Measuring the landward Gulf Stream front variability off Cape Hatteras with HF Radar

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Abstract— **A decade of coastal ocean radar surface current observations of the Gulf Stream off Cape Hatteras, NC have been collected that offer to provide key new insights into the temporal and spatial variability of the Gulf Stream in this region. The Gulf Stream is believed to have a profound influence on the complex current dynamics off of Cape Hatteras, NC that result from the convergence of many different water masses in the region. Although essential to understanding oceanography off the NC coast, and to linkages beyond the region, Gulf Stream variability in this area has been difficult to quantify because of the challenge involved in obtaining observations of consistent spatial and temporal resolution over long time periods. Analysis of Long Range Seasonde Coastal Ocean Radar (Codar) ocean surface current measurements from two sites in NC may provide estimates of the landward Gulf Stream edge over a nearly continuous ten-year period. Radar surface current measurements are made hourly, more frequently than satellite measurements, and provide more consistent coverage of the Gulf Stream than many historical measurement techniques. The 5MHz radars typically make surface current measurements across the entire cyclonic shear zone on the landward side of the Gulf Stream. These measurements may provide methods to define Gulf Stream location, width, transport and variability of these properties over time and alongshore, providing insights into the current dynamics off Cape Hatteras, NC.**

We here present a method to identify the landward Gulf Stream position and width of the cyclonic shear zone from radar surface currents. The method of front detection developed associates the landward Gulf Stream front with maxima in the radial current shears. Maxima are chosen within regions of consistent coverage over the time period sampled. The locations where the Gulf Stream first enters and exits the radar coverage area are apparent as large radial speeds measured by the radar, and one bearing is chosen from each region for analysis. However in a region between these two zones the Gulf Stream is perpendicular to the radials and the method can not be used. This method can be applied to each of three radars located in the vicinity of Cape Hatteras.

I. Introduction

A Coastal Ocean Radar (Codar) from Codar Ocean Sensors has been in operation in the Cape Hatteras National Seashore on the beach in Buxton, North Carolina from the fall of 2003 until the present. An additional radar was added in November 2013 on the Core Banks of North Carolina. A single Codar measures the radial component of the ocean surface current relative to the radar in the top two to three meters of the water column. Radial currents are produced every hour. Each radial current vector is a three hour average, with the spatial resolution decreasing as a function of range from the radar. Each vector is a spatial average over an annulus bounded by a 5.85 km range difference, and five degree bearing separation. The Codar range varies from 100 to 200 km. Range variation is due to environmental factors such as ionospheric interference from the radar signal reflection off the ionosphere, nonlocal interference, and variation in the ocean wave field reflecting the radar signal.

The long term consistent hourly surface current measurements from the Buxton and Core Banks radars offer to provide new insights about the temporal and spatial variability of the landward Gulf Stream front and width of the cyclonic shear zone off of Cape Hatteras. Hourly radar surface current measurements are more frequent than satellite measurements, and provide more consistent coverage of the Gulf Stream than many historical measurement techniques. The 5MHz radars typically make surface current measurements across the entire cyclonic shear zone on the landward edge of the Gulf Stream. The radar provides more consistent observations of the Gulf Stream location over space and time than satellite Sea Surface Temperatures (SST's) because the radar estimations are not limited by cloud cover, observing frequency, and small temperature gradients between inshore water and the Gulf Stream typical in the summertime south of Cape Hatteras. There are limitations to the radar, however; drawbacks include the 6 km resolution, whereas Advanced Very High Resolution Radiometer (AVHRR) satellite SST's have 1.09 km resolution (http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html), and site specific challenges related to quantifying uncertainty in the radar measurements (Liu et al. 2010).

The Gulf Stream is apparent in the radial current coverage area in two zones (Fig. 1). The Gulf Stream enters from the south of the coverage area where it appears as large negative current speeds moving toward the radar. The Gulf Stream exits the radar coverage to the northeast in the area of large positive radial current speeds. Between these two zones, the Gulf Stream is perpendicular to the radials, and single site observations cannot provide a good approximation of Gulf Stream location.

Our method determines the location of the shoreward edge of the Gulf Stream, and width of the cyclonic shear zone, at two bearings from each radar site. Two bearings are selected: one from the region of coverage where the large negative current speeds indicate the Gulf Stream enters the radar coverage, the other from the region of large positive speeds where it exits (Figure 1). Bearings are chosen within these two regions based on large radial velocities and consistency in coverage over the sampling period.

Along each bearing, the Gulf Stream landward edge location G_r is estimated to be at the maximum gradient component of the averaged radial speeds (v_r), determined by taking the maximum of the absolute value of the derivative of the averaged speed with respect to range at a given bearing (Θ) (Eq.1), and inshore of the maximum radial current on that bearing.

$$G_r(\Theta) = |(\partial v_r/\partial r)|_{max} \qquad (1)$$

The maximum radial current is assumed to be the center of the Gulf Stream jet, and the distance between the maximum shear along that bearing and the maximum current speed is the width of the Gulf Stream cyclonic shear zone.

Previous attempts were made to develop estimates of the entire Gulf Stream edge within individual radar radial footprints, but were complicated by variability in radar coverage due to interference and environmental conditions. Simplifying the algorithm to focus on only two bearings has yielded preliminary Gulf Stream position estimates with short period variability from 3-7 days that is expected in this area (Savidge and Bane 2001).

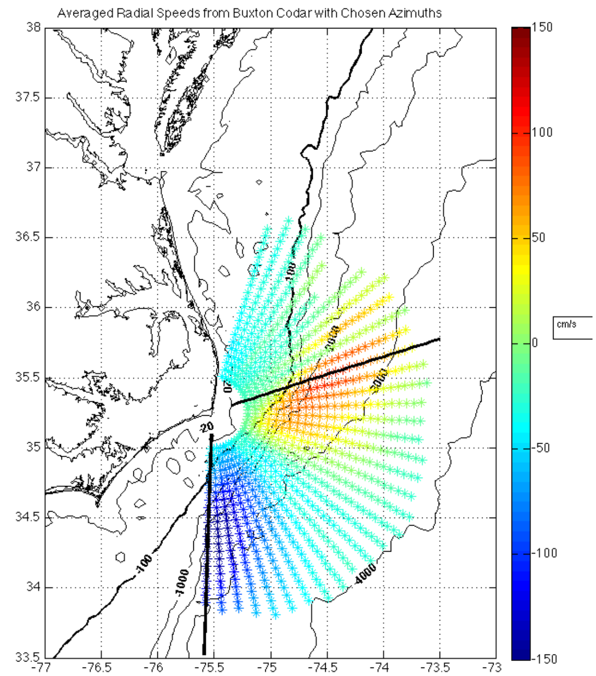

Figure 1: Averaged radial speeds from the Buxton, NC Codar from November-December 2014 with chosen Gulf Stream analysis bearings in black. By convention, negative (cool) speeds are toward the radar and positive (hot) speeds are away.

The utility in determination of the edge with the radar lies in the nearly continuous temporal coverage, permitting assessment of front variability on times scales from hours to years, and the ability of the radar to detect the Gulf Stream landward edge when heavy cloud cover obstructs satellite imaging, or warmer inshore water temperatures minimize the gradient between the inshore waters and the Gulf Stream too much to determine the edge with SST's.

II. Methods

There are known quality control problems with the radar current measurements that are being addressed simultaneously with the development of our Gulf Stream radar estimates. We have chosen to work with this data set despite these problems, developing the algorithms so that the quality-controlled data can be immediately used to improve our estimations when it is available. We highlight work done with the Buxton, NC Codar system, but the algorithms are developed to be applicable to the radial currents from the recently deployed radar on the Core Banks of North Carolina and the Duck, NC Codar system that has been running since 2003.

To increase the accuracy of our method using the data in its present state, we chose only radial current measurements with consistent coverage over the time period sampled. At each location, only radial velocities that were present at least 70% of the time over 64 days of hourly radial velocity measurements were used in analysis (Figure 2).

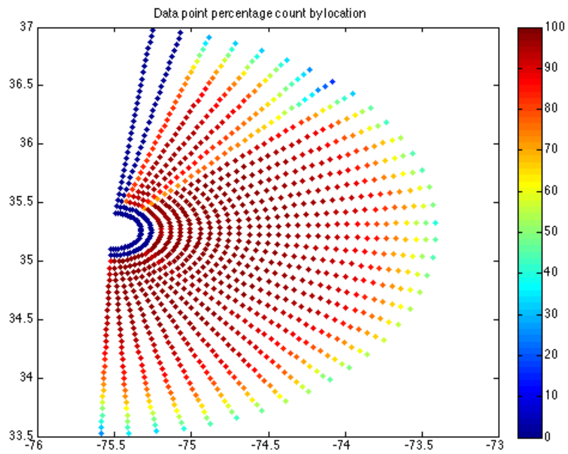

Figure 2: Coverage percentage over sampling time period at each radial velocity measurement location.

The two bearings (Figure 1) used for estimating the Gulf Stream position are selected by averaging the radial speed over all ranges at each azimuth, and choosing the two bearings where the maximum and minimum values occur over the sampling period. The radial velocities at those two bearings are then smoothed (Figure 3) and interpolated (Figure 4) to improve the data quality for analysis. The rapid change in speed marks the landward Gulf Stream front.

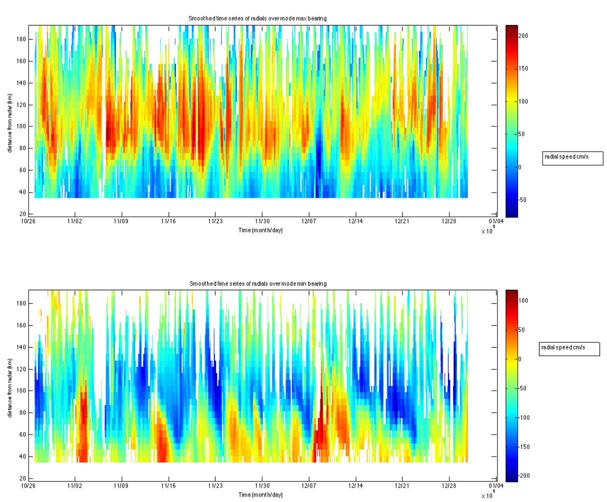

Figure 3: Smoothed radial velocities as a function of distance from the radar over the time series at each selected bearing. Maximum (minimum) radial velocity bearing is the top (bottom) figure.

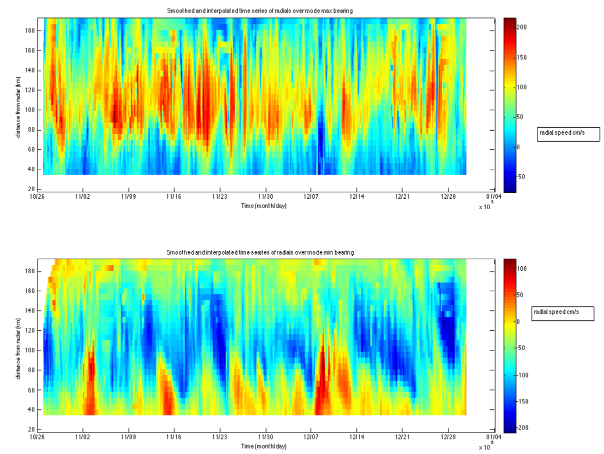

Figure 4: Smoothed and interpolated radial velocities as a function of distance from the radar over the time series at each selected bearing. Maximum (minimum) radial velocity bearing is the top (bottom) figure.

Smoothed interpolated radial velocities compare favorably with raw data when both are averaged over the time series (Figure 5) and compared over all ranges, providing confidence that improving the radar data for analysis in this manner does not alias results.

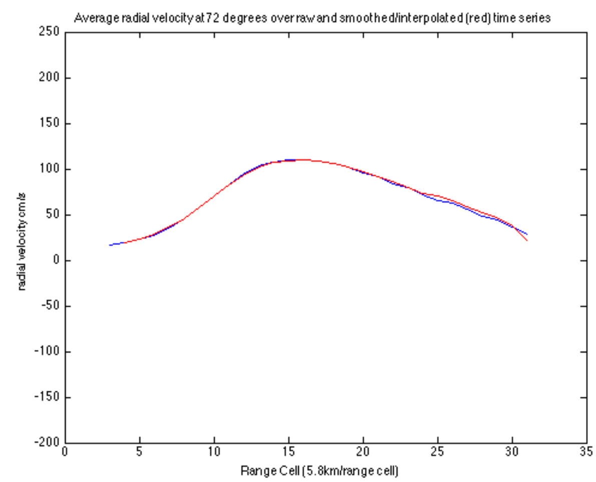

Figure 5: Radial velocities from 72 degree bearing smoothed and interpolated speeds (red) and raw speeds (blue) time averaged over the sampling period at all ranges from the radar.

Using the smoothed interpolated radial currents along both selected bearings, we identify G_r and the range to the maximum current.

III. Preliminary Results

Our method assumes the landward edge of the Gulf Stream can be identified in the radial current speeds by locating the maximum shears in the coverage area along radar bearings – one in the region the Gulf Stream enters the radar coverage and one where it exits. Along those same bearings, the width of the cyclonic shear zone is the distance between the landward Gulf Stream edge and the maximum current velocity. This distance is likely affected by the crossing angle of the selected bearings and the Gulf Stream meanders to an extent that has not yet been determined. However, in estimates made so far, the separation between the position estimates is relatively consistent along both bearings (Figure 6).

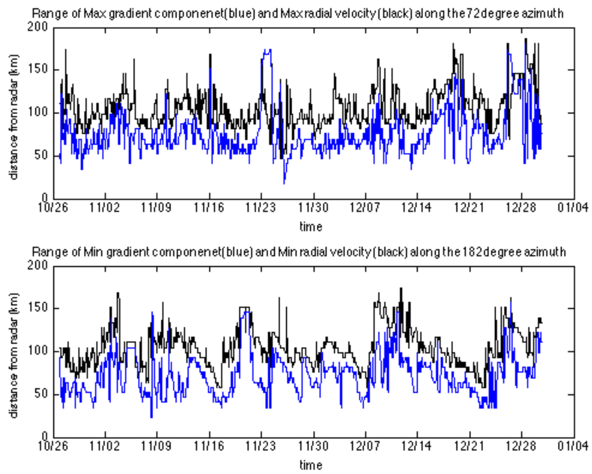

Figure 6: Maximim (minimum) gradient component distances from the radar are in black, and radial velocity maximum distances are in blue on the top (bottom) panel over the time period sampled.

The variability in distance to the gradient component and maximum (minimum) radial velocities are correlated in this preliminary analysis. The average cyclonic shear zone width from this method is 32 km along the 72-degree bearing, and 29 km along the 182-degree bearing.

Along both bearings Gulf Stream position varies over a range of time scales, with a weekly period of roughly 50 km range being most obvious along the southward bearing. Along the ENE bearing the variations are of smaller magnitude and possibly of shorter period. Daily period variations are more pronounced along the ENE bearing.

IV. Future Applications

Variability in range of maximum radial shear, maximum radial current velocity, and width of the cyclonic shear zone determined by the difference in distance to both, is likely due to variability in Gulf Stream position, and orientation of the Gulf Stream with respect to the radar. We have begun using these parameters to determine Gulf Stream orientation as well as position variability. Applying these methods to two additional radars, one at Duck, NC about 100 km north and another in the Core Banks of NC about 95km south of the Buxton, NC radar will contribute to this assessment.

Ultimately, radial currents from individual radars are combined to form total surface currents by the Codar systems. We have explored using these total surface currents, and the relative vorticity in the surface currents to identify the Gulf Stream edge and cyclonic shear zone with some success. Using total surface currents from combined radials from individual radars that were not previously quality controlled has proven challenging thus far because of known problems with the radar measurements. We anticipate this method will yield more promising results for comparison with the individual radar estimates as data quality is improved.

Effectiveness of this method will be evaluated based on historical methods of Gulf Stream observation, for example the alignment of the sea surface temperature expression of the Gulf Stream from Advanced Very High Resolution Radiometry (AVHRR) and Moderate Imaging Resolution Spectroradiometer (MODIS) satellite SST data, shipboard Acoustic Doppler Current Profiler (ADCP) data, and Navy Gulf Stream Frontal Charts available bi-daily (http://www.opc.ncep.noaa.gov/sst/NavyFeatures.shtml). Recent cross isobath ship-board ADCP current and SST measurements of the Gulf Stream in this region should provide an estimate of the expected offset between Gulf Stream frontal determination from SST gradients and current shears.

References

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[2] Savidge, D. K., and J. M. Bane, 2001. Wind and Gulf Stream Influences on Along-shelf Transport and Off-shelf Export at Cape Hatteras, North Carolina. *J. Geophys. Res.*, 106(C6), 11,505-11,527