

Observed Surface Currents During the Chesapeake Bay Outflow Plume Experiments

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Abstract

As part of the Naval Research Laboratory (NRL) and Office of Naval Research (ONR) sponsored Physics of Coastal Remote Sensing Research Program (CoRS), two high frequency (HF) radar experiments were conducted from Sept to Oct 1996 (COPE-I) and from Oct to Nov 1997 (COPE-III) off Virginia Beach, VA to study buoyant outflows from the Chesapeake Bay. Ocean surface currents were measured using the 25.4 MHz mode of the Ocean Surface Current Radar (OSCR) at 20 min intervals at a horizontal resolution of approximately 1 km over a $30 \text{ km} \times 44 \text{ km}$ domain. During COPE-III, comparisons to coincident subsurface current measurements at $\approx 2 \text{ m}$ beneath the surface from four broad-band Acoustic Doppler Current Profilers (ADCP) revealed *RMS* differences of 6.8 to 11.3 cm s^{-1} . Regression analyses indicated slopes of $O(1)$ with correlation coefficients exceeding 0.9. From the HF-derived surface currents, the M_2 tidal current amplitude had a maximum of about 55 cm s^{-1} at the Chesapeake Bay mouth. Semidiurnal tidal currents were predominantly barotropic ranging from 10 to 25 cm s^{-1} at the ADCP moorings. Comparisons of the M_2 tidal currents between COPE-I and COPE-III data sets indicated consistent agreement over most of the radar domain except in the plume turning regime where nonlinear interactions may be more important in the coastal dynamics.

1 Introduction

The Chesapeake Bay system is surrounded by tributaries along both the eastern and western shores of Virginia that contribute to a fresh-water influx into this broad and complex estuary. In this regime, terrestrial-atmospheric-estuarine interactions have a pronounced impact on the coastal oceanic circulation by modulating buoyancy fluxes within the Chesapeake Bay (CB). The largest amount of fresh-water influx occurs during the spring due to increased precipitation by winter storms over the Middle Atlantic Bight. In the spring transition period, restratification occurs within the estuary due to this higher fresh-water volume entering the CB from its tributaries. By contrast, autumn months usually have a lower fresh-water influx due to drier atmospheric conditions. However, this region is susceptible to landfalling tropical cyclones that increase precipitation and flooding during the hurricane season (Marks *et al.* 1998). In either scenario, the fresher CB water is ejected as a thin lens with lower salinity concentrations compared to the adjacent coastal waters. This fresh-water plume turns anticyclonically under the influence of planetary vorticity and is generally trapped within a few deformation radii of the coast (Boicourt 1981).

Central to the question of coastal ocean response to the buoyancy forcing, surface current measurements from the Ocean Surface Current Radar (OSCR) were acquired during the Chesapeake Bay Outflow Plume Study in 1996 just south of the CB mouth (COPE-I). The observations indicated both energetic semidiurnal tidal currents exceeding 50 cm s^{-1} at the CB mouth and episodes of strong buoyant outflows on the continental shelf (Shay *et al.* 2001). In the first year (COPE-I), record rainfall generated one of the largest freshwater outflow conditions at the CB due to landfalling tropical cyclones Bertha and Fran. The net transport increased by more than three standard deviations (to $4021 \text{ m}^3 \text{ s}^{-1}$) than the normal values of transport (Marmorino *et al.* 1999). During the COPE-III experiment in fall 1997, more typical, outflow conditions of $O(500 \text{ m}^3 \text{ s}^{-1})$ existed as drier atmospheric conditions prevailed.

As shown in Fig. 1, the radar domain for COPE-III was the same one used during COPE-I (Haus *et al.* 1998). However, during COPE-III, two additional radar systems were also deployed that involved both the US Naval Postgraduate School’s Coastal Ocean Dynamics Application Radar (CODAR) as described

by Paduan *et al.* (2001), and the University of Michigan’s Multifrequency Coastal Radar (MCR) as discussed by Teague *et al.* (2001). In addition, the Naval Research Laboratory (NRL) deployed an array of upward-looking Acoustic Doppler Current Profilers (ADCP) spanning the inner to mid-shelf south of the CB (Hallock and Marmorino 2001). One of the objectives of COPE-III was to compare and contrast the performance of these different surface current radars overlooking a coastal ocean area dominated by semidiurnal tides and buoyant outflows. Such an area provides a good test in resolving differences between the three radar platforms relative to moored ADCP measurements. However, in this study, experimental results obtained from CODAR and MCR relative to the ADCP mooring data are only briefly discussed as it is not the intent of this paper to compare and contrast the characteristics and resolution capability of each radar system.

Rather the objective of this note is to improve our understanding of the surface flow field influenced by semidiurnal tides during periods when weak (COPE-III) and strong (COPE-I) buoyant outflow conditions were observed from two sets of OSCR-derived surface currents. These measurements were acquired approximately one-year apart in the Fall of 1996 (3 weeks) and 1997 (≈ 5 weeks). Thus, a primary objective is to examine differences in tidal current statistics between these two data sets. The experimental design is discussed in Section 2. Observational comparisons including the four moored ADCPs are described in Section 3. Surface and subsurface currents are analyzed in Section 4 for tidal content with an emphasis on the semidiurnal band (M_2) and diurnal (K_1) constituents for comparison to the COPE-I results. Section 5 briefly summarizes these results.

2 Experimental Design

2.1 HF-Radar

The HF-mode (25.4 MHz) of the OSCR system was deployed from 13 Sept to 6 Oct 1996 (COPE-I) and from 20 October to 30 November 1997 (COPE-III). For both experiments, the Master site was located at Fort Story, a US Army Military Reservation ($36^\circ 55' \text{ N}$, $75^\circ 59.5' \text{ W}$), whereas the Slave site was deployed approximately 20 km south at the US Navy Fleet Combat Training Center Atlantic ($36^\circ 45.6' \text{ N}$, $75^\circ 57' \text{ W}$)

as shown in Fig. 1. Sixteen element receive arrays were oriented at 200°T and 120°T at the Master and Slave sites, respectively (Haus *et al.* 1998). These phased array orientations provided optimal coverage of the experimental domain with respect to the NRL Physics of Coastal Remote Sensing (CoRS) program objectives. Communications were facilitated by UHF between the two sites for surface current mapping at 20 min sample intervals at 700 cells at 1 km resolution over 44 km.

The HF radar coverage was constrained by the physical orientation and placement of the phased arrays. The angle of intersection (Δ) between two radial beams must fall between $30^\circ \leq \Delta \leq 150^\circ$ for reliable vector current measurements (Graber *et al.* 1997). This beam intersection angle restriction may be relaxed to include cells outside of this envelope, however, vector currents are not as reliable under these circumstances. Intersection angles were inadequate to resolve the vector currents at seven cells in the northeast and southeast corners of the domain.

For COPE-I, the resulting data set was 22.78 days in length starting at 2000 UTC 13 Sept (YearDay 257) and extending to 1240 UTC 6 Oct (YD 280) 1996. Of these time steps, 170 ($\approx 11\%$) were linearly interpolated. The largest data gap occurred on YD 260-261 when 90 samples were missing due to a faulty generator at the Master site. Shay *et al.* (2001) only used data starting after this interpolation period (≈ 19 days) to avoid any temporal aliasing of the M_2 tidal current. These surface current data were subsequently smoothed with a 3-point Hanning window. Although OSCAR operations began at 1850 UTC 14 Oct (YD 287) 1997, nearly continuous COPE-III measurements started on 2250 UTC 27 Oct (YD 300) and ended 1050 UTC 30 Nov (YD 333). During that period, approximately 108 samples ($\approx 5\%$) of the data were linearly interpolated. Approximately 33 days of good data were acquired during COPE-III which resolved the major tidal constituents (Foreman 1977).

2.2 Surface Currents

Over a 36-h period during COPE-III (three M_2 tidal cycles), surface current images indicated a buoyant jet intrusion on to the continental shelf that lead to the formation of a coastal front during upwelling favorable winds (Hallock and Marmorino 2001). As shown in Fig. 2a, a strong southward-flowing jet of

about 80 to 90 cm s⁻¹ occurred on 23 Oct (YD 296) as fresher, buoyant water was ejected from the CB, and subsequently turned southward due to planetary vorticity. Six hours later (Fig. 2b), a coastal jet of 50 to 60 cm s⁻¹ was located over the inner shelf beginning in the Plume Turning Region (PTR) located south of the bay mouth and within two deformation radii of the coast (≈ 12 km). Surface flows near the mouth indicated a flooding tide suggesting the importance of the semidiurnal tidal cycle. A strong surface current was emanating from the CB mouth as the ebbing tide (consistent with the semidiurnal cycle) was in phase with buoyant outflow early on 24 Oct (Fig. 2c). Over the following six hours, an elongated pattern of small-scale surface flows was formed within 2 deformation radii from the coast. This region stretched from the CB mouth to the southern part of the radar domain. While vortices have been previously observed by Harrison *et al.* (1964), the apparent life-time of these features is about six hours. One possibility is that this feature represents an interaction between the surface winds and the spring tide (Marmorino *et al.* 1999). Over the next six hours (Fig. 2e), a coastal front was formed where flows along its' western boundary were towards the east at speeds exceeding 60 cm s⁻¹. On the eastern side of the boundary, currents were directed towards the northeast at 20 to 30 cm s⁻¹. By 1910 UTC, a strong convergence front had formed as these energetic flows were predominately oriented towards the north. This front moved approximately 6 to 8 km eastward over this six-hour interval, equating to an approximate propagation speed of ≈ 1 km h⁻¹ or approximately 27 cm s⁻¹ (Fig. 2f). This frontal speed was slightly higher than the 20 cm s⁻¹ reported by Hallock and Marmorino (2002). However, their calculation was for the last part of the above interval and based on the three inner-shelf ADCP moorings (A_1, A_2, A_3).

2.3 ADCP Moorings

As part of the NRL CoRS research initiative, five upward-looking, broad-band ADCP (see Fig. 1) were deployed at moorings A_1 to A_5 oriented in a cross-shelf direction (Hallock and Marmorino 2002). The ADCPs operated at 307.2 KHz, and sampled subsurface currents by a burst of 120 pings over one minute (0.5-s intervals), which was repeated at five minute intervals. Vertical bin widths were set to 1 m with current samples within 2 m of the surface and 4 m from the bottom. Noise induced from side-lobe

contamination of the acoustic backscattered signals and from wind effects precluded detailed comparisons to bins < 1.5 m. The ADCP array was deployed in the central portion of the OSCR domain starting in 10 m of water and extending to 20 m over the shelf. However, the A_1 mooring was located in a region where the radar intersection angle (exceeded 150°) was not optimal to resolve the current vector based upon the Geometric Dilution of Precision (Chapman *et al.* 1997). Thus, the A_1 data will not be used in the vector current comparisons below.

2.4 Velocity Profiles

Observed vertical structural variations of the horizontal currents at the ADCP mooring are shown in Fig. 3. One of the most salient features of the vertical structure was the coherence in the velocity signals. This structure suggests that a large part of the signal is barotropic as found during COPE-I. Early in the time series, near-surface currents (~ 2 m) revealed an energetic southward flow exceeding 75 cm s^{-1} from 20 Oct (YD 293) to 23 Oct (YD 296). These energetic flows were confined to the upper 5 m at A_2 although a southward flow was evident throughout the column. On 28 Oct (YD 301), a strong southward current of 70 to 75 cm s^{-1} was followed by oscillatory flow presumably associated with tidal currents which was more apparent in mid-depth to near-bottom flows. Another strong near-surface episode occurred on 9 Nov (YD 313) as currents approached 70 cm s^{-1} . These strong pulses of southward flows in the upper 6 m over the continental shelf are consistent with buoyant outflow plumes emanating from the CB mouth.

3 Comparisons

3.1 Time Series

As the quality of the COPE-I measurements have been documented elsewhere (Shay *et al.* 2001), the quality of the observed HF-radar derived surface currents from OSCR during COPE-III will be assessed by comparing these data to subsurface ADCP measurements. To facilitate direct comparisons between the subsurface and surface currents, five-minute mooring data were subsampled at 20 min intervals. Surface and subsurface data were combined to form profiler time series to assess data consistency over a 13-d period

at the ADCP mooring locations. Currents were rotated by 20° to form cross-shelf current (U positive at 70°T) and along-shelf current (V positive at 340°T) time series. As shown in Fig. 4, surface and subsurface (2 m) records indicated consistent agreement at mooring A_2 , and were dominated by semidiurnal tidal oscillations. Surface currents in the along-shelf directions ranged between $\pm 50 \text{ cm s}^{-1}$ with a predominant southward flow on YD 301 and YD 313 when it exceeded -75 cm s^{-1} . There was little difference between the surface and subsurface currents, presumably due to buoyant outflows. Cross-shelf surface currents were slightly weaker as the subsurface currents followed the surface flows. While intermittent periods occurred when subsurface currents were larger than the surface currents, bulk current shears over the $\approx 2 \text{ m}$ layers were weak ($< 10^{-2} \text{ s}^{-1}$).

Statistical measures of the relationship between the surface and subsurface current vectors are the complex correlation coefficient and phase angle (Kundu 1976). This phase angle represents the average cyclonic angle of the subsurface current vector with respect to the surface current vector. Magnitudes of the complex correlation coefficients exceeded 0.9, and the phases indicated a consistent anticyclonic veering of the current with depth except for half-day period 6 due to the interpolated surface current during this period, and again from 20 to 22 half-day periods. Over the 13-day time series, complex phases ranged from -29° to 11° .

As shown in Fig. 5, similar results were observed at the A_3 mooring where the predominant flow was dominated by the M_2 tidal currents. Subsurface currents at 2.2 m followed the surface flows in both directions. As shown in Fig. 5c, bulk shears over this layer were weak as at A_2 and A_4 (not shown). With the exception of half-experimental day periods 3 and 6, correlation coefficients exceeded 0.8 and the phase angles ranged between -35° to 9° . The negative phase angles over most of the series indicate that the subsurface current vector veered anticyclonically with depth with respect to the surface current vector.

3.2 Regression Analyses

Subsurface ($\approx 2 \text{ m}$) current components were regressed against the surface current components at the A_2 , A_3 and A_4 moorings (Fig. 6). Based on a linear fit, biases at mooring A_2 were 4.7 and -1.8 cm s^{-1} with

slopes of 1.1 and 0.9 for the cross- and along-shelf current components, respectively (Table 1). Histograms for the current differences revealed a variability envelope of $\pm 20 \text{ cm s}^{-1}$ at mooring A_2 (not shown). Biases at mooring A_3 were approximately 2 cm s^{-1} whereas the slopes of the regression curves were $O(1)$. At the A_4 mooring, biases were even less, but with a slightly larger slope for the along-shelf current component. Histograms for the current differences revealed a variability envelope of $\pm 20 \text{ cm s}^{-1}$ at the moorings as current differences followed a theoretical Gaussian distribution (not shown). As the individual correlation components exceeded 0.87 at all of these moorings, the *RMS* differences were 9 to 11 cm s^{-1} at A_2 , but decreased to 8 cm s^{-1} at A_3 , and to less than 7 cm s^{-1} at A_4 . That is, *RMS* differences decreased in the offshore direction perhaps due to less influence from episodic buoyant outflow plumes.

As noted above, the CODAR and MCR operated concurrently for most of the time during the OSCR deployment (Paduan *et al.* 2001; Teague *et al.* 2001). The CODAR system was deployed south of OSCR’s sites to minimize potential interference because of similar frequencies and its continuous mode operation. By contrast, MCR system was colocated with OSCR because of its differing transmit frequencies from 4.8 to 21.8 MHz (Teague *et al.* 2001). The footprint of these HF radars overlapped a significant portion of the domain and included the moored cross-shelf array of ADCPs (See Fig. 1). Based on hourly measurements, *RMS* differences between CODAR and the ADCP radial current speeds ranged from 13 to 16 cm s^{-1} using the ideal beam pattern, and 10.5 to 13.4 cm s^{-1} for the measured beam pattern (Paduan *et al.* 2001). These radial current estimates from CODAR are difficult to directly relate to *RMS estimates* of the cartesian current components reported here. However, for the MCR, *RMS* differences ranged between 5 to 12 cm s^{-1} for the 21.8 MHz channel at four of the ADCP moorings (Teague *et al.* 2001). These estimates indicated consistent agreement with those found here from A_2 through A_5 . While smoothing the raw surface currents from OSCR over hourly time scales would have reduced these differences, these *RMS* differences from the 20-min samples of ≈ 7 to 11 cm s^{-1} found here approached those found in data from Duck94 experiment (Shay *et al.* 1998).

4 Tidal Current Variability

Tidal currents are determined from the 33-d time series from the COPE-III measurements, and compared to those found from COPE-I data set. Currents were fit to the tidal constituents of the semidiurnal (M_2) and diurnal (K_1) tides using a harmonic analysis package (Foreman 1977; Prandle 1987). Since the current vector can be represented by a complex rotating vector, ellipse parameters of the M_2 tidal currents are determined at each grid point, and results from the COPE-I and COPE-III data sets are compared. This approach provides a reasonably good test for consistency between the two data sets spaced one year apart.

4.1 Horizontal Variations

As shown in Fig. 7, M_2 current amplitudes and tidal ellipse orientations were similar over the radar domain with a few exceptions. First, the COPE-III results indicate larger amplitudes of 40 cm s^{-1} just south of the PTR. This is an area where stationary eddies appear intermittently due to the interaction of the spring tide and the wind field (Marmorino *et al.* 1999). In addition, buoyant plume outflows may be confined to a smaller PTR than in the COPE-I measurements because of the higher outflow volume observed in 1996. This effect may result in stronger nonlinear interactions in the PTR in COPE-III and account for some of ≈ 5 to 6 cm s^{-1} tidal current differences within 2 deformation radii of the coastline (Fig. 6c). Along the northern boundary, the COPE-III measurements indicated a 4 to 5 cm s^{-1} difference over 20 radar cells whereas tidal gradients were more diffuse in COPE-I than during COPE-III. Away from these small areas, differences were $\pm 2 \text{ cm s}^{-1}$ with more than 50% of the cells exhibiting virtually no difference in the M_2 tidal current amplitudes.

Of particular interest here is how the COPE-III M_2 tidal currents relate to those derived from COPE-I. Based on 602 points, cross-shelf currents from these two data sets agreed well as shown in Fig. 8. Regression analyses indicated a slope of 0.9 and a bias less than 1 cm s^{-1} . The corresponding phases for the M_2 cross-shelf tidal current also indicated a direct relationship where the slope was 1.1. By contrast, the along-shelf

tidal component suggested a weaker relationship between the two data sets. For example, the slope was 0.6, indicating that the COPE-I along-shelf tidal current was more energetic than that observed during COPE-III. Moreover, the maximum along-shelf current amplitude was about 18 cm s^{-1} compared to more than 40 cm s^{-1} in the cross-shelf direction. Given the predominance of the tidal currents in the cross-shelf direction, major axes of the current ellipses in both data sets showed much better agreement. Here, the regression slope was 0.9 with a bias of 1.2 cm s^{-1} (Fig. 8e). The ellipse orientations ranged between -60° and -10° where the slope was 0.8 with a bias of -10° . Generally, these analyses suggest similar structure in the M_2 tidal currents, but the COPE-I data contains more energy than observed in COPE-III data. Since buoyant outflows were a factor of two to three times larger in the COPE-I data (Marmorino *et al.* 1999), the M_2 tidal current variations between the two data sets may be due to nonlinear interactions. This difference needs to be more fully explored in numerical model studies (i.e. Wheless and Valle-Levinson 1996).

4.2 Vertical Structure

The duration of the coincident COPE-III subsurface measurements of $\approx 13 \text{ d}$ is sufficient to determine tidal velocities for the M_2 and K_1 tidal constituents (Table 2). Comparisons between the surface layer and 2 m revealed fairly consistent agreement where the along-shelf component dominated the tidal current amplitudes. Surface and subsurface K_1 amplitudes differed by less than 1.6 cm s^{-1} at all three moorings. Except for weak diurnal tidal currents at 2 m on the A_2 mooring, phase differences in the vertical were less than 15° . By contrast, the M_2 tidal constituents were more energetic at the moorings. Differences in the M_2 current amplitudes were less than 2 cm s^{-1} except at A_2 where the cross-shelf current and phase differences were 3.4 cm s^{-1} and less than 10° , respectively. Explained variances by these two constituents in the surface layers exceeded 20%, and the general trend in variance explained decreased in the offshore direction, consistent with COPE-I results. In the subsurface layers, cross-shelf tidal currents explained more variance than in the along-shelf direction. Given the marked agreement in the two levels (particularly the M_2 tidal constituent), tidal currents were generally depth-independent as found in COPE-I (Hallock *et al.*

To examine this vertical independence, the tidal profile time series, consisting of the M_2 and K_1 tidal constituents, were vertically averaged and compared to the surface tidal current (Fig. 9). Vertically averaged flows in both the cross-shelf and along-shelf directions show agreement to the surface tidal flows. Differences between the depth-averaged and surface tidal currents were less than 2 cm s^{-1} for these current components, leading to a directional offset of $\approx 5^\circ$ between the surface and depth-averaged tidal flows at A_4 . In COPE-I, this directional offset was 16° at the ADCP moorings. *Residual* flows, defined here as the observed less the depth-averaged flows, were 2 to 4 cm s^{-1} over the time series. In the lower layers, the increased residual flows may be due to the influence of bottom friction and its impact on the current profile (Prandle 1987). Tidal ellipses (not shown) in the near-bottom layers also indicated more of a rectilinear flow than the elliptical current paths observed in the surface layers. These results point to the importance of barotropic processes associated with the M_2 tide in this regime.

5 Summary

Measurements during COPE-III were consistent with the COPE-I data sets. The nearly continuous surface current data set from COPE-III consisted of a 33-d time series between 27 Oct to 30 Nov 1997. This time series was longer than the COPE-I data set acquired in 1996 (Haus *et al.* 1998). During COPE-III, concurrent ADCP profiles were acquired at five locations in the cross-shelf direction in the core of the radar domain. (Hallock and Marmorino 2002)

RMS differences between the observed (raw) surface and subsurface velocities range from 6.8 to 11.3 cm s^{-1} . The differences found here suggest that the HF radar was working well as they are similar to those found in Duck94 experiment (Shay *et al.* 1998). Correlation coefficients, calculated between surface and the subsurface current vector from the 2-m bin data from four of the ADCPs, exceeded 0.9 over the time series with relatively small phase angles between the surface and subsurface vector from the 2-m bins from four of the five ADCPs. The general agreement between the MCR and the ADCP current components

is encouraging given its capability to sample four different depths (Teague *et al.* 2001). Clearly, more detailed assessments of these independent radar systems are needed to fully explore their characteristics in a domain dominated by the M_2 tides and episodic buoyant outflows.

The M_2 tidal constituent from COPE-III data dominated the tidal currents in accord with results found from COPE-I (Shay *et al.* 2001). Moreover, the vertical structure of the tidal currents indicate a depth-independent component that agrees well with surface tidal currents based on a combination of the M_2 and K_1 constituents. These depth-averaged currents in the tidal band ranges from 15 to 20 cm s^{-1} . This result suggests that perhaps the linear barotropic modeling approach of Hallock *et al.* (2002) used on COPE-I data may be more applicable to the COPE-III data given the weaker buoyant outflows. However, given the differences in the strength of buoyant outflows between COPE-I and COPE-III data sets, the effect of these nonlinear interactions between the tides and buoyant outflows under upwelling and downwelling favorable winds needs to be studied within the framework of three-dimensional numerical modeling such as Wheless and Valle-Levinson (1996).

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	u					v						
	$\overline{u_o - u_2}$	ρ_u	$u_o - u_{2rms}$	m_u	b_u	$\overline{v_o - v_2}$	ρ_v	$v_o - v_{2rms}$	m_v	b_v	γ	ϕ
	cm s ⁻¹		cm s ⁻¹		cm s ⁻¹	cm s ⁻¹		cm s ⁻¹		cm s ⁻¹		°
A2	4.2	0.89	11.3	1.1	4.6	-0.9	0.95	9.5	0.9	-1.8	0.94	-9
A3	0.9	0.90	8.6	1.0	1.9	-3.5	0.91	8.7	1.1	-1.6	0.91	-4
A4	-0.8	0.90	6.8	1.0	0.2	-2.7	0.90	7.9	1.2	-0.9	0.90	2
A5	-1.7	0.95	6.8	1.1	-0.8	-3.6	0.87	10.1	1.2	-1.7	0.94	12

Table 1: Summary of surface ($_o$) and subsurface ($_2$) mean differences, standard deviations, *RMS* differences, regression curve slope and biases for the u and v current components, respectively observed at the four moorings (A2, A3, A4 and A5) and the complex correlation coefficient and phase over the observed concurrent time series of about 13-days. The time series at the A5 mooring was only for five days.

	K_1				M_2				u			v		
Depth	u	ϕ_u	v	ϕ_v	u	ϕ_u	v	ϕ_v	σ_o^2	σ_p^2		σ_o^2	σ_p^2	
m	cm s ⁻¹	°	cm s ⁻¹	°	cm s ⁻¹	°	cm s ⁻¹	°	cm ² s ⁻²		%	cm ² s ⁻²		%
A2														
0	2.7	66	3.6	-135	12.3	3	21.5	144	288	77	27	920	239	26
2	1.1	42	4.2	-149	8.9	7	22.8	138	172	46	27	976	263	27
A3														
0	3.3	64	4.8	-142	10.7	-6	13.5	154	271	62	23	529	106	20
2.2	3.3	64	5.5	-137	12.7	-10	14.	148	227	66	29	367	77	21
A4														
0	1.7	76	5.6	-129	9.	0.	10.9	171	215	43	20	348	77	22
1.8	2.	77	4.2	-127	10.6	-6	10.0	164	176	58	33	231	60	26

Table 2: Amplitudes (u,v) and relative phases (ϕ_u, ϕ_v) of rotated diurnal (K_1) and semidiurnal (M_2) tidal components derived from a harmonic analysis of the OSCR surface currents (z=0) and the ADCP near-surface current measurements during COPE-III experiment based on 992 points. Observed (σ_o^2) and predicted variance (σ_p^2) and variance explained (%) are based on the K_1 , and M_2 tidal constituents.

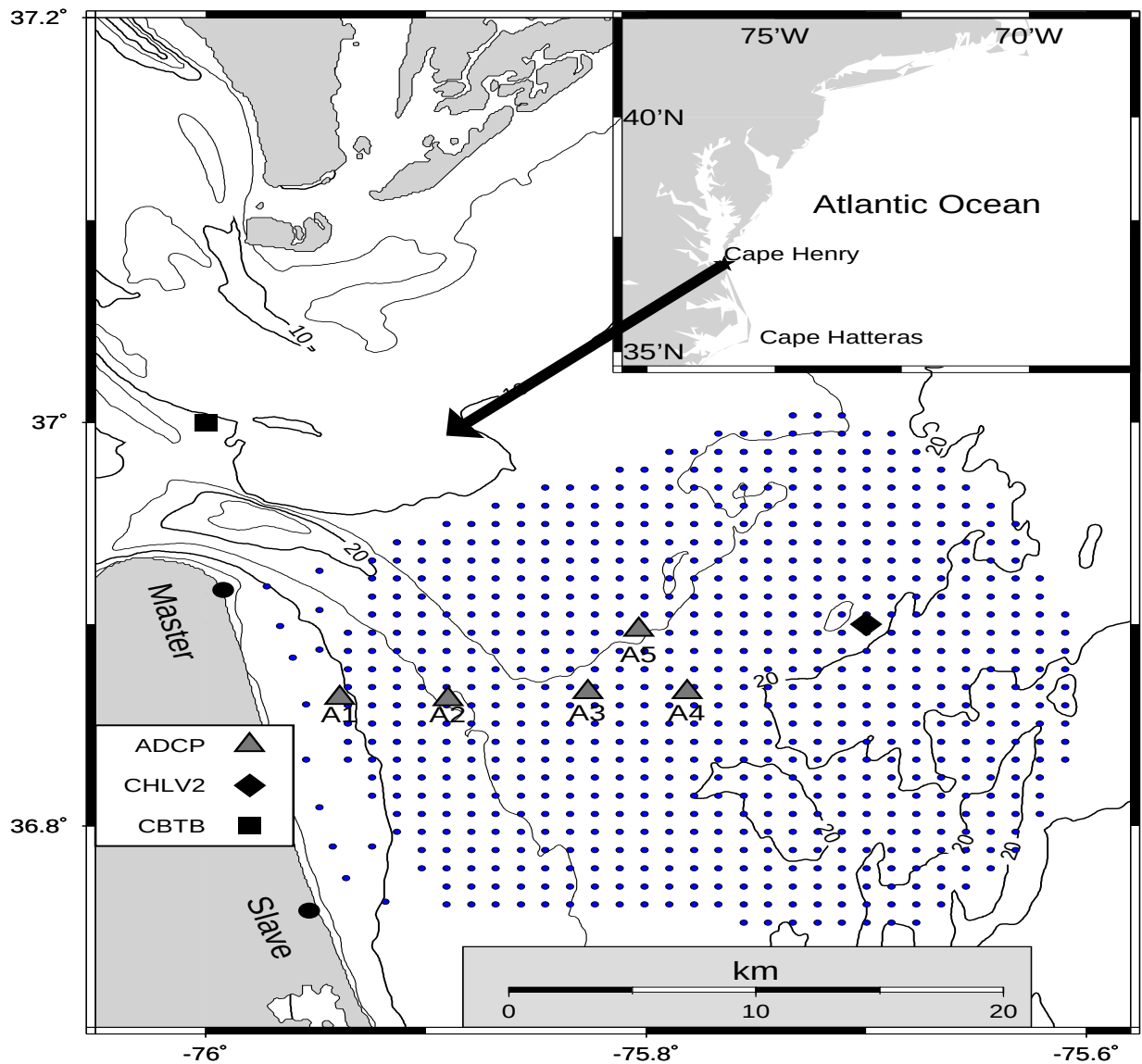


Figure 1: Experimental HF radar domain (dots) of Naval Research Laboratory COPE-III during October and November 1997. Five ADCP moorings are depicted by triangles, NOAA Sea Level Station is a square, and the Chesapeake Light Tower is a diamond relative to smoothed topography. Master and Slave sites were located at Fort Henry and Dam Neck.

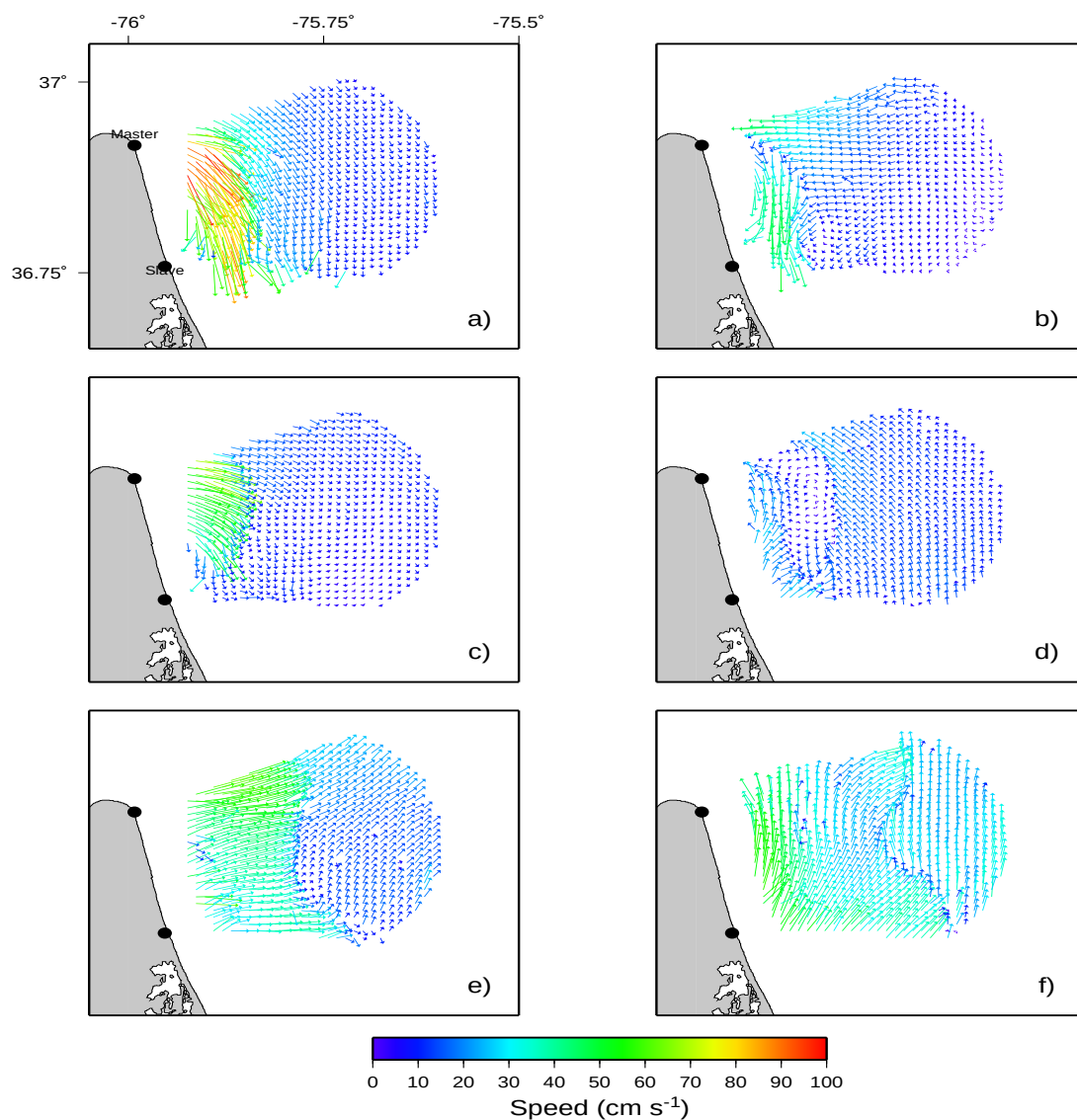


Figure 2: Observed surface current images at the beginning of the COPE-III deployment for : a) 1310 UTC 23 Oct; b) 1910 UTC 23 Oct; c) 0110 UTC 24 Oct; d) 0710 UTC 24 Oct; e) 1310 UTC 24 Oct; and f) 1910 UTC 24 Oct. The color bar depicts current speed in cm s^{-1} .

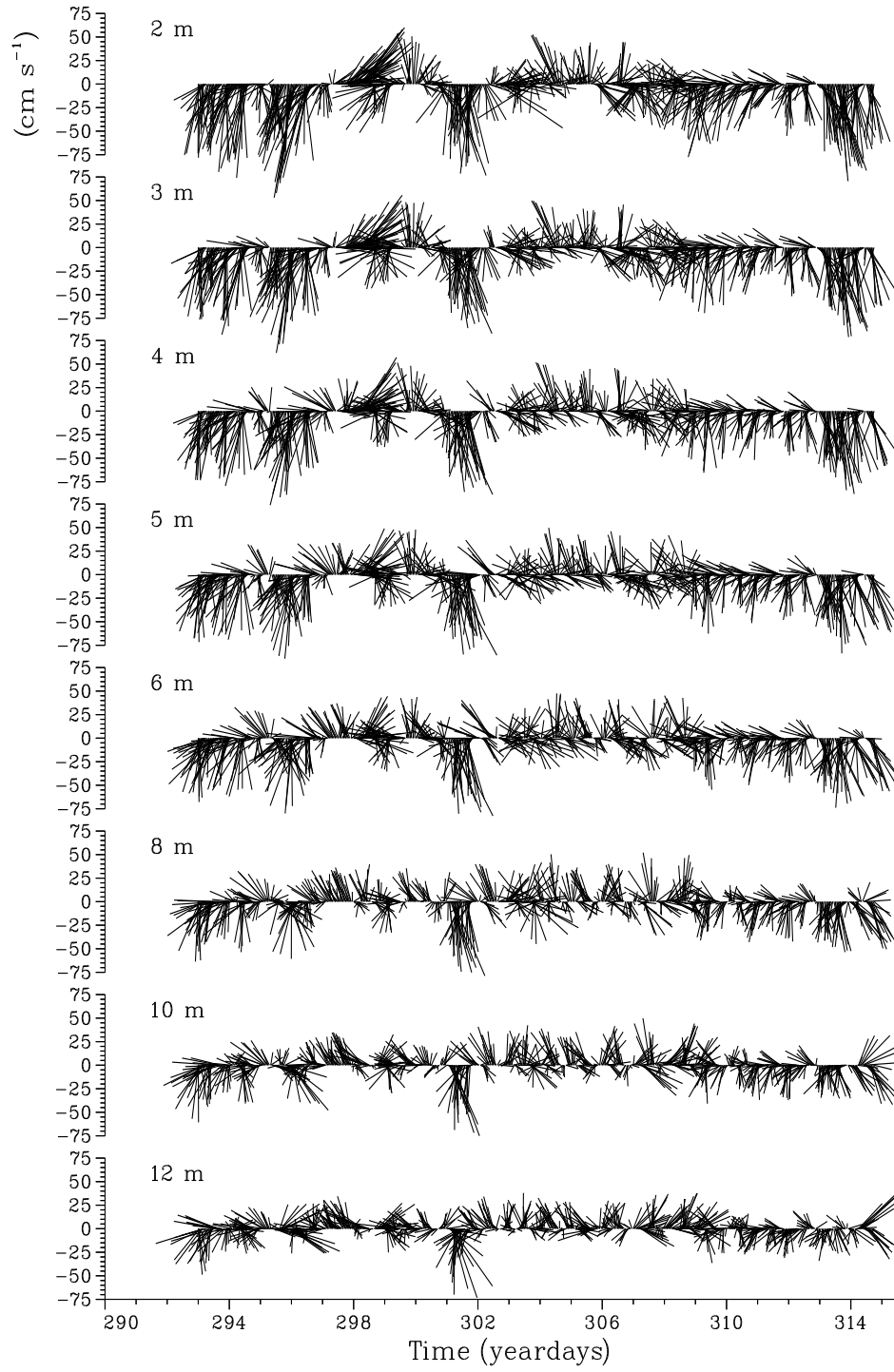


Figure 3: Vector plots of rotated current profiles (340°N) observed at ADCP A_2 mooring for the smoothed and subsampled currents at 40 minute intervals at selected depths.

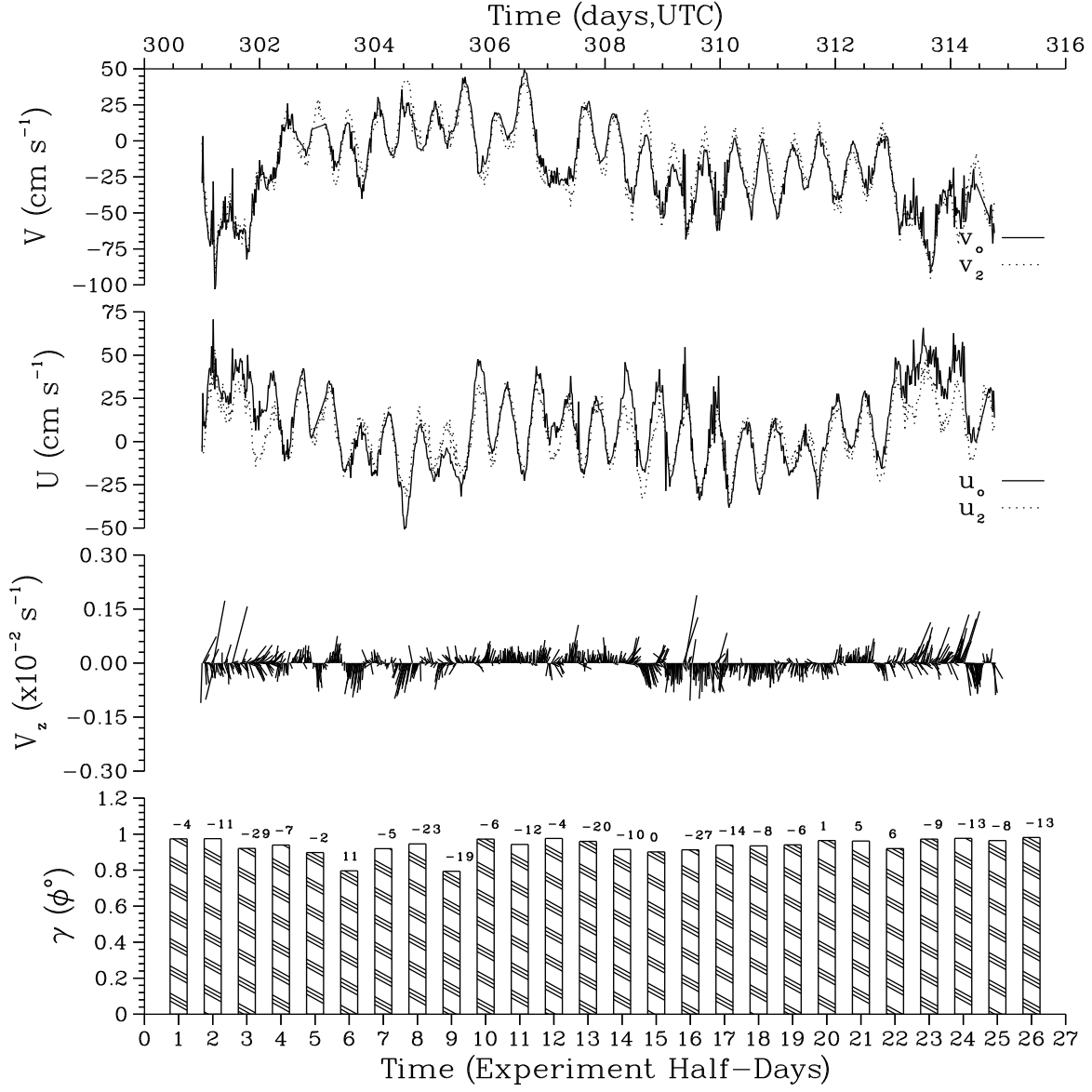


Figure 4: Observed time series at A₂ mooring from YD 300 (27 Oct) to YD 316 (10 Nov) 1997 during Cope-III for the surface (solid) and 2 m (dotted) a) cross-shelf component (cm s⁻¹), b) along-shelf component (cm s⁻¹), c) vertical current shear (x10⁻² s⁻¹) over a 2 m layer, and d) half-daily averaged (36 points) complex correlation coefficients (≤ 1) and complex phase angles (°) listed above each bar.

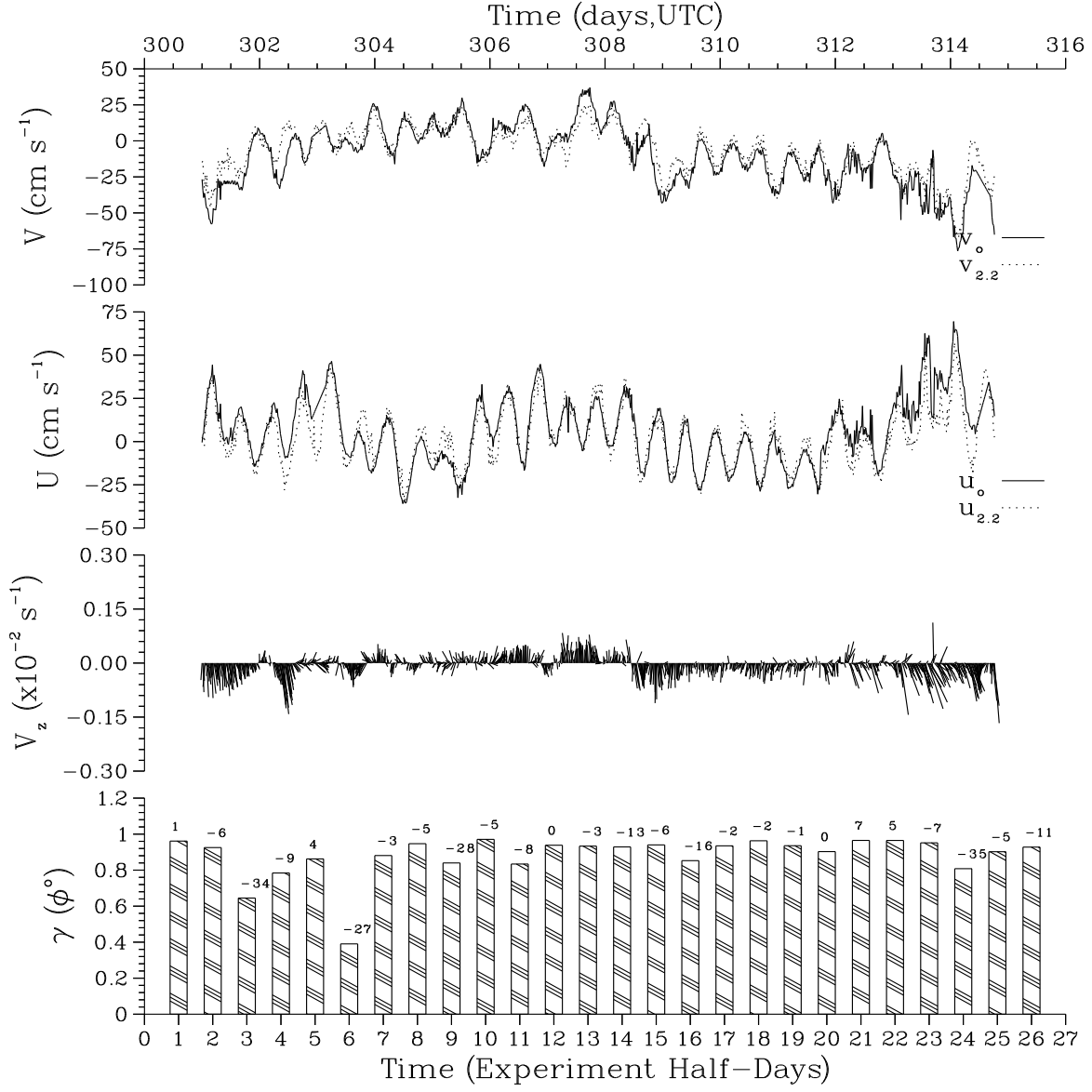


Figure 5: Observed time series at A_3 mooring from YD 300 (27 Oct) to YD 316 (10 Nov) 1997 during Cope-III for the surface (solid) and 2 m (dotted) a) cross-shelf component (cm s^{-1}), b) along-shelf component (cm s^{-1}), c) vertical current shear ($\times 10^{-2} \text{ s}^{-1}$) over a 2 m layer, and d) half-daily averaged (36 points) complex correlation coefficients (≤ 1) and complex phase angles ($^\circ$) listed above each bar.

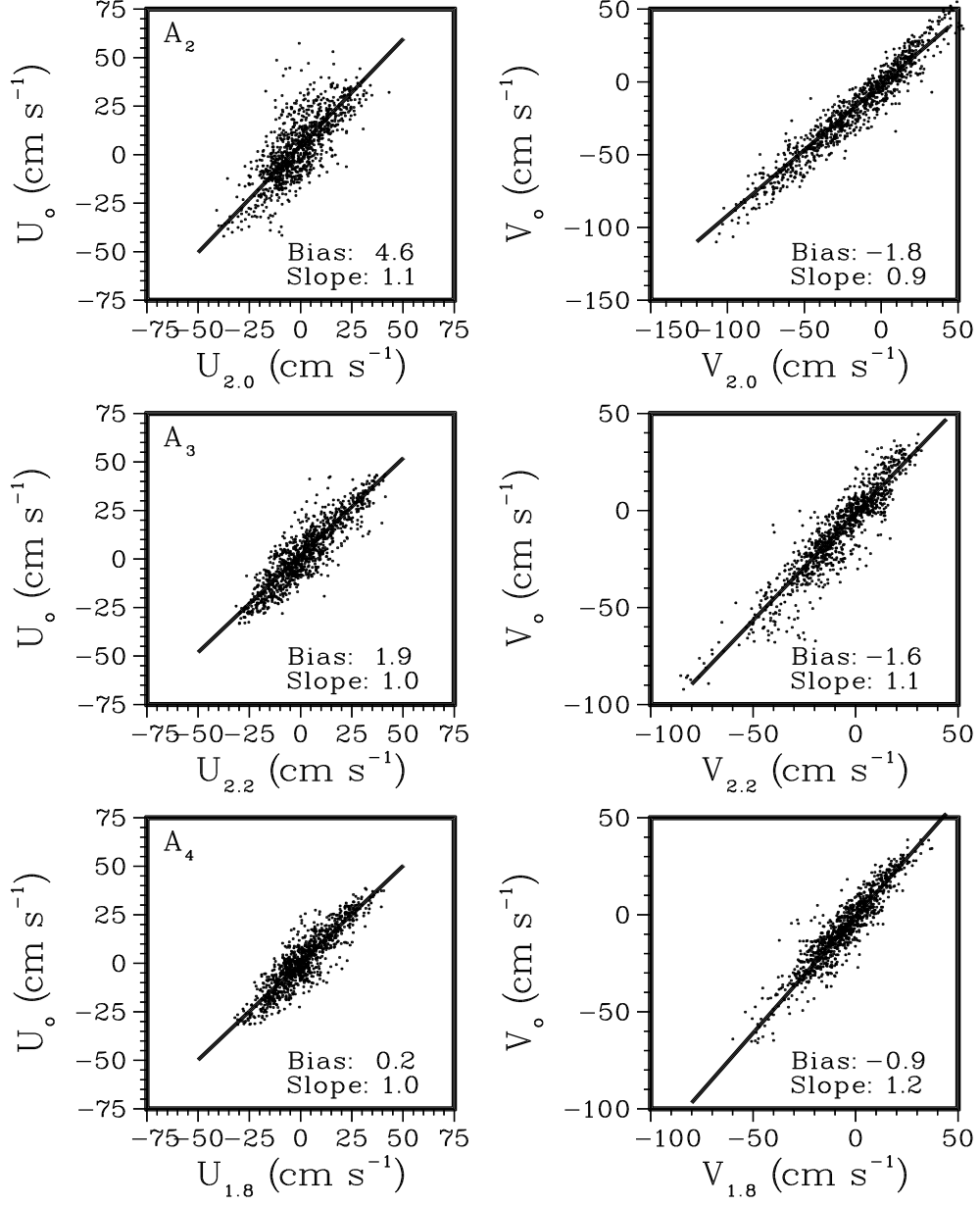


Figure 6: Regression analyses of surface (ordinate) and subsurface (abscissa) currents for the cross-shelf (left panels) and along-shelf (right panels) surface (o) and subsurface (2) currents at ADCP moorings A_2 , A_3 and A_4 in cm s^{-1} . Regression curves (solid) represent the best fit to the data with the biases and slopes given on the graphs.

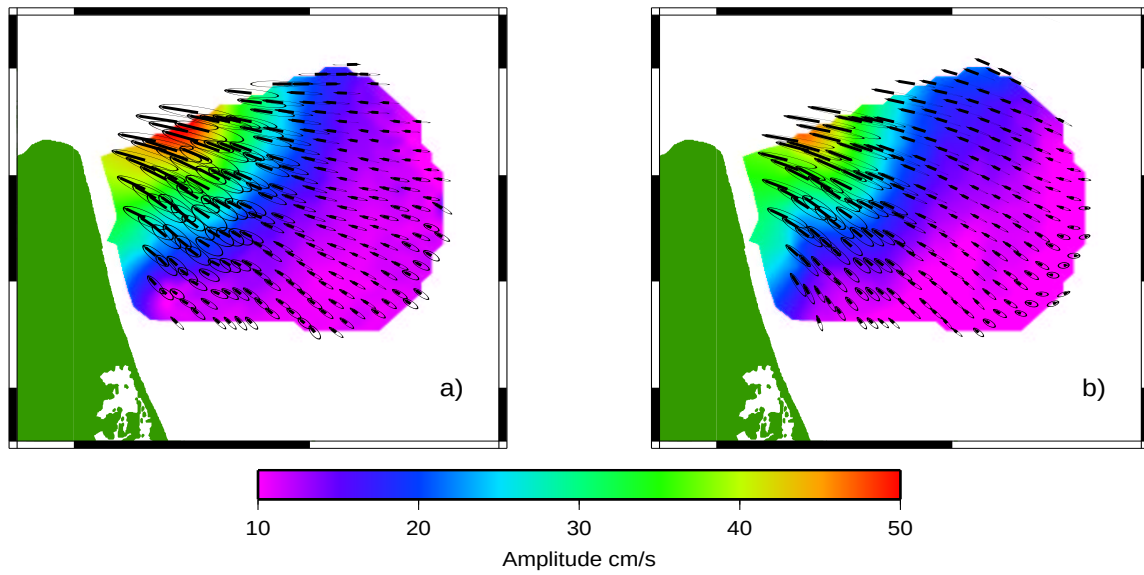


Figure 7: Magnitude of the M_2 tidal current and their ellipses from a) COPE-I, and b) COPE-III.

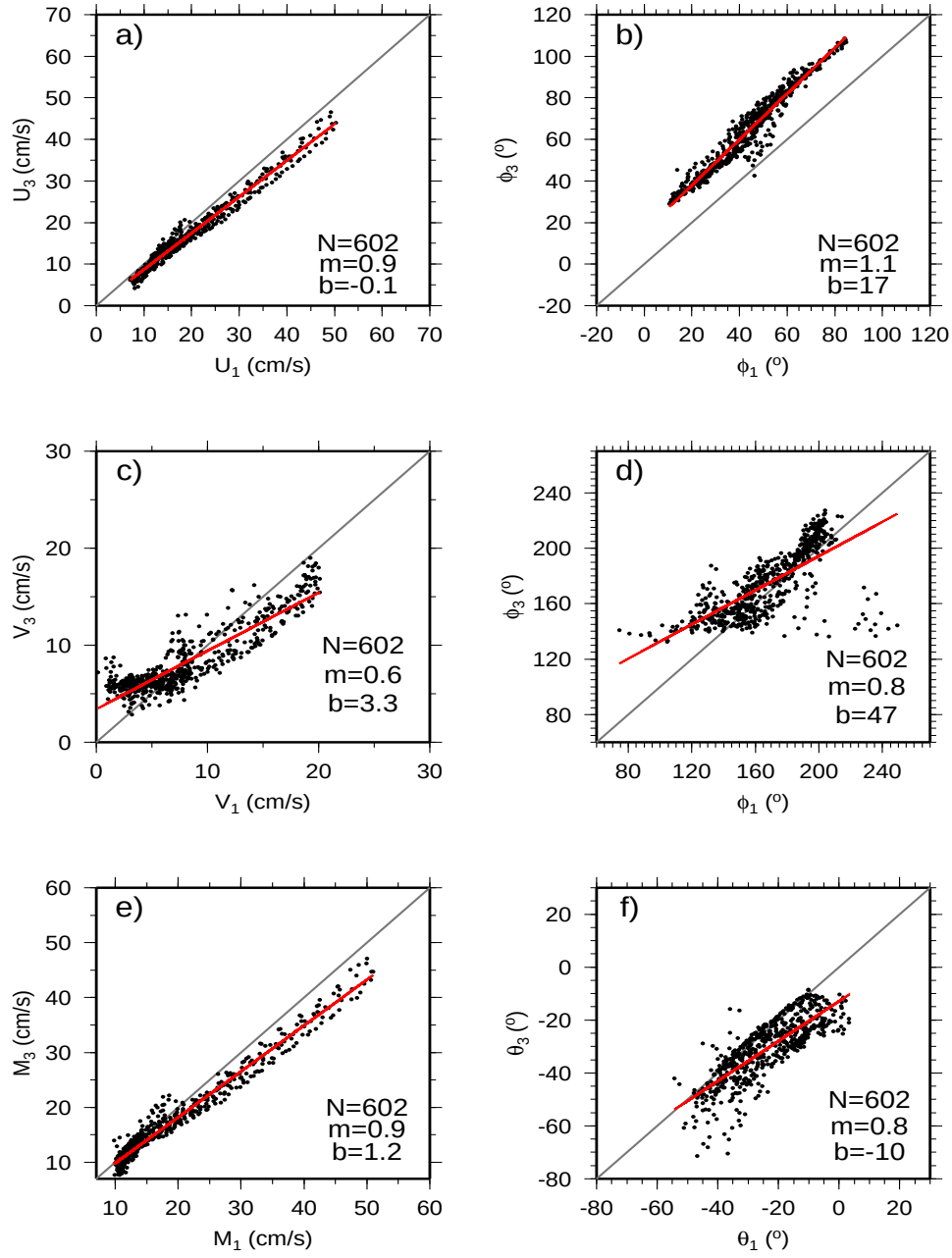


Figure 8: Comparisons of COPE-I (abscissa) and COPE-III (ordinate) M_2 tidal currents for a) cross-shelf amplitude (cm s^{-1}), b) cross-shelf phase ($^\circ$), c) along-shelf amplitude (cm s^{-1}), d) along-shelf phase ($^\circ$), e) major axes (cm s^{-1}), and f) ellipse orientation ($^\circ$) relative to a cyclonic rotation from east from 602 cells. The best fit regression curve (red line) is based on the slope (m) and bias (b) given in the lower left side of the panels.

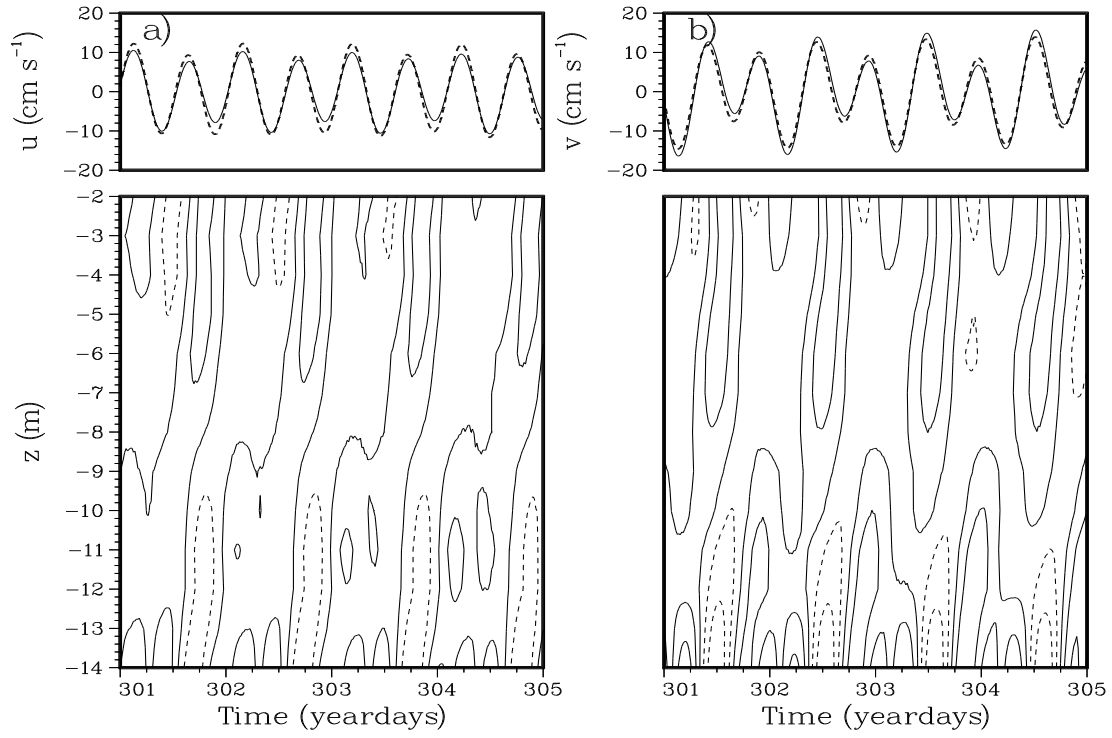


Figure 9: Four-day time tidal time series from the A_4 mooring for the a) cross-shelf and b) along-shelf currents. The upper panels represent the surface tidal current (solid) and the depth-averaged tidal current (dotted) and the lower panels represent the difference between the tidal and depth-averaged currents based on the M_2 and K_1 tides.