ON THE ADRIATIC TIDAL CURRENTS DERIVED FROM DRIFTER DATA

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Approved for release by: ……………………………………………

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1. Introduction

1.1 Tidal Currents and Circulation in Adriatic

The Adriatic Sea can be defined as 800-km long and 150-km wide a channel-like-arm of the Mediterranean Sea, which is elongated in the southeast-northwest direction, open at the southeast end with the Strait of Otranto (Figure 1.1). It can be divided into two basins with different bathymetry characteristics. The north basin has a bottom slope downward towards the southeast end with depths less than 300-m, whereas the southern basin is much deeper with the depths over 1200-m (Figure 1.2).

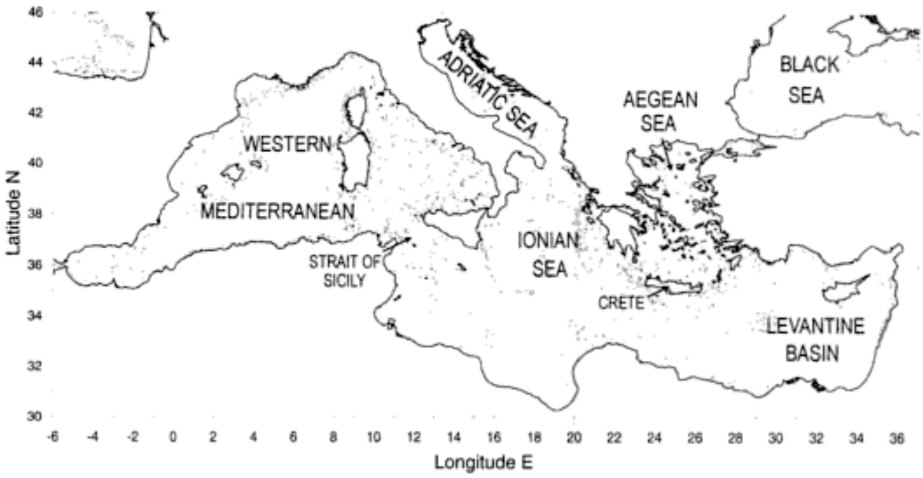


Figure 1.1. The Adriatic Sea in the context of the Mediterranean Sea (Cushman-Roisin, 2001).

At a basin-scale, the general circulation is cyclonic (counterclockwise), due to the combination of a northwestward inflow along the eastern side (Eastern Adriatic Current, EAC), and southeastward flow along the western side (Western Adriatic Current, WAC) (Orlic et al., 1992). Thus, circulation cells are cyclonic (counter-clockwise) in the basin. The WAC is primarily formed due to the Po River, which is located in the northwestern part of the basin. The EAC brings Levantine Intermediate waters and Ionian surface waters into the Adriatic basin. In addition to the EAC - WAC currents and the riverine inputs, the general circulation is also affected by northeasterly wind (bora), a cold katabatic wind that develops in the lee of the Dinaric Alps along the Adriatic coast, shown in Figure 1.2. The bora wind affects both the water characteristics and circulation, especially in the shallow northern end of the sea. It forms two gyres, one cyclonic in the far north and other anti-cyclonic just south of the first one (Zore-Armanda and Gacic, 1987; Kuzmic and Orlic, 1987; Orlic et al., 1994). The other strong wind pattern is the sirocco, which blows from the southeast side of the Adriatic. It shows less gustiness than bora, but longer fetch.

The mean flow map assembled by Poulain (2001) suggests that the basin-wide cyclonic circulation in the Adriatic basin presents three re-circulation cells, located in the northern, central and southern part of the basin. Poulain (2001) also determined the seasonal variability of the statistics of the near surface currents. Gyres and coastal currents are mostly prevailing in the summer and fall, whereas the maximum velocity variance was found in the middle and southern sub-basins in fall; however high variance values were also evidenced in winter. The southern basin tends to re-circulate around the Southern Adriatic Pit (Figure 1.2).

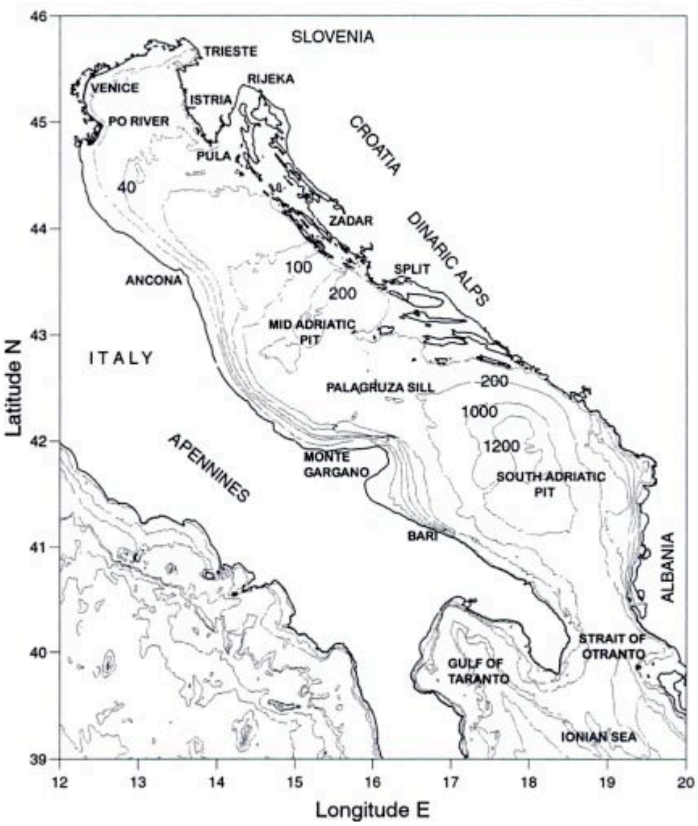


Figure 1.2. Geography and bathymetry of the Adriatic Sea (depths are in meters) (Cushman-Roisin, 2001).

Tides in the Mediterranean Sea are, in general, negligible but are enhanced in the northern part of the Adriatic Sea, and in the Gulf of Trieste, located in the northernmost sector of the Adriatic Sea. Tides, in the area present a mixed type-behaviour, with four major semidiurnal (M2, S2, N2, K2) and three major diurnal (K1, O1, P1) constituents, where M2 constituent dominates and K1 is the second most powerful one among all. They are listed with the respective symbol, period and highest amplitude in Table 1.1 below. As seen in the table, the maximum amplitudes occur on the northern coastline between Venice and Trieste (Cushman-Roisin, 2001).

All semi-diurnal tides (M2, S2, K2 and N2) have a similar structure at around mid-width East of Ancona. On the other hand, all the diurnal tides (K1, O1 and P1) show a longitudinal increase of amplitude from Southeast to Northwest, and a cross-basin phase propagation from the Albanian/Dalmatian coast to Italian shore. While the semi-diurnal tides are having a rotating pattern, and are appearing to consist of several waves propagating in different directions along the Adriatic Sea major axis, the diurnal tides have simpler structure, that can be described by a single travelling wave across the basin's minor axis (Polli, 1960).

Tides	Period	Max Amplitude	Port the max observed
M2	12.421 hrs	26.6 cm	Trieste
S2	12.000 hrs	16.0 cm	Trieste
K2	11.967 hrs	5.3 cm	Venice-Lido
N2	12.658 hrs	4.7 cm	Falconara
K1	23.932 hrs	20.1 cm	Porto Piave Vecchia
O1	25.819 hrs	6.4 cm	Trieste
P1	24.066 hrs	6.2 cm	Trieste

Table 1.1 Principal tides of Adriatic, their period, their maximum amplitude and the port where the maximum is observed (Polli, 1960).

The M2 tidal current ellipses, which were extracted by Cavallini (1985) are noticeably elongated and tend to be aligned along the axis of the basin. The magnitude of the tidal currents hardly exceeds 6 cm/s, and the phase progression is counterclockwise to the north and clockwise to the south. Mosetti and Purga (1990) also show that M2 tidal currents are the largest in the Gulf of Trieste, with maximum amplitudes noting exceed 4 cm/s.

Here we present results from the analysis of data provided by drifters, which were deployed in different parts of Adriatic Sea between 21 September 2002 and 29 July 2004 under the DOLCEVITA project, which stands for Dynamics of Localized Currents and Eddy Variability in the Adriatic that is explained in Section 2.

2. Data

2.1 DOLCEVITA

DOLCEVITA (Dynamics of Localized Currents and Eddy Variability in the Adriatic) was an international project focusing on the Adriatic Sea sponsored by the Office of Naval Research (ONR) and involving several oceanographers, both experimentalists and modelers, of the United States and Europe. The main objective of the DOLCEVITA project was to quantify the kinematic and dynamic properties of the Northern and Middle Adriatic Sea. The data set analyzed in this project starts on 21 September 2002 and ends on 29 July 2004. This database contains the data of 120 satellite-tracked surface drifters released in the Northern and Middle Adriatic Sea. However, this report focuses on a smaller number of drifters (55) that satisfied a minimum record length of 61.50 hours. They were eliminated according to criteria introduced in Section 2.3.

Surface drifter data originate from a wide set of platforms, such as the modified CODE, CODE/Tz, WOCE-SVP, SVP/OCM, MINIMET (WOTAN) and CMOD (XAN-3) drifters. Most drifters, like the modified CODE type, measure the surface currents within the first top meter of water column. Other drifters sample data at depths ranging between 15 and 50 m. All of them measure Sea Surface Temperature (SST). Some of them get the temperature data at various levels in the water column with a thermistor chain (CODE/Tz and CMOD (XAN-3)). Other drifters measure water optical properties (SVP/OCM) and the MINIMET (WOTAN) measures wind speed and direction.

Most drifters were released during oceanographic surveys onboard NRV Alliance (ADRIA02 and ADRIA03), R/V Knorr (DV-1 and DV-2) and R/V Hidra (EACE) while the other drifters were released from ship-of-opportunity (R/V OGS-Explora, ferry boats, small boats).

All drifters were tracked by, and transmitted data to, the Argos Data Collection and Location System (DCLS) carried by NOAA polar-orbiting satellites. Drifter positions were estimated from the Doppler shift with the help of relative motion between the drifter and the satellite. Some of the drifters were equipped with an additional global positioning system (GPS), which permits to obtain a finer resolution both in time (every hour or half an hour) and space. In addition, the GPS data time series are not continuous. Intervals without data for a few hours are often seen. (Poulain, 2003).

2.2 Drifter Deployments

The drifters were generally deployed at the beginning of the small-scale surveys conducted with the Trisoarus towed vehicle in two different cruises (DOLCEVITA-1 and DOLCEVITA-2) at different periods. The small-scale surveys during which drifter were deployed were carried out to sample dynamical features in four areas of the northern and middle Adriatic: the Mid Adriatic Filament or the northeastern part of the Mid Adriatic Pit (also called Jabuka Pit), the North Adriatic Filament near the tip of Istria (off Pula), the WAC off Rimini-Pesaro and the Po River Plume (Figure 2.1).

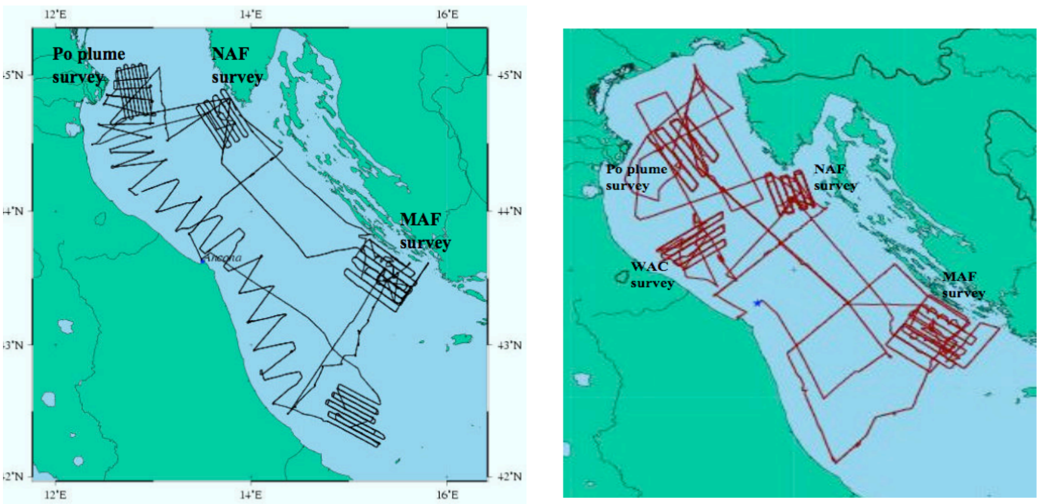


Figure 2.1. Ship track of R/V Knorr during the DOLCEVITA-2 cruise (on the left) and during the DOLCEVITA-1 cruise (on the right) in the northern and middle Adriatic. The small-scale surveys are shown.

CODE drifters in their cardboard boxes were deployed from the starboard side of the ship while the ship was steaming at about 6-7 knots while towing the vehicle. All the other drifters with drogues and thermistor chains were deployed from the stern when the ship speed was varying in 1-2 knots.

Some GPS drifters when they hit the shore or were taken by the fishermen, were taken out, recovered and deployed again in the same way with the same name/number but with a different letter in the beginning to be recognized easily.

2.3 Data Interpolation and Filtering

The raw position data were edited for outlier and spikes using statistical and manual techniques (Hansen and Poulain, 1996). Latitudes and longitudes were interpolated at 0.5-hour intervals. Velocity is calculated by using finite difference of successive positions. Among the 89 GPS drifters that were deployed in different parts of the Adriatic, the ones containing useful data reduced to 55 drifters. The reduction was due to short data segments or position acquisition system, such as the blocking and the breakdown of the system. In Figure 2.2, shows the GPS tracks of CODE drifters.

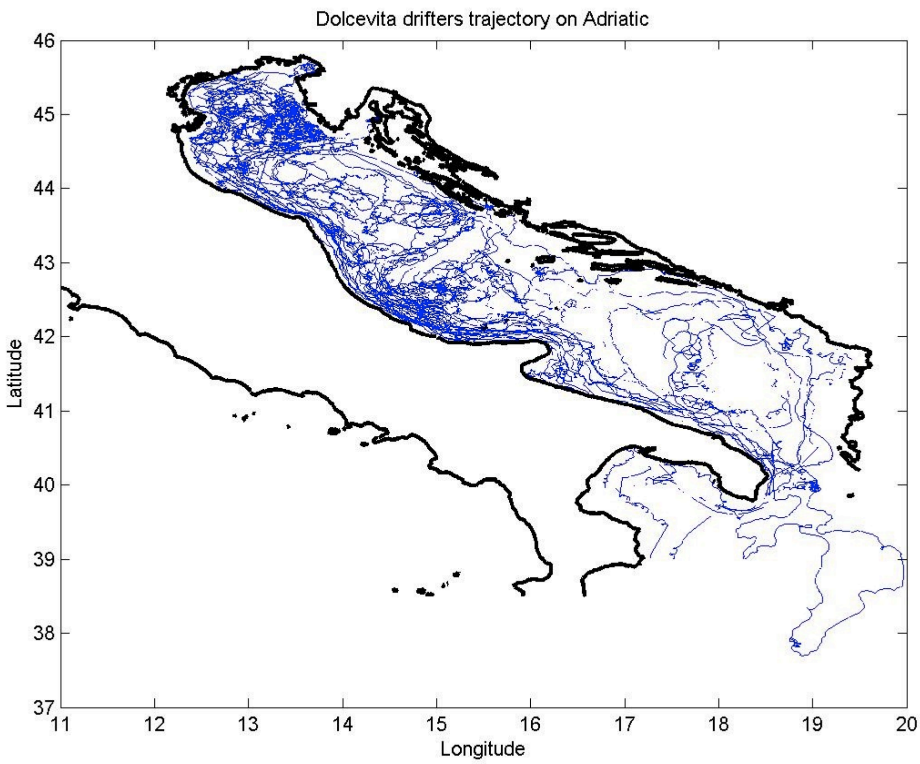


Figure 2.2: GPS trajectories of the CODE drifters in Adriatic Sea between 21 September 2002 and 29 July 2004.

3. Method

3.1 Harmonic Analysis

Harmonic Analysis method allows you to reconstruct a signal by means of a series of harmonic functions and to define the amplitudes and phases of different frequency constituents that are hidden in the data. However, unlike the Fourier analysis, it uses predefined frequencies, which are preferred to be the ones that belong to a signal. In addition, we want to determine the amplitudes and phases of the largest number of frequency components possible by using as short time series as possible. Since we have more frequency values than prescribed ones, we have to deal with a huge number of data. This leads us to use the harmonic analysis method in which we can specify the frequencies to be examined and apply the least-square method to solve for the constituents.

Suppose we want to determine the amplitudes and phases of a set of M harmonic constituents at M specified frequencies. In this case, q=0,1,…,M and Bo=0 so that the total number of harmonic coefficients to determine is 2M+1; this requires at least N>>2M+1 observations to resolve the frequency content 2M+1 << N.

For M possible harmonic constituents, the time series $x(t_n)$, n=1,2,…,N describing the sampled data set can be expressed as a finite sum of harmonic constituents:

$$x(t_n) = \bar{x} + \sum_{q=1}^{M}\left[A_q \cos\left(2\pi f_q t_n\right) + B_q \cos\left(2\pi f_q t_n\right)\right] + x_r(t_n) \tag{3.1}$$

in $\bar{x}$ where is the mean value of the observations, x_r is the residual portion of the time series, $t_n = n\Delta t$ the length of the record, and C_q, f_q, *and* φ_q are respectively the amplitude, frequency, and phase of the qth constituent that we have specified. This equation can be written also as

$$x\left(t_n\right) = \bar{x} + \sum_{q=1}^{M}\left[A_q \cos\left(2\pi f_q t_n\right) + B_q \sin\left(2\pi f_q t_n\right)\right] + x_r\left(t_n\right) \tag{3.2}$$

where the amplitude and the phase are defined as

$$C_q = \sqrt{A_q^2 + B_q^2} \tag{3.3}$$

$$\varphi_q = \tan^{-1}\left(B_q / A_q\right) \tag{3.4}$$

for q=0, …, M. To reduce the errors, the mean value, $\bar{x}$, should be subtracted from the record prior to the computation of the Fourier coefficients.

The purpose of the least-square method is to minimize the variance, e^2, of the residual time series $x_r(t_n)$ in the equation 3.1

$$e^2 = \sum_{n=1}^{N} x_r^2 = \sum_{n=1}^{N} \left\{ x(t_n) - \left[\bar{x} + \sum_{q=1}^{M} \left[A_q \cos\left(2\pi f_q t_n\right) + B_q \sin(2\pi f_q t_n) \right] \right]^2 \right\} \tag{3.5}$$

Taking the partial derivatives of (3.5) with respect to A_q and B_q, and setting the results to zero, gives 2M+1 simultaneous equations for the M+1 constituents, where q=0,…,M for A and q=1,…,M for B,

$$\frac{\partial e^2}{\partial A_q} = 2\sum_{n=1}^{N} \left\{ x_n - \left(\bar{x} - \sum_{q=1}^{M} \left[A_q \cos\left(2\pi f_q t_n\right) + B_q \sin\left(2\pi f_q t_n\right) \right] \left[-\cos\left(2\pi f_q t_n\right) \right] \right) \right\} = 0$$

$$\frac{\partial e^2}{\partial B_q} = 2\sum_{n=1}^{N} \left\{ x_n - \left(\bar{x} - \sum_{q=1}^{M} \left[A_q \cos\left(2\pi f_q t_n\right) + B_q \sin\left(2\pi f_q t_n\right) \right] \left[-\sin\left(2\pi f_q t_n\right) \right] \right) \right\} = 0 \tag{3.6}$$

The equations above (3.6) requires matrix equation solutions of the form Dz = y in where D is an (M+1)x(M+1) matrix includes sine and cosine summation terms, y is a vector (column matrix) incorporating summations over the data series and z is a column matrix containing the required A_q and B_q. To calculate the z results through the matrix equation we get the equation below

$$z = D^{-1} y \tag{3.7}$$

where D^{-1} is the inverse of the matrix

$$D = \begin{bmatrix} N & c_1 & c_2 & \dots & c_M & s_1 & s_2 & \dots & s_M \\ c_1 & cc_{11} & cc_{12} & \dots & cc_{1M} & cs_{11} & cs_{12} & \dots & cs_{1M} \\ c_2 & cc_{21} & cc_{22} & \dots & cc_{2M} & cs_{21} & cs_{22} & \dots & cs_{2M} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ c_M & cc_{M1} & cc_{M2} & \dots & cc_{MM} & cs_{M1} & cs_{M2} & \dots & cs_{MM} \\ s_1 & sc_{11} & sc_{21} & \dots & sc_{1M} & ss_{11} & ss_{12} & \dots & ss_{1M} \\ s_2 & sc_{21} & sc_{22} & \dots & sc_{2M} & ss_{21} & ss_{22} & \dots & ss_{2M} \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ s_M & sc_{M1} & sc_{M2} & \dots & sc_{MM} & ss_{M1} & ss_{M2} & \dots & ss_{MM} \end{bmatrix} \tag{3.8}$$

and y and z are column vectors

$$y = \begin{bmatrix} yc_0 \\ yc_1 \\ yc_2 \\ \dots \\ yc_M \\ ys_1 \\ ys_2 \\ \dots \\ ys_M \end{bmatrix} \text{ and } z = \begin{bmatrix} A_0 \\ A_1 \\ A_2 \\ \dots \\ A_M \\ B_1 \\ B_2 \\ \dots \\ B_M \end{bmatrix} \tag{3.9}$$

The elements of Equations (3.8) and (3.9) are defined as

$$c_k = \sum_{n=1}^{N} \cos\left(2\pi f_k t_n\right)$$

$$s_k = \sum_{n=1}^{N} \sin\left(2\pi f_k t_n\right)$$

$$cc_{kj} = cc_{jk} = \sum_{n=1}^{N} \left[\cos\left(2\pi f_k t_n\right)\cos\left(2\pi f_k t_n\right)\right]$$

$$ss_{kj} = ss_{jk} = \sum_{n=1}^{N} \left[\sin\left(2\pi f_k t_n\right)\sin\left(2\pi f_k t_n\right)\right] \tag{3.10}$$

$$yc_k = \sum_{n=1}^{N} x_n \cos\left(2\pi f_k t_n\right)$$

$$ys_k = \sum_{n=1}^{N} x_n \sin\left(2\pi f_k t_n\right)$$

At this point the harmonic analysis of the original series can solve the amplitudes and the phases of the constituents in frequency in two different methods:

Method 1: All the frequencies of all constituents included in the analysis will be simultaneously used in least square method and solved at once. In this case the matrix D will have size of 15x15.

Method 2: One single frequency will be needed at a time to solve for the corresponding amplitude and phase. This should be repeated for all the constituents (in case of the Adriatic Sea area, 7 times, one for each tidal constituent). Therefore the matrix D will have a size 3x3.

Finally, the coefficient A_0 represents the time-averaged value of the original signal. Once the coefficients are determined via the least-squares fit, a “synthetic” time series can be reconstructed for each frequency and the overall contribution of tides to ocean current variability can be estimated by summing the synthetic signals.

Additionally, the relative contribution of tidal energy to the current tidal in the Adriatic Sea, is generally expressed in terms of the ratio between the variance of the synthetic signal, and that of the sampled signal variance, which needs to be smaller than one (3.11 and 3.12).

$$ExplainedVariance = \sum\left(u_i\left(t\right) - u_i - u_r\left(t\right)\right)^2 \qquad 3.11$$

$$SignalVariance = \sum\left(u_i\left(t\right) - u_i\right)^2 \qquad 3.12$$

The ability of tides to quantify the current variability is exposed by this ratio, which is called Skill and is equal to EV(Explained Variance) / SV(Signal Variance).

4. Results

The harmonic analysis method described in the previous section was used to analyze velocity data sampled from a set of 55 drifters deployed in the Adriatic Sea in the period between 21 September 2002 and 29 July 2004. As previously mentioned (section 2), data have been quality-controlled for spikes and have been interpolated at 0.5-hour time intervals.

Figure 4.1 shows, as a scatterplot diagram, both components of velocity (u and v) of all the drifters included in the analysis. The left-hand side plot includes velocity outliers, that is, when velocity observations exceeding 100 cm/s in absolute value. These values are considered unreal so they were excluded from the dataset; after their removal, velocity observations are clustered in a more limited interval (right-hand side).

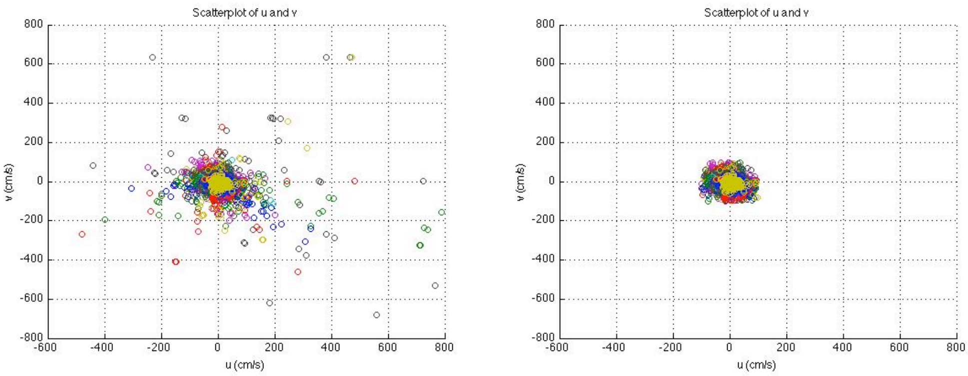


Figure 4.1: The scatterplot of all the velocity components (u and v) for all 55 drifters used in this study is given to the left; to the right, the scatterplot of u and v components after discarding the values bigger than 100 cm/s and smaller than -100 cm/s is presented.

4.1 Results based on the Individual Drifters

The harmonic analysis was first performed on the time series of near-surface current records collected from each individual drifter, in order to determine the dominant features of the record. Results below are obtained from two drifters; b04020 and a04001. They show that currents can be expressed as the combination of high frequency tidal motion and non-tidal component over a broad frequency spectrum.

Figure 4.2 shows the trajectory of the drifter b04020. The drifter path can be divided into three main parts in Adriatic Sea. The first part, in the northern sector, presents three eddy-like structures and captures the well-known northern cyclonic circulation cell. South of this area, the drifter trajectory shows no significant structures along the Italian coast to the west. However, a mesoscale circulation cell appears in the middle of the basin in correspondence to the Gargano peninsula, and a third sub-basin wide circulation cell appears to the South, at the Otranto Strait area, at the Adriatic-Ionian boundary.

Figure 4.3 presents the time series evolution of u and v velocity components obtained from drifter b04020 using the Method 1 (section 3). The blue curves are the original velocity data (after the outlier removal), whereas the red curves indicate the predicted tidal motion based on the tide model using the harmonic constants obtained from the analysis. This dataset has the longest time series in this study, approximately 13 months covering the period June 2003-July 2004, allowing for an accurate determination of the tidal constituents and an accurate resolution of tidal frequencies.

The time series evolution of current velocities shows some interesting feature and intrinsic variability over time, presumably reflecting the drifter movement in the basin. The first part of the dataset (June – October) generally shows lower amplitudes and the presence of short-period (high-frequency) oscillations (Fig 4.3). A seasonal variability can be detected, with winter months (October to February) presenting less high-frequency variability but larger velocity amplitudes, with maxima occurring in December and March when surface circulation is most likely enhanced by wind events. Higher-frequency motions appear again in the velocity record in the last part of the data set, similarly to what observed in the June – October period at the beginning of the data set, although with larger velocity extremes.

The amplitudes and phases of the seven dominant tidal constituents for the Adriatic Sea are given in Table 4.1; the predicted tidal currents are given in Figure 4.3, along with the original velocity time series. As can be seen from Figure 4.3, tides (red curves) do not significantly contribute to current energy since tidal currents are typically one order of magnitude smaller than the total currents in the area sampled by the drifter. Tidal currents span 5-7 cm/s in amplitude, whereas drifter velocities are as high as 90 cm/s. The average for u is 0.54 cm/s and for v it is -0.81 cm/s, where the standard deviation for u is 15.65 cm/s and for v it is 17.92 cm/s. According to Table 1, for the u velocity component K1 (diurnal) has the largest amplitude and for the v component it is M2 (semi-diurnal) constituent. These two constituents have the largest energy contribution to the total current. The skill is 0.81% for u (K1) and 0.89% for v (M2). S2 and P1 have also quite large amplitude and skill values that cannot be ignored. K2, N2 and O1 have the minimum amplitudes, which means that they have the lowest contribution to the circulation with skill values smaller than 0.15%. The skill value for the combination of all constituents is 2.7% for u component whereas it is 2.1% for v component.

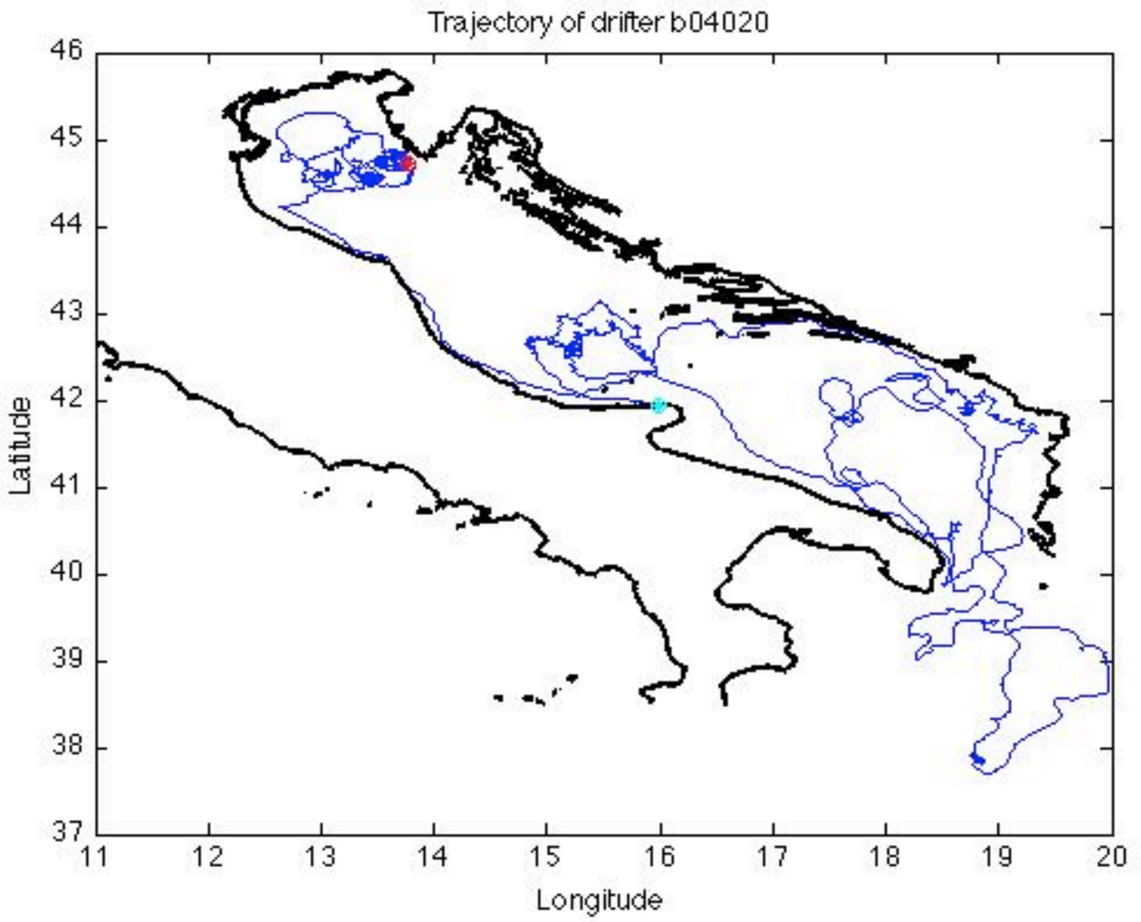


Figure 4.2 Trajectory of drifter b04020 in the Adriatic Sea between June 2003 and July 2004, where the red dot is where it was deployed and the cyan point is where it was picked up.

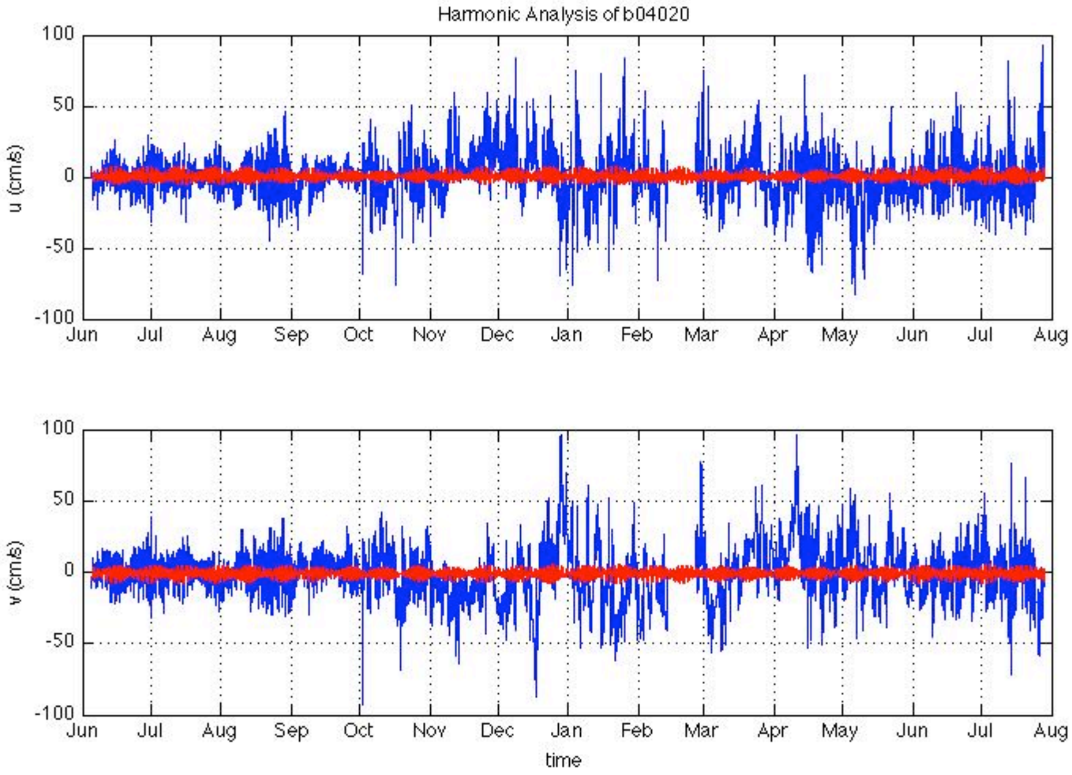


Figure 4.3 Results of the harmonic analysis of u and v velocity components for the drifter b04020. Blue curves indicate the original data obtained from the drifter and the red curves show the predicted tidal current curve based on the tide model using the harmonic analysis method. Time period: June 2003-July 2004.

Tides	**M2**	**S2**	K2	N2	**K1**	O1	**P1**
Amplitude-Cu (cm/s)	**1.67**	**1.45**	0.51	0.41	**1.99**	0.75	**1.64**
Phase-Φu (degrees)	**108.74**	**-8.58**	-130.84	-25.37	**-8.20**	81.45	**-82.16**
Skill u (%)	**0.57**	**0.43**	0.05	0.03	**0.81**	0.12	**0.55**
Amplitude-Cv (cm/s)	**2.39**	**1.32**	0.52	0.36	**1.68**	0.96	**1.23**
Phase-Φv (degrees)	**-74.43**	**-161.72**	45.97	-163.18	**-173.24**	-107.02	**112.46**
Skill v (%)	**0.89**	**0.27**	0.04	0.02	**0.44**	0.14	**0.23**

Table 4.1 Amplitude, phase and skill of each constituent using harmonic analysis method for the drifter b04020. The dominating tides are M2 and K1 with the largest amplitudes.

Tidal ellipses for the two dominant tidal constituents, the semi-diurnal (M2) and diurnal (K1) tides, are shown in Figure 4.4, using Method 2. As mentioned before, these tides are the largest contributors to tidal currents. Amplitudes are comparable for both current components (being respectively, 1.67 and 1.99 cm/s for the u component, and for 2.39 and 1.68 cm/s for the v component). M2 presents a counter-clockwise rotation, whereas K1 is characterized by a clockwise rotation.

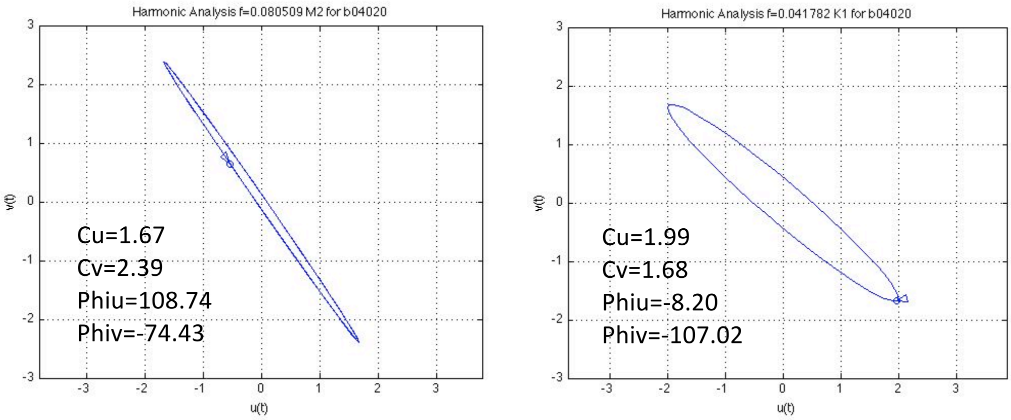


Figure 4.4 Tidal ellipses for the drifter b04020 when the f=0.080509 (M2) (left) and when f=0.041782 (K1) (right) with the amplitude and phase values separately for u and v velocity components. Dot refers the first values of u and v in the dataset, and arrow represents the direction of the circulation.

Figure 4.5 shows the trajectory for drifter a04001, deployed on 7 February 2003 on the eastern coast and reaching the Italian coast to the west after 17 days (24 February 2003). The corresponding time series of drifter velocities are given in Figure 4.6, overlaid with the tidal currents as synthesized from the harmonic analysis results.

The average for u component is -5.76 cm/s and for the v component is -4.97 cm/s, whereas the standard deviation for u is 8.58 cm/s and for v is 10.35 cm/s. The total variability for u component (blue curve) went from -10 to -35 cm/s in 2-3 days then changed the direction and speeded up again to +16 cm/s the next day. Due to the short time series the tidal frequency resolution is not as good as the previous example. This variability is much greater than the expected tidal current (red curve) for u, which is between -5 and +5 cm/s in this case.

The largest energy contribution is coming from the K1 constituent with the 5.76 cm/s amplitude value and 22.5% of skill for the u component. For v there are three constituents that have similar values in amplitude and skill, S2, K2 and P1, with the amplitudes around 4.5-5 cm/s and skill around 9.40-11.90%.

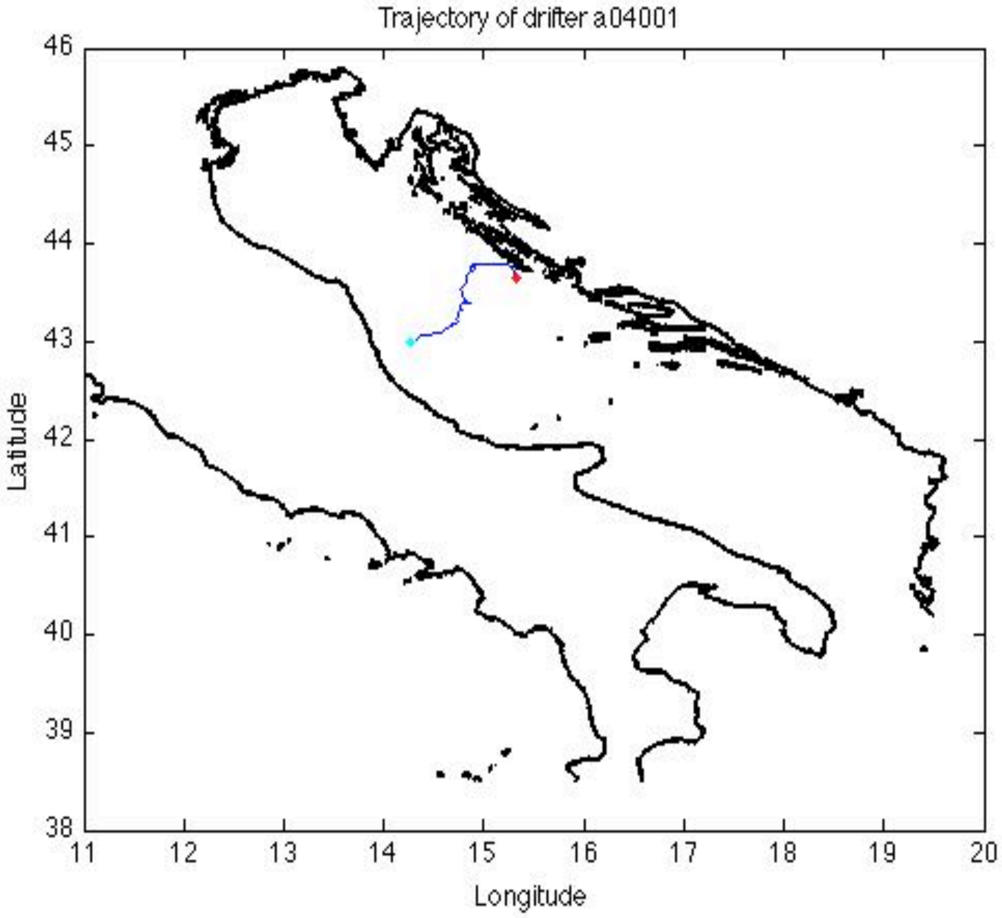


Figure 4.5 Trajectory of drifter a04001 in the Adriatic Sea between 7 - 24 Feb 2003, where the red dot is where it was deployed and the cyan point is where it was picked up.

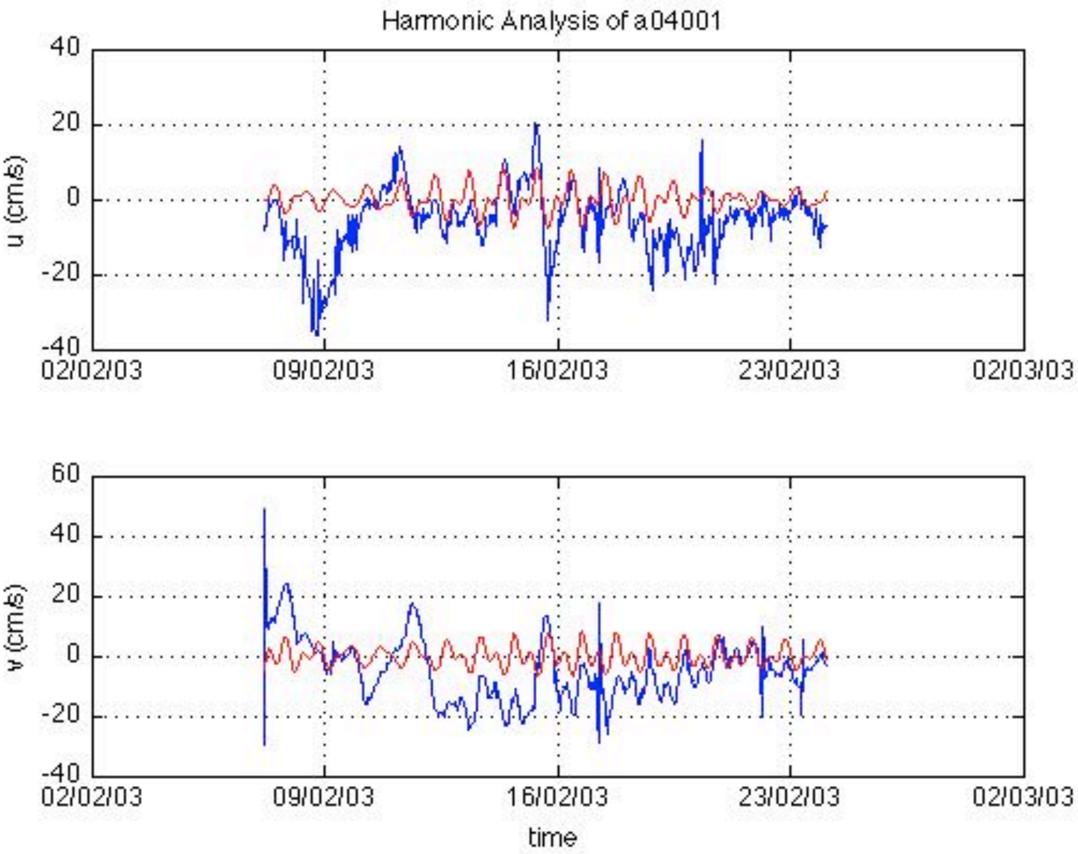


Figure 4.6. Results of the harmonic analysis of u and v velocity components for drifter a04001. Blue curves indicate the original data obtained from the drifter and the red curves show the predicted tidal current curve based on the tide model using the harmonic analysis method. Time period: 07 Feb - 24 Feb 2003.

Tides	M2	S2	K2	N2	**K1**	O1	P1
Amplitude Cu (cm/s)	2.23	2.07	1.98	0.34	**5.76**	1.68	2.71
Phase Φu (degrees)	-25.84	-95.45	146.16	-100.71	**44.10**	-154.59	-175.60
Skill u (%)	3.35	2.91	2.66	0.08	**22.51**	1.93	4.97
Amplitude Cv (cm/s)	**3.05**	**5.04**	**4.48**	0.40	1.52	0.42	**4.68**
Phase Φv (degrees)	**158.94**	**127.61**	**-11.79**	164.37	16.43	37.78	**-155.89**
Skill v (%)	**4.35**	**11.92**	**9.42**	0.07	1.08	0.08	**10.27**

Table 4.2. Amplitude, phase and skill of each constituent using harmonic anaylsis method for the drifter a04001. The dominating tides are M2, S2, K2, K1 and P1 with the largest amplitudes.

The tidal current ellipses for S2 and K1 by using Method 2, are shown in Figure 4.7. For the semi-diurnal tide (S2) the amplitudes for u and v are 2.07 and 5.04 cm/s, while for the diurnal tide (K1) the values are 5.76 and 1.52 cm/s. The rotation is counter-clockwise for S2 and clockwise for K1 (Fig 4.7).

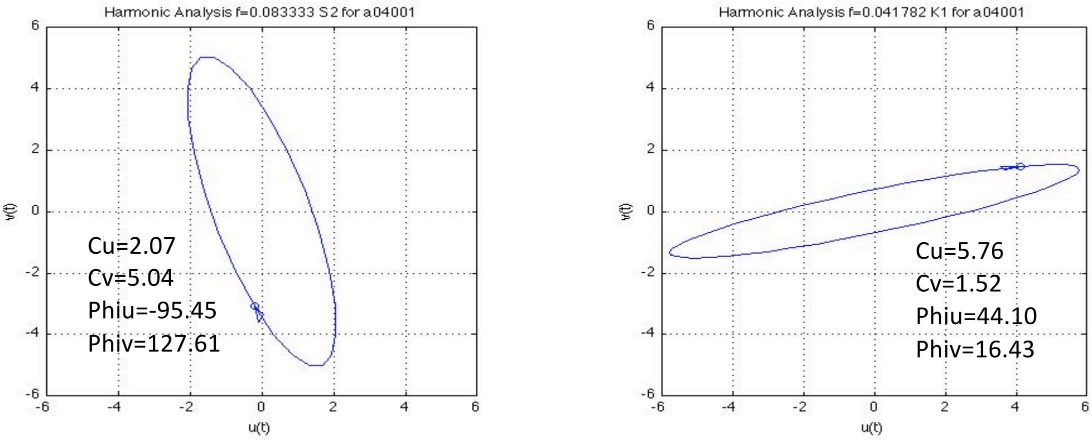


Figure 4.7. Tidal current ellipses for drifter a04001 when the f=0.083333 (S2) (left) and when f=0.041782 (K1) (right) with the amplitude and phase values separately for u and v velocity components. Dot refers the first values of u and v in the dataset, and arrow represents the direction of the circulation.

4.2. Results Based on a Geographical Area

This section shows the results of harmonic analysis of time series data sampled by using Method 1 (section 3) over a grid box with ¼˚ longitudinal and latitudinal resolution**.** Time series was included with all the drifters passing in the grid box, if the velocities are simultaneous, they were averaged and the time with no observations were filled with NaNs. Additionally, velocities larger than 100 cm/s are excluded after they were interpolated at 0.5-hour intervals.

The first example area is chosen from the northern Adriatic, for the grid box with the largest drifter data density; the grid box is located in 44.75-45.00 N and 13.25-13.50 E (Figure 4.8).

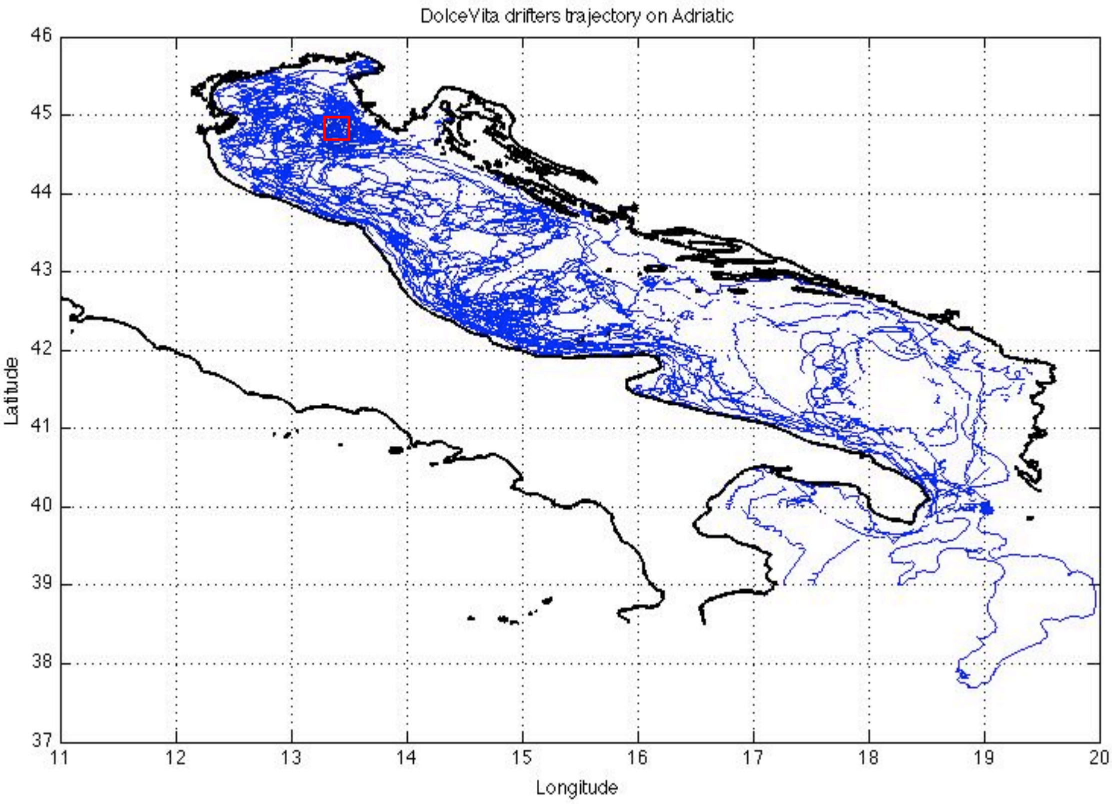


Figure 4.8. The geographical area grid chosen in the Adriatic Sea basin to analyze the tidal motion with harmonic analysis method – red box – 44.75-45 N and 13.25-13.50 E.

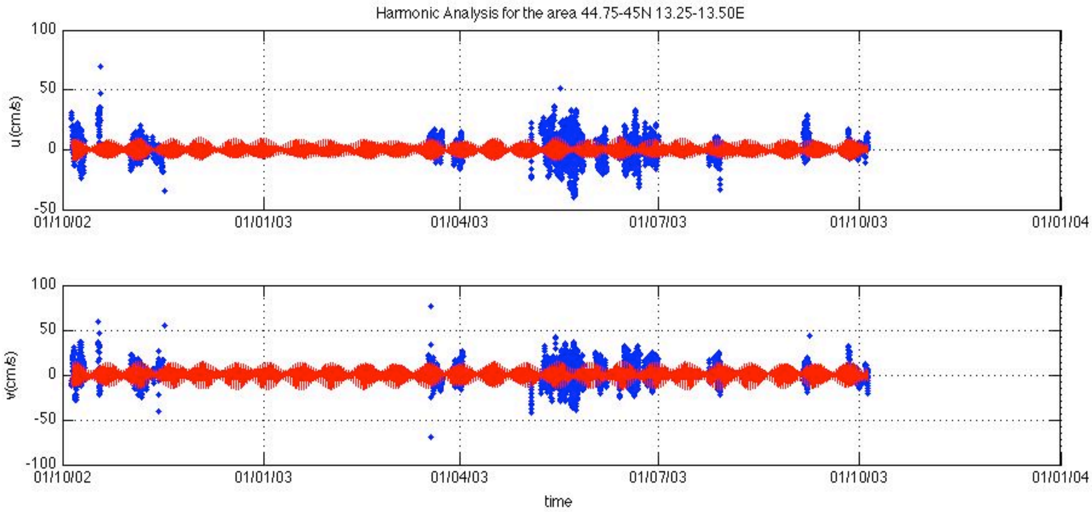
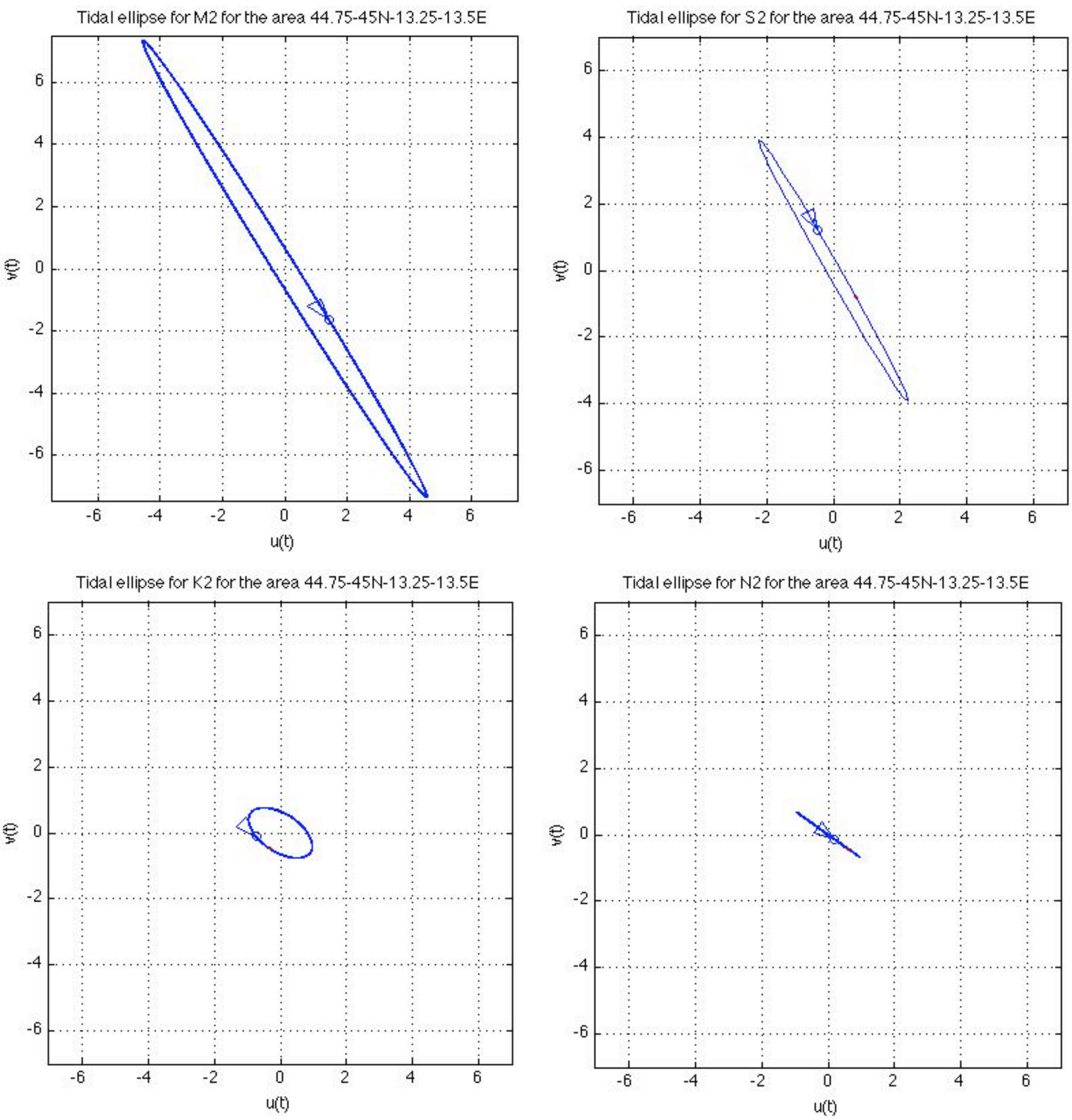


Figure 4.9. Harmonic analysis of the velocity components time series over the given geographical area (44.50-44.74N 13.25-13.50E) using Method 1. (upper plot is u and lower plot is v).

Velocity components (u and v) time series for the selected area are shown in Figure 4.9 (Method 1). As seen from the figure, the data in the area is not continuous over time. Despite the large temporal gaps, the harmonic analysis on the velocity data extracted the dominant tidal constituents by using Method 2 (see ellipses in Figure 4.10).



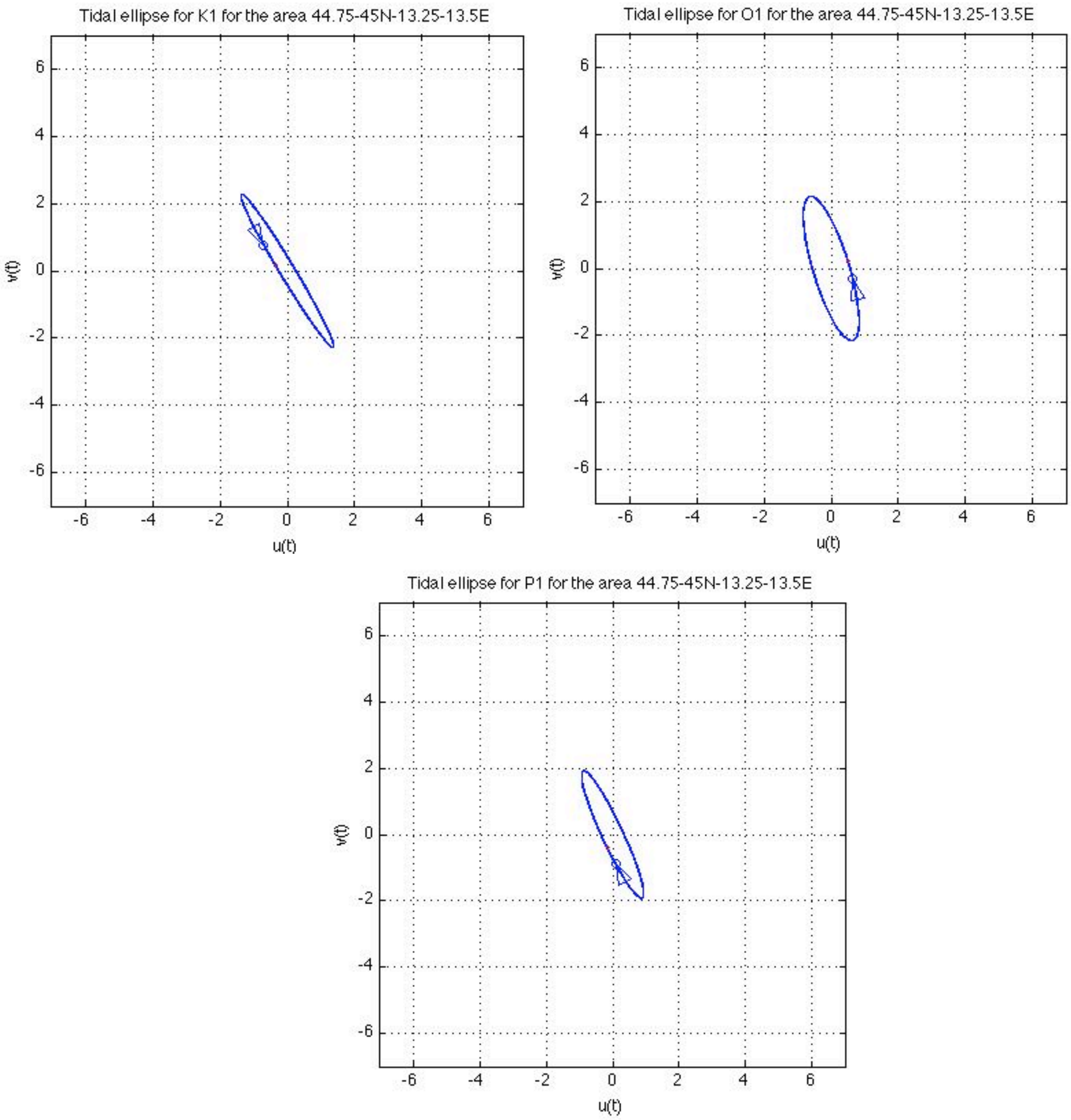


Figure 4.10. Tidal ellipses for all the constituents for the geographical area 44.50-44.75 N and 13.25-13.50E (Method 2). The blue marker is the starting point of the ellipse, the arrow indicates the sense of rotation

Together with Table 4.4, Figure 4.10 show that the dominating tidal constituents in this area are M2 and S2, with the amplitude values of 4.25 and 2.22 cm/s for u and 7.34 and 3.90 cm/s for v. The skill for the M2 constituent is 8.53% for u, and 16.77% for v.

Tides	**M2**	**S2**	K2	N2	K1	O1	P1
Amplitude (Cu) (cm)	**4.57**	**2.22**	0.97	0.94	1.38	0.83	0.94
Phase (Φu) (degrees)	**71.97**	**102.02**	139.42	78.34	120.47	-38.91	-84.58
Skill – u (%)	**8.53**	**2.02**	0.38	0.37	0.78	0.28	0.36
Amplitude (Cv) (cm)	**7.34**	**3.90**	0.77	0.67	2.28	2.15	1.93
Phase (Φv) (degrees)	**-102.85**	**-71.87**	-99.12	-100.86	-70.29	98.28	117.12
Skill – v (%)	**16.77**	**4.74**	0.18	0.14	1.62	1.44	1.76

Table 4.4. The amplitude, phase and skill for all tidal constituents as a result of the harmonic analysis method for the geographical area 44.50-44.75 N and 13.25-13.50 E.

Another example area is chosen near the center of the Adriatic Sea, which is near the Mid Adriatic Pit, where the depth reaches to 270 m. Latitude and longitude coordinates are: 42.05-42.30 N and 14.95-15.20 E.

The distribution of the velocity components are much more sparse than the previous region as seen in Figure 4.12; using harmonic analysis method 1 (section 3). Despite the large number of drifter crossing this area, the average drifter residence time was limited, presumably due to the presence of strong coastal currents in the area.

Harmonic analysis results suggest that each tidal constituents play a comparable role to the definition of tidal currents in the area (Table 4.5). S2, K2, K1 and O1 have the biggest amplitudes for the u component, whereas M2, K2, N2 and K1 are the dominant constituents for v component. However, consistently with results from either individual drifters or distinct geographical areas, the skill values are not very high for both velocity components, being approximately 2%. In comparison with other data set, tidal ellipses (Fig 4.13) have more circular shapes, due to the smaller difference between the major and the minor axis amplitudes.

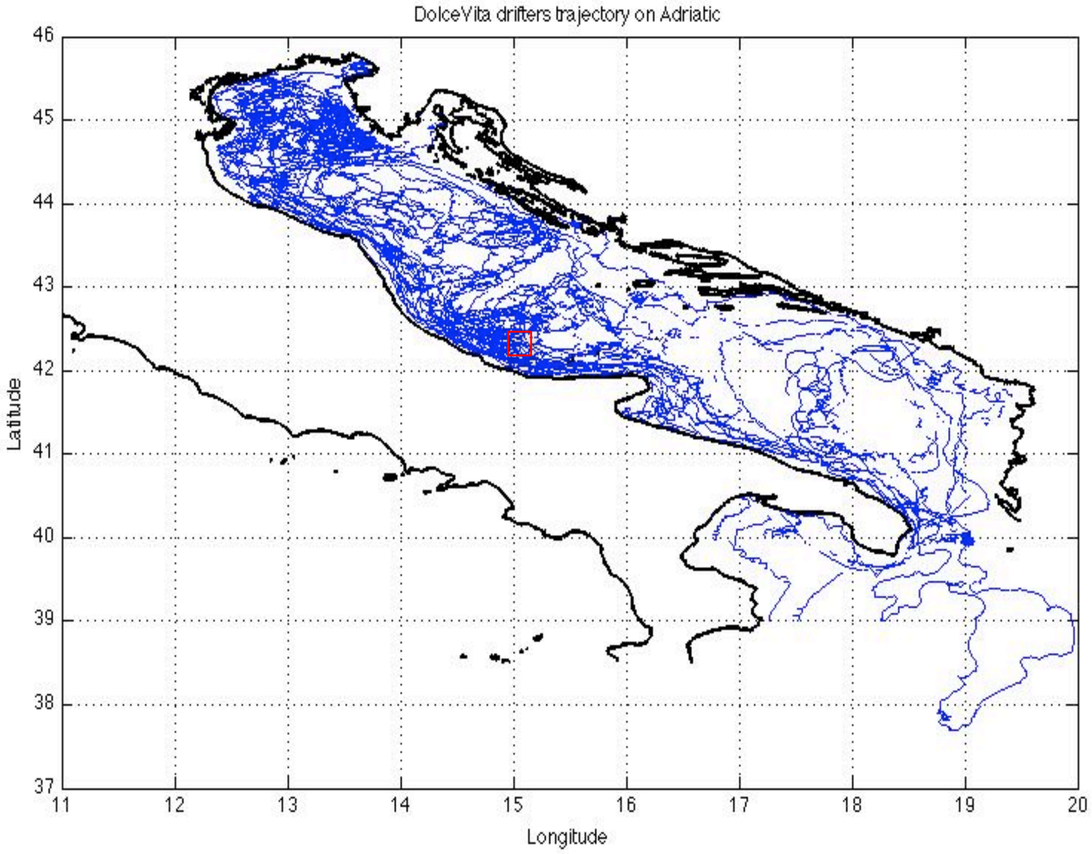


Figure 4.11. The geographical area grid chosen in the Adriatic Sea basin to analyze the tidal motion with harmonic analysis– red box – 42.05-42.30 N and 14.95-15.20 E.

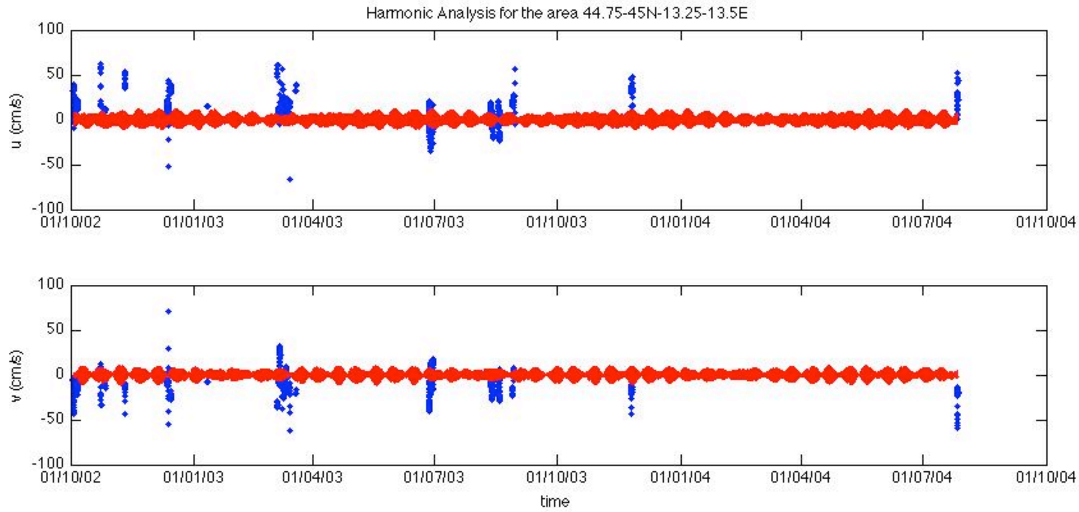
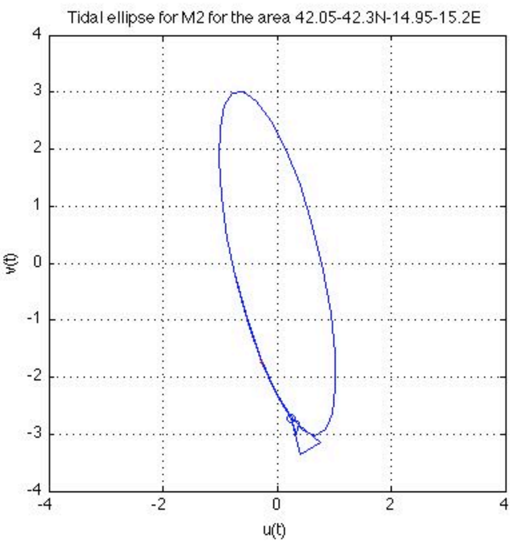
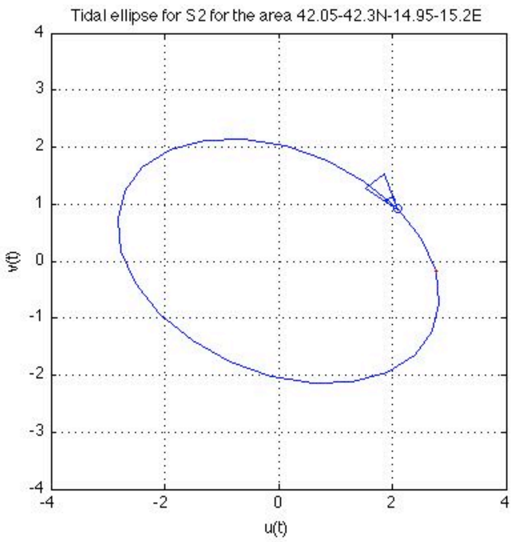
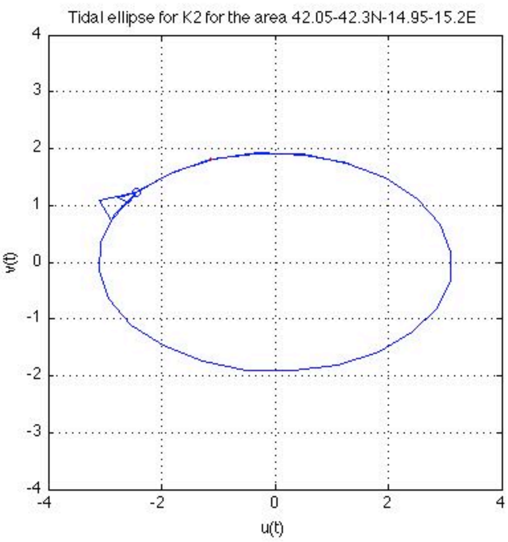
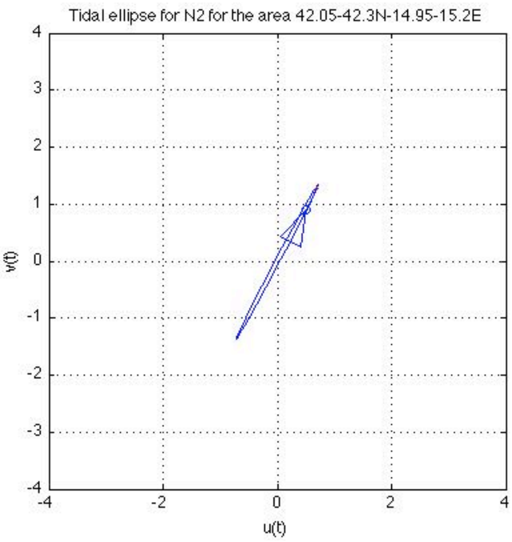


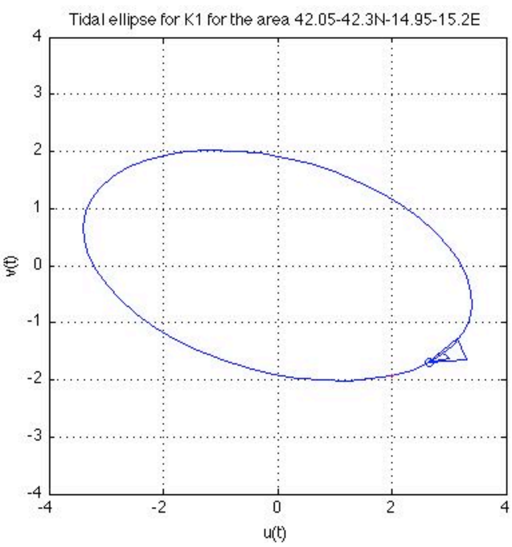
Figure 4.12. Harmonic analysis of the velocity components time series over the given geographical area (42.05-42.30N 14.95-15.20E) using method 1. (upper plot is u and lower plot is v).

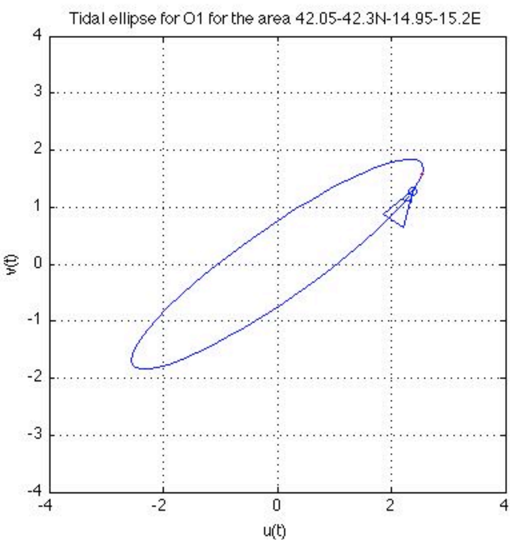

Tidal ellipse for M2 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)


Tidal ellipse for S2 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)


Tidal ellipse for K2 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)


Tidal ellipse for N2 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)


Tidal ellipse for K1 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)


Tidal ellipse for O1 for the area 42.05-42.3N-14.95-15.2E
v(t)
u(t)

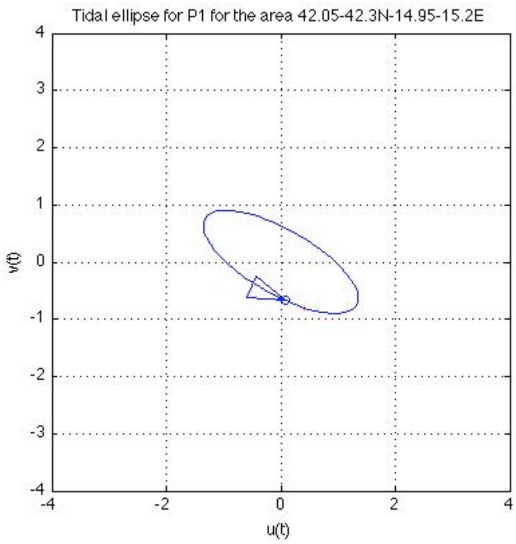


Figure 4.13. Tidal ellipses for all the constituents for the geographical area 42.05-42.30 N and 14.95-15.20E. (Method 2). Dot refers the first values of u and v in the dataset, and arrow represents the direction of the circulation.

Tides	M2	S2	K2	N2	K1	O1	P1
Amplitude (Cu) (cm)	1.03	**2.83**	**3.13**	0.72	**3.40**	**2.56**	1.36
Phase (Φu) (degrees)	-75.56	**45.52**	**141.52**	44.73	**-38.87**	**21.77**	86.96
Skill – u (%)	0.19	**1.42**	**1.74**	0.09	**2.05**	**1.17**	0.33
Amplitude (Cv) (cm)	**3.02**	**2.15**	**1.93**	1.36	**2.02**	1.85	0.90
Phase (Φv) (degrees)	**154.07**	**-64.81**	**50.66**	48.23	**-147.38**	45.92	-137.68
Skill – v (%)	**2.48**	**1.25**	**1.01**	0.50	**1.10**	0.93	0.22

Table 4.5. The amplitude, phase and skill for all tidal constituents as a result of the harmonic analysis method for the geographical area 42.05-42.30 N and 14.95-15.20 E.

4.3 Results for the Whole Adriatic Sea

This section represents the results obtained with the harmonic analysis method (method 2) for all the seven tides compiled separately over the Adriatic Sea. Figure 4.14 summarizes the number of drifter data in each ¼° grid box in the whole basin where the threshold is 100 points for each grid box. According to the figure, in the southern part of the basin there were not many drifters observed or not many appropriate data were obtained. Most drifters provided data in the northern and middle part of the Sea where they were deployed.

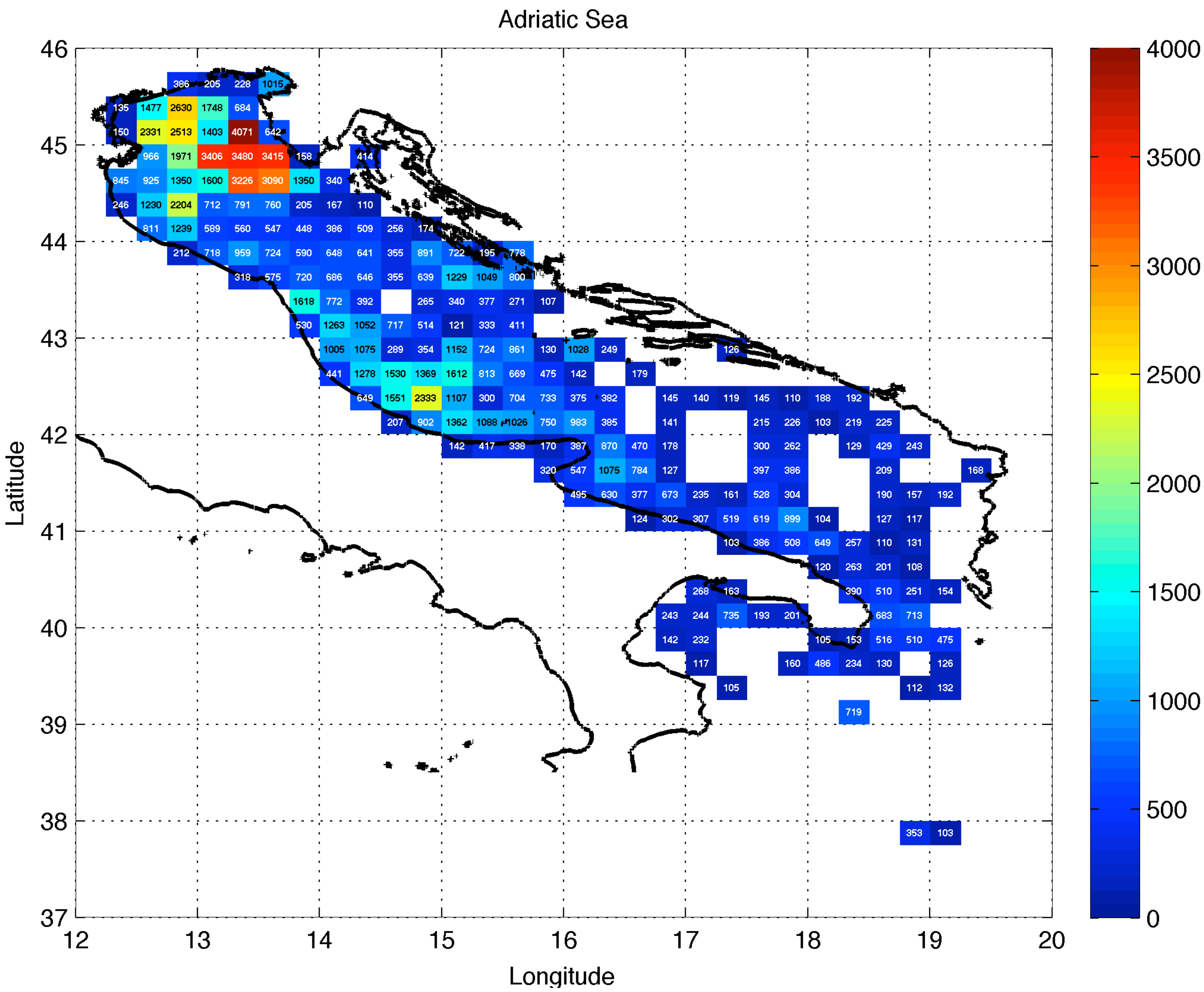


Figure 4.14: Number of drifter observations in each ¼° grid box in the Adriatic Sea.

The plots below, are the combination of all tidal ellipses for each constituent for all the grid boxes over Adriatic Sea. The seven figures are represented by means of the tidal current ellipses and the colormap of the amplitude of the major axis in each grid box obtained from the CODE-GPS drifter data.

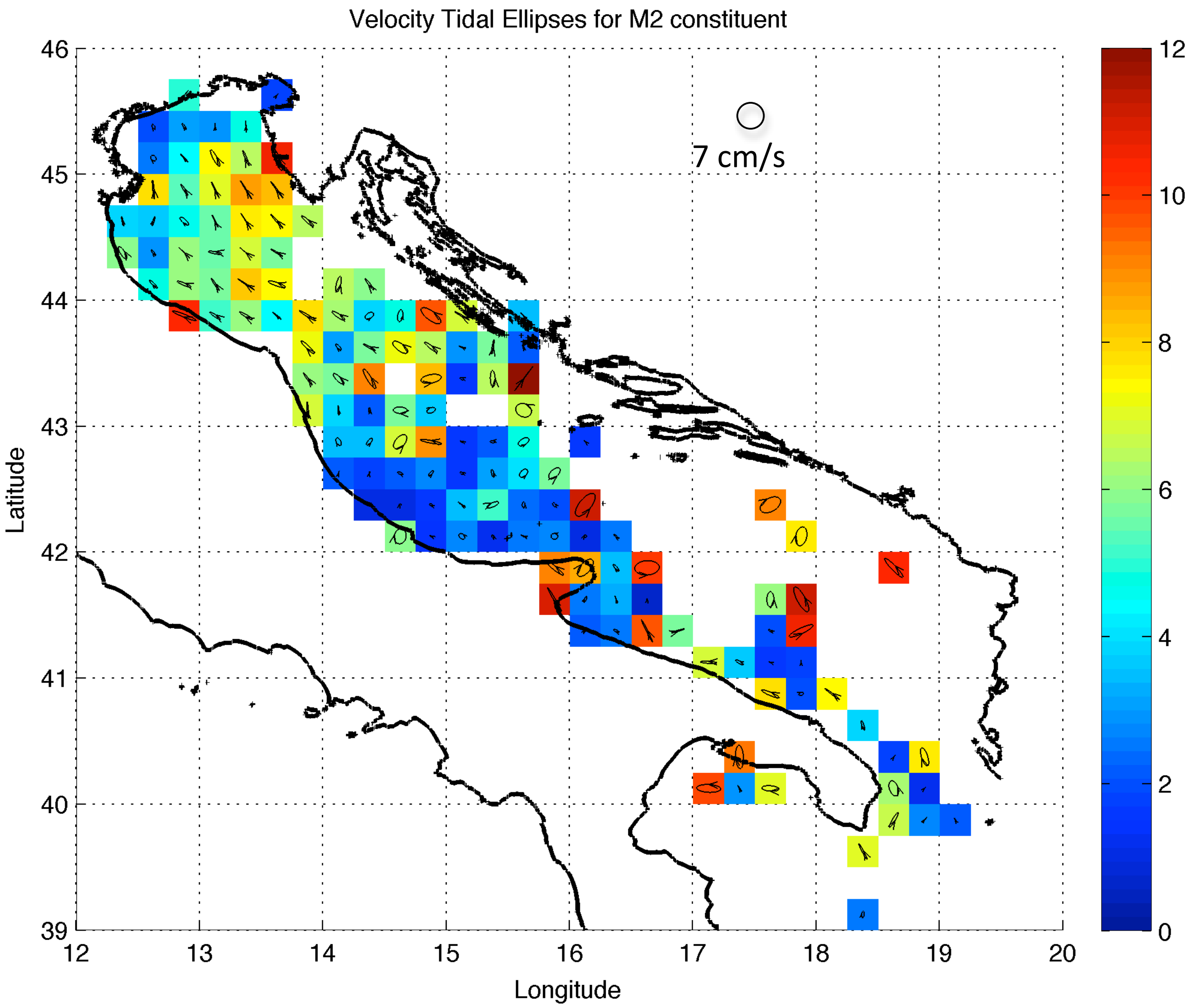


Figure 4.15: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for M2 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted

As seen in Fig 4.15, the tidal current M2 shows larger amplitudes in the northern and central part of the basin, and reduces its amplitudes near the center (especially near the coasts). The two regions are separated approximately in correspondence to the 200 m depth contour which is the center of the basin extending across the basin from Croatian coast to Italian coast (see Figure

1.2). Tidal ellipses show a preferential orientation parallel to the Adriatic Sea major axis, with nearly rectilinear patterns, in good agreement with the results from previous studies in the area.

Similar behavior is observed for the S2 component (Fig 4.16), except that the amplitudes in the northern part are smaller than the one of the M2 component. The sense of rotation of the currents do not follow one pattern. In the central basin velocity increases but the sense of rotation stays the same along the Italian coast.

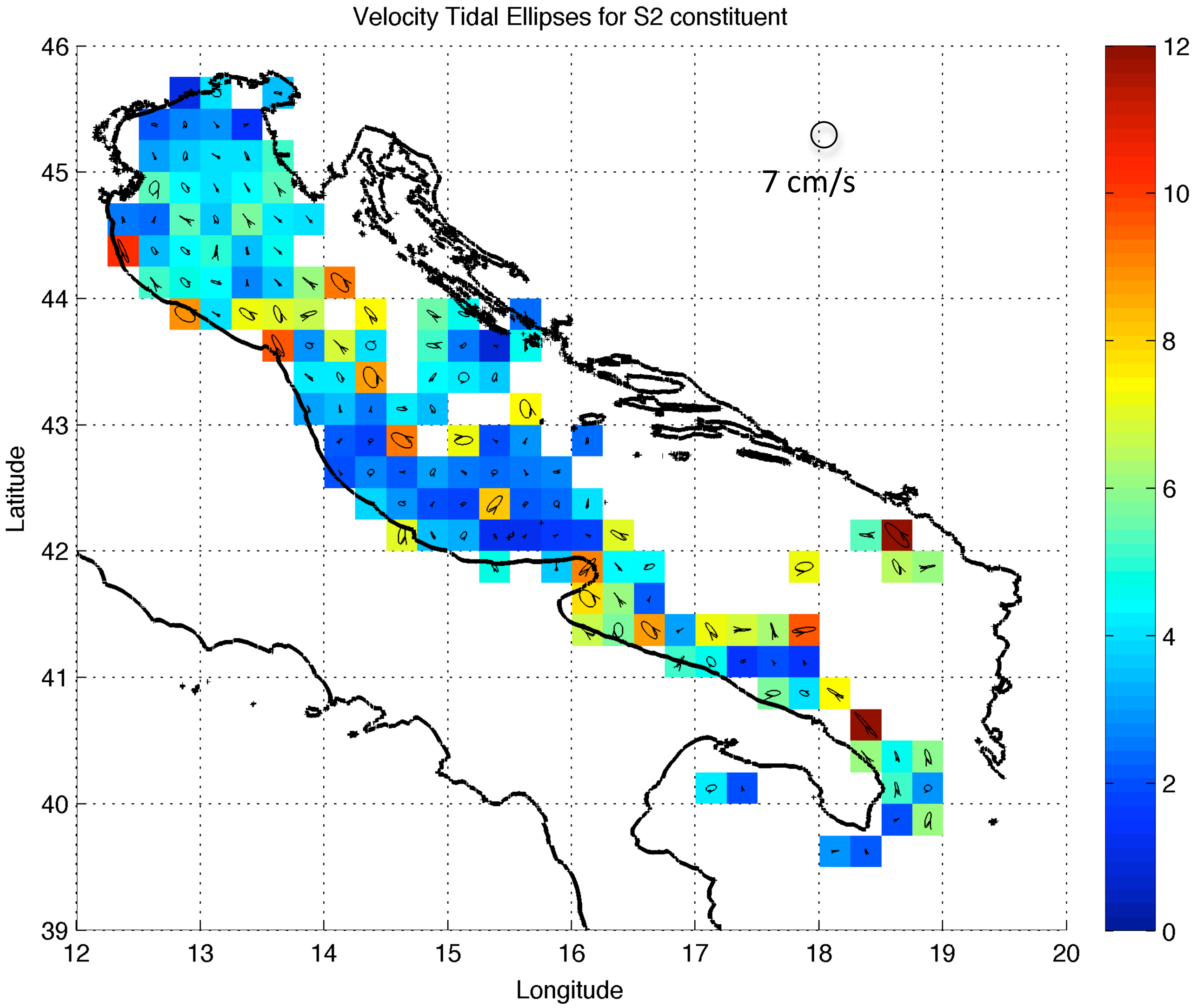


Figure 4.16: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for S2 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

In Figure 4.17, which refers to the K2 tidal current estimated from the drifter data, smaller velocity values are observed all over the Adriatic basin compared to the first two semidiurnal tides. As reported in Table 1.1, K2 is one of the weak constituents in this area, as well as P1 (Fig 4.18), O1 (Fig 4.20) and N2 (Fig 4.21) tides, which will be mentioned in the following figures.

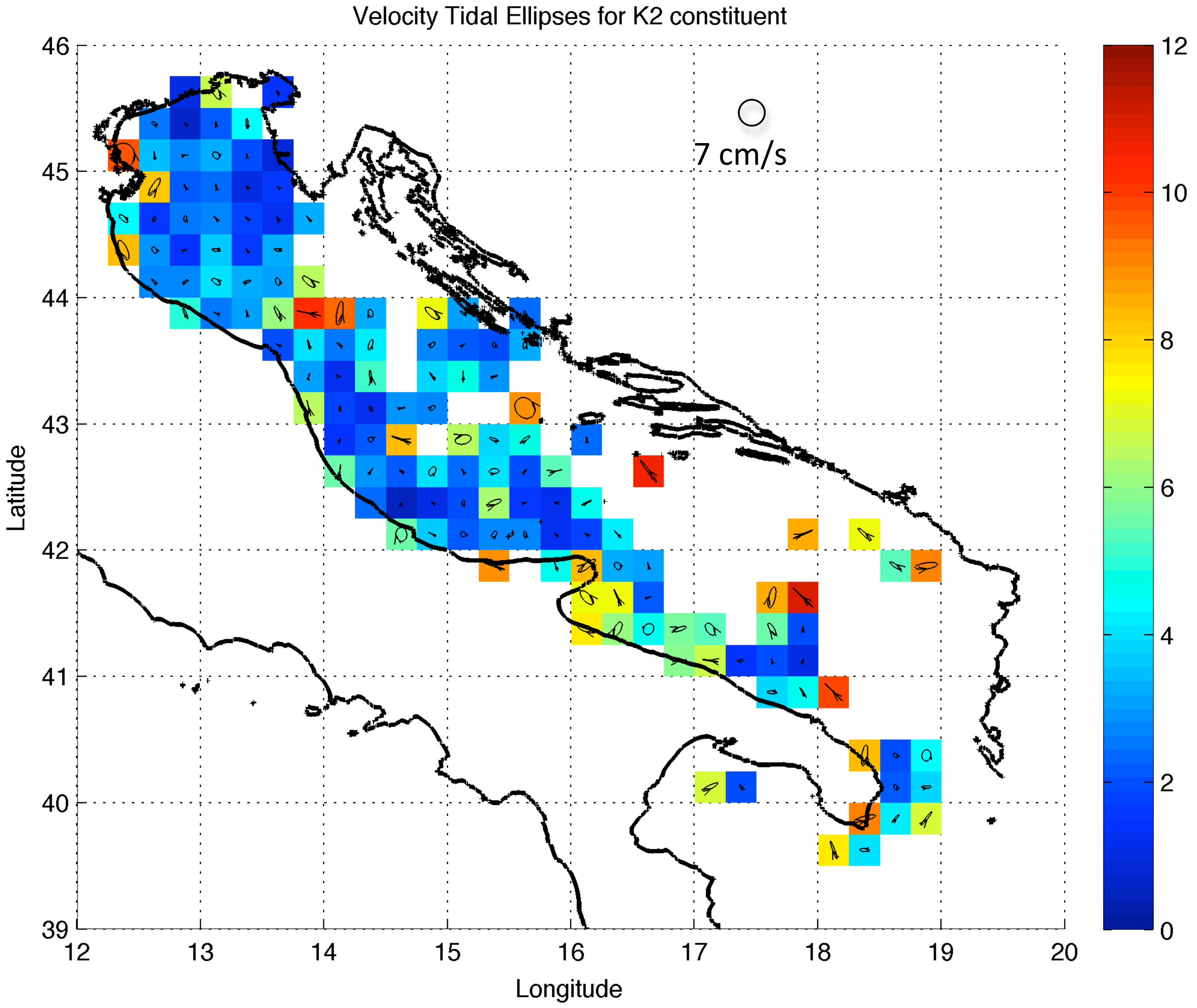


Figure 4.17: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for K2 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

In Figures 4.18 and 4.20, which represent the tidal ellipses for the N2 and O1 tides, respectively, the amplitudes and the intensity of the currents are shown. Especially in the northern and central part of the basin these values are very similar. The rotation of the circulation for N2 current is clockwise, while it is hard to talk about one particular rotation for O1 currents.

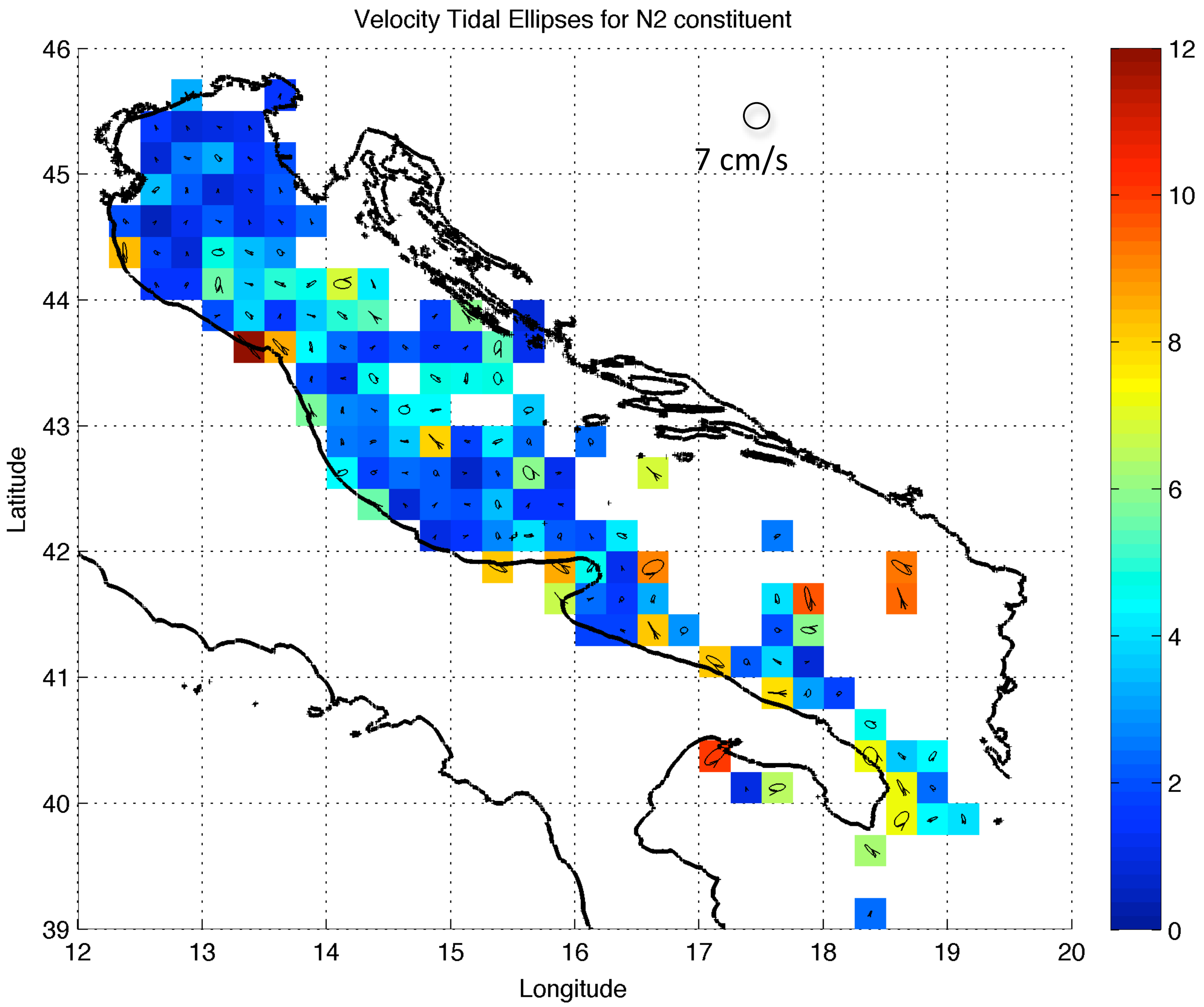


Figure 4.18: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for N2 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

Figures 4.19 and 4.21 represent the tidal current ellipses for the K1 and P1 tides, respectively. They are located near the Italian coast and have very similar behavior both in intensity and sense of rotation.

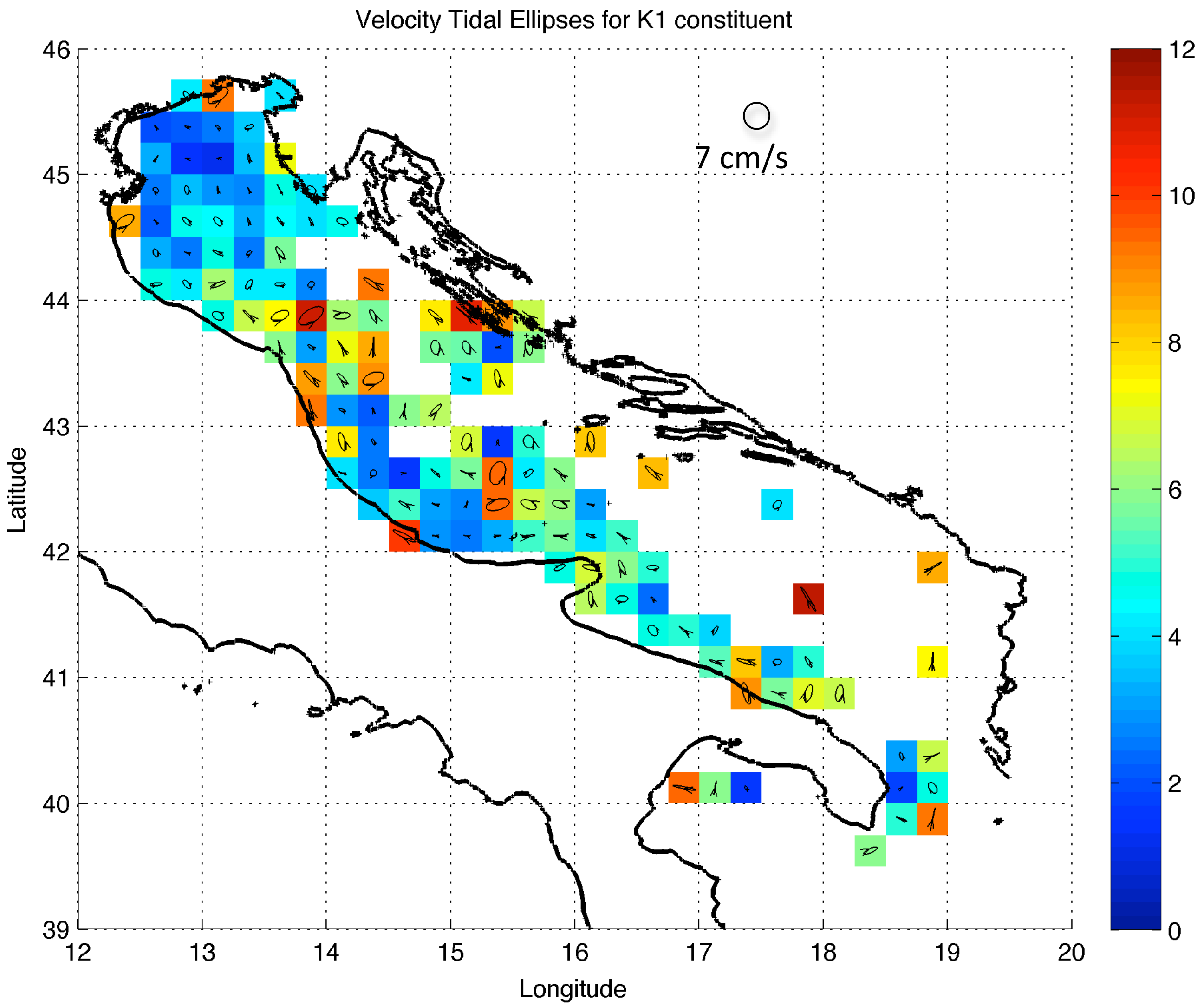


Figure 4.19: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for K1 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

Figure 4.19 represents the K1 tidal ellipses, which is particularly effective along the coast of Ancona (between north and central basin). While the circulation is parallel to the coast of Italy in the south of Ancona, it forms wider ellipses with a counter-clockwise rotation just above Ancona basin towards north where the Po River outflows into the Adriatic.

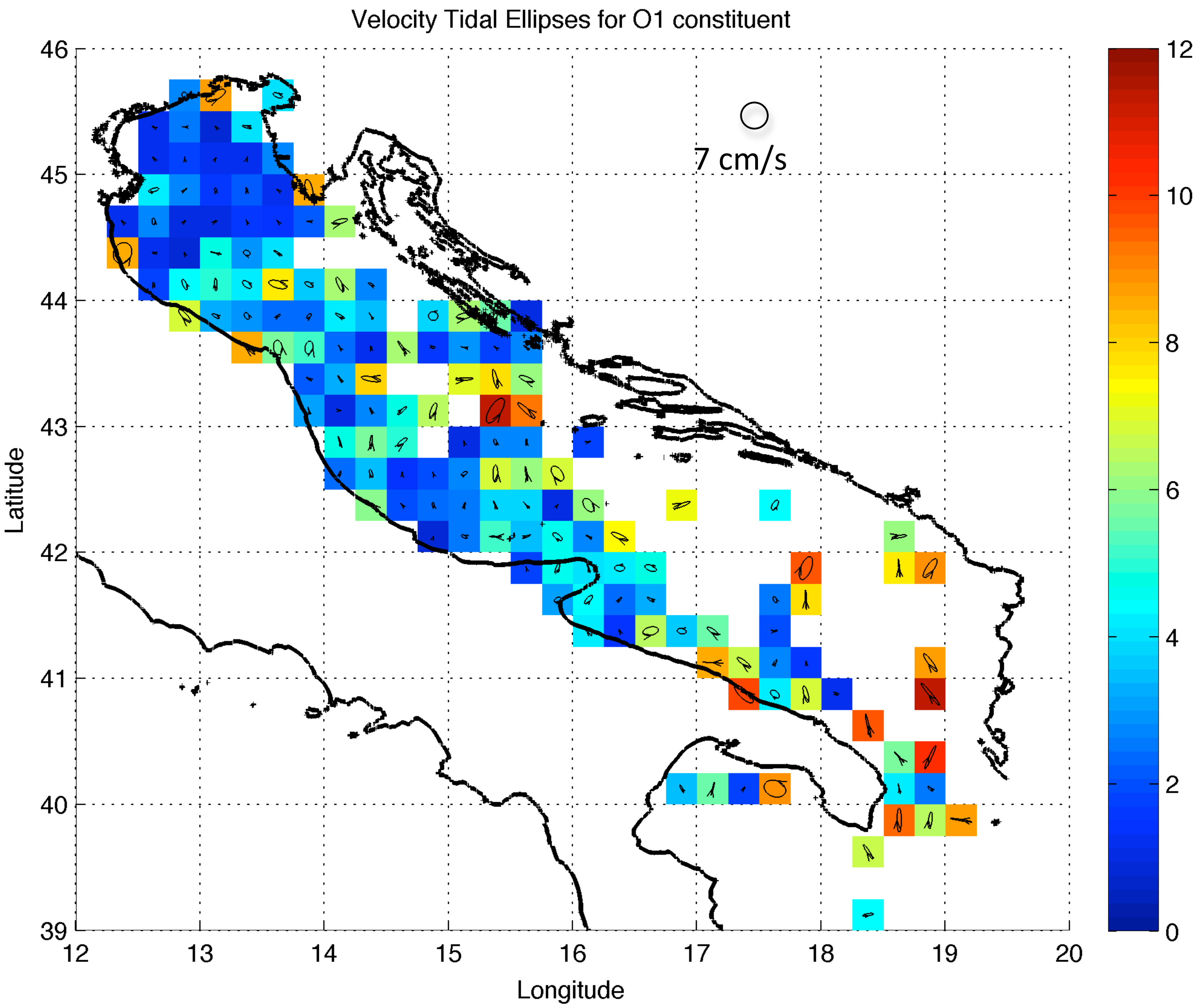


Figure 4.20: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for O1 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

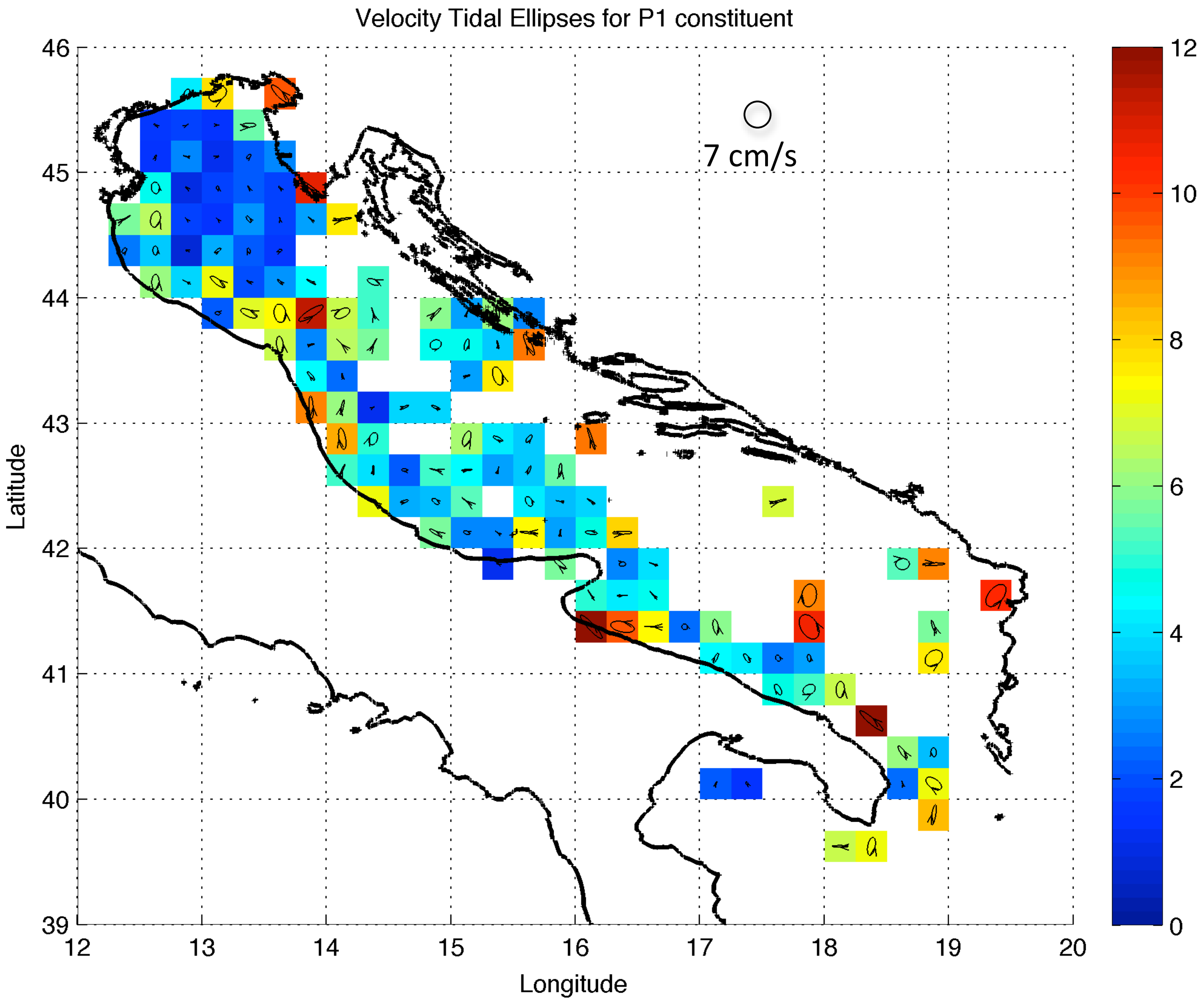


Figure 4.21: Tidal current ellipses. Colormap is the amplitude of major axis in each grid box obtained from CODE-GPS drifter data for P1 constituent for Adriatic Sea (method 2). Bins with less than 100 drifter observations were omitted.

5. Conclusion

The data of 55 CODE satellite-tracked surface drifters were used to study the tidal currents in the Adriatic Sea between 21 September 2002 and 29 July 2004. Harmonic analysis method was used to analyze velocity data sampled from these drifters after they had been eliminated from spikes and interpolated at 0.5 hours time intervals. In addition, velocity values exceeding 100 cm/s in absolute value were excluded from the dataset since they were considered unreal.

Results obtained both from the individual drifters and in geographical areas show that the circulation on the Adriatic Sea is not dominated by the tidal currents. However we can talk about some tidal constituents in the area that are dominant compared to others. As an example M2, semi-diurnal tidal constituent shows larger amplitudes in the northern and central part of the basin whereas it has smaller amplitudes in the center, especially near the coasts. Also, the major axis of the tidal ellipses are parallel to the coasts which shows similarity with some previous studies in the area (Cavallini, 1985 and Mosetti, 1990). Another dominant constituent is the S2 semi-diurnal tide, which has larger amplitudes especially in the central-northern part, however with a different sense of rotation than M2. In the central basin of the Adriatic Sea the velocity values increase but the direction of rotation stays the same. S2 tide has smaller amplitudes in the northern Adriatic. K1 is the third dominant constituent in the basin with larger amplitudes in the central part of the basin. In the north, the ellipses are not very large, except along the coast in north of Ancona where the Po River discharges. Tidal currents K2, N2, P1 and O1 have much smaller contributions on the circulation in the entire Adriatic basin.

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