Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Wind-driven Currents in Mediterranean Drifter Data

by

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

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1 Introduction

This work is part of Work Package 3 (Subtask 3130: Calculation of a mean dynamic topography of the Mediterranean sea) of the MFSTEP (Mediterranean Forecasting System Toward Environmental Prediction) project sponsored by the European V Framework Program Energy, Environment and Sustainable Development.

The main objective is to extract the wind-driven currents from the data of surface drifters in the Mediterranean Sea. Wind-driven ageostrophic currents are estimated by fitting various forms of the Ekman model to the drifter velocities. Following Ralf and Niiler (1999) and Rio and Hernandez (2003), the wind-driven component (Ekman balance) can be expressed generally as follows:

$$\boldsymbol{U}_{wind\text{-}driven} = \boldsymbol{t} / (r\, f\, H^*) = \boldsymbol{b}\boldsymbol{t}^{\,a} f^{b} D_T^{\,c} \qquad (1)$$

where $\boldsymbol{t}$ is the wind stress, r is the water density, H^* is the depth scale for turbulent stress, $\boldsymbol{b}$ is a constant and DT is the depth of the top of the thermocline. The exponents a, b, c are constants. Contrary to Ralf and Niiler (1999) and Rio and Hernandez (2003) in which a mean geostrophic circulation based on hydrographic climatologies or on satellite altimetry data is removed, respectively, model (1) is directly applied to the low-pass filtered drifter velocities.

The drifter and wind datasets are briefly described in Section 2. The surface drifter data between 1995 and 1999 (5 years) are used in conjunction with the wind speed and stress of ECMWF and NOGAPS products. As explained in Section 3, the wind products are interpolated at the drifter locations. Linear regression models are applied for the entire Mediterranean Sea and for the Ionian and Adriatic separately, in order to study the wind effects in open sea and coastal conditions, respectively. The regression models are also used after removing the drifter-inferred mean surface circulation and after a binning of the drifter and wind data in boxes of 1° x 1° x 2 days so as to reduce the variance presumably not related to the wind forcing. Regressions are done in scalar form for the down and cross-wind directions, but also in vectorial form using a complex representation.

Results are presented in Section 4, including numerous scatter diagram plots and statistical parameters for the various regression models considered. In Section 5, these results are summarized and confronted to the results of Ralf and Niiler (1999) and Rio and Hernandez (2003). The best model for extracting the wind-driven currents in our Mediterranean drifter dataset is suggested.

2 Data

2.1 Drifter data

The dataset used in this study comes mostly from modified CODE surface drifters. CODE refers to the type of drifter used in the Coastal Dynamics Experiment in the early 1980's (Davis, 1985). An antenna extends from the top of the main tubular body of the drifter to transmit data to, and to be located by, the Argos System on board the NOAA polar orbiting satellite. Radially protuberating out of the tube, four identical vanes, which extend the entire length of the tube, reduce the drifter's slip. Four spherical floats attached to the upper portion of each vane provide buoyancy (Poulain, 1999, 2001; see Figure 1). The modified CODE drifter was shown to follow the surface currents with an accuracy of ~2 cm/s. The wind-induced slip amounts to 0.1-0.2% of the wind speed (Poulain and Ursella, 2004).

The Mediterranean drifter data set spans the period between 1986 to 1999 (see temporal distribution in Figure 2). The data utilized in this study include only the drifter measurements relative to the Mediterranean Sea from 1995 to 1999, where the maximum concentration of drifters is present. Out of a total of 522 drifters deployed in the Mediterranean, the data of only 245 drifters, with a drogue centered in the first meter of water (mostly CODE drifters), were used in this study. The maximum coverage of drifter tracks is in the Adriatic and the Ionian Seas (Figure 3).

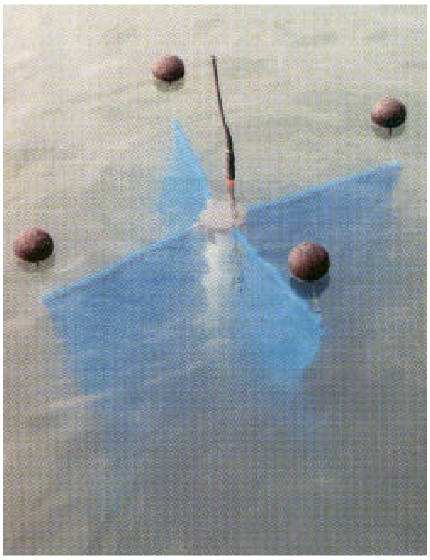

Figure1: Modified CODE drifter floating in the water.

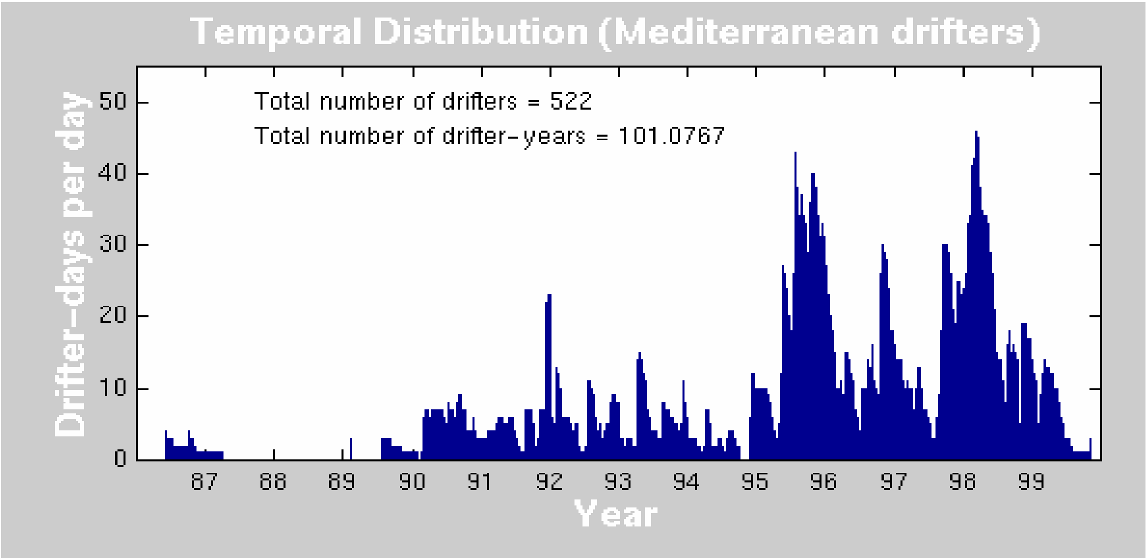

Figure 2: Temporal distribution of the Mediterranean Sea drifter population from 1986 to 1999.

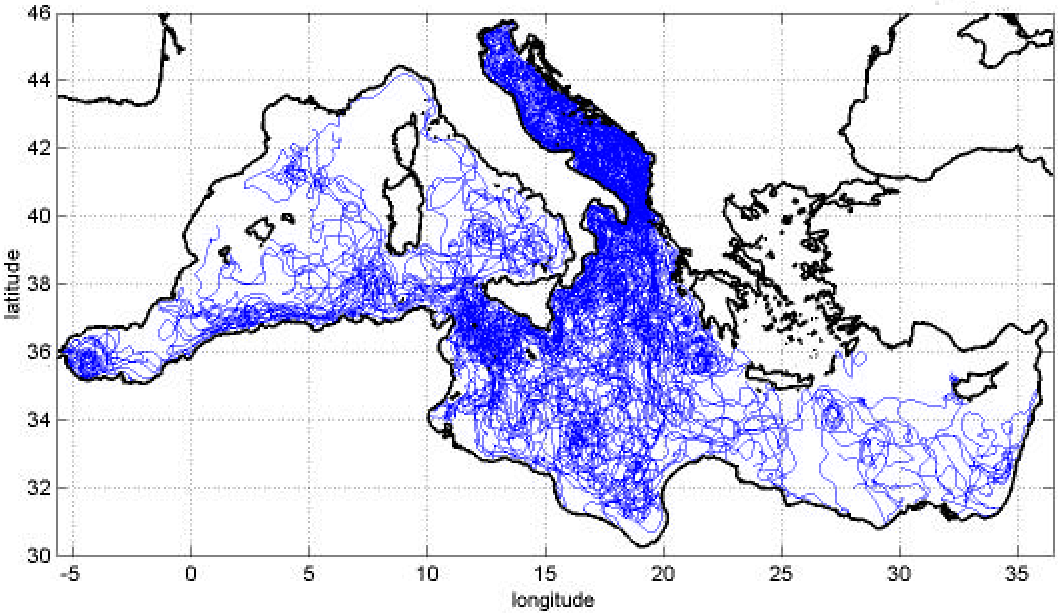

Figure 3: Spatial distribution of the drifter tracks in the Mediterranean Sea.

The raw ARGOS drifter data were first edited to eliminate spikes then through objective analysis (kriging) the data were interpolated on a regular grid (0.2 day intervals). A low-pass filter (1.5 days) was used to detide and to eliminate inertial oscillations from the data set (Poulain et al., 2004). The geographic positions were sub-sampled at 00, 06, 12, 18 UTC and the drifter velocities were computed by finite differences. Only data at 00 UTC were used in this work

2.2 Wind data

Three wind datasets were used:

- The NOGAPS (Navy Operational Global Atmospheric Prediction System) products, with 0.75° resolution. The surface (1000 hPa) wind velocity at 00 UTC were utilized.

- The ECMWF (European Centre for Medium-range Weather Forecasts) 40-year re-analysis products, called ECMWF-ra, with 0.5° resolution. The wind velocity chosen is the closest to the sea surface (10 m) at 00 UTC. The mean ECMWF-ra wind velocity for the years 1995 to 1999 and the corresponding variance are shown in Figures 4 and 5 to illustrate the main characteristics of the wind over the central Mediterranean. The major wind regimes can be seen: The NW mistral in the Western Basin and Strait of Sicily, the NE bora in the Adriatic and the etesian in the Eagean Sea. In the central Ionian the ellipses are almost circles showing isotropic variance. In contrast, the variance of the wind is higher in the north-south direction in the Adriatic Sea while in the Strait of Sicily the major direction of variability is northwest-southeast.

- The ECMWF analysis products (called ECMWF-a) with 0.5° resolution. The wind velocity chosen is the closest to the sea surface (10 m) at 00 UTC. The data were only obtained between January and September 1999.

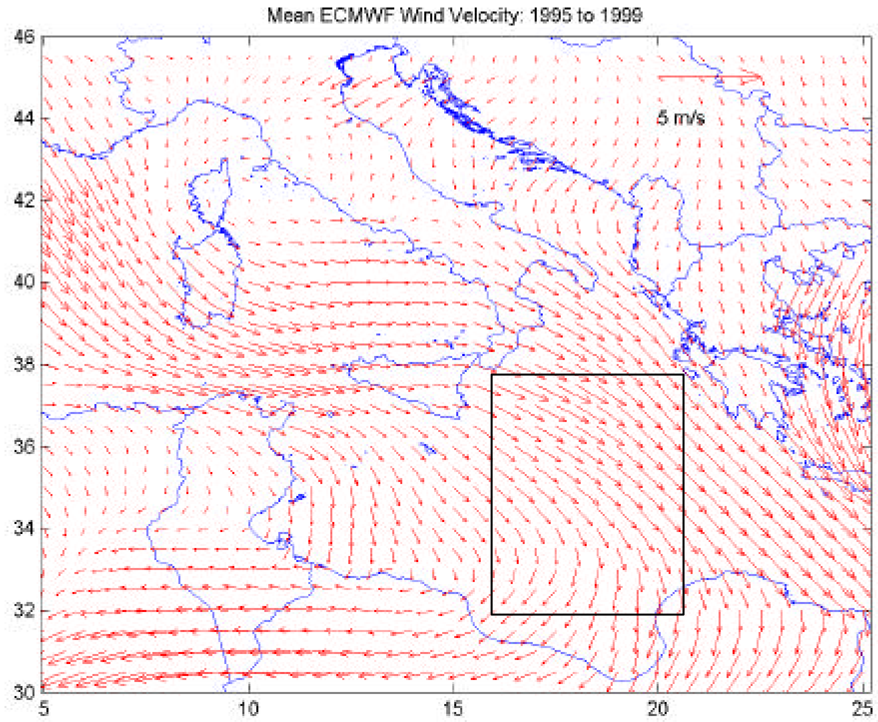

Figure 4: Mean ECMWF-ra surface wind velocity for the period 1995-1999 computed on a 0.5° resolution grid. The green box shows the open Ionian Sea area considered in the regressions.

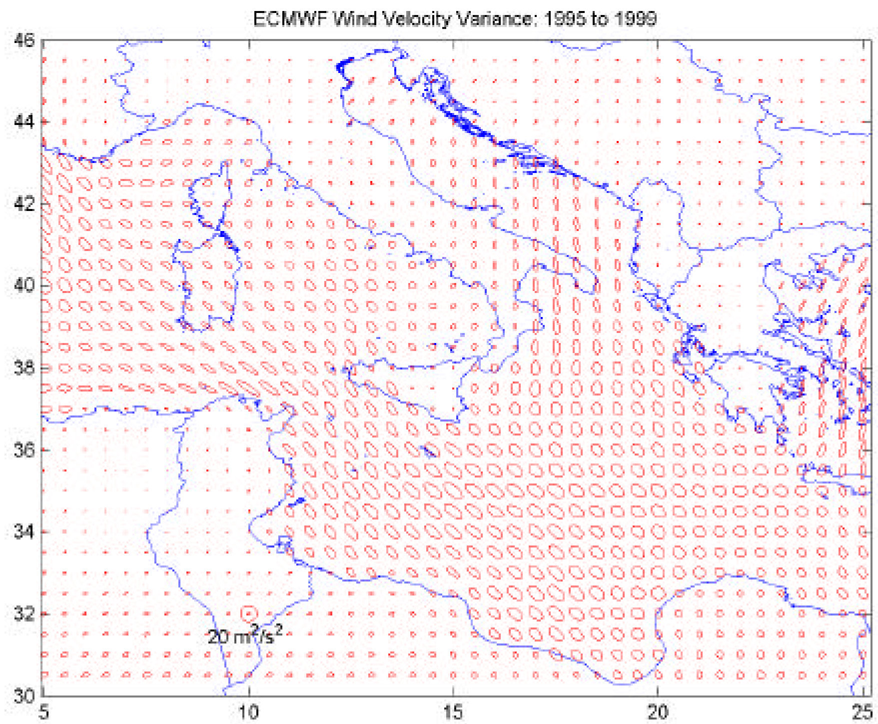

Figure 5: Same as in Figure 4 but with wind velocity variance ellipses.

3 Methods

3.1 Linear interpolation, projection and binning

The wind field was linearly interpolated in space and time to obtain a wind estimate collocated with our drifter observations. The wind field was always chosen at 0:00 UTC. The down and cross wind (to the right) drifter velocity components were then computed by projecting the drifter velocities parallel and perpendicular to the wind.

To remove the velocity variance due to the mean circulation that is generally not directly related to the wind forcing, we also subtracted the mean circulation inferred from the drifters form the drifters velocities. Figure 6 shows the mean circulation after binning the drifter velocities in 0.5°x0.5° bins for the Ionian and Adriatic Seas only. The down and cross wind components were computed as above.

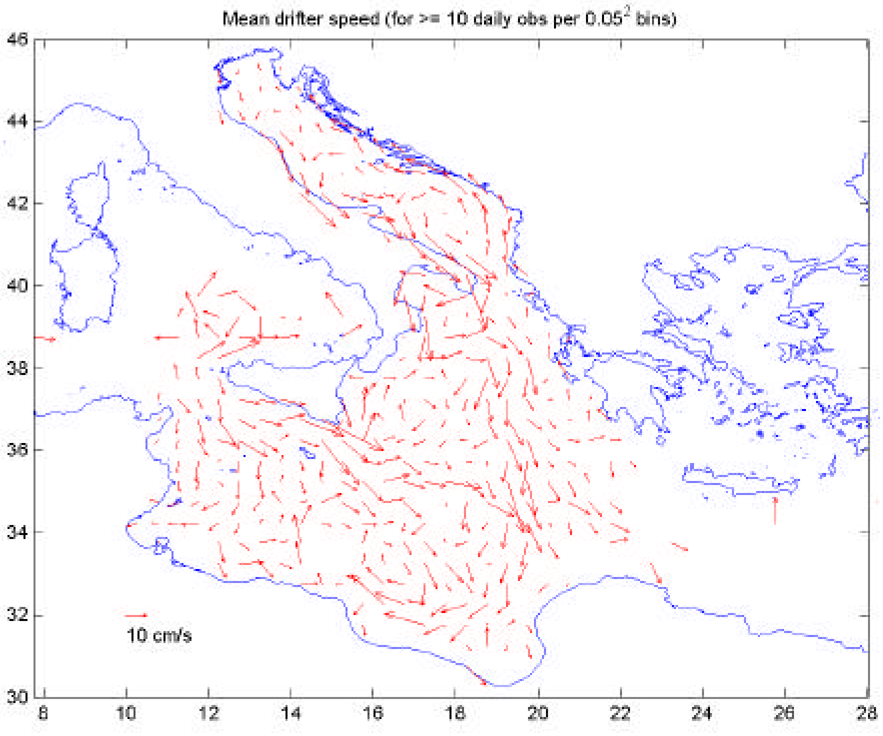

Figure 6: Mean circulation computed from the drifter velocities in 0.5°x0.5° bins. Only the bins with more than 10 observations are used.

Finally, the drifter and wind velocities data were averaged in no-overlapping bins of 1° x 1° x 2 days to reduce the variance at scales smaller than 2 days and smaller than 100 km. The averaged drifter/wind velocities were assigned at the center of the 1° x 1° bins and at 00 UTC with 2 days intervals. The down and cross wind components were computed as above.

3.2 Regression models

Following Ralph and Niiler (1999) and Rio and Fernandez (2003), the surface drifter velocity can be expressed as a function of wind speed or wind stress in the following general form:

$$\boldsymbol{U}_{drifter} = a + b\,\boldsymbol{t}^{\,c} + error\,. \tag{2}$$

Practically, we have considered the following linear models:

$$\boldsymbol{U}_{drifter} = a + b\,\boldsymbol{U}_{wind} + error\,, \tag{3}$$

$$\boldsymbol{U}_{drifter} = a + b|\boldsymbol{U}_{wind}|\,\boldsymbol{U}_{wind} + error\,, \tag{4}$$

$$\boldsymbol{U}_{drifter} = a + b\,\boldsymbol{t} + error\,, \tag{5}$$

that is, regressions of the drifter velocities on the wind velocities, on the wind pseudo-stress and on the wind stress, respectively.

The above regression models were applied in two different ways:

(1) Vectorial model using complex representation. For example (3) was used in the following form:

$$Ud + i\,Vd = (a+ic) + (b+id)\,(Uw + i\,Vw) + (e+i\,f) \tag{6}$$

or

$$Ud + i\,Vd = aa\,\exp(iPA) + bb\,\exp(iPB)\,(Uw + i\,Vw) + (e+i\,f)\,, \tag{7}$$

where $\boldsymbol{U}_{drifter} = (Ud, Vd)$, $\boldsymbol{U}_{wind} = (Uw, Vw)$, error = (e, f) and $i^2 = -1$.

(2) Regression models between the down and cross-wind components of the drifter velocity and the wind velocity or stress. For example (3) was applied as:

$$\boldsymbol{U}_{drifter\text{-}down} = a + b|\,\boldsymbol{U}_{wind}\,| + error\text{-}down\,, \tag{8}$$

$$\boldsymbol{U}_{drifter\text{-}cross} = a + b|\,\boldsymbol{U}_{wind}\,| + error\text{-}cross\,. \tag{9}$$

In all the above regression models, the skill or coefficient of determination, is equal to the ratio of the variance explained by the model over the drifter velocity variance.

$$\text{Skill} = r^2 = 1 + \text{error}^2 / \text{variance}\,, \tag{10}$$

where variance = VAR($\boldsymbol{U}_{drifter\text{-}down}$) or VAR($\boldsymbol{U}_{drifter\text{-}cross}$) or VAR($U_d$)+VAR($V_d$) and error = *error-down* or *error-cross* or VAR(e)+VAR(f), respectively.

4 Results

4.1 Regressions using wind speed

4.1.1 ECMWF-ra and NOGAPS winds

The first regression analyses were done between the drifter and the ECMWF-ra wind velocities for the entire Mediterranean Sea, using all the drifter data at 0 m. The regression was also computed for the Adriatic and the Ionian Sea separately, in an attempt to see if there is any difference of the wind effect in a semi-enclosed basin (such as the Adriatic) and in a larger and less constrained basin (e. g., the Ionian). The same regression was also computed using the NOGAPS wind fields.

The linear regression for the Mediterranean Sea (Figure 8) yields a slope of 0.94±0.04 and an intercept of 0.45±12.84. The latter is not significant since the error is quite high. The coefficient of determination (r^2, the percentage of the total variation of the downwind drifter velocity that is explained or accounted for by the fitted regression) is ~3%. The regression between the crosswind drifter velocity and the wind speed shows an even lower coefficient of determination (~1%) with a slope of 0.53±0.03. Performing the regressions in the complex domain, we obtained a skill of ~8%, a slope near 1 and a veering of 23º to the right of the wind (see Table 1).

For the Ionian Sea (Figure 7) the slopes for the down and crosswind components are 0.76 and 0.54, respectively. Note that the number of points taken into account is 4211, less than a fourth than for the previous regression analysis in the Mediterranean Sea. Only 2% of the variance is explained in the downwind direction and even less (1%) for the crosswind component. Performing the regressions in the complex domain, we obtained a skill of 8%, a slope near 1 and a veering of 32º to the right of the wind (see Table 1).

The Adriatic Sea dataset comprises 8726 points, that is, twice the points used in the Ionian (Figure 9). The skill is relatively high for the downwind component (3%) whereas it is negligible for the other component (~0.2%). The slope for the downwind component is near 1. Performing the regressions in the complex domain, we obtained a skill of 6%, a slope near 1 and a veering of 45º to the right of the wind (see Table 1).

The regressions for the Mediterranean, Ionian and Adriatic Seas were also performed using the NOGAPS wind. The results obtained (see Figures 10, 11 and 12) are quite similar to those using the ECMWF-ra winds (the drifters go downwind and mostly to the right of the wind) but the skills are reduced and do not exceed 3.5% (for the complex regression in the Ionian). Since the NOGAPS give worst results (lower skills of the regression models), the subsequent analyses were not performed with these wind products.

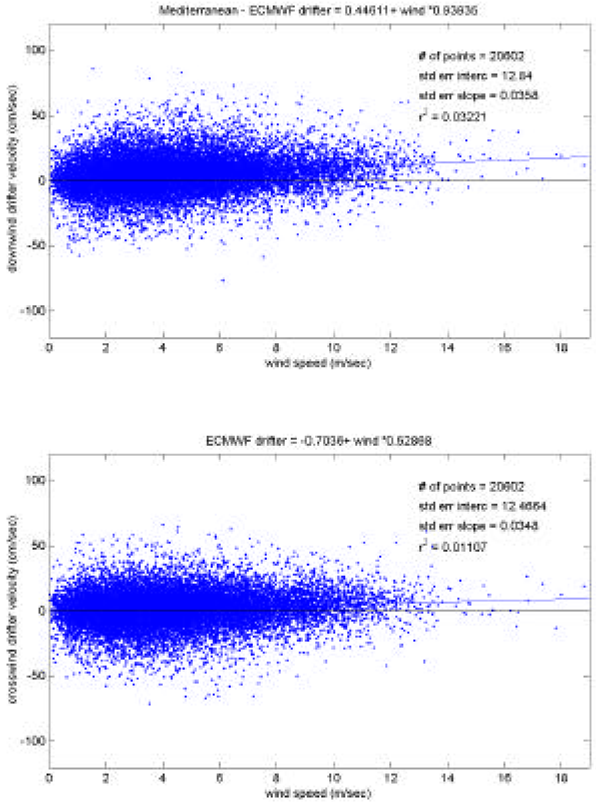

Figure 7: Scatter plots of the downwind (top panel) and crosswind (bottom panel) drifter velocity components versus ECMWF-ra wind speed for the entire Mediterranean Sea. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination.

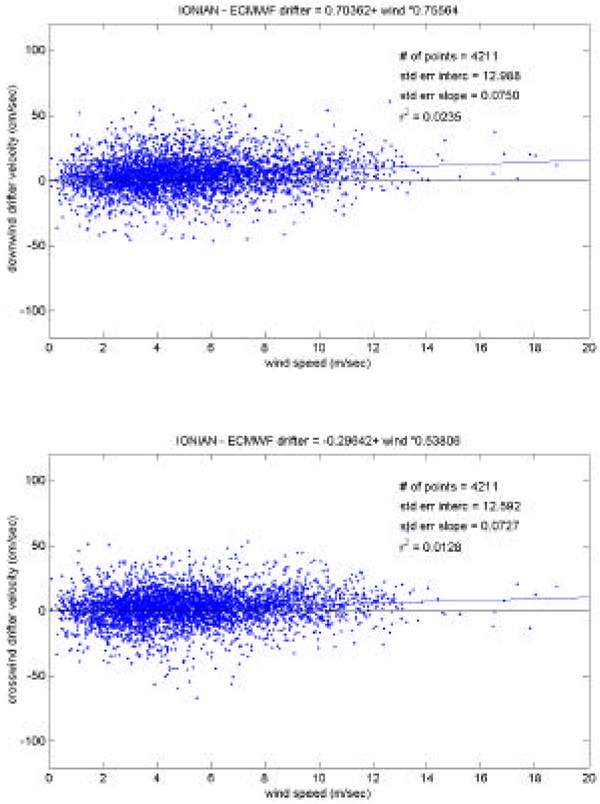

Figure 8: Same as in Figure 7 but for the Ionian Sea.

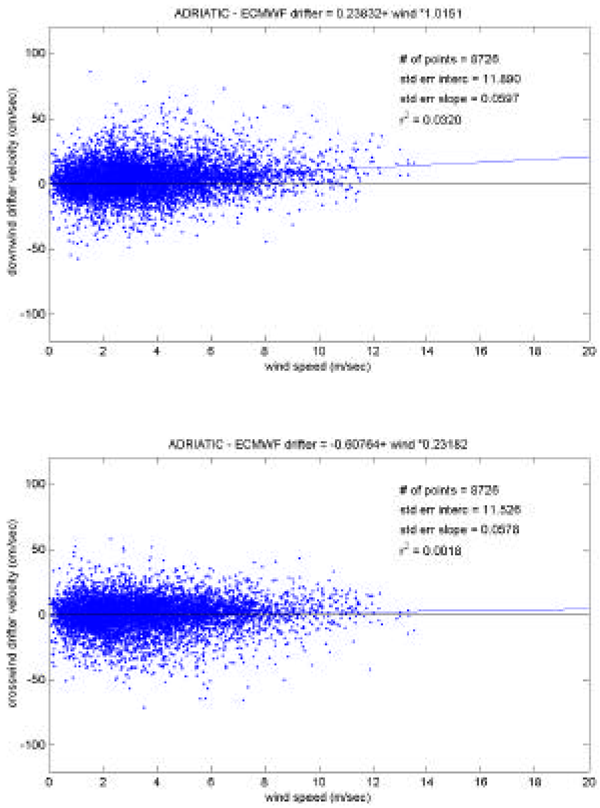

Figure 9: Same as in Figure 7 but for the Adriatic Sea

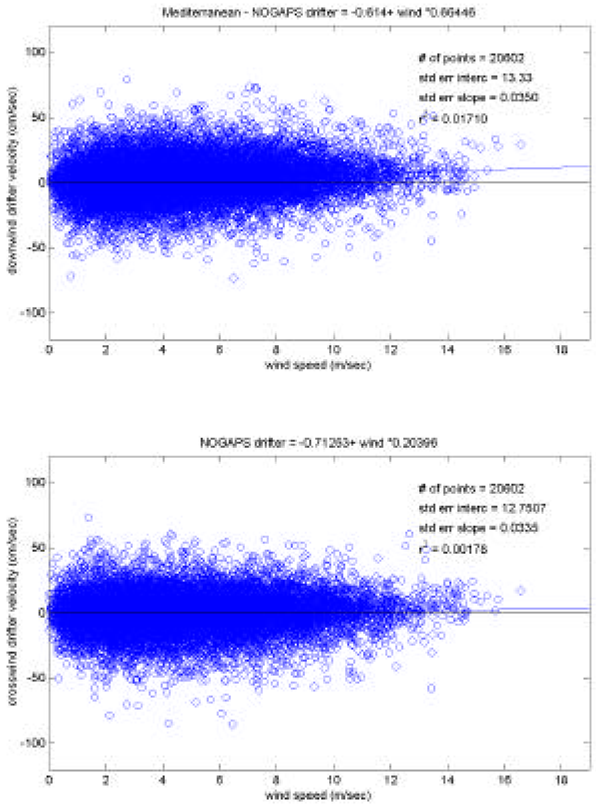

Figure 10: Same as in Figure 7 but using the NOGAPS winds for the Mediterranean Sea.

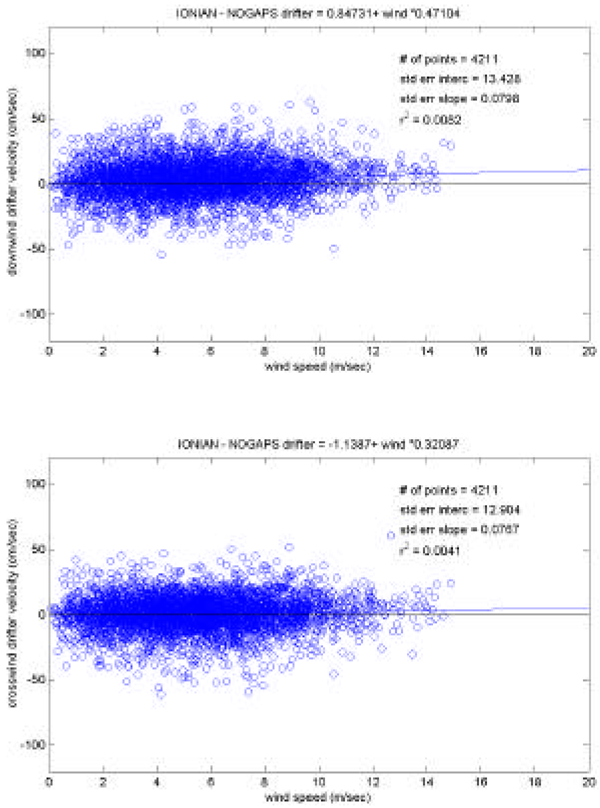

Figure 11: Same as in Figure 7 but using the NOGAPS winds for the Ionian Sea.

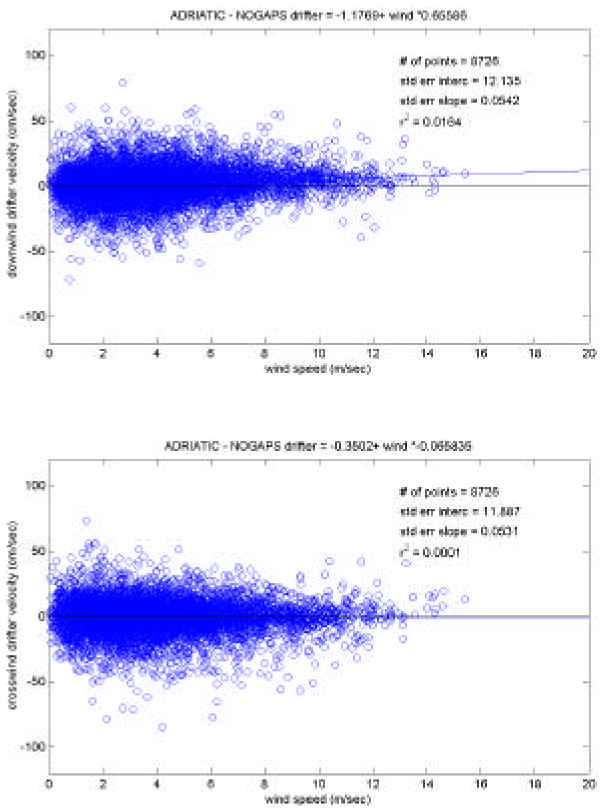

Figure 12: Same as in Figure 7 but using the NOGAPS winds for the Adriatic Sea.

The statistical parameters obtained with the regressions discussed above are summarized in Table 1.

4.1.2 Low-pass filtered ECMWF-ra winds

The ECMWF-ra winds were low-pass filtered with a Hamming filter (with cut-off period of 1.5 days) so as to relate drifter and wind data filtered in the same way. The results (Figures 13-15 and Table 1) are essentially identical to those obtained with the non-filtered winds, except that the skills are slightly increased (reaching 8.7% instead of 7.9% for the complex regression in the Mediterranean.

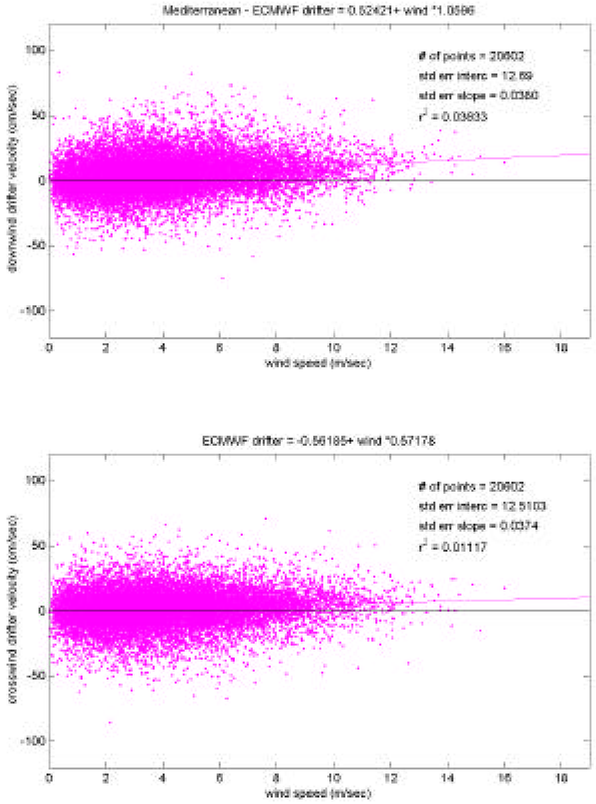

Figure 13: Scatter plots of the downwind (top panel) and crosswind (bottom panel) drifter velocity components versus low-pass filtered ECMWF-ra wind speed for the entire Mediterranean Sea. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination.

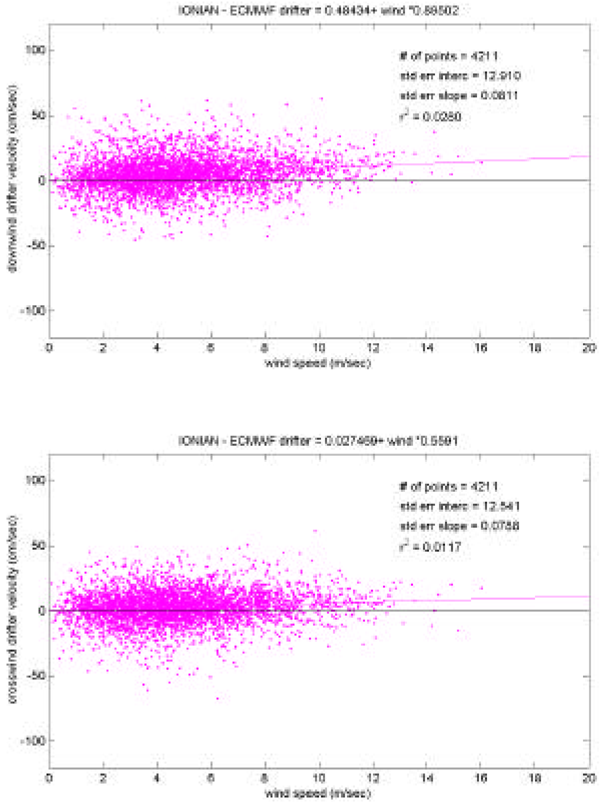

Figure 14: Same as in Figure 13 but using the filtered ECMWF-ra winds for the Ionian Sea.

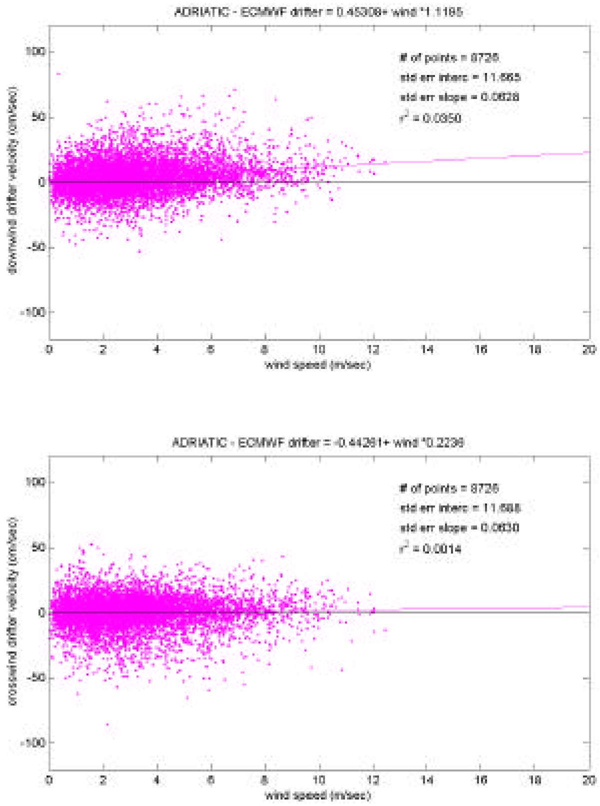

Figure 15: Same as in Figure 13 but using the filtered ECMWF-ra winds for the Adriatic Sea.

4.1.3 ECMWF-ra winds, after removing the mean circulation

Regression computations were performed between the residual drifter velocities (the drifter data from which the mean circulation shown in Figure 6 was removed) and the ECMWF-ra wind velocities. The analyses were performed for the entire Mediterranean Sea (Figure 16), for the Ionian Sea (Figure 17) and for the Adriatic Sea (Figure 18). The results are also summarized in Table 1.

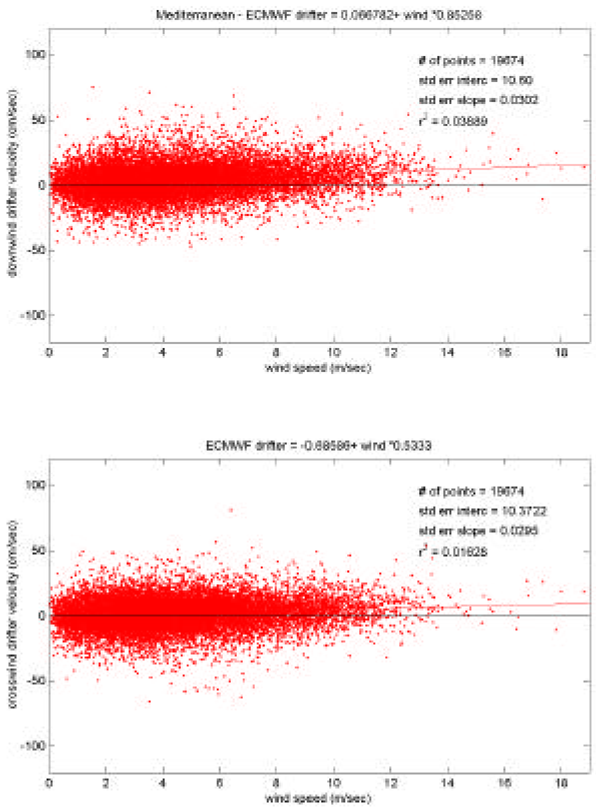

Figure 16: Scatter plots of the downwind (top panel) and crosswind (bottom panel) residual drifter velocity components versus ECMWF-ra wind speed for the entire Mediterranean Sea. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination. Residual drifter velocity is defined by subtracting the Eulerian mean circulation depicted in Figure 6 from the drifter velocity.

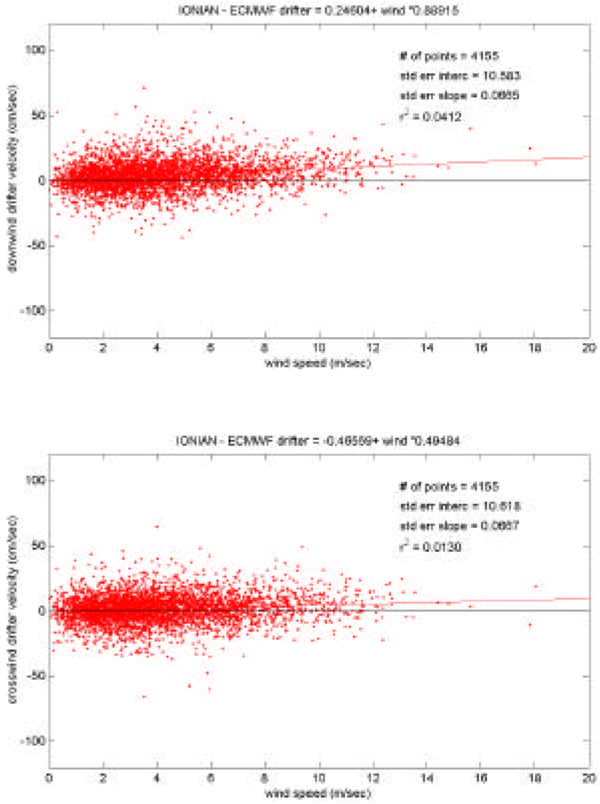

Figure 17: Same as in Figure 16 but using the ECMWF-ra winds for the Ionian Sea.

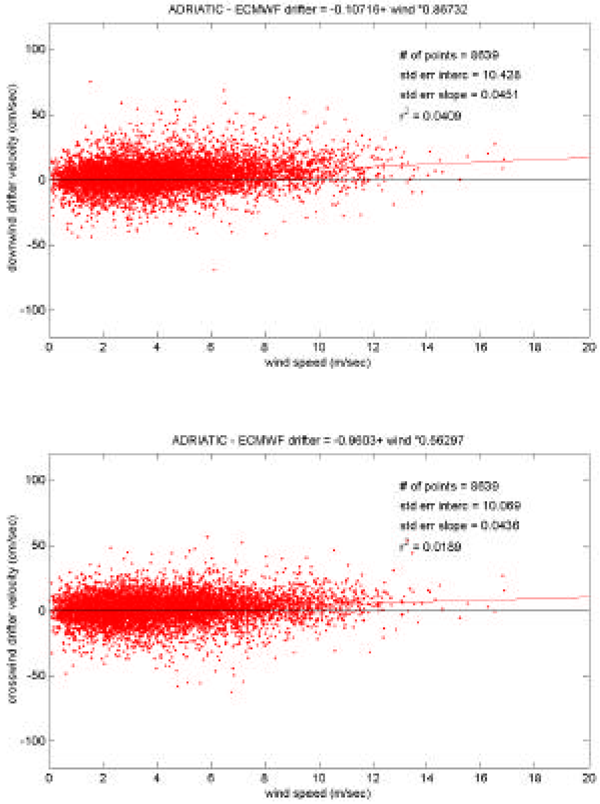

Figure 18: Same as in Figure 16 but using the ECMWF-ra winds for the Adriatic Sea.

4.1.3 ECMWF-ra winds, after binning in 1° x 1° x 2 days

The binning in domains of 1° x 1° x 2 days reduced considerably the number of points considered in the regressions (for instance in the Mediterranean the number of points decreased from 20602 to 11963). The regressions plots (Figures 19 to 21) and statistical results (Table 1) indicate a higher skill (up to 10.6% for the complex regression in the Mediterranean).

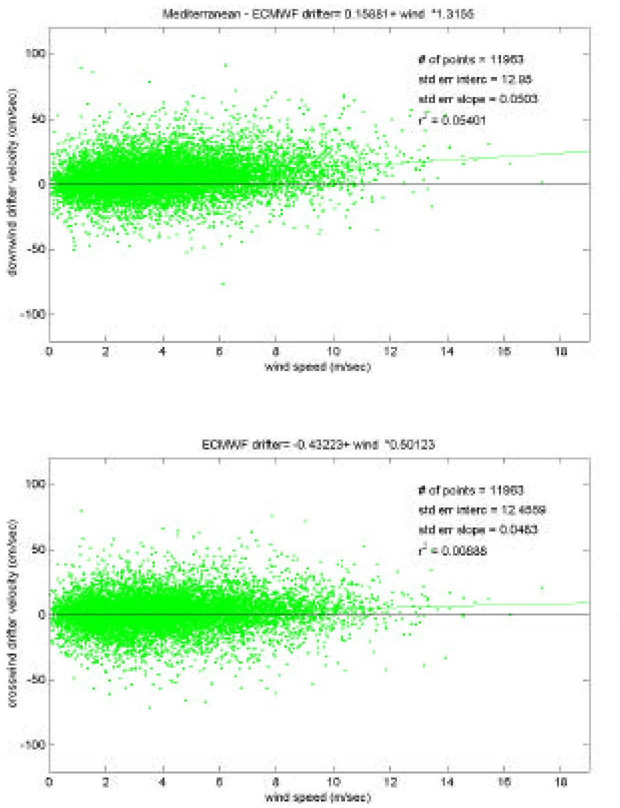

Figure 19: Scatter plots of the downwind (top panel) and crosswind (bottom panel) binned drifter velocity components versus binned ECMWF-ra wind speed for the entire Mediterranean Sea. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination. Both the drifter and wind datasets were averaged in no-overlapping bins of 1° x 1° x 2 days.

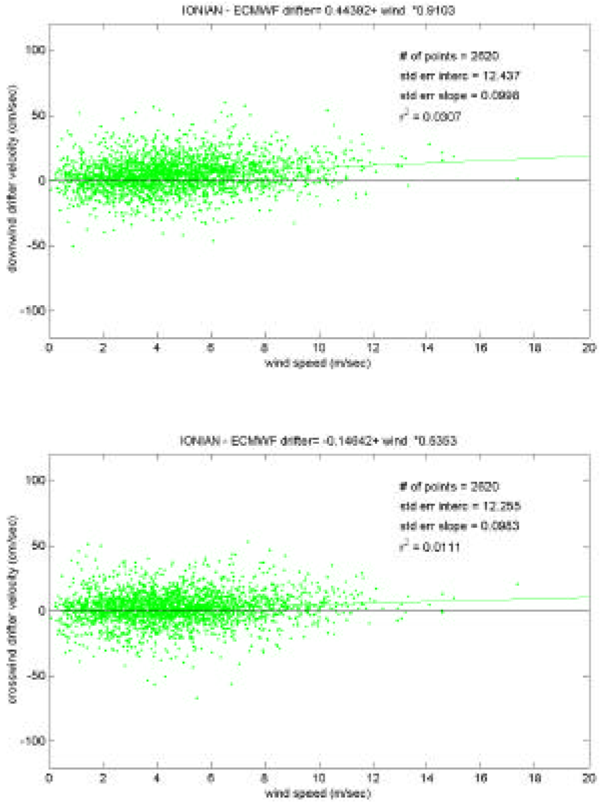

Figure 20: Same as in Figure 19 but using the ECMWF-ra winds for the Ionian Sea.

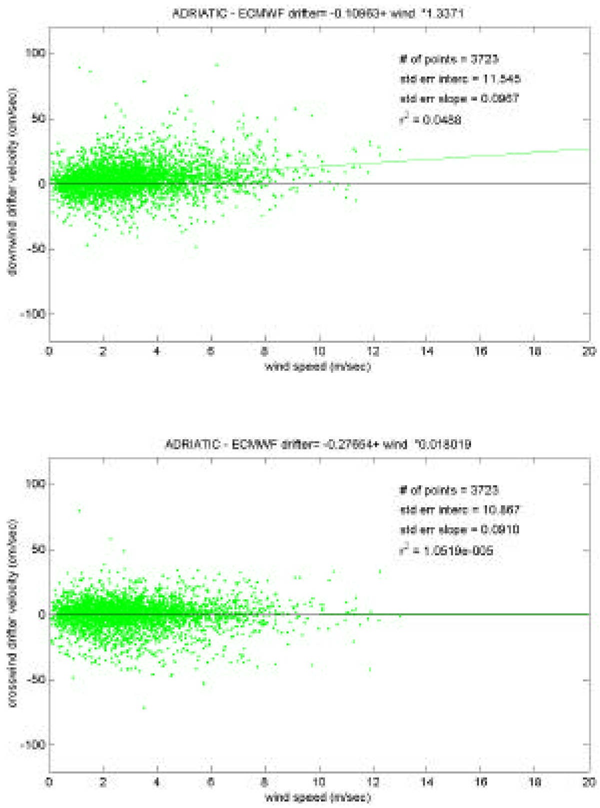

Figure 21: Same as in Figure 19 but using the ECMWF-ra winds for the Adriatic Sea.

4.2 Regressions using the ECMWF-ra wind stress

Regressions using the ECMWF-ra wind stress were computed for the Mediterranean (Figure 22), the Ionian (Figure 23) and the Adriatic (Figure 24) Seas.

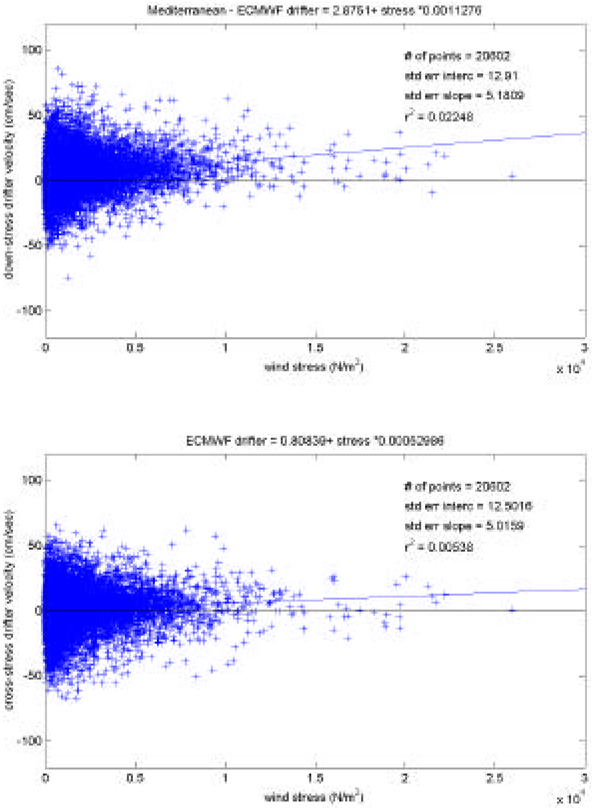

Figure 22: Scatter plots of the downwind (top panel) and crosswind (bottom panel) drifter velocity components versus ECMWF-ra wind stress for the entire Mediterranean Sea. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination.

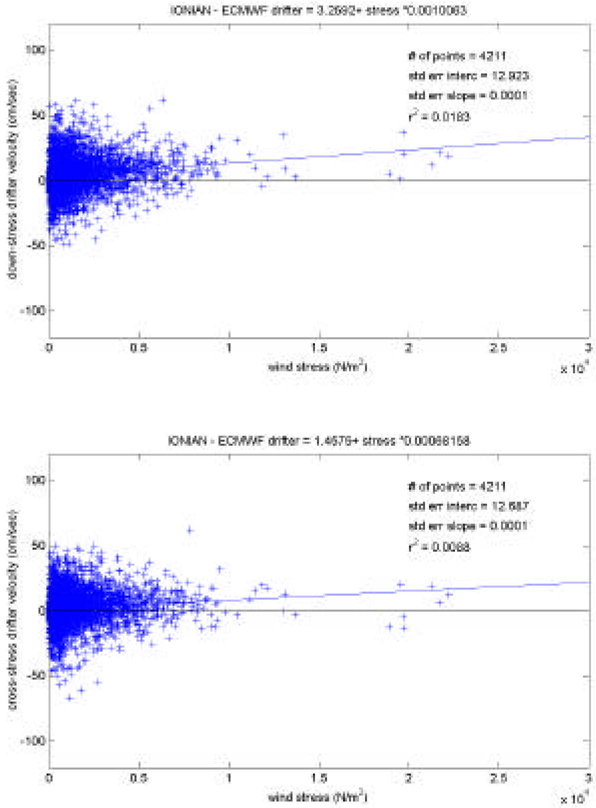

Figure 23: Same as in Figure 22 but using the ECMWF-ra wind stress for the Ionian Sea.

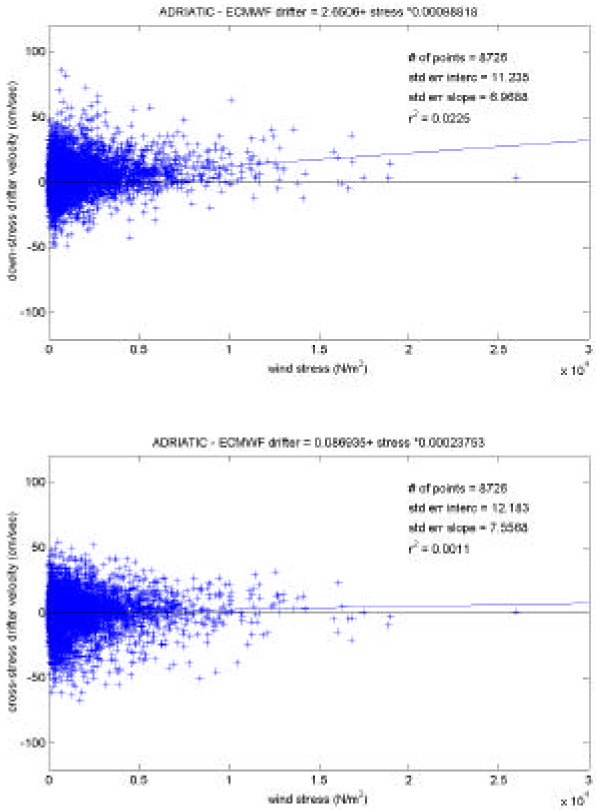

Figure 24: Same as in Figure 22 but using the ECMWF-ra wind stress for the Adriatic Sea.

4.3 Regressions using 1999 wind speed (ECMWF-ra and ECMWF-a)

It is useful to compare the regression results using the winds of the ECMWF analysis and 40-years re-analysis on the same drifter data, that is, for a reduced portion of the drifters spanning January to September 1999. The results are illustrated for the Mediterranean in Figures 25 and 26, whereas Table 1 includes the regression statistics for Mediterranean, Ionian and Adriatic Seas.

Although the skill values are larger when using the analysis winds (up to 10.7% for the complex regression in the Adriatic), the results are essentially the same for both wind products in the downwind and complex regressions. The statistics for the open Ionian are not robust due the low number of points there in 1999 (only 81 points).

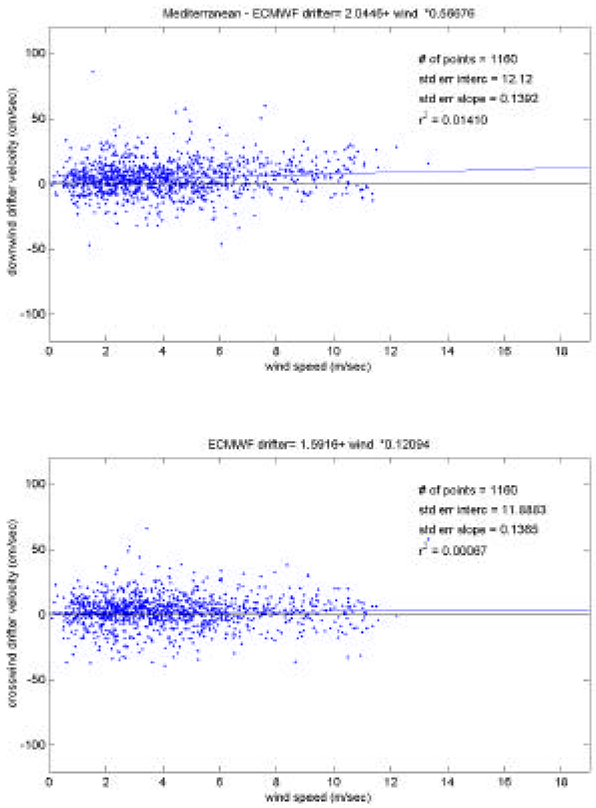

Figure 25: Scatter plots of the downwind (top panel) and crosswind (bottom panel) drifter velocity components versus ECMWF-ra wind speed for the entire Mediterranean Sea between January and September 1999. The regression line is plotted (see equation written in title of panel). Some regression statistics are posted: the number of points used, the standard errors on the intercept and on the slope, and the coefficient of determination.

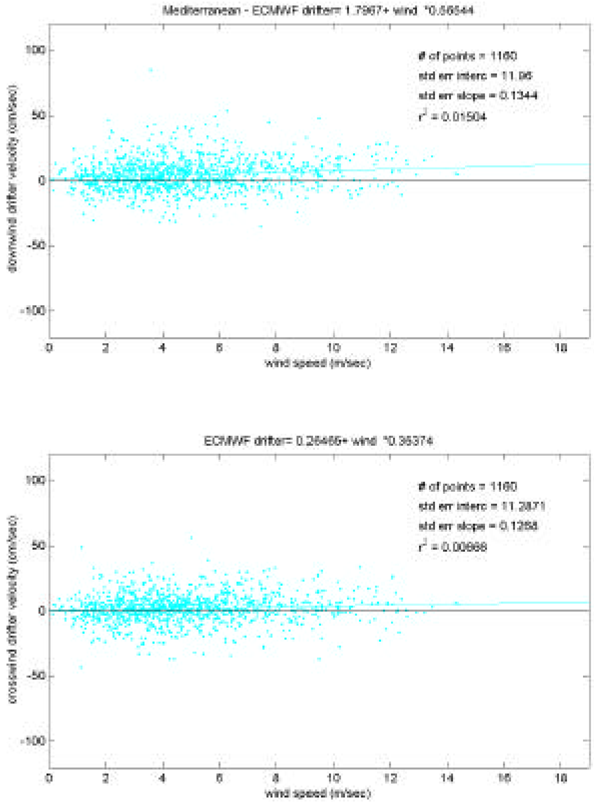

Figure 26: Same as in Figure 25 but using the ECMWF-a winds.

5. Conclusions

All the linear regression models described above reveal that the surface drifter velocities contain a significant wind-driven component which is downwind and mostly to the right of the wind, in good agreement with Ekman's theory. The magnitude of the wind-driven drifter velocities is about 1% of the wind speed. This is an order of magnitude larger than the drifter slippage (0.1-0.2%; Poulain and Ursella, 2004).

If we were to choose one simple and unique model for the Mediterranean, we would adopt the following relation:

$$\boldsymbol{U}\mathit{wind\text{-}driven}\ (\text{cm/s}) = 1.2\ \exp(-i24^{\circ})\ \boldsymbol{U}\mathit{wind}\ (\text{m/s}),$$

between the low-pass filtered drifter data and the low-pass filtered ECWM-ra winds. A significant portion (~9%) of the surface circulation variance is explained by this model.

Separating the Adriatic and the open Ionian basins, we see that the veering to the right of the wind-driven currents is larger for the Ionian (~30º) and smaller for the Adriatic (~5º). Removing the mean drifter currents, we obtain about the same veering for the two areas (21-24º). If we average the drifter and wind data in bins of 1º x 1º x 2 days, the veering for the Ionian stays about the same (30º). In contrast, it is reduced to about 1º for the Adriatic probably because the averaging scale is too large for this limited basin where coastal effects are important.

Using the wind stress did not improve the skill of the regression models (maximum of ~6%) so we believe that a model based on wind velocity is better. In the continuation of this work we will consider various powers of the wind speed (between 1 and 2, following Ralph and Niiler, 1999) to see if the skill can be improved. The ECMWF-a wind products appear to be better correlated with the drifter data (a skill of ~11% is observed for the Adriatic using the 1999 data) but the results (magnitude and veering) are similar to those obtained with the ECMWF-ra winds. It is planned to obtain the ECWMF-a products for the 5 years of interest (1995-1999) to try the regression model will all the drifter data.

		Down			Cross			Vectorial		
	# points	a	b	r^2 (%)	a	b	r^2 (%)	BB	PBB	r^2 (%)
Wind velocity										
NOGAPS Med	20602	-0.61	0.66	1.7	-0.71	0.20	0.2	0.55	-11.52	2.43
NOGAPS Ionian	4211	0.85	0.47	0.8	-1.14	0.32	0.4	0.57	-21.39	3.48
NOGAPS Adriatic	8726	-1.18	0.66	1.6	-0.35	-0.07	0.0	0.45	17.03	1.43
ECMWF-ra Med	20602	0.45	0.94	3.2	-0.7	0.53	1.1	1.07	-23.22	7.86
ECMWF-ra Ionian	4211	0.7	0.76	2.4	-0.3	0.54	1.3	0.90	-32.29	7.81
ECMWF-ra Adriatic	8726	0.24	1.02	3.2	-0.61	0.23	0.2	1.08	-5.09	6.44
Mean removed										
ECMWF-ra Med	19674	0.07	0.85	3.9	-0.07	0.53	1.6	1.06	-23.53	8.10
ECMWF-ra Ionian	4155	-0.5	0.72	2.8	-0.47	0.50	1.3	1.10	-21.82	8.07
ECMWF-ra Adriatic	8639	0.1	0.96	4.6	-0.96	0.56	1.9	1.06	-21.03	8.11
Binning										
ECMWF-ra Med	11963	0.16	1.32	5.4	-0.43	0.50	0.8	1.35	-19.54	10.62
ECMWF-ra Ionian	2620	-0.35	1.49	5.7	-0.15	0.54	1.1	0.98	-29.84	8.12
ECMWF-ra Adriatic	3723	0.43	1.04	3.4	-0.28	0.02	0.0	1.32	1.46	8.32
Smoothing										
ECMWF-ra Med	20602	1.06	0.52	3.63	0.57	-0.56	1.1	1.22	-23.70	8.68
ECMWF-ra Ionian	4211	0.9	0.48	2.8	0.56	0.03	1.2	1.01	-32.06	8.32
ECMWF-ra Adriatic	8726	1.12	0.45	3.5	0.22	-0.44	0.1	1.25	-5.22	6.98
Wind stress										
ECMWF-ra Med	20602	2.88	0.00	2.2	0.8	0.00	0.5	0.00	-23.52	6.24
ECMWF-ra Ionian	4211	3.26	0.00	1.8	1.46	0.00	0.9	0.00	-31.04	5.92
ECMWF-ra Adriatic	8726	2.65	0.00	2.2	0.09	0.00	0.1	0.00	-8.25	4.72
Wind 99 velocity										
ECMWF-a Med	1160	0.57	1.80	1.5	0.35	0.26	0.7	0.93	-23.93	8.96
ECMWF-a Ionian	81	0.76	0.55	2.3	0.07	1.66	0.0	0.83	-38.34	7.74
ECMWF-a Adriatic	593	0.62	2.38	1.7	0.4	-0.46	0.9	1.08	-18.15	10.72
ECMWF-ra Med	1160	0.57	2.04	1.4	0.12	1.59	0.1	0.98	-20.46	7.85
ECMWF-ra Ionian	81	0.57	1.78	0.9	0.03	3.69	0.0	0.83	-33.99	5.82
ECMWF-ra Adriatic	593	0.63	2.42	1.7	0.27	0.96	0.4	1.12	-11.94	8.96

Table 1: Summary of regression statistics. See text for the definition of symbols.

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