# Dynamic observations in the Hampton Roads region: how surface currents at the mouth of Chesapeake Bay may be linked with winds, water level, river discharge and remote forcing from the Gulf Stream

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***Abstract*— The study analyzed nine years of hourly surface currents measured by high-frequency Coastal Ocean Dynamics Application Radar (CODAR) near the mouth of Chesapeake Bay (CB) [1-3]. These observations, available in near real-time, have many practical usages for search and rescue, tracking pollution, navigation, Navy operations, and assimilation into numerical ocean models. It is important to understand the dynamics of the CB and to better deal with the impacts from climate change, such as accelerated sea level rise and flooding [4-7]. So far, not much research has been done on the relation between the surface current data and other observations such as coastal sea level, local wind forcing and river discharge into CB. Recent studies also show potential remote influence on the region from variations in the Atlantic Ocean circulation, and in particular, studies found that when the Gulf Stream (GS) slows down, coastal sea level along the U.S. Mid-Atlantic coast rises [8]. Therefore, the study examined potential connections between the observed transport of the Florida Current [9] (the upstream part of the GS) and the radar surface currents. Various analysis methods were implemented to find links between the different observations, and variability was assessed on a wide range of time scales, from hourly and monthly variations to interannual and longer trends. The results show how different forcings impact the surface currents on different time scales and provide better understanding of dynamic observations in the CB.**

***Keywords—Chesapeake Bay, high-frequency coastal radar, ocean currents, tides, river discharge, Gulf Stream.***

## I. Introduction

The area around the Chesapeake Bay (CB) is populated by many communities along its shores (as many as 18 million people live in the CB watershed). The bay is the largest U.S. estuary (~280km long and mean depth of ~8m, Fig. 1), providing an important wetland ecosystem for many species. The population and the wetlands are affected by climate change and especially by the increased frequency of flooding events due to sea level rise [5]. Local sea level rise is faster in the region due to land subsidence and potential slowdown of the Gulf Stream [4-8], thus having large environmental, economic, and human health consequences for communities along the Bay. Many factors can affect the health of the CB, including precipitations, heat waves, river runoffs, storm surges, winds, sea level rise and remote influence from the Atlantic Ocean. Therefore, this study focused on the dynamics near the mouth of the CB using nine years of hourly surface current observations (hereafter called "CODAR currents"); we examined the links between these currents and other observations such as winds, river discharges, sea level and the Gulf Stream. To our knowledge, this is the first time that all these observations are linked in a single study. The general goal here is to improve our understanding of the dynamics of the CB, the different forcing involved, and the variability on different time scales, from hourly to interannual scales.

## II. Data and Methods

### *A. Data*

The data used include the following observations (see Fig. 1 for location of various observations):

SURFACE CURRENTS. The hourly CODAR data from 2009-2018 includes 197 points (Fig. 2) that were averaged to create time series of surface currents. The current vectors are transformed by rotating the axis 45° so that surface currents were analyzed in the Northwest-Southeast directions (positive values represent currents out of the bay). Daily and monthly means were also calculated to be compared with daily and monthly data of other observations, and to eliminate tidal variability.

WATER LEVELS. Three NOAA tide stations were used: Chesapeake Bay Bridge Tunnel (CBBT), Sewell's Point (near Norfolk), and Kiptopeke on the Eastern Shore (Fig. 1). Data were downloaded in 6-minute increments and averaged to calculate hourly, daily, and monthly water levels (see [4] for more analysis of sea level rise in the tide gauges of the CB).

WIND DATA. Wind speed and direction data were collected at the CBBT meteorological station; the 6-minute data were averaged to calculate daily and monthly values.

Zonal (U) and meridional (V) components were calculated from the wind speed and direction. Rotating the axis 45° matched the direction of the CODAR currents (positive U values indicate wind out of the bay).

RIVER DISCHARGE. Daily river discharge data were collected from three U.S. Geological Survey (USGS) stations: the Susquehanna River, Potomac River, and James River; these three rivers are the primary freshwater sources to the Chesapeake Bay. The daily data was also summed and averaged to calculate total monthly mean river streamflow.

FLORIDA CURRENT. Daily transport (in Sverdrup units, 1sv=million cubic meter per second) from cable measurements at 27°N across the Florida Straits was obtained from NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML; [9]). This observation of the Florida Current (FC) represents the upstream portion of the GS; studies show negative correlation between the GS flow and sea level along the U.S. East Coast [8, 10].

## *B. Methods*

Various data analysis methods were used in this study, from simple linear correlation to more sophisticated statistical methods, such as spectral analysis and spectral coherence, Empirical Mode Decomposition [11], and Wavelet analysis. Here, only some example analyses will be shown for time scales ranging from hourly tides to the seasonal cycle and interannual variations; for full range of analyses of all data, hourly, daily, and monthly, see [3].

The empirical mode decomposition (EMD) method is a nonlinear, nonstationary time series analysis that decomposes the time series data into a finite number of intrinsic mode functions with time-variable amplitudes and frequencies. After filtering all oscillation modes, the nonlinear trend is extracted as well. EMD analysis of most tide gauges in the CB shows for example a clear nonlinear sea level acceleration trend [4]. EMD allows for comparisons of different time series to see at what time scales they are correlated or not. One advantage of EMD over standard statistical methods like spectral analysis, is that it can detect nonstationary signals, such as infrequent storm surge in sea level; it can also detect long-term trends that do not complete full cycles. The 9-year data analyzed is a relatively short record, so that long-term trends cannot be reliable. Nevertheless, the record is likely affected by decadal variability which are unresolved and will appear as trends over the record length. The main goal here is to compare the different data sets with the surface currents to examine the dynamic forcing near the mouth of the CB. Comparing different analysis methods is also a useful exercise to evaluate the practicality of different methods.

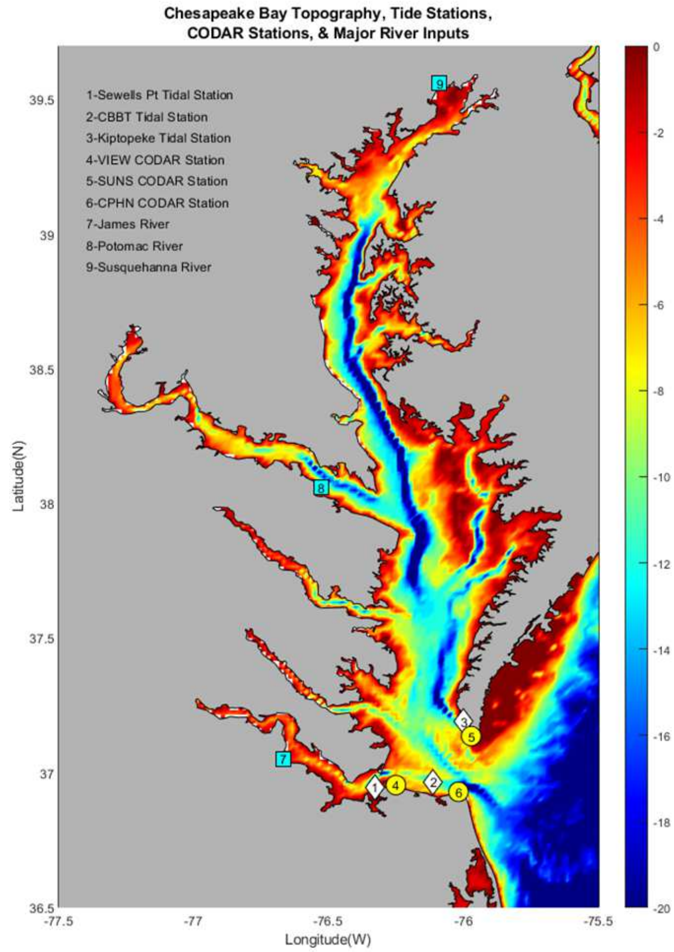


Fig. 1. Topographic map (depth in m) of the CB and location of observations. Numbers 1-3 indicate tide gauge locations, numbers 4-6 are CODAR locations, and numbers 7-9 are river discharge locations.

# I. RESULTS

## *A. Tidal Currents and Water Level*

While the semidiurnal tides in CB dominate the daily pattern of surface currents in and out of the bay (Fig. 2), daily currents are also influenced by the daily wind cycle and other factors. The relation between the daily tides and the daily water level is not simple (Fig. 3). Unlike typical coastal dynamics where maximum tidal currents usually occur during peak ebb and peak flood (between high and low tides), the tides entering the CB have characteristics of a progressive wave with maximum flood current near high tide, and the maximum ebb current near low tide. A general pattern can be seen where the average current velocity has two peaks of positive current out of the bay for each peak in water level, but there are also significant deviations from day to day due to other impacts, such as variations in the wind, and differences between the Spring tide and the Neap tide. Note also that there is slight shift in the phase of the tide between water level in CBBT near the mouth of the CB and Sewell's Point farther west in the southern CB.

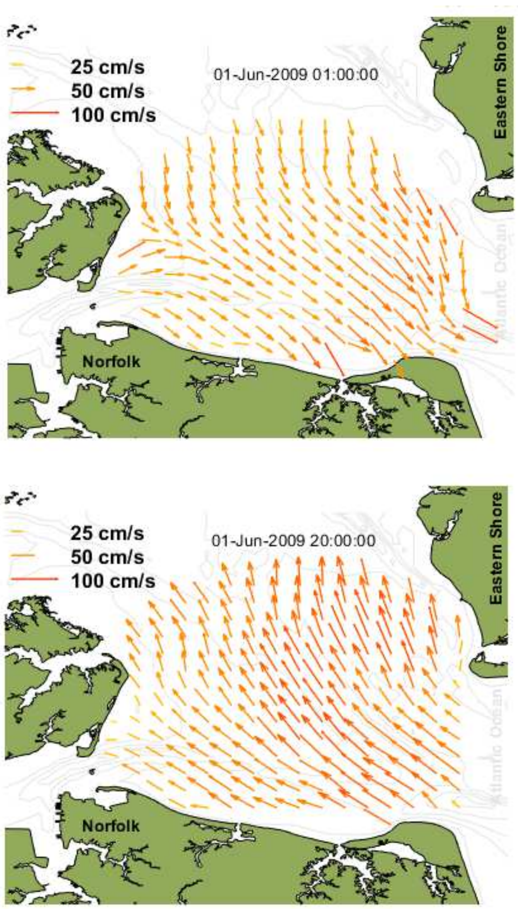


Fig. 2. An example of surface currents obtained by CODAR near the mouth of the Chesapeake Bay during ebb (upper panel) and flood (lower panel).

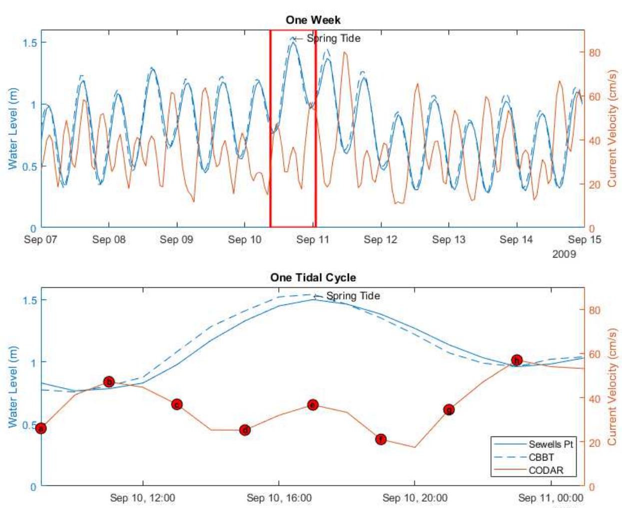


Fig. 3. Example of water level at two locations (blue lines) and CODAR currents during a week (upper panel) and one tidal cycle (lower panel).

## B. Surface Currents and Wind

The spectrum for surface currents (Fig. 4a) indicates maximum power at two frequency bands: one at low frequency near the annual cycle, and one at high frequency near a weekly cycle, with reduced power between these two bands, around periods of one to three months. The low energy in the middle of the CODAR spectrum is quite peculiar and not typical to most oceanographic time series, it may reflect a combination of different forcing that cancel each other. The spectrum of the zonal U wind (Fig. 4b) shows somewhat similar pattern with energy at high-frequency that is probably associated with weather systems passing over the study area, and energy at low-frequency associated with the seasonal cycle of the wind. The wind also has a gap at mid frequencies, but not as obvious as the one seen in the surface currents. In any case, it is not surprising that surface currents are largely driven by wind, but the pattern of the currents in the CB is more complicated than simple wind-driven currents since tides and other factors such as outflows from rivers and inflows from the Atlantic Ocean can also impact the currents near the mouth of the CB.

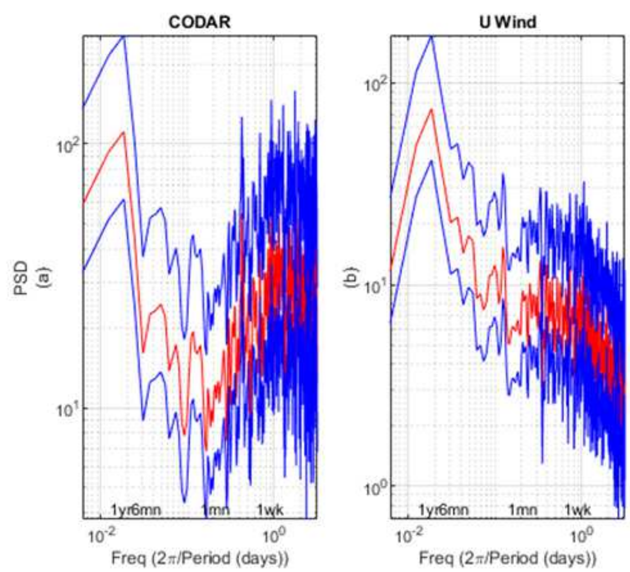


Fig. 4. Power spectral density (red lines) of (a) surface currents and (b) zonal wind, with 95% confidence level (blue lines).

## C. Seasonal Pattern

Monthly mean values of the different observations (surface currents, water level, wind, river discharge, and the Gulf Stream) provide the seasonal pattern and shown in Fig. 5. Surface currents (Fig. 5a) are in average positive (~7 cm/s out of the CB) as common for estuaries with more river discharge into the bay than water lost to evaporation and exchange with the open ocean. The maximum currents are found in January-March (and a smaller peak in November-December) and seem to be driven by a combination of zonal wind (Fig. 5d) which is maximum in January and river discharge (Fig. 5e) which is maximum in March-April. The minimum current velocity in September coincides with the minimum U wind velocity. Unlike the daily cycle (Fig. 3) where currents and water level have similar patterns, the seasonal water level (Fig. 5b) is quite different than the pattern of currents, with high water level in September-October and low water level in January. While the low water level in January may be linked with the large outflow from the CB at that time, the maximum water level in September-October is likely driven by the annual tidal cycle (the fall "King Tide") and by the drop in the GS flow between August and November (Fig. 5f), as shown by previous studies of the seasonal cycle of flooding in the region [12]. In general, the seasonal pattern of the GS seems in opposite phase with the surface currents, with maximum GS flow when CB currents out of the Bay are near their minimum. Studies show that GS flow is anticorrelated with coastal sea level, so it may affect inflow/outflow to the CB, but the physical mechanisms connecting CB currents and GS currents offshore are not yet clear and may involve the seasonal pattern of other coastal currents along the U.S. East Coast.

### *D. EMD and Long-Term Correlations*

Applying the EMD analysis to the daily records of all the different observations breaks down the records into different modes, allowing examination of the correlation between data at different time scales; such correlations are shown in Fig. 6 for time scales between weekly variability to ~5-year cycles. Note that because of the relatively short record (9 years) correlations of the low frequency modes may not be statistically significant, but nevertheless they may indicate some trends that are consistent with the dynamics involved. Correlation of currents with water levels (Fig. 6a) are very similar at the three stations for time scales less than ~1 year, with best correlation (-0.4) at around biannual cycles, which may be driven by the biannual long tidal cycle [12]. The negative correlation is consistent with the fact that larger flow out of the bay will cause sea level in the bay to drop. At longer time scales correlation with water level is different for different stations (negative for Kiptopeke, but positive for Sewell's Point), which may be due to different local wind pattern along the Eastern Shore versus inland near Norfolk. Correlation of currents with zonal wind (red line in Fig. 6b) is small for the highest frequencies (positive, as expected), but negative correlations at time scales around 5 years cannot be explained and may be related to unresolved decadal variations of wind over the Atlantic Ocean. Correlation of currents with river discharge (red line in Fig. 6c) shows two peaks, positive correlation around 45-days period and negative correlation around 6-month to 1-year period. Positive correlation is expected based on the seasonal cycle (Fig. 5), but those correlations are relatively small (less than 0.2) so may not be statistically significant.

The correlation of currents with the GS (blue line in Fig. 6c) is quite interesting, with strongest correlation (-0.36) at about 6-month period, which is also the largest negative correlation of currents with water level (Fig. 6a).

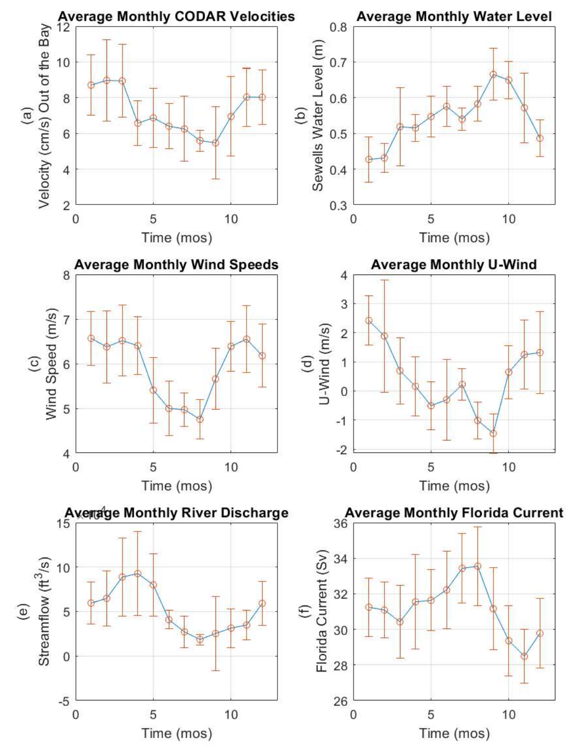


Fig. 5. The seasonal pattern of (a) CODAR currents out of the CB, (b) water level, (c) wind speed, (d) zonal wind, (e) river discharge and (f) Gulf Stream transport (Florida Current).

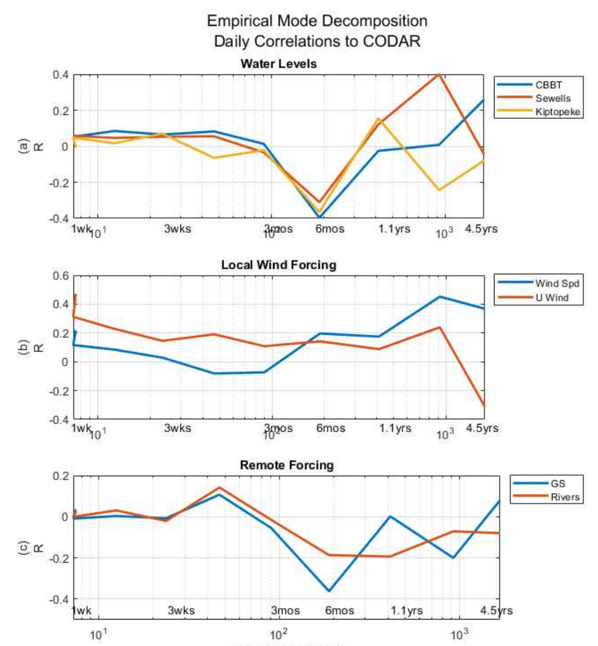


Fig. 6. Correlation between daily CODAR currents out of the CB and (a) water level, (b) wind, and (c) Gulf Stream flow and river discharges. Oscillations at different periods were detected by the EMD modes.

The negative correlation between the currents and the GS are consistent with the opposite phase of the seasonal cycle (Fig. 5), but not completely understood since the GS flow, the currents in the bay, the wind, and water level are all connected and influence each other.

Overall, the EMD analyses provided complex and not always easily explained, information regarding both the individual time series trends over different time scales, as well as their correlations to each other at these different frequencies. A significance test [3] found that the CODAR dataset produced modes with more than 95% significance at the high frequency (daily) and annual scales, whereas most of the other datasets had more significant modes at both high and low frequencies. While not statistically significant, qualitatively, some of the low frequency modes represent trends that are consistent with the dynamics involved. However, they may be a part of longer decadal oscillations of unknown origin not captured within this nine-year dataset.

## II. Summary and Conclusions

The goal of the study was to get a better understanding of the different forcing of the surface currents at the mouth of the Chesapeake Bay as measured by 9 years of hourly observations by the high-frequency Coastal Dynamics Application Radar (CODAR) and study the different time scales involved. Various statistical analysis techniques were tested, which provided additional information on the usefulness of different analysis methods. While semidiurnal tides dominated the daily pattern of surface currents and water levels in the CB, the subtidal signal of currents in high frequency is driven mostly by variations in local wind. However, forcing, at lower frequencies with periods of weeks to years are more complicated since they are driven by the combination of indirect forcing from river discharge and the Gulf Stream, so not all the links could be easily explained.

In summary, the study demonstrates the complex nature of the surface currents data and the interconnections between the different factors and different time scales affecting the currents at the mouth of the Chesapeake Bay. For example, the increased eastward wind during the fall will increase the outflow, while at the same dime the decreased GS flow during the fall will drive higher sea level and increased inflow into the CB. This analysis may be the first of its kind in the attempt at combining all these different observations in a single study, and it points to the need of long-term observations in the Chesapeake Bay.

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We would like also to add a special gratitude to our late colleagues Larry Atkinson (1941-2020) who provided huge contribution over many years to the CODAR project at CCPO and to ocean observing systems elsewhere.

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