CODAR Observed Spatial Resolution of Tidal Dynamics Along the Lower Delmarva Peninsula.

Alexander R. Davies

[1]Ajoy Kumar, Ph.D.
Department of Earth Science
Millersville University

John Moisan, Ph.D.
Hydrospheric and Biospheric Sciences Laboratory
NASA/GSFC Wallops Flight Facility

ABSTRACT

A long term coastal ocean observational network is being developed in order to improve our understanding of the dynamics of coastal environments. One aspect of this observing system is the deployment of High Frequency Radar (primarily CODAR) systems that can measure surface coastal ocean currents on hourly timescales up to 200 km offshore and at spatial resolutions of about 10 km. Tidal harmonics were computed using a year of observations from 3 CODAR systems deployed along the Delaware, Maryland, and Virginia coast under support from the NOAA Integrated Ocean Observing System (IOOS). The resulting tidal current estimates were then removed from the raw HF Radar current estimates to render a composite of the mean surface circulation pattern for this coastal ocean region. Tidal currents in this region account for up to 60% of the total current variability, particularly at the mouth of the Chesapeake Bay. Using the tidal harmonics, a year's worth of daily progressive vector diagrams were analyzed in order to ascertain the level of 'jitter' that one could expect from obtaining hourly images from a geostationary hyperspectral ocean color satellite.

Keywords: CODAR; Delmarva coast; Harmonic Analysis; Ocean Radar; Environmental Remote Sensing; Tidal Influence

The Wallops Coastal Ocean Observation Laboratory (WaCOOL) is a collaborative effort by the National Aeronautics and Space Administration (NASA), Wallops FlightFacility (WFF), the National Oceanic and Atmospheric Administration (NOAA), theCenter for Innovative Technology (CIT), and other academic and commercial institutes to study the coastal waters surrounding the Delmarva Peninsula (Delaware,Maryland, and Virginia). With this goal in mind, the Hydrospheric and BiosphericSciences Laboratory (HBSL) at WFF strategically deployed two CODAR Ocean Sensors (COS). One is located on Assateague Island, a barrier island along the Delmarva Peninsula, at 38º 12' 20.81"N and 75º 09' 10.50"W and the other is located on CedarIsland, VA at 37º 40' 22.31"N and 75º 35' 38.06"W.

[1]Faculty mentor and correspondence
ajoy.kumar@millersville.edu

COS high frequency radar systems work by propagating an electro-magnetic wavegererated from an onshore transmitterdirected toward the sea surface. Upon contact, the incidentelectro-magnetic wave is scattered in all directions by the rough surface via BraggScattering (Fu and Ferrari, 2008). The only signal that is recoverable by the COS antenna is that which is backscattered off a radially propagating wave with a wave number exactly twice thetransmitted wave number. The surface wave speed is calculated based on the Doppler shift. However, only surface wave speeds can be calculated for points within theoverlapping field of view from each COS sensor. To arrive at the final wave speeddata product (referred to as total velocity), the calculated wave speed from each sensoris averaged. The data set used in this study was pre-processed to calculate the totalvelocity by the WFF Coastal Data Acquisition and Archive Center (CODAAC).

The objective of this study was to demonstrate the use of high frequency radars for observing tidally forced currents along the coastal shelf, specifically off the eastern shore of Virginia. An additional outcome was to qualitatively show that tidal features are identifiable within the resolution limitations of satellite remote sensing technologies; of particular interest are hourly images from a geostationary hyperspectral ocean color satellite.

Satellite altimeter measurements over the past quarter-century have provided a means to study mesoscale ocean features, but the need exists for high resolution observations, particularly in coastal waters (Fu and Ferrari, 2008) where tidal forcing is typically dominant. A full understanding of localized coastal ocean dynamics and circulation is only obtained once the tidal forcing has been identified. Since tidal dynamics can drastically vary from one coastal region to another (Defant, 1958), an ideal tool for understanding tidal forcing over long temporal and spatial scales is high resolution satellites.

METHODS

The COS observational area in this study contains 1,257 individual data points with each representing a 6 km grid. Mean, hourly surface u and v component total velocities are recorded at each point. A CODACC developed filtering algorithm was implemented to remove poor observations at each of the 1,257 individual data points resulting in a temporally inconsistent dataset. Thus, grid points that failed to contain sufficient observations needed to identify tidal harmonics, with phases up to half a year in length, were removed. The observational period was limited to January 1, 2007 through December 31, 2007.

Given the temporal data gaps and often inconsistent time-steps within the filtered total velocity data, harmonic analysis was the best method to identify the tidal constituents. This is because the tidal signal can be predicted discretely based on known frequencies. In general, any time series of N observations can be represented by a Fourier series of length n = N/2 given by:

$$y(t) = y_{mean} + \sum_{k=1}^{n/2}[A_k cos(w_k t) + B_k sin(w_k t)] \quad (1)$$

where y_{mean} is the mean velocity, ω_k represents the harmonic frequencies (i.e. known tidal frequencies), and the coefficients A_k and B_k are specific for each harmonic and need to be solved (Wilks, 2006).

When using harmonic analysis to identify tides, only the thirty-six tidal dominant components were considered. These harmonics are well known and identifiable based on their phase speed and frequency. This simplifies equation (1) to require *k* running from 1 to 36. For the purposes of this study, any signal that cannot be reconstructed via the thirty-six known tidal harmonics is considered residual data. The characteristics of all thirty-six tidal harmonics are readily available through NOAA via the website:

www.tidesandcurrents.noaa.gov.

For this study, the *u* and *v* components were analyzed separately and re-constructed at the end—an approach equivalent to the separation of variables. Calculating the thirty-six sets of tidal coefficients (*i.e.* A_k and B_k) at each data point is often done using a multiple linear regression. However, the problem can be represented simply by using linear matrix notation, a method found in Wilks (2006) and Press *et al*. (2002), to name a few.

$$Ax = B \quad (2)$$

Matrix B represents the u or v component of the velocity time series for a given grid point. Matrix A represents either the sine or cosine function containing the expression ($\omega_k t$) used in equation (1). This expression corresponds uniquely with each of the individual thirty-six tidal harmonics. Matrix x represents the tidal coefficient to be solved. Specifically, Single Value Decommission Single (SVD) decomposes matrix A into an n x m orthogonal array, an n x n diagonal array, and the transpose of an n x n orthogonal array. Matrix x can be solved using backward substitution (Press *et al*., 2002).

To bring additional clarity to these methods, for any given grid point, the matrix equation can be used to solve equation (2) for the *x* matrix. This is done four times representing each set of coefficients (i.e. A_k and B_k) and each of the horizontal velocity components. For this study, the residual velocities are simply the current that cannot be accounted for using this harmonic re-construction of the tidal signature. The residual velocities are solved by subtraction the tidal signature from the raw, observational data (contained in matrix B) for each time step.

To determine if tidal forcing along the continental shelf can identified within the resolution limitations of space-born remote sensing technology, it is critical to determine how tidal forcing will influence the location of a parcel at any given time. A finite differencing scheme was used to represent the tidal forcing on a parcel of water for anytime interval with a temporal spacing of one minute. This technique assumes that the parcel of water starting at a given location, (0,0) in an *x*-*y* plane, will retain the harmonic forcing from the initial starting location throughout. This assumption is likely strong for short time periods (i.e. hours to days) but will likely fold over longer time periods due to larger displacements from the initial point where the initial tidal signal is no longer a valid forcing term.

Thus, the finite differencing scheme was only used to construct daily parcel trajectories based on the tidal forcing at the initial time and location. If each daily representation started at the arbitrary point (0,0) in an *x*-*y* plane, they can be plotted on top of each other. Thus, directional variability and co-variability can be assessed via principle component analy-

sis (PCA). Using the eigen values and the linearly independent eigenvectors from PCA, scaled variance position ellipses can be constructed for a given data point (Preisendorfer, 1988).

RESULTS AND DISCUSION

PCA is a strong tool for statistically recognizing patterns within a data set while highlighting the similarities and differences within a time series (Preisendorfer, 1988). Additionally, variance ellipses give a sense of co-variability about the data while square-root ellipses provide more information since the original units are preserved.

To confirm that tidal forcing along the continental shelf is identifiable within the resolution limitation of geostationary hyper-spectral ocean color satellites, a 250 m^2 grid would be required to compare with the standard deviation ellipses. The standard deviation ellipses represent the first order, standard deviation of a tidally-forced parcel of water at each observational point, all else being equal. Figure (1) shows the standard deviation ellipses for each point overlaid with a 5 km^2 grid. This grid spacing is more than sufficient to confirm the capabilities of the remote sensing technology.

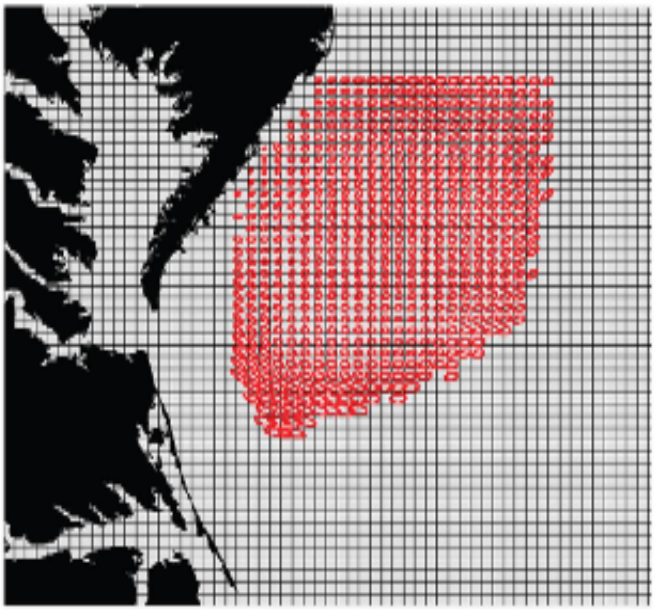

Figure 1: Tidally-forced standard deviation ellipses overlaying a 5 km^2 grid to highlight that satellite's with a 250 m2 spatial resolution will be able to identify and characterize tidal dynamics along the continental shelf.

In addition this study also sheds additional light on current behavior along the mid-Atlantic bite. Figure (2) shows the mean residual current in this region for 2007. Along thenorthern half of the field of view, the mean current is southerly and follows the shore with currents approaching 10 cm/s. The southern half of the field of view appears to be dominated by outflow from the Chesapeake Bay. The Coriolis effect becomes evident as water exiting the mouth of the

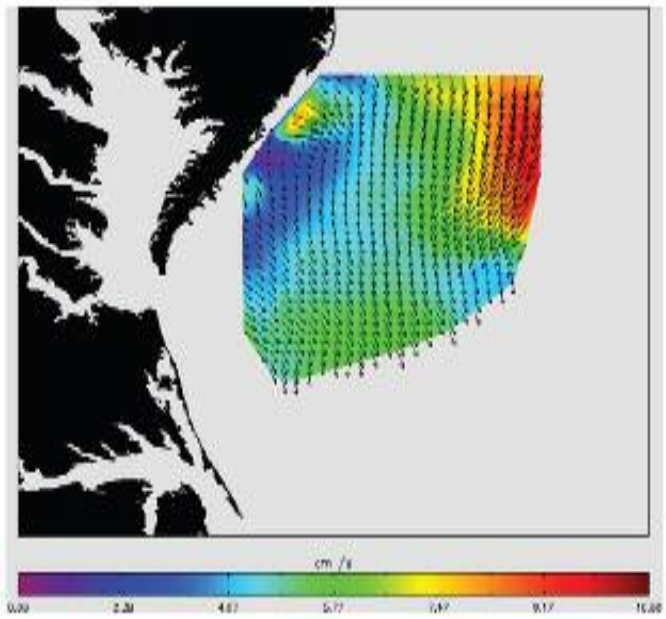

Figure 2: COS observed mean residual current velocities for 2007.

Chesapeake Bay is being forced south. The flow into, and out of, the mouth of the Chesapeake Bay is tidally dominated. This tidal surge is confirmed in Figure (3) which plots the percent of the total observed current which can be accounted for by the tides. Values above70% are found on the southern end of the field of view which intuitively makes sense because that region is tidally dominated.

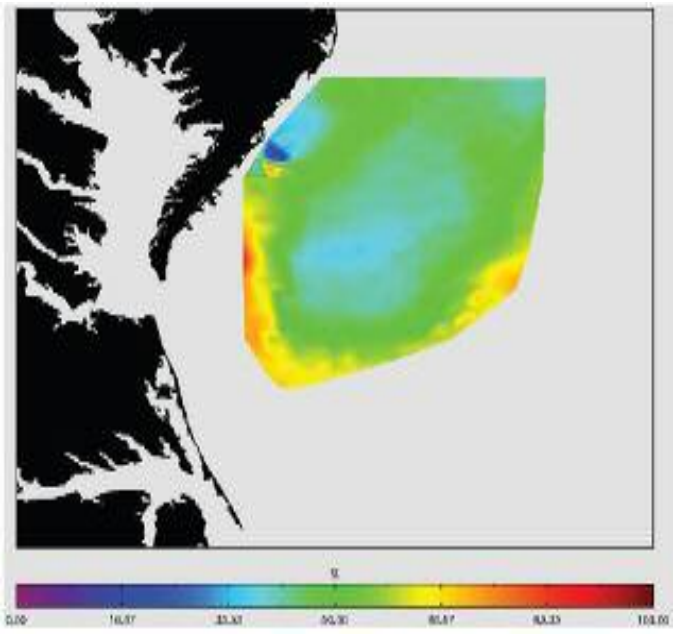

Figure 3: Percent of the Mean Surface Current accounted for by the tidal forcing.

CONCLUSION

In this paper we have analyzed CODAR derived currents to estimate the mean surface circulation pattern in the region around Delmarva. The objective of this study was to understand the level of sloshing one could expect in a 24 hr. period due to tides. Our results showed that the tides account for nearly 60% of the variation particularly at the mouth of the Chesapeake Bay. These variations are observable from satellites with a 250 m^2 resolution. Thus, our study confirms that high resolution satellite observations can be used to study the dynamics created by tides along the coast. These results will be useful for developing satellite derived algorithms from future hyper-spectral geostationary satellite observations.

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