A COMPARISON OF TWO METHODS MEASURING SURFACE COASTAL CIRCULATION: CODAR VERSUS SATELLITE ESTIMATION USING THE MAXIMUM CROSS-CORRELATION TECHNIQUE

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Abstract. *Numerous methods exist to measure surface current in the ocean. This study offers the first comparison of CODAR with the Maximum Cross Correlation Technique (MCC), which are two remote methods. Four months of CODAR vector fields were provided by the Rutgers University Coastal Ocean Observation Laboratory, and MCC velocities were compiled by the Colorado Center for Astrodynamics Research. The geographic area covered was located offshore the coast of New-Jersey. MATLAB scripts were written to average and geographically filter the data before errors could be calculated. Results showed a 0.15 and 0.14 m s^{-1} RMS error in east-west and north-south components respectively, and an overall 0.20 m s^{-1} RMS error in velocity magnitude. This error range is in agreement with published comparisons of CODAR and MCC with other current measuring methods. Possible error sources include averaging and interpolating process, resolution difference, or tides. Further analysis is required to assess the importance of each error factor. The MCC technique, however, has limitations to such a comparison due to cloud cover and thermal gradient strength, which restricted the number of comparisons.*

1. Introduction

Knowing the coastal circulation is decisive in several fields including safety, commerce, or recreation. Accurate data about surface current speed and direction help in many applications: rescue operations for men or ships, predicting the target zone of an oil spill, forecasting fisheries areas in phytoplankton-rich waters, or money saving for cargo companies to navigate along the current. These facts are also the many reasons for oceanographers to study coastal currents.

Ocean currents are observed remotely or *in situ*. Remote methods include radars or satellites, which use either altimetry or radiometry to estimate the current. *In situ* methods are current meters anchored at fixed locations, CTD casts, or drifters. This study compares a remote-sensing radar called CODAR to radiometer satellite imagery processed with the Maximum Cross-Correlation technique (MCC). The purpose is to find the magnitude of errors between both methods and possibly merge them to obtain a more accurate perspective of the coastal surface circulation. The sequential satellite data offers the advantage of providing a general look at the coast, and the radar is directly within the area providing real-time data.

a) CODAR

Coastal Ocean Dynamics Application Radars (CODAR) are deployed along the coast in New Jersey and Connecticut for this study. They are operated by Rutgers University Coastal Ocean Observing Laboratory (R.U.C.O.O.L) and the University of Connecticut (U.Conn). Several sites are equipped with an emitter and a receiver. The emitter sends a radio signal offshore (figure 1), which propagates in the water until it hits a wave of wavelength 3 to 50 m. Then the radio signal is scattered around. It will return to the receiver only if the resulting ocean wavelength

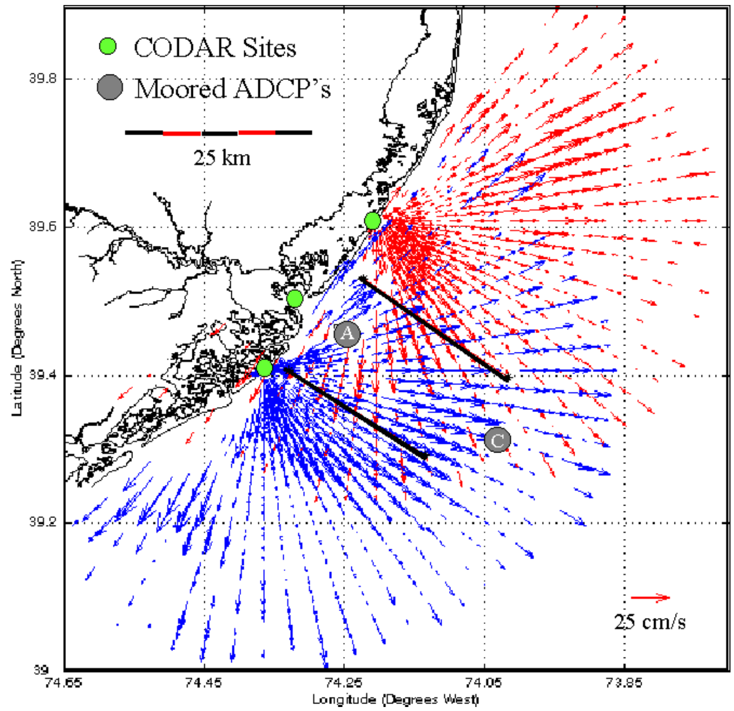

Figure 1 – CODAR antennae sites along New-Jersey sending radio signals in radial path. (http://marine.rutgers.edu/)

is exactly half of the radar wavelength, and if the wave follows a radial path towards or away from the antenna. This is called the Bragg scattering effect. When two pulses are sent with a known time delay, the difference in the return delay will indicate if the wave is moving towards or away from the receiver, according to the Doppler Shift principle. Since the wave velocity is estimated from the deep-water celerity equation knowing its wavelength, then the difference between the expected and the actual velocity is due to the underlying water current (www.codaros.com).

Each antenna can emit and receive from only one radial direction, but the water may be moving at an angle from the site. To obtain accurate results, several sites have their own antennae and the signals received are combined to have readings of the same target in the ocean, but from different antennae. Hence, the net speed and direction of the target is determined precisely. This process allows obtaining surface current maps up to 100 miles offshore.

b) MCC

The determination of surface current from satellite imagery is different. The process is called the Maximum Cross-Correlation technique, and was developed by William Emery in 1986, now working at the Colorado Center for Astrodynamic Research (CCAR). The method uses two infrared images (AVHRR). Each picture is filtered for clouds before any analysis (Bowen et al., 2002). The first image is divided into subwindows, and color patterns are cross-correlated with subwindows from the second image (Figure 2). The size of the search windows on the second image corresponds to the largest expected displacement of the color feature from the first window. When the pattern is located on the second image, the difference in location

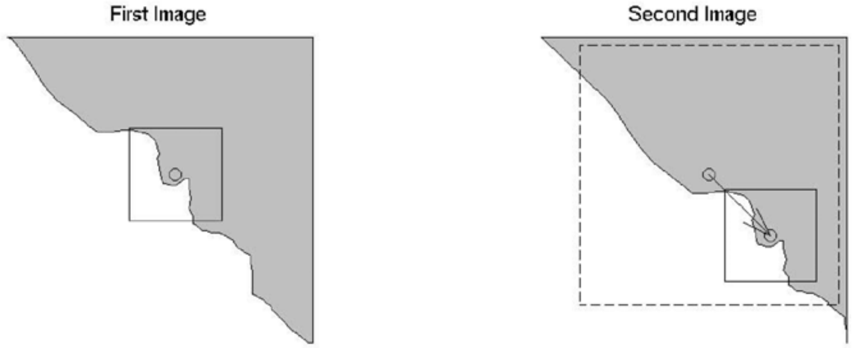

Figure 2 – Thermal feature cross correlation between first image and second image subwindows. (www.ccar.colorado.edu)

gives an estimate of the distance it traveled, which in turn gives the velocity. Best results are obtained if the time delay between both images is under 12 hours, and the correlation is only estimated if at least 60% of the pixels between both subwindows correspond to each other. When the velocity vectors are calculated, a filter is then applied to remove erroneous values. Error sources arise from accidental pattern matching, and are corrected using a ±95% confidence interval that random patterns are rejected. To ensure quality, every vector must have a number of neighbors matching the velocity, or it is removed. Errors also accounts for spatially non-uniform heating or cooling due to clouds, which can be limited by keeping the delay between images to under 9 hours (Tokmakian et al, 1990). The precision of the velocities is estimated between 0.08 and 0.2 m s^{-1} (Bowen et al., 2002). This technique computes only advective sea surface velocity. As the surface displacement of a feature is used to calculate the vectors, it does not take into account non-advective surface processes (e.g. diffusion). In addition, the method does not inform about the driving forces of the current, which include geostrophic and wind driven components (Emery et al., 1986). Cloud cover also limits the method as AVHRR cannot record data under clouds.

c) Comparisons to other methods

Each of these methods was compared to other ocean current measuring techniques as quality insurance. MCC using AVHRR images was compared to altimetric data and showed root-mean-square (RMS) differences between 0.25 and 0.30 m s^{-1} (Bowen et al., 2002). When compared to ADCP, MCC underestimated the velocity by 35% and by 56% for drifters (Kelly and Strub, 1992). Finally, Tokmakian et al. (1990) suggested uncertainties ranging from 0.10 to 0.25 m s^{-1} with dynamic heights and ADCP values.

CODAR was compared to ADCP measurements by Paduan and Rosenfeld (1996), who reported an RMS error of 0.06 to 0.11 m s^{-1}. Kohut et al. (1999) nevertheless found a difference of 0.7 m s^{-1} and Emery (2004) obtained errors of 0.07 to 0.19 m s^{-1} between the same instruments. CODAR, however, was never compared to satellite derived surface current. This study is the first attempt to do so.

After gathering data from Rutgers, UConn and from CCAR for an overlapping time and space, MATLAB was used to show how well both data sets matched. Methods, results and discussion are presented in the following paper.

2. Methods

a) Data

CODAR data were downloaded for four months to represent an annual cycle: October 2001, January, April and July 2002. The geographic area covered is between 76.0ºW - 67.0ºW longitude and 37.5ºN – 42.0ºN latitude. The data included longitude, latitude, east-west (U) and north-south (V) velocity component. The Rutgers files were 3-hourly centered averages, whereas the U.Conn files were 1-hourly centered averages. CODAR vector coverage depends on the wave climate: the more the waves, the more the vectors. The CCAR team produced the vector fields for the overlapping time and space. This technique was applied to the east coast for the first time for this project. They provided 118 files, each based on a pair of images between 3 and 12 hours difference. As the technique relies on color gradients (of temperature in this case), if the coastal area does not present enough thermal features, no vector fields can be produced.

b) MATLAB scripts

A series of MATLAB scripts was written, some inspired by an R.U.C.O.O.L code, to conduct the analysis. The first step was to average the CODAR file over the same time window that was covered by the MCC files. It selected only vectors from the same geographic location in all files being averaged. The output was a matrix with latitude, longitude, U and V velocity components. Next, both vector fields were displayed on a common map to evaluate the overlap of both sets (Figure 3). Indeed, a comparison can only be done if there are sufficient data from both sets, for the same time and location. A first series was selected where the overlap was appropriate. Then were the MCC matrix and the averaged CODAR filtered to keep data points that were only within 5 km from each other (Figure 4). This would avoid interpolation errors in the next step. Since each data set came with its own grid and locations did not match, both sets were interpolated on a common grid (Figure 5). The number of points on the grid is a user-defined parameter that can be refined until the best results are obtained. An arbitrary choice of 50 points in longitude and latitude was chosen for all files. It produced interpolated velocity components at newly defined longitude and latitude. The number of common points depends on the size of overlapping area between both sets of vectors. Then the global grid had to be filtered for unwanted data automatically created by the gridding function from MATLAB. It creates by default a rectangle of values, even though the original values did not cover the entire rectangle. Consequently, locations that did not have velocity components associated with it were rejected, leaving only a restricted amount of quality data. Finally for the manipulations, the vector difference between MCC and CODAR was calculated, resulting in a vector field that represented the error in U and V between both sets (Figure 6). The error in velocity magnitude was root mean squared to represent the typical magnitude of errors (Wilks, 1995).

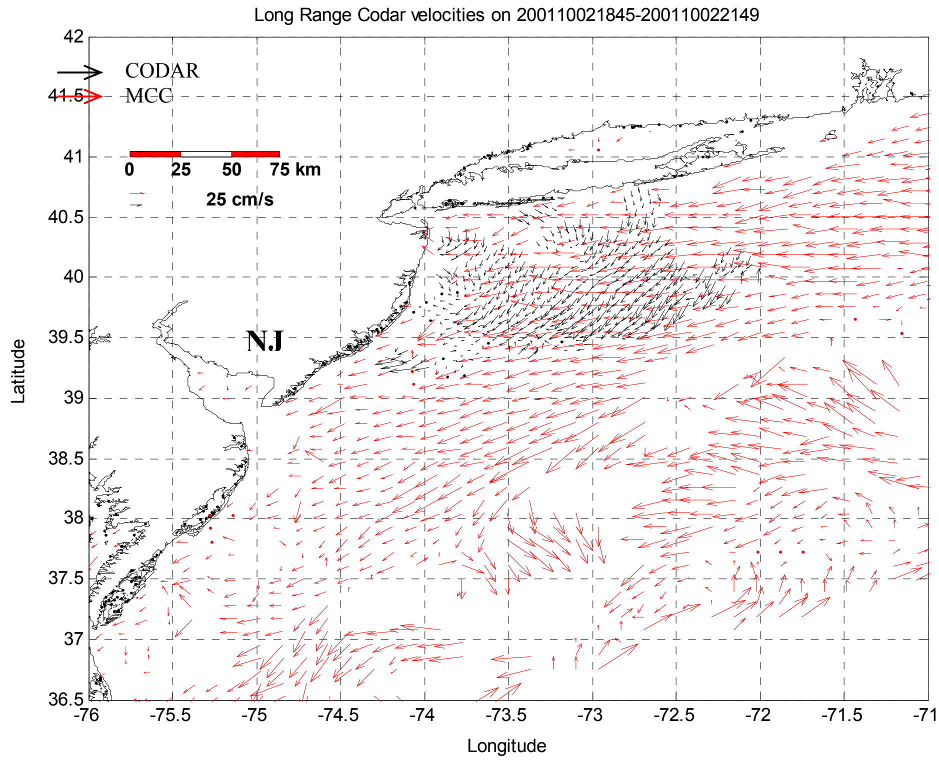

Figure 3 – Overlap of CODAR and MCC vector fields.

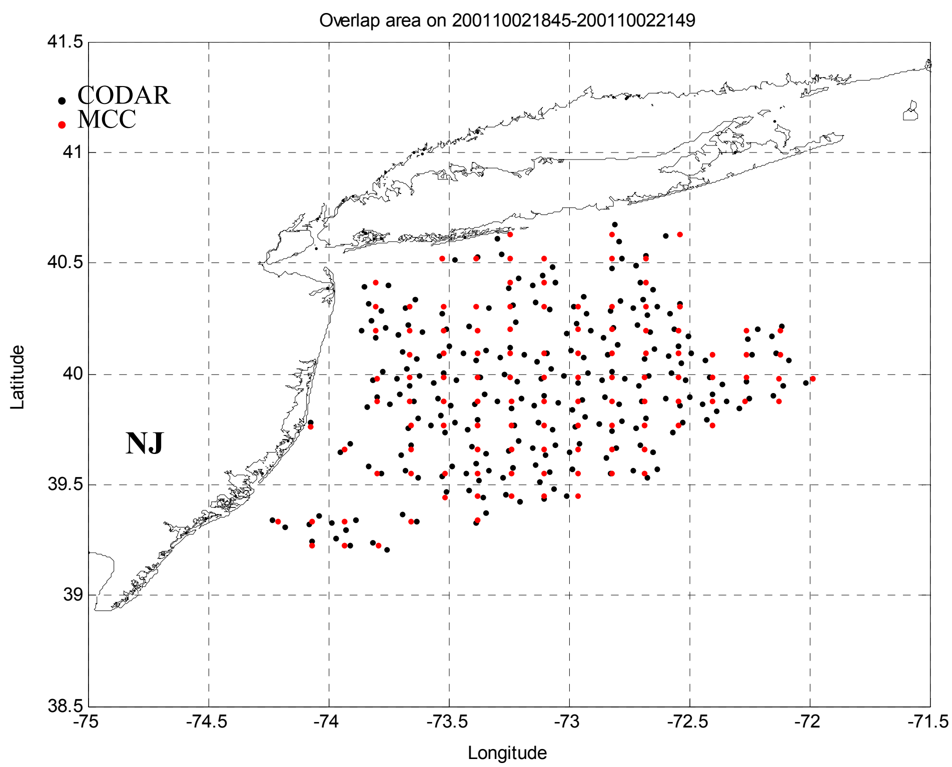

Figure 4 – Selected points within 5 km from each other

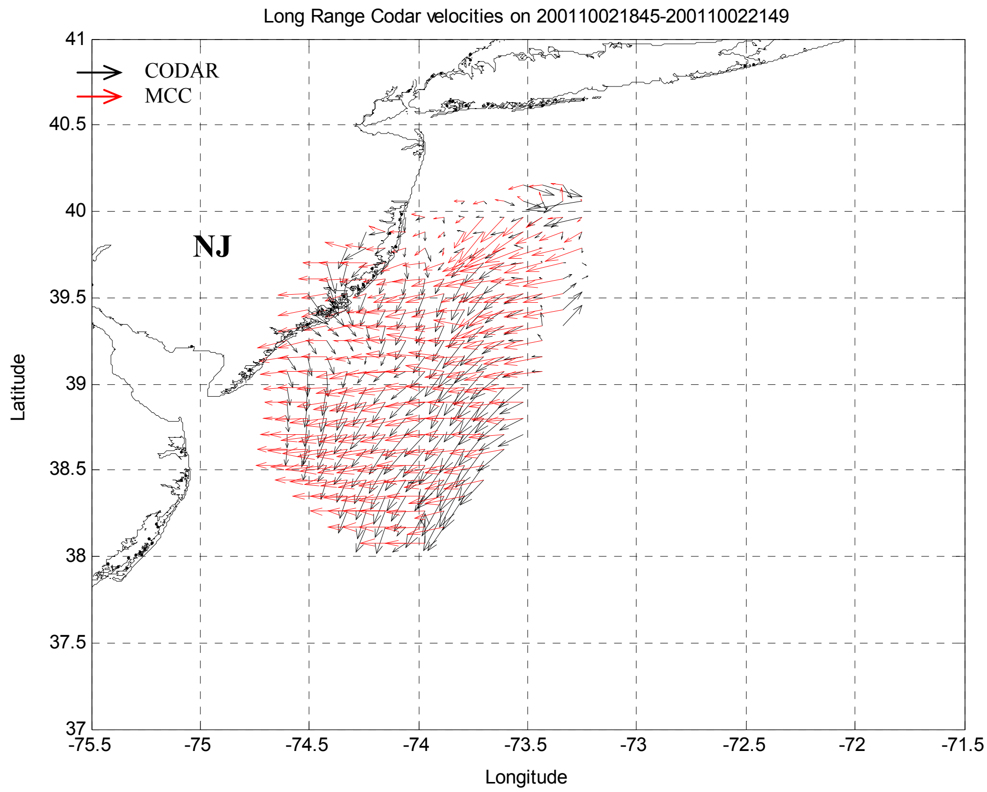

Figure 5 – CODAR and MCC vectors on the common grid (vectors not at the same scale)

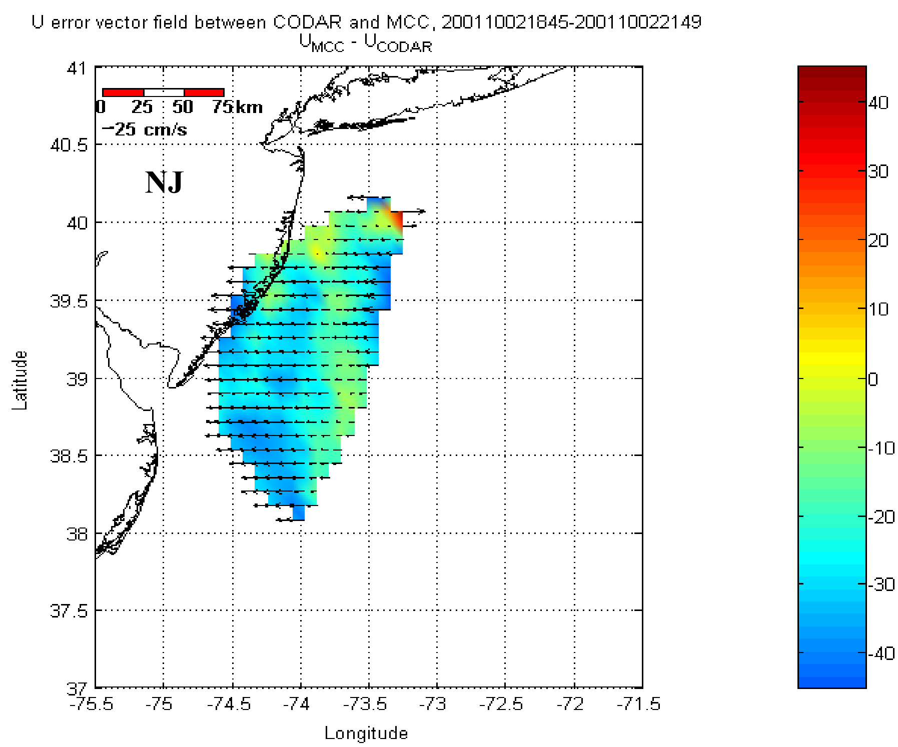

Figure 6 – Example of error field where CODAR was subtracted from MCC

3. Results

a) Data availability

CODAR data were consistently available, except for a small gap of three days in October 2001. MCC data however were more scarce as only 118 vectors fields were available out of all the images pair possible in four months. Out of these, only 27 had a sufficient overlap with the CODAR data, which makes 77% of data unusable. Out of the 23% of good MCC vectors, 19% were in October 2001, and for January, July, and April 2002, 59%, 0% and 22%. None of the July 2002 files had a sufficient overlap as there was no overlap with Rutgers CODAR, and the UConn CODAR resolution was too fine. Indeed, for the UConn data coverage, only a few MCC points were overlapping, which was considered too little for a good analysis.

b) Error in U, V and magnitude

Results showed a variety of errors. In the best case, the overlap had a consistent acceptable difference of -10 to 10 cm s^{-1} (Figure 7). The color bar in Figure 7 indicates that this result is good, since neither CODAR nor MCC dominates. In other case, there is a strong dominance of CODAR or MCC, or locally both, as shown in Figure 8, 9 and 10. Small errors or local dominances were most frequently observed in U and V directions, as well as for the magnitude. RMS errors were 0.15, 0.14 and 0.20 m s^{-1} for east-west, north-south and magnitude, respectively.

When plotting U_{RMS} versus V_{RMS} in Figure 11, an increasing trend is observed, meaning that the RMS errors in V increases as the RMS errors in U increases, which was expected. In the same way, RMS errors in magnitude increase with increasing velocity (Figure 12).

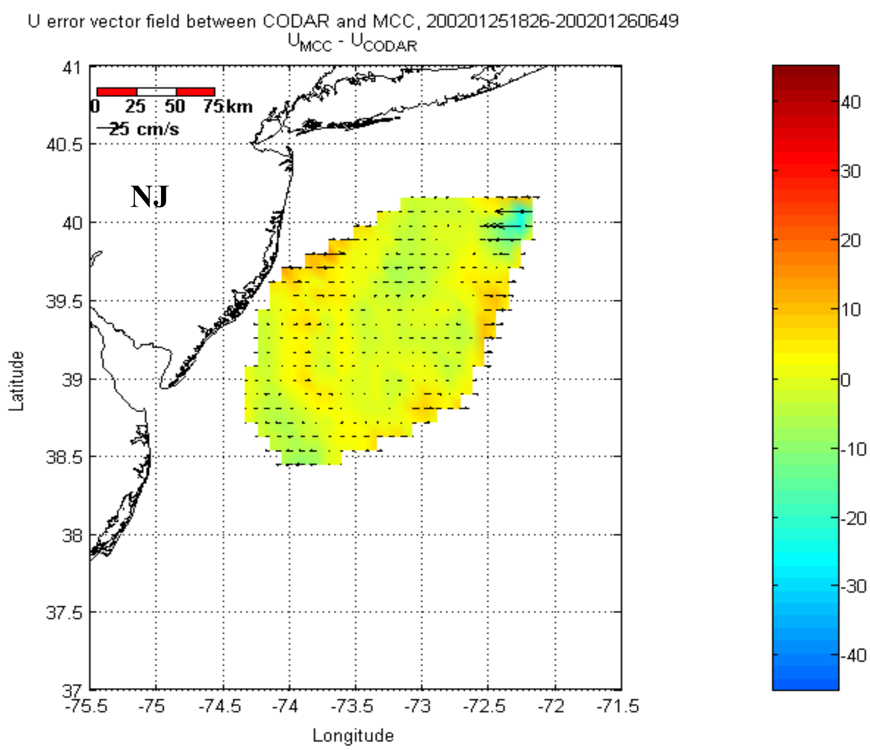

Figure 7 – Error in the U direction between CODAR and MCC with an acceptable range

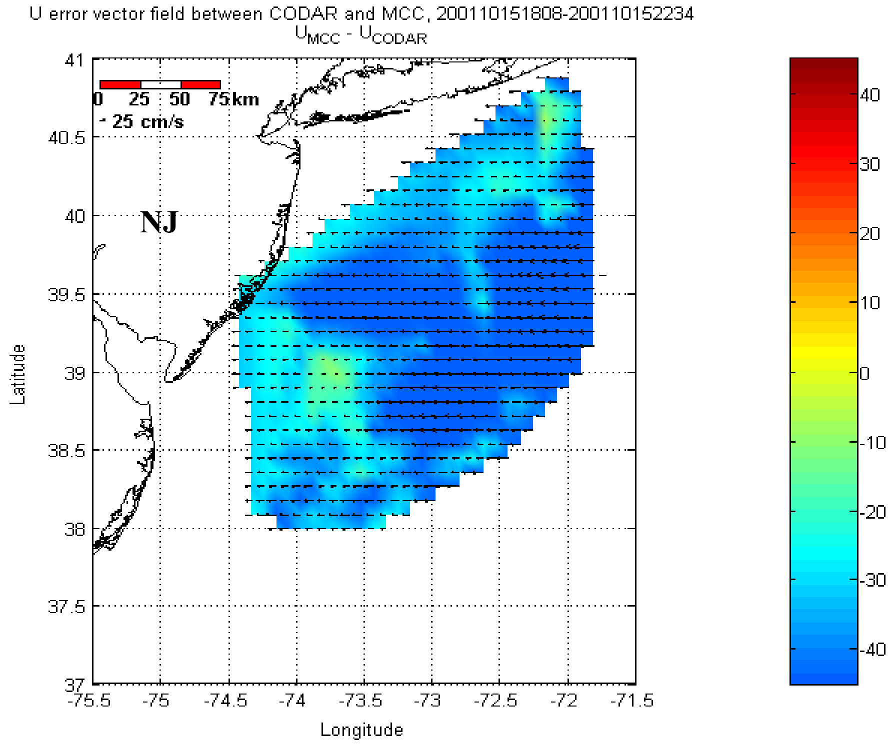

Figure 8 – Strong dominance of CODAR with respect to MCC

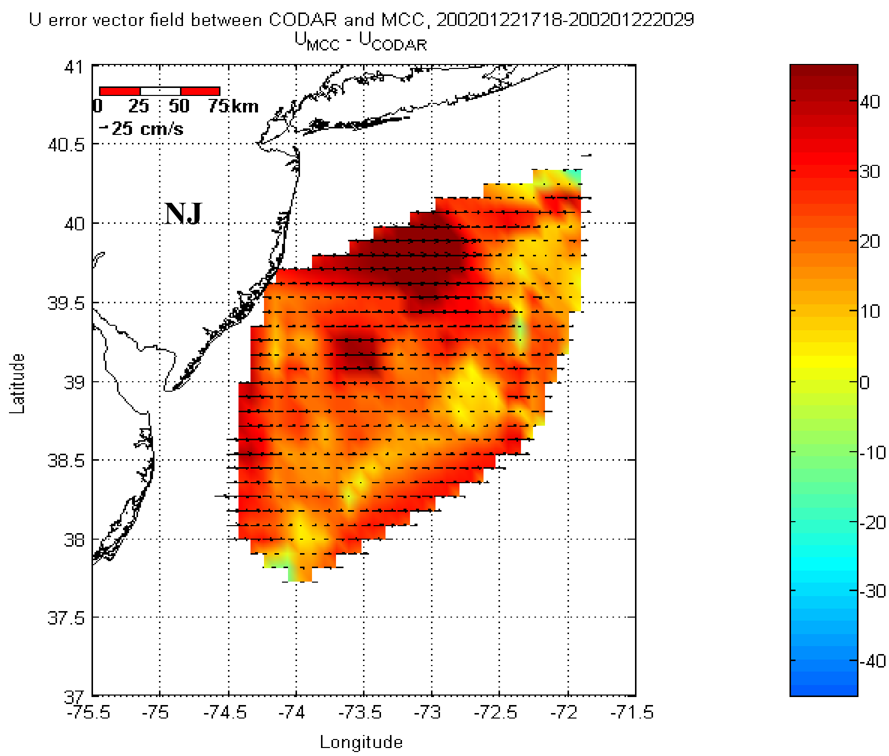

Figure 9 – Strong MCC dominance with respect to CODAR

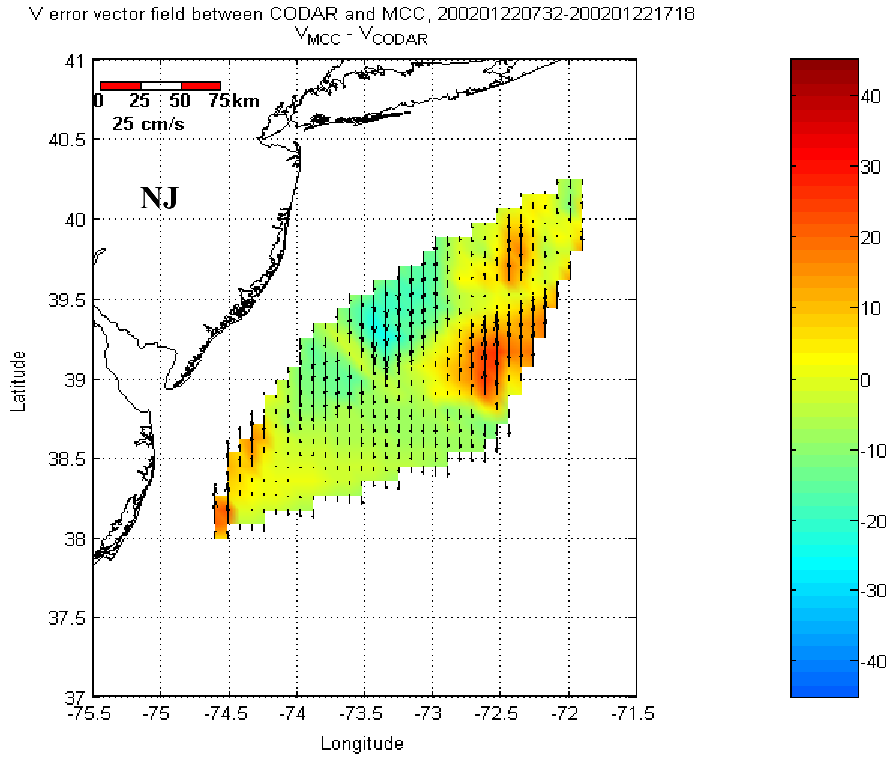

Figure 10 – Mixed results where CODAR and MCC are locally dominant

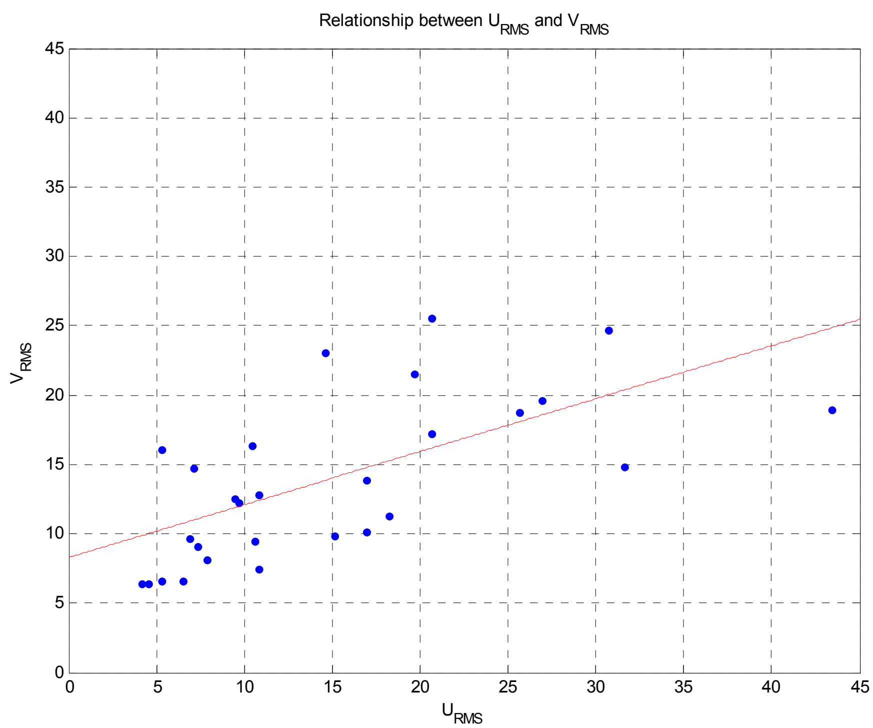

Figure 11 – Relationship between U_{RMS} and V_{RMS} where the best fit line shows an increasing trend

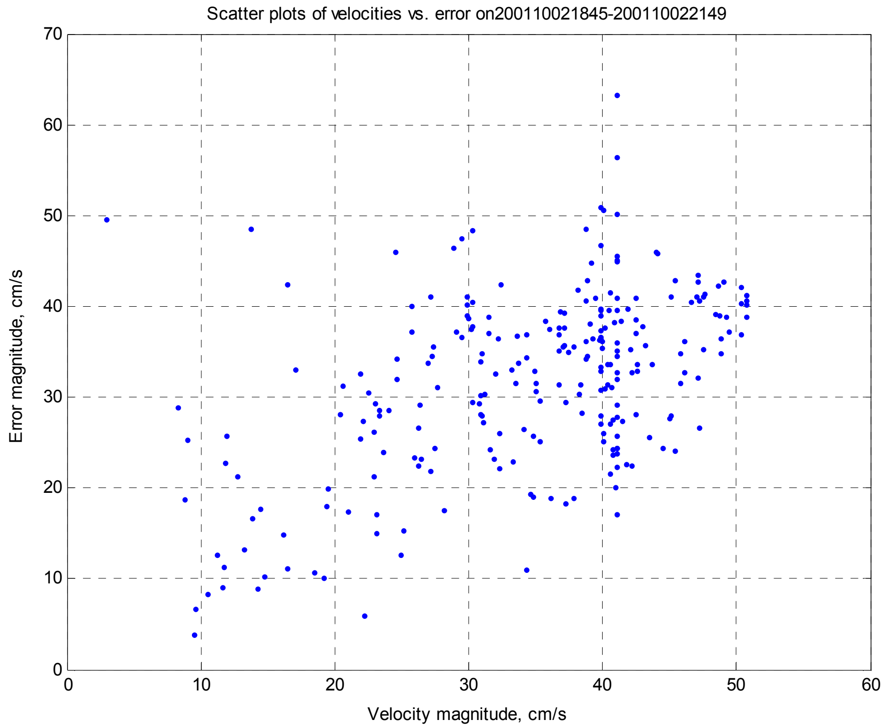

Figure 12 – Magnitude error as a function of the velocity magnitude shows an increasing trend

4. Discussion

a) Limitations of the method

Before any analysis of the previously exposed results, it is worth mentioning the limitations of such a comparison. CODAR data are extensively archived, so it is easy to use. AVHRR images, however, have many limitations. First, although images are largely available, only cloud free, or partially cloud-free, pictures are useable. Clouds block out any outgoing energy radiating back from Earth, preventing data underneath to be recorded. Then, only pictures with a ground control point can be used, so that they can be georeferenced (Dick O'Donnell, 1998). And finally, thermal gradients, which are the basis of the MCC technique, must be strong enough to be detectable. With all these considerations in mind, it is easily understandable why there were only 118 files available.

The fact that only 27 comparisons were performed shows how inconsistent the coverage area of MCC was. CODAR is regularly recorded in the same zone. MCC, however, only records random areas in the same region as CODAR, according to clouds formation and displacement.

b) Error sources

According to the RMS errors, there are larger inaccuracies in the U direction. This result was not expected because of the tides. Indeed, tides in this region are in the north/south direction. In the middle of the Atlantic Ocean is an M_2 amphidromic point, which corresponds to no water elevation. Tidal waves are propagating in the North Atlantic Basin around this point in a cyclonic direction. Consequently, as it reaches the New Jersey coast, it propagates in a north south direction, adding to the corresponding velocity component.

Looking at the dominant colors in the U and V directions, it shows that MCC seems to underestimate CODAR in U, but seems to overestimate CODAR in V. This may be caused by the tides again. CODAR, measuring the velocity from within the water, may be able to account for the vertical shear associated with the faster velocities in U. Then as MCC cannot detect this shear, CODAR velocities should be faster.

One of the steps in this comparison was to average CODAR raw files over the same time window covered by the MCC files. However, the averaged CODAR could not exactly correspond to the MCC period. The resulting CODAR was up to 90 min longer or shorter on both ends. It is tempting to think that this additional time will induce errors. Nevertheless, it was not the case. Figure 13 and 14 illustrate that with a difference in time as little as 30 min, or as big as 175 min, the resulting error was of the same order.

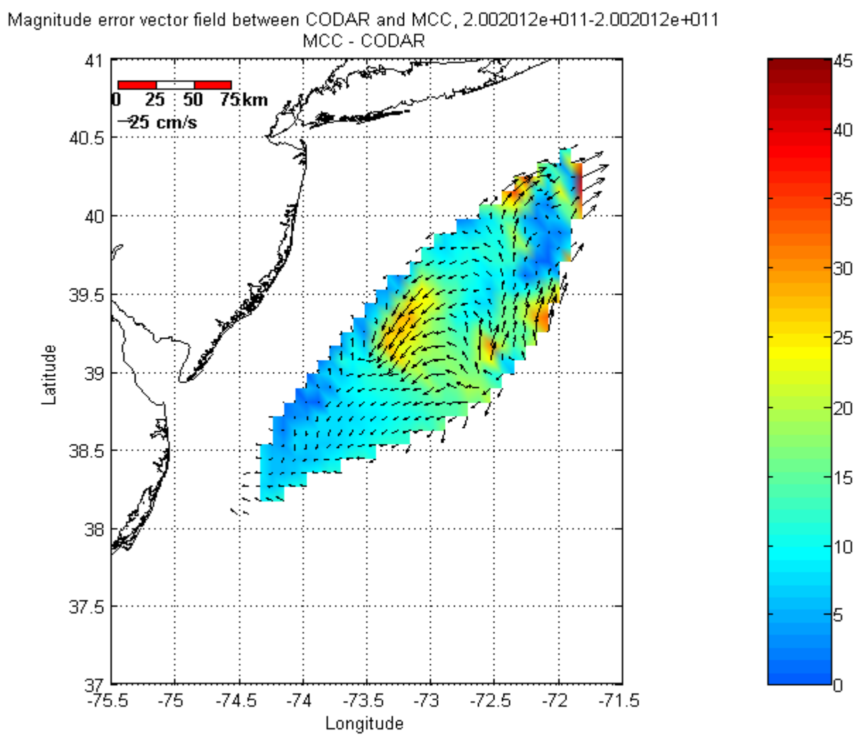

Figure 13 – Magnitude error produced from an averaged CODAR file only 30 minutes longer than the corresponding MCC file

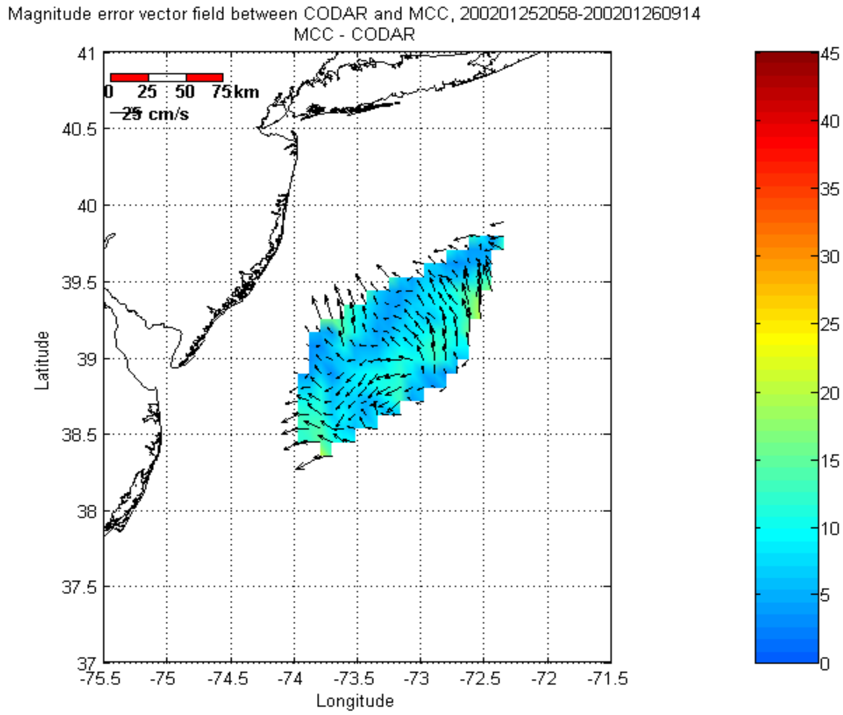

Figure 14 – Magnitude error produced from an average CODAR file 175 min longer than the corresponding MCC file

There could be a link however between this extra time and errors. Depending on when in the tidal cycle the time was added, the difference in velocity could be large. On a daily tidal cycle, there are two high tides, and two low tides (Figure 15). These moments in the cycle correspond to slow tidal velocities. However, the velocity increases tremendously in-between, with a peak in the middle of the change in tide. If the added time corresponds to the peak velocity, then the overall velocity will be larger than the other set of data.

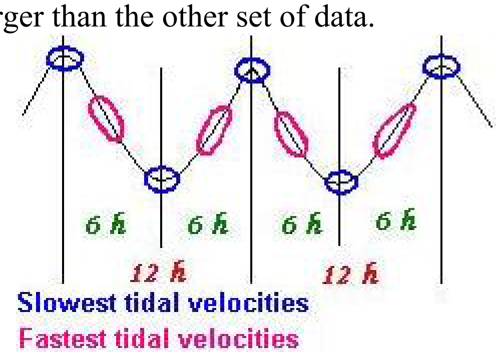

Figure 15 – Tidal cycle in 24 hrs

MCC data were sometimes patchy, or patches devoid of data were sometimes created when selected only points close from each other. When gridding, MATLAB was filling in the gaps using the linear interpolation technique. It is possible that the software creates values that are slightly out of the range of velocities. If this happens when overall velocities are small, then errors can be created that are proportionally big. At this time, the interpolation function could not be checked, but its error generating possibility is not excluded.

MCC and CODAR each have their own resolution, 1 km, and 6 km respectively. Since it is different, it can easily be a source of error as well. A simple calculation can give an estimate of the error magnitude. The average period covered by the files was 8 hrs.

$$\frac{1km}{8hr} = \frac{100000cm}{28800s} = 3.5\ cm\ s^{-1}\ \text{(MCC)}$$

$$\frac{6km}{8hr} = \frac{600000cm}{28800s} = 20.8\ cm\ s^{-1}\ (\text{CODAR})$$

Errors up to 3.5 cm s^{-1} for MCC and 20.8 cm s^{-1} for CODAR can exist.

The last error source that could be deduced from this analysis lies in the MCC method. The technique uses thermal gradients. If a gradient is weak, the software may be able to detect it, but the thermal feature tracked may not be perfectly recognized. However, with a strong thermal gradient, features can be easily identified. Figure 16 depicts a circular shaped small error area. It could be a warm ring that pinched off from the Gulf Stream that is traveling northward. As this picture was in October, the surrounding waters are expected to be cold. It creates a strong gradient with the warm waters in the ring. In this case, MCC detects the velocity better, which could explain the circular shaped small error area.

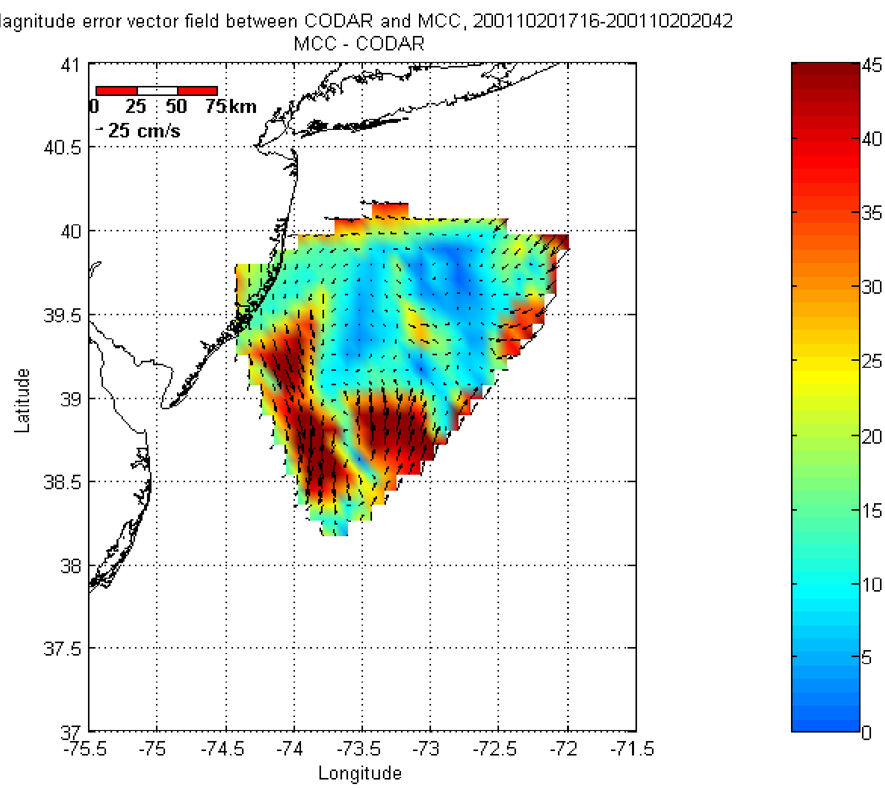

Figure 16 – Circular shaped small error maybe due to a warm ring

5. Conclusion

The error previously found between CODAR, MCC and other methods were between 0.10 and 0.70 ms^{-1}. This study shows an error between CODAR and MCC of 0.20 ms^{-1}, which is in the same range. This was expected as each measuring technique was compared to other technique to ensure quality. It is even reassuring considering that most of the error sources were not addressed yet. The known error sources of the comparison itself come from the averaging and gridding processes, the difference in resolution, and the tides. CODAR do not present error sources at this time, besides noise, and is widely available. MCC on the other-hand presented more problems as the AVHRR images it uses, i.e. with no cloud cover, were scarce, the overlap with CODAR data was not consistent and the thermal gradient had to be strong enough to be detectable. These multiple issues about MCC are a limitation to such a comparison, although both techniques are proven to work. Further analysis is required however, to address each error factor, and possibly yield to a merging of both techniques for a more accurate surface velocity map.

6. Future work

A statistical analysis should be performed on the present results as well as on the final results when obtained, to quantify the improvement when addressing each error factor. A Principal Component Analysis should be performed to inform about the variance of the data about their mean and along a different set of axes from the original one (Preisendorfer, 1988). The technique consists of looking at the variance of anomalies within the data, that is, the variance of the data from which the mean was subtracted. A new set of axes would be created, centered on the mean, and rotated by θ radians, where θ is the first principal angle. It represents the maximum and minimum values of the variance s^2 in the rotated frame. These two angles are 90º apart. The principal vectors constitute a new basis of the data space and are not correlated. The reader is referred to complementary readings for further information on principal component analysis.

Tidal influence should be addressed to quantify the errors, which may be generated. A comparison of the results of the present study with drifters would also help ensure the quality of our analysis. Having already three months of data, the fourth one being not suitable, it would be interesting to look at any seasonal trends. The ultimate goal would be to merge CODAR and MCC to produce an accurate surface velocity map.

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