ATLANTIC AREA Transnational Programme INVESTING IN OUR COMMON FUTURE

European Union European Regional Development Fund

ARCOPOL PLATFORM

Activity 5

Task 5.3.1: Report on turbulence parameterization

ARCOPOLplatform

Improving maritime safety and Atlantic Regions' coastal pollution response through technology transfer, training and innovation

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1. Summary

The main purpose of this work is to apply a method to calculate water eddy diffusivity on the basis of different fixed data sources, in order to be used as input in Lagrangian spill models on different case study areas, under the available operational model for the Portuguese coast (PCOMS). This work is integrated in task 5.3.1.

Using the data obtained through current meters deployment, and wave glider, the turbulence values for the different case study sites and conditions were estimated, analysed and compared with the bibliography. Results obtained compare well with the bibliography to other regional zones.

The same methodology can be deployed with the same data or other datasets, to different circulation models, knowing that high resolution models must take in consideration smaller averaging time periods.

2. Introduction and objectives

Ocean transport, dispersion processes, like spreading of oil spills in the ocean, are at the present time simulated using Lagrangian stochastic models coupled with Eulerian circulation models (Dominicis et al, 2012). Most of the Lagrangian stochastic and deterministic oil spill models proposed in the literature, as like the ones used by IST, with MOHID framework, use as input data the mean velocity fields provided by Eulerian hydrodynamics models based on different horizontal diffusivity parameterizations, sometimes connected to turbulence closure sub-models. In problems such as spreading of oil spills in the ocean, the understanding of statistical properties of Lagrangian trajectories in turbulence is crucial.

The relationship between descriptions of turbulence from the point of view of a still observer (Eulerian description) and that of a particle moving with the flow (Lagrangian description) remains unresolved in the theory of turbulence (Xia, et al 2013). In a turbulent flow, the velocity at a point will appear to an observer to be “random” or “chaotic”.

Using the Lagrangian approach, each particle displacement is described by an average motion and a fluctuating part. The first one represents the advection associated with the Eulerian current field of the circulation models while the second one describes the sub-grid scale diffusion. IST has performed several exercises using drifter buoys in order to validate hydrodynamic models, and calibrate turbulence, diffusion and wind coefficients. Lagrangian approach has the advantage of easily allow to simulate different type of hydrocarbons, inert substances, HNS, under different conditions, using different values of wind influence, turbulence, and diffusion.

Turbulence is difficult to define exactly, nevertheless, there are several important characteristics that all turbulent flows possess. These characteristics include unpredictability, rapid diffusivity, high levels of fluctuating vorticity, and dissipation of kinetic energy. (Webster, et al).

Here we will try to determine the turbulence diffusivity from high frequency velocity measurements in the areas of study (inside the Portuguese coast). The measurements are deployed in specific areas, not covering the entire Portuguese coast. Further studies and measurements should then complement the present study in order to obtain more information about turbulence along the Portuguese coast.

The methodology applied to compute the turbulence diffusivity is adopted from previous studies, as proposed in Dominicis et al, 2012. Further details are described in the following section.

3. Methodology

In the study of tracer dispersion, the simplest parameterization is obtained using "scale separation", by assuming the scales of the turbulence are infinitesimal compared with the scales of the mean field (Taylor 1921). Under this assumption, the evolution of a passive tracer can be approximated by an advection–diffusion equation, which describes the balance of the mean concentration, C, as for molecular diffusion, i.e. it is the advection–diffusion equation replaced by an "eddy diffusivity" coefficient:

$$\frac{\partial C}{\partial t} + \mathrm{U}.\nabla C = \nabla.(k\nabla C) \quad \text{eq. 1}$$

where U=(U, V, W) represents the mean velocity field vector and K is the eddy diffusivity tensor which parameterizes the turbulence or the unresolved scales in the Eulerian framework.

This "eddy diffusivity" coefficient can be obtained by integrating Lagrangian trajectories simulated by random walk processes. The Lagrangian method can represent the tracer transport more easily than the Eulerian one because the computational cost is concentrated only where the particles are located.

The applicability of the advection–diffusion equation is often questionable for oceanographic problems, as noticed by a number of authors (e.g., Davis 1987; Zambianchi and Griffa 1994; Falco et al. 2000).

For non-uniform nature of the observed data, the turbulent components (u'i, u'ii) can be calculated as the difference between the instant velocities and the mean velocity calculated over the whole sampling period, using the autocorrelation function. The integral of the autocorrelation is generally time dependent and does not approach a constant limit as t increases.

Lagrangian turbulent velocity correlation coefficient is an important physical quantity in turbulent diffusion problems. Generally, the use of the autocorrelation coefficient in the Taylor statistical diffusion theory allows calculating the dispersion parameters associated to the turbulent diffusion modeling studies (Taylor, 1921).

The Lagrangian autocorrelation function along a generic i-axis can be defined as (Poulain and Niiler 1989):

$$R_i(\tau, T, t_0, x_0, y_0) = \frac{\frac{1}{T}\int_{t_0}^{t_0+T} u_i'(x_0,y_0,t)u_i'(x_0,y_0,t+\tau)\mathrm{d}t}{\frac{1}{T}\int_{t_0}^{t_0+T} u_i'(x_0,y_0,t)u_i'(x_0,y_0,t)\mathrm{d}t} = \frac{\langle u_i'(x_0,y_0,t)u_i'(x_0,y_0,t+\tau)\rangle_{\mathrm{L}}}{\langle u_i'(x_0,y_0,t)^2\rangle_{\mathrm{L}}} \quad \text{eq. 2}$$

Where T is the time interval over which the Lagrangian average < L > is calculated and u' is a residual velocity, or standard deviation (σ), obtained by subtracting the mean velocity for each drifter:

$\sigma_i = u_i - \overline{u_i} = u_i - < u_i >_L$ eq. 3

Considering the study developed by Dominicis et al, 2012, the diffusivity, K_i, and the Lagrangian integral time scale, T_i, components (where i=1, 2, 3 refer to the x, y, z Cartesian axis, respectively), can be determined using the (Taylor 1921) theory, starting on measured velocities, and assuming stationary and homogenous turbulence.

Using the quality-checked measured surface velocity data (u), mean surface velocities ū and the turbulent σ components can be estimated. Dominicis studies show that the diffusivity and the turbulent time scale take different values depending on the method used in the calculation of the mean flow velocity, depending in how accurate is its calculation. In general, it is believed that ū is a good approximation of the Eulerian fields, or mean fields, simulated by the ocean circulation models.

Following the Taylor (1921) theory (Eq. 5), the diffusivity can be calculated by the velocity variance:

$$Ki(t) = (\sigma_i^2)\ \ \mathrm{T} \quad \text{(eq. 4)}$$

$$Kii(t) = (\sigma_{ii}^2)\ \ \mathrm{T} \quad \text{(eq. 5)}$$

Where i, and ii are the along-current, and across-current velocities components, respectively.

The Lagrangian integral time scale is the time over which a tracer "remembers" its velocity. The integral time scale components (Ti, Tii) can be calculated as the integral of the velocity autocorrelation up to the first zero-crossing.

Lagrangian eddy length scale (L_L) is the corresponding space length for the determined integral time scale, and based on standard deviation (u'):

$$L = \sigma\ T_L \quad \text{(eq. 6)}$$

All statistical and turbulence parameters (standard deviation, variance, T_L, L_L, K) are integrated based on the average of the zonal and meridional components.

Our goal is to find a value of diffusivity to be used in Eq. 2, where the mean flow will be provided by the coastal circulation models (PCOMS for Portuguese coast – 6km resolution). Assuming different averaging periods, we can find the range of mean velocities that will refer to structures with spatial scales in the order of magnitude of the spatial steps of the circulation models (for instance, in a range of mean velocities of 0.1-0.2m/s for PCOMS model, which has a 6km spatial step, averaging time periods between 16.6h – 8.3h) must be taken in consideration. Those averaging periods corresponding to each model resolution and each range of mean velocities, will then be used to determine the fluctuation velocities (standard deviation, or variance), lagrangian integral time scales and finally, the diffusivities.

Since we are using surface water measurements from systems that are not directly influenced by the wind, one must have in consideration that the turbulent diffusivity is only related with water velocity, and therefore is underestimated in relation to surface drifters, subject to direct wind effect.

An additional note is the fact that MOHID lagrangian model doesn't directly use diffusivity as a parameter – it uses instead the standard deviation of the random movement, which can be obtained as mentioned above, and the mix length (corresponding to the length of a computational cell). Thus, MOHID doesn't require the determination of diffusivity coefficient (K). Anyway, diffusivity will be computed here, as a normal reference to compare with other models.

4. Study areas & observations

Lisbon- Tagus estuary

Several measurements were performed on Tagus Estuary to measure currents velocity with ADCP's and current meters.

Figure 1- Tagus Estuary Location

4.1 Current measurements: Aquadopp and ADCP

Current measurements using ADCP were performed by IST, in the scope of different projects. These different deployments had different proposes: to "identify" local hydrodynamic recirculations forced by tide, characterize local hydrodynamics, calibrate and validate models. Although more data exist for the region of study (several short time periods of measurements, around 4h each), we will only take in consideration a survey with a time series long enough to allow us to apply the selected methodology of determining turbulent diffusion.

Table 1. ADCP deployment dates, duration, and measurement frequency.

Date	*Duration*	*Measurement frequency (minuts)*	*location*
3 to 22 July 2008	19 days	15	Guia (Cascais)

4.2 Waveglider

During the months of April and June 2015, a Wave Glider SV2, an autonomous vehicle equipped with several sensors, was launched in the vicinity of Nazaré, a coastal town in centre of Portugal. The mission included the measurements of currents, waves and atmospheric parameters in several areas interesting for the exploration of marine renewable energies. This Wave Glider SV2 named "Hermes" was equipped with:

- Atmospheric station: Airmar 200WX
- ADCP sensor (hydroacustic current meter): WorkHorse Monitor 300 kHz from Teledyne RD Instruments
- Wave sensor (wave motion): MOSE-G Datawell
- CTD (Temperature and conductivity): GPCTD from Sea-Bird Electronics
- Telemetry: Iridium SBD for navigation and compressed data and Iridium RUDICS for the ADCP only

The area covered by the study correspond to the central coast of the Portuguese Coast. The study area is limited in the North by the Nazaré canyon and its surroundings. The area of study was in the area comprised between the coordinates (Longitude (9W, 9.53W) Latitude (39.36N, 39.98N)

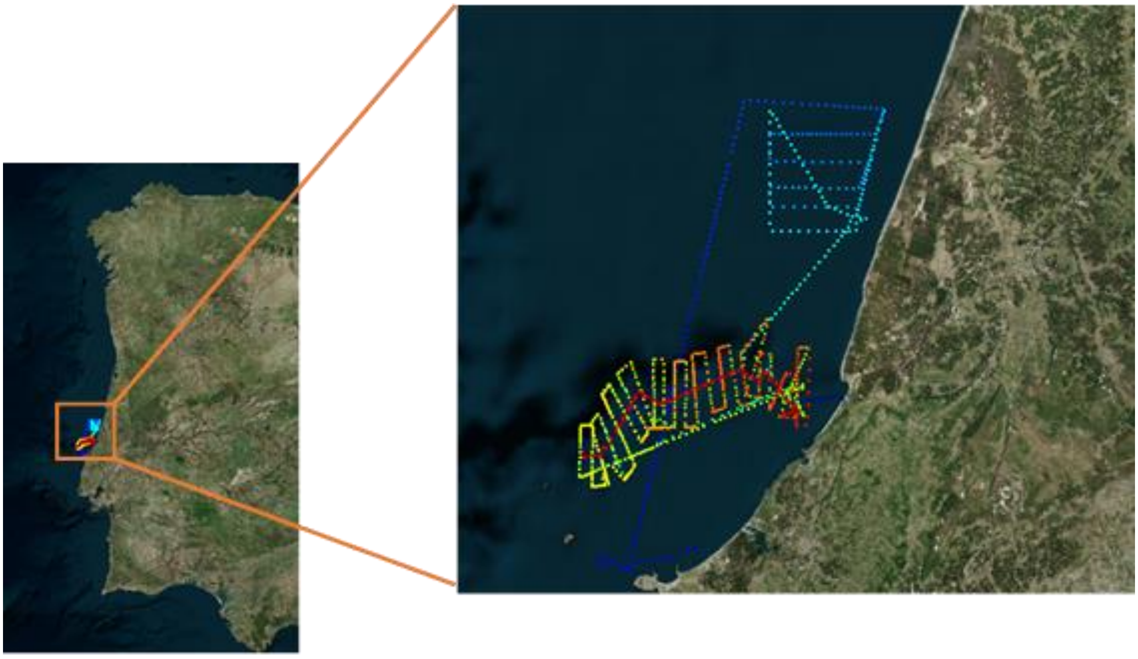


Figure 2- wave glider data acquisition location, in the Portuguese Coast, near Nazaré.

Among the survey data, the time period described in the following table was selected. This was a continuous period, without any blank periods, therefore very useful for the purpose of this work.

Table 2. ADCP deployment dates, duration, and measurement frequency.

Date	*Duration*	*Measurement frequency (minuts)*	*location*
26 April - 4 May 2015	9 days	2	Nazaré (Center of Portugal)

5. Areas of study- Model applications/domains

The coastal applications are operated by the MOHID Modelling System that is an open source numerical model programmed in ANSI FORTRAN 95 mainly developed at Instituto Superior Técnico since 1985 (http://www.mohid.com).

Several coastal and estuarine model domains are implemented for the Portuguese coast. Those models are forced by PCOMS Portuguese Coast Operational Model System, thus we have centered our object of study precisely on PCOMS model.

PCOMS- open boundary conditions

Open boundary conditions to PCOMS were considered from Mercator-Ocean GLOBAL_ANALYSIS_FORECAST_PHYS_001_002 (available at MYOCEAN website) for North Atlantic region at a spatial resolution of 18x13 km. The vertical resolution of the database includes 43 vertical layers between 0-6000m. The database contains the average daily distribution of the following parameters: Temperature; Salinity; Velocity; Water level

Tide

The PCOMS is forced by the FES 2004 (Finite Element Solution) tide model (Lyard *et al.*, 2006), based on a hydrodynamic model which assimilates tide gauges and altimeter data (Topex/ Poseidon and ERS-2). The FES 2004 model comprises global coverage of tidal components at resolution of 1/8°. The tide is propagated from PCOMS to the Tagus estuary model domains with the Flather (1976) radiation scheme, which enables to radiate external gravitational waves over the perturbation produced by other mechanisms, as the wind and the Coriolis force.

6. Results

This chapter is divided in two sections, represented by the different regions considered: Guia (using a fixed ADCP) and Nazaré (using wave glider).

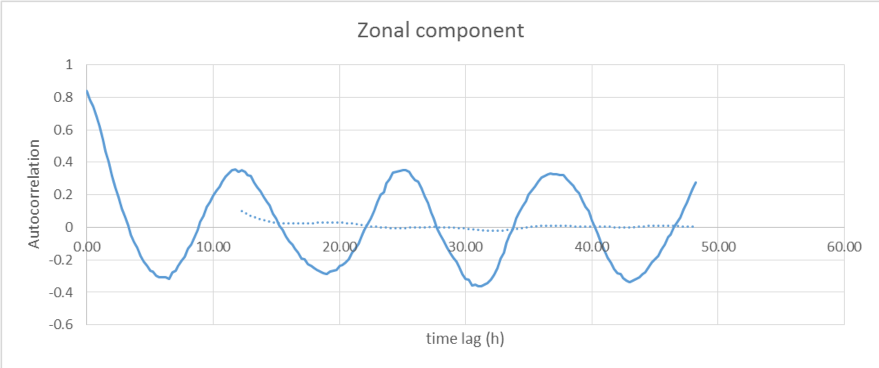
6.1 Guia (Cascais) – ADCP

Based on the range of velocities found for this area (see next table), the determination of lagrangian integral times (TL), as well as LL and K, was subdivided based on a averaging period of 7 days, in order to find the turbulence associated to a cell of 6 km. Therefore, two different time series of 7 days were used: 2-7-2009 to 9-7-2009, and 11-7-2009 to 17-7-2009.

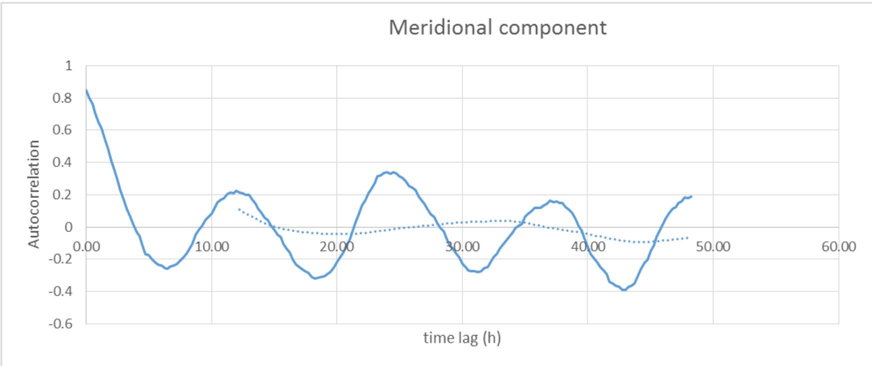
The analysis was also performed for each of the velocity components.

	2-7-2009 to 9-7-2009			11-7-2009 to 17-7-2009			Integration		
Parameters	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude
Min (m/s)	-0.316	-0.487	0.001	-0.188	-0.562	0.004	-0.316	-0.562	0.001
Max (m/s)	0.399	0.199	0.523	0.433	0.088	0.672	0.433	0.199	0.523
Average (m/s)	0.082	-0.164	0.221	0.0953	-0.192	0.239	0.089	-0.178	0.230
Dt (min)	15								
σ (m/s)	0.109	0.114	0.111	0.103	0.104	0.103	0.106	0.109	0.107
σ2	0.012	0.013	0.012	0.010	0.010	0.010	0.011	0.012	0.012
T_L (h)	5.25	5.5	5.375	3.5	4	3.75	4.38	4.75	4.56
L_L (km)	2.063	2.252	2.158	1.292	1.494	1.393	1.678	1.873	1.775
K (cm^2/s)	2.25×10^{5}	2.56×10^{5}	2.41×10^{5}	1.33×10^{5}	1.55×10^{5}	1.44×10^{5}	1.79×10^{5}	2.06×10^{5}	1.92×10^{5}

The data obtained here in this zone is highly influenced by semi-diurnal tidal forces, which underestimates turbulent diffusion (because decreases lagrangian integral timescale). To minimize this effect, a moving average of 12.5h was applied to the autocorrelation function, increasing the integral time scale (the zero-crossing value for the auto correlation).



(a)



(b)

Figure 3 – Lagrangian autocorrelation function versus time lag. Dashed line is the moving average trend line filtering semi-diurnal tide. Period between 2-7-2009 to 9-7-2009

Based on the integral time scale obtained with the trendlines, the new turbulence results were obtained and compiled as followed.

	2-7-2009 to 9-7-2009 (filtered)			11-7-2009 to 17-7-2009 (filtered)			Integration		
Parameters	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude
T_L (h)	27	43	35	24.5	15	19.75	25.75	29	27.38
L_L (km)	10.612	17.612	14.112	9.049	5.604	7.326	9.830	11.608	10.719
K (cm^2/s)	$1.16x10^6$	$2.00x10^6$	$1.58x10^6$	$9.28x10^5$	$5.81x10^5$	$7.55x10^5$	$1.04x10^6$	$1.29x10^6$	$1.17x10^6$

Thus, at the end, a value of $1.17x10^6$ cm^2/s was obtained for the eddy diffusivity, which compares well with other values obtained in the literature (De Dominicis, et al., 2012). The variance of 0.012 is a value according with what was expected and similar to what has been used previously as "VARVELH" parameter in MOHID model in the study area.

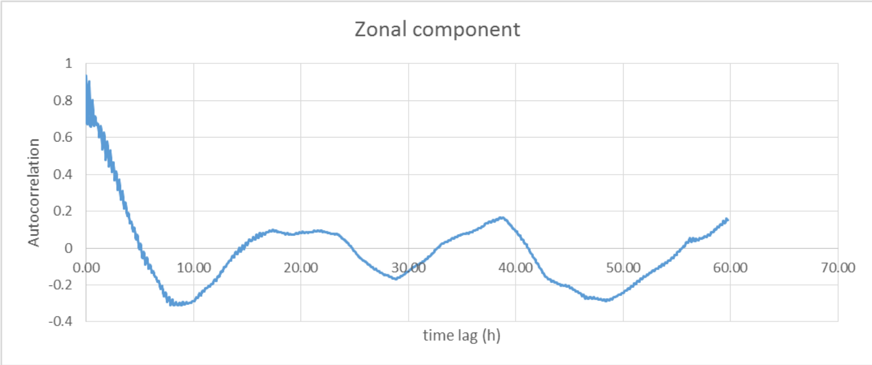
6.2 Nazaré – Wave glider

Based on the range of velocities found for this area (see next table), the determination of lagrangian integral times (TL), as well as LL and K, was subdivided based on an averaging period of 5 days, in order to find the turbulence associated to a cell of 6 km. Therefore, two different time series of 5 days were used: 24-4-2015 to 1-5-2015, and 30-4-2015 to 4-5-2015.

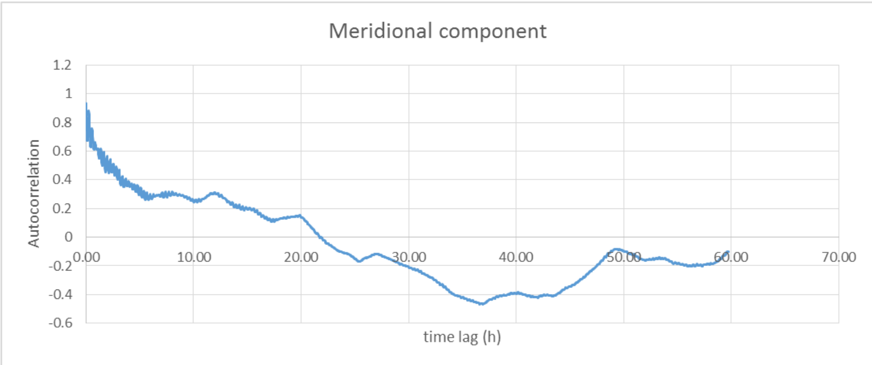
The analysis was also performed for each of the velocity components.

	24-4-2015 to 1-5-2015			30-4-2015 to 4-5-2015			Integration		
Parameters	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude	Zonal (west-east) velocity	Meridional (South-North) velocity	Velocity magnitude
Min (m/s)	-0.612	-0.678	0.058	-0.713	-0.569	0.014	-0.713	-0.678	0.014
Max (m/s)	0.729	0.724	0.729	0.725	0.818	0.818	0.729	0.818	0.818
Average (m/s)	0.019	0.102	0.403	-0.073	-0.059	0.381	-0.024	0.027	0.393
Dt (min)	2								
σ (m/s)	0.287	0.288	0.287	0.283	0.278	0.280	0.285	0.283	0.284
σ2	0.082	0.083	0.083	0.080	0.077	0.079	0.081	0.080	0.081
T_L (h)	4.93	21.73	13.33	4.33	4.4	4.37	4.63	13.07	8.85
L_L (km)	5.093	22.511	13.802	4.410	4.399	4.404	4.752	13.455	9.103
K (cm^2/s)	$1.46x10^6$	$6.48x10^6$	$3.97x10^6$	$1.22x10^6$	$1.55x10^6$	$1.23x10^6$	$1.35x10^6$	$3.85x10^6$	$2.60x10^6$

The data obtained here in this zone is not influenced by semi-diurnal tidal forces, as it can be seen in the next figure – there was no need of applying a filter to the autocorrelation, as proceeded with the data from the ADCP in the previous section.



(a)



(b)

Figure 4 – Lagrangian autocorrelation function versus time lag. Dashed line is the moving average trend line filtering semi-diurnal tide. Period between 24-4-2015 and 1-5-2015

A value of 2.60×10^6 cm^2/s was obtained for the eddy diffusivity, which compares well with other values obtained in the literature (De Dominicis, et al., 2012). The variance for this data set is 0.081. In general, values obtained for Nazare are higher than the ones obtained in Guia.

7. Final Remarks

The determination of eddy diffusivity on this report followed the same methodology previously adopted to other areas, and the results obtained are in good agreement. However, some assumptions and limitations must be referred:

- In this study, instead of using velocities from drifter buoys, results were obtained directly from current measurements (both in fixed stations and moving equipments). The main consequence of this is the fact that velocities were measured below the surface (thus totally transported by water), while the surface drifting buoys also move based on wind and waves (Stokes drift). Anyway, it is well known that usually drifters tend to overestimate the influence of wind, when compared with trajectory of oil spills, for instance. Based on that, we consider that the results obtained here are reasonable.
- Although the measurements in Guia are usually 3m below the free surface, in the wave glider, measurements are between 6 and10 m, which is not exactly the surface. PCOMS model (and other regional models as well) usually have a first vertical layer that covers depths between 0,1 and 3m (depending of sea surface elevation). For this reason, values obtained for turbulence in Nazare must be lower than what they would be if measuring in a layer closer to the free surface (surface turbulence is usually higher due to wind, for instance). Even though, turbulence obtained in Nazare is higher than the Guia.
- Much more data was available, however they have blank periods without data, or represent a very short period for turbulence analysis.
- Values obtained for Guia were measured during summer, and for Nazare, during the spring season. A more diverse analysis would give an idea of the seasonal variability on turbulence.
- Although values obtained for turbulent diffusivity in Guia and Nazaré are in the same order of magnitude, they are significantly different, giving the idea that the turbulence can have important spatial variability along the Portuguese coast. Nevertheless, adopting approximate values based on the results from this work is a reasonable approach when no more data is available in the region of study.

In the future, more data should be obtained with the same kind of equipment, in the area of study, and in parallel, model validation with surface drifters should also be continuously pursued.

8. References

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