Proceedings of the 2nd Marine Energy Technology Symposium
METS2014
April 15-18, 2014, Seattle, WA

MODELING IMPACTS OF ENERGY EXTRACTION FROM THE GULF STREAM SYSTEM

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ABSTRACT

Ocean currents are an attractive source of clean energy due to their inherent reliability, persistence and sustainability. The Gulf Stream system, particularly the Florida Current, is of interest as a potential energy resource for some coastal states within the USA. However, little is known about the potential impacts of extracting energy from this unconfined flow field. The presented study takes two approaches to evaluate the modifications of the flow field upon extraction of significant energy from the Florida Current. First, the theoretical momentum balance in the Gulf Stream system is examined using the two-dimensional ocean circulation equations based on the assumptions of the Stommel model for subtropical gyres with additional turbine drag formulated and incorporated into the model to represent power extraction by turbines. The impact of the extraction is evaluated by examining the new circulation patterns such as the flow diversion around the turbine extraction region. Secondly, a full numerical simulation of the ocean circulation in the Atlantic Ocean is performed using Hybrid Coordinate Ocean Model (HYCOM) and power extraction from the Florida Current is modeled as additional momentum sink. Various scenarios with different turbine distributions are tested. Effects of power extraction are shown to include flow rerouting from the Florida Strait channel to the east side of the Bahamas. Other effects, such as changes to the residual kinetic energy as well as the water level variations are also evaluated for different scenarios.

1 INTRODUCTION

There is a growing interest in renewable energy around the world. In the past three decades global energy consumption has almost doubled [1], while it is predicted that the global fossil fuel reserves will last no more than one century [2]. Reducing fossil fuel imports from foreign regions can also improve domestic energy independence. Renewable energy has great benefits compared to fossil fuels, including environmental improvement, fuel diversity and national security if it can supply a significant portion of the country's energy needs. Furthermore, renewable energy industry investments will most likely be spent on materials and infrastructure rather than on energy imports, and therefore will help spur local economies by creating more jobs [3].

One frontier of renewable energy is in the ocean. Although oceans cover more than 70% of the earth's surface and are promising reservoirs of alternative energy resources, energy production from the ocean presently makes up a negligible portion of our daily energy supply. However, it was predicted that the worlds electricity produced by ocean based devices could reach more than 7% by 2050 [4]. In countries with coastlines, coastal areas are usually home to a wealth of natural and economic resources and are typically among the most developed areas in the country. Renewable energy from the coastal and offshore regions can be conveniently used to supply the most populated areas in the country if harvested efficiently from the ocean. Fast moving ocean currents are a significant reservoir of kinetic energy. Since water is about 800 times denser than air, ocean currents of about 1/9 the speed of wind have comparable kinetic power density with wind.

Ocean currents are the continuous flow of ocean water in certain directions. However, ocean currents can vary greatly in terms of their dominating driving forces, spatial locations, and temporal and spatial scales. The major driving forces for large scale currents (on the order of 1000 km length-scale) include wind stress, temperature and salinity differences (or associated density difference). Besides these, 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 by coastal long waves, for example).

Surface ocean currents are generally wind driven and de-

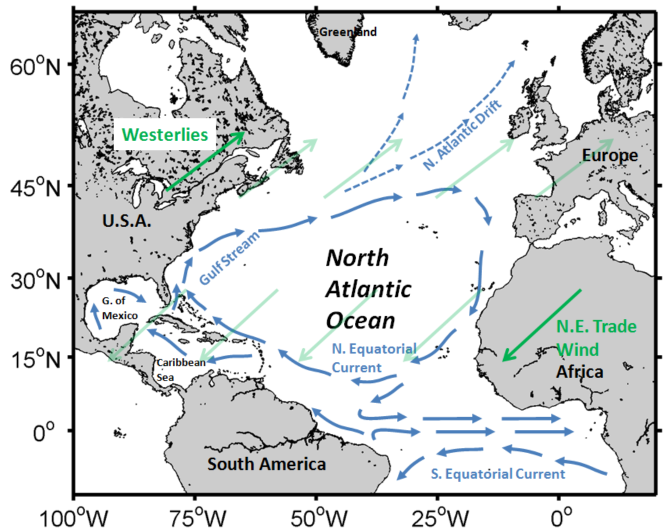

FIGURE 1. SCHEMATIC OF THE NORTH ATLANTIC SURFACE OCEAN CIRCULATION.

velop their typical clockwise spirals in the northern hemisphere and counter-clockwise rotation in the southern hemisphere. The Gulf Stream system is an example of wind driven currents in northern hemisphere, which is intensified at the western boundary of the Atlantic Ocean due to Coriolis effect (see Figure 1). Beginning in the Caribbean and ending in the northern North Atlantic, the Gulf Stream is one of the world's most intensely studied current systems. On average, the Gulf Stream is approximately 90 km wide and 1000 m deep. The current velocity is fastest near the surface, with the maximum speed typically exceeding 2 m/s [5–7]. The average volume flux in the Florida Current is approximately 31 Sv, and the kinetic energy flux approximately 22 GW [8]. The variability of the Gulf Stream occurs on multiple time scales, from seasonal to weeks [9, 10].

An ocean current energy converter extracts and converts the mechanical energy in the current into a transmittable energy form. A variety of conversion devices are currently being proposed or are under active development, from a water turbine similar to a scaled wind turbine, driving a generator via a gearbox, to an oscillating hydrofoil which drives a hydraulic motor. The available in-stream power per unit area, or power density P_{stream}, is calculated using the equation

$$P_{stream} = \frac{1}{2}\rho V^3 \tag{1}$$

where ρ is the density of water and V is the magnitude of the velocity. This represents the power available at the individual device level. However, the total power extraction potential from ocean currents is not simply superposition of power density from individual devices. The dynamics of ocean circulation and accumulative effects of converters need to be accounted. Various ocean current energy assessment studies have been performed for the Gulf Stream system. The earliest systematic research programs on ocean current energy assessment for the Gulf Stream date back to 1970s. 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 [11]. A more conservative prediction suggested an amount of up to 1 GW kinetic energy can be extracted from the Gulf Stream by turbine arrays without seriously disrupting climatic conditions [12]. However neither study elucidated on the details of their resource estimates. A recent study considered the power potential as a fraction of the undisturbed power density and predicted 20-25 GW of available power from the Gulf Stream [13]. However it is believed that kinetic power extraction potential from ocean currents is not equivalent to the undisturbed power density and the effect of power extraction on the flow itself needs to be evaluated [8]. By using a simplified ocean circulation model and including the cumulative effects from power extraction, it was estimated that the upper limit of the theoretical power potential from the Florida Current portion of the Gulf Stream system to be approximately 5 GW in average flow conditions [14].

Energy extraction from the Gulf Stream could disrupt the natural flow condition and have significant impact on the background flow. However, effects of energy extraction from the Gulf Stream system are still largely unknown. This study takes two different approaches to evaluate the modifications of the flow field due to energy removal from the Gulf Stream system, particularly the Florida Current. One approach utilizes a two-dimensional idealized ocean circulation model and represents the presence of turbines as linearized drag force. The other approach features a more realistic representation of the Gulf Stream system with a full numerical simulation of the North Atlantic circulation. Impacts of energy extraction are evaluated in terms of the changes in surface current speed, energy flux and Sea Surface Height (SSH) in the vicinity of the power extraction site.

2 IDEALIZED OCEAN MODEL

An analytical model based on the assumptions proposed by Stommel [15] is applied to investigate energy dissipation from added turbines, a more realistic measure of extractable energy resources from the Gulf Stream system. The computational domain is a simplified rectangular basin with a flat bottom representing the North Atlantic Basin. The positive x direction ($0 \le x \le a$) is aligned with longitudinal direction (eastward) and the positive y ($0 \le y \le b$) is aligned with latitudinal direction (northward). The horizontal extensions of the idealized basin are based on the real dimensions of the North Atlantic Basin.

2.1 Governing Equations

Water density is constant and the flow is assumed steady in this simplified ocean model. In the ocean, the advective terms (nonlinear terms) are much smaller than the Coriolis term (i.e. Rossby Number $\ll 1$), and therefore can be neglected in this simplified model [16]. The reduced shallow water quasi-geostrophic equations consist of two horizontal momentum equations and the continuity equation:

$$-fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + (F_x + W_x)/\rho \tag{2a}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + (F_y + W_y)/\rho \tag{2b}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2c}$$

where $\rho(kg/m^3)$ is the water density, $p(kg\ m^{-1}s^{-2})$ is the pressure, $f(s^{-1})$ is the Coriolis parameter, W_i is the surface wind stress in i direction, F_i is the opposing forces associated with natural friction, turbulence, and turbine drag in i direction ($i = x, y$). (x, y) are the east-west, north-south coordinates, and (u, v) are two corresponding horizontal velocity components. The pressure is assumed to be hydrostatic. Wind stress and friction forces are simplified as suggested by [15]. By introducing the streamfunction ψ to reduce the number of unknowns and using a linear drag function, the governing equation can be simplified to (refer to [17] for more mathematical details)

$$\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right) + \frac{H\beta}{C_d}\frac{\partial\psi}{\partial x} = \frac{\tau_0\pi}{\rho b C_d}\sin(\frac{\pi}{b}y), \tag{3}$$

where β is the β plane approximation constant, H is the ocean depth, $u = \frac{\partial\psi}{\partial y}$ and $v = -\frac{\partial\psi}{\partial x}$, C_d is the drag coefficient, and τ_0 is the maximum wind stress. The streamfunction can be solved analytically as

$$\psi(x,y) = \frac{b^2}{\pi^2}N\left(\frac{1-e^{m_2 a}}{e^{m_1 a} - e^{m_2 a}}e^{m_1 x} + \frac{e^{m_1 a} - 1}{e^{m_1 a} - e^{m_2 a}}e^{m_2 x} - 1\right)\sin(\frac{\pi y}{b}). \tag{4}$$

where $M = \frac{\beta H}{C_d}$, $N = \frac{\tau_0\pi}{\rho b C_d}$, $m_1 = -\frac{M + \sqrt{M^2 + \frac{4\pi^2}{b^2}}}{2}$ and $m_2 = -\frac{M - \sqrt{M^2 + \frac{4\pi^2}{b^2}}}{2}$. Horizontal flow velocity components can be derived from differentiating the streamfunction with respect to x and y. The model parameters (H, C_d and τ_0) have been calibrated against 7 years of Hybrid Coordinate Ocean Model (HYCOM) data provided by The HYCOM Consortium (http://www.hycom.org) [8]. The calibration ensures that the idealized ocean model reproduces reasonable volume and kinetic energy fluxes for the natural flow condition within the western boundary layer that represents the Gulf Stream current.

2.2 Impacts of Energy Extraction

To incorporate the impact of energy extraction by turbines in the momentum balance, the natural drag coefficient C_d is replaced with $C_d + C_t$, where C_t is the additional drag coefficient representing the turbines. To realistically represent the scenario of extracting power from the fastest western boundary currents, a spatially varying turbine drag coefficient C_t profile is designed such that C_t peaks in the middle of the western boundary where the ocean current is the strongest and decays to zero away from the Gulf Stream region. The turbine drag coefficient profile is specified as

$$C_t(x,y) = C_{t0}e^{-\frac{x^2+(y-\frac{1}{2}b)^2}{\varepsilon}} \tag{5}$$

where C_{t0} is the peak value of the turbine drag coefficient, and ε is a parameter controlling the approximate area of the turbine region. Large ε corresponds to a relatively large area with turbines, while small ε corresponds to a relatively small area with turbines. An example illustrating the spatially varying C_t is shown in Figure 2. The second order partial differential governing equation

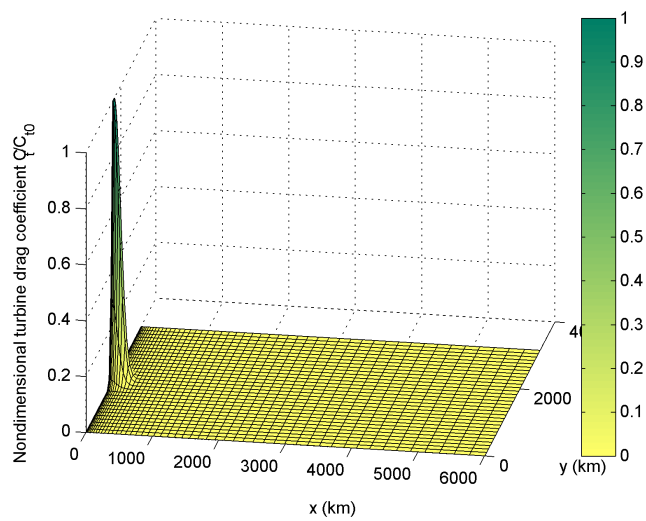

FIGURE 2. DISTRIBUTION OF THE NON-DIMENSIONAL LOCALIZED TURBINE DRAG IN THE GULF STREAM ($\varepsilon = 10^4\ km^2$).

can no longer be solved analytically when the spatially varying

C_t is included; therefore a numerical solution is obtained. A finite difference approach with non-uniform mesh is used to discretize the domain, and the implicit solution is sought. The detailed derivation and validation of the numerical solution can be found in [14]. The total power dissipation from the turbine drag is evaluated by

$$D_{turbine} = \int C_t(x,y,C_{t0},\varepsilon)|V(C_t(x,y,C_{t0},\varepsilon))|^2 dA \qquad (6)$$

Different ε values in Equation 5 result in different scenarios with varying surface area occupied by turbines. When $\varepsilon \approx 1.8\times10^4 km^2$, the surface area with turbines is approximately $2\times10^4 km^2$, close to the actual surface area of the Florida Current. The peak power removal from the flow by turbines in this scenario was found to be about 5 GW with $C_{t0} = 0.08$ [14]. The effect of turbines on the flow field in the Gulf Stream is found to be primarily confined in the neighborhood of the turbine region.

Figure 3 shows the changes in the two velocity components along the western boundary layer ($x = 0$) in response to the localized turbine drag in the Gulf Stream. The meridional (v) velocity in the turbine region decreases significantly due to the high resistance from turbines. The meridional velocity is reduced to about a quarter of the original magnitude at the location with peak energy dissipation by turbines. Outside the turbine region, the meridional velocity change is negligible, therefore creating two residual velocity peaks immediately up and down stream of the turbine region along the western boundary. The zonal (u) velocity responds differently to the additional turbine drag. The zonal velocity changes direction in both the upstream and downstream of the turbine region along the western boundary. The zonal velocity magnitude increases due to the turbine presence. In the upstream, the undisturbed current flow has a westward zonal velocity component. Additional turbine drag inhibits the flow from continuing westward and guides it eastward to get around the high resistance area. Similarly in the downstream, the zonal velocity is eastward when undisturbed, but turns westward with the addition of turbines.

Since the additional turbine drag significantly reduces meridional velocity in the Gulf Stream, and both Coriolis force and natural drag force are linearly related to the velocity magnitude, a corresponding reduction in Coriolis force in zonal direction and reduction in natural drag in meridional direction are also expected. However the added turbine drag compensates for some of the reduction in natural drag, and therefore a significant change in total drag does not occur. Addition of turbine drag reduces the pressure gradient in the middle of the western boundary. Once integrated, the pressure gradient provides the sea surface elevation with the addition of the turbine drag. Figure 4 shows the undisturbed sea surface level (Figure 4a), sea surface level with additional turbine drag (Figure 4b) and their difference (Figure 4c). In the region with additional turbine drag, a significant drop ($> 0.5m$) in the sea surface level is observed. The sea surface level upstream of the obstruction sees a slight water level rise to build up potential energy to get through.

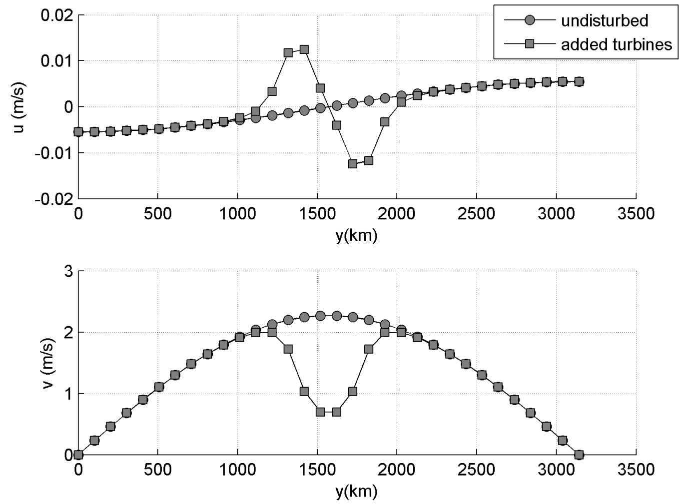

FIGURE 3. COMPARING ZONAL (u), AND MERIDIONAL (v) CURRENT VELOCITY COMPONENTS ALONG THE WESTERN BOUNDARY LAYER ($x = 0$) FOR UNDISTURBED CIRCULATION AND CIRCULATION WITH LOCALIZED TURBINE DRAG.

3 NUMERICAL SIMULATION WITH HYCOM

Although the 2D analytical model presented in section 2 is capable of solving for the bulk flow, the simplification of the 2D model makes it difficult to include the impact of the actual bottom topography and forcings on the currents. Therefore a full numerical simulation of the ocean circulation in the Atlantic ocean is performed with HYCOM to provide more realistic representations of the circulation system. The power extraction with turbines is incorporated in the model's momentum equations as an extra momentum sink and the effects of power extraction are studied.

3.1 Model Configurations

HYCOM is a finite difference, hydrostatic, Boussinesq primitive equation ocean circulation model evolved from the Miami Isopycnic Coordinate Model (MICOM) [18, 19], which has already been subjected to numerous ocean circulation related studies. HYCOM uses orthogonal grids in the horizontal and hybrid coordinate in the vertical. The vertical coordinate is isopycnal in the open, stratified ocean, and smoothly transitions to a terrain-following coordinate in shallow coastal regions. In the

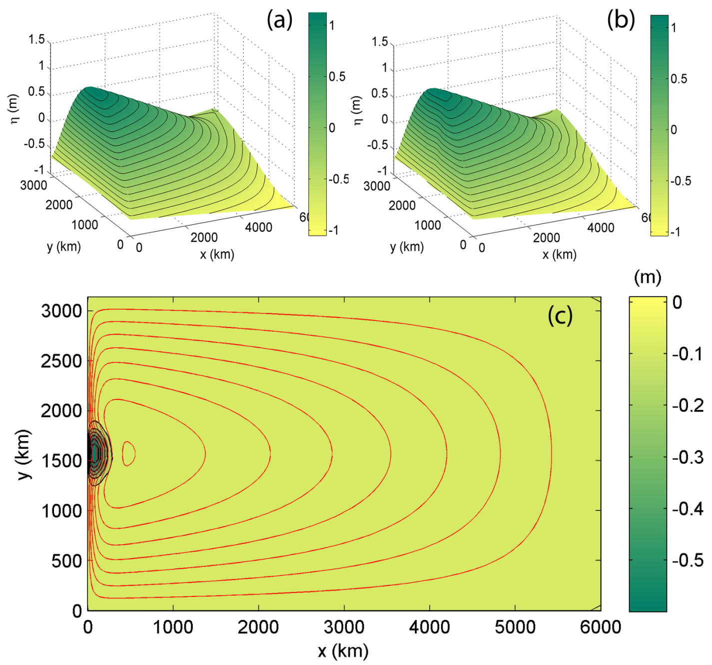

FIGURE 4. OCEAN SURFACE ELEVATION WITH LINES OF CONSTANT PRESSURE FOR (A) UNDISTURBED CASE, (B) CASE WITH ADDITIONAL TURBINES, AND (C) THE SEA SURFACE CHANGE AFTER ADDITIONAL TURBINE DRAG IS ADDED WITH STREAMLINES SHOWING THE CURRENT DIRECTION.

mixed layer or unstratified seas, it uses z-level coordinate. The hybrid coordinate system provides flexible and dynamic options for different regions of the ocean, and extends the geographic range of applicability of traditional ocean circulation models.

The domain is selected to include the majority of the North Atlantic ocean, extending from 98W to 20E in longitude and from 10S to 55N in latitude as shown in Figure 5, such that the model is able to capture the entire subtropical gyre of the Gulf Stream system. The grid points use a mercator projection with the horizontal resolution of 1/5 degree at the equator, sufficiently fine enough to resolve the Gulf Stream current. The number of vertical layers is set to 22. Five-minute resolution global ocean depth and land surface elevation data is used to construct the bathymetry of the computational domain. The ocean depth dataset is developed from multiple data sources and compiled at NGDC (National Geophysical Data Center) [20]. The 5-minute bathymetry data was first interpolated to HYCOM bathymetry, and the ocean depths at the HYCOM grid was averaged over (3×3) grid patch for smoothness. In order to simplify the model domain and remove oceans and inland seas with negligible impact on the subtropical circulation, the Pacific Ocean and the Mediterranean Sea have been landmasked (or removed) from the

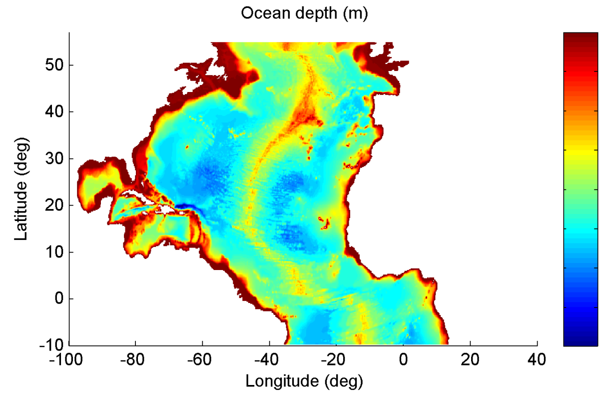

FIGURE 5. HYCOM COMPUTATIONAL DOMAIN WITH BATHYMETRY.

model domain.

The model domain has closed eastern and western boundaries, and has the open ocean boundary located in the southern and northern ends. At the closed lateral boundaries, namely the coastlines, a no-slip boundary condition is applied. At the open lateral boundaries (i.e. the southern and northern lateral boundaries), the boundary conditions are derived from “closing” the open boundaries by forcing zero flow across the boundaries but to strongly relax temperature and salinity to climatology data near the open boundaries. Within a buffer zone of about 5 degrees from the northern and southern boundaries, the model potential temperature and salinity are restored to a monthly ocean climatology obtained from the Naval Research Laboratory (NRL) LEVITUS climatology files [21].

The atmospheric forcing includes surface momentum flux from wind stress, heat flux and fresh water flux. Monthly climatological forcing from the European Center for Medium-Range Weather Forecasts reanalysis (ERA15 [22]) is used to provide surface flux. The ERA-15 archive contains global analyses for all relevant weather parameters from 1979 to 1994. The ocean state is initialized by the salinity and temperature fields interpolated from the Levitus climatology [21]. The North Atlantic subtropic gyre is primarily driven by surface wind stress. Although the mean transport of the Gulf Stream represents the northward return flow of wind-driven southward flow over the interior of the basin, the seasonal variation of the Florida Current is largely due to the variation of the meridional wind stress along the coast [23].

The quasi-geostrophic currents in the North Atlantic ocean spin up and reach equilibrium fairly quickly. The evolution of the region-wide mean kinetic energy for 7 years of the baseline case run from a cold start is used as a proxy of the adjustment process. The region-wide mean kinetic energy starts with an initial spike, which comes from the initial relaxation to climatology at the open boundaries. The mean kinetic energy then decays and

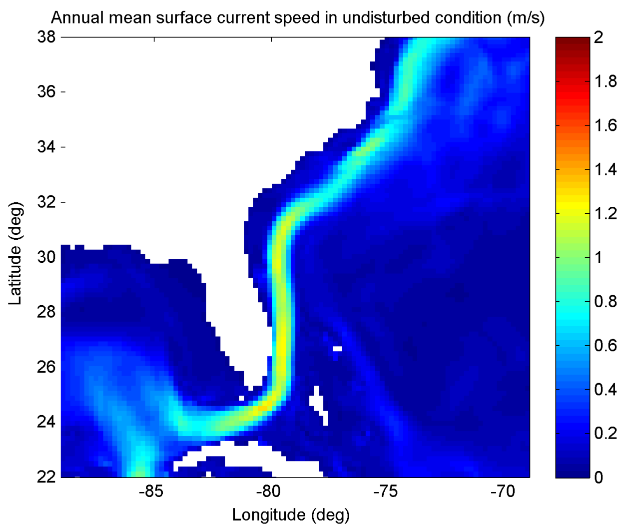

FIGURE 6. ANNUAL MEAN SURFACE CURRENT SPEED FOR THE BASELINE CASE (M/S).

reaches a fairly stable state with fluctuations after approximately one year. Therefore the quasi-geostrophic currents are considered to have reached equilibrium state after 6 years of spin up. Additional turbine drag is added to the model equations at the end of the 6th year. Considering the flow field needs to adjust to the additional turbine drag force to reach equilibrium again, the first 3 months of simulation with power extraction is not used for analysis. Results of 3 years with the power extraction are used for analysis in this study.

The model results in the baseline case show higher current speed and hence higher power density in the Gulf Stream current than ocean currents elsewhere, especially the portion of the Gulf Stream system within the Florida Strait region usually referred to as the Florida Current (Figure 6). The annual mean surface current speed is nearly 2 m/s in the Florida Current, and the top 200 m of the water column in the Florida Current features a mean power density up to 1500 $\mathrm{W/m^2}$.

However, by comparing the volume transport in the Florida Current calculated from model results and from submarine cable measurement, it is found that the model underestimates the volume transport by approximately 15%. Such underestimation has also been documented by [13, 24], and is believed to be associated with insufficient horizontal grid resolution. Therefore, the power estimation is anticipated to be low. While we expect a lower power potential estimate from the model, the model results still provide sufficient data to shed light on the effects of power extraction from the Florida current on the flow field.

3.2 Modeling Turbines

In order to evaluate the effect of power extraction on the flow, the momentum equations of the model in locations where devices are to be deployed are modified. The additional momentum sink by the turbines is included in the governing equations at the computational cells where conversion devices are located. Applying the same method used by Defne [25], the retarding force from turbines per unit cross-sectional area is

$$T_i = -\frac{1}{2} C_{ext} \rho u_i |\vec{V}| \tag{7}$$

where C_{ext} is the extraction coefficient, u_i is one velocity component ($i = x, y$), and $|\vec{V}|$ is the flow speed. The coefficient C_{ext} controls the amount of dissipation due to turbines in the computational cell. The retarding force per unit volume included into the model equations to simulate additional turbine drag is

$$T_i' = -\frac{1}{2} \frac{C_{ext} \rho}{\triangle h} u_i |\vec{V}| \tag{8}$$

where $\triangle h$ is the model layer thickness, which varies with depth and location. The total extracted power by turbines from one vertical layer is then

$$P_l = -\sum_{i,j} \vec{T}'_{i,j} \cdot \vec{V}_{i,j} \triangle x_{i,j} \triangle y_{i,j} \triangle h = \sum_{i,j} \frac{1}{2} C_{ext} \rho |\vec{V}_{i,j}|^3 \triangle x_{i,j} \triangle y_{i,j}. \tag{9}$$

where i and j are horizontal computational grid indices, $\triangle x_{i,j}$ and $\triangle y_{i,j}$ are horizontal grid spacings in x and y directions, and P_l is the extracted power from one computational layer. The total power extraction from the turbine farm is the summation of Equation 9 from all layers with turbines:

$$P_{total} = \sum_l P_l = \sum_{i,j,l} \frac{1}{2} C_{ext} \rho |\vec{V}_{i,j}|^3 \triangle x_{i,j,l} \triangle y_{i,j,l}. \tag{10}$$

where l is the computational layer index.

Turbines are not recommended to be placed in the upper 50 m of water column to prevent navigational hazards, and not deeper than 200 m since the majority of energy flux in the cross-section is concentrated in the upper 200 m of the water column [13]. Therefore, in the following experiments, the momentum sink due to turbines is only added to computational cells between approximately 50 m and 200 m deep in the water, although the depth range of turbine deployment may not be exact given that the HYCOM model uses a combination of non-uniform coordinates including isopycnal, terrain-following and z-level coordinates in the vertical.

In this study, 3 different turbine layouts are discussed. One layout (case 1) represents an extreme scenario in which the horizontal extent of the turbine region occupies the majority of the surface area in the Florida Current. The turbine region extends from about 79.8W to 79.2W in longitude, and from approximately 25.8N to 28.0N in latitude, covering a surface area of approximately 2.1×10^4 km^2. This is a hypothetical case dedicated to studying the possible extreme effects of energy extraction on the flow field. The second layout (case 2) represents a more realistic scenario in which an array of turbines is deployed at approximately 60-100 m deep and extends from 80W to 79W in longitude across the Florida Strait covering a surface area of approximately 1.6×10^3 km^2. The array is located at 26.9N and covers the spacing of one grid cell (approximately 0.2 degree). The third layout (case 3) has the same surface area as case 2, but is oriented along the center of the Florida Current, parallel to the coast. A summary of all three cases is given in Table 1. In case 1, the turbine region occupies a great portion of the water area in the Florida Current, and about 2.4 GW of power is dissipated from the turbines. Although no explicit relationship between C_{ext} and turbine parameters has been established, it was estimated that turbines on the order of 4000 will be needed to achieve the power extraction in case 1 if cumulative effects of turbines are neglected [26]. Case 3, although has the same turbine area as case 2, dissipates slightly more energy from the turbines than case 2. It indicates that the arrangement of turbines along the center of the Florida Current where the flow is the strongest can harvest more power than placing the same number of turbines perpendicular to the flow direction across the channel.

TABLE 1. SUMMARY OF 3 DIFFERENT POWER EXTRACTION CASES.

Cases	Approx. surface area (km^2)	Approx. depth (m)	Extraction coefficient	Mean power (GW)
case 1	$2.1 \times 10^4 km^2$	50-200	0.02	2.4
case 2	$1.6 \times 10^3 km^2$	60-100	0.2	0.4
case 3	$1.6 \times 10^3 km^2$	60-100	0.2	0.6

3.3 Effects of Power Extraction from the Florida Current

The additional turbine drag slows down the current flow through the Florida Strait channel and causes reduction in the residual kinetic energy flux in the channel. Figure 7 shows the original kinetic energy flux in the Florida Current together with the residual energy flux for the 3 extraction cases. The power dissipation by turbines from the 3 cases is also shown in Figure 7. It is shown that the residual energy flux and the power dissipation do not add up to the original energy flux, indicating a net kinetic energy loss in the Florida Current due to the diversion of the course of the current flow. It is interesting to notice that when the energy flux is the strongest in summer time, the power extraction is not necessarily the strongest due to higher bypassing occurring in summer leading to lower energy extraction. Table 2 summarizes the impacts of turbines in 3 different cases. The effects of the power extraction are further examined by analyzing the spatial and temporal changes in the mean surface current speed, and water level for different power extraction cases.

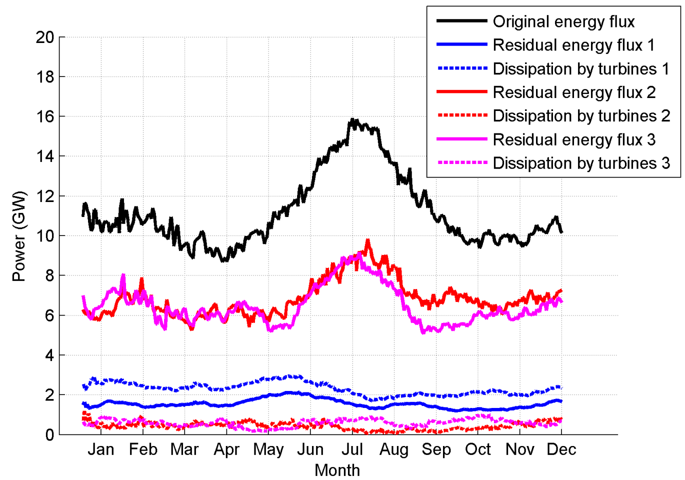

FIGURE 7. THE 3-YEAR MEAN KINETIC ENERGY FLUX AND POWER DISSIPATION BY TURBINES FOR DIFFERENT CASES.

TABLE 2. SUMMARY OF IMPACTS OF POWER EXTRACTION FOR DIFFERENT CASES TOGETHER WITH RELATIVE CHANGES AS PERCENTAGES OF THE ORIGINAL LEVELS.

Cases	Mean energy flux drop(GW)	Max. mean vel. drop (m/s)	Max. mean SSH drop (m)
case 1	9.6(85%)	1.0(83%)	0.48(107%)
case 2	4.5(40%)	0.6(50%)	0.13(59%)
case 3	4.6(41%)	0.7(58%)	0.10(45%)

3.3.1 Change in Mean Surface Current

The effect of power extraction on the hydrodynamics of the flow field is analyzed through the change of surface current magnitude. Figure 8 shows the difference of the mean surface current speed between case 1 and the baseline previously shown in Figure 6. The rerouting of the surface current flow is very obvious in this case. The mean current speed in the Florida Strait drops by up to 1

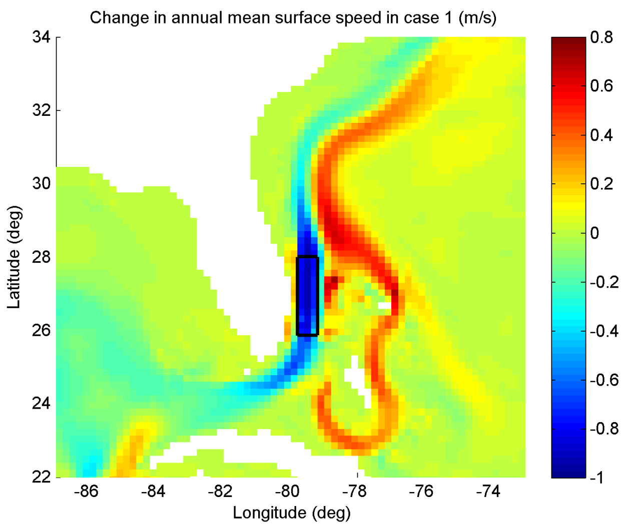

FIGURE 8. CHANGE IN MEAN SURFACE CURRENT SPEED FOR CASE 1 (TURBINE REGION HIGHLIGHTED WITH A BOX).

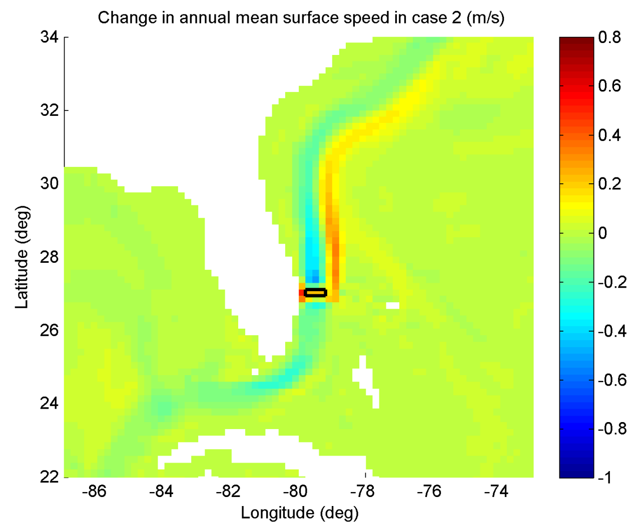

FIGURE 9. CHANGE IN MEAN SURFACE CURRENT SPEED FOR CASE 2 (TURBINE REGION HIGHLIGHTED WITH A BOX).

m/s, which agrees with the estimate from the analytical model result in section 2.2. As the upper portion of the water way in the Florida Strait is partially blocked by the presence of the turbines, the surface flow entering the Florida Strait changes direction and moves toward the southeast to go through the channel between Cuba and the Bahamas. Further downstream it flows along the east coast of the Bahamas to the north and merges back with the original Gulf Stream. The ocean current speed increase on the east of the Bahamas due to the rerouting can be as high as 0.8 m/s. Therefore the current exiting from the Florida Strait slows down and the newly formed strong flow occurs to the east, resulting in a slight shift of the path of the Gulf Stream to the east.

For cases 2 and 3, due to the lower strength of power extraction, a prominent rerouting of the surface ocean current does not occur (Figures 9 and 10). The effect of the power extraction has a smaller spatial extent and most of the flow modification is located in the vicinity of the turbine region. Immediately downstream of the turbine region features the greatest current speed drop of about 0.6-0.7 m/s. The surface current speed downstream of the turbine region to the east of the Gulf Stream path increases as a result of the flow redirection. The current speed increases on both sides of the turbine area as the flow seeks to bypass the area with high turbine resistance.

3.3.2 Change in Sea Surface Height (SSH) The effect of power extraction on the hydrodynamics of the flow field is also demonstrated by the mean water level change. As additional turbine drag changes the local momentum balance, the pressure gradient will be modified accordingly, which in turn

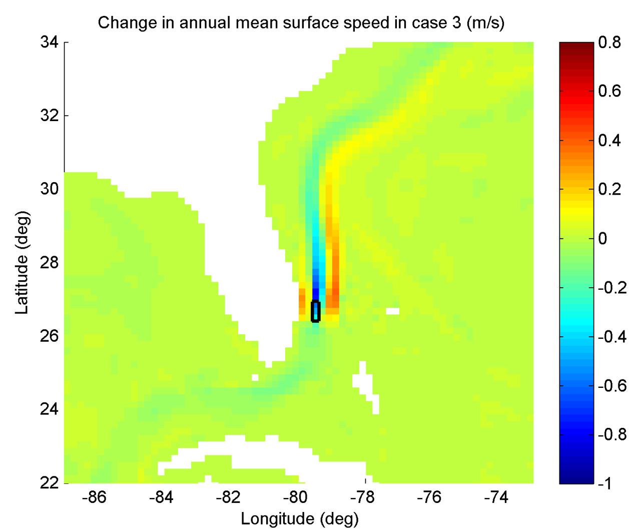

FIGURE 10. CHANGE IN MEAN SURFACE CURRENT SPEED FOR CASE 3 (TURBINE REGION HIGHLIGHTED WITH A BOX).

leads to modified SSH. The maps of water level difference between the undisturbed case and three cases with power extraction are shown in Figures 11, 12 and 13 with arrows showing the current directions. As turbine drag is added in the Florida Current in case 1, we observe a significant water level drop in the vicinity of the turbine region and the maximum water level drop is approximately 0.5 m, which is close to the prediction from Section 2.2. Furthermore, a general water level rise along the coast of the

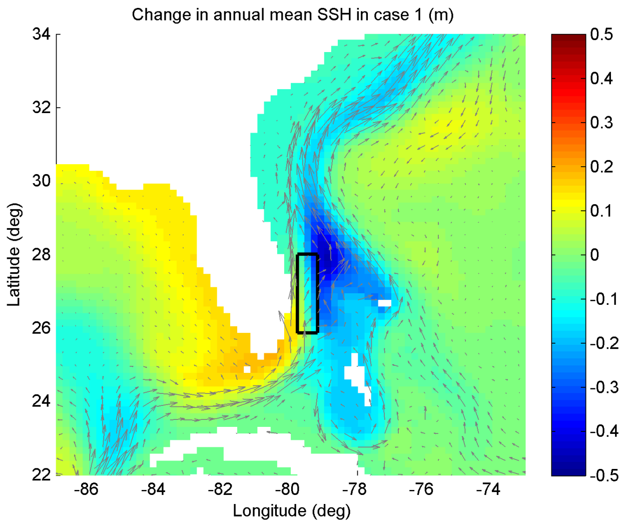

FIGURE 11. CHANGE IN MEAN SSH FOR CASE 1 (TURBINE REGION HIGHLIGHTED WITH A BOX).

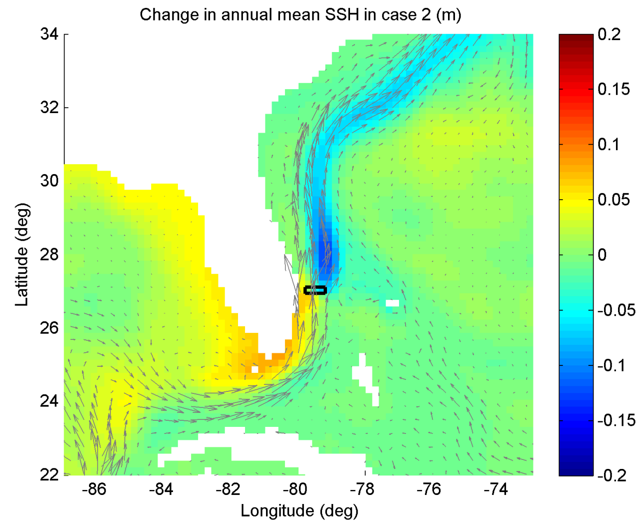

FIGURE 12. CHANGE IN MEAN SSH FOR CASE 2 (TURBINE REGION HIGHLIGHTED WITH A BOX).

Gulf of Mexico and Florida is also seen. The greatest water level increase could reach as high as 0.2 m.

For cases 2 and 3, since power is extracted from a much smaller area of the Florida Current, the effect in terms of water level change is of similar nature but relatively weaker than in case 1. The area downstream of the turbine region with significant water level drop becomes smaller. The greatest water level rise occurs along the Florida coast upstream of the turbine region. Similarly a water level rise is seen along the most of the Gulf coast. Generally the turbine arrangement in case 2 is shown to have greater impact on the SSH than in case 3 due to relatively greater turbine cross-sectional area in the flow direction.

4 SUMMARY

The Gulf Stream system, especially the Florida Current, has rich kinetic energy resource that could be potentially harvested. However, little is known about the potential impacts of extracting energy from this current flow system. To assess the impacts of energy extraction from the Gulf Stream system, two approaches are taken. The first approach uses an idealized ocean circulation model based on the assumptions of the Stommel model for subtropical gyres, and additional turbine drag is formulated and incorporated in the model to represent power extraction by turbines. It is found that the impact of the power extraction is primarily constrained in the vicinity of the turbine region. Extracting energy over a region comprised of the Florida Current portion of the Gulf Stream system could result in a significant reduction of flow strength and water level drop in the power extraction site, and cause redirection of the Florida Current to further offshore.

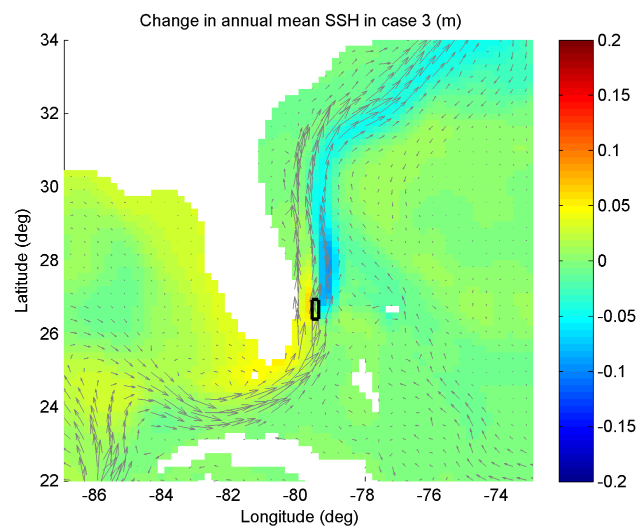

FIGURE 13. CHANGE IN MEAN SSH FOR CASE 3 (TURBINE REGION HIGHLIGHTED WITH A BOX).

A full numerical simulation of the Atlantic ocean circulation is also performed in this study using HYCOM to obtain a more realistic representation of the circulation system, and additional momentum sink is added at the designated location to model power extraction. Flow redirection to the east of the Bahamas is confirmed when the turbine region covers the majority of the surface area in the Florida Strait. However when the area of the turbine region is reduced, the flow redirection becomes less prominent, and so are the current speed changes. A significant water level drop is observed downstream of the power extraction site together with a water level rise upstream along the coasts of the Gulf and Florida. The sum of dissipated power from turbines and the residual energy flux in the Florida Current is lower than the original energy flux, indicating a net kinetic energy loss due to flow rerouting.

ACKNOWLEDGMENT

This study was supported by the U.S. Department of Energy, Wind and Hydropower Technologies Program award number DE-EE0002661. Any opinions, finding, and conclusions or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the Department of Energy.

REFERENCES

[1] ExxonMobil, 2012. 2012 the outlook for energy: A view to 2040. Tech. rep., ExxonMobil.

[2] Shafiee, S., and Topal, E., 2009. "When will fossil fuel reserves be diminished?". *Energy Policy,* ***37***(1), pp. 181–189.

[3] AWEA, 2012. AWEA U.S. wind industry annual market report: Year ending 2011. Tech. rep., American Wind Energy Association.

[4] Esteban, M., and Leary, D., 2012. "Current developments and future prospects of offshore wind and ocean energy". *Applied Energy,* ***90***(1), pp. 128–136.

[5] Stommel, H., 1965. *The Gulf Stream: A physical and dynamical description. Second edition*. University of California Press, Berkeley, CA.

[6] Richardson, P. L., 1985. "Average velocity and transport of the Gulf-Stream near 55w". *Journal of Marine Research,* ***43***(1), pp. 83–111. Adx33 Times Cited:110 Cited References Count:42.

[7] Fratantoni, D. M., 2001. "North Atlantic surface circulation during the 1990's observed with satellite-tracked drifters". *Journal of Geophysical Research-Oceans,* ***106***(C10), pp. 22067–22093.

[8] Yang, X., Haas, K., and Fritz, H., 2013. "Theoretical assessment of ocean current energy potential for the Gulf Stream system". *Marine Technology Society Journal,* ***47***(4).

[9] Kelly, K. A., and Gille, S. T., 1990. "Gulf-stream surface transport and statistics at 69-degrees-w from the geosat altimeter". *Journal of Geophysical Research-Oceans,* ***95***(C3), p. 3149.

[10] Hogg, N. G., and Johns, W. E., 1995. "Western boundary currents". *Reviews of Geophysics,* ***33***, pp. 1311–1334.

[11] Lissaman, P. B. S., 1979. "Coriolis program". *Oceanus,* ***22***(4), pp. 23–28.

[12] Von Arx, W., Stewart, H., and Apel, J., 1974. "The Florida Current as a potential source of usable energy". In Proc. Mac Arthur Workshop Feasibility of Extracting Usable Energy from the Florida Current, pp. 91–101.

[13] Duerr, A. E. S., and Dhanak, M. R., 2012. "An assessment of the hydrokinetic energy resource of the Florida Current". *Ieee Journal of Oceanic Engineering,* ***37***(2), pp. 281–293.

[14] Yang, X., Haas, K., and Fritz, H., 2014. "Evaluating the potential for energy extraction from turbines in the Gulf Stream system". *Renewable Energy,* ***(under review)***.

[15] Stommel, H., 1948. "The westward intensification of wind-driven ocean currents". *Transactions American Geophysical Union,* ***29***, pp. 202–206.

[16] Vallis, G., 2006. *Atmospheric and oceanic fluid dynamics : fundamentals and large-scale circulation*. Cambridge University Press.

[17] Stewart, R., 2008. Introduction to physical oceanography. Open Source Textbook at http://oceanworld.tamu.edu/ (accessed 2012).

[18] Bleck, R., 2002. "An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates". *Ocean Modelling,* ***4***(1), pp. 55–88.

[19] Halliwell, G. R., 2004. "Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid-Coordinate Ocean Model (HYCOM)". *Ocean Modelling,* ***7***(34), pp. 285 – 322.

[20] NGDC, 1995. Terrainbase, global 5-minute ocean depth and land elevation, from NGDC. Tech. rep., Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

[21] Levitus, S., and Boyer, T., 1994. World ocean atlas 1994. Tech. rep., NOAA Atlas NESDIS, NOAA, Silver Spring, Md.

[22] Gibson, J., Kllberg, P., Uppala, S., Hernandez, A., Nomura, A., and Serrano, E., 1997. ERA description. Tech. rep., ECMWF ERA-15 Project Report Series 1.

[23] Boning, C. W., Doscher, R., and Budich, R. G., 1991. "Seasonal transport variation in the western subtropical north-atlantic - experiments with an eddy-resolving model". *Journal of Physical Oceanography,* ***21***(9), pp. 1271–1289.

[24] Neary, V., Gunawan, B., and Ryou, A., 2012. Performance evaluation of HYCOM-GOM for hydrokinetic resource assessment in the Florida Strait. Tech. rep., Oak Ridge National Laboratory.

[25] Defne, Z., 2010. "Multi-criteria assessment of wave and tidal power along the Atlantic coast of the southeastern USA". PhD thesis, Georgia Institute of Technology.

[26] Yang, X., Haas, K., and Fritz, H., 2014. "National geodatabase of ocean current power in USA". *Renewable and Sustainable Energy Reviews,* ***(under review)***.