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Evaluation of Flow Features Responsible for Extreme Events at a Potential Ocean Current Energy Extraction Location within the Gulf Stream

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Abstract

Energy dense offshore ocean currents can be found off the east coast of most continents, with time average energy densities exceeding 3 kW/m^3 in top locations. The entirety of the open-ocean current based electricity production potential available to the continental U.S. can be found off the southeast U.S. coastline, with the most energy dense areas found off Florida's and North Carolina's east coasts. Prior studies provide detailed statistics related to ocean current speed, direction, and energy density at several discrete locations and map some of these statistics as a function of horizontal location and/or depth. However, they do not provide a good understanding of the flow features associated with the extreme current events identified within these data sets and therefore do not provide a strong basis for forecasting extreme events. Using bottom mounted acoustic Doppler current profiler (ADCP) data, this study first identifies extreme ocean current events (5 strongest and 5 weakest currents) that have affected a proposed ocean current energy production site over the past 15 years. Concentrating on the Florida Straits and the Gulf of Mexico, additional data types are used to map and quantify flow features associated with these extreme events. Key features include the propagation of eddies, edges of the Gulf Stream, and path of the Gulf of Mexico Loop Current. Understanding these features' progression will ultimately lead to a better understanding of extreme events, enabling the correlation between flow features and their impact on the ocean current resource, helping lay the foundation for extreme ocean current event prediction.

Keywords: Ocean Current Energy; Marine Renewable Energy; Resource Assessment; Ocean Eddy Detection; Gulf Stream Current

1. Introduction

Creating electrical power from river, tidal, and ocean currents without the use of dams is a rapidly expanding renewable energy field. In the US, these resources have on average an estimated 14 GW (river), 50 GW (tidal), and 19 GW (ocean) of technically extractable power, which combined equates to 23% of the 362 GW average 2011 US electricity generation. The entire 19 GW of open-ocean current based electricity production potential is located off the southeast US, with the most energy dense currents located off the east coast of Florida. Several prototype turbines have been developed to harness this energy, and a small amount of open-ocean testing has been conducted.

To characterize this ocean current resource in terms of energy and flow statistics several studies have been conducted using both experimental measurements and numerical model generated data [1]. These studies highlight top areas for ocean current energy production, the variability of this resource at numerous locations, resource behavior during extreme wind events (hurricanes), and other flow statistics important for system design and energy production analyses. Numerical studies have mapped mean energy globally, showing regions where energy densities exceed 2000 W/m^2 [2-3]. They have also been used to estimate the total extractable energy from this resource [3]. Measurement based studies have also been conducted, showing even greater energy densities exceeding 3000 W/m^2 in areas and providing detailed information on current variability [3-5]. However, current studies do not provide a good understanding of the flow features associated with extreme current events and do not provide the information necessary for forecasting these events.

Flow features within the Gulf Stream profoundly influence its dynamics. For example, eddies up to around 10 km in diameter regularly travel along the western edge Gulf Stream current in this area and the distance from shore of the western edge of the Gulf Stream varies in location. Eddies transport heat, impact nutrient concentrations and alter flow speed and direction. Sea surface temperature maps can directly showcase eddy formation and propagation due to the thermal mixing and upwelling/downwelling associated with these features. Therefore, understanding the formation and behavior of flow features, like eddies, within the Gulf Stream is vital to the prediction of extreme oceanic events.

Therefore, this project utilizes bottom mounted acoustic Doppler current profiler (ADCP) data to identify extreme ocean current events that have impacted potential ocean current energy production sites over the past 15 years (Section 2). It then utilizes sea surface temperature data to map flow features throughout the Gulf Stream and Canny edge detection to help highlight these features (Section 3). An evaluation of the 5 strongest and 5 weakest currents are provided in Section 4, followed by concluding remarks in Section 5.

2. Extreme Event Detection

From 2009 to 2017, ADCPs were deployed near seven primary longitudes in the Florida Straits near a latitude of 26°04'N (South "S" locations) and 26°29'N (North "N" locations). The locations of the measurements are indicated in Fig. 7 with an "x" placed at each deployment location. The deployments considered as a single location for the conducted analysis are also indicated. These locations were selected to measure current velocity from approximately the Gulf Stream's western edge to its core.

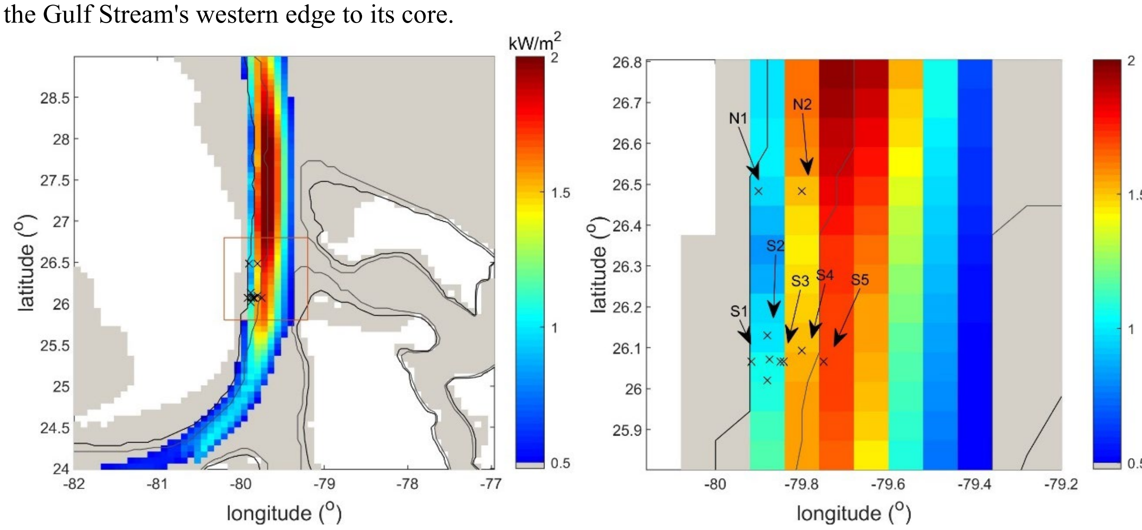


Fig. 1 Locations of bottom-mounted ADCPs used in this study (represented as "x") and buoy groups of nearly constant longitude indicated by text areas plotted atop of HYCOM-based average KEF (kW/m2) to show relative proximity to the resource. Contour lines are included at 250 m and 500 m isobaths, and the figure on the right is a subset of the figure on the left. Please note that HYCOM typically predicts the core of the Gulf Stream to be slightly further offshore in this area than measurements suggest, so the ADCPs are slightly closer to the core of the Gulf Stream than shown in this area.

These locations are identified in this paper as locations S1 to S5 and N1 to N2, with lower numbers being closest to shore. Data utilized from these four sites include the following locations, total water depths, and date ranges:

- S1: (26°04'N; 79°55'W; 260 m) 1,191 days of data spanning: Feb. 27, 2009-Mar. 20, 2009; Aug. 23, 2011-Nov. 16, 2011; Nov. 16, 2011-Apr. 3, 2012; May 22, 2012–Dec. 17, 2012; and May 27, 2013-June 2, 2015.
- S2: 726 days of data including: May 22, 2012-June 27, 2012 (26°04.3'N; 79°52.5'W; 290 m); May 26, 2013-May 5, 2014 (26°01.2'N; 79°52.8'W; 290 m); and May 27, 2013-April 29, 2014 (26°07.8'N; 79°52.8'W; 290 m).
- S3: (26°04'N) 1082 days of data including: Feb. 27, 2009-Mar. 25, 2010 (79°50.5'W; 340 m); Nov. 16, 2011-Apr. 6, 2012 (79°51'W; 320 m); May 22, 2012-Dec. 17, 2012 (79°51'W; 320 m); and May 24, 2013-April 29, 2014 (79°51'W; 320 m).
- S4: (26°05.6'N, 79°48'W; 500 m) 58 days of data spanning: Sep. 7, 2017 – Nov. 3, 2017.
- S5: (26°04'N; 79°45'W; 640 m) 294 days of data spanning: Feb. 27, 2009 - Dec. 10, 2009.
- N1: (26°29.0'N; 79°54'W; 290 m) 390 days of data spanning: Aug. 27, 2015 – Oct. 20, 2016.
- N2: (26°29.0'N; 79°48'W; 425 m) 326 days of data spanning: Aug. 27, 2015 – June 17, 2016.

These ADCP data were processed to find the five strongest and five weakest currents from these data sets for a depth of 75 meters, which are provided in Table 1. Interestingly, while several hurricanes passed through this region during the measurement campaign only one of these events occurred within the two months following a hurricane. This was the strongest current event, which occurred on the same date that Hurricane Irma was impacting this region.

Table 1: Locations and dates of the 5 strongest and 5 weakest currents found within the processed ADCP data sets.

Speed Rank	**Latitude**	**Longitude**	**Water Depth**	**Date**	**Time**	**Speed**
Strongest	26° 05.6' N	79° 48' W	500 m	9/11/17	4:50 PM	2.583 m/s
2nd Strongest	26° 29.0' N	79° 48.0' W	425 m	9/11/15	10:15 PM	2.541 m/s
3rd Strongest	26° 29.0' N	79° 54.0' W	290 m	7/25/16	1:45 PM	2.509 m/s
4th Strongest	26º 04.3' N	79º 51.0' W	320 m	7/23/13	12:15 AM	2.500 m/s
5th Strongest	26º 01.2' N	79º 52.8' W	290 m	7/22/13	11:30 PM	2.482 m/s
Weakest	26° 29.0' N	79° 54.0' W	290 m	9/22/15	3:30 AM	0.003 m/s
2nd Weakest	26º 04.3' N	79º 55.0' W	260 m	11/17/14	12:29 AM	0.026 m/s
3rd Weakest	26º 01.2' N	79º 52.8' W	290 m	2/27/14	10:15 PM	0.026 m/s
4th Weakest	26º 04.3' N	79º 55.0' W	260 m	11/1/11	8:05 AM	0.040 m/s
5th Weakest	26º 04.3' N	79º 51.0' W	320 m	5/25/12	9:50 PM	0.135 m/s

3. Feature Detection using Sea Surface Temperature

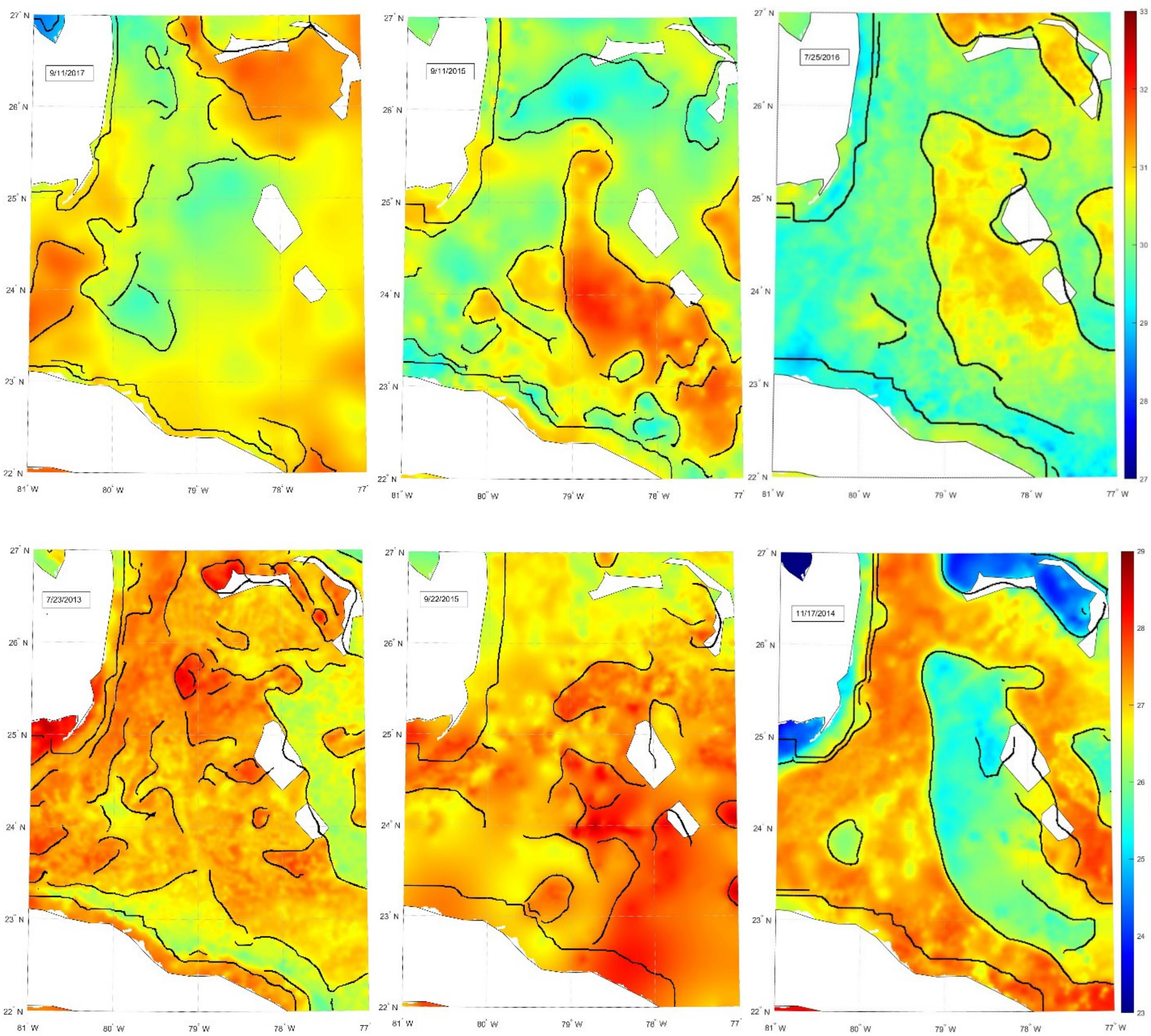
To detect flow features associated with extreme events identified within ADCP data, sea surface temperature data from NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) are utilized. PO.DAAC seeks to preserve ocean and climate data operated by the Jet Propulsion Lab in Pasadena, California. Sea surface temperature data provides temperature gradients important for identifying ocean current features, helping to identify optimal sites for energy extraction [6].

Canny edge detectors were thus used to observe the Gulf Stream's western and eastern edges. This process includes setting a standard deviation associated with the application of a Gaussian blur filter. Then, it detects the specific locations on cartographic diagrams with the largest gradients [6]. Canny edge detectors have been validated through several studies [7] to observe the western and eastern edges of the Gulf Stream.

4. Event Analyses

This section uses the sea surface temperature-based feature detection approach (Section 3) to evaluate each of the 10 events identified in Section 2. As listed in Section 2, the five strongest current speeds encompassed a range between 2.482 m/s and 2.583 m/s, with the strongest current induced by the passing of Hurricane Irma. Figure 2 (Top & Left-Center Images) depicts the perturbations in sea surface temperature on the days in which these strong current speeds transpired in conjunction with illustrations of the edges where the largest thermal gradients are present. Distinct characteristics associated with the western and eastern edges of the Florida Current are displayed. For instance, the western edge of the Florida Current is lucidly defined between 79.8º W and 79.9º W on July 25, 2016, where a current speed of 2.509 m/s was detected. The eastern edge is also clearly shown, however, a section of this edge branches off more eastward between the approximate latitude transects of 25.8º N and 26.7º N. Although the Canny edge detector highlights the western and eastern boundaries of the Florida Current without much variation, there are some days in which the Canny edge detector observed large gradients at different locations on certain days like July 23, 2013. On this day, a current speed of 2.5 m/s was measured by one of the bottom-mounted ADCP instruments. Dissimilarities are shown near the center of the Florida Current downstream near a latitude of 25.5º N and a longitude of 80º W. Additionally, thermal gradients with circular edges are shown near the eastern edges of the Florida Current as well as off the western coast of the Bahamas.

Furthermore, Figure 2 portrays intermittencies with detailed boundaries included by the Canny edge detector of the western and eastern edges of the Florida Current. As delineated in Section 2, the five weakest current speeds span magnitudes between 0.003 m/s and 0.135 m/s. As with the days associated with the strongest current speeds, the days on which the weakest current speeds also exhibit pronounced attributes regarding the western and eastern edges of the Florida Current (Middle-Center, Middle-Right & Bottom Images). For example, clear western and eastern boundaries are perceived by the Canny edge detector on November 17, 2014, where a current speed of 0.026 m/s was observed. At the western edge, there seems to be extensions of the boundary in the eastward direction at latitudes of approximately 25.3º N and 26.3º N, likely signaling meandering patterns. Alternatively, the boundaries recognized by the Canny edge detector on September 22, 2015, represent a discernible western edge, but a variable eastern edge. More specifically, the eastern edge upstream is scattered and branches off at some sections close the Bahamas; this can be noticed at latitudes of 24.7º N and 25.8º N. Furthermore, the eastern edge downstream does not portray distinguishable thermal gradients.



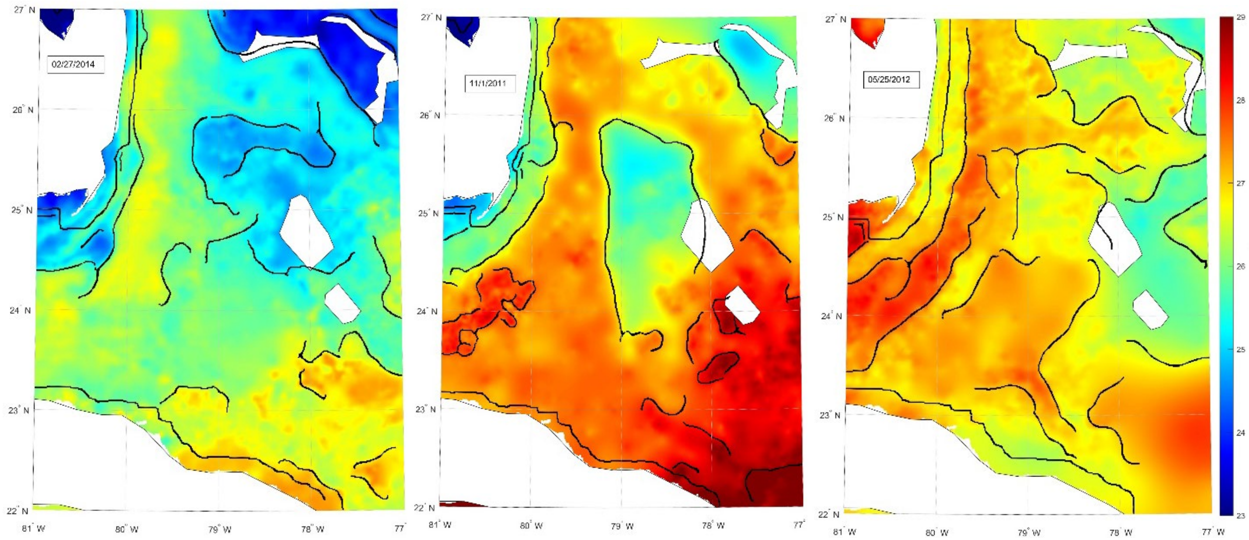


Fig. 2 Strongest five current events with Strongest (top-left), 2nd Strongest (top center) and 3rd Strongest (top right), 4th & 5th strongest (middle left), Weakest (middle-center), 2nd weakest (middle-right), 3rd weakest (bottom-left), 4th weakest (bottom-center), and 5th weakest (bottom-right). Locations of bottom-mounted ADCPs used in this study (represented as "x") and the 4th and 5th strongest currents were measured by neighboring ADCPs within hours of each other so these are represented by a single SST image (middle left).

When examining each of the plots from Figure 2, fascinating aspects from these depictions can be noted. For instance, the western edge of the Florida Current appears to have much more consistency as opposed to the eastern edge in relation to thermal gradients. As shown in each of the plots, the Canny edge detector displays a clear boundary at the western edge. Moreover, ocean features like small-scale eddies appear to be prevalent near a latitude of 25.5º N near longitudinal coordinates where bottom-mounted ADCP instruments were deployed. Most eddies near this region have colder cores, as shown in most of these plots, which represent counterclockwise-rotating eddies. This pattern is typical along the western edge of the Florida Current as sections of the current exhibit instabilities due to the close proximity of the shoreline. However, the plot encompassing sea surface temperature variations on May 25, 2012, shows warmer core eddies near the 26º N latitude transect. Furthermore, there are patterns observed with the positional aspects of the Florida Current's western edge when contrasting the days with the strongest and weakest currents. For example, the western edge appears to typically extend eastward and southward from the Florida shoreline upstream on the days with the weakest current speeds. However, the western edge appears to be in closer proximity to the Floridian coastline upstream on the days where the strongest current speeds are detected.

5. Conclusion

This study has explored potential optimal sites for harnessing ocean current energy through the understanding of flow features responsible for extreme events. Sea surface temperature perturbations from satellite technology identify small-scale eddies near the western edge of the Florida Current for the majority of the days analyzed, such as the current on September 11, 2015. Additionally, meandering characteristics have been observed at both the western and eastern edges of the Florida Current, with the western edge showing a more consistent boundary. Other noticeable characteristics involve the latitudinal and longitudinal coordinates of the western edge of the Florida Current upstream, with a more streamlined boundary near the shore of Florida on days with the strongest current speeds.

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