. 27, 2009-Dec. 10, 2009. It is worth noting that some of these B2 ADCP data were compared with HYCOM by [6] producing similar findings.

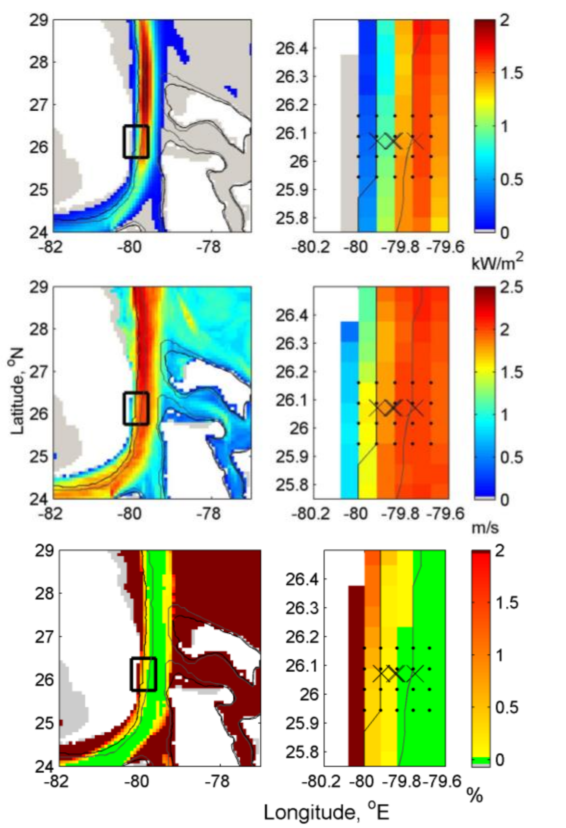

Figure 3: HYCOM-calculated comparison characteristics in the Southeast U.S. zone (left) near ADCP measurements (right), at a depth of 20 meters, between 2009 and 2012: time-averaged KEF (top), maximum flow speed (middle), and percent time that flow reversals are present (bottom). Contour lines are included at 250 m (black) and 500 m (dark grey) isobaths, ADCP locations are marked with an '×', and dots indicate nearby HYCOM grid points.

The maximum time-averaged KEF predicted by HYCOM at 26°5.33'N (the closest latitude to ADCP locations) was 1.6 kW/m^2 at 79°45.6'W (the corresponding HYCOM grid point is just to the East of B1). This is 21% less than the maximum HYCOM estimated KEF off the Southeast US, indicating that ADCP measurements are likely not located in the most energy dense resource in this region (this is also evident in Figure 3). The maximum flow speed at the buoy latitude was predicted to occur at 79°50.4'W (one grid point closer to shore), and the current reversal found closest to the current's core (west, and inshore) was estimated by HYCOM at a grid point just inshore of B3 (79°55.2'W). At this location, HYCOM predicted a total of two reversals over the evaluated four year range. No current reversals were predicted by HYCOM at grid points between the ADCP buoys.

Data suggest that near the surface, HYCOM estimated mean current speeds are less accurate at grid points further from the current's core (Figure 4). From west to east, HYCOM calculated mean current is under-predicted by 28%, 16%, and 8% 50 m below the sea surface. While the mean current predictions converge towards measured values near the core of the Gulf Stream, HYCOM significantly under-predicts the variability of the current speed at all locations. Maximum current speeds at a depth of 50 m are under-predicted by HYCOM by 37%, 26% and 19% from west to east.

A statistical approach was also applied to flow speed data to evaluate similarity between model and measured data. The distribution of current speeds was compared using a 75% to 15% window. In other words, when all velocity magnitude data is collected and grouped according to value, do model and measured data set distributions match within these thresholds? When flow speed values are evaluated this way, from west to east, HYCOM predicted the window to be 0.37 m/s, 0.35 m/s, and 0.35 m/s; while ADCP measured data are 0.68 m/s, 0.58 m/s, and 0.44 m/s. The resulting velocity window difference calculated by HYCOM when compared with ADCP data was therefore 46%, 39%, and 21% smaller, respectively. Because recorded data are not available east of the Gulf Stream core, it is unclear if HYCOM is under-predicting the spatially-averaged near surface volumetric flow rate through the Florida Straits, or if HYCOM is predicting the core of the current further offshore than it was measured. However, it is clear that HYCOM under-predicts velocity distribution (Figure 4).

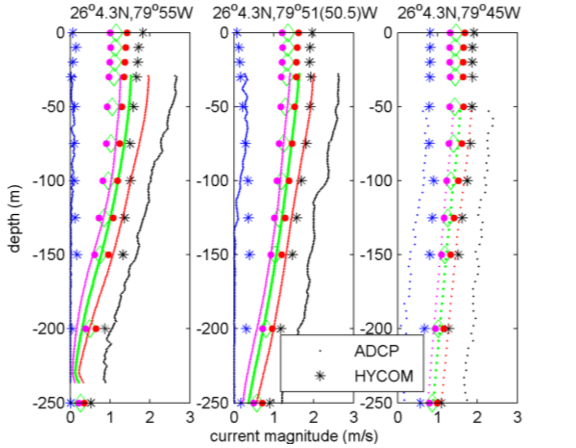

Figure 4: HYCOM vs. ADCP minimum (blue), 75% (magenta), mean (green), 15% (red), and maximum (black) flow speeds at three ADCP locations off the coast of Florida. The larger symbols (asterisk, diamond and large dot) indicate HYCOM data and the smaller indicate ADCP data (ADCP data look like lines in left two plots).

To investigate accuracy when using HYCOM energy assessments in this region, Figure 5 shows the mean and standard deviation of KEF. HYCOM underestimates KEF at all locations, with error increasing with distance from the core. From west to east, HYCOM underestimates KEF at a depth of 50 m by 65%, 44%, and 25%. This suggests that HYCOM provides very conservative energy estimates (for this zone, at least) due partially to an under-prediction of current variability, with error increases with westward distance from the predicted core partially caused by an under-prediction of mean current. This result suggests that shallow (near shore) locations not be excluded as potential development sites based solely on HYCOM-predicted energy estimates. The mean ADCP based KEF at 50 m are 2.01, 2.18, and 2.12 kW/m^2 from west to east; all being greater than the maximum HYCOM KEF for this depth in the SE US region (1.93 kW/m^2) presented by [1].

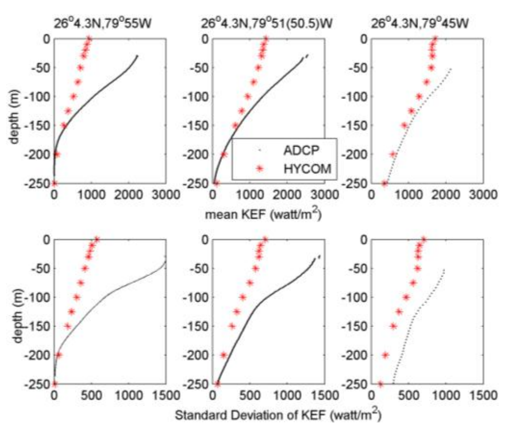

Figure 5: HYCOM vs. ADCP KEF (top) and standard deviation of KEF (bottom) at the three evaluated ADCP locations offshore Florida.

Figure 6 highlights the variability of current direction for HYCOM and ADCP measurements. The HYCOM model underestimates the standard deviation of flow direction at a depth of 50 m (from 6 to 45%). Model data also appears to do a fair job predicting locations and frequency of current reversals (in this region) at a depth of 50 m. While the somewhat coarse HYCOM grid makes this analysis difficult to visualize, reversals were only measured by B3 at a depth of 50 m 0.085% of the time (9.5 hours out of 455 measurement days). Similarly, at the evaluated buoy latitude, the first HYCOM grid point west of the furthest west ADCP buoy predict a single reversal at a depth of 50 meters during the evaluated 460 days. This equates to reversals occur 0.21% of the time.

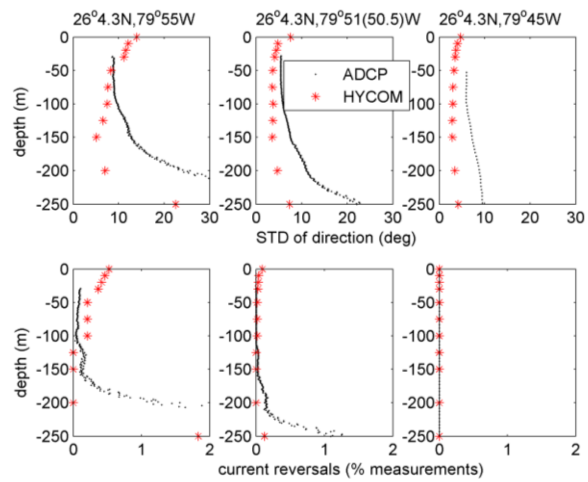

Figure 6: HYCOM vs. ADCP standard deviation of flow direction in degrees and percent of time that flow reversals occur at each ADCP location offshore Florida.

South Africa

The Agulhas Current is a wind-driven surface current off the east coast of South Africa. The Mozambican and Madagascar Currents accompanied by the Agulhas Current retroflection feed into this body of water which flows closely along the continental shelf. The continental shelf is approximately 25 km wide and remains consistently narrow between Maputo (25.965 S 32.589 E) and Port Elizabeth (33.967 S 25.583 E), excluding the region just south of Durban (29.850 S 31.017 E) known as the Natal Bight. The change in morphology is the catalyst of infrequent solitary cyclonic meanders called Natal Pulses. These phenomena, which move southward along the coast line and can grow up to 150 km in diameter, displace the core of the Agulhas Current seaward for up to 40 days in one area [8]. Although the presence of Natal Pulses causes sporadic variability in the current, it is the narrow shelf and steep slope which stabilizes the current

This region's comparison study uses ADCP data from three locations (location 1: 33°42.49'S 27°16.8'E, location 2: 33°9.0'S 28°5.94'E, and location 3: 32°30.12'S 28°48.0'E), arranged parallel to the coastline, deployed nearly continuously during 2009-2012 (see figures 11-13), each indicated by an "x" in Figure 7.

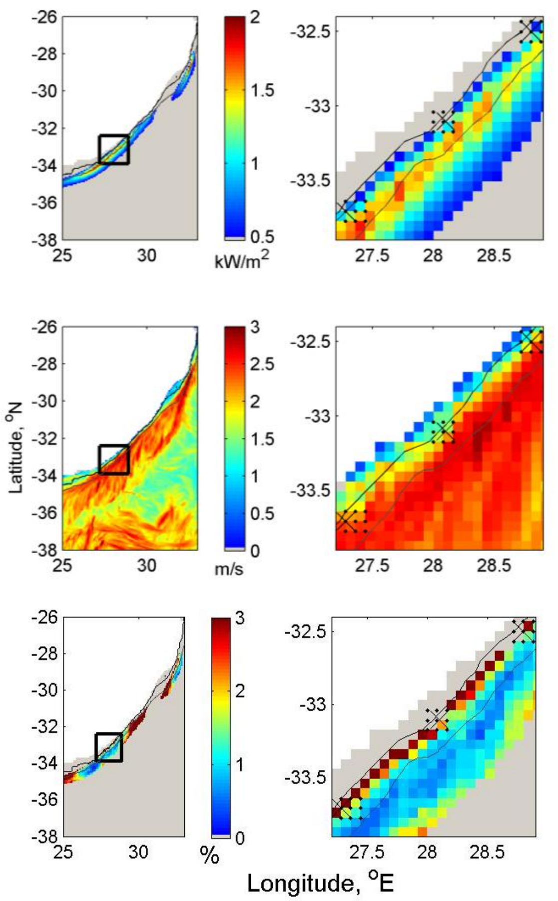

Figure 7: HYCOM-calculated flow characteristics off South Africa's coast (left) and near ADCP measurements (right), at a depth of 20 meters, between 2009 and 2012. Presented characteristics include temporally-average KEF (top), maximum flow speed (middle) and percent time that flow reversals are present (bottom). Contour lines are included for 100 m (black) and 1000 m (dark grey) isobaths, ADCP locations are marked using an '×', and dots indicate HYCOM grid points near ADCP buoys.

Buoys were all deployed near the 100 m isobath, on the continental shelf. While it has been found that the core of the current runs alongside the continental shelf, based on an evaluation that mooring challenges in greater than 100 m depth were significant, ADCPs were restricted to these locations. HYCOM predicts the Agulhas core to reside closer to the 1000 m isobath (approximately 50 km from the shore) and Rouault and Penven [16] have found that the core lies approximately 20 km from the shore at East London (32.97°S and 27.87°E), with the use of SEVIRI SST data.

HYCOM predicts the maximum KEF off the South African coast during the considered period as 1.83 kW/m^2, which occurred at 28°47.2'S and 32°28.8'E. At this location, the percentage of current reversals was 1.5%. This location is several hundred kilometers north of the ADCP measurements. However, a only slightly less energy dense current, with a KEF of 1.76 kW/m^2, is found at 33°50.47'S and 27°21.6'E which in close to the furthest south ADCP buoy (within the area depicted on the right side of Figure 7). At this location, the percentage of current reversals was 1.0%. ADCP data at three locations is used to verify the performance of the HYCOM model off the South African coastline to carry out site selections for potential ocean current turbine deployment.

Figure 8 shows current flow speed statistics calculated by HYCOM versus those measured by ADCPs. At the three ADCP locations, HYCOM estimates the mean current speed reasonably well, with the exception of depths above 50 m. At location 1, HYCOM-calculated mean current flow is over-predicted by 38% at 50 m and 14% at 20 m. HYCOM however under-predicted mean current speeds at locations 2 and 3, by -1% and 5% at 50 m, and 26% and 23% at 20 m below the sea surface.

HYCOM also poorly estimates extreme conditions, since throughout the water column there is a large inconsistency between the measured maximum speed and the predicted maximum speed. At locations 1, 2 and 3, HYCOM under-predicted the maximum speed by 20%, 31%, and 19% at 20 m depth. The HYCOM model also underestimates resource separation between 75% and 15% exceedance bands. HYCOM predicted this separation to be 0.98 m/s, 0.77 m/s, and 0.85 m/s for locations 1-3, respectively, while ADCP measurements show that this was 1.08 m/s, 1.15 m/s, and 0.97 m/s. The resulting percent errors in this separation were 9%, 33%, and 12%, respectively.

These data suggest that near the surface, HYCOM-estimated current speeds become less accurate. This divergence can be explained by either the presence of surface shear from wind forcing which increases the current's speed at shallower depths (not compensated for in HYCOM), or HYCOM predicts the location of the core to be further off-shore than it is measured. As is the case with Southeast U.S. comparison results, ADCP data off the South African coast is not available further seaward, and neither theory can be confirmed.

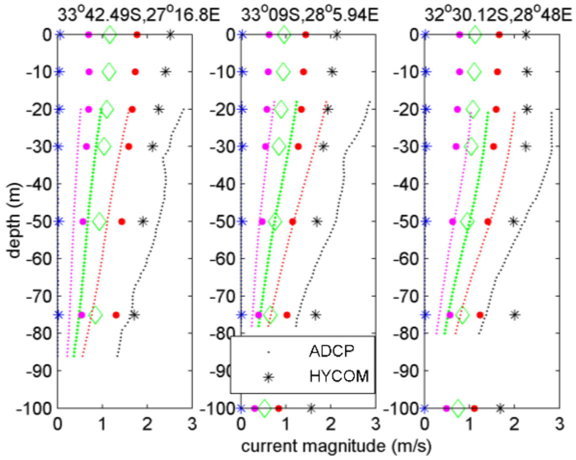

Figure 8: HYCOM vs. ADCP minimum (blue), 75% (magenta), mean (green), 15% (red), and maximum (black) flow speeds at three ADCP locations off the coast of South Africa. The larger symbols (asterisk, diamond and large dot) indicate HYCOM data and the smaller indicate ADCP data (ADCP data look like lines in left two plots).

Figure 9 shows the mean and standard deviation of KEF comparison results between measured and model data. At ADCP location 1, HYCOM overestimates the mean energy resource with an associated error of 18% at 20 m depth. It is seen that for locations 2 and 3, HYCOM significantly underestimates the KEF near the surface, with an error of 58% and 54% at 20 m. As well, there is an overestimation of mean KEF below 50 m for all locations, resulting from an incorrect depth versus KEF profile. However, it must be noted that, in order to calculate KEF, speed is cubed and the error between actual and numerical data sets is cubed as well, resulting in significant cascading inaccuracies between 50 m and the surface, as seen in Figure 9. This inaccurate model-based profile can be misleading to ocean energy developers when investigating depths suitable for turbine deployment. Further, locations 2 and 3 have been identified as potential deployment locations for ocean current turbines from the ADCP measurements, due to a desirable measured KEF of 1582 W/m^2 and 2164 W/m^2, respectively. It is worth nothing that the measured KEF at location 3 is greater than then any predicted by HYCOM to exist in the South Africa region. Hence, if HYCOM is solely used to identify potential deployment sites, the maximum available KEF in the region would be significantly underestimated and shallower locations such as the ADCP measurement locations might be overlooked.

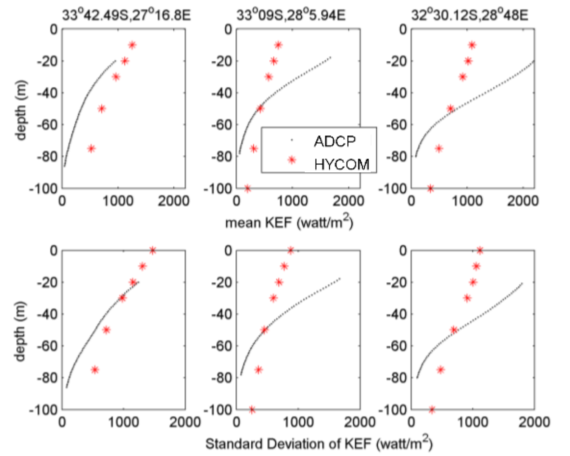

Figure 9: HYCOM vs. ADCP KEF (top) and standard deviation of KEF (bottom) for each ADCP off South Africa's coast.

With respect to direction variability, Figure 10 highlights how HYCOM portrays the current to be less variable than it actually is. At 20 m depth, HYCOM under predicts the percentage of current reversals by 73%, 31% and 61% at locations 1, 2 and 3, respectively. This under-prediction may falsely indicate suitability for power production. HYCOM may be performing poorly with respect to velocity magnitude and current flow direction because of the proximity of ADCP locations to the coast and rapid changes in bathymetry between the 1000 m and 100 m isobaths over a short distance of ~25 km combined with coarse resolution of the model.

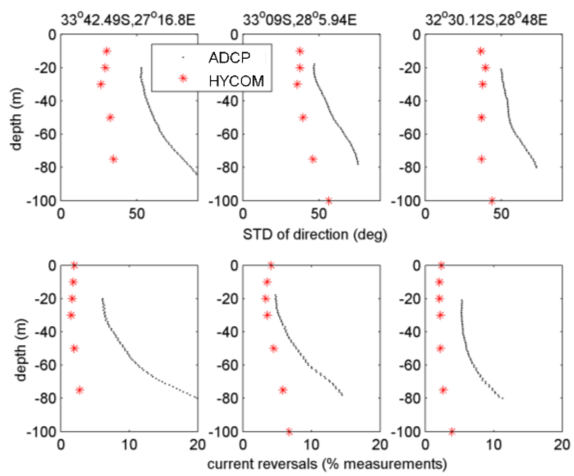

Figure 10: HYCOM vs. ADCP standard deviation of flow direction in degrees and percent of time that flow reversals occur at each ADCP location off South Africa's coast.

Figures 11, 12 and 13 show time series plots of the flow speed, highlighting the variability of the current. Owing to the presence and irregular occurrence of Natal Pulses in the Agulhas Current, it is important to investigate whether HYCOM accurately captures this major phenomenon. The presence of a Natal Pulse is recognized as a drop in the current speed to near zero. Although this does not indicate the current stops, instead, the current core has been displaced by the Pulse, and hence the primary current no longer flows over the ADCP.

These figures show that the HYCOM model maps the presence of Natal Pulses at corresponding dates which match those recorded by the ADCPs. This correlation is seen by the corresponding near-zero velocity bands which penetrate the entire water column for approximately 30 day intervals in both HYCOM and ADCP plots for each location. As seen in Figure 11, the presence of a Natal Pulse is visible on either side of May 2010, in both the HYCOM and ADCP data. The comparison also highlights that the HYCOM model underestimates the current velocity in the near-surface region (between 0 m and 50 m depths), which reiterates the findings based upon Figure 8.

Of additional note, the number of Natal Pulses observed in the selected period is unusually high. The typical average frequency is approximately 1.6 occurrences a year [13], and as noted by [13], 2010 was an exceptional year which saw three Natal Pulses travel the length of South Africa's eastern coastline. At the very least, this data is valuable to developers to determine how long and how often a turbine array would be unable to produce electricity (capacity factor).

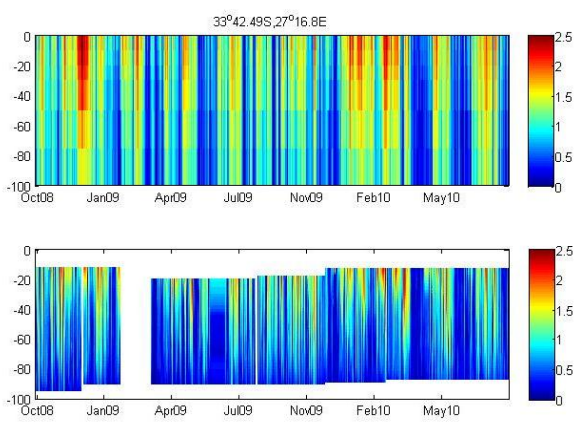

Figure 11: Time series vs. depth for HYCOM (top) and ADCP (bottom) data at location 1. The color scales indicate current speed [m/s].

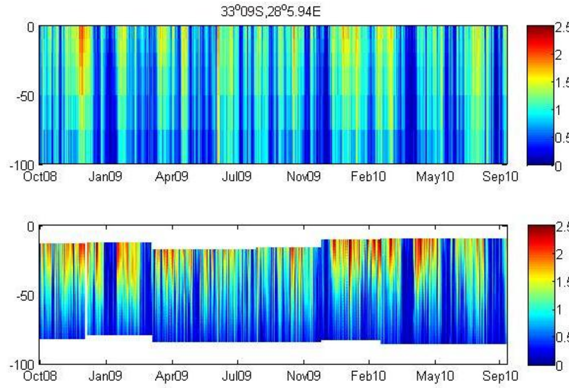

Figure 12: Time series vs. depth for HYCOM (top) and ADCP (bottom) data at location 2. The color scales indicate current speed [m/s]

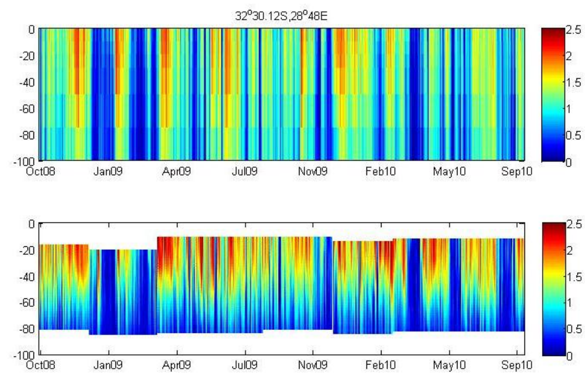

Figure 13: Time series vs. depth for HYCOM (top) and ADCP (bottom) data at location 3. The color scales indicate current speed [m/s].

CONCLUSION

Open-ocean currents such as the Gulf Stream, Agulhas, and Kuroshio occur in all the world's ocean basins, and marine hydrokinetic energy resources are associated with many of them. This study briefly evaluated global ocean current energy resources based upon four years of HYCOM-predicted simulation data. Time-averaged kinetic energy (power) densities were calculated at each grid point, at a 20 m depth, and points which exceeded 0.5 kW/m^2 were used to define eight regions of interest, including their frequency of current reversals.

HYCOM predictions of flow speed, KEF, and flow direction were then compared with ADCP data in two regions that are being considered for electricity production: the Southeast U.S. and South Africa. All of the evaluated buoy locations (three from Southeast U.S. and three from South Africa) were inshore (west) of the primary core of the respective current. The variability of current speed was under-predicted and the mean current speed at all but one of the locations was also under-predicted near the sea surface, resulting in underestimations of the available power in five locations, by up to 65%. The variability of the available energy at each of the locations was also under-predicted. HYCOM predictions of near surface flow direction were also under-predicted at all locations with errors between 6 and 45%. In summary, HYCOM has problems in predicting the location (core) of currents, near surface current velocities, and current variability.

Despite the lack of exact correlation with measurements, HYCOM does appear to be a useful tool for preliminary identification of areas to develop for ocean current energy production. All metrics but occurrences of current reversals (which were well captured by HYCOM) were generally under-predicted. Although such a tool is preferred to under-predict important variables, this study highlighted the requirement to obtain site-specific long term measurements for final site selection and development.

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