Variations in the path of the Mediterranean Outflow

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Abstract

The Mediterranean Outflow Water (MOW) exits through the Strait of Gibraltar as a localized jet which extends far from the source region, following the slope of the Iberian Peninsula and into the Bay of Biscay. This work examines the principal features of the MOW in several locations along its path and how it changes throughout the different seasons. We use the MEDREA model to characterize the trajectories of the particles along the path of the MOW, with special attention to its core velocity and the diffusion characteristics west of Gibraltar. The results show the presence of a westward MOW flow all year long in the Gulf of Cadiz, extending poleward during summer along the western part of the Iberian Peninsula. However, the model results do not confirm the univocal arrival of the MOW to the Bay of Biscay.

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1. Introduction

Despite the North Atlantic Ocean is the most observed and investigated of all the world's oceans, many features of its circulation are still not properly understood. As compared to western boundary flows, the currents in the eastern Atlantic are relatively weak and variable. During the last decades a number of experiments have taken place in the eastern North Atlantic Ocean, aimed at improving our understanding of its dynamics (e.g. CAMBIOS, ARCANE, CANIGO, CHAOS). For example, the principal objective of CANIGO (1996-1999) was to further understand the circulation and properties of the Easter North Atlantic Ocean between the Canary and Azores and the Strait of Gibraltar.

One of the central issues of this project was to study the Gulf of Cadiz, in the region influenced by the outflow of Mediterranean Water (MW) through the Strait of Gibraltar.

The eastern part of the North Atlantic Ocean is largely affected by the presence of MW formed within the Mediterranean Sea, in a dry and warm climate which causes intense evaporation and the production of a dense and saline water type. Deep water formation takes place in the Gulf of Lion, in the western Mediterranean basin, and in the Adriatic and Aegean Seas, in the eastern Mediterranean basin. A mixture of Levantine Intermediate Water, originally formed in the eastern basin, and Upper Deep Mediterranean Water, formed in either basin, eventually flows out of this basin through the Straits of Gibraltar and enters the Gulf of Cadiz. It has been argued that most of the exiting water is Levantine Intermediate Water (Bryden and Stommel, 1984) although it is likely that the exact contribution of each water mass changes from year to year. The MW entering the Atlantic Ocean as a bottom flow has salinity 38.4 and temperature 13.5°C (EMA, 2003).

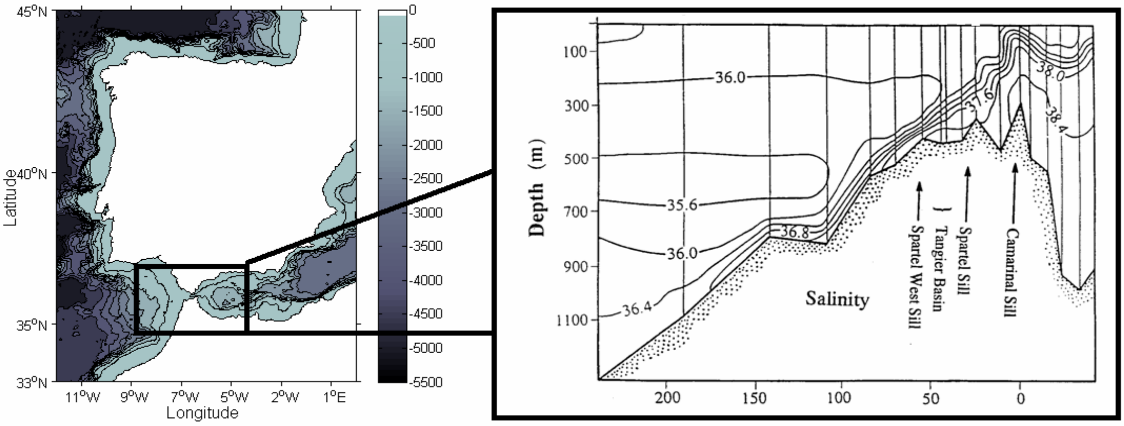


Figure 1. Bathymetry near the Iberian Peninsula and salinity section along the western end of the Strait of Gibraltar, reproduced from Price et al (1993). West of Gibraltar there are several sills that are overtaken by the salty MOW as it flows into the open ocean, before in turns west along the Iberian slope.

For the MW to exit the Strait of Gibraltar it has to surpass the Camarinal and Espartel Sills. When the MW overcomes the Espartel Sill (360 m depth, Fig. 1) it is named Mediterranean Outflow Water (MOW) (Baringer and Price, 1997). After this last sill the current increases its speed, largely controlled by the bathymetry, until it reaches the continental slope where it deflects northwestwards (Gasser et al., 2011). The MOW then follows the slope from the Gulf of Cadiz until the Bay of Biscay.

The geomorphological features of the shelf and the continental slope of the Strait of Gibraltar and the Gulf of Cadiz region determine the path of the outflow. The velocity of the flow is directly proportional to its negative buoyancy and to the bottom slope. The velocity reaches quite large values, well above 1 m s^{-1}, which drives internal instabilities that are responsible for the mixing of the Mediterranean outflow with the overlying North Atlantic Central Waters (Baringer and Price, 1999). During its early outflow stages, warm and very saline water follows the topography of the Gulf of Cadiz as a bottom current with high velocities. The density of this exiting water is quite large, about 1030 kg m^{-3}, so that, if untransformed, it would reach the bottom of the Atlantic Ocean. However, as the plume descends the continental slope it entrains the overlying North Atlantic Central Waters (NACW) and becomes progressively diluted (Johnson et al., 2002; Price et al., 1993).

The high velocities induced by the sloping bottom, particularly in regions where it increases locally, produces subcritical conditions. This causes localized mixing which eventually leads to the formation of two different MOW cores (Baringer and Price, 1997; Ambar et al., 2002; Gasser et al., 2011). The two cores find their equilibrium depths after passing Portimao Canyon at 8.32ºW (EMA 2003). The upper core is located around 650 m depth, with $T \cong 13.5$ºC and salinity $S \cong 36.5$, and the lower core is located around 1100 m depth, with $T \cong 12.5$ºC and salinity $S \cong 36.6$ (Ambar et al., 1999; Baringer and Price, 1999; Johnson et al.2002; EMA 2003).

Habgood et al. (2003) argue that the MOW can be very erosive and even change the features of the bathymetry. A recent study by Gasser et al. (2011) has demonstrated the clear correlation between the intensity of the flow and the bottom topography. Recent measurements, carried out during July 2011, have shown the existence of bottom channels used by the MOW to reach the continental slope, suggesting there may be several submarine waterfalls where the flow is substantially accelerated (J. L. Pelegrí, personal information).

Near Cape St. Vicente the flow is strongly affected by the bathymetry (Prater and Sanford, 1994), leading to the formation of very stable Mediterranean eddies (meddies), anticyclonic lenses of warm and salty MW with diameters ranging from 40 to 100 km and vertical extensions between about 600 and 1300 m (Richardson et al, 2000; Johnson et al. 2002). Bower et al. (1995, 1997) identified this Cape as a site for meddy formation, with a formation rate of 15 or 20 per year. The meddies may last up to several years, therefore becoming a very efficient mechanism for salt transfer to the open ocean (Richardson et al., 2000).

As the MOW surpases Cape St. Vicente it turns northwards, following along the continental slope (Richardson, 2000). Ambar (2002) indicates that there is a tendency for the lower core to meander off-shore after it turns around Cape St. Vicente, while Zenk and Armi (1990) and Johnson et al. (2002) argue that the upper core maintains its northward path close to the continental slope. Along its path the MOW experiences mixing, either locally through shear velocity or as structures detach from the current. This leads to the salinification of the whole region, through a saline tongue that extends westward across the North Atlantic basin (Price, 1993). It has been postulated that the MOW also has a non-local effect as it may affect the formation of the Azores Current (Jia, 2000).

The MOW continues its northward penetration along the continental slope of the Iberian Peninsula, where it coexists with the presence of other processes such as upwelling, equatoward currents and filaments (Relvas et al., 2007). Relvas et al. (2007) have also provided evidence that the subsurface circulation in the coast of Portugal is closely linked to the presence of MW at intermediate levels. In the Galician slope the MOW predominantly turns east into the Bay of Biscay, flowing along the northern Iberian slope (Iorga and Lozier, 1999).

The aim of this study is to understand the variability of the MOW and to assess the magnitude of its seasonal variability. For this purpose, we will examine the current fields as inferred from a numerical model and explore how the MOW propagating path and diffusion patterns may change with season as well as with distance from its source in the western end of the Strait of Gibraltar.

2. Methods

Our study is focused on the continental slope and the adjacent deep ocean of a relatively large area, from the western end of the Strait of Gibraltar (about 6ºW, 35ºN; Strait Gibraltar) to the northern part of the Iberian Peninsula (6ºW, 44ºN). For this study we have used a program called Connie2. This program uses output currents from oceanographic models and particle tracking techniques to display parcel trajectories and to estimate connectivity statistics. The technique has been validated with in situ data taken in the west coast of Australia (Condie et al., 2005).

Connie2 uses different circulation models for each part of the world. For the Atlantic region of the Iberian Peninsula the model used is the MEDREA model (The Mediterranean Sea Reanalysis) developed using the OPA 8.1 code for the Mediterranean Sea and adjacent Nord Atlantic Ocean region. This model has a 1/16º resolution and assimilates different data types forms part of the Mediterranean ocean Forecasting System (MFS). The data assimilating model has a 1/16º horizontal resolution and includes realistic evaporation and river discharges.

To analyze the direction of the currents we seed particles in several locations near the continental slope, along the expected path of the MOW. We seed particles at a constant rate of 25 per grid cell a day during a given period in locations to the south, west and north of the Iberian Peninsula. The southern locations are west of the Strait of Gibraltar, within the Gulf of Cadiz and off Cape St. Vicente. The western locations are off Lisbon and Porto. The northern locations are in front of Ferrol and Gijon.

As the depth of the MOW changes with distance from Gibraltar and splits into two different cores, we have chosen three different depths. We select 313 m in the eastern part of the Gulf of Cadiz in order to examine the early trajectories of the MOW as they exit the Strait of Gibraltar. Elsewhere we have selected two different depths: 710 and 1011 m in order to respectively track the upper and lower cores of the MOW.

As we are interested on the seasonal variations in the mean and diffusion patterns associated to the MOW, we seed the particles during the first day of March, June, September and December of two different years (2006 and 2007) and examine their trajectories during one full month. Specifically, as the program provides the percentage of particles that reach different locations along the MOW’s path, we have used three different distances in order to estimate the advective and diffusive velocities. The advective velocity is taken to correspond to the mean velocity field, estimated from the distance reached by 50% of the particles. The diffusive velocity, on the other hand, is estimated from the distances reached by most and just a few of the particles. The reasoning is that the diffusive motions influence (either enhancing or diminishing) the actual total motion of the water particles: constructive diffusive interferences will cause the water particles to reach further beyond the mean position and destructive interferences will cause them to move much shorter distances. We take the 80% and 10% levels as indicative of these constructive and destructive interferences (the 90%

level is not used as it happens that the grid cell adjacent to the launching position is always reached by 90% of the water particles).

We may calculate a ratio between the diffusive displacement (the distance between the positions reached by 80% and 10% of the particles) and the advective or displacement (the distance between the launching location and the position reached by 50% of the particles). This diffusive-advective coefficient, indicative of the importance of the diffusive motions as compared with the (mean) advection, is defined as

$$r = \frac{l_t}{l} \tag{1}$$

In this last expression l_t is the diffusive displacement and l is the advective displacement. This coefficient gives us the relative importance of the advective and diffusive terms as compared with the advective ones.

The diffusive-advective coefficient, together with the mean velocity (related to the distance reached by 50% of the water particles, may be used to obtain an estimate of the horizontal diffusion coefficient. Two characteristic advective and diffusive momentum terms are $\bar{u}\frac{\partial \bar{c}}{\partial x}$ and $\frac{\partial\left(\overline{u'c'}\right)}{\partial x} = K_h \frac{\partial \bar{c}}{\partial x}$, respectively. In these expressions $\bar{u}$ is the mean velocity, $\bar{c}$ is the concentration of some water property and K_h is the horizontal diffusion coefficient. If we non-dimensionalise and equate these two terms, an estimate of the horizontal diffusion coefficient is given by:

$$K_h = r\,\bar{u}\,\Delta x \tag{2}$$

To compute K_h we take Δx = 8.74 km, the horizontal resolution of the model.

3. Results

3.1 Trajectories

The MOW has been studied many times in the past, even through seismic reflection profiles in the Gulf of Cadiz and western Iberian coast that cross the path of the Mediterranean undercurrent (Buffettt et al., 2009). The MOW exits the Gibraltar Strait and plunges into the eastern Gulf of Cadiz, initially flowing west channeled by the bathymetry. The trajectories obtained from Connie2, for the different months and during two consecutive years (2006 and 2007), are consistent with these results.

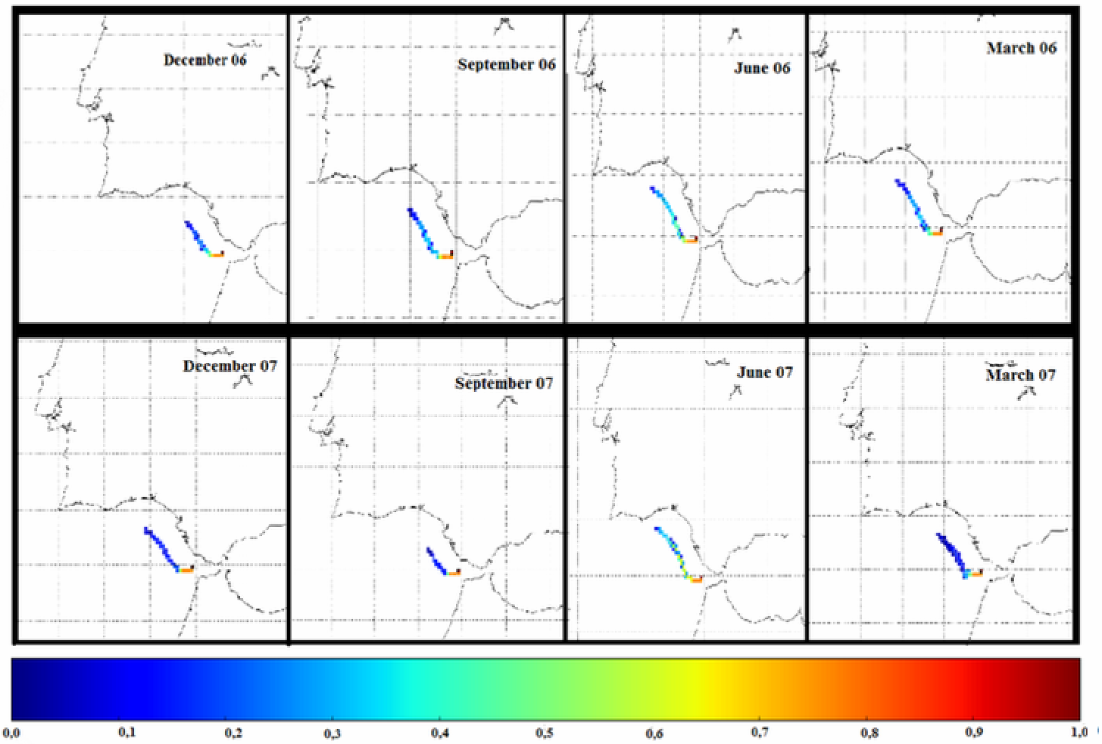


Figure 2. Seasonal variation in the path of the particles launched at a depth of 313 m west of Gibraltar, over Espartel Sill. The particles were launched in the first day of the indicated month. The color bar shows the probability (in percentage) that every each particle passes over each grill cell. White areas indicate that no particles have passed.

In Figure 2 we may see how, at about 36.06ºN - 6.63ºW, the current changes direction and flows northwestwards, following the Iberian continental slope in the Gulf of Cadiz (Iorga and Lozier, 1999). Figure 2 illustrate that as the MOW passes the western Espartel Sill it turns north for all different months and years. However, this figure also confirms that the extension of a one-month trajectory displays substantial differences between adjacent years and from one month to another. Comparing these two years we may say that, at a depth of 313 m, the MOW current in the Gulf of Cadiz is strongest in summer and weakest in autumn (Table 1).

Table 1. Distance reached by the particles launched west of Gibraltar at the beginning of each season in 2006 and 2007.

Season	2006 (km)	2007 (km)
March-313	138.8	125.7
June-313	151.4	174.0
Septembre-313	123.8	88.2
Diciembre-313	108.5	127.2

The current follows the slope south of the Iberia Peninsula along the Gulf of Cadiz (Appendix, Fig. A1) until it reaches Cape St. Vicente. There it splits into two distinct cores, at different depths, and the MOW turns north following the continental slope (Fig. 3). The upper core follows the slope of the Iberian Peninsula northwards, while the lower core most of the year extends westwards entering into the open ocean. An exception appears to occur en September, when the lower core also extends north following the Iberian margin. During 2006 the lower core reached about 152 km in September and the upper core stretched about 163 km in December. However, in 2007 the lower core reached its northernmost position during March, extending about 122 km, and the upper core moved a distance of 147 km.

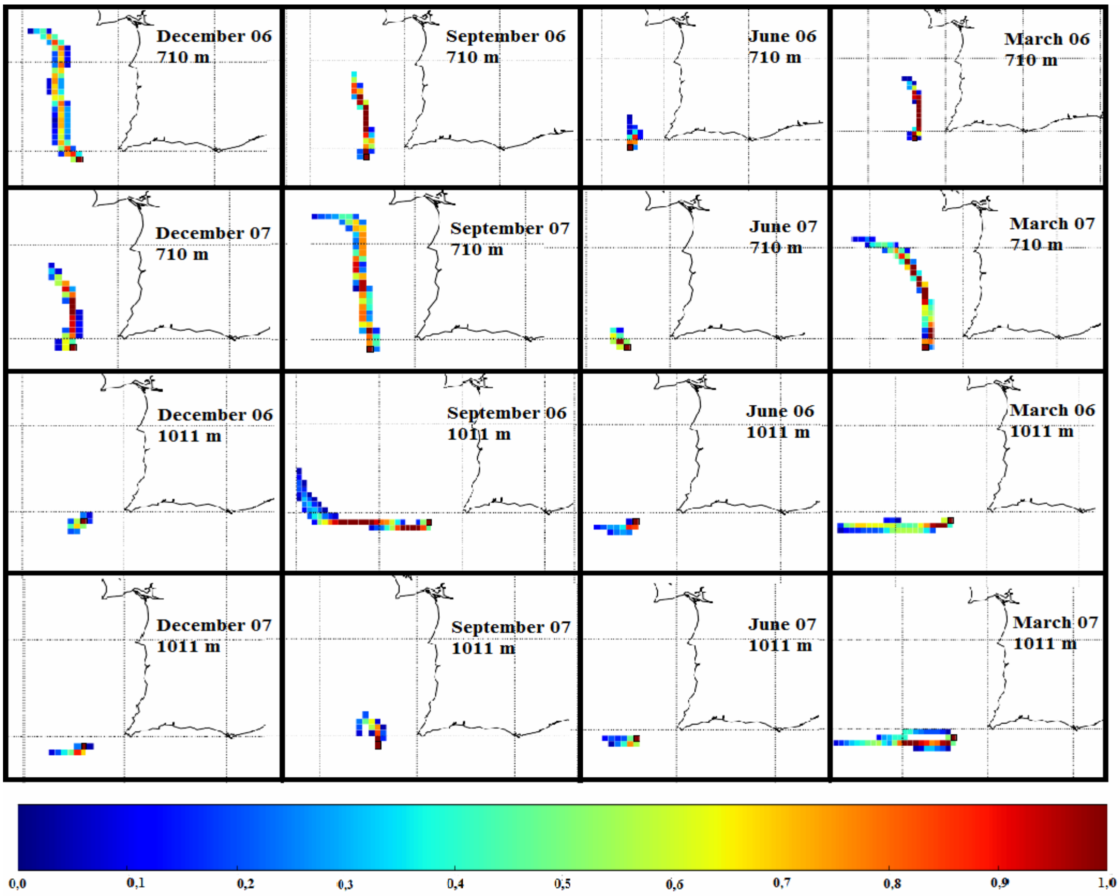


Figure 3. Seasonal variation in the path of the particles launched at depths of 710 and 1011 m off Cape St. Vicente. The particles were launched in the first day of the indicated month. Color code is as in Figure 2.

The current continues its northward advance until Lisbon all year long (Fig. A2), however stretching very different distances during the different months. During 2006 the longest distance for the lower core is was 72 km while for the upper core it was 87 km. In 2007 the longest distances for both cores took place in September, with distances about 84 km (upper core) and 90 km (lower core).

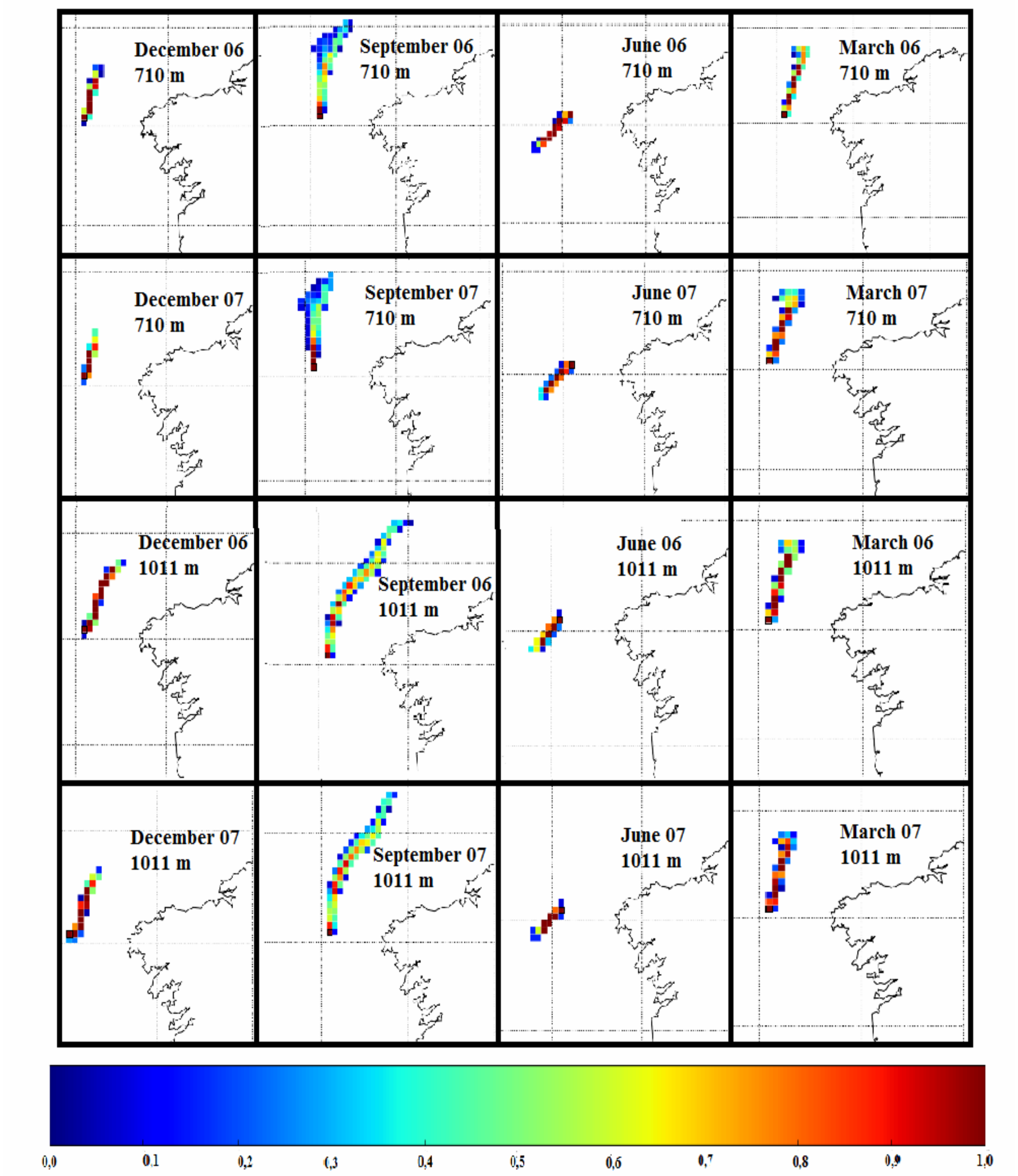


Figure 4. Seasonal variation in the path of the particles launched at depths of 710 and 1011 m off Galicia. The particles were launched in the first day of the indicated month. Color code is as in Figure 2.

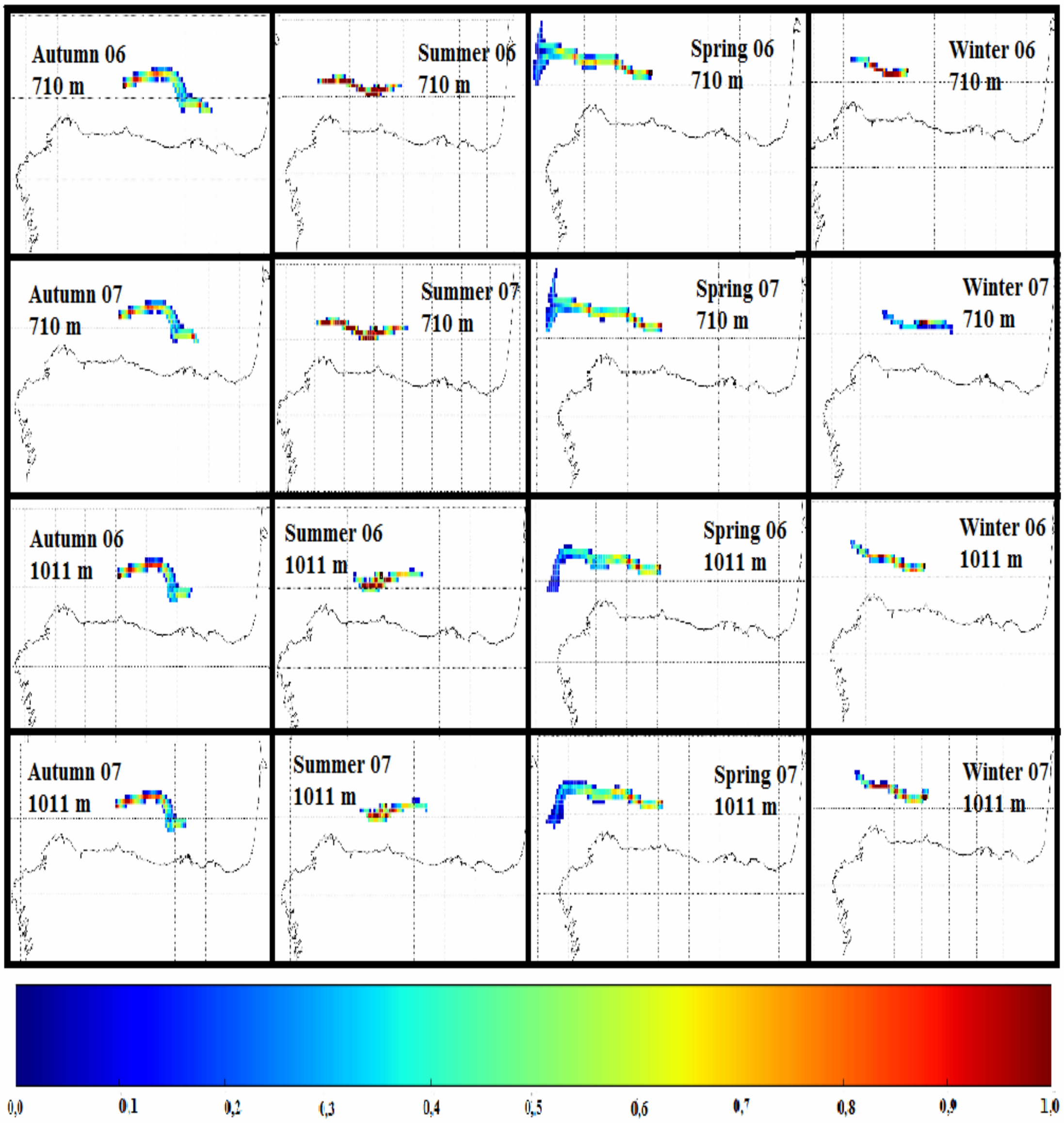
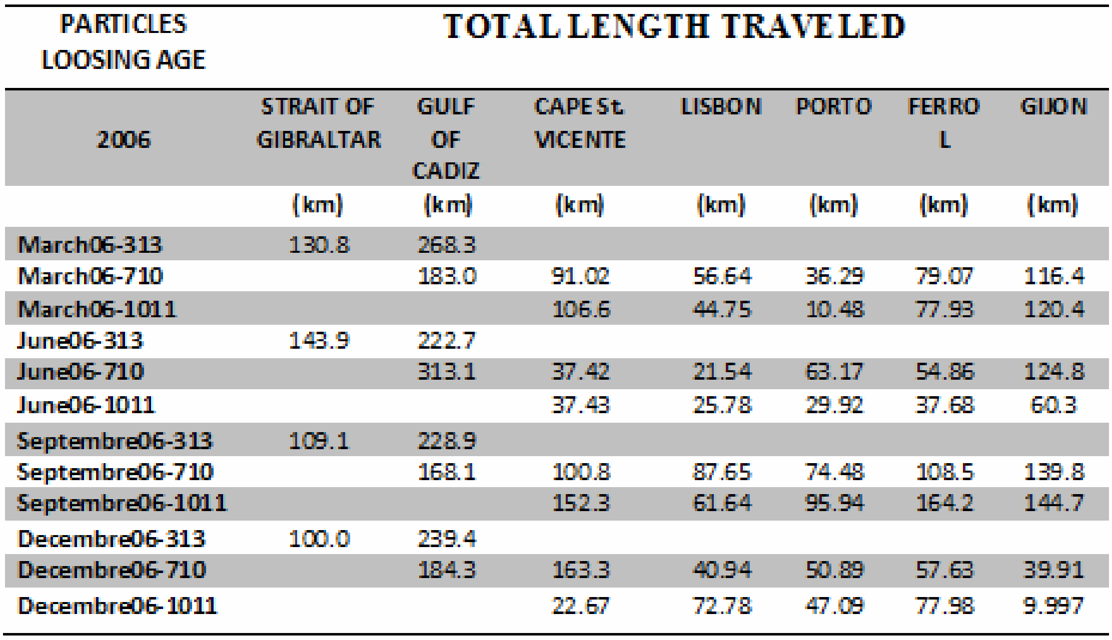


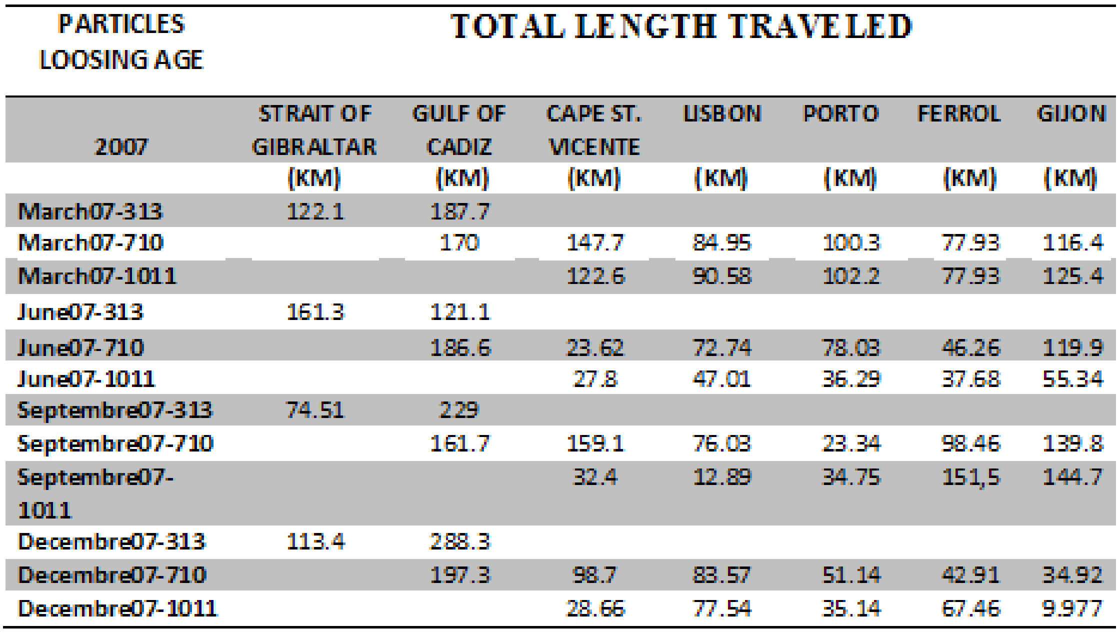
Figure 5. Seasonal variation in the path of the particles launched at 710 and 1011 m off Asturias. The particles were launched in the first day of the indicated month. Color code is as in Figure 2.

To analyze the Porto zone, we show the trajectories for the entire season (Fig. A3). The flow follows north during winter with very little perturbations, in contrast with autumn and spring, when cyclonic and anticyclone eddies are present. In autumn 2007 the current reverts direction at both depths; in autumn 2006 it does so only at 710 m. When the MOW arrives to the Northwest corner of the Iberian Peninsula, it follows the slope and turns east (Fig. 4). The longest distance traveled by the water particles occurs at the beginning of autumn during both years. At 710 m depth this distance corresponds to about 108 km and 98 km for 2006 and 2007 respectively. At 1011 m distances were about 164 km and 151 km for 2006 and 2007 respectively (Table 2**)**.

Table 2. Distance reached by particles launched at the beginning of each season at three different deeps (313, 710 and 1011 m).



PARTICLES LOOSING AGE	TOTAL LENGTH TRAVELED						
2006	STRAIT OF GIBRALTAR	GULF OF CADIZ	CAPE St. VICENTE	LISBON	PORTO	FERRO L	GIJON
	(km)	(km)	(km)	(km)	(km)	(km)	(km)
March06-313	130.8	268.3					
March06-710		183.0	91.02	56.64	36.29	79.07	116.4
March06-1011			106.6	44.75	10.48	77.93	120.4
June06-313	143.9	222.7					
June06-710		313.1	37.42	21.54	63.17	54.86	124.8
June06-1011			37.43	25.78	29.92	37.68	60.3
Septembre06-313	109.1	228.9					
Septembre06-710		168.1	100.8	87.65	74.48	108.5	139.8
Septembre06-1011			152.3	61.64	95.94	164.2	144.7
Decembre06-313	100.0	239.4					
Decembre06-710		184.3	163.3	40.94	50.89	57.63	39.91
Decembre06-1011			22.67	72.78	47.09	77.98	9.997



PARTICLES LOOSING AGE	TOTAL LENGTH TRAVELED						
2007	STRAIT OF GIBRALTAR (KM)	GULF OF CADIZ (KM)	CAPE ST. VICENTE (KM)	LISBON (KM)	PORTO (KM)	FERROL (KM)	GIJON (KM)
March07-313	122.1	187.7					
March07-710		170	147.7	84.95	100.3	77.93	116.4
March07-1011			122.6	90.58	102.2	77.93	125.4
June07-313	161.3	121.1					
June07-710		186.6	23.62	72.74	78.03	46.26	119.9
June07-1011			27.8	47.01	36.29	37.68	55.34
Septembre07-313	74.51	229					
Septembre07-710		161.7	159.1	76.03	23.34	98.46	139.8
Septembre07-1011			32.4	12.89	34.75	151,5	144.7
Decembre07-313	113.4	288.3					
Decembre07-710		197.3	98.7	83.57	51.14	42.91	34.92
Decembre07-1011			28.66	77.54	35.14	67.46	9.977

Finally, in the northern part of the Iberian Peninsula (Fig. 5) the direction of the flow changes dramatically with season. In autumn the current goes east and reaches the maximum distances; however, during spring the current changes its direction westward (Table 2). During the rest of the year the current changes within one same season.

3.2 Velocities West of Gibraltar

In this section we present the velocity of the current at 313 m as it exits the Strait of Gibraltar into the Gulf of Cadiz. The results are presented for first seven days of each season (Fig. 6). As the MOW crosses the Espartel Sill it initially flows into the Gulf of Cadiz with quite high velocities but these rapidly decrease. This is possibly caused by an actual decrease in the speed of the MOW but may also be related to the fact that the MOW deepens so that our constant depth level (313 m) is not capable of properly tracking the core of the MOW. Table 3 shows that the largest velocities occurred during June 2006, with a speed of 0.118 m/s, and December 2007, with a maximum speed of 0.122 m/s.

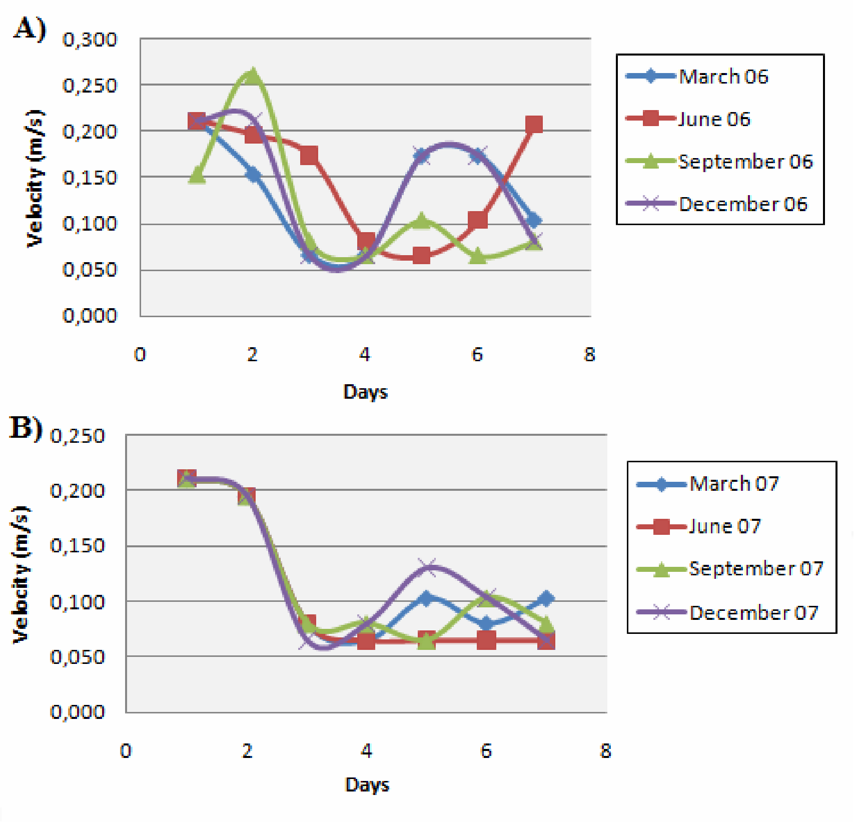
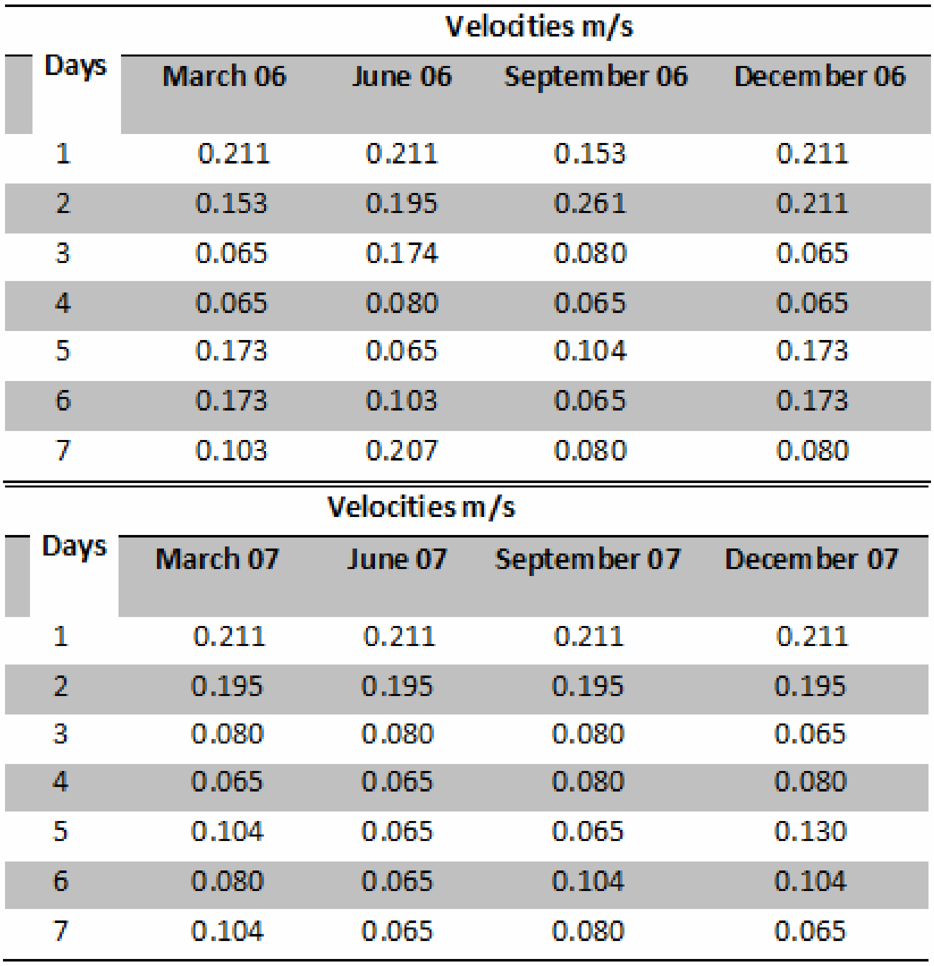


Figure 6. Speed of water parcels at 313 m, during the first seven days of their trajectory, after release at west Espartel Sill during different months. A) Speed variation for 2006, B) Speed variation for 2007.

3.3 Diffusive Motions

Our study area is affected by the presence of different oceanographic features which lead to diffusive motions, therefore affecting the mean advective velocity. To try to understand the importance of these processes we have computed the relative size of the mean advective and diffusive velocities, as explained in Section 2. Table 4 presents the diffusive-advective coefficient (*r*), the diffusive velocity and the horizontal diffusion coefficient at different times using this methodology. The diffusive velocity is around 0.04 m/s during all months and years, and the coefficient *r* ranges between 1.3 and 5.1.

Table 3. Velocities in the Strait of Gibraltar at 313 m as estimated during the first week of each season.



Days	Velocities m/s			
	March 06	**June 06**	**September 06**	**December 06**
1	0.211	0.211	0.153	0.211
2	0.153	0.195	0.261	0.211
3	0.065	0.174	0.080	0.065
4	0.065	0.080	0.065	0.065
5	0.173	0.065	0.104	0.173
6	0.173	0.103	0.065	0.173
7	0.103	0.207	0.080	0.080

Days	Velocities m/s			
	March 07	**June 07**	**September 07**	**December 07**
1	0.211	0.211	0.211	0.211
2	0.195	0.195	0.195	0.195
3	0.080	0.080	0.080	0.065
4	0.065	0.065	0.080	0.080
5	0.104	0.065	0.065	0.130
6	0.080	0.065	0.104	0.104
7	0.104	0.065	0.080	0.065

The results indicate that during most of the time the current is largely affected by diffusive process. The intensity of these processes, however, changes, reaching an absolute maximum on March 2006, when the coefficient was 5.118, and an absolute minimum on June 2007, when the coefficient was 1.309. However, in March of 2007 the coefficient was 2.940, a relatively large value but yet much smaller than in 2007. Something similar happens in September, the coefficient was 4.479 in 2006 and only 2.967 in 2007.

Finally, we have used the above results (Table 4) together with the advective velocities (Table 3) in order to compute an estimate for the horizontal diffusion coefficient from equation (2). The largest coefficients correspond to high advective velocities and diffusive-advective coefficients. The mean horizontal diffusive coefficient is 369 m^2/s, a value consistent with repots in the literature for intense ocean jets (Bower et al. 1985).

Table 4. Diffusive-advective coefficient, diffusion velocity (m/s) and horizontal diffusion coefficient (m^2/s) along the path of the MOW in the eastern Gulf of Cadiz at 313 m at the beginning of each season.

Period	r	Diffusion Velocity	Horizontal Diffusion Coefficient
March 06	5.1	0.045	393
June06	2.1	0.051	449
September 06	4.5	0.041	355
December 06	3.2	0.034	294
March 07	2.9	0.041	362
June 07	1.3	0.058	507
September 07	3.0	0.027	235
December 07	4.6	0.041	355

4. Discussion

4.1 Characteristics of MW

The Mediterranean Sea is a semi-enclosed marginal basin in which strong evaporation exceeds the sum of precipitation and river runoff. This water deficit transforms the Mediterranean waters into a relatively salty and dense water mass (salinity 38.3 and potential density of 28.95 kg m^{-3}) (Xu et al., 2007). As this Mediterranean Water flows westward out of the Strait of Gibraltar and into the Gulf of Cadiz (Gasser et al., 2011), it mixes with the overlying North Atlantic Central Water. This process decreases the MOW density until it eventually finds a neutrally-buoyant density level (Baringer and Price, 1997). Mixing is intermittent and the outflow splits into two main cores, an upper one at depths about 700 m and a lower one at depths about 1100 m. The MOW flows towards the west and northwest, initially following the bathymetry and later along the continental slope. The configuration of the shelf and the continental slope of the Strait of Gibraltar region determine the path of the outflow (Baringer and Price, 1999).

4.2 MOW mean path

Our study endorses early observations that the MOW exits through the Strait of Gibraltar and follows the bathymetry westward until 36.06ºN where it changes its direction to the north, along the continental slope and into the northern Gulf of Cadiz. During these early stages the trajectory of the water particles is quite constant all year long, although there are significant variations in the mean and diffusive speeds throughout the year (Fig. 2). The longest path west of Gibraltar takes place at the beginning of the year, running 143 km and 161 km for 2006 and 2007, respectively. These seasonal changes are in agreement with early results by Ambar et al. (1999). Peliz et al. (2009) also proposed that these changes are induced by a covariance between the winds and the net transport of the MOW.

As the current passes Cape St. Vicente the trajectory remains fairly constant at 710 m depth, following the slope and turning north. In general, there appears to be an increase in the distance reached by the water parcels between spring and summer, except off Porto where the current appears to be largely affected by the bathymetry and the existence of a countercurrent. As a consequence the current at 710 m weakens during the beginning of the year but increases during summer. On the other hand, at 1011 m depth the current rums westwards except during September, where the current experiences little changes in direction (Fig. 3). At this depth there is also a decrease in the extension of the water parcels during summer.

Relvas et al. (2007) have suggested that the intensity of the current is related to changes in the intensity of the winds. He proposed that a poleward current exists all year long in the top 100 m water column, which may perhaps affect the intensity of the MOW. Huthnance et al. (2002) also observed a poleward current between surface and 600 m. Garcia Lafuente et al. (2008) indicate that during summer the poleward current disappears, being replaced by an undercurrent. Our results do suggest the existence of a poleward summer undercurrent, yet weak, at about 710 m.

Our results off Galicia suggest that the MOW may penetrate into the Bay of Biscay only on some seasons. The presence of the MOW off Galicia and in the Bay of Biscay is also supported by several observations. Garcia Lafuente et al. (2008) found

Mediterranean Water off Galicia at depths about 700 and 1000 m. They also reported that during the upwelling season it is possible to find MW as shallow about 100 m depth.

Diaz del Río et al (1998) affirmed that Intermediate Mediterranean Water (IMW) flows along the west coast of the Iberian Peninsula until Cape Finisterre where it turns to the east, into the Bay of Biscay. These authors suggest that the seasonal variations are related to the presence of Labrador Water and report the existence of intermittent inversions. Our results appear to confirm the existence of substantial variability, with current inversions, at the depth levels of the MOW (Fig. 7). The only season when the current is capable of entering the Gulf of Biscay is during summer, particularly at 1011 m.

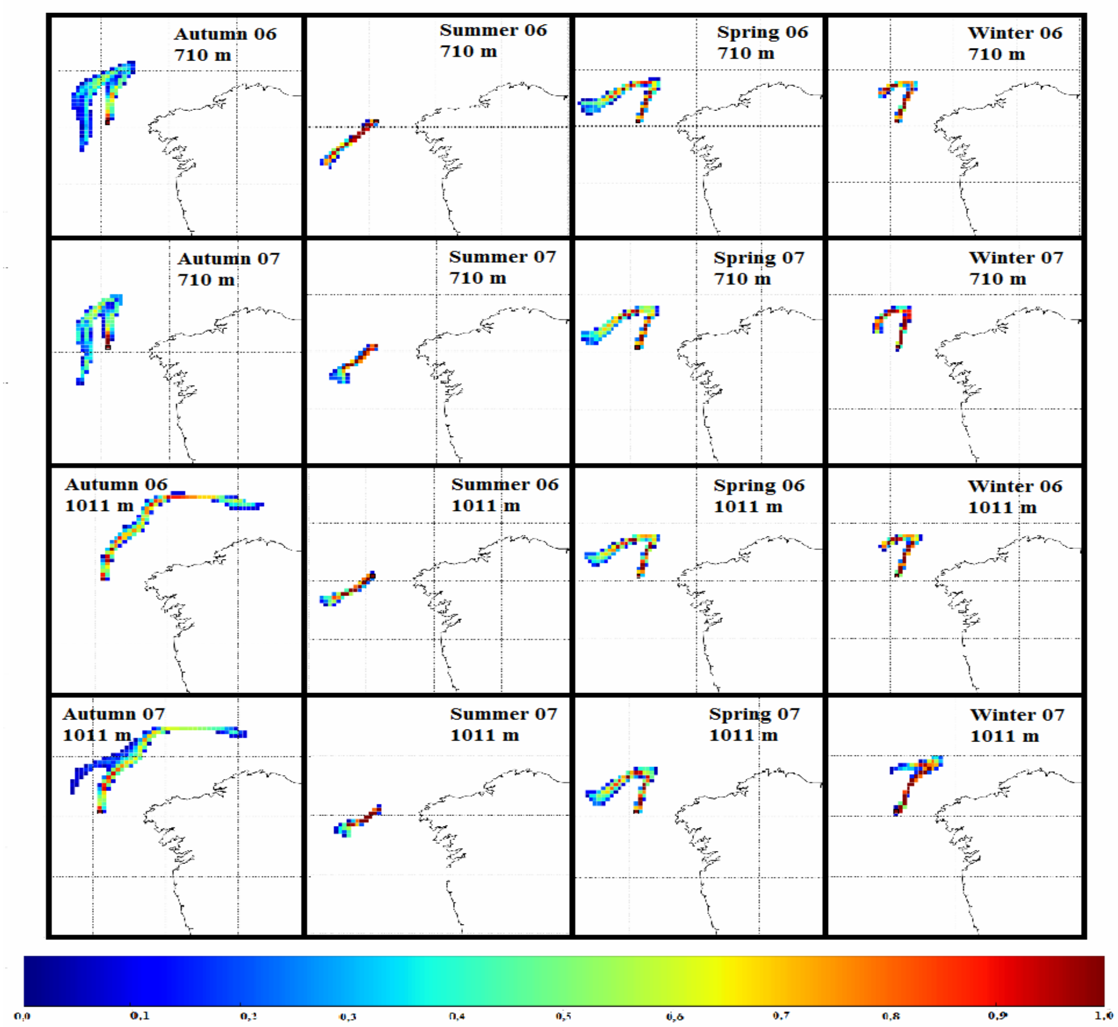


Figure 7. Seasonal variation in the path of the particles launched at 710 and 1011 m off Galicia. The particles were launched in the first day of the indicated month and tracked during one entire season (3 months). Color code is as in Figure 2.

4.3 Velocities and diffusivity

Our results agree with previous observations of a winter weakening in the northward penetration of the MOW (Peliz et al., 2009). This is clear from our 2006 results but yet in 2007 the weakening occurred in September. In contrast, the speed clearly increases in the summer months during both years. The highest speeds were observed in summer 2006 (0.058 m/s) and 2007 (0.067 m/s) (Table 7).

Table 5. Dates of average speed for the first 7 days of each season in m/s.

Months	**Average Speed**	
	2006	2007
March	0.052	0.047
June	0.058	0.067
September	0.047	0.034
December	0.040	0.048

The increase in the mean velocities is associated to an increase in the horizontal diffusion coefficient. The largest values respectively are 449 and 507 m^2/s during summer 2006 and 2007. In contrast, the smallest December 2006 and September 2007, respectively with 294 and 236 m^2/s. These results suggest that an increase in the speed of the mean flow leads to enhanced instability and diffusive type motions, therefore resulting in a higher horizontal diffusive coefficient.

5. Conclusions

The Mediterranean Basin, one of the largest in the world, is characterized by an excess evaporation over precipitation which leads to the production of relatively salty and warm waters. This water is so dense that, if it was not diluted, it could reach the bottom of the Atlantic Ocean. However, as the MOW exits the Strait of Gibraltar at levels about 300 m deep and plunges in the eastern Golf of Cadiz it undergoes substantial mixing and dilution, actually splitting into two different cores which eventually reach equilibrium levels near 700 and 1100 m depth.

Our analysis has focused on the behavior of the different sectors of the MOW after exiting the Strait of Gibraltar: west of Gibraltar, as it reaches Cape St. Vicente, in the western Iberia slope (off Lisbon and Porto), as it reaches Cape Finisterre, and in the

Bay of Biscay. The results show that the model is in general capable of tracking the path of the MOW; there are some exceptions, however, in the southwestern and northwestern corners of the Iberian Peninsula. In the southwestern corner, for example, the upper core does follow the continental slope but the lower core stretches into the open ocean. In the northwestern corner, in contrast, only the lower core can penetrate into the Bay of Biscay, doing so during summer.

It is not clear whether our results may be related to the depth selected for launching the water parcels. The depth selection was constrained by the number of available depths in the model configuration. This caused that the shallow selection (303 m) was only appropriate for water parcels shortly after exiting the western end of the Strait of Gibraltar; soon afterwards these depths are far too shallow to track the MOW. Further beyond the selected depths are 710 and 1011 m, which do appear to be closer to the actual MOW propagation depths, yet possibly a little too deep. This difference may be critical near prominent geomorphological features such as Cape St. Vicente and Cape Finisterre, causing that the water particles depart from the continental slope and become lost into the deep ocean. Nevertheless, our results do illustrate the existence of significant seasonal variations that have been reported in the literature. For example, along the western margin of the Iberian Peninsula the poleward MOW appears to intensify during the summer season.

Finally, our study has allowed us to assess the relative importance of diffusion on the resulting path of the MOW shortly after it exits the Strait of Gibraltar (in the eastern Gulf of Cadiz). We have observed a significant seasonal change in the average velocity during ours two years of study, with the maximum velocities occurring in summer and the minimum in winter (2006) or autumn (2007). The horizontal diffusion coefficients are well correlated with the mean velocity, ranging between a mean autumn-winter value of 310 m^2/s and a mean spring-summer value of 428 m^2/s.

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Appendix

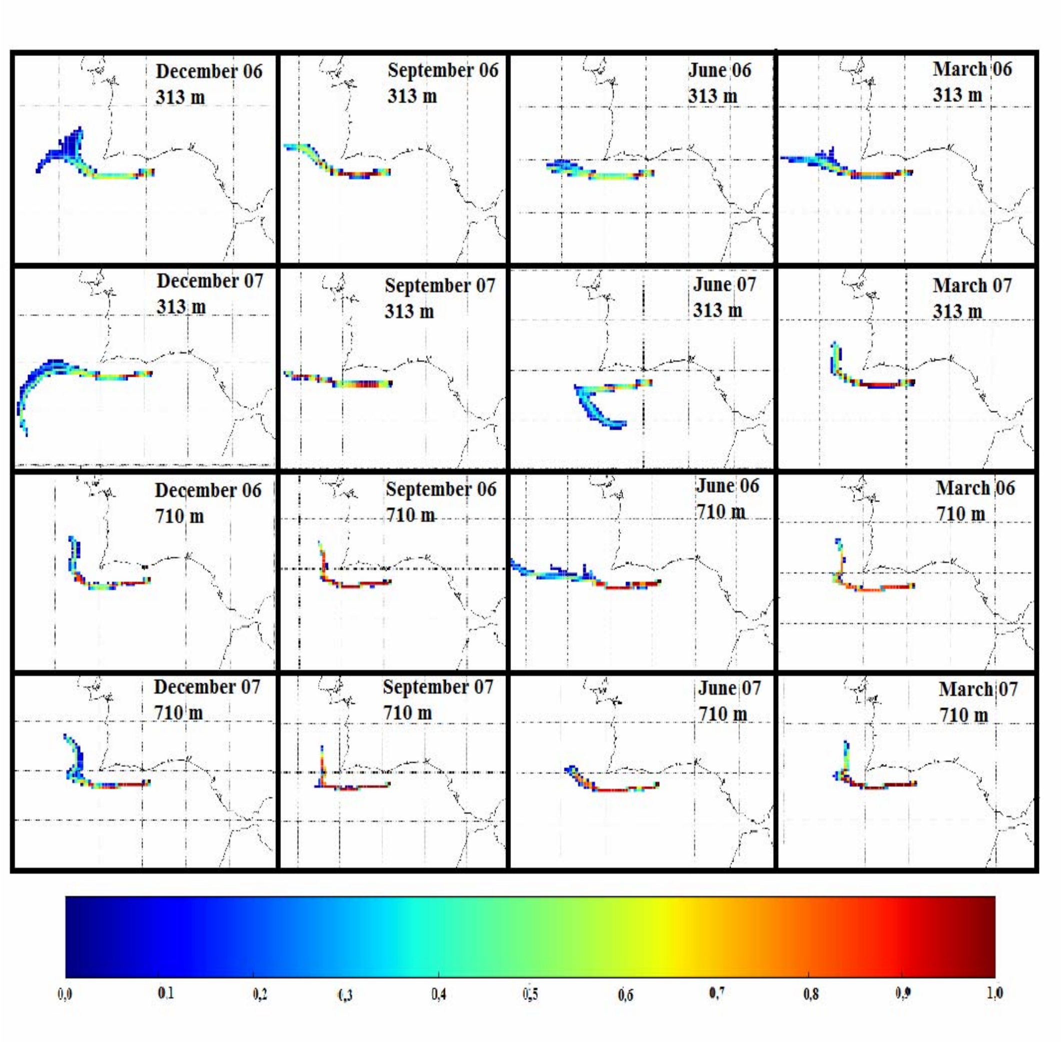

Figure A1. Seasonal variation in the path of the particles launched at 313 and 710 m depth off the northern Gulf of Cadiz. The particles were launched in the first day of the indicated month. Color code is as in Figure 2.

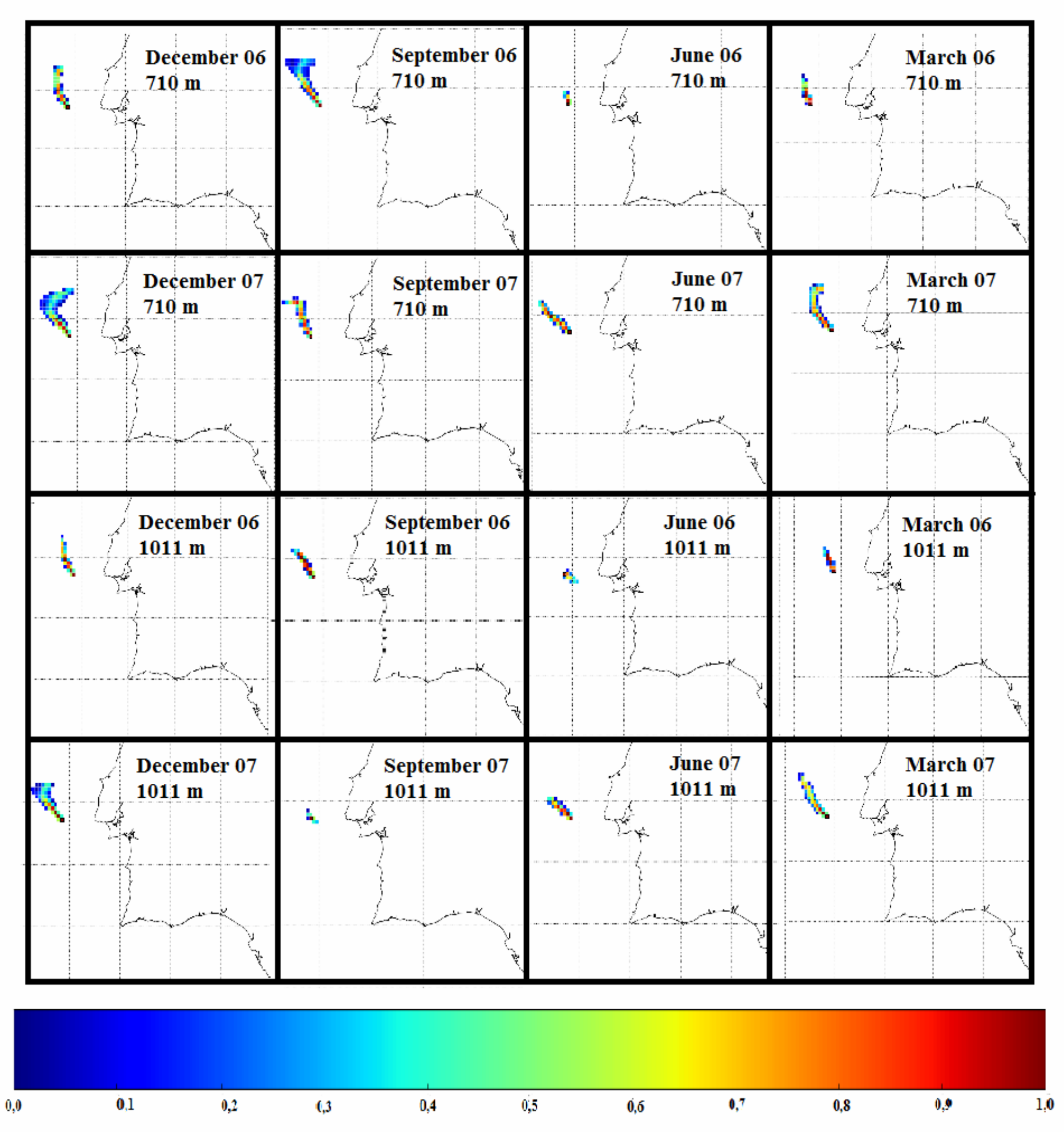

Figure A2. Seasonal variation in the path of the particles launched at 710 and 1011 m off Lisbon. The particles were launched in the first day of the indicated month. Color code is as in Figure 2.

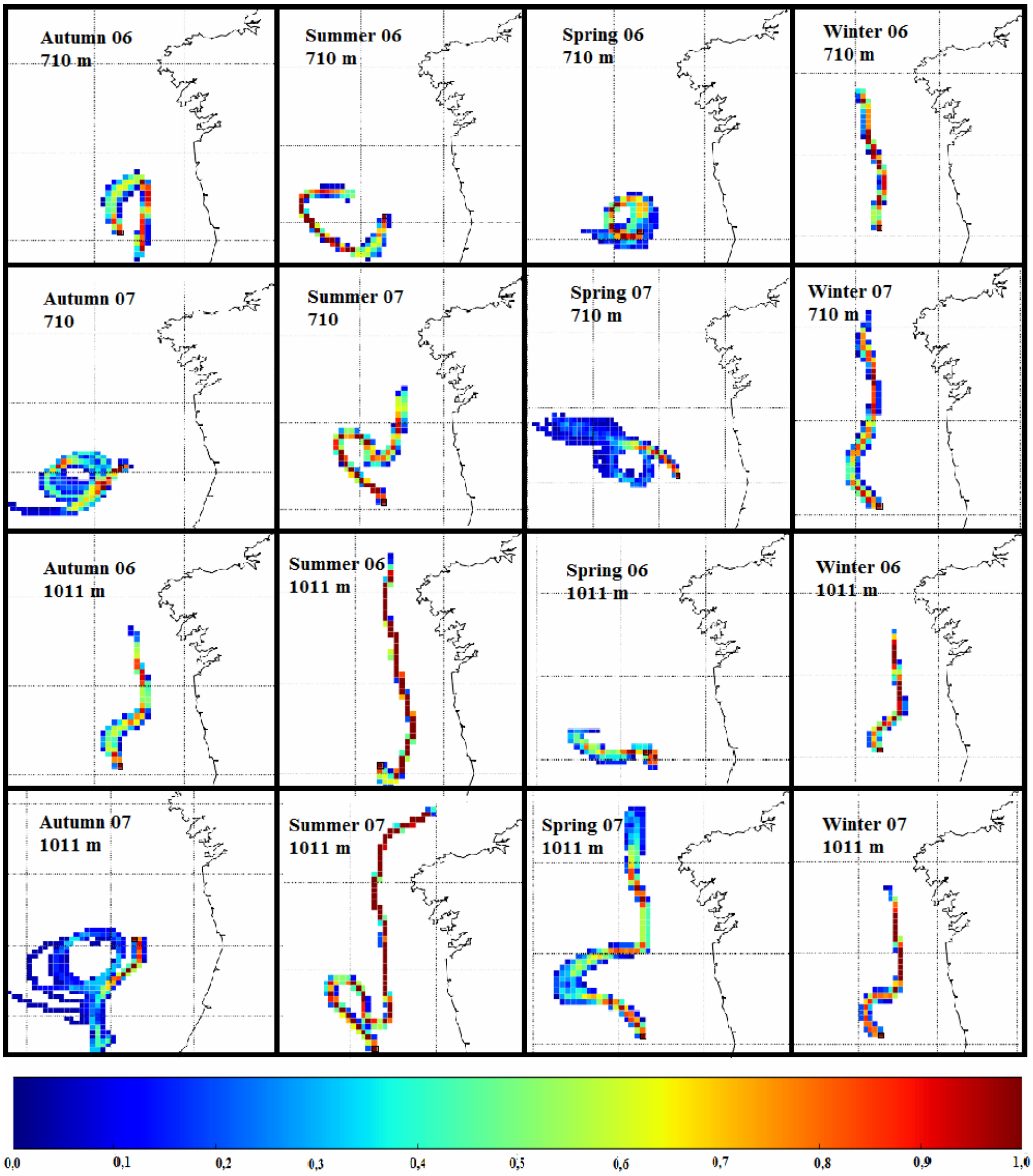

Figure A3. Seasonal variation in the path of the particles launched at 710 and 1011 m off Porto. The particles were launched in the first day of the indicated month and tracked during one entire season (3 months). Color code is as in Figure 2.