Comparison of Buoy and Altimeter-Derived Shelf Currents Using an Optimal Operator

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***Abstract*—We compare *in situ* current measurements with remotely sensed surface currents from satellite altimetry calculated using a novel operator to estimate geostrophic currents with minimum noise. Buoys from the Texas Automated Buoy System measured currents in the shallow waters of the Louisiana/Texas shelf. The optimally derived currents from TOPEX/Poseidon and Jason-1 are shown to be highly correlated even in this shallow water environment.**

***Index Terms*—Coastal oceanography, satellite altimetry.**

I. Introduction

As SHOWN in [1], satellite altimeters are capable of resolving deep ocean mesoscale features in the Gulf of Mexico. They compare surface current velocities from nearly 775 drifting buoys with TOPEX/Poseidon and European Remote Sensing 2 (ERS-2) altimeter-derived currents and show that there is good agreement between the two instruments for depths greater than 200 m; however, on the shelf the comparison breaks down when using the same spatial and temporal scales as used in the deep ocean.

In this letter, we use a novel operator [2] to derive accurate, short-scale crosstrack currents from TOPEX/Poseidon (T/P) and compare them against currents measured by two *in situ* moorings that lie along the satellite track. The purpose is to define the skill and limitations of using altimeter-derived currents in shallow water environments.

II. Data Collection and Methods

During a six-month period from March through September of 1999, two current meter buoys were moored along the T/P descending track number 52 as shown in Fig. 1. These buoys were operated as part of the Texas Automated Buoy System (TABS), operated by the Geochemical and Environmental Research Group at Texas A&M University (http://tabs.gerg.tamu.edu/Tglo) with funding from the National Ocean Partnership Program [3]. Each buoy was located in shallow water less than 105 m deep; however, the second buoy, N, was located on the shelf break and was influenced by the deep water dynamics to a greater degree than Buoy M. The buoys were removed in late 1999 and a new buoy placed at the location of buoy N in 2002.

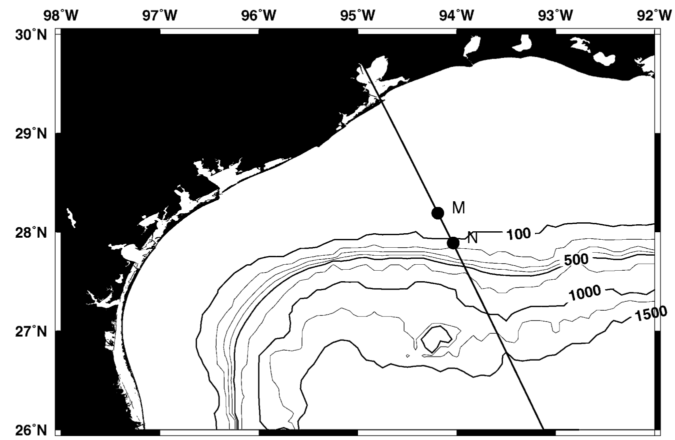

Fig. 1. Descending track 52 of the original TOPEX/Poseidon mission and the current Jason-1 mission. TABS buoys M and N are marked. The water depth at each buoy is 57 and 105 m, respectively.

Buoy M used a Marsh–McBirney electromagnetic current meter located 2.5 m below the surface at a water depth of 57 m. Buoy N originally used an Acoustic Doppler Current Profiler (ADCP) located 2 m below the surface at a water depth of 105 m. This instrument measured current profiles in bins down to full water depth. The first bin of ADCP data was centered at about 9 m depth. In 2002, the ADCP on Buoy N was replaced by an Aanderaa acoustic digital current sensor (DCS) which measured currents at 2.5 m depth [4].

Currents at both sites are affected by winds and along- and off-shelf currents with winds more dominant at M than N. The difference in depth of the current measurement at the two sites and to a lesser extent measurement techniques (ADCP measuring at 9-m depth versus electromagnetic and DCS measuring at 2.5-m depth) allow us to analyze altimeter and buoy data at the two independent sites.

Each buoy averages its measurements over half-hour periods and records this information. Using these half-hour samples, the data are low-pass filtered at 40 h to remove short-term, high-frequency inertial effects. The filtered buoy sample closest in time to the satellite overpass is used to compare against the satellite-derived current. For buoy M there were 28 coincident T/P measurements from March 3, 1999 until November 25, 1999. For buoy N, there were 20 coincident T/P measurements from March 3, 1999 until September 7, 1999, 17 coincident T/P samples from February 6, 2002 until August 3, 2002, and 45 coincident Jason-1 measurements from February 6, 2002 until July 26,

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2003. These relatively short series will be compared to investigate how well the altimeter-derived currents resolve the fine scale structure measured by the buoys.

The source of the altimetry data are the geophysical data records (GDR) as distributed by the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC). Data were taken from the T/P merged GDRs (MGDR-B) and the Jason-1 GDRs. Only Ku-band samples with a range RMS less than 0.15 cm, a pointing angle of less than 0.04°, and a frame with a minimum number of valid samples of 75% of the high-rate data are used; all others samples (including any sampled by the Poseidon-1 altimeter) are ignored. This criteria eliminates 15% of the data. Sea surface height anomalies (SSHA) are computed by subtracting the altimeter range measurement and ocean tide provided by the GOT00.2 model [5] from the orbit height.

These SSHA values are interpolated to the 1-Hz reference ground track based on T/P cycle 18. In the case of high-rate sampling, the data were interpolated to the 10-Hz reference ground track based upon the same cycle 18. For Jason-1, which provides 20-Hz high-rate data, these data were compressed via pairwise averaging into 10-Hz data consistent with T/P. The interpolation/extrapolation method determines the value at the reference ground track point from the two nearest sub-satellite points within 12 km. This produces a consistent database with a minimal effect from smoothing.

III. Spectral Characteristics of the Buoy-Measured Currents

The low-pass filtered buoy values for the zonal (u) and meridional (v) components of the velocity are combined to calculate a cross-track velocity in the same orientation of the altimeter track (23.98°). This time series of cross-track velocities was analyzed to understand the spectral components of the currents measured.

For each buoy time series, the frequency at which all lower frequencies describes half of the signal variance is found. This range of frequencies illustrates the primary power band of the signal for the given buoy. Similarly, the decorrelation period of each buoy signal is found using the method presented in [6]. Last, by removing frequencies greater than the Nyquist of the altimeter sampling (9.92 days), the amount of the total signal variance sampled by the altimeter is found. Table I lists the results of this analysis.

TABLE I
Spectral Characteristics of the Time Series Sampled by Each Buoy. The Half-Power Period Is the Minimum Number of Days Required to Account for Half of the Total Signal Variance. The Altimeter Variance Coverage Gives the Percentage of the Total Signal Variance That the Satellite Altimeter Samples

Buoy	Coverage	Half-Power Period (days)	Decorrelation Scale (days)	Altimeter Variance Coverage
M	3/2/99 to 12/1/99	34.14	17.73	59.0%
N	3/1/99 to 9/12/99	18.96	18.56	49.3%
N	1/29/02 to 7/12/02	16.25	6.73	32.2%
N	7/25/02 to 11/18/02	14.84	8.08	33.0%
N	1/30/03 to 8/3/03	13.65	17.35	42.3%

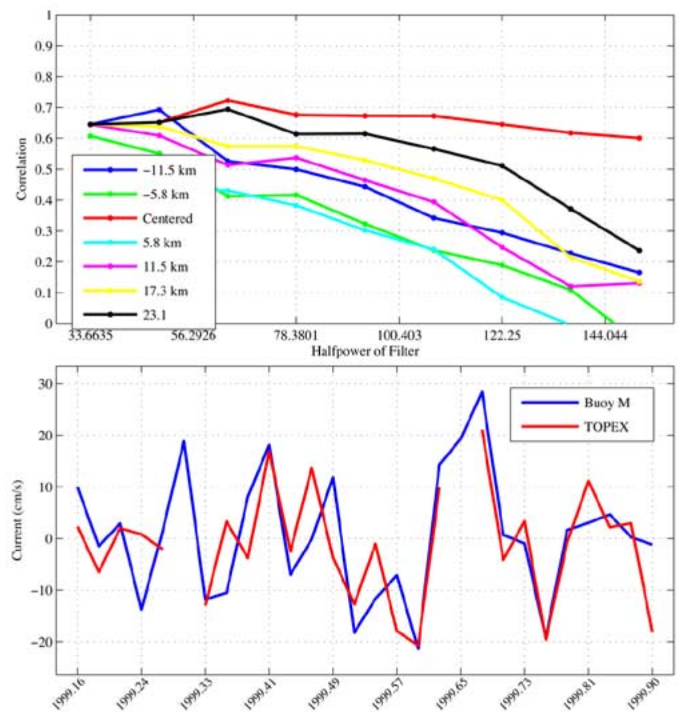

Fig. 2. Comparison between 1-Hz TOPEX and Buoy M during 1999. (Top) Correlation of currents versus difference operator orientation. (Bottom) Time series comparing optimal altimetric match and buoy with 72.2% correlation and an orientation that is centered with 63.71-km half power point.

IV. Comparison of Buoy- and Altimeter-Derived Currents

Comparison between remote and *in situ* instruments can be difficult for a number of reasons. In shallow water, frictional, ageostrophic currents are dominant; whereas, with altimetry measurements, only geostrophic currents are calculated. These buoys in the shallow water measure absolute Eulerian currents including the frictional component along with inertial currents that altimetry cannot resolve. Using both 1-Hz and high-rate (10 Hz) data from T/P and Jason-1, currents between the various instruments are compared.

For each buoy, the coincident altimetric slope is computed for a variety of window orientations (boundaries and sizes) and the series of altimeter measurements are compared to the buoy series. The window selections vary with two parameters: boundary relative to the buoy location and filter length. By varying the boundary before or after the buoy location, it can be determined whether shallow or deep waters are influencing the measured current and by varying the operator length, the length scale of the currents are determined. Because buoy M is in shallow waters, it would be expected that the currents are equally influenced by water along the satellite track before and after the buoy location; whereas, with buoy N on the shelf break, more track samples after the buoy (deeper waters) should have a greater influence on the currents. Using the optimal difference operator, these parameters (slope distance and orientation) are varied to

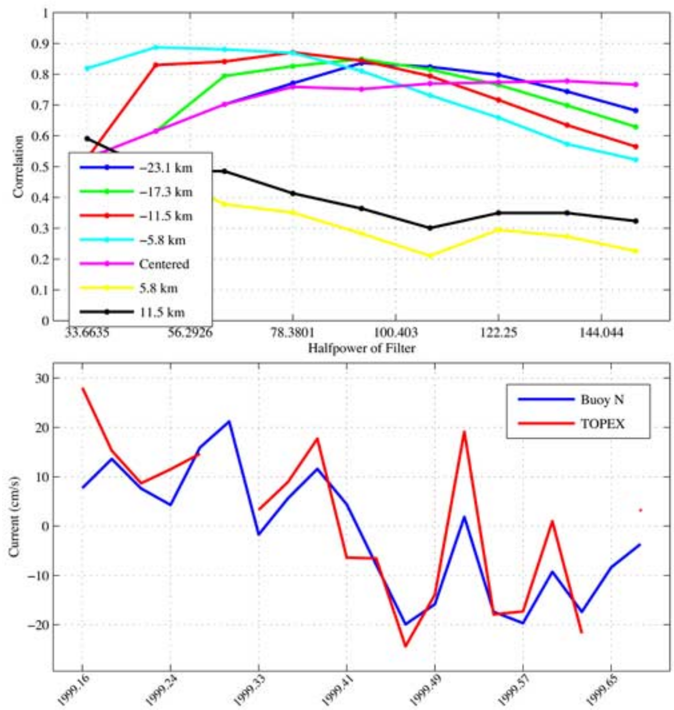

Fig. 3. Comparison between 1-Hz TOPEX and Buoy N during 1999. (Top) Correlation of currents versus difference operator orientation. (Bottom) Time series comparing optimal altimetric match and buoy with 88.7% correlation and an orientation with a boundary of 5.77-km data before the buoy—in shallow water—and 48.84-km half power point.

generate a variety of geostrophic current estimates. The correlation coefficients of the two series are computed and compared.

1) 1-Hz Comparison: At 1-Hz sampling, the distance between each satellite sample is approximately 5.77 km. Buoy M is compared using boundaries varying from 11.54 km before the buoy location to 23.1 km after the location. The boundary limits the height values available to the optimal difference operator when computing the slope from altimetry (e.g. when a slope is calculated over 100 km of samples with a boundary of 11.54 km before the buoy, 88.46 km of altimeter samples after the buoy is used). When the slope is "centered," no boundaries are in place and all available data over the operator length are used.

As shown in Fig. 2, there is strong correlation between the buoy cross-track measurement and the satellite-derived cross-track measurements. The boundary location had minor effect on the comparison confirming the hypothesis that points before and after equally contribute; indeed, the optimal match uses a "centered" orientation. As the size of the slope calculation increases, the correlation decreases giving an optimal fit at ∼64-km operator half power. This optimal result corresponds to a filter width of nine altimeter samples at 1 Hz. This suggests that the dominant signal that is captured by both the buoy and satellite is roughly 64-km wavelength equally distributed about the buoy location.

Fig. 3 presents the data from buoy N. This buoy is positioned on the shelf break in a different regime than buoy M. In fact, as shown in the figure, points that lie beyond the shelf break are most important to the slope calculation as placing a boundary

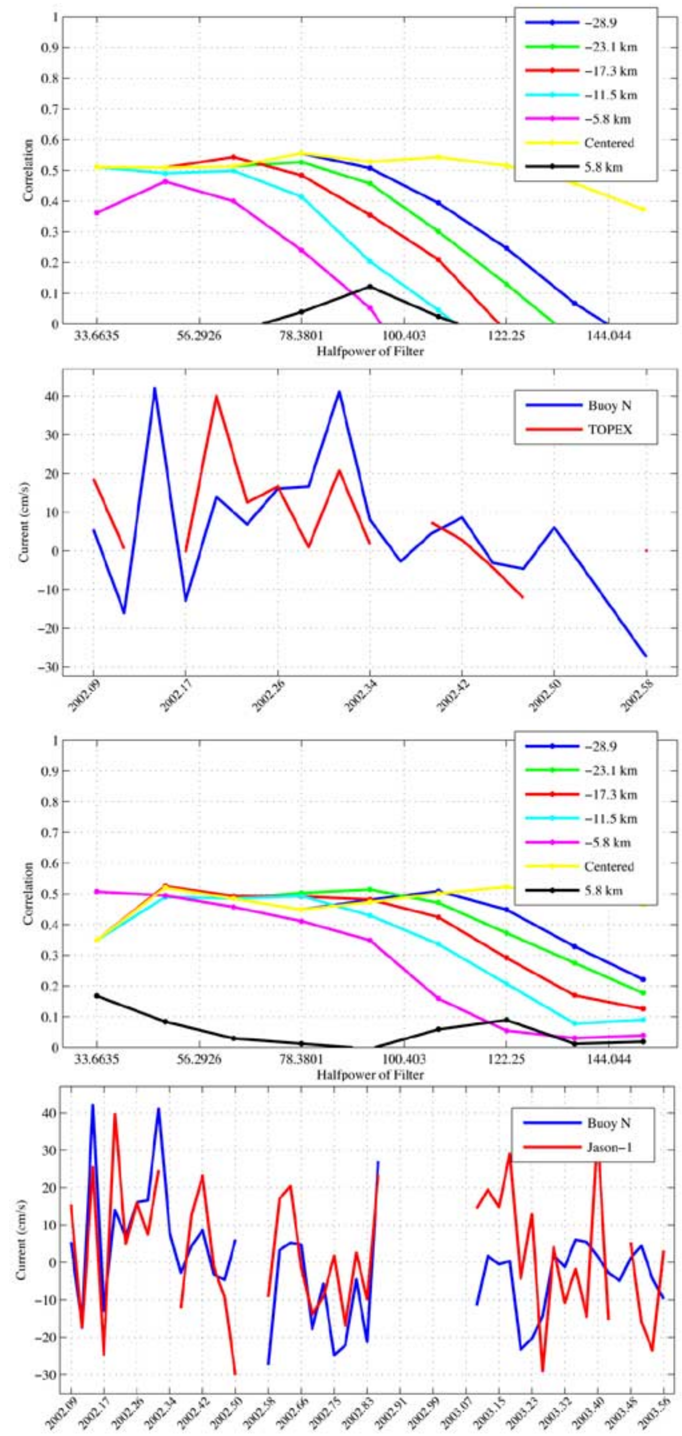

Fig. 4. (Top to bottom) Correlation of 1-Hz TOPEX-derived currents and Buoy N during 2002–2003 versus difference operator orientation. Time series of best TOPEX match with 55.5% correlation using a "centered" orientation with 78.38-km half power point. Correlation of Jason-1 derived currents versus difference operator orientation. Time series of best 1-Hz Jason-1 match with a 52.5% correlation and an orientation boundary of 23.1 km in shallow and a 93.11-km half power point.

after the buoy yields little correlation between the two signals. The deeper waters dominate the dynamics measured by the buoy and the altimeter. This is evidenced by inspection of the boundaries placed before the buoy (in the shallower waters). The optimal comparison uses only 5.77 km of data in the shallower

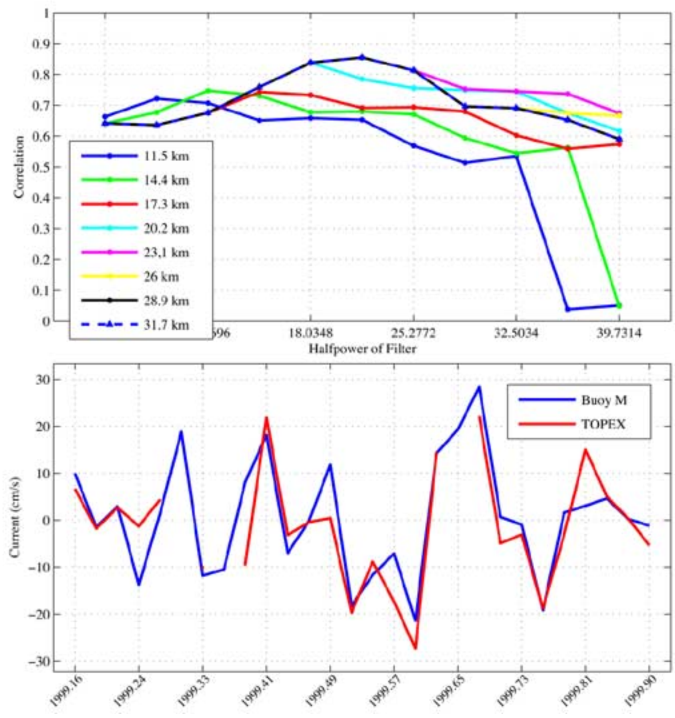

Fig. 5. Comparison between 10-Hz TOPEX and Buoy M during 1999. (Top) Correlation of currents versus difference operator orientation. (Bottom) Time series of best altimetric match with 85.5% correlation and a boundary of 28.9 km pas the buoy with a 54.17-km half power point.

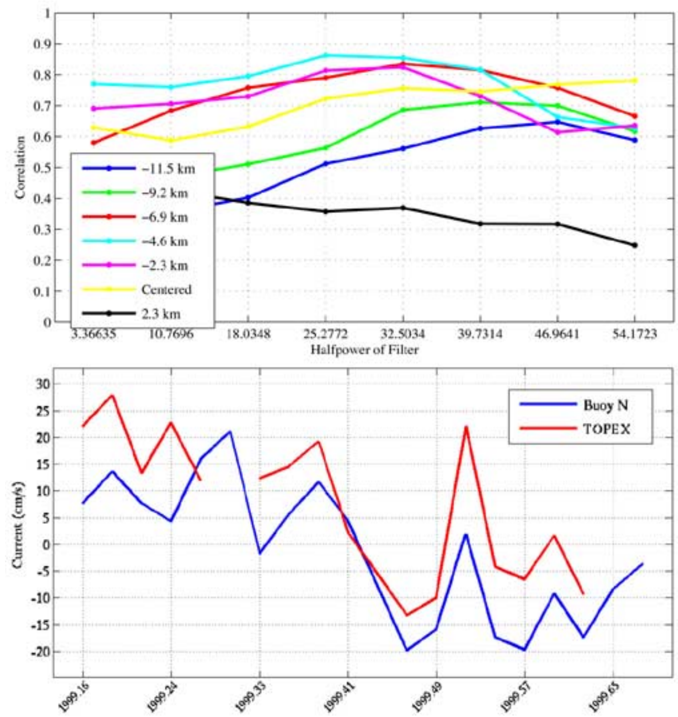

Fig. 6. Comparison between 10-Hz T/P and Buoy N during 1999. (Top) Correlation of currents versus difference operator orientation. (Bottom) Time series of best altimetric match with 86.3% correlation and an orientation with a limit of 4.6-km data in shallow and a 57.8-km half power point.

water with all other data from the deeper shelf break waters. With a half power of ∼49 km, the signals are in the mesoscale (the first-baroclinic mode of the Rossby radius of deformation in the GOM averages 36.5 km).

At the end of 1999, both buoys M and N were decommissioned. In 2002, buoy N was replaced with a new buoy at 2 m depth rather than the 9 m depth of the original; moreover, the new buoy had several lengthy data outages. Using the data from this buoy, the same comparisons can be made to both TOPEX and Jason-1 during its validation phase when both missions were in coincident orbits. Fig. 4 shows that the comparisons between this newer buoy and the two satellites are poor in comparison to the 1999 comparisons. The data in the beginning of 2002 were on par with the original 1999 correlations; however, later time periods—particularly in 2003 (as shown in the Jason-1 panel)—were very poor. Based upon the earlier 1999 results and the results of the 2002 buoy, the depth of the measurement has a significant effect on the results. At the upper portion of the mixed layer, the surface effects (wind, wave, etc.) captured by the buoy cannot be resolved by the altimeter.

2) 10-Hz Comparison: When comparing a single ground location as with a buoy measurement, the highest resolution satellite data will provide the best comparison. The previous comparisons are performed using the high-rate 10-Hz data from TOPEX and Jason-1. In the 1-Hz study, the nearest satellite measurement to buoy M is 2.57 km away. With the 10-Hz study, the nearest measurement is 0.62 km away from the buoy. Additionally, with a higher number of points available, the number of orientation possibilities increase, which allows for finding the optimal correlation.

The high-rate comparison to buoy M is shown in Fig. 5. The operator orientation began with similar parameters to the 1-Hz case, and were narrowed to the region that gave the highest results. In doing so, it was found that more shallow values have a slightly greater influence than the deeper values. The optimal result was found with a "centered" orientation and a 54.17-km half power point. This is similar to the 1-Hz case with a slightly shorter signal; therefore, with the consistent results, the increased resolution is shown to give a more precise comparison.

Fig. 6 shows the high-rate results for buoy N during 1999. Like the buoy M comparison, the results are consistent with the 1-Hz case. A high correlation between the buoy and satellite measurements is achieved when only the immediate shallow water points are included. In the high-rate case, only 4.6 km of shallow data are used with a 48.8-km filter operator. In this case, the maximum correlation drops slightly as the 1-Hz data are smoothed and eliminate much of the higher frequency noise.

Like the 1-Hz results for replacement buoy N, the high-rate results are consistent for the initial period; however, the results are very poor for the 2003 period when the buoy was positioned in the upper mixed layer. In Fig. 7, the results are shown to be virtually identical to the 1-Hz results in the TOPEX case. For Jason-1, a slightly better orientation was found to match the 2003 period along with the initial 2002 period. The results were "centered" as opposed to having a shallow boundary with a similar window width as TOPEX. The most interesting results of the two separate buoy N cases is that the orientation is dependent upon shallow points which is opposite of what is found

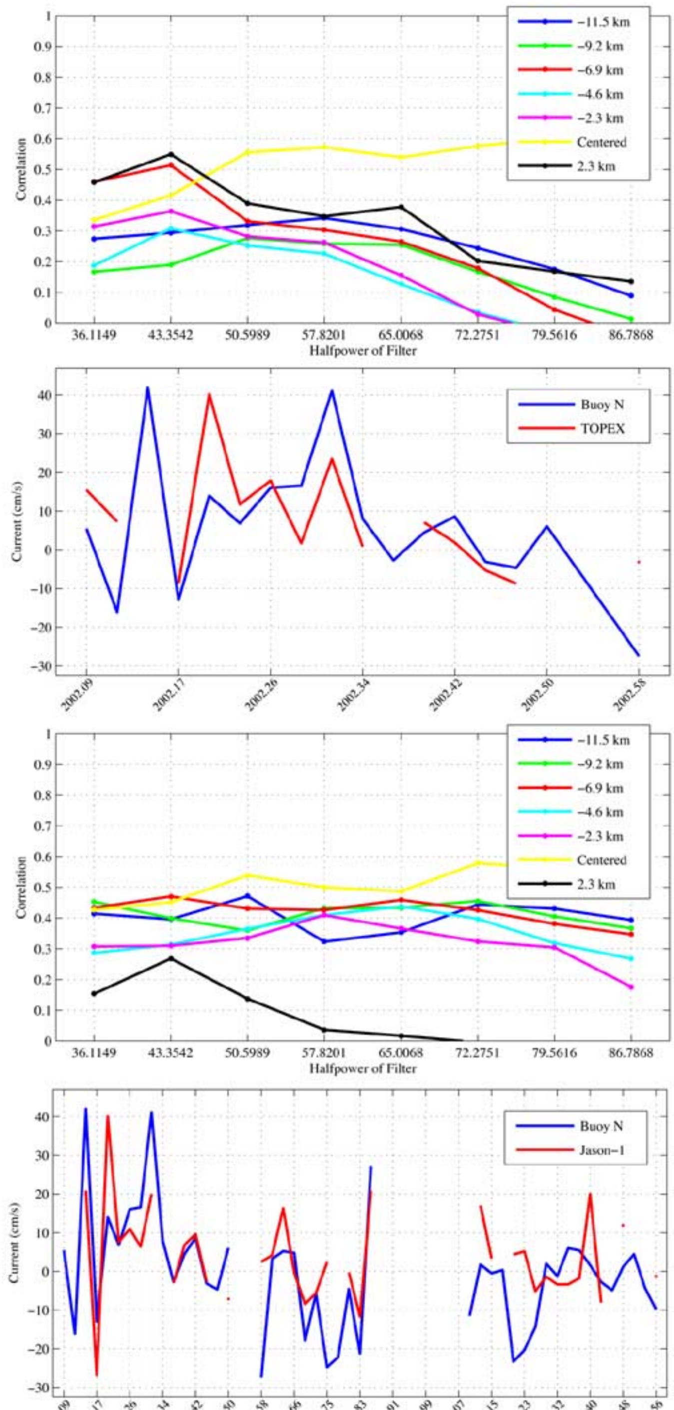

Fig. 7. (Top to bottom) Correlation of 10-Hz TOPEX-derived currents and Buoy N during 2002–2003 versus difference operator orientation. Time series of best TOPEX match with 57.9% correlation using a "centered" orientation with 79.6-km half power point. Correlation of Jason-1 derived currents versus difference operator orientation. Time series of best 1-Hz Jason-1 match with a 60.2% correlation, a "centered" orientation, and a 72.3-km half power point.

during the 1999 samples and may be an indication of the more shallow location of the newer buoy.

V. Conclusion

Although a difficult comparison to perform due to the different scales that each instrument is measuring, the correlations between the satellite altimeters and the Jason-1 buoys are strong and lead to greater confidence that the optimal difference operator using uncorrected height data is a valid and robust method for calculating oceanic currents.

The differences between the two buoy N results seem to be a consequence of the shallow depth of the replacement buoy. In 1999, the hypothesis that deeper water would dominate the flow is valid; however, with a different buoy in 2002, poor correlations were found, and the correlations show equal weighting for the shallow points.

With the TABS comparison, altimetry-derived geostrophic currents from the optimal difference operator have been shown to compare very well in shallow, energetic regions of the ocean. This method can be a powerful and valid tool for global mesoscale studies even in some of the most difficult sampling environments.

Acknowledgment

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