Dynamical Characteristics of the Adriatic Sea using Lagrangian Methods
(Settore scientifico-disciplinare)

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**Riassunto**

Le correnti e i processi di trasporto oceanici a grande scala e a mesoscala svolgono un ruolo cruciale in una varietà di campi, siano essi puramente d’interesse scientifico o applicativo. Tra le diverse strumentazioni oceanografiche a disposizione per lo studio della circolazione oceanica, le boe di deriva di tipo lagrangiano (o “drifters” lagrangiani) sono particolarmente adatte allo studio dei processi di trasporto in oceano data la loro capacità di seguire il moto delle particelle d’acqua e, in definitiva, delle correnti.

Nelle aree costiere e nei bacini semi-chiusi, lo studio dei processi di trasporto associato alle correnti è particolarmente importante a causa dell’impatto di inquinanti, di sostanze rilasciate da relitti, di oil-spill sugli ecosistemi costieri, sulle attività economiche e sulle zone costiere densamente abitate.

Il mare Adriatico, un bacino semi-chiuso del mar Mediterraneo, è, da questo punto di vista, un’area sensibile e presenta una serie di complessi fenomeni di circolazione quali intense correnti costiere e strutture vorticose a differente scala spaziale.

Lo scopo di questa tesi è quello di simulare e quindi studiare i fenomeni di dispersione di traccianti passivi attraverso le proprietà statistiche delle correnti nel mare Adriatico utilizzando correnti superficiali prodotte da modelli di circolazione e da dati sperimentali derivati da drifters reali.

La tesi è suddivisa in capitoli strutturati come articoli scientifici indipendenti e “auto-consistenti”, pronti ad essere sottomessi a riviste scientifiche di tipo “peer-reviewed”.

**Il capitolo 2** contiene le statistiche dei tempi di transito e dei tempi di residenza nelle acque superficiali del mare Adriatico, calcolate a partire da dati derivati da drifters reali e da simulazioni numeriche lagrangiane. I risultati delle analisi dei dati derivati da drifters reali mostrano in generale una sottostima delle statistiche, data la loro vita operativa relativamente breve (tempo di emivita di 40 giorni). Il problema del bias introdotto dalla breve vita dei drifters reali può essere risolto mediante l’integrazione delle traiettorie di particelle sintetiche su scale temporali più lunghe (750 giorni) con opportuni modelli di circolazione. Per particelle numeriche rilasciate nella parte più settentrionale del bacino Adriatico, l’utilizzo di un modello statistico di avvezione-diffusione associato alla circolazione superficiale fornisce una scala temporale di 216-260 giorni come tempo massimo di uscita dal bacino stesso. In modo analogo, per una particella in ingresso nel bacino nel lato orientale dello stretto di Otranto, il modello fornisce una stima di 170-185 giorni per il tempo di uscita lungo il lato
occidentale del canale di Otranto. I tempi di residenza nel bacino Adriatico sono dell’ordine dei 150-168 giorni.

Nel Capitolo 3, si esaminano le caratteristiche della dispersione di coppie di drifters superficiali. La dispersione relativa ($D^2$) è calcolata a partire da drifters rilasciati nel mare Adriatico nel periodo 25 Agosto 1990 - 1 Gennaio 2007, sulla base di diverse separazioni iniziali (chan). La dispersione relativa viene interpretata sulla base di due distinti regimi. Il primo, è un regime non-locali che cambia secondo una funzione esponenziale del tempo; il secondo è un regime locale che può essere a sua volta diviso in tre regimi distinti: Richardson-type ($D^2 \sim t^3$), ballistic-type ($D^2 \sim t^2$), ediffusive-type ($D^2 \sim t$). A partire dalle traiettorie dei drifters, sono state inoltre ricavate le distribuzioni dei campi degli esponenti di Lyapunov a scala-finita (finite-scale Lyapunov exponent, FLSE) e le Lagrangian Structure Functions (LSF), che descrivono le proprietà fisiche intrinseche ad una data scala per il mare Adriatico. Sono stati inoltre calcolati altri descrittori statistici (angolo medio di separazione, displacement kurtosis, e dispersione assoluta) che permettono una conoscenza più dettagliata del comportamento delle coppie di drifters.


Al fine di validare il modello, le statistiche di trasporto delle particelle numeriche attraverso tre sezioni lungo la costa italiana (Conero, Gargano e stretto di Otranto) sono state confrontate con le statistiche di trasporto derivate dai drifter per le stesse aree. Il confronto suggerisce che le particelle numeriche derivate dalla simulazione modellistica sono più lente delle particelle “simulate” a partire da campi di velocità dei drifters, a causa di un minor contenuto energetico delle correnti stimate dal modello numerico nel periodo considerato.

Dopo aver filtrato la circolazione euleriana media, per le particelle numeriche sono state inoltre calcolate le statistiche lagrangiane per l’intero bacino adriatico. I valori di momento angolare medio, di diffusività e covarianza sono minori di quanto calcolato dai drifter reali; tuttavia la scala temporale integrale lagrangiana rimane invariata tra i due casi (simulazioni - dati reali).

Al fine di tener conto delle diverse condizioni meteorologiche tra il 2007 e 2008, e dei diversi valori di energia cinetica del campo medio ($\text{MKE} = 3.14e-009$, $3.79e-009$ $\text{km}^2\text{s}^{-2}$ per
gli anni 2007 e 2008) e di energia cinetica media del campo turbolento (2.56e-009 e 2.90e-009 km²s⁻² per il 2007 e 2008), e per valutare la loro diversa influenza sulle scale di trasporto, i confronti e le statistiche sono state ripetute separatamente per i due anni. I risultati ottenuti hanno evidenziato che gli effetti della circolazione indotta dal vento a nord del fiume Po, e gli effetti dell’apporto di acque dolci del fiume Po stesso sulla circolazione superficiale determinano valori confrontabili dei tempi di residenza (182 giorni e 185 giorni) per i due anni esaminati (2007 e 2008).

Keywords: Adriatic Sea, Lagrangian Statistics, Transit and Residence Times, Relative Dispersion, Finite-Scale Lyapunov Exponent.
Chapter 1

Introduction

1.1 Objectives and structure of the thesis

Lagrangian drifters are especially suitable to study transport processes since they move with the currents following closely the motion of water parcels, at least at the large and mesoscale, considering that transport by ocean currents plays a crucial role in many scientific and applied marine issues.

In the coastal zone and semi-enclosed seas, transport by surface currents are even more important due to the variety of flotsam and jetsam, like debris, pollutants, oil spills, persons lost at sea, etc., encountered in the vicinity of populated coasts and highly navigated areas.

The Adriatic Sea is an interesting and challenging place for such kind of problems because of strong boundary currents and interior gyres.

The objective of this thesis is to simulate and study passive tracer dispersion by statistical properties of the currents in the Adriatic Sea from velocity data produced by numerical model outputs and real drifter data set.

Each chapter of thesis consists of the content of manuscript which is ready to be submitted to peer reviewed journals.
In chapter 2, the entire surface drifter dataset available in the Adriatic Sea (1990-2007) is used in concert with a Lagrangian circulation model to estimate the surface residence time in the basin, and surface transit times between different locations within the semi-enclosed sea. In particular, the transit times before leaving the Adriatic via the western Otranto Channel and the transit times after entering the basin through the eastern Otranto Channel are considered in order to investigate the exchange between the two sub-basins.

In chapter 3, we examine the relative dispersions, finite-scale Lyapunov exponents and Lagrangian structure function using 358 surface drifters deployed in the Adriatic Sea for different initial separation distances. We apply both chance and original pairs in this study.

In chapter 4, in order to investigate the transport properties of the basin, we have decided to utilize a numerical model, to generate synthetic particles from the velocity fields obtained by the MIT general circulation model implemented in the Adriatic Sea for the period from October 2006 till the end of 2008. The aim of this work is to quantify the near-surface transport properties in the Adriatic Sea, a semi-enclosed basin by using synthetic drifters. In the second part of this chapter, values of Lagrangian velocity covariance, diffusivity, mean angular momentum, Lagrangian time and space scales have been calculated to have more comparisons and differences between the behavior of trajectories in 2007 and 2008.
Chapter 2

Transit and Residence Times in the Surface Adriatic Sea as Derived from Drifter Data and Lagrangian Numerical Simulations

Abstract:

Statistics of transit and residence times in the surface Adriatic Sea, a semi-enclosed basin of the Mediterranean, are estimated from drifter data and Lagrangian numerical simulations. The results obtained from the drifters are generally underestimated given their short operating lifetimes (half life of $\sim 40$ days) compared to the transit and residence times. This bias can be removed by considering a large amount of numerical particles whose trajectories are integrated over a long time (750 days) with a statistical advection-diffusion model of the Adriatic surface circulation. Numerical particles indicate that the maximum transit time to exit the basin is about 216-260 days for objects released near the northern tip of the Adriatic, and that a particle entering on the eastern Otranto Channel will typically exit on the other side of the Channel after 170-185 days. A value of 150-168 days is estimated for the residence time in the Adriatic basin.

This work is under review to be published on Ocean Science Journal (An Interactive Open Access Journal of the European Geosciences Union).
2.1 Introduction

Transport by ocean currents plays a crucial role in many scientific and applied marine issues. For instance, basin scale circulation and mesoscale currents are responsible for the advection and mixing of water mass properties, and hence control their distribution. Near-coastal currents contribute significantly to the mixing of coastal waters with the open sea. In the coastal zone and semi-enclosed seas, transport by surface currents are even more important due to the variety of flotsam and jetsam, like debris, pollutants, oil spills, persons lost at sea, etc., encountered in the vicinity of populated coasts and highly navigated areas (Jordi et al., 2006; Davidson et al., 2009). Ocean currents also play a major role for the transport of eggs and larvae (Hare et al., 2002), and can have a significant effect on marine animal migration patterns (for instance for turtles in the Mediterranean, Hays et al., 2010).

A useful indicator for water mass mixing, and biogeochemical processes, is the residence time in a basin, that is, the mean time that a water particle stays in the basin. The concept of residence time has been described and applied in several coastal areas and semi-enclosed seas (see for instance, Takeoka, 1984; Buffoni et al., 1997; Falco et al., 2000). The transit time probability density function (pdf) is a diagnostic commonly used to summarize the rate at which water particles are transported from one region to another via a multiplicity of pathways (Holzer and Hall, 2000). The first moment of this pdf, referred to as the mean transit time or mean age, has become an important transport diagnostic commonly used by both the observational and modeling communities.

Observations of ocean currents and dispersion with surface drifters have been used effectively to describe and quantify the transport characteristics from the global scale (Niiler et al., 2003) to marginal seas (Falco et al., 2000; Lacorata et al., 2001) and
selected coastal areas (Haza et al., 2010; Veneziani et al., 2007, Choukroun et al., 2010). In particular, the Adriatic Sea, a semi-enclosed basin of the Mediterranean, connected to the Ionian Sea through the Otranto Channel (Figure 2.1), has been extensively studied over the last decades with surface drifters. The mean surface circulation, its seasonal and mesoscale variability, and the role of the wind-forcing have been investigated by Poulain (2001) and Ursella et al. (2006). Adriatic surface transport properties have been studied by Falco et al. (2000). Relative dispersion as measured by drifters has been addressed by Lacorata et al. (2001) and the statistical prediction of drifter trajectories has been discussed by Castellari et al. (2001) and Veneziani et al. (2007).

The entire surface drifter dataset available in the Adriatic Sea (1990-2007) is used in concert with a Lagrangian circulation model to estimate the surface residence time in the basin, and surface transit times between different locations within the semi-enclosed sea. In particular, the transit times before leaving the Adriatic via the western Otranto Channel and the transit times after entering the basin through the eastern Otranto Channel are considered in order to investigate the exchange between the two sub-basins. Two major problems arise when using real drifters to estimate residence or transit times: (1) The finite lifetime (“mortality”) of the drifters and the scarcity of drifter data can introduce significant random and bias errors. The statistical results can also be dependent upon the specific deployment locations selected; (2) The trajectories of surface drifter can be directly affected by the winds and waves, and as a result, deviate from those of real water particles. The first problem can be assessed and somehow alleviated by using a statistical model, whose parameters are derived from the drifter data themselves, to generate the tracks of many and long-lived numerical particles, from which the statistics are calculated. For the second problem, we can correct the drifter velocities (see Poulain et al., 2009) to remove the direct-
wind effect, which is not easy in the Adriatic where winds are highly variable both in space and time, but it is impossible to reconstruct wind-independent drifter tracks and to estimate the transport properties based on them. As a result, caution is needed when applying our results to surface water transports, but they are certainly useful estimates for debris and oil spills which also are directly affected by the winds.

2.2 Data and methods

2.2.1 Data

Surface drifters were used in the Adriatic Sea since 1990 to study the spatial structure and temporal variability of its circulation (Poulain, 2001 and references therein; Ursella et al., 2006). In total 358 satellite-tracked drifters were operated in the Adriatic basin, between 25 August 1990 and 1 January 2007. All drifters used the satellite Argos system for the telemetry of the data and their localization. Some drifters were equipped with a Global Positioning System (GPS). The majority of the drifters were CODE drifters designed to measure the currents in the first meter under the sea surface (Davis, 1985; Poulain, 1999) with accuracy less than 3 cm s$^{-1}$ (see Poulain et al., 2012 and references therein).

The raw drifter positions were edited to remove spikes and outliers, filtered to remove high-frequency currents (tidal and inertial currents) and interpolated at fixed 6-h intervals (Hansen and Poulain, 1996; Poulain, 2001). Velocities were calculated as finite differences between successive positions. The geographic drifter positions were transformed into distances from a central point (longitude 16°E15’, latitude 42°N45’) after a counter-clockwise rotation of 45 degrees of the Adriatic Sea. All the results in this chapter are presented in this reference system.
2.2.2 Methods

The mean surface flow in the Adriatic Sea was computed by averaging all the drifter velocities in circular bins of 10 km radius organized on a uniform grid with 10 km cell size (Figure 2.1). Only bins with at least 5 observations were considered for the pseudo-Eulerian statistics. Similar pseudo-Eulerian velocity averages were computed by Poulain (1999, 2001) and Ursella et al. (2006).

A Lagrangian statistical model, whose parameters are derived from the data, was used to generate numerical particles. It is based on the assumption that the transport of a particle can be separated into two processes: the advection due to the mean velocity field \( U \) and the turbulent transport \( u' \) that is characterized from the diffusivity \( K \) (Falco et al., 2000). Bold italic symbols represent 2D vectors. The mean flow \( U \) was taken as the one estimated from the real drifters. The model is a “random flight model” (Thompson, 1986; Falco et al., 2000) and its equations are in the zonal direction (x-coordinate):

\[
\begin{align*}
\frac{dx}{dt} & = (U + u') dt, \\
\frac{du'}{dt} & = -\left( \frac{1}{T_{Lx}} \right) u' dt + \sqrt{\frac{\sigma_x^2}{T_{Lx}}} dw,
\end{align*}
\]

where \( \sigma_x^2 \) is the velocity variance, \( T_{Lx} \) is the Lagrangian integral time scale (for \( t \gg T_{Lx} \), \( T_{Lx} = K/\sigma_x^2 \) and \( dw \) is a random increment from a normal distribution with zero mean and second order moment. The same equations are valid for the meridional direction (y-coordinate). The time step \( dt \) was taken as 1 h and the model parameters were taken from Poulain (2001): \( \sigma_x^2 = 106 \text{ cm}^2\text{s}^{-2} \), \( \sigma_y^2 = 70 \text{ cm}^2\text{s}^{-2} \), \( T_{Lx} = T_{Ly} = 1.6 \) days (a mean value between 2.1 and 1.1 days for the along- and across-basin directions, respectively). Each numerical particle trajectory was obtained by integrating equations (2.1) and (2.2) with a different realization of the turbulent process and interpolating \( U \) between grid points using a Runge-Kutta fourth-order
Lagrangian interpolation scheme. Eight numerical particles were “deployed” at each grid point of the grid with 10 km resolution and spanning the entire Adriatic, so that, in total, 1000 particles were integrated over a period of 750 days. The choice of 1000 numerical particles is quite arbitrary, it is however important that it is much larger than the number of real drifters in order to provide robust statistical results. Thanks to a reflection condition, the numerical particles approaching the coast are bouncing back inside the basin. They can exit at the Otranto Channel but are not considered if they re-enter the Adriatic Sea.

Two sections were chosen in the Otranto Channel (Figure 2.1b). The western one corresponds to the outflow and connects the Italian coast at point [341.1,-70.8] km to point [365.9,-43.2] km where the speed of the mean flow derived from the drifters is equal to zero. The second section on the eastern side connects the Albanian coast ([371.3, 13.82] km) point to point [350, -30] km where the mean flow is nil. It corresponds to the inflow into the Adriatic Sea. The trajectories of the real drifters and numerical particles exiting through the Otranto Channel section were selected. After having divided the basin in squares of size 25 km of side, the pdfs of the transit times to exit the Adriatic Sea (i.e., to cross the western Otranto section), its mean and standard deviation and the number of observations were calculated in each square. Likewise, the transit time pdfs of the drifters and numerical particles entering the basin through the eastern Otranto section were calculated for all the squares in the basin. Note that if many 6-h observations of the same drifter are included in a given square, all the sub-tracks initiating from these observations were considered to compute the transit time statistics.

The residence time is defined as the average time spent by a tracer particle in the basin. The normalized population in the basin, \( C(t) \), and its residence time, \( T \), are defined by Buffoni et al. (1997):
where \( c(t,x) \) is the average normalized tracer concentration at point \( x \) and time \( t \), and \( \Omega \) represents the basin. \( C(t) \) and \( T \) can also be defined in the Lagrangian framework as:

\[
C(t) = \frac{N(t)}{N(0)} \quad \text{(2-5)}
\]

\[
T = \lim_{t \to \infty} T^* \quad \text{(2-6)}
\]

\[
T^* = \frac{tN(t)}{N(0)} + \sum_{i=1}^{N_e(0)} \frac{t_{e_i}}{N(0)} \quad \text{(2-7)}
\]

where \( N(0) \) is the number of tracer particles initially deployed in the basin, \( N(t) \) is the number of particles at time \( t \), \( N_e \) is the number of particles that have already escaped the basin at time \( t \), and \( t_{e_i} \) is the escape time of the \( i^{th} \) particle. Note that for the calculation of the residence time the southern boundary of the Adriatic Sea in the Otranto Channel is taken as the 40\(^{th}\) parallel north.

### 2.3 Results

The mean surface circulation in the Adriatic Sea estimated from the real drifters (Figure 2.1) shows the basin-scale cyclonic circulation with Ionian waters entering on the eastern flank of the Otranto Channel and flowing northwestward off Albania and Croatia as the Eastern Adriatic Current (EAC). The basin-scale circulation is actually composed of 3 cyclonic cells with waters from the EAC splitting and crossing the basin at the levels of the northern walls of the southern and central Adriatic Pits, and in the vicinity of the Istrian Peninsula (Poulain, 2001; Poulain and Cusman-Roisin, 2001). A forth cyclonic loop appears near the northern end of the basin. Along the Italian coast, a strong coastal current, the Western Adriatic Current (WAC), flows
towards the southeast and the surface waters eventually exit on the western side of the Otranto Channel.

Figure 2.1 (a) Drifter trajectories in the Adriatic Sea for the period August 1990 – January 2007. (b) The mean flow obtained by averaging the drifter data in circular bins of 10 km radius. Selected geographical names and two sections in the vicinity of the Otranto Channel are shown, as well as the three squared areas considered for the transit time pdf’s shown in Figures 2.2 and 2.4.

Example of pdf’s of the transit times of numerical particles between areas selected in the northern, central and southern Adriatic (see squares in Figure 2.1b) and the western Otranto Channel are shown in Figure 2.2. In total, more than 1800 tracks connect the areas to the Otranto section, including all the sub-tracks of the same numerical particle as long as the 6-h observations are localized in the departure
squared area. The distributions are not Gaussian, with mean values of about 210, 168 and 121 days, respectively for the areas in the northern, central and southern Adriatic.

Figure 2.2 Example of transit time pdf’s computed from numerical (right) and real (left) particles starting in the selected areas shown in Figure 2.1b in the northern (top), central (middle) and southern (bottom) Adriatic and leaving the Adriatic Sea through the western Otranto Channel.

The pdf’s are significant skewed with a long “tail” corresponding to long transit times. The maximum transit time is about 736.75 days, which is less than the integration times of the numerical particles (750 days). Thus we can assume
negligible effect of the finite lifetime on the transit time statistics. With real drifters, the number of tracks is drastically reduced (39 to 242) and the mean transit times are 153, 58 and 52 days, whereas the maximum transit time is 239.5 days (for the northern box).

Despite the above-mentioned problems of non-gaussianity and limited number of real drifter observations, it is interesting to look at the spatial distribution of the mean transit times to exit through the Otranto Channel as estimated from both real and numerical particles (Figure 2.3). The tracks of all the real drifters which exited the Adriatic are also shown. Along the Italian coast, in the WAC, the mean transit time of numerical particles is less than 90 days south of Gargano, and less than 140 days south of Conero. In front of the Po River it is about 190 days, and stays above this value on the eastern side of the basin as far south at the eastern Otranto Channel. In the mean sense, a surface particle entering at Otranto stays in the Adriatic about 180 days before exiting on the other side of the channel. The transit time standard deviation varies between 65 days (near the exit) and 135 days (in most of the basin).

If the same statistics are computed with the real drifters, the spatial distribution of mean transit time is very different and values are systematically smaller: it is maximal off the Istrian Peninsula (> 200 days) but it is less than 100 days in most of the Adriatic. Specifically, it is about 80 days near Conero and 55 days near Gargano.

Let us now consider the transit times of surface drifters and numerical particles after their entrance in the eastern Otranto Channel. The transit time pdfs to reach the selected squared areas depicted in Figure 2.1b are shown in Figure 2.4. Compared to the distributions considered before (Figure 2.2) the number of tracks is considerably reduced: only 175 (62) numerical (real) tracks reach the square in the southern Adriatic. Mean transit times for numerical particles range in 129-225 days, compared to 27-62 with real drifters.
Figure 2.3 Trajectories of the real drifters exiting the Adriatic Sea (a). Geographical distribution of the mean transit times to exit via the western Otranto Channel (through section shown with black line) estimated from real drifters (b) and numerical particles (c).
Figure 2.4 Same as Figure 2.2 but for the drifters entering through the eastern section of the Otranto Channel and reaching the areas depicted with squares in Figure 2.1b.

The tracks of the real drifters entering the Adriatic Sea via the western Otranto section, and the mean transit times to reach all the areas of the Adriatic with real and numerical drifters are displayed in Figure 2.5. The mean transit time from Otranto Channel is less than 135 days in the EAC as far north as the Dalmatian Islands in
front of Split, Croatia. It reaches 180 days in the vicinity of the Istrian Peninsula. Maximal values larger than 250 days are found in the open central Adriatic.

Figure 2.5 Trajectories of the real drifters entering the Adriatic Sea (a). Geographical distribution of the mean transit time after entering on the eastern side of the Otranto Channel (through section shown with black line), estimated from real drifters (b) and numerical particles (c).
In the WAC, values range between 150 and 230 days. In agreement with the results shown in Figure 2.3c, the mean transit time from the eastern to the western sides of the Otranto Channel is about 180 days with standard deviation of 135 days. The standard deviation around these values vary essentially between 20 and 165 days. For the real drifters, mean transit times from the Otranto Channel are significantly lower and are bounded by 150 days. Maximal values appear in the open central Adriatic. In the WAC south of Gargano values are near 100 days, that is the same order of magnitude as with the numerical particles.

Finally the residence time, $T^*$, was estimated from the real drifters and numerical particles (Figure 2.6 and Table 2.1). For the real drifters, $T^*$ was calculated using only the 83 drifters which exited through the Otranto Channel. Saturation occurs after 150 days and the residence time $T$ is about 70 days. In contrast, with numerical particles, $T^*$ reaches 168 days after the maximum integration period of the particles (750 days). The rate of change of $T^*$ at 750 days is equal, by taking the temporal derivative of equation (2.7), to the percentage of particle remaining in the basin, i.e., $(1000-986) / 1000 = 1.4\%$. Thus, $T^*$ appears to asymptote to a constant value near 170 days.

![Figure 2.6 Residence time $T^*$ versus time estimated from the real drifters and the numerical particles.](image-url)
We have checked that the numerical drifter population is decaying quasi-exponentially. Theory shows that for an exponentially decaying population, the residence time converges, as time increases, to a constant value equal to the half life divided by ln(2). Hence, the half life of the numerical particles in the Adriatic basin is about 120 days.

In order to assess the sensitivity of the transit and residence time results, we have also integrated the particles with a random flight model whose parameters correspond to the values found by Ursella et al. (2006) for the northern and central Adriatic. Values of \( \sigma^2_x = 77 \text{ cm}^2\text{s}^{-2}, \sigma^2_y = 51 \text{ cm}^2\text{s}^{-2}, T_L = 1.3 \text{ days} \) yield the following results: mean transit time between area off Istria (northern Adriatic) and western Otranto Channel of 216 days, and residence time of 150 days. If the numerical particles are only advected by the mean flow (case of no turbulence), the mean transit between the northern Adriatic and Otranto areas is about 100 days, and the residence time is about 250 days. Numerical particles were also integrated over 1000 days yielding slightly superior values. Transit times between the entrance and exit through the Otranto Channel were also considered. A mean value of 130 days was found for the case without turbulence whereas the other simulations yielded values of 170-185 days. All the statistical results are summarized in Table 2.1.
Table 2.1 Summary of transit and residence time statistics using numerical particles.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Integration time</th>
<th>$T^*$</th>
<th>Transit Time (Trieste-Otranto)</th>
<th>Transit Time (Otranto-Otranto)</th>
<th>Number of particles exiting Adriatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>No turbulence</td>
<td>750 days</td>
<td>250</td>
<td>100 days</td>
<td>130 days</td>
<td>678</td>
</tr>
<tr>
<td>Turbulence (Poulain, 2001)</td>
<td>750 days</td>
<td>166</td>
<td>250 days</td>
<td>180 days</td>
<td>986</td>
</tr>
<tr>
<td>Turbulence (Poulain, 2001)</td>
<td>1000 days</td>
<td>168</td>
<td>260 days</td>
<td>185 days</td>
<td>998</td>
</tr>
<tr>
<td>Turbulence (Ursella et al., 2006)</td>
<td>750 days</td>
<td>150</td>
<td>216 days</td>
<td>170 days</td>
<td>995</td>
</tr>
</tbody>
</table>

2.4 Discussion and conclusions

This chapter describes the piece of work combining experimental data and modeling to obtain a better insight of the large scale dynamics of the Adriatic Sea. It provides the continuation of the work that has been carried out for years now with consideration for residence time and transit times. Estimating transport timescales using drifters is not a "new" subject, but the data are original, considering that compared to the other related works, we used all drifters deployed in Adriatic Sea (358 surface drifter) between 25 August 1990 and 1 January 2007 (from Dolcevita, Dart, Med and Egitto projects). A large number of drifters in these experiments helps us to be more precise regarding obtained results and this is the best one can do at present. Nevertheless, the other difference is the approach that has been used for different places and areas to calculate the transit time.

Therefore residence and transit times for the Adriatic surface circulation have been estimated from real data provided by satellite-tracked drifters and from tracks of numerical particles integrated with a simple statistical Lagrangian model. The results
obtained with the real drifters are systematically underestimated due to the limited operating period of the drifters. In fact, drifters in the Adriatic Sea have a typical mean half-life of 35-40 days (Poulain, 2011; Ursell et al., 2006) which can be less than some transit times and less than the residence time in the basin. As a result, transit time pdfs are significantly biased or skewed towards low values. In addition, the statistical results can also be dependent on the specific deployment locations. In contrast, with the tracks of numerical particles integrated for a long period (750 days) with a statistical Lagrangian model whose foundation is based on the real drifter results (in terms of mean flow and eddy kinetic energy or diffusivity levels) one can control the deployment array (e.g, uniform throughout the basin), the lifetime (750 days with no mortality and no stranding), and the number (1000) of particles. Using a simple advection-diffusion model, we have obtained more accurate and robust results for the transit times of objects (water particles, pollutants, oil spills, persons, etc.) in the Adriatic Sea under the influence of the near-surface currents, and to a lesser extent, of the local winds. For instance, we have found that the maximum mean time to exit the basin is 216-260 days for objects released in the very northern Adriatic, and that in the mean sense, a particle entering the Adriatic through the eastern Otranto Channel will exit the basin on the other side of the channel after about 170-185 days. We have also estimated that the residence time, that is the mean time a particle randomly deployed in the Adriatic stays in the basin before exiting, is 150-168 days. This value is lower than 200 days, the estimate of Falco et al. (2000) using numerical simulations of drifters released in the vicinity of the eastern Otranto Channel. This discrepancy is mostly due to the different deployment strategy: here numerical particles are deployed uniformly throughout the basin, and those caught in the fast WAC probably contribute to reduce the residence time.
The half life of 120 days corresponding to our numerical drifter population in Adriatic Sea was found significantly longer than the half life of the real drifters (∼40 days) operated in this marginal sea.

More accurate transit and residence times could be estimated by considering numerical simulations with space-dependent and non-isotropic velocity variance, integral time scale and diffusivity, as it is known that these values vary significantly in the basin and also with the proximity of the coast (see for example Ursella et al., 2006). The transport statistics could also be estimated for the different seasons of the year since the Adriatic circulation is known to vary seasonally (Poulain, 2001). But this can become a useless endeavor and better results are not guaranteed. It is proposed instead to use high-resolution hydro-dynamical models of the Adriatic circulation, possibly tuned in order to have the same mean flow and energy levels as the drifters, to integrate numerical particles in time-dependent velocity fields and compute Lagrangian statistics such as the transit and residence times.

References


Haza, A., Ozgokmen, T., Griffa, A., Molcard, A., Poulain, P.-M. and Peggion, G.:


Chapter 3

Relative Dispersion in the Adriatic Sea Derived from Drifter Data

Abstract:

In this chapter we examine the dispersion characteristics of surface drifter pairs in the Adriatic Sea. Relative dispersion of all surface drifters deployed in the Adriatic Sea between 25 August 1990 and 1 January 2007 has been calculated for different initial separation distance, using both chance and original pairs.

Relative dispersion \( D^2 \) is explained in two different regimes. First non local regime which changes as an exponential function of time, the second one is local regime and it can be divided in three separated parts, Richardson \( (D^2 \sim t^3) \), ballistic\( (D^2 \sim t^2) \) and diffusive\( (D^2 \sim t) \) regimes. The distribution of finite-scale Lyapunov exponent (FLSE) fields in the Adriatic Sea and Lagrangian Structure Function (LSF) have also been calculated from drifter trajectories, which both describe intrinsic physical properties at a given scale, also values of mean separation angle, displacement kurtosis and absolute dispersion have been found which can help us to know more about the behavior of pair trajectories.

3.1 Introduction

Relative dispersion is used in many practical applications such as understanding and predicting the spreading of pollutants and biological quantities in the ocean.
Relative dispersion has become an area of intensive research (e.g. LaCasce and Bower, 2000; Mariano and Ryan, 2006), but it remains unclear to what extent regimes of relative dispersion are realized in the ocean and, in particular, in complex coastal flows.

Several floats were deployed in pairs in the North Atlantic Current program, and it was the first effort to study relative dispersion on isopycnal surfaces (Rossby, 1996; Griffa et al., 2007).

Relative dispersion in the Adriatic Sea has been examined by Lacorata et al. (2001) using 37 real drifters and an idealized kinematic numerical model.

Haza et al. (2008) used synthetic drifter trajectories computed from velocity data produced by a high-resolution NCOM model to investigate the scaling of relative dispersion and the distribution of finite-scale Lyapunov exponent (FSLE) fields in the Adriatic Sea.

Poje et al. (2010) mentioned that the energetic meso-scale features of the flow that are relatively insensitive to the resolution of finer scale motions can control particle dispersion at large time and space scales.

On the other hand the Finite-Scale Lyapunov Exponent (FSLE), introduced for the predictability problem (Aurell et al., 1997; Artale et al., 1997), is a suitable tool to describe non-asymptotic properties of transport.

The aim of this chapter is to examine the dispersion characteristics of surface drifter pairs in the Adriatic Sea for different initial separation distances.

In this work we address to the following question: “what are the regimes of relative dispersion in the Adriatic sea?”

Compared to the other related works, we used all drifters deployed in Adriatic Sea between 25 August 1990 and 1 January 2007. A large number of drifters in these
Relative dispersion in the Adriatic Sea derived from drifter data

experiments help us to be more precise regarding obtained results and this is the best one can do at present.

In particular the values of finite-scale Lyapunov exponent (FLSE) fields in the Adriatic Sea and Lagrangian Structure Function (LSF) are calculated from drifter trajectories, which both describe intrinsic physical properties at a given scale.

3.2 Data set and methods

Surface drifters were used in the Adriatic Sea since 1990 to study the spatial and temporal variability of its circulation (Poulain, 2001 and references therein; Ursella et al., 2006). In total 358 satellite-tracked drifters were operated in the Adriatic basin, between 25 August 1990 and 1 January 2007. All drifters use the satellite Argos system for the telemetry of the data and their localization. Some drifters were equipped with a Global Positioning System (GPS). The majority of the drifters were CODE drifters designed to measure the currents in the first meter under the sea surface (Davis, 1985; Poulain, 1999).

Different initial separations are used for identifying pairs. We did it for the range between $0 < \delta_0 < 1$ and $149 < \delta_0 < 150$ km and the values of dispersion and other related parameters are calculated for all these cases.

The numbers of pairs as a function of initial separation are tabulated in Table 1. After the pairs were found, various quantities such as Relative dispersion, absolute dispersion, relative diffusivity, Finite-Scale Lyapunov Exponent and Lagrangian structure function, have been calculated.
Table 3.1 Number of pairs as a function of initial separations

<table>
<thead>
<tr>
<th>Initial separation distance (km)</th>
<th>0-1</th>
<th>2-3</th>
<th>9-10</th>
<th>22-23</th>
<th>41-42</th>
<th>43-44</th>
<th>53-54</th>
<th>60-61</th>
<th>84-85</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pairs</td>
<td>196</td>
<td>140</td>
<td>53</td>
<td>151</td>
<td>100</td>
<td>121</td>
<td>86</td>
<td>93</td>
<td>117</td>
</tr>
</tbody>
</table>

Relative dispersion, which has an important role in turbulent theory and is related to scalar fluctuations in the flow field, is given by (Batchelor, 1952):

\[
\left\langle D_{ij}^2(t) \right\rangle \equiv \frac{1}{N_{\text{pairs}}} \sum_{i,j} y_i(t) y_j(t) \tag{3-1}
\]

\[
\left\langle D^2 \right\rangle \equiv \left\langle D_{11}^2 \right\rangle + \left\langle D_{22}^2 \right\rangle \tag{3-2}
\]

where \( y_i \) is the separation along \((i = 1)\) or across-basin \((i = 2)\) direction and \( N \) is the number of pairs. The average is over all pairs of particles.

The absolute dispersion is calculated by:

\[
\left\langle X_{ij}^2(t) \right\rangle \equiv \frac{1}{M_{\text{particles}}} \sum_{\text{particles}} \left( x_i(t) - \left\langle x_i(t) \right\rangle \right) \left( x_j(t) - \left\langle x_j(t) \right\rangle \right) \tag{3-3}
\]

where \( x_i \) is the particle displacement from its initial position and \( M \) is the number of particles.

The relative diffusivity is given by (Batchelor, 1952):

\[
K_{ij}(t) \equiv \frac{1}{2} \frac{d}{dt} \left\langle D_{ij}^2(t) \right\rangle \tag{3-4}
\]

where the single subscript, \( i = 1, 2 \), indicates displacements along- and across-basin directions, respectively.
Also it would be useful to calculate the relative velocities

\[ \langle \left( \frac{dD_i}{dt} \right)^2 \rangle = \langle (u_i(t) - u_j(t))^2 \rangle \]

(3-5)

where \( u_i \) and \( u_j \) are the velocities and single subscript, \( i = 1, 2 \), indicates displacements along- and across-basin directions, respectively.

Another metric related to relative dispersion is the Finite-Scale Lyapunov Exponent introduced by Artale (1997) and Aurell (1997):

\[ \lambda(\delta) = \frac{\ln(r)}{\langle \tau_r(\delta) \rangle} \]

(3-6)

where \( \langle \tau_r(\delta) \rangle \) is the averaged time required to separate from a distance of \( \delta \) to \( r\delta \).

The ratio \( r \) is often referred to as the doubling factor even though it is not necessarily equal to 2 for example in this work we used 1.4.

The value of \( r \) must be larger than one, thus \( r\delta_0 - \delta_0 \geq \Delta t \Delta v \) where \( \Delta v \) is the velocity difference between particles in a pair, this leads to \( r_{\min} = 1 + \Delta t \Delta v / \delta_0 \) (Haza et al., 2008).

Another interesting quantity related to FSLE is the Lagrangian structure function (LSF), and it is defined as:

\[ \nu(\delta) = \left\langle \sqrt{(u_i - u_j)^2 + (v_i - v_j)^2} \right\rangle_{\delta} \]

(3-7)

\( u \) and \( v \) are the velocities along and across-basin direction respectively, where the average is over all pairs at the moment in which the separation reaches a scale \( \delta \).

Another measurement related to pair particles is the angle between their velocities (Koszalka et al., 2009).
\[ \theta = \cos^{-1}\left( \frac{\mathbf{u}_1 \cdot \mathbf{u}_2}{\|\mathbf{u}_1\| \|\mathbf{u}_2\|} \right) \]  

(3-8)

We also calculated kurtosis:

\[ ku = \frac{< D^4 >}{(< D^2 >)^2} \]  

(3-9)

Gaussian distributions have a kurtosis of three.

3.3 Results

3.3.1 Relative dispersion

To examine the relative dispersion we used equation (3-1) for all pairs.

Figures 3.1a,b,c show relative dispersion for drifter pairs with the initial separations \( 0 < \delta_0 < 1, 0 < \delta_0 < 2 \) and \( 2 < \delta_0 < 3 \) km for three sample cases. The plots show that the relative dispersions exhibit nonlinear initial growth, followed by approximately linear growth after 20~25 days for all cases. For the initial separation less than 1 km the exponential regime is extended for less than one day but for the larger initial separation this region grows till 3 days. So three distinct growth phases exist. At first time steps just for few days (in some cases just one day), pair separation grow exponentially with time, after this phase relative dispersion growth is scaling approximately like \( t^2 \) and finally for time larger than a month relative dispersion slows down considerably to the diffusive regime. By increasing the value of initial separation distance the time range which is dominated by nonlocal regime increases.

For the small initial separation distance (less than 1 km) we can see that the Richardson law exists and after this part the ballistic (shear) region appears and then dispersion slows down to diffusive regime but for large values of initial separation
after nonlocal regime relative dispersion enters directly to the diffusive regime or maybe it is better to say super diffusive region scaling nearly ballistically.

The absolute (single particle) dispersion also is used for more comparison. Figure 3.1d shows the absolute dispersion for all drifters data set vs time. As it is clear from Figure 3.1d the absolute dispersions appear to grow linearly in time after only the first few days. The maximum value of relative dispersion is a bit larger than its absolute counterpart. While the absolute dispersion appears to increase linearly after $2 \sim 2.5$ days, the relative dispersion exhibits nonlinear growth but the length of this region for different value of initial separation is changeable. For plot which shows the absolute dispersion distribution we have two different slopes. For the first days (till 2 days) the absolute dispersion growth is scaling approximately like $t^2$, after this it increases with slope of $t$. 
Figure 3.1 The relative dispersion for the original pairs and chance pairs. (a) Total relative dispersion (solid line) for pairs with initial distance between $0 < \delta_0 < 1$ km. (b) Total relative dispersion for pairs with initial distance between $2 < \delta_0 < 3$ km. (c) Total relative dispersion for pairs with initial distance between $0 < \delta_0 < 2$ km. (d) The absolute (single particle) dispersion (solid line) for all particles.
3.3.2 Relative diffusivity

Figure 3.2 shows the values of relative diffusivity. The relative diffusivity increases up to a scale of roughly 100 km; it is approximately constant thereafter and somewhat less than twice the absolute diffusivity.

![Graph showing relative diffusivity](image)

**Figure 3.2 Relative diffusivity plotted against separation. The solid black line is the diffusivity from differencing the dispersion, plotted against the square root of the dispersion and blue line shows the absolute diffusivity.**

If we divide the relative diffusivity distribution in three phases, they would be discussed as:

The diffusivity exhibits an approximate power law dependence, with \( K \sim \delta^n \), with 4/3. Changing the value of initial distance separation doesn't affect more on distribution of relative diffusivity especially for starting part of constant region.

The first phase depends to the first 3 days, as we discussed before for relative dispersion it changes exponentially and it is nonlocal regime. It means in this phase dispersion is dominated by eddies with scales larger than the pair separations. We can say that the relative diffusivity increase rapidly during the initial phase just for few days and it has a slope like \( \delta^2 \).
Second phase is the region where we have Richardson and ballistic regime, so in this regime the relative diffusivity is related to separation with \( \delta^{4/3} \) and as mentioned before for most of the test cases it continues till 100 km.

The other result belongs the third phase which relative dispersion has a slope like \( t \), so relative diffusivity is constant in this region although the plot for this regime is a bit noisy.

### 3.3.3 Finite-Scale Lyapunov Exponent (FSLE) & Lagrangian structure function (LSF)

As a further test we calculated Finite Scale Lyapunov Exponents (FSLE) for drifter pairs with different initial separation distance, but found no evidence for exponential growth (Figure 3.3a).

![Figure 3.3 The Finite Scale Lyapunov Exponent (FSLE) from both original pairs and chance pairs. (a) FSLE for pairs with initial distance between \( 0 < \delta_0 < 1 \text{ km} \) (solid line) and \( 2 < \delta_0 < 3 \text{ km} \) (solid line with rectangular symbols). (b) Lagrangian structure function (LSF) values for different initial separation distances.](image-url)
So it is clear that the exponential range for relative dispersion extends more than finite scale Lyapunov exponent, maybe because the initial pair separations are too large compared to the energy-containing scale, $L_E$.

Let’s to discuss more about the slopes for FSLE plots. In case of standard diffusive $D(t) = t$ we can say $\lambda(\delta) \sim \delta^{-2}$ (a linear growth in the relative dispersion would cause $\left(\frac{1}{\tau_r}\right)$ to decrease like $\delta^{-2}$) and on the other local regimes $\lambda(\delta)$ is proportional to $\delta^{\frac{3}{2}}$ and $\delta^{-1}$ for the slopes which follows Richardson law and ballistic regimes, respectively.

For non local regimes where relative dispersion has an exponentially increase the FSLE plot shows maximum value of Lyapunov exponent but as mentioned before we didn't find the FSLE plateau.

We can conclude that when $\lambda(\delta) = $ constant, we have exponential separation between trajectories where the pair spreading can be dominated by eddies larger than the separation scale.

As mentioned by LaCasce (2010) "the chance pairs have a longer initial adjustment prior to the exponential growth phase" (see Babiano et al., 1990).

The other main result is that by increasing the initial separation distance the slope of $\lambda(\delta)$ vs $\delta$ decreasing and the major part of the plots will have the diffusive regimes with slopes $\delta^{-2}$ and this is in agreement with what we also found for the relative dispersion before and to be more precise it is better to say that the relative dispersion in the Adriatic circulation is generally super-diffusive, scaling nearly ballistically and also for major part of tests which we did for different values of $\delta_0$ it is obvious that the slope of FSLE on local regime is so close to ballistic regimes.
For the initial distance $0 < \delta_0 < 1$ km we can also find that there is a region which is between Richardson and ballistic regimes but mostly close to ballistic one.

Following the same procedure it is helpful to compute Lagrangian structure function (LSF).

Figure 3.3b shows plots for LSF, it is clear that the LSF has the same behaviors for finite scale Lyapunov exponent by dimensional arguments and it is expectable that the LSF is proportional to the finite scale Lyapunov exponent.

### 3.3.4 Separation angle

Figure 3.4 shows the mean angle for all pairs with different initial separation distances.

For all cases during the first days, drifters move together and separate slowly, but after 3 days the mean angle increasing and they move more independently thereafter.

For the pairs with initial separation distance $(0 < \delta_0 < 1)$ the mean angle separation after 10 days increasing faster and after 60 days reaching to $80^\circ$ and the slope of increment separation angle slows down and reaches to $90^\circ$ till 100 days.

The other cases have fairly similar behavior for mean separation angle distribution. In the cases which we have the larger initial distance we can expect that the value of separation angle will be larger but after 10 days we see the slopes of increment slow down and more slower than the first case $(0 < \delta_0 < 1)$ but after 60 days the values of $\theta$ are the same and increasing of $\theta$ going with the same slopes for all cases approximately. Also we can say that till 3 days the pairs are correlated for all cases and after 10 days most pairs are decorrelated.
Relative dispersion in the Adriatic Sea derived from drifter data

3.3.5 Displacement distributions

Histograms of the displacements were found for all sets and at all times, and the kurtoses were calculated for pairs with initial distances between $2 < \delta_0 < 3$, $5 < \delta_0 < 6$, $24 < \delta_0 < 25$, $29 < \delta_0 < 30$, $41 < \delta_0 < 42$, $84 < \delta_0 < 85 \text{ km}$. The results in Figure 3.5 are somewhat noisy, but the general pattern is clear. The kurtoses are elevated in the first days for all cases and thereafter the kurtoses falling to three.

Figure 3.4 The mean separation angle between the individual velocities for different initial distances.
3.3.6 Mean square relative velocity

We examined the mean square relative velocities as a further comparison. Figure 3.6 shows the mean square relative velocities for different initial separation distance. Each component has been normalized by twice the single particle velocity variance in the same direction.

First and second plots in Figure 3.6 exhibit a growth in relative velocities over the first 35 days and longer, indicating accelerating pair velocities for drifter pairs with $2 < \delta_0 < 3$ km and $29 < \delta_0 < 30$ km; thereafter the normalized variances are near unity, on the other hand Figures 3.5c and 3.5d show the normalized velocities oscillate about 1 the entire time for pairs with $61 < \delta_0 < 62$ km and $84 < \delta_0 < 85$ km.
Relative dispersion in the Adriatic Sea derived from drifter data

Figure 3.6 The relative velocity variances vs. day for all cases. (a) The relative velocity variances (solid line is the relative horizontal velocity variances and dashed line is the relative vertical velocity) vs. day for pairs with initial distance between $2 < \delta_0 < 3$. (b) The relative velocity variances for pairs with initial distance between $22 < \delta_0 < 23$. (c) The relative velocity variances for pairs with initial distance between $61 < \delta_0 < 62$ km. (d) The relative velocity variances for pairs with initial distance between $84 < \delta_0 < 85$. The variances have been normalized by twice the single particle variances, a value of unity indicates the relative velocities are decorrelated.
3.4 Conclusions

For practical problems in geophysical fluid dynamics and as a classical area of study in fluid mechanics quantification of relative dispersion is important. Study of relative dispersion in the Adriatic Sea has been limited by the limited number of drifter pairs launched with small initial separations.

Our main objective is to study the relative dispersions, finite-scale Lyapunov exponents and Lagrangian structure function using 358 surface drifters deployed in the Adriatic Sea between 25 August 1990 and 1 January 2007. We found both chance and original pairs for different initial separation distances.

The Adriatic Sea is an interesting and challenging place for relative dispersion problems because of strong boundary currents and interior gyres.

In general our results indicate that the relative dispersion in the Adriatic Sea is super-diffusive, scaling nearly ballistically in agreement with Lagrangian observation from a high-resolution coastal model (see for instance Haza et al., 2008).

References


Chapter 4

Lagrangian Statistics from a High-Resolution MITgcm Simulation in the Adriatic Sea

Abstract:

The aim of this work is to quantify the near-surface transport properties and residence times in the Adriatic semi-enclosed basin by using synthetic drifters. We analyzed the simulated trajectories computed from the daily averaged velocity fields obtained by the MIT general circulation model implemented in the Adriatic Sea and integrated for the period from October 2006 till the end of 2008. Each numerical particle trajectory was obtained by integrating and interpolating velocity field between grid points using a fourth-order Runge–Kutta scheme and bilinear interpolation. In particular the surface circulation properties in two contrasting years (2007 with mild winter and cold autumn, 2008 with normal winter and hot summer) are here compared.

A comparison between the transport statistics for numerical particles crossing three selected sections located along the Italian coast (Conero and Gargano Promontories and Strait of Otranto) and the similar statistics driven by an existing climatology of the Adriatic surface velocity field (obtained by drifters measurements) has been carried out in order to corroborate the model results.

Results indicate that the numerical particles are slower in this simulation when comparing them with the particles simulated by the flow field obtained by real
drifters. This is because of the less energetic flow field generated by the MIT general circulation model during the selected years.

Lagrangian statistics for the entire Adriatic basin after removing the mean Eulerian circulation for numerical particles have also been calculated and it can be found that the values of mean angular momentum, diffusivity and Lagrangian velocity covariance are less than the real drifter observations, but maximum Lagrangian integral time scale is the same. Because of the weather condition observed in 2007 and 2008, and the different kinetic energy of the mean flow (the yearly averages of MKE are 3.1408e-009 and 3.7907e-009 \( km^2 s^{-2} \) in 2007 and 2008 respectively) and the mean eddy kinetic energy (2.5638e-009 (2.8961e-009) \( km^2 s^{-2} \) in 2007(2008)) during these years, the comparison between transport properties and Lagrangian statistics has been done considering these two different periods. The obtained results showed that the effects of wind driven recirculation in north of the Po River (which would be as a sea response to the Bora wind field) and Po River discharge on surface circulation induce the value of residence time to be similar during two years (182 (185) days in 2007 (2008)).

4.1 Introduction

The aim of this work is to quantify the near-surface transport properties and Lagrangian statistics in the Adriatic semi-enclosed basin using synthetic drifters computed from the velocity fields obtained by the Adriatic Sea model developed by Querin et al. (2013) using the MIT general circulation model code. Daily averaged surface velocity fields have been used to estimate the transport statistics for numerical particles crossing in three selected sections located along the Italian coast. In particular the surface circulation simulated for two years are considered: 2007-warm, 2008-regular.
4.1.1 Background
The mean Adriatic general circulation in the surface layers is characterized by one
cyclonic gyre in which sea water flows northwards (the East Adriatic Current; EAC), and along the Italian coast (West Adriatic Current; WAC).
Recirculation cells are present at the latitude of the Palagruza sill, the mid Adriatic
pit in front of Split and south of the Istrian Peninsula (Mazzelle, 1914; Feruglio, 1920; Orlic et al., 1992; Artegiani et al., 1997; Poulain, 1999, 2001; Ursella et al., 2006).
This type of circulation is showed in the dynamic height maps relative to depths
between 50 and 200 m compiled by Zore (1956) from hydrographic measurements.
She also indicated the influence of topography on the current field and a strong
seasonality of currents near the coast that is stronger in summer (winter) along the
Italian coast (eastern side). This was only partially confirmed by Poulain (2001)
who has evidenced that the WAC can be located within 10 km of the Italian
coastline and is a bit stronger in summer and it is almost the same during the other
seasons while the EAC is stronger in fall. Summer and fall are the most energetic
seasons (Poulain, 2001; Ursella et al., 2006). In winter and spring maximum
velocities are concentrated near the coast (Poulain, 2001). Mean kinetic energy is
maximal in fall and winter. In the southern WAC speeds are larger and the
velocities measured during spring are lower compared to the other seasons.
The Adriatic surface circulation reveals a strong seasonality which can be explained
in terms of wind-forcing variability (Zore-Armanda, 1966). With Bora wind, the
across-basin re-circulating currents and the WAC are intensified while in Sirocco
regime northward flow without re-circulation dominates in the eastern part of the
basin (Ursella et al., 2006). Moreover, a strong dependence between the WAC and the Po River run-off was observed. The river run-off influenced not only the currents, with an increase of the speed during the high discharge rate, but strengthened also the recirculation around the Middle Adriatic Pit (MAP) (Ursella et al., 2006).

Magaldi et al. (2010) studied the response of the Western Adriatic Current to wind forcing. They considered two types of wind: Idealized and realistic wind conditions by the complex geomorphology of the middle Adriatic basin. They found that the Adriatic Promontories in the absence of wind cause the current to be separate and induce instabilities.

The chapter is organized as follows: Section 4.2 provides information on the Adriatic OGCM (Massachusetts Institute of Technology general circulation model) and the Lagrangian model used to compute the numerical experiments. The statistical results of transit times along the Italian coast (Conero Promontory, Gargano peninsula, Strait of Otranto) computed from numerical particles during 2007 and 2008 are presented in section 4.3.1.

In Section 4.3.2 Lagrangian statistics of the Adriatic Sea in 2007 and 2008 obtained by synthetic drifters and comparison with data (drifter data) are assessed. Section 5 contains the discussion and conclusion about the results.
4.2 Methods and data

In order to investigate the transport properties of the basin, we decided to use a numerical model, to generate synthetic particles from the velocity fields obtained by the MIT general circulation model implemented in the Adriatic Sea for the period from October 2006 till the end of 2008.

4.2.1 The Adriatic OGCM

The MITgcm (Massachusetts Institute of Technology general circulation model [Marshall et al., 1997]) is a three-dimensional, finite volume, general circulation model. The semi-implicit over-arching algorithm of the MITgcm solves the non-hydrostatic, Navier-Stokes equations adopting an implicit linear formulation of the free-surface.

The formulation of the free-surface includes a fully implicit barotropic time stepping, which is unconditionally stable but tends to damp the fast gravity waves.

Vertical diffusion and viscosity terms in the horizontal momentum equations are treated implicitly in time. They are solved using a backward method.

Querin et al. (2006) applied the MITgcm code to a specific sub-basin of the Adriatic Sea (the Gulf of Trieste) using a non-hydrostatic approximation but with different resolution, parameterizations and forcings.

The surface forcing is obtained by interpolating the atmospheric heat and mass fluxes computed by the MFS (Mediterranean ocean Forecasting System) model and the high-resolution wind fields provided by the models ETA006 and ALADIN. The runoff of the main rivers is considered explicitly and imposed as a lateral open boundary condition. The overall implementation of the model is described in detail in Querin et al. (2013).
Tidally induced residual currents in Adriatic Sea are generally supposed to be negligible for large part of the basin and have therefore not considered in these simulations.

More information about the code can be found in the available documentation: (http://mitgcm.org/public/r2_manual/latest/online_documents/manual.pdf).

**4.2.2 The Lagrangian model**

Each numerical particle trajectory was obtained by interpolating $U$ (velocity fields) between grid points and integrating

$$dx = (U) \cdot dt$$  \hspace{1cm} (4-1)

using a fourth-order Runge–Kutta scheme. The time step $dt$ was taken as 1 h.

Considering that the flow fields obtained by the MITgcm in this study are daily averages, linear interpolation in time was applied.

A reflection condition also was used here (same as chapter 2), in case the particles approach the coast line they would come back newly inside the basin.

**4.2.3 Protocol of the numerical experiments**

Overall 1080 particles were integrated over a period of one year (2007 or 2008). The resolution of grid points in both zonal and meridional directions is 0.03125°. The choice of 1080 numerical particles is quite arbitrary. The particles deployed uniformly inside the basin at the same time. We have decided to focus our attention on three sections along the Italian coast that are our study objects.

The First section is named “S1” and it is located in front of the Conero Promontory, a zone in which we recorded the maximum speeds of the WAC. The considered section is a line which connects the following points: [43° 55’ 4’’ N, 14° 16’ 4’’ E]; [41° 59’
Lagrangian Statistics from High-Resolution MITgcm Simulation in the Adriatic Sea

The first point is arbitrary while the second is located where the mean flow is zero.

The section named “S2” goes from the point [41° 59’ 1”N, 16° 23’ 2” E] to another zero mean flow points of space coordinates [42° 19’ 4” N, 16° 42’ 59” E]. This zone is situated in front of the Gargano Promontory.

The third section (“S3”) is located close the Strait of Otranto along a line which connects the following points: [40° 23’ 58” N, 18° 40’ 21” E]; [40° 47’ 18” N, 19° 12’ 47” E]. The section ends where the speed of the WAC is equal to zero in figure 4.1 and the EAC begins in front of the Albanian coast.

Then we have extracted the trajectories from numerical particles passing through each section. After the basin subdivided in squares of 25 km of side, in every square, the value of standard deviation, mean time and most frequent value of time for numerical particles to cross every section have been calculated.

To compare the results related to transit times for numerical particles during 2007 and 2008 with drifter data we selected 6 regions inside the basin as shown in Figure 4.1. Selection of the mentioned regions is not arbitrary considering that we found high number of real data (drifter data) in these areas. R1, R2 and R3 represent the south of the Istria (the north end of the Adriatic), northern and central Adriatic Sea respectively. We selected R4, R5 and R6 to display the regions related to the south of Adriatic, eastern Adriatic Sea and near the Albanian coast (particles entering to the basin from this side).
4.2.4 Statistical analysis of the numerical results

In the second part of this chapter, Lagrangian statistics have been calculated to have more comparisons and differences between the behavior of trajectories in 2007 and 2008. The value of Lagrangian velocity covariance, diffusivity, mean angular momentum, Lagrangian time and space scales have been computed.

Averaging over time and space computed at time lag $\tau$ before (after) the particles are located in a given domain is specified by symbol $\langle \rangle_L$.

So the Lagrangian mean velocity is: $\langle u_i \rangle_L(\tau)$.

The Lagrangian velocity covariance matrix is given by ($i$ and $j$ here represents along and across basin direction respectively as shown in Figure 4.21a):

$$p_{ij}(\tau) = \langle u_i'(0)u_j'(0) \rangle_L$$

(4-2)
where \( x_i(\tau) \) and \( u'_i = u_i - \langle u'_i \rangle_L \) \( (i = 1, 2) \) are respectively the particle position and residual Lagrangian velocity components.

The diffusivity matrix (Davis, 1991) is therefore defined as:

\[
K_{ij}(\tau) = \left\langle u'_i(0) \left( x_j(0) - x_j(-\tau) \right) \right\rangle_L
\]

(4-3)

The Lagrangian covariance related to diffusivity matrix by

\[
K_{ij}(\tau) = \int_{-\tau}^{0} \mathcal{P}_{ij}(t) dt
\]

(4-4)

The mean angular momentum which is the difference between the off-diagonal elements of the diffusivity matrix is given by:

\[
M(\tau) = K_{21}(\tau) - K_{12}(\tau) = \left\langle u'_2(0) \left( x_1(0) - x_1(-\tau) \right) \right\rangle_L
- \left\langle u'_1(0) \left( x_2(0) - x_2(-\tau) \right) \right\rangle_L
\]

(4-5)

The Lagrangian integral time and space scales are finally defined as:

\[
T_{ij}(\tau) = \frac{K_{ij}(\tau)}{\mathcal{P}_{ij}(0)}
\]

(4-6)

\[
L_{ij}(\tau) = \frac{K_{ij}(\tau)}{\sqrt{\mathcal{P}_{ij}(0)}}
\]

(4-7)

Kinetic energy (per unit mass) of the mean flow is given by:

\[
MKE = \frac{1}{2} \left( <u_1^2> + <u_2^2> \right)
\]

(4-8)

And mean eddy kinetic energy (EKE) is defined by:

\[
EKE = \frac{1}{2} \left( <u'_1 u'_1> + <u'_2 u'_2> \right)
\]

(4-9)
4.3 Result and discussion

4.3.1 Statistics of transit times along the Italian coastline

The Adriatic mean surface circulation maps derived from the numerical particles in 2007 and 2008 (Figures 4.2a, b) show the EAC and the WAC along east coast and Italian coast respectively, the three recirculation cells are visible in correspondence of the Palagruza sill, the mid Adriatic pit in front of Split and south of the Istrian Peninsula (Poulain, 2001; Cushman-Rosin et al., 2001).

The mean flow maps generated by synthetic trajectories in 2007 and 2008 confirm most of the results obtained before from drifter observations (chapter 2) and hydrographic data.

The surface circulation at the north of Po River (the north end of the Adriatic) is the isolated cyclonic gyre (It is visible just in the mean surface circulation map in 2008). The result indicates that the mentioned semicircular anticlockwise flows developed under the influence of wind-stress curl.

Moreover, an anticyclonic pattern which is located off the Istria between a cyclonic structure in the northern basin up to the Po River delta and the branch of the EAC recirculation (Ursella et al., 2006) doesn't appear for mean circulation maps generated by model during both years.
Figure 4.2 Mean flow field and circulation in the Adriatic Sea obtained by numerical particles, in 2007 (a), in 2008 (b).
4.3.1.1 S1 Transect: Conero Promontory

Mean times to cross the S1 section for numerical particles in 2007 (Figure 4.3a) are minimal till the section off the Italian coast in the northern Adriatic Sea (2-35 days), while the mean times in the northern Adriatic recirculation cell are about 40-100 days.

The standard deviation in that zone is 10-40 days and in front of the tip of Istrian Peninsula is about 30-45 days, but areas with more higher variability can be detected in the central Adriatic Sea (45-70 days); (Figure 4.5a).

High mean times for numerical particles in 2007 are visible in the Southern Adriatic Pit (SAP), near the Strait of Otranto (180-220 days); (Figure 4.3a) and down to the section along the Italian coast close to the Gargano Promontory (200-230 days).

Most of the observations are located in the northern Adriatic Sea.

A numerical particle in 2008 needs in mean 3 months to go to the S1 section from the tip of Istria (Figure 4.3b). Instead, the interval 160-180 days is the mean time to arrive in S1 from an area located in the proximity of Strait of Otranto and its standard deviation is 60-65 days (Figure 4.5b).

Numerical particles in 2008 are, notably in front of Istrian coast. The mean time enhances moving toward north along Italian coast and east toward Croatian coast. High mean times are detectable in the middle and the southern Adriatic Sea and they increase from east to west (Figure 4.3b).

The standard deviation is low along the Italian coast in 2007 and in the northern Adriatic Sea in 2008 (Figure 4.5a and Figure 4.5b), for the entire Adriatic, it is much higher during 2008 than 2007.

Most of numerical particles in both years (2007 and 2008) are located in the northern Adriatic Sea and in the eastern part of the middle Adriatic Sea.
Figure 4.3 Mean time to cross Conero Promontory (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.4 Most frequent value of time to cross Conero Promontory (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).
Tables 4.1a, b, c present the brief review of mean times, standard deviation and most frequent values of time for 4 data sets crossing Conero Promontory (drifter data (used in chapter 2), synthetic drifters in 2007 and 2008 as explained before in this chapter and numerical particles (ND) obtained in chapter 2).

As it was expected results indicate that the values of mentioned parameters (mean times, standard deviation of time and most frequent values of time) for real drifters are lower compared to numerical observations because of the short lifetime (“mortality”) of real drifters (as discussed in chapter 2).

We cannot say that which year (2007 or 2008) has a better agreement with numerical particles obtained by real drifter mean flow field (let’s to say them in this chapter Numerical Drifter (ND) to be distinguished from synthetic drifters obtained by velocity flow field generated by MITgcm) although the mean time that numerical particles in 2007 need to cross S1 section is close to ND values. But regarding
standard deviation and most frequent values of time, 2008 values have more similarity to ND observations. (For more details please see Figures 4.4 and 4.5)

Table 4.1a Mean time to cross Conero Promontory (days)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real drifter</td>
<td>45</td>
<td>43</td>
<td>48</td>
<td>87</td>
<td>63</td>
<td>72</td>
</tr>
<tr>
<td>Synthetic drifters in 2007</td>
<td>80</td>
<td>70</td>
<td>140</td>
<td>212</td>
<td>183</td>
<td>177</td>
</tr>
<tr>
<td>Synthetic drifters in 2008</td>
<td>110</td>
<td>80</td>
<td>155</td>
<td>174</td>
<td>155</td>
<td>152.5</td>
</tr>
<tr>
<td>ND</td>
<td>95</td>
<td>77</td>
<td>130</td>
<td>183</td>
<td>156</td>
<td>171</td>
</tr>
</tbody>
</table>

Table 4.1b Standard deviation of time to cross Conero Promontory (days)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real drifter</td>
<td>24.5</td>
<td>33</td>
<td>18</td>
<td>16</td>
<td>36</td>
<td>34.5</td>
</tr>
<tr>
<td>Synthetic drifters in 2007</td>
<td>26</td>
<td>44.5</td>
<td>48</td>
<td>55</td>
<td>42</td>
<td>33</td>
</tr>
<tr>
<td>Synthetic drifters in 2008</td>
<td>57</td>
<td>63.5</td>
<td>68</td>
<td>65</td>
<td>71</td>
<td>69</td>
</tr>
<tr>
<td>ND</td>
<td>63</td>
<td>58</td>
<td>92</td>
<td>69</td>
<td>83</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 4.1c Most frequent value of time to cross Conero Promontory (days)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real drifter</td>
<td>25</td>
<td>15</td>
<td>38</td>
<td>86</td>
<td>26</td>
<td>31.5</td>
</tr>
<tr>
<td>Synthetic drifters in 2007</td>
<td>74</td>
<td>32</td>
<td>132</td>
<td>221</td>
<td>164</td>
<td>124</td>
</tr>
<tr>
<td>Synthetic drifters in 2008</td>
<td>58</td>
<td>32</td>
<td>185</td>
<td>166</td>
<td>86</td>
<td>92</td>
</tr>
<tr>
<td>ND</td>
<td>65</td>
<td>21</td>
<td>35</td>
<td>121</td>
<td>107</td>
<td>71</td>
</tr>
</tbody>
</table>
4.3.1.2 S2 Transect: The Gargano peninsula

Looking the Gargano mean times map (Figure 4.6a) obtained from synthetic trajectories in 2007 shows that higher values are in the north-eastern Adriatic Sea, eastern part of the middle Adriatic Sea and on the SAP. Numerical particles need in mean 130-160 days to go to the S2 section from the tip of Istria (Figure 4.6a) with a standard deviation about 50-65 days (Figure 4.8a). The higher mean crossing time (200-220 days) is near the Strait of Otranto (Figure 4.6a). Numerical maps in 2008 (Figures 4.7b, 4.6b, 4.8b) show that the most frequent value of time for a particles to go to S2 from Istrian coast is about 60-80 days with a standard deviation of 50-70 days. High mean times are observable in the south-western Adriatic Sea (Figure 4.6b) close to Otranto.

Most of numerical particles are located in the northern and middle Adriatic Sea, but it is also remarkable the amount of particles bring by the south Adriatic recirculation cell; no more observations are present along the Italian coast, close to the south of S2

![Mean time to cross Gargano Promontory for numerical particles in 2007(days)](a)

![Mean time to cross Gargano Promontory for numerical particles in 2008(days)](b)

Figure 4.6 Mean time to cross Gargano Promontory (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).
Figure 4.7 Most frequent value of time to cross Gargano Promontory (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.8 Standard deviation of time to cross Gargano Promontory (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).
As the same comparison that we did before for trajectories crossing S1 section, now we repeat this method for particles crossing the Gargano peninsula (tables 2a, b, and c).

We can see that real drifters move so faster than 3 other data sets related to numerical trajectories, but in the central Adriatic Sea (R3 region) we found some similarities between drifter data and numerical observation during both years, otherwise in the other parts of the basin the mean time that drifter requires to cross the Gargano peninsula is less than synthetic particles.

This time our results indicate that values of mean transit time during 2008 (crossing S2 section) are close to ND values (as opposed to what we obtained for particles crossing S1 section).

By comparing the standard deviation of time (between 4 data sets), we couldn't have the general conclusion to say which year has a better agreements with the other data sets; just we can add that the standard deviation of time for trajectories crossing S2 section in the southern Adriatic Sea during 2007 is close to ND values.

The comparison results indicate that in the eastern part of the southern Adriatic basin there is a better agreement between the of most frequent value of time computed from ND (Numerical Drifters in chapter 2) and synthetic drifters in 2007, nonetheless in the northern Adriatic most frequent value of time during 2008 is more similar to ND data.

| Table 4.2a Mean time to cross Gargano peninsula (days) |
|---|---|---|---|---|---|
| R1 | R2 | R3 | R4 | R5 | R6 |
| Real drifters | 47 | 62 | 57 | 92 | 66 | 78 |
| Synthetic drifters in 2007 | 142 | 121 | 82 | 174 | 182 | 178 |
| Synthetic drifters in 2008 | 124 | 101 | 74 | 181 | 150 | 166 |
| ND | 178 | 138 | 78 | 166 | 153 | 171 |
Table 4.2b Standard deviation of time to cross Gargano peninsula (days)

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
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<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
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<td>Real</td>
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<td>31.5</td>
<td>30</td>
<td>36</td>
<td>28</td>
<td>37</td>
</tr>
<tr>
<td>drifers</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic</td>
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<td>61</td>
<td>52</td>
<td>65</td>
<td>68</td>
<td>88</td>
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<td></td>
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<td>56</td>
<td>59</td>
<td>58</td>
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<td>57</td>
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<td>drifers in 2008</td>
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<tr>
<td>ND</td>
<td>88</td>
<td>92</td>
<td>77</td>
<td>98</td>
<td>64</td>
<td>86</td>
</tr>
</tbody>
</table>

Table 4.2c Most frequent value of time to cross Gargano peninsula (days)

<table>
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<tr>
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<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
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<td>37.5</td>
<td>42.5</td>
<td>57.5</td>
<td>43</td>
<td>62</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic</td>
<td>88</td>
<td>58</td>
<td>74</td>
<td>124</td>
<td>168</td>
<td>71</td>
</tr>
<tr>
<td>drifers in 2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic</td>
<td>78</td>
<td>76</td>
<td>69</td>
<td>153.5</td>
<td>146.5</td>
<td>161.5</td>
</tr>
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<td>drifers in 2008</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ND</td>
<td>77</td>
<td>65</td>
<td>47</td>
<td>109</td>
<td>127</td>
<td>74</td>
</tr>
</tbody>
</table>

4.3.1.3 S3 Transect: The Strait of Otranto

Numerical particles need more than 180 days to go from the tip of Istria to the S3 section (Figure 4.9a), with a standard deviation of 55-65 days in 2007 (Figure 4.11a). In the area extended for 100 km up to S3 section along the Italian coast, mean time values are less than 20 days. Numerical particles maps in 2007 (Figure 4.9a) show higher values of the mean time in the northern Adriatic Sea and off the Albanian and the Croatia coast. Most of the observations are in front of the Istrian Peninsula, in the WAC and in the SAP from southern recirculation cell. Few observations are found in the area close to the Albanian coast, revealing that the
probability that a particle deployed in such zone to cross S3 is very low, because it has a tendency to enter in WAC and then to escape from the Adriatic Sea.

The mean time for numerical particles during 2008 to move from the tip of Istria to the S3 section is about 200 days, with a standard deviation about 50-70 days (Figure 4.9b) which is so close to what we obtained for numerical drifters in chapter 2 (210-260 days).

Results during 2008 indicate that higher values of mean time are observable in the central and northern Adriatic Sea and eastern part of the southern Adriatic Sea (Figures 4.9b and 4.11b).

Figure 4.9 Mean time to exit Otranto (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).
Figure 4.10 Most frequent value of time to exit Otranto (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.11 Standard deviation of time to exit Otranto (days) for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Following the same procedure, as I did in sections 4.3.1.1 and 4.3.1.2, tables 4.3a, b, c show the comparison between drifter data and numerical results. For real drifters close to Gulf of Trieste it takes about 100 days to exit from the basin, as we
discussed in chapter 2, but for numerical particles it takes more than 166, 174 days in 2007 and 2008 respectively. In most part of the domain the standard deviation and most frequent values of time obtained from the synthetic drifters during 2008 have a better agreement with ND values. (Figures 4.10 and 4.11). The different levels of mean kinetic energy (MKE) during 2007 and 2008 make some additional differences regarding the mean transit time which particles need to cross each section, as I will discuss in the next part of this chapter.

<table>
<thead>
<tr>
<th></th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
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<td><strong>Real drifters</strong></td>
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<td>103</td>
<td>65</td>
<td>64</td>
<td>97</td>
<td>69</td>
</tr>
<tr>
<td><strong>Synthetic drifters in 2007</strong></td>
<td>166</td>
<td>154</td>
<td>124</td>
<td>88</td>
<td>156</td>
<td>154</td>
</tr>
<tr>
<td><strong>Synthetic drifters in 2008</strong></td>
<td>168</td>
<td>152</td>
<td>156</td>
<td>130</td>
<td>164</td>
<td>123</td>
</tr>
<tr>
<td><strong>ND</strong></td>
<td>224.5</td>
<td>164</td>
<td>132.5</td>
<td>97</td>
<td>178</td>
<td>161</td>
</tr>
</tbody>
</table>

**Table 4.3a Mean time to exit the Strait of Otranto (days)**

<table>
<thead>
<tr>
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<th>R4</th>
<th>R5</th>
<th>R6</th>
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<tr>
<td><strong>Real drifters</strong></td>
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<td>35</td>
<td>34</td>
<td>28.5</td>
<td>56</td>
<td>33</td>
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<tr>
<td><strong>Synthetic drifters in 2007</strong></td>
<td>52</td>
<td>62</td>
<td>51</td>
<td>56</td>
<td>64</td>
<td>51.5</td>
</tr>
<tr>
<td><strong>Synthetic drifters in 2008</strong></td>
<td>54.5</td>
<td>77.5</td>
<td>71</td>
<td>74.5</td>
<td>76</td>
<td>74</td>
</tr>
<tr>
<td><strong>ND</strong></td>
<td>96</td>
<td>89</td>
<td>92</td>
<td>102</td>
<td>82</td>
<td>105</td>
</tr>
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</table>

**Table 4.3b Standard deviation of time to exit the Strait of Otranto (days)**
Table 4.3c  Most frequent value of time to exit the Strait of Otranto (days)

<table>
<thead>
<tr>
<th></th>
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<th>R4</th>
<th>R5</th>
<th>R6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Real drifters</strong></td>
<td>56</td>
<td>94</td>
<td>56</td>
<td>29</td>
<td>55</td>
<td>52</td>
</tr>
<tr>
<td><strong>Synthetic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>drifters in</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>121</td>
<td>160.5</td>
<td>96.5</td>
<td>91</td>
<td>86</td>
<td>98</td>
</tr>
<tr>
<td>Synthetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>drifters in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>107</td>
<td>153</td>
<td>136</td>
<td>21</td>
<td>65</td>
<td>82</td>
</tr>
<tr>
<td><strong>ND</strong></td>
<td>167.5</td>
<td>139.5</td>
<td>74</td>
<td>18</td>
<td>82</td>
<td>195</td>
</tr>
</tbody>
</table>

The residence time, $T^*$, was calculated for the numerical particles during 2007 and 2008 (Figure 4.12). With numerical particles, $T^*$ reaches 182 days after the maximum integration period of the particles (365 days). The pattern is the same for both years, although the 2008 residence time is a bit lower than 2007 value during first 250 days. Results show that the value of residence time is higher during both years compared to what we carried out for numerical particles in chapter 2 (more than 20 days). It is another reason to say that the flow field generated by the MIT general circulation model during the selected years is less energetic than the Adriatic surface velocity field as obtained by drifter measurements.
As it was mentioned before, we had two contrasting years (2007 with mild winter and cold autumn, 2008 with normal winter and hot summer). We expected that the residence time for numerical particles would be different, but the obtained results showed that the residence time value is similar for two years. To find the reasons for this result we analyzed the main forcings, i.e. wind speed, wind stress, heat fluxes and Po River discharge during these periods.

We obtained that the Po River discharge shows a major difference between two years (the average over summer shows better this difference (607.2111 (m$^3$/s) in 2007, 1125.5 (m$^3$/s) in 2008).

On the other hand the wind speed effects also should be considered. As the mean flow map during 2008 clearly shows, there is a wind driven recirculation pattern up to Po River and off the Istria which creates a closed system for numerical particles to stay there for a longer time, but in 2007 we cannot see this condition. This cyclonic gyre in the north and anticyclonic gyre south of the Po River, which doesn't appear for yearly mean circulation maps generated by model in 2007 and 2008,
would be as a sea response to the wind field (Bora wind field). To prove our previous result it would be helpful to present the wind field plots (direction frequencies of wind speed distribution) in the northern Adriatic Sea during selected years (Figure 4.13). As the comparison plots show the wind speed (force) during winter (January, February and March) in 2008 was higher (stronger) than 2007 in the northern Adriatic Sea, which conforms to our results.

Also the results related to the mean and most frequent values of time for numerical particles crossing Otranto Channel and the Gargano peninsula prove that because of the Po River discharge effects, the particles between Conero Promontory and the Strait of Otranto move faster in 2008 compared to 2007, but in the northern Adriatic because of the reason that we explained on previous paragraph (Bora wind field), particles in 2007 move faster than numerical drifters during 2008 (Figures 4.6, 4.7, 4.9 and 4.10).

Figure 4.13: Wind speed distribution (m/s) in the northern Adriatic Sea during 2007 winter (a) and 2008 winter (b) (the colors in box show the selected range for the wind speed (m/s))
So we can say that the effects of wind driven recirculation cells in the northern Adriatic Sea (north of the Po River) and Po River discharge on surface circulation induce the value of residence time to be similar during two different years.

**4.3.2 Lagrangian statistics of the Adriatic Sea in 2007 and 2008 obtained by synthetic drifters**

From a theoretical point of view, the calculation of Eulerian statistics should be done by an ensemble of many data realizations obtained in the Adriatic Sea.

On the other hand, for calculation of Lagrangian velocity statistics, they are computed over an ensemble of selected particles. In our case we assumed each observation in the domain as a deployment position from which the particle is followed. Lagrangian statistics are calculated for positive and negative time lags (Davis, 1991).

For computing the Lagrangian statistics for the entire Adriatic basin in 2007 and 2008, first the deterministic Eulerian mean flow has been subtracted from the individual particle velocities. The mean Eulerian velocity field was interpolated at the particle locations using bilinear interpolation.

The Lagrangian statistics are presented in Figures 4.14, 4.15, 4.16 and 4.17 for time lags ranging from -10 to 10 days in 2007 and 2008. They are also summarized in Table 4.4 compared to real drifters by Poulain (2001).

The variance at zero time lag reaches over 85 (35) ($10^{-10} \text{ km}^2 \text{s}^{-2}$) in 2007 and 75 (40) ($10^{-10} \text{ km}^2 \text{s}^{-2}$) in 2008 in the along- and across-basin directions, respectively (Figures 4.14a and 4.15b). The along- and across-basin directions are shown in Figure 4.21.
Table 4.4 Lagrangian statistics for the whole Adriatic basin in 2007 and 2008 using synthetic drifters compared by real drifters (Poulain, 2001).

<table>
<thead>
<tr>
<th>Direction</th>
<th>Variance $(cm^2 s^{-2})$</th>
<th>Diffusivity $(cm^2 s^{-1})$</th>
<th>Lagrangian integral time (days)</th>
<th>Lagrangian integral length scale (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Along</td>
<td>Across</td>
<td>Along</td>
<td>Across</td>
</tr>
<tr>
<td>Real drifters</td>
<td>Poulain, 2001</td>
<td>106.3</td>
<td>70.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Synthetic drifters in 2007</td>
<td>85</td>
<td>35</td>
<td>1.45</td>
<td>0.5</td>
</tr>
<tr>
<td>Synthetic drifters in 2008</td>
<td>70</td>
<td>40</td>
<td>1.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The along-basin diffusivity reaches extremum values $(1.45*10^{-3} km^2 s^{-1})$ and $(1.40*10^{-3} km^2 s^{-1})$ after about 10 days in 2007 and 2008, respectively.

In the across-basin direction, values are $0.5*10^{-3} km^2 s^{-1}$ after 4 days in 2007 and $0.4*10^{-3} km^2 s^{-1}$ after 3 days in 2008 (Figures 4.15a and 4.15b).

Maximum Lagrangian integral time scales are about 2.05 (1.45) days for the along (across) basin direction in 2007 and 1.85 (1) days for the along (across) basin direction in 2008 (Figures 4.16a and 4.16b).

The Lagrangian integral length scale is equal to about 13 and 7.15 km, for the along- and across-basin directions in 2007, and about 14.8 and 6 km in 2008.
Figure 4.14 Lagrangian statistic (velocity covariance) calculated for the entire Adriatic basin after removal of the mean Eulerian circulation. Statistics are shown versus time lag between -10 and 10 days, for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.15 Lagrangian statistic (diffusivity) calculated for the entire Adriatic basin after removal of the mean Eulerian circulation. Statistics are shown versus time lag between -10 and 10 days, for numerical particles in 2007 (a), for numerical particles in 2008 (b).
Figure 4.16 Lagrangian statistic (integral time scale) are shown versus time lag between -10 and 10 days, for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.17 Lagrangian statistic (Mean angular momentum) calculated for the entire Adriatic basin after removal of the mean Eulerian circulation. Statistics are shown versus time lag between -10 and 10 days, for numerical particles in 2007 (a), for numerical particles in 2008 (b).
In this section, diffusivities, integral time and length scales and velocity covariance computed from the observed drifters are compared with the same quantities calculated from the synthetic drifters in 2007 and 2008.

Figure 4.18a shows the value of velocity covariance along (across) basin direction for numerical particles in 2007 and 2008 vs. drifter data.

In across basin direction the value of velocity covariance obtained from synthetic drifters in both years show the same pattern, where for all time lags they are less than drifter data.

In the along basin direction although we see the same behavior, but the values of velocity covariance for numerical drifters in 2007 during the first time lags are a bit higher than the drifter observations.

The results confirm that the velocity fluctuations terms for real drifter data are higher than numerical values (related to synthetic drifters in 2007 and 2008).

The same comparison has been done between modeled and drifter diffusivities. In the along basin direction, drifter diffusivities are lower than the numerical values till the time lag that they (numerical diffusivities) reach to the maximum values, and there after the drifter diffusivities increase faster. We can add that the modeled diffusivities in 2008 are closer to real drifter quantities than the other year (2007) values, considering that the diffusivities in 2008 is a bit lower than 2007 values (Figure 4.18b).

In the across basin direction the value of Kyy during 2008 is so similar to real drifter observation, but in 2007 they have different behavior versus drifter data especially for large time lags. In this direction also results indicate that the 2007 diffusivities are more than 2008 data (Figure 4.18b).
Both years have the same pattern during the first time lags nonetheless with good approximate, diffusivities across basin direction in 2008 have equal values with drifter data.

Comparing Lagrangian time and length scales obtained by numerical observations during 2007 and 2008 with drifter data shows that there is a very good agreement and similarity between numerical and experimental results. It indicates that the time and distance over which real and synthetic drifters remember their path are the same, although this is a bit different for numerical trajectories during 2007 in the across basin direction (Figures 4.18c and 4.18d).

The importance of these quantities is more sensible when we want to generate fluctuation terms (coherent turbulence) by using some models such as random flight model as discussed in chapter 2.
Figure 4.18  Comparison between the Lagrangian statistics in 2007, 2008 and drifter data. Velocity covariance (a), Diffusivity (b), Lagrangian integral time scale (c), Lagrangian integral length scale (d)
It would be helpful to compute the kinetic energy of the mean flow (MKE) and the mean eddy kinetic energy per unit mass (EKE) to see the differences between energy distribution in the basin during 2007 and 2008 (Figures 4.19 and 4.20). MKE maps for 2007 and 2008 show that the energy of mean flow during 2007 in some parts are lower than 2008, especially in central and northern Adriatic Sea. It can be added that the mean flow generated by model is less energetic than the mean flow obtained by drifter observations, and this is more notable in the northern Adriatic Sea in 2007 because of the less energetic wind field (Bora wind field) that was observed during winter 2007.

Figure 4.19 the kinetic energy of the mean flow (MKE) for numerical particles in 2007 (a) and 2008 (b)
Figures 4.21 and 4.22 display the two components of diffusivity for trajectories in 2007 and 2008. The numerical along-basin component of diffusivity in the Adriatic Sea in 2007, in western part of southern Adriatic close to Italian coast exhibit the highest values over the domain $[9–12 \times 10^3 \text{ km}^2\text{s}^{-1}]$. Moderate values $[1.5 \times 10^3 \text{ km}^2\text{s}^{-1}]$ are seen in the Northern Adriatic Sea, the central Adriatic Sea, and the eastern part of southern Adriatic Sea; in 2008 the along-basin diffusivity exhibit the highest values close to Italian cost in both central and southern Adriatic, eastern part of central Adriatic Sea and near Po River over the domain $[5–10 \times 10^3 \text{ km}^2\text{s}^{-1}]$. Moderate values $[1.4 \times 10^3 \text{ km}^2\text{s}^{-1}]$ in 2008 can be observed in the central part of Northern Adriatic Sea, close to the Gulf of Trieste, and near Istrian coast line. The along- and across-basin directions are shown in Figure 4.21. The highest across-basin diffusivities in 2007 $[4-5 \times 10^3 \text{ km}^2\text{s}^{-1}]$ are in the southern Adriatic Sea close to Albania coast line and the highest value of the across-basin diffusivities in 2008 are in

Figure 4.20 the mean eddy kinetic energy per unit mass (EKE) for numerical particles in 2007 (a) and 2008 (b)
the eastern part of southern Adriatic Sea. Values in the other part of the domain are less than $1 \times 10^{-3}\ m^2/s$ in both years. In regions such as western and eastern part of southern Adriatic, in middle of central Adriatic Sea and along the Italian cost the diffusivities are high because in these parts of domain eddies form but away from these current systems the diffusivities are lower because of weak eddies.

Figure 4.21 The along-basin, $K_{xx}$, diffusivities ($m^2/s$), for numerical particles in 2007 (a), for numerical particles in 2008 (b) for real drifters (c).
Figure 4.22 The across-basin, $K_{yy}$ diffusivities ($km^2/s$), for numerical particles in 2007 (a), for numerical particles in 2008 (b) for real drifters (c).
The differences between 2007 and 2008 diffusivities are best represented by dividing the 2007 quantities by the 2008 values (Figure 4.23). The 2007 along-basin diffusivities are more than 1.5 times greater than the observed results in 2008 for southern Adriatic Sea and also close to Italian coastline in northern Adriatic and eastern part of the basin.

The across-basin diffusivities in 2007 also have the mean value more than 2.4 times greater than the observed results in 2008 in the southern Adriatic, western part of central Adriatic Sea and some dispersive regions in the northern Adriatic especially close to Po River. In the remaining regions, ratios are generally close to 0.75. In both cases the diffusivities of the 2007 and 2008 modeled trajectories are low.

Figure 4.23 Ratios of the along-basin modeled diffusivities (a), Ratios of the across-basin modeled diffusivities (b).
In Figures 4.24 and 4.25, timescales in 2007 and 2008 together are seen. The along-basin timescales in 2007 are higher (5–12.5 days) in southern Adriatic Sea and close to Italian coast line in central and northern Adriatic; otherwise the scales are 0.5–1.5 days but in 2008 the higher values also can be found in middle of central Adriatic Sea.

In most parts of the domain longer timescales in along-basin direction in 2008 than the 2007 values are seen.

The across-basin timescales for both years follow the same pattern. The high values are seen in eastern southern Adriatic, circulation center in central Adriatic and also close to Po River in the northern Adriatic Sea (Figure 4.25). The ratios indicate that 2007/2008 values are 2 to 4 times greater in the southeastern part of the domain, middle of southern and northern Adriatic and also close to the Italian coast in the northern Adriatic Sea than the 2007/2008 values in other bins at the other part of the Adriatic Sea. Otherwise, values are less than unity (Figure 4.26).

Results show that in the energetic parts of the domain such as southern Adriatic Sea and close to Italian coast in the basin the timescales are long; it means particles remember their path for a longer time.
Figure 4.24 The along-basin, $T_x$, modeled Lagrangian integral timescales (days), for numerical particles in 2007 (a), for numerical particles in 2008 (b) for real drifters (c).
Figure 4.25 The across-basin, $T_y$, modeled Lagrangian integral timescales (days), for numerical particles in 2007 (a), for numerical particles in 2008 (b) for real drifters (c).
Length scales from the simulated trajectories in 2007 and 2008, and the ratio of the
two sets of scales are presented in Figures 4.27, 4.28 and 4.29. Highest values are
seen in the energetic current systems in southern Adriatic Sea and close to Italian
coast line in central Adriatic and the shortest scales are found especially in the
northern Adriatic Sea for both years.

The 2007 along-basin length scales are more than 1.5 times higher than the obtained
results in 2008 for southern Adriatic Sea and also close to Italian coast line in
northern Adriatic, eastern part of the basin and some dispersive regions in the
central Adriatic Sea.

The across-basin length scales in 2007 as the across-basin diffusivities have the
mean value more than 2.5 times greater than the observed results in 2008 in the
southern, western part of central Adriatic Sea and also close to Po River. In the
remaining regions ratios are mostly close to 0.5.
Figure 4.27 The along-basin, $L_x$, modeled Lagrangian integral space scales (km), for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.28 The across-basin, $L_y$, modeled Lagrangian integral space scales (km), for numerical particles in 2007 (a), for numerical particles in 2008 (b).
Figure 4.29 Ratios of the along-basin modeled Lagrangian integral space scales (a), Ratios of the across-basin modeled Lagrangian integral space scales (b).

The histograms of the diffusivities in 2007 and 2008 (Figures 4.30 and 4.31) and the other set of scales (Figures 4.32, 4.33, 4.34 and 4.35) are shown for both the along- and across-basin directions in this section.

The along-basin 2007 diffusivities range from 0.1 to 14 (10^{-3} km^2 s^{-1}) with most values in the range 0.1 to 3 (10^{-3} km^2 s^{-1}) but the across-basin diffusivities range from 0.1 to 4 (10^{-3} km^2 s^{-1}) with most values in the range 0.1 to 1 (10^{-3} km^2 s^{-1}).

The 2008 along-basin diffusivities are distributed in the range 0.1 to 12 (10^{-3} km^2 s^{-1}) with most values in the range 0.1 to 4 (10^{-3} km^2 s^{-1}).
Figure 4.30 Histograms of the along-basin diffusivities \( (K_{xx}) \) \( (\text{km}^2/\text{s}) \), for numerical particles in 2007 (a), for numerical particles in 2008 (b).

Figure 4.31 Histograms of the across-basin diffusivities \( (K_{yy}) \) \( (\text{km}^2/\text{s}) \), for numerical particles in 2007 (a), for numerical particles in 2008 (b).
The 2007 timescales (Figures 4.32 and 4.33) show a range from 0.5 to 12 days with the majority in the range from 0.5 to 2 days in both directions. The 2008 time scales range from 0.5 to 15 days for the along-basin direction.

**Figure 4.32** Histograms of the along-basin modeled Lagrangian integral timescales (Days), for numerical particles in 2007 (a), for numerical particles in 2008 (b).

**Figure 4.33** Histograms of the across-basin modeled Lagrangian integral timescales (Days), for numerical particles in 2007 (a), for numerical particles in 2008 (b).
The along-basin 2007 length scales (Figure 4.34a) have a range from 2 to 100 km, with the most scales between 2 and 40 km but the across-basin 2007 length scales cover a range from 2 to 90 km with the majority in the range from 2 to 20 km (Figure 4.35a).

![Histograms of the along-basin modeled Lagrangian integral space scales (km), for numerical particles in 2007 (a), for numerical particles in 2008 (b).](image)

The along-basin 2008 length scales show a range from 2 to 100 km with most values in the range 2 to 30 ($10^{-3} \text{km}^2 \text{s}^{-1}$); however in 2008 for the across-basin case length scales are more in the 2–20 km range and less in the 40–60 km. (Figures 4.34 and 4.35)
4.4 Summary and Conclusion:

Lagrangian statistics, obtained from numerical drifters, were used to quantify the Adriatic Sea circulation during two contrasting years (2007 with mild winter and cold autumn, 2008 with normal winter and hot summer). Synthetic drifters were computed from the velocity fields obtained by the Adriatic Sea model developed by Querin et al. (2013) using the MIT general circulation model code. Mean daily surface velocity fields were employed to estimate the transport statistics for numerical particles crossing in three selected sections located along the Italian coast (Conero and Gargano Promontories and Strait of Otranto). A comparison between numerical observations (during 2007 and 2008) and real drifter data has been done.
We have found that the mean flow maps generated by synthetic trajectories in 2007 and 2008 confirm most of the results obtained before from drifter observations (chapter 2) and hydrographic data, nonetheless an anticyclonic pattern which is located off the Istria between a cyclonic structure in the northern basin, up to the Po River delta and the branch of the EAC recirculation (Ursella et al., 2006) doesn't appear for yearly mean circulation maps generated by model in 2007 and 2008.

The transport statistics show that mean times to cross the S1 (Conero Promontory) section for numerical particles in 2007 and 2008 are minimal (2-35 days) up to the section off the Italian coast in the northern Adriatic; higher variability of standard deviation can be detected in the central Adriatic Sea for both years. We found that the high mean times for numerical particles in 2007 are detectable on the SAP and near Strait of Otranto (180-220 days) and down to the section along the Italian coast close to the Gargano Promontory (200-230 days), in 2008 high mean times are in the middle and the southern Adriatic Sea and they increase from east to west.

Comparison with real data (drifter observations) confirms that the values of mean times, standard deviation of time and most frequent value of time for drifters are lower than numerical particles observation, because of the short life time, "mortality", of the real drifters as discussed in chapter 2.

The Gargano mean times map shows that in 2007, higher values are in the north-eastern Adriatic Sea, eastern part of middle Adriatic Sea and on the SAP. Numerical maps in 2008 displays that the most frequent value of time for a particles to go to S2 from Istrian coast is about 60-80 days with a standard deviation of 50-70 days. High mean times in 2008 for particles crossing S2 are observable in the south-western Adriatic Sea (Figure 4.5b) close to Otranto.

In addition, real drifters move so faster than numerical particles to cross Gargano Promontory but in the central Adriatic Sea (R3 region) we found some similarities
Regarding transit times between drifter data and numerical observation during both years.

Results related to transit times demonstrate that numerical particles in 2007 need on averaged more than 180 days to go from the tip of Istria to the S3 section (Strait of Otranto) but the mean time for synthetic particles in 2008 is about 200 days, which is close to what we obtained for numerical drifter in chapter 2 (210-260 days).

During 2007, our observations show that higher values of the mean time to cross S3 section are associated with numerical particles released in the northern Adriatic Sea and off the Albanian and the Croatia coast, in 2008 higher values are found in the central and northern Adriatic and eastern side of the southern Adriatic Sea.

We also calculated residence time during two years. The 2008 residence time is a bit lower than the 2007 value during first 250 days, but it is higher during both years compared to what we carried out for numerical particles in chapter 2. In general we expected that the residence time for numerical particles would be more different during two years, nonetheless the obtained results showed that the residence time value is similar in 2007 and 2008 (182 (185) days in 2007 (2008)). We found that the Po River discharge exhibits larger value in 2008. Also the mean flow plot for 2008 clearly shows that there is a wind driven recirculation pattern in the northern Adriatic up to Po River and off the Istria which creates an isolated cyclonic gyre that forces the numerical particles to stay there for a longer time, but this is not the case for 2007. We conclude that the combined effects of these two parameters (wind speed and Po River discharge) induce the value of residence time over the entire basin to be similar during two different years.
Results related to Lagrangian statistics show that the along-basin diffusivity reaches extremum values \((1.45 \times 10^{-3} \text{km}^2 \text{s}^{-1})\) and \((1.40 \times 10^{-3} \text{km}^2 \text{s}^{-1})\) after about 10 days in 2007 and 2008, respectively.

The numerical along-basin component of diffusivity in the Adriatic Sea in 2007, in the western part of southern Adriatic close to Italian coast exhibits the highest values over the domain. In 2008 we see the highest values close to Italian cost in both central and southern Adriatic, eastern part of central Adriatic Sea and near Po River over the domain. The highest across-basin diffusivities in 2007 lie in the southern Adriatic Sea close to Albania coast line and the highest value of the across-basin diffusivities in 2008 are in the eastern part of southern Adriatic Sea.

In general Adriatic diffusivities are mostly the same during two years because the Lagrangian scales are similar (1–3 days versus 1–10 days) although we found that the kinetic energy of the mean flow (MKE) is a bit higher in 2008 respect to 2007 while the value of EKE for two years are so close \((2.5638e-009 \text{ (2.8961e-009) (km}^2 \text{s}^{-2})\) in 2007(2008)). As we expected that the diffusivity seems to be affected by the mean eddy kinetic energy.

As a last point for the second part of this chapter we would say that there is a good agreement between Lagrangian statistics obtained by real drifter data and numerical particles in both years, although the real drifter observations are a bit higher than numerical ones, because the Lagrangian scales are a bit larger (15% more) and the energy levels are higher for drifter data in the coastal areas.
References


Chapter 5

Conclusions

In this work we simulated and studied passive tracer dispersion by statistical properties of the currents in the Adriatic Sea from velocity data produced by numerical model outputs and real drifter data set. Each numerical particle trajectory was obtained by integrating and interpolating velocity field between grid points using a fourth-order Runge–Kutta scheme and bilinear interpolation.

Two kinds of mean velocity field were used: 1) the mean surface flow in the Adriatic Sea which was computed by averaging all the drifter velocities in circular bins of 10 km radius organized on a uniform grid with 10 km cell size, 2) the mean daily surface velocity field generated by the MITgcm in two contrasting years (2007 with mild winter and cold autumn, 2008 with normal winter and hot summer) which is daily average.
The results of this study can be categorized as following:

- **Statistics of residence and transit times in the Adriatic Sea**

  We estimated residence and transit times for the Adriatic surface circulation from 358 real data provided by satellite-tracked drifters and from tracks of numerical particles integrated with a simple statistical Lagrangian model (chapter 2). In addition, synthetic drifters were used; these drifters were computed from the velocity fields obtained by the MIT general circulation model implemented in the Adriatic Sea and integrated for the period from October 2006 till the end of 2008 (chapter 4).

  Due to the limited operating period of the drifters the results obtained with the real drifters are systematically underestimated; indeed the typical mean half-life time for real drifters in the Adriatic Sea (35-40 days) is less than the residence time in the basin. In addition, the statistical results for real drifters can be dependent on the specific deployment locations but in contrast for numerical particles one can control the deployment array (e.g., uniform throughout the basin), the lifetime and the number of particles (1000 particles (chapter 2) and 1080 particles (chapter 4)).

  We can conclude that the numerical results are more reliable than the experimental ones, because by using numerical particles (in chapters 2 and 4) we have obtained more accurate and robust results for the transit times of objects (water particles, pollutants, oil spills, persons, etc.) in the Adriatic Sea under the influence of the near-surface currents, of the local winds. We have also estimated that the residence time, that is the mean time a particle randomly deployed in the Adriatic stays in the basin before exiting, is 150-180 days (doing many numerical experiments in chapters 2 and 4) and this discrepancy is mostly due to those particles caught in fast WAC probably contribute to reduce the residence time.
In general we expected that the residence time for numerical particles generated by the velocity fields obtained by the MITgcm would be more different during two years (2007 and 2008), because of the weather condition observed in 2007 and 2008, and the different kinetic energy of the mean flow (the yearly averages of MKE are \(3.1408\times10^{-9}\) and \(3.7907\times10^{-9}\) \(km^2s^{-2}\) in 2007 and 2008 respectively) and the mean eddy kinetic energy \((2.5638\times10^{-9} (2.8961\times10^{-9}) \(km^2s^{-2}\) in 2007(2008)) during these years, nonetheless the obtained results showed that the residence time value is similar in 2007 and 2008 (182 (185) days in 2007 (2008)). We found that the Po River discharge exhibits larger value in 2008. Also the mean flow plot for 2008 clearly shows that there is a wind driven recirculation pattern in the northern Adriatic up to Po River and off the Istria which creates an isolated cyclonic gyre that forces the numerical particles to stay there for a longer time, but this is not the case for 2007. We conclude that the combined effects of these two parameters (wind speed and Po River discharge) induce the value of residence time over the entire basin to be similar during two different years.

Results related to transit times displayed that numerical particles in 2007 need on averaged more than 180 days to go from the tip of Istria to the S3 section (Strait of Otranto) but the mean time for synthetic particles in 2008 is about 200 days, which is close to what we obtained for numerical drifters in chapter 2 (210-260 days).

The pdf’s of the transit times of numerical particles between areas selected in the Adriatic Sea show that the distributions are not Gaussian and the pdf’s are significant skewed with a long “tail” corresponding to long transit times but as a result for drifters, transit time pdfs are significantly biased or skewed towards low values.
• **Lagrangian statistics for the whole Adriatic basin**

Our results demonstrated that Adriatic diffusivities are mostly the same during two years (2007 and 2008) because the Lagrangian scales are similar (1–3 days versus 1–10 days) although we found that the kinetic energy of the mean flow (MKE) is a bit higher in 2008 respect to 2007 while the value of EKE for two years are close ($2.5638e-009 (2.8961e-009) \ (km^2 \cdot s^{-2})$ in 2007(2008)). As we expected that the diffusivity seems to be affected by the mean eddy kinetic energy.

Results in chapter 4 prove that there is a good agreement between Lagrangian statistics obtained by real drifter data and numerical particles in both years, although the real drifter observations are a bit higher than numerical ones, because the Lagrangian scales are a bit larger (15% more) and the energy levels are higher for drifter data in the coastal areas.

• **Relative Dispersion in the Adriatic Sea**

In the other part of the thesis (chapter 3) quantities such as Relative dispersion, absolute dispersion, and Finite-Scale Lyapunov Exponent (FSLE), were calculated for drifter pairs.

We found that three distinct growth phases exist. At first time steps just for few days (in some cases just one day), pair separation grow exponentially with time, after this phase relative dispersion growth is scaling approximately like $t^2$ and finally for time larger than a month relative dispersion slows down considerably to the diffusive regime.

In general our results indicate that the relative dispersion in the Adriatic Sea is super-diffusive, scaling nearly ballistically in agreement with Lagrangian observation from a high-resolution coastal model.
• **Suggestions**

For the future there are several pending and new open questions to address:

First, the model which was used in chapter 2 (random flight model) should be improved or using another kind of models based on the Wiener process and Thomson’s criterion to generate the stochastic parts related to Lagrangian turbulence processes.

Second, applying mean Eulerian velocity fields with different implementations such as: model resolution, better turbulence parameterization, drag coefficient, and including wave propagation, Stokes drifts and the tidal currents those weren't used in this study.