NATIONAL GEODATABASE OF OCEAN CURRENT POWER RESOURCE IN USA

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Abstract

Ocean currents represent an alternative source of clean energy given their inherent reliability, persistence and sustainability. The general ocean circulation is characterized by large rotating ocean gyres resulting in rapid ocean currents along the western boundaries because of the Coriolis Effect. The Gulf Stream system is formed by the western boundary current of the North Atlantic Ocean flowing along the east coast of the United States, and is of particular interest as a potential energy resource for the United States. This study presents a national database of ocean current kinetic energy resource derived from seven years of numerical model simulations to help advance awareness and market penetration for ocean current energy. A web based GIS interface is provided for dissemination of the national energy resource data:

<http://www.oceancurrentpower.gatech.edu/>. The website includes GIS layers of computed monthly and yearly mean ocean current speed and associated power density along the coastlines of the United States, as well as joint and marginal probability histograms for current velocities at a variable horizontal resolution of 4 to 7 km. Various tools are provided for viewing, identifying, filtering and downloading the data from this website. The Gulf Stream system, especially the

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Florida Current, concentrates the highest kinetic power density ($> 2000 \text{ W/m}^2$). The majority of the kinetic power and its variability are only present in relatively shallow water given the strong correlation with the surface wind stress. The kinetic energy flux in the Florida Current is estimated over 30 years to provide temporal variability of the undisturbed kinetic energy with high statistical significance. Available power of approximately 5 GW associated with the undisturbed natural flow condition from the Gulf Stream system is predicted based on hypothetical turbine parameters. Successful development of renewable energy generation requires further studies to account for more precise technical, economic and environmental constraints.

Keywords: ocean currents, hydrokinetic energy; Gulf Stream system; resource assessment

1. Introduction

There is a growing interest in renewable energy around the world. Concerns about environmental pollution and climate change are among the driving forces for seeking affordable and environmentally friendly energy alternatives [1]. The decrease in fossil fuel reserves makes renewable energy attractive to both the government and the industry as the importance of renewable energy is increasingly recognized. In the past three decades global energy consumption almost doubled [2], while some predict the global fossil fuel reserves may be exhausted within a century [3]. Some countries are also seeking energy independence by reducing fossil fuel imports from foreign regions and developing domestic alternatives of clean energy. Renewable energy has great benefits compared to fossil fuels, including environmental improvement, fuel diversity, and national security if supplies cover a significant portion of the country's energy demands. Furthermore, the investment into the renewable energy industry will

most likely be spent on materials and infrastructure rather than on energy imports, thereby spurring local economies through the creation of jobs [4, 5].

The world's oceans cover more than 70% of the earth's surface and are a promising reservoir of alternative energy resources. Energy production from the ocean presently constitutes a negligible portion of our daily energy supply, while the worldwide electricity produced by ocean based devices is predicted to reach more than 7% by 2050 [6]. In countries with ocean access, coastal areas concentrate a wealth of natural and economic resources and are typically among the most developed areas in a country. Renewable energy from coastal and offshore regions is well positioned to supply countries' most populated areas if efficient harvesting is feasible.

Ocean currents are the continuous flow of ocean water in certain directions, and can vary greatly in terms of dominating driving forces, spatial locations, temporal and spatial scales. Fast moving ocean currents are rich in hydrokinetic energy. Since water is about 800 times denser than air, ocean currents of about 1/9 the wind speed carry comparable kinetic power density to wind. The major driving forces for large scale currents (on the order of 1000 km length-scale) are wind stress, and temperature and salinity differences (or associated density differences). Besides, meso-scale (on the order of 100 km length-scale) ocean currents can also be driven by tides, river discharge and pressure gradients (generated by sea surface slope setup from coastal long waves, for example). Among these forces, only the astronomical tidal forcing is deterministic, and thus allows for accurate forecasting. Tidal forcing, however, has a negligible contribution on the Gulf Stream ocean current system [7, 8]. Therefore, this study only examines the non-deterministic forces, among which the most important are wind and density differences, and uses a probabilistic approach to define the ocean currents.

Surface ocean currents are generally wind driven and develop their typical clockwise spirals in the northern hemisphere and counter-clockwise rotation in the southern hemisphere because of the imposed wind stresses. The Gulf Stream system exemplifies wind driven currents in the northern hemisphere intensified at the western boundary of the Atlantic Ocean because of the Coriolis effect. Beginning in the Caribbean and ending in the northern North Atlantic, the Gulf Stream is one of the world's most intensely studied ocean current systems. On average, the Gulf Stream is approximately 90 km wide and 1,000 m deep. The current speed is fastest near the surface with the maximum speed typically exceeding 2 m/s [9], [10] and [11]. The Gulf Stream system's time scales vary from seasonal (stronger in the fall and weaker in the winter) to weekly [12-14]. Stronger meandering occurs primarily downstream of Cape Hatteras, North Carolina.

An ocean current energy converter extracts and converts the mechanical energy of the current into a transmittable energy form such as electricity. A variety of conversion devices have been proposed or are currently under active development. Such devices include water turbines similar to scaled wind turbines driving a generator via a gearbox, and oscillating hydrofoils driving a hydraulic motor. The available in-stream kinetic power per unit area, or power density P_{stream} from ocean currents, is calculated using the equation

$$P_{stream} = \frac{1}{2}\rho V^3 \quad (1)$$

where ρ is the density of water and V is the magnitude of the current velocity. This equation represents the power available at the individual device level.

The total power extraction potential from ocean currents, however, does not simply correspond to the superposition of individual power densities from multiple devices. The dynamics of ocean circulation and accumulative effects of converters need to be considered. A number of ocean

current energy assessments have been performed in the past to evaluate the power potential of the Gulf Stream system. The earliest systematic studies date back to the 1970's. A research project named "Coriolis Program" predicted that an amount of about 10 GW of hydrokinetic power could be extracted from the Gulf Stream using turbines [15]. A more conservative prediction suggested an amount of up to 1 GW of kinetic energy can be extracted from the Gulf Stream by turbine arrays without seriously disrupting climatic conditions [16]. However neither study elucidated on the details of their resource estimates. A recent study by Duerr and Dhanak [17] considered a fraction of the undisturbed kinetic power density in the Gulf Stream as equivalent to the available power potential. They estimated approximately 20 to 25 GW of available hydrokinetic power in the Florida Current based on the computer model Hybrid Coordinate Ocean Model (HYCOM) data. Duerr and Dhanak [17] further stated that the power potential reduces to 1-4 GW if some operational constraints are applied. Yang et al. [18] concluded that kinetic power extraction potential from ocean currents should not be considered equivalent to the undisturbed power density, and the accumulative effect of power extraction on the flow itself needs to be considered. By using a simplified ocean circulation model and including the cumulative effect from power extraction, Yang et al. [19] estimated the upper limit of the theoretical power potential from the Florida Current portion of the Gulf Stream system to be approximately 5 GW for average flow conditions.

The present study provides the characterization of ocean currents along the coasts of the United States from a probabilistic perspective with an emphasis on the energetic Gulf Stream system. A GIS database with a web interface disseminates data to interested parties and the general public. The kinetic energy flux is considered a primary indicator of the kinetic energy reserve, and therefore 30 years of kinetic energy flux time series are predicted and used to provide estimates

of the temporal variation of the kinetic energy transport in the Florida Current with statistical significance. The available power in the undisturbed natural flow condition from the Florida Current is approximated based on assumed turbine parameters.

2. Methodology – Creation of the Database

The creation of the GIS database relies on numerical model data providing high spatial and temporal resolution as well as statistically significant duration (~ 7 years). The US coastal areas have been divided into a number of sub-regions. For regions with multiple model data available, observational drifter data (<http://www.aoml.noaa.gov/phod/dac/index.php>) is used to validate and select the best model data for the database creation. Several different ocean model data from various sources were obtained and compared with ocean surface drifter data in terms of their statistical agreement. The data with the highest statistical agreement with the surface drifter data were selected for each area. The method and procedure of model selection are documented in great detail in [20]. The model selection results are summarized in Table 1 and visually presented in Figure 1. Among all the available ocean model data, Hybrid Coordinate Ocean Model (HYCOM) and Navy Coastal Ocean Model (NCOM) model data have statistically better agreement with the drifter data and therefore were selected for this study. HYCOM is a data-assimilative, hybrid isopycnal-sigma-pressure, primitive equation ocean circulation model that evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM) [21] and [22]. In the HYCOM online data server (<http://www.hycom.org>), two different sets of real-time modeling data are publicly available. HYCOM-NCODA Global Analysis (HYCOM Global) provides a global coverage, while HYCOM-NCODA Gulf of Mexico Analysis (HYCOM GoM) covers the Gulf of Mexico area at finer resolution. NCOM is primarily based on Princeton Ocean Model (POM) and the Sigma/Z-level Model (SZM). NCOM has free surface and is based on primitive

equations and the hydrostatic, Boussinesq, and incompressible approximations [23]. The NCOM data of the U.S. east coast for 2009-2010 were obtained from the Naval Research Laboratory. As shown in Figure 1, on the west and Alaska coasts (blue color), 7 years of global HYCOM data were selected. On the east coast (magenta color), a combination of 2 years of NCOM and 5 years of global HYCOM data were selected. On the Gulf and Florida coasts (red color), 7 years of HYCOM GoM data were selected. The database stores the joint velocity magnitude and direction probability histograms ($P_{i,j}$) computed from 7 years of data as

$$P_{i,j} = \frac{n_{i,j}}{N}, (i = 1, 2, \dots, K; j = 1, 2, \dots, L) \quad (2)$$

where i and j are the indices, and K and L are the number of bins for velocity magnitudes and directions. $n_{i,j}$ is the number of observations in each bin and N is the total number of observations. The joint probability histogram can be calculated based on the entire 7 years of data ($N \approx 2555$) or data from one particular month ($N \approx 210$). The marginal probability histograms (P_i, P_j) can be derived by summing $P_{i,j}$ up along either velocity magnitudes or directions:

$$P_i = \sum_{j=1}^L P_{i,j} \quad (3)$$

$$P_j = \sum_{i=1}^K P_{i,j}. \quad (4)$$

3. Methodology - Dissemination of the Database

An interactive and web-based GIS system has been developed using the selected model data to facilitate dissemination of the ocean current power information to interested users including electric power utilities, policy makers, regulators, and turbine manufacturers. The webpage can be accessed at <http://www.oceancurrentpower.gatech.edu/>. The GIS tools allow the user to

interact with the ocean current database. The ocean current data is stored in a geodatabase that enables the search query function via a rich internet application (RIA) supported by ArcGIS server. Users can interact with the map using the pull down menus on the top or widgets on the right side of the page. Besides the map navigation functions, the RIA also enables users to identify the source data, retrieve the ocean current information for a given location, and export the selected data. In summary, this system provides the following capabilities:

- View GIS layers and map display of monthly and yearly mean surface currents and power densities.
- View and download velocity probability distribution along the U.S. coastline at a number of different water depths.
- Download monthly and yearly mean surface current velocities and power densities for various regions.

This website provides functionality similar to the tidal energy website (<http://www.tidalstreampower.gatech.edu/>) documented in Defne et al. [24]. Key components were modified as described below to further enhance the technical capabilities.

3.1. Data Layers

The web page consists of multiple layers (one data points layer and a set of color mapped raster layers) that can be switched on and off from the data layers widget. The color mapped raster layers include maps of the water depth, the mean current speed for each month and the total, and the mean kinetic power density. These layers are generated by interpolating the model results from computational grids onto an ArcGIS raster grid and serve for a rapid visual examination. The data point layer contains more detailed information that corresponds to actual model grid

points and can be queried through the interactive tools, and is therefore more suited for in-depth analyses.

Figure 2 shows an example of the web interface (<http://www.oceancurrentpower.gatech.edu>) that has the map of the United States in the background with the map of the mean surface current speed along the coastline on top. The web interface has four interactive buttons (“Map”, “Navigation”, “Tools” and “Help”) on the top and multiple widget windows on the right. A pull down menu will appear once the mouse pointer hovers on the button icon. On the right of the screen is the area of interactive widgets. Corresponding widget windows will appear in this area upon activation of different functions. The database also provides different widget windows: “Overview map”, “Data layers”, and “Show legend”. The “Overview map” widget shows the location of the current map view in the context of the larger geographical area. The “Data layers” widget toggles between 15 different data layers on the map to display. The “Show legend” widget shows the legend for data from all different layers.

3.2. Identify Tool

The Identify tool under the “Tools” menu shown in Figure 2 is used to identify a single data point either by clicking on the map or by specifying a longitude and latitude. The Identify tool returns the model data of the selected point. Both the joint and marginal histograms from the database for ocean current velocity can be plotted for any specific month or the entire year according to Equations 2-4. These histograms facilitate an overview of the probabilistic nature of the ocean current resource at a selected location. Similarly, the vertical variation of the current speed at corresponding locations can also be plotted with the identify tool. Once a data point is identified, the point will be highlighted in green, and information including longitude, latitude,

water depth, mean current speed, mean power density and speed standard deviation will show in the widget window. Further instructions will also be given in the widget window to show plots of “Vertical speed profile”, “Joint probability histogram”, “Marginal probability histogram” or “Download spreadsheet”. For example, Figure 3 shows an example of the vertical structure of current speed profiles for a location approximately 20 miles offshore from West Palm Beach, Florida (26.912N, 79.680W) generated by the database. Figure 3a shows the monthly variability of the vertical structure of the velocity and Figure 3b shows the variability in the vertical structure in terms of the standard derivation around the mean value. Figure 3 illustrates how the vertical structure of the current speed at this particular location remains similar with mostly an increase in velocity magnitude for higher flow conditions.

Figures 4a and 4b show the annual joint and marginal probability histograms of the surface current velocity according to Equations 2-4 for the same location (26.912N, 79.680W) respectively. Figure 4a provides the distribution of current velocity in both magnitude and direction in a polar coordinate system, and helps users identify the dominant current speed and direction. The distance from the origin to the bright red area in the joint histogram in Figure 4a indicates the dominant velocity magnitude (~ 1.8 m/s) and the angle indicates the dominant velocity direction (~ 90 degrees). The distribution is calculated based on 7 years of daily snapshot data subject to uncertainty, which is addressed with a certain confidence interval level. A brief discussion on the confidence interval for the probability distributions provided from this database is given in the Appendix.

3.3. Filter Tool

The filter tool also under the “Tools” menu is used to download data at selected grid points. A single point or multiple points can be selected using the filter tool by drawing a rectangular window or polygon. Data in the selected area can be filtered based on the water depth, mean current magnitude or mean power density specified by the user or a combination of them prior to downloading. This provides the user with the option to focus on the areas meeting certain criteria such as a minimum depth or a minimum speed. A SQL Server database was created to store a copy of the non-spatial tabular data in the geodatabase to improve the performance of the export functions. A REST Web service was developed through Visual Studio .NET that executes a SQL transaction to implement the search query over the SQL Server database to generate the output spreadsheet. This approach provides a rapid response time. Once an area is selected by the user, a button will appear to prompt the user to download a spreadsheet. The spreadsheet includes geographical coordinates, the modeled depth, the mean surface current speed for each month and one entire year, the current speed standard deviation, the mean power density and the name of the region for each grid point in the selected region.

4. Results - Variability of the Florida Current

The GIS map of the mean surface current power density shows that the Florida Current has the highest power density ($> 2000 \text{ W/m}^2$) along the United States coast. Therefore extracting renewable energy from ocean currents in this region is particularly attractive for local electricity needs because of the proximity of the Florida Current to the large population in southeastern Florida metropolitan area ($< 50 \text{ km}$). This section, therefore, presents an in-depth analysis of the variability of ocean currents from the Florida Current in the context of ocean current kinetic energy extraction.

4.1. Data Validation for the Florida Current

Model validation is conducted for this region based on two additional measurement datasets: submarine cable data and Acoustic Doppler Current Profiler (ADCP) data. The telecommunication cables running almost perpendicularly across the Florida Strait from West Palm Beach, FL to Eight Mile Rock, Grand Bahamas Island (<http://www.aoml.noaa.gov/phod/floridacurrent/>) can be used to measure the volume transport through the Florida Strait. This measurement is based on the working principle that the flow through the earth's magnetic field can induce a voltage in the cable providing a measure of the volumetric flow after calibration [25]. The volume flux obtained from the submarine cables can be used to explore correlations between volume flux and kinetic energy flux in the Gulf Stream. The long cable data measurement record (from 1982 to present) provided by the Atlantic Oceanographic and Meteorological Laboratory of NOAA is extremely valuable. Figure 5 shows the comparison of the 30-day running averaged volume flux in the Florida Current between HYCOM GoM model data and the submarine cable measurement from 2004 to 2010. The mean volume flux is 31.6 Sv from HYCOM GoM and 31.3 Sv from the cable measurement. In addition, the correlation coefficient between the two time series is approximately 0.77, indicating strong agreement between two datasets. This verifies the quality of the model data in predicting the bulk flow properties in the Florida Current.

In Figure 6, the vertical structure of the current speed averaged over one-year period of record from HYCOM GoM data is compared with ADCP data provided by the Southeast National Marine Renewable Energy Center at Florida Atlantic University (<http://snmrecwebext.eng.fau.edu/resource-measurement-modeling/available-data/>) for the same period of time and location. Figure 6 shows the comparison in terms of the mean, minimum and

maximum current speed. The model data accurately predicts the mean vertical speed profile as well as the minimum and maximum speed for this selected location. This verifies the quality of the model data in reproducing realistic vertical flow structures within the Florida Current.

A more detailed validation of the HYCOM model is provided by Neary et al. [26] with emphasis on the high power density region in the Florida Strait. Their aim was to examine the deviation of HYCOM GoM outputs from the HYCOM GLOBAL model, and those based on three independent observation sources: NOAA's submarine cable transport data, Florida Atlantic University's (FAU) ADCP data at a high power density location, and the Southeast Coastal Ocean Observing Regional Association's (SECOORA) HF radar data in the high power density region of the Florida Strait. Comparisons with these three independent observation sets, and HYCOM GLOBAL outputs, indicate discrepancies with HYCOM model outputs. Overall the HYCOM GoM model can provide a best-practical assessment of the ocean current hydrokinetic resource in high power density regions like the Florida Strait. However, predictions may be improved through advanced data assimilation and model forcing for periods with less accurate predictions of temporal transport variation. Large scale ocean currents such as the Gulf Stream system are primarily driven by winds. However other factors could also affect the characteristics of the current velocity, such as the rotation of the earth, density differences, tides, river discharge, surface air pressure differences, bottom friction, and ocean topography. Therefore the fluctuation of current velocities varies with different time scales from hours to weeks to years. Tides cannot be resolved in our analysis since time series of daily velocities are used in this study. Further additional independent observational data sources may be included to improve predictions.

4.2. Spatial variability in the Florida Current

The spatial variation of the Florida Current is investigated by examining the distribution of the mean and standard deviation (STD) of the current speed on the ocean surface as well as in a vertical cross-section plane shown in Figures 7 and 8. The portion of the Gulf Stream system in the Florida Strait (i.e. the Florida Current) is shown to be predominantly flowing northward. The core of the current where the flow is the strongest is concentrated within about 100 m of the surface layer and spans about half of the channel width. The core of the Florida Current is slightly offset westwards of the channel centerline (Figures 7a and 8a) reducing the potential cost of transmitting extracted power to shore, assuming extraction devices are likely to be deployed close to the core of the current flow. Figures 7b and 8b show the level of variability of the current speed in the Florida Current. The highest temporal variability in the Florida Current is located on the edge of the strongest current facing the Florida shoreline. The variability of the core of the current is relatively weak. Comparing daily and monthly snapshots of the current speed distribution shows that high variation usually occurs near the edge as a direct result of the meandering and seasonal broadening of the core of the current flow. The ratio of standard deviation to the mean value, also known as the coefficient of variation, is plotted in Figures 7c and 8c, which show a low level of variability inside the core of the current and relatively high variability outside the core. According to the GIS maps from the database, as the current flows northward past the Florida Strait, the variability increases partly because of the decrease of geographical constraint from the bathymetry.

4.3. Temporal variation of the kinetic energy flux in the Florida Current

The kinetic energy flux is a primary indicator of the undisturbed hydrokinetic energy reserve in ocean currents. The kinetic energy flux E_f in the Florida Current can be integrated from HYCOM data as

$$E_f = \frac{1}{2} \rho \int |\vec{V}|^2 \vec{V} \cdot d\vec{A} \quad (5)$$

where ρ is the water density, $\vec{V}$ is the velocity vector and $d\vec{A}$ is the cross-sectional vertical area.

The mean level of energy flux in the Florida Current is calculated from 7 years of model data to be approximately 22.6 GW with variability at multiple time scales from weeks to years.

The change of energy flux at different levels in the water column is examined by integrating the energy flux density across the channel width but not over depth. Figure 9 shows the kinetic energy flux density (GW/m) as a function of the depth for 4 different months and the annual mean. The general shape of different curves in Figure 9 is similar to the vertical profile of the current speed, strongest near the surface and weakest near the bottom. Figure 9 also shows that more than half of the total kinetic energy flux is concentrated in the upper 200 m of the water column in the Florida Current. Monthly variability becomes negligible below 100 m water depth, implying that the monthly variability mostly results from seasonal variation of surface momentum flux such as surface wind stress. The summer season features the highest level of energy flux while winter has the lowest. February and May have flux levels comparable to the annual mean.

The kinetic energy flux is of great interest in this study since the goal is associated with estimating power potential from ocean currents. The cable measurements provide 30 years of

volume flux in the Florida Current; however, there is no measurement of the kinetic energy flux, and the time series of kinetic energy flux data is limited to the 7 years of model data. Therefore it is meaningful to seek a solid relationship between volume flux and kinetic energy flux so that longer and statistically more significant record of kinetic energy flux can be projected based on 30 years of historical volume flux data from the cable measurement. To establish a statistical relationship between volume flux and kinetic energy flux, the 7 years of HYCOM data is divided into two groups, 2004 to 2006 and 2007 to 2010. The data from 2007 to 2010 is used to establish an empirical statistical relationship between volume flux and energy flux in the Florida Current. The time series of the volume and kinetic energy fluxes of 2007-2010 are plotted in Figure 10a. The empirical statistical relationship between volume and kinetic energy fluxes is then established with a least square fit in the following form

$$E_f = aQ^n \quad (6)$$

with coefficients a and n to be determined. The fitted curve is shown in Figure 10b with coefficients $a = 0.001592$, $n = 2.766$ and $R^2 = 0.72$.

To test the robustness of this empirical relationship, the volume flux data of 2004-2006 from the cable measurement is used as input in the above equation. A time series of the predicted kinetic energy flux for 2004-2006 is therefore generated as the output. Figure 11 shows the time series of kinetic energy flux from both the HYCOM model data and from the prediction by the cable data for 2004-2006. A 30-day running average is applied to both signals for smoothing. Some months of cable data are missing, and therefore result in a number of gaps in the data predicted by the cable measurement. The actual time series (blue) and the prediction (red) in Figure 11 have reasonable agreement featuring a correlation coefficient of approximately 0.70.

The above experiment verifies the robustness of the empirical statistical approach in predicting kinetic energy flux from volume flux by the cable measurement. Therefore a more dependable relationship between volume flux and kinetic energy flux from longer duration of data in the Florida Current is computed based on 7 years of HYCOM data with $R^2 = 0.75$:

$$E_f = 0.001598 Q^{2.764} (GW) \quad (7)$$

The 30-year time series of kinetic energy flux computed using Equation 7 with 30-day running average is then calculated and plotted in Figure 12 together with 95% confidence interval. The predicted mean kinetic energy flux from 30 years of cable data is about 22.8 GW, and the standard deviation is about 5.4 GW.

Figures 13 and 14 show both monthly and yearly variations of the mean kinetic energy flux computed based on 30 years of data. The 95% confidence interval for the monthly mean energy flux is also plotted in Figure 13 as error bars to resolve the uncertainty. The much longer duration of data record (30 years) provides a narrower confidence interval demonstrating the improved level of confidence. The mean kinetic energy flux is the highest in the summer, particularly in July when the peak occurs (~25.57 GW). The lowest mean energy flux occurs in November (~20.30 GW), which is in agreement with previous findings. The kinetic energy flux also shows very strong year to year variability as seen in Figure 14. The annual mean power reaches a high 27 GW in 2002, and a low 18 GW in 1991.

5. Results - Available Power

From a practical point of view, it is helpful to quantify the undisturbed kinetic power in terms of hypothetical turbine arrays. Although this approach is neglecting the effects of extraction, it

helps to determine the approximate size and capacity of turbine arrays necessary to extract a certain amount of power. To examine the undisturbed kinetic power from hypothetical turbine arrays, it is assumed that turbines are uniformly deployed 50 m below the sea surface in the Gulf Stream and current velocities from the database are used to calculate the power. The principle velocity component in the Florida Current is northward along the channel, and the undisturbed kinetic power (P_k) from this turbine array is estimated using

$$P_k = \Sigma \frac{1}{2} \rho |V|^3 E_f A_s A_c N \quad (8)$$

where V is the current speed at the assumed turbine depth, ρ is the water density (1025 kg/m³), E_f is the assumed efficiency (40%), A_s is the swept area of device (1600 m²), A_c is the surface area of computation cell (~16 km²) and N is the assumed number of devices per unit surface area (1/4km²) corresponding to 2 km spacing between devices. Open ocean turbine technology is not yet fully developed and tested; therefore it is not possible to obtain all the technological details of turbines to be used for the Florida Current. Estimates are based on assumed turbine parameters, but any modification would produce a corresponding linear change in the total power estimate. Equation 8 also does not account for operational availability or downtime for maintenance and repairs.

The turbine region is specified within a box area covering the water area between Florida to the Bahamas shown in Figure 15. Turbines are assumed to be uniformly deployed in this area with the specified parameters. From a technological point of view, most devices require a minimum “cut-in” flow speed at which devices will start producing power. Therefore devices should only be deployed in areas where the mean speed exceeds a certain threshold. For this analysis the

threshold is set to 1 m/s, which reduces the surface area of the turbine region to the area marked by black dots shown in Figure 15 (approximately $2.0 \times 10^4 \text{ km}^2$).

Figure 16 shows the average monthly variation of the power generation from this hypothetical turbine array with error bars representing the level of uncertainty. The peak power is shown to occur in July and reaches almost 7 GW and the lowest power occurs in November and is about 4.3 GW. The annual mean kinetic power from this hypothetical turbine array is about 5.2 GW corresponding to a mean power per device of approximately 1.1 MW based on approximately 4500 devices installed. In the analytical analysis of the theoretical power potential from the Florida Current by Yang et al. [19], the theoretical maximum power potential from the region with comparable surface area representing the Florida Current is approximately 5.1 GW, comparable to the estimated P_k from Equation 8.

Comparison between the estimated P_k and the theoretical power potential from the Florida Current shows the feasibility of achieving the theoretical power limit by the commonly used approach based on undisturbed power density when typical, but still hypothetical, turbine parameters are used. However the estimate of P_k carries uncertainty and could vary significantly by adjusting turbine parameters. In addition, the estimate of P_k based on undisturbed power density is only meaningful when the accumulative effect of power extraction on the flow field is relatively small. The flow speed will be reduced as an increasing amount of energy is extracted and consequently a larger number of turbines will be needed to extract the same amount of power. Therefore the estimate of P_k based on the undisturbed velocity field is only useful for providing an order of magnitude for the number of devices, and is not recommended to be used solely for determining the maximum available power.

6. Conclusions

The ocean currents along the U.S. coastline were characterized by using 7-year ocean model data collected from various sources. The selected ocean model data were used to develop a geodatabase that maps the ocean current energy resource distribution for the entire U.S. coastline, and also provides a database of the joint velocity magnitude and direction probability histograms for offshore areas within approximately 200 miles of the U.S. coast. The ocean model data were validated using submarine cable and ADCP measurements, and results indicate a reasonable accuracy of the model data allowing a best-practical prediction. The database is accessible through a web interface <http://www.oceancurrentpower.gatech.edu>, which provides rapid visual examination of the resource distribution. The web interface also provides tools to view, identify, query and download data from the database. The GIS maps illustrate that the Florida Current has the highest mean surface power density among all ocean current sites within the U.S., with a mean surface power density exceeding 2000 W/m^2 , while most of the U.S. offshore waters have a mean surface power density lower than 100 W/m^2 . The majority of the kinetic energy in the Florida Current is concentrated in the upper 200 m of the water column.

The Florida Current features characteristic seasonal variation, with the current flow being stronger in the summer time and relatively weaker in the winter time. Strong seasonal variability is prevalent in the upper layer of the water column (approximately upper 100 m), while the variation in deeper water is negligible, indicating an apparent correlation between the seasonal variability of the transport in the Florida Current and the seasonal variation of the surface wind stress. As the Gulf Stream flows northward past Cape Hatteras into the wide open ocean, the variability greatly increases.

High kinetic power density is a good indicator of the rich kinetic energy potential from ocean currents. A 30-year kinetic energy flux series was predicted in this study to estimate the temporal variability of the Florida Current with high statistical significance. The available power associated with the undisturbed natural flow condition from the Gulf Stream system is estimated using assumed turbine parameters purposefully selected to match the total theoretical power estimate of approximately 5GW from [19]. Even if only 30% of this power is recovered, the power generation will be more than that from a typical nuclear reactor, enough to support a million homes based on the information published by the U.S. Energy Information Administration [27].

Successful development of renewable energy generation requires approaches that are technically feasible, economically viable, socially acceptable, and environmentally compatible [28]. This may lead to a number of additional constraints. Power extraction from ocean currents could have significant effects on the local and global flow hydrodynamics, and, therefore could possibly change the water quality, sediment transport, and cause other ecological impacts. These issues need to be addressed when developing an ocean current energy site.

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Appendix A

The probability distribution of the current speed from the GIS database

(<http://www.oceancurrentpower.gatech.edu/>) shows the probability of a current speed residing in particular intervals. The level of confidence interval of the probability distribution quantifies the uncertainty associated with the distribution. In general, the estimator of proportion in each interval $\hat{p}$ is given by

$$\hat{p} = \frac{X}{n} \quad (\text{A.1})$$

where X is the number of elements in the interval, and n is the total number of elements. When n is large, the sample proportion $\hat{p}$ is well approximated as normal with mean $\hat{p}$ and standard

deviation $\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$ [29]. Therefore a confidence interval for $\hat{p}$ is given by

$$\left(\hat{p} - z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}, \hat{p} + z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \right) \quad (\text{A.2})$$

where $z_{\frac{\alpha}{2}}$ denotes the upper $\frac{\alpha}{2}$ point of the standard normal distribution. For a 95% confidence interval, $\alpha = 0.05$, $z_{\frac{\alpha}{2}} = 1.96$. Using 7 years of daily data, $n \approx 7 \times 365 = 2555$. Defining

$\gamma = z_{\frac{\alpha}{2}} \sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$, γ is computed as a function of probability $\hat{p}$, as shown in Figure A.1a. For

example, Figure A.2a shows the example of the probability of surface ocean current speed at (26.912E, 79.600W). For a certain speed value (e.g. ~ 1.52 m/s), there is a corresponding

probability p' (0.06) as marked by the dash line in Figure A.2a. In Figure A.1a, $p' = 0.06$

corresponds to a value of $\gamma' \approx 0.0095$. Therefore the confidence interval for $p' = 0.06$ is

approximately $(p' - \gamma', p' + \gamma')$ or $p'(1.52 \text{ m/s}) = 0.06 \pm 0.0095$. The dashed curves in Figure

A.2a show the 95% confidence interval for the probability distribution of the current speed. Similarly, for the monthly probability histograms estimated from 7 years of data, the total number of elements $n \approx 7 \times 30 = 210$. The procedure to obtain 95% confidence interval of the probability is the same, but a different curve for the confidence interval as shown in Figure A.1b, needs to be used as illustrated by the example provided in Figure A.2b. Clearly the uncertainty for the monthly distribution is much higher due to the reduction in the number of data points.

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Figure 1: Map showing different colors representing different combinations of selected model data used to create the database for different regions.

Figure 2: The GIS map of the mean surface ocean current speed with pull down menus at the top and interactive widgets on the right (<http://www.oceancurrentpower.gatech.edu>).

Figure 3: An example of vertical structure of the current speed at (26.912N, 79.680W): (a) monthly variation and (b) annual average plus or minus the standard deviation (STD); red dots and stars highlight the annual mean velocity profiles.

Figure 4: An example of the (a) joint and (b) marginal probability histograms of surface current velocity at (26.912N, 79.680W).

Figure 5: Comparison of 30-day running averaged volume flux in the Florida Current from cable measurement and from HYCOM GoM model data.

Figure 6: Comparison of one-year averaged vertical current speed profiles between ADCP measurement and HYCOM GoM data at approximately (26.07N, 79.84W).

Figure 7: Florida Current: (a) annual mean surface current speed, (b) standard deviation, and (c) the coefficient of variation.

Figure 8: Cross-sectional distribution of (a) the annual mean current speed, (b) the standard deviation, and (c) the coefficient of variation in Florida Current at the latitude of 26.6264N.

Figure 9: The vertical kinetic energy flux density in the Florida Current for arbitrary months (Feb., May, Jul., and Nov.) and the annual mean.

Figure 10: (a) Time series of the volume and kinetic energy flux (2007-2010) from HYCOM model data, and (b) the least square fit of the relationship between volume and kinetic energy flux with 95% confidence interval based on data from 2007 to 2010.

Figure 11: Comparing 30-day running-averaged kinetic energy flux prediction from 2004 to 2006 from cable data with the energy flux calculated from HYCOM model data.

Figure 12: Projected 30-year time series of 30-day running averaged kinetic energy flux using historical cable data with 95% confidence interval.

Figure 13: Monthly variation of mean kinetic energy flux with a 95% confidence interval based on projected 30 years of kinetic energy flux.

Figure 14: Yearly variation of mean kinetic energy flux in the Florida Current based on projected 30 years of kinetic energy flux (cable data in the year of 1999 is missing).

Figure 15: Map with the box showing the original turbine area and black dots representing the area with mean current speed exceeding 1m/s.

Figure 16: Monthly variation of total kinetic power in the Florida Current with 95% confidence interval.

Figure A.1: Confidence interval profiles for probability estimation based on (a) daily data of 7 years, and (b) daily data for an individual month of 7 years.

Figure A.2: An example of the probability distribution and 95% confidence interval of surface current speed at (26.912E, 79.600W) estimated from (a) daily data of 7 years, (b) daily data of only December.

Table 1: Ocean model data selected for different areas along the United States coast.

Location	Selected Model (time-span)
East coast	HYCOM Global (5yrs) & NCOM (2yrs)
Florida Strait	HYCOM GoM (7yrs)
Gulf of Mexico	HYCOM GoM (7yrs)
West, Alaska and Hawaii coasts	HYCOM Global (7yrs)

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8

Figure9

Figure10

Figure11

Figure12

Figure13

Figure14

Figure15

Figure16

Figure A.1

Figure A.2