Modelling Hydrodynamic and Particle Transport Processes in the Nazaré Submarine Canyon off Portugal

by

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Uma Após Uma

Uma após uma as ondas apressadas
Enrolam o seu verde movimento
E chiam a alva ,spuma
No moreno das praias.
Uma após uma as nuvens vagarosas
Rasgam o seu redondo movimento
E o sol aquece o ,spaço
Do ar entre as nuvens ,scassas.
Indiferente a mim e eu a ela,
A natureza deste dia calmo
Furta pouco ao meu senso
De se esvaiar o tempo.
Só uma vaga pena inconsequente
Pára um momento à porta da minha alma
E após fitar-me um pouco
Passa, a sorrir de nada

Ricardo Reis, Heterónimo de Fernando Pessoa

Abstract

Submarine canyons are giant topographic features that cut the continental shelves and slopes throughout the world's oceans. Submarine canyons are hotspots of biodiversity supporting large and diverse benthic and pelagic fauna communities attracted by the heterogeneity of different substrates. The faunal communities exhibit particular adaptations to the canyon characteristics under the influence of physical oceanographic processes, organic matter availability and sediment transport processes. Physical processes in submarine canyons tend to be highly complex and their study is exceedingly difficult on account that many of the most important processes are episodic in nature. The advances in the technological development of sampling and surveying equipment in recent decades has led to detailed exploration of these ecosystems, and has brought new insights into the oceanographic, biologic and sediment dynamics of these systems.

The application of process-oriented numerical models has allowed an integrated approach to the simulation of spatial and temporal continuity that cannot be achieved by current analytical methods. Models facilitate the capability to bridge the gap between small and large scale processes, and this inherent property has made them an essential tool for understanding complex processes such as canyon dynamics and transport of particulate material and pollutants within.

This work focused on the Nazaré submarine canyon, the largest submarine canyon on the Portuguese continental margin. Over the last decades several studies have addressed the hydrology, hydrodynamics, particle fluxes and food-web dynamics of this system. Among such studies, a preliminary modelling study was applied to the Nazaré canyon. This work attempted to better understand the dynamics of submarine canyons by a physically integrated modelling approach that utilized an in depth approach relative to previous works by adding to the model simulations of the canyon, more realistic boundary conditions, refined grid and lagrangian particle-transporting model. The 3D hydrodynamic model was forced by a regional operational model at the open boundaries and with the solution of an atmospheric forecast model at the surface, and validated using Argo floats and remote sensing data of the sea surface temperature (SST). The model results were compared to a sporadic upwelling event which was observed by remote sensing data along the Portuguese coast during spring 2009.

The model simulations coincided with beginning of the upwelling season along the Portuguese coast which occurs seasonally between April and September. The upwelling occurring at the Nazaré canyon's head bring deep nutrient-rich waters to the surface, thus enhancing primary production in the near-coastal area. This process is important to the trophic chain as it increases the general productivity and impacts the socio-economic activities of the area, such as in the fishing industry. The hydrodynamic model was used to explain the role of the canyon in enhancing upwelling relative to the open slope, as well as on the polarization of the currents along the canyon axis from the 2500 m depth up to the 150m.

Additionally, the transport of organo mineral aggregates (OMAs) and pollutants were simulated by coupling the hydrodynamic model with a lagrangian model. This approach brought forth new information on the transport and dispersion of the OMAs and pollutants within the canyon. The lagrangian results allowed the comparison of the transport patterns of three different aggregate size classes (429, 2000 and 4000 µm) along the Nazaré canyon. For the OMAs, the results showed that the carbon flux in the canyon was neither constant, nor unidirectional and that there were preferential areas where deposited matter was resuspended and redistributed. During the modelling period, the Nazaré canyon acted as a depocenter of sedimentary organic matter rather than a conduit of OMAs to the deep sea, as reported by other authors. The transport of the larger class size of OMAs (2000 and 4000 µm) was less pronounced than for the medium sized OMAs (429 µm) resulting in the carbon deposition and consequently a decrease in the phytodetrital carbon flux along the canyon was observed. These findings are crucial to the understanding of oceanic carbon sequestration at the continental margin, and therefore, important in evaluating the role of submarine canyons within the global carbon cycle. In addition, this thesis described the transport and deposition pathways of pollutants such as benthic marine microplastics between the coast and the deep sea through the Nazaré canyon using the same lagrangian approach. The model results indicated that transport of benthic marine microplastic is not regular throughout the Nazaré canyon, with stretches of the upper canyon acting more as locations of pellet deposition than conduits of pellet transport. Also it suggested that topography and depths of internal wave action may contribute to the lack of homogeneity in the predicted transport. Lastly, the results allowed the evaluation of the impact of the anthropogenic pollutants to the canyon's ecosystem and may contribute to future guidelines on plastic disposal policies.

Chapter 1

Introduction

Submarine canyons are key environments on the continental margin that are affected by dynamic geological and physical oceanographic processes. Physical processes in submarine canyons tend to be highly complex and their study is exceedingly difficult on account that many of the most important processes are episodic in nature.

Substantial transport of aggregated particulate matter is assumed to take place in submarine canyons, thus establishing an exchange of particulate organic and inorganic matter between coastal areas and the deep sea. Aggregates, composed of varying amounts of organic and mineral materials, are the major components of particulate matter in the benthic boundary layer of marginal seas and the open ocean. The aggregates act as excellent vehicles for lateral transport of organic carbon, and the transport processes are fundamental in the exchange of organic carbon between coastal seas and the deep ocean.

The Nazaré Canyon, a large submarine canyon on the Portuguese continental margin, has been subject to extensive research in the last 15 years. However, only a preliminary modelling approach to represent the system dynamics has been pursued. The work by Garcia (2008) introduced the modelling approach into the canyon by analyzing the resuspension processes and transport of fine sediments within the canyon. The results of the model rendered the ability to describe particular features of the canyon such internal waves and fine sediment transport along the canyon. Since then, the model has undergone substantial revisions to resolve a number of improvements. Important improvements include more realistic boundary conditions in the modelled domain by coupling the Nazaré canyon model to a regional forecast model for the Iberian coast, as well as refining the model grid. In addition, the transport model dually benefited from this improved nesting configuration by additionally gaining the ability to run offline simulations, and therefore be able to study past episodic events.

Numerical models based on physical processes occurring in nature, allow an integrated approach to the simulation of spatial and temporal continuity that cannot be achieved by current analytical methods. By coupling transport models with hydrodynamic models, it is possible to relate information from different fields, thereby enabling the establishment of causal relations and the possibility to analyse feedback loops in the system. Models facilitate the capability to bridge the gap between small and large scale processes, and this inherent property has made them an essential tool for understanding complex processes such as canyon dynamics and transport of particulate material and pollutants within.

This work attempted to better understand the dynamics of submarine canyons by a physically integrated modelling approach by utilizing a more in depth approach relative to the previous work by Garcia (2008). This work considered the boundary conditions provided by an operational circulation model and an atmospheric forecast model, the model grid refinement, and a new approach in the residence time concept of the lagrangian results. The hydrodynamic model was applied to the Nazaré canyon, validated, and then utilized to simulate a sporadic upwelling event. Using a lagrangian model, the model afforded the description of spatial and temporal transport of the OMAs and pollutants through the canyon as a result of ocean currents and tides.

1.1 Submarine Canyons

Submarine canyons are geohydrological structures located along continental margins incising the continental shelves and steep slopes. Harris and Whiteway (2011) performed an inventory of large submarine canyons and estimated that ~ 6000 submarine canyons form the underwater structures throughout our world's oceans. The study characterized the frequency and geomorphology differences of the canyons, proposing that active continental margins contained 15% more canyons (2586) than passive margins (2244). Moreover, the canyons on active margins were steeper, shorter, and more closely spaced than on passive margins. They conclude that most of the canyons were located in geographical areas with relatively high rates of glacial and/or fluvial export of sediments to the continental margins over geological timescales.

The exchange between shelf and deep waters is promoted at continental margins where dense shelf water cascading (DSWC) and upwelling usually occur. The cascading and the upwelling of cold and dense waters are often channelled through canyons thereby intersecting the margin. The DSWC deals with winter cooling of shallow shelf waters promoted by katabatic winds which form a cold dense water mass which cascades down the canyon. This process is often described in submarine canyons such as in the Gulf of Lions margin (Canals et al., 2006), the Adriatic margin (Trincardi et al., 2007) or the Gulf of Thermaikos (Estournel et al., 2005). Equatorward winds parallel to the coast, along the eastern continental margins, induce upwelling and bring deeper rich nutrients waters to the surface. In the last decades, a number of studies have addressed the upwelling in the submarine canyons area such as in Monterey canyon (Broenkow and Smethie, 1978), Astoria canyon (Hickey, 1997), and Nazaré canyon (Mendes, 2011). The upwelling and DSWC brought to the surface (upwelling) or out to the deep sea (DSWC) exchanges cold and dense waters rich in nutrients, and thus have major socio-economic impacts on local fisheries.

The submarine canyons are active conduits for sediment transportation from the coasts to the deep sea (Khripounoff et al., 2003; Puig et al., 2004; Canals et al., 2006). They also act as sinks where sediment accumulates at unusually high rates, especially at times of high sea level (de Stigter et al., 2007; Masson et al., 2010, 2011). Canyons act as channels for enhanced transport of organic matter (Canals et al., 2006), yet additionally they act as sites for organic carbon burial (Canals et al., 2006; Masson et al., 2010; Pusceddu et al., 2010). Moreover, submarine canyons can be both transport channels and deposition areas for anthropogenic pollutants (Puig et al., 1999; Paull et al., 2002; de Jesus Mendes et al., 2011; Mordecai et al., 2011).

It has been estimated that 15% of global submarine canyons support intense deep sea biomass hotspots (De Leo et al., 2010) which in turn emphasizes the role of submarine canyons as biological hotspots (Rowe et al., 1982; Vetter and Dayton, 1999; Duineveld et al., 2001; Tyler et al., 2009; De Leo et al., 2010). This classification is quite controversial (Masson and Tyler, 2011) as some published studies show canyons as areas of high biodiversity (Rowe et al., 1982; Vetter and Dayton, 1999; Tyler et al., 2009) while others propose that canyon biodiversity is significantly different in comparison with the open slope (Duineveld et al., 2001). Yet others suggest the presence of lower biodiversity in the canyon relative to the adjacent slope (García et al., 2007; Koho et al., 2008). The driving forces that lead to biodiversity distribution patterns are not yet clearly understood. However, the studies above clearly demonstrate that canyon morphology and associated substrate heterogeneity have a substantial impact on the canyon's biodiversity, and on the transport and distribution of organic matter down the canyon to the final carbon sequestration in sediments.

For a better understanding of the relation between canyon morphology, sediment/organic matter transport, biodiversity, and carbon cycle, it is crucial to identify and relate the processes leading to sediment/organic matter spatial and temporal distribution along canyons. The Nazaré canyon is one of the most studied canyons with extensive background data, and as such, it is a perfect case study for testing and validating a modelling approach.

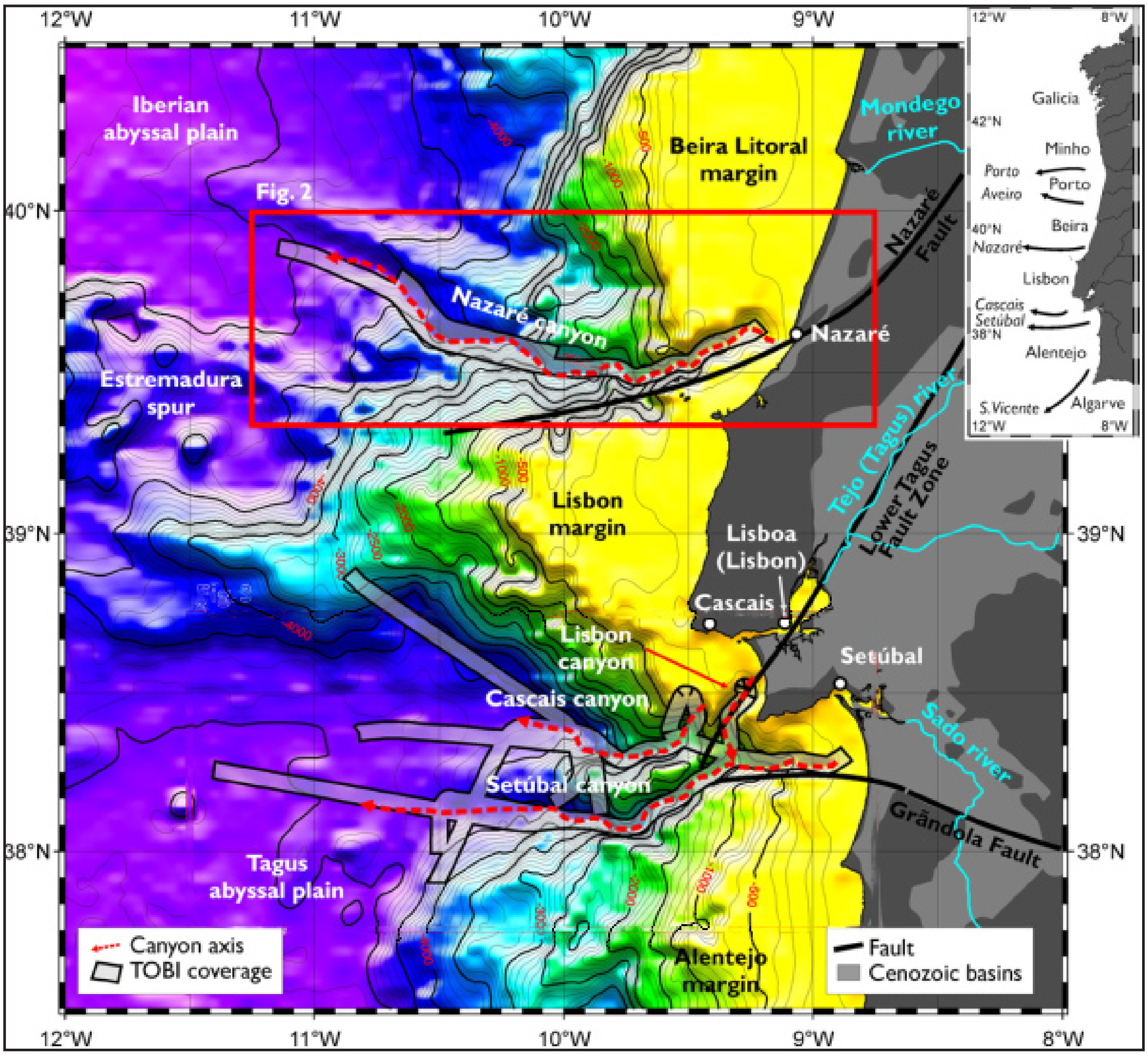

Figure 1.1: Bathymetric map of the Central Portuguese continental margin, with location of main rivers and submarine canyons indicated. Main structural trends were determined by Pinheiro et al. (1996) and Alves et al. (2003). Contours are depicted every 100 m. Coverage of TOBI side-scan sonar data acquired by National Oceanography Centre, Southampton is shown in light gray. Modified after Lastras et al. (2009).

1.2. Study area

1.2.1 The Portuguese margin

The Portuguese continental margin is characterized by a relatively narrow shelf (20-50 km wide and with a slope of ~1º), connected to a steep (6-7º) irregular slope through the shelf break at water depths ranging from 100 to 200 m (Weaver and Canals, 2003; Lastras et al., 2009). The margin is dissected by several long submarine canyons namely from north to south: Porto, Aveiro, Nazaré, Cascais, Lisboa-Setúbal, and São Vicente (Alves et al., 2003). These canyons are the major corridors for the shelf sediment transport, as sediment gravity flows to the abyssal plain (Vanney and Mougenot, 1990; Lastras et al., 2009). The rivers Douro, Mondego, Tagus, and Sado are the main suppliers of terrigenous sediment to the shelf, while the Douro and Tagus are the major contributory rivers (Jouanneau et al., 1998; Lastras et al., 2009; Fig. 1.1).

The shelf dynamics depend on the seasonal and intensity evolution of two major atmospheric systems, the Azores High and the Iceland Low (Wooster et al., 1976; Vitorino et al., 2002). In summer, when the Azores High is located over the central Atlantic and the Iceland Low weakens, northerly winds drive an equatorward jet over the western Iberian shelf and upper slope, inducing coastal upwelling (Fiúza et al., 1982). The summer wave regime is accompanied by low energy wave conditions, with significant wave heights of about 2 m (Pires, 1985). In winter, when the Azores High is located at the most southern position and the Iceland Low reinforces, southwesterly winds induce a downwelling regime over the shelf and drive a poleward flow (Vitorino et al., 2002). The winter wave regime is highly energetic, with significant wave heights exceeding 5 m during storms (Vitorino et al., 2002).

Five different water masses were identified (Mazé et al., 1997; Fiúza et al., 1998) at the west Iberian coast. Along the shelf and upper slope, the North Atlantic Central Water (NACW) extends between a subsurface salinity from ~100 m to ~500-600 m depth. In NACW, the Portugal Current prevails during northerly winds and drives the coastal upwelling, whereas the Portugal Coastal Countercurrent prevails during winter with a poleward surface flow. Underlying this water mass, from ~600 m to 1500 m, is the Mediterranean Water (MW) which can be identified by a strong thermohaline maximum. The MW spreads along the Portuguese continental slope, and entrains in the North Atlantic Deep Water (NADW) which is then called the Deep Intermediate Water (DIW). The NADW has higher salinities and lower temperatures (~2.5 ºC) than the DIW.

The tidal currents are an important oceanographic feature along the western Portuguese margin. The currents propagate from south to north and are dominated by the semi-diurnal tides with the major contribution from the M_2 tide and a secondary contribution from the S_2 (Vitorino et al., 2002; Quaresma et al., 2007). The tidal currents interact with the continental slope topography. According to the characteristics of the topography and the water column stratification, they can leak their energy into internal tidal motions which propagate towards deeper levels. The highest turbidity over the upper slope, at the level of the MW, is due to the action of internal waves (McCave and Hall, 2002). Internal waves and tides play an important role in sediment dynamics on the shelf (Quaresma et al., 2007) and at the upper reaches of canyons (de Stigter et al., 2007). Submarine canyons behave like a trap for internal waves, particularly to the internal tides. In the Nazaré canyon, the tidal currents are the main driving forces for sediment resuspension and transport from upper to middle canyon (de Stigter et al., 2007).

1.2.2 Nazaré Canyon

In the last 15 years, this canyon has been investigated in the framework of European research projects, such as OMEX II (van Weering and McCave, 2002), EUROSTRATAFORM (Weaver et al., 2006), HERMES (Weaver and Gunn, 2009) and HERMIONE projects. The results based on data acquired in the frameworks of the last two projects, have been published in a special issue of Deep Sea Research II (Masson and Tyler, 2011). The Nazaré submarine canyon has been extensively studied in terms of its geomorphology and sedimentology (Schmidt et al., 2001; van Weering et al., 2002; de Stigter et al., 2007; Oliveira et al., 2007; Arzola et al., 2008; Lastras et al., 2009; Masson et al., 2010, 2011), geochemistry (Epping et al., 2002; García et al., 2008; García and Thomsen, 2008) and biology (García et al., 2007; Koho et al., 2007, 2008; Ingels et al., 2009; Amaro et al., 2009; Tyler et al., 2009; Cunha et al., 2011).

The Nazaré canyon is a giant topographic feature (~210 km) incising the Portuguese continental shelf and slope. It extends landward from just before the Nazaré beach where it has a depth of <50 m, to the west of the Iberian Abyssal Plain where it ends at ~ 4900 m water depth. The canyon is not connected to a river system and the adjacent coastal area is characterized by beaches and sea cliffs.

According to Lastras et al. (2009), the canyon can be divided into three sections based on the hydrography and its physical characteristics. The upper section embraces a V-shaped valley incised into the shelf starting at canyon´s head and extending to a depth of 2700 m and is branched by a short side-valley called Vitória tributary. The middle section is characterized by a broad meandering valley with terrace slopes descending from 2700 m to 4000 m depth, while the lower section resembles a flat floored valley which descends to a depth of 5000 m (Fig. 1.2).

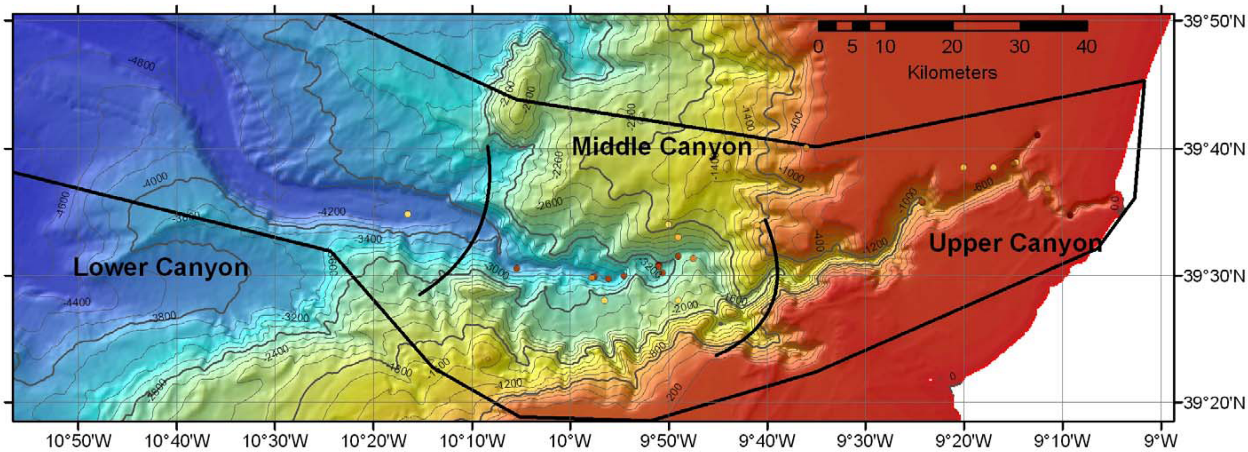

Figure 1.2 Bathymetry map of the Nazaré Canyon. The black polygon delineates the three main sections of the canyon. Modified after Huvenne et al. (2013).

The sedimentation processes in the canyon are controlled by oceanographic and meteorological driving forces even if the canyon is not directly connected to a major river sediment input (de Stigter et al., 2007; Martín et al., 2011; Masson et al., 2011). The bulk of the organic matter within the canyon is derived from terrestrial sources (Epping et al., 2002), and the oceanographic regime favours sedimentation and burial of suspended materials, which explains the high contents of organics and the fast deposition rates observed in the Nazaré canyon (Schmidt et al., 2001; Van Weering et al., 2002; Epping et al., 2002; De Stigter et al., 2007; García et al., 2008).

The hydrodynamic processes are intensified by the rugged topography because the internal waves are preferentially formed in the canyon (Quaresma et al., 2007) and trapped as internal tidal energy. This mechanism is responsible for sediment transport and resuspension at the shelf (Quaresma et al., 2007) and in the upper section of the canyon (De Stigter et al., 2007).

Martín and coworkers (2011) analyzed the near bottom particle dynamics for the upper and middle Nazaré canyon and determined two contrasting dynamic environments. In the upper section (1600 m depth), high current speeds with spring tides up to 80 cm s^{-1} and high mass fluxes of particulate matter (mean 65 g m^{-2} d^{-1}; maximum 265 g m^{-2} d^{-1}) were registered. In contrast at the deepest station (3300 m), the mass fluxes were below 10 g m^{-2} d^{-1} and were not affected by high current speeds. The authors also concluded that storms can trigger sediment transport at the middle Nazaré canyon.

An overview of the role of the benthic fauna in carbon flow and food web dynamics within the canyon has been investigated (Ingels and Vanreusel, 2013) by compiling several studies related to the Nazaré canyon. The work summarized that the trophic status of faunal communities inside the canyon exhibit particular adaptations under the influence of enhanced organic matter availability and the characteristic of the sediment transport processes. The major conclusions of the investigation were that megafauna dominate the three sections of the Nazaré canyon. Additionally, the upper and middle sections of the canyon can be considered as hotspots of megafauna's biomass and production, demonstrating the important role of carbon re-mineralization. However, descending the canyon the mega- and macrofauna contributions are reduced as a response to the combination of high sediment deposition and increased hydrodynamic disturbance, with an increase of the meiofauna contribution. Lastly, in the lower section of the canyon, prokaryotes may dominate the carbon processing.

Due to their oceanographic features, submarine canyons are areas of fast net transport of particulate material so that the lower slope and its faunal community are supplied with labile organic matter (Thomsen et al., 2002; de Jesus Mendes et al., 2007b). Hence, the transport of organic particles in submarine canyons is relevant in terms of global carbon sinks and sources budgets (Thomsen et al., 2002; Accornero et al., 2003; Masson et al., 2010). Assuming the same principle, pollutants are also subjected to rapid transport to the deep ocean (Thomsen et al., 2002; de Jesus Mendes et al., 2011). Recently, remotely operated vehicle (ROV) video surveys of benthic marine litter in the submarine canyons off the coast of Portugal reported highest abundances in canyon heads located off the coast of populated cities. In light of this, submarine coastal canyon systems may also function as dispersal and transport conduits for benthic microplastics of coastal and fluvial origin (Mordecai et al., 2011).

1.3 Particle Dynamics

The biological processes throughout the marine systems are critical mechanisms to remove CO_2 from the atmosphere. Thus, the global primary production plays an important role in contributing to balance the ecosystem equilibrium. Wind driven upwelling events can sustain high levels of global primary production along continental margins (Joint et al., 2001). Besides the contribution of in situ biogenic particles, the continental margins are exposed to organic and lithogenic particles with terrestrial origin from river discharges, land run-off, and aeolian transfers (Epping et al., 2002). A similar modus operandi is expected of anthropogenic pollutants.

The vertical flux of particles from surface waters lead to the evolution of aggregate size, transformation and their sinking to the deep sea floor (Turley, 2000). The aggregates are a mixture of living and dead phytoplankton, zooplankton, bacteria, protists, detritus, excretory products such as faecal pellets, and marine gels (Thomsen and McCave, 2000; Karakas et al., 2009). During descent, these aggregates are a food source to the pelagic and benthic fauna. The organic matter is remineralized in the first 100 m below the surface, consequently, only a small percentage of the surface primary production arrives to the deep sea (Turley, 2000). Upon arrival to the sea bed, the consumed aggregates during descent are remineralized by either the microbial community or benthic organisms. However, part of this organic matter is too refractory to be recycled (Siegenthaler, 1993) and is buried in the sediments thereby removing the carbon for a timescale of centuries to millions of years (Turley, 2000).

The lateral transport of particles is controlled by the hydrodynamics in the benthic boundary layer (BBL). The aggregates transported within the BBL are continuously subjected to aggregation and disaggregation processes (Thomsen, 1999). They are modified and reshaped in the BBL, and turned into organo-mineral aggregates (OMAs). When settled to the sea bed, OMAs are more easily remobilized than in the sediment surface beneath (Thomsen and Gust, 2000; de Jesus Mendes et al., 2007a). While being transported to greater depths, the OMAs are usually subjected to increasing hydrostatic pressure which inhibits their colonization by the bacterial community. As a result, the reduction of the bacterial colonization of OMAs supplies the deeper ocean with more labile organic matter (de Jesus Mendes et al., 2007b). The marine sediments act as a sink for hydrophobic contaminants (Ricking et al., 2005). Therefore, OMAs are important vehicles of organic pollutants transport within the BBL (de Jesus Mendes et al., 2011).

1.4 Framework, aims and approaches of this PhD study

This study was conducted within the Hotspot Ecosystem Research on the Margins of European Seas (HERMES) and the Hotspot Ecosystem Research and Man‘s Impact On European Seas (HERMIONE) research projects. Within these projects, the Nazaré canyon was commonly investigated as one of the study sites. In the last two decades, previous European research projects such as OMEX II (van Weering and McCave, 2002) and EUROSTRATAFORM (Weaver et al., 2006) also contributed to the actual knowledge about the Nazaré canyon.

1.4.1 The HERMES project

HERMES was a European research project funded under the European Commission’s Sixth Framework Programme and ran from April 2005 to March 2009. The project involved 50 partner organizations from 18 nations and was structured in 10 work packages (WP). The study areas included biodiversity hotspots such as cold seeps, cold-water coral mounds and reefs, canyons and anoxic environments, and communities found on open slopes extending from the Arctic to the Black Sea. The WP 5 dealt with canyons systems and generated a large variety of data on biodiversity, geology, sedimentology, biogeochemistry, and physical oceanography that have been published widely.

1.4.2 The HERMIONE project

The HERMIONE project was follow-on from HERMES project, funded by the European Commission’s Seventh Framework Programme. The project started work in April 2009, and ran for 3 years, with completion in March 2012. It included new science areas, such as the seamounts and hydrothermal vents and new field sites in the Arctic. The project brought together 38 partners, who tried to focus on the anthropogenic impact and policy development. HERMIONE consisted of 9 WP, in which WP 2 focused on ten submarine canyons ecosystems. In addition 7 cross-WP themes (T) were considered: T1- Climate-driven change; T2- Anthropogenic impacts; T3- Episodic events; T4- Ecosystem distribution/connection; T5- Biological capacities; T6- Biodiversity & ecosystem function; T7- Societal and economic impacts.

The hydrology, hydrodynamics, particle fluxes and food quality results on environmental drivers in European canyons have been published widely, with a special issue dedicated to the Geology, Geochemistry, and Biology of Submarine Canyons West of Portugal (Masson and Tyler, 2011). Analysis of newly acquired data and samples from the HERMIONE project is in progress and several papers from the project have been submitted or in preparation.

1.4.3 Aims of PhD study

The beginning of this study coincided with the ending of the HERMES project, and the start of the HERMIONE project. The research aims focus on the Nazaré canyon, which was commonly investigated in both projects. Experimental observations on benthic marine aggregates resuspension and transport characteristics from canyons and open slopes have been compiled for the last two decades by OceanLab researchers at Jacobs University. This work complemented and integrated the research multidisciplinary approaches with the application of a numerical model. This work was aimed at answering the following questions:

- Were the main oceanographic processes in Nazaré canyon correctly simulated by a hydrodynamic model?
- Was the lagrangian model approach able to provide a better understanding of the transport of organo-mineral aggregates (OMAs) in the Nazaré canyon?
- What were the main transport differences in OMAs with different aggregate size classes?
- How was the carbon flux through the canyon?
- What were the transport patterns of pollutants, such as benthic marine microplastics within the canyon?

To answer the questions above, several approaches were used:

1 <u>Simulation of the Nazaré canyon hydrodynamics</u>

A hydrodynamic model was applied during the spring/summer months of 2009 and the autumn/winter months of 2011 following a nested configuration scheme with the boundary conditions provided by an operational model system and atmospheric forecast model. To confirm that the model could adequately reproduce the circulation patterns within the canyon and adjacent slope, the hydrodynamic model was first validated. Subsequently, a sporadic upwelling event in the canyon‘s area was detected by remote sensing data and simulated by the model. The model results were compared for the occurrence and absence of the upwelling events within the canyon and adjacent slope. The model simulations were performed for the spring since it corresponded to a period when the phytoplankton production were expected to rise along the Portuguese margin.

2 Identification of OMAs size class and physical parameters

The OMAs of three different size classes (429, 2000 and 4000 µm) were selected. The 429 µm corresponded to a dominant class of aggregates with the same median aggregate parameter size observed at several European continental margins and slope. The 2000 and 4000 µm were selected to represent phytodetritus aggregates. The critical shear velocities (U^*_{cr}), critical deposition velocities (U^*_{d}), and particle settling velocities (Ws) were determined for the three different aggregate sizes.

3 Simulation of the OMAs transport within the canyon

A lagrangian model coupled to the hydrodynamic model was used to simulate the transport patterns and dispersion of the three different OMAs class size during spring 2009. Ten boxes of same dimensions were distributed along the Nazaré canyon area at water depths between 59 and 3189 m.

4 Evaluation of the lateral carbon flux through the Nazaré canyon

The lagrangian results were used to describe spatial and temporal OMAs transport during spring 2009. The dispersion patterns, residence time estimation, and travel trajectories of organic particles of different sizes under spring hydrodynamic conditions were studied. To characterize the OMAs behavior, the average distance, displacement, and velocity of OMAs of different sizes for each box were determined.

5 Simulation of the benthic marine microplastics pollution transport through the Nazaré canyon

Data comprising required physical parameters from preproduction pellets were necessary to simulate the transport and deposition pathways of benthic marine microplastic pollutants within the canyon. The model was run for two distinct periods (spring/summer 2009 and autumn/winter 2011), and the transport model configuration was the same as for the OMAs and four boxes at 59 m, 262 m, 331 m, and 2657 m depths were placed along the upper part of the Nazaré canyon. The pellet’s residence time and transport patterns were then estimated by the lagrangian model results.

The following five hypotheses (H1 - H5) were investigated:

H1 – The Nazaré canyon is an active conduit of OMAs from the shelf to the deep sea;

H2 – The carbon flux in the canyon is unidirectional and constant.

H3 – The Nazaré canyon promotes the transport of pollutants, as benthic marine microplastics, to the deep sea;

H4 – The model will be able to simulate the main oceanographic features within the canyon;

H5 – The presence of the submarine canyon enhances the upwelling relative to the open slope.

The questions and hypothesis that drove this work were addressed in three manuscripts comprise of chapters 2 to 4 of this thesis:

Chapter 2 (1st Manuscript) investigates the transport patterns of three different classes of organo-mineral aggregates along the Nazaré canyon during spring 2009. The hydrodynamic model reproduces the canyon dynamics, while the transport model describes and compares the transport patterns of OMAs. Here, the lagrangian model setups are described in detail. The results provide a spatial and temporal approach of quantifying the carbon flux through the canyon.

Chapter 3 (2nd Manuscript) is a co-author contribution, and describes the transport and deposition pathways of benthic marine microplastic pollution in the Nazaré canyon following the same approach as for the OMAs.

Chapter 4 (3rd Manuscript) complements the first manuscript by presenting the hydrodynamic model validation by comparison with remote sensing data and Argo floats. The model results compare a sporadic upwelling event in the canyon with adjacent slope occurred during spring 2009. The model describes the circulation patterns along the canyon‘s area.

Finally, **Chapter 5** summarizes the thesis work, validates the hypotheses, and presents an outlook on future research.

1.5 Methods

1.5.1 Physical Parameters of Benthic Aggregates and Preproduction Pellets

Laboratory studies are required to understand and quantify the transport processes of the aggregates. In this study, the physical parameters of the aggregates, such as the median size (d_{50}), settling velocities (Ws), critical erosion velocities (U_{cr}), and critical deposition velocities (U_d) (converted to bottom shear stress, τ_{cr} and τ_d , Table 1.1) are mandatory to perform the lagrangian simulations.

The median aggregates sizes (429 μm) were constituted of organic matter (≤ 80% by weight) and lithogenic material (≥ 20%). The aggregates with larger dimensions (2000 and 4000 μm), also known as fluffy phytodetrital aggregates, were constituted of small amounts of lithogenic material and were highly transparent (>80% organic matter) (Thomsen et al., 2002). The 429 μm aggregates belongs to a dominant class of aggregates with the same median aggregate parameter size observed at the Western Barents Sea, the North East Greenland Sea, the Celtic Sea, the Nazaré and Setúbal canyons (Thomsen and Graf, 1995; Thomsen and Ritzrau, 1996; Thomsen and van Weering, 1998; de Jesus Mendes and Thomsen, 2007) and were sampled during OMEX I, OMEX II, EUROSTRATAFORM and HERMES projects (Wollast and Chou, 2001; Weaver et al., 2006; Weaver and Gunn, 2009). The 4700 μm aggregates corresponds to the high density (HD) plastics (black preproduction pellets) from a sample collected in Los Angeles County, California (Ballent et al., 2013).

Table 1.1 Data comprising the physical data of OMAs and HD black pellets used in the model simulations: aggregate size d (μm); settling velocity Ws (cm s^{-1}); critical and depositional bottom shear stresses τ_{cr} and τ_d (N m^{-2}) (Thomsen et al., 2002; de Jesus Mendes and Thomsen, 2007; Pando et al. 2013; Ballent et al., 2013).

Aggregates	d [μm]	Ws [cm s^{-1}]	τ_{cr} [N m^{-2}]	τ_d [N m^{-2}]
OMAs	429	0.001	0.050	0.003
OMAs	2000	0.303	0.038	0.030
OMAs	4000	0.477	0.026	0.020
HD Black Pellets	4700	0.028	0.140	0.087

1.5.2 Modelling Approach

The applications of lagrangian transport models coupled to hydrodynamic models have a high potential to predict various environmental scenarios. They can be powerful tools to analyse dispersion processes of specific phenomena such as harmful algal blooms (Velo-Suárez et al., 2010; Wynne et al., 2011), to evaluate scenarios in risk analyses for the authorities (Santoro et al., 2011) and prediction of the trajectory of floating objects as in the case of oil spills (Carracedo et al., 2006). The application of lagrangian models in operational forecast models has been applied to maritime search and rescue operations (SAR) (Breivik and Allen, 2008; Davidson et al., 2009), with backtracking capabilities (Abascal et al., 2012), and emergency response to oil spills (Castanedo et al., 2006).

In this study, the MOHID model (www.mohid.com) was used to simulate the Nazaré canyon dynamics. MOHID is an open-source water modelling system continuously being developed at MARETEC, a research group at Instituto Superior Técnico (IST), Lisbon, Portugal, created and lead by Prof. Ramiro Neves. It can be used for open and coastal waters (MOHID Water) as well as in watersheds, rivers and soils (MOHID Land).

MOHID Water model is able to simulate a broad range of processes and scales from coastal areas to open ocean. Therefore, it has been applied at different marine systems worldwide, in the framework of both research and consulting projects.

Along the Portuguese coast, several model applications have been performed at estuaries such as the Sado estuary (Martins et al., 2002), the Tagus estuary (Braunschweig et al., 2003; Saraiva et al., 2007; Mateus et al., 2012b); at coastal lagoons (Martins et al., 2003; Vaz et al., 2007; Malhadas et al., 2010); other coastal areas (Ruiz-Villarreal et al., 2002; Leitão et al., 2005; Carracedo et al., 2006; Mateus et al., 2012a) and to the open ocean (Coelho et al., 2002; Santos et al., 2002, 2005).

Recently, an application for the entire Portuguese Coast was implemented as an operational system - MOHID-PCOMS - MOdelação HIDrodinâmica Portuguese Coast Operational Modelling System (Mateus et al., 2012a); it produces 3 day forecast on a daily basis. Modelling results are quality checked and archived, constituting a valuable basis for future research, namely to be applied as boundary conditions for high resolution applications such as the Nazaré canyon.

1.5.3. MOHID Water

The MOHID Water is a numerical model programmed in ANSI FORTRAN 95 (Fernandes, 2005) and can be edited in any operating system (Windows, Linux, Unix) and environment. The model originally developed by Neves (1985) and further developed by Santos (1995), Martins (1999), Leitão (2002), and Mateus et al. (2012a) can be applied to simulate water dynamics, dispersion phenomena using a lagrangian and eularian approach, wave propagation, sediment transport, water quality and biogeochemical processes within the water column and exchanges with the bottom. The model uses an objected-orientated programming philosophy (Decyk et al., 1997) and can be subdivided in several modules which simulate different processes. Also, the model can perform different simulations (1D, 2D or 3D; Miranda et al., 2000) and can be used in an one-way nesting scheme (Leitão et al., 2005; Mateus et al., 2012a).

In terms of processes, the main modules relevant in this work are:

- Hydrodynamic Module: Computes the non-turbulent flow properties, such as water level, velocities, water fluxes in a eulerian approach;
- Turbulence Module: Manages the turbulent flow properties, such as viscosities, diffusivities, turbulent kinetic energy and uses the formulation from the General Turbulence Ocean Model (GOTM);
- Water Properties Module: Manages the water properties processes, such as temperature, salinity, density using a eulerian approach;
- Lagrangian Module: Manages the processes governing water properties evolution using a lagrangian approach.

1.5.3.1 Hydrodynamic Module

This is a 3D baroclinic model which solves primitive equations for incompressible flows in orthogonal horizontal coordinates. In order to simplify the calculus, the model considers the Coriolis force, the hydrostatic and Boussinesq approximations, and the pressure term divided into barotropic and baroclinic components.

The spatial discretization uses a finite volume approach to discretize the equations in a curvilinear structured grid (Martins, 1999; Martins et al., 2001). The grid is staggered horizontally using the Arakawa concept (Arakawa, 1966) and the model supports the use of the Sigma, Cartesian and fixed depth vertical coordinates, allowing its application in areas with different geometric characteristics. The advection-diffusion of all properties can be discretized by the centred differences, upwind, and TVD (Total Variation Diminishing) schemes.

The temporal discretization is based on a semi-implicit ADI (Alternate Direction Implicit) algorithm to compute the sea level evolution with two time levels per iteration, following the Leendertse scheme (Leendertse, 1967). All motion processes are solved in an explicit approach using the Thomas algorithm (Fernandes, 2005) expect for the ones more prone to instability (barotropic pressure, bottom shear stress and vertical diffusion) that are solved with an implicit approach.

Open boundary conditions can be imposed as fixed values, using radiation schemes or a combination of these two. Tide forcing can be based on files with amplitude and phase of tidal harmonic components, and time series of water level average at a specific locations (e.g. FRS (Flow Relaxation Scheme); Flather, 1976). Closed boundary conditions may be used to model intertidal areas (Fernandes, 2005), and are capable to handle slipping or non-slipping conditions.

1.5.3.2 Turbulence Module

The numerical resolution of the hydrodynamic module equations is discrete in both space and time, and these equations are solved assuming Reynolds decomposition. The general approach to calculate the turbulent term in this module is by assuming its proportionality to the spatial gradient of the average property which is transported. This average property may be derived by utilizing a constant turbulent viscosity, and defining the horizontal and vertical resolution in the specific application model (Fernandes, 2005).

The vertical turbulence is parameterized using the turbulence module of the GOTM (General Turbulence Ocean Model; http://www.gotm.net./) and is incorporated in the MOHID code, thereby, providing the turbulent viscosities from the average of the flow properties.

1.5.3.3 Water Properties Module

This module deals with the water properties (e.g. temperature T, salinity S), transport, and evolution by solving the general advection-diffusion equations. The horizontal and vertical terms of these equations may be resolved by using an explicit or implicit approach. The advection term may be resolved by various discretization schemes, such as the centred differences, upwind, and TVD schemes. The density is calculated based on the state equation for T, S, and pressure from UNESCO (1983). The temperature and the salinity changes are due to the transport patterns of the flow from punctual discharges, surface fluxes like heat fluxes (solar radiation, infrared radiation, latent, and sensible heat in the case of the temperature) and mass exchanges (evaporation and precipitation in the case of the salinity).

1.5.3.4 Lagrangian Module

This module utilizes the tracers' concept, which is based on the simulation of the tracers' movement in a lagrangian referential. The advantages of its application are that this approach avoids the instability problems from explicit resolution of the advective transport term equation and can be applied to areas with complex features and abrupt gradients. The tracers are characterized by their spatial coordinates (x, y and z), volume, and in this study the properties of the organo-mineral aggregates (Pando et al., 2013) and benthic marine pollutants (Ballent et al., 2013) such as settling velocity, critical shear erosion, and critical shear deposition. The random movement of the tracers are influenced by the velocity field from the hydrodynamic module, wind from the atmospheric module, the spreading velocity from the oil dispersion module, or by random velocities. This module may interact with other modules in order to simulate different processes (e.g. oil dispersion, water quality, sediment transport) and is capable to calculate the residence time (Braunschweig et al., 2003; Saraiva et al., 2007; Malhadas et al., 2009; Ballent et al., 2013; Pando et al., 2013).

The tracers are placed at origins and when related to a common origin, they share the same list of properties and use the same parameters for the random movement. These origins may release the tracers with different space and temporal approaches. In space, the origins may release the tracers as point origin (in a certain point), box origin (in a certain area) and accident origin (in a circular form around a point). While, in time, the tracers may be release in a continuous origin (during a certain period of time), an instantaneous origin (in one instant), and a moving origin (during a certain period of time along a defined track). The origins may be compiled in groups, and in the output files which facilitate the analysis of the results. In order to calculate the residence time, tracers may be distributed inside of monitor boxes (mb). The residence time of the water in the mb is calculated by the interval of time required to replace the initial water volume in the mb by new water (Braunschweig et al., 2003). A new approach of this concept has already been applied (Ballent et al., 2012; Pando et al., 2013) based on the temporal interval required by the OMAs and pollutants to leave each monitor box, and considered the area of the box.

1.5.4 MOHID-PCOMS operational system

The first attempts to have an operational model running for the West Iberian Coast was made by Riflet and coworkers (Riflet et al., 2008). Currently, the MOHID-PCOMS system (Mateus et al., 2012a) runs daily in a full operational mode with a 3 day forecasting (http://forecast.maretec.org/) of the West Iberian coast. The operational model is based on the MOHID model (described above) with two nested domains:

- Domain 1: 2D barotropic model with 0.06º spatial resolution forced with FES2004 global tidal solution, using a Blumberg-Kantha radiation scheme (Blumberg and Kantha, 1985) along the ocean boundary.
- Domain 2: 3D baroclinic model with 0.06º spatial resolution and 50 vertical layers (43 Cartesian coordinates at the bottom and 7 Sigma coordinates at the upper 10 m). It is forced by the Mercator-Ocean PSY2v4 (version operational since January 2011) North Atlantic solution composed linearly with the FES2004 tide solution. Temperature and salinity initial conditions are interpolated directly from the Mercator-Ocean fields. The system is one-way coupled offline with the atmospheric forecast model MM5 (described below).

Atmospheric forcing is given by the weather forecasts produced by MM5 (Dudhia et al., 2005) model running operationally at IST for Continental Portugal (http://meteo.ist.utl.pt). The model is composed of two nested domains with a spatial resolution of 27 and 9 km for Continental Portugal, with initial and boundary conditions provided by GFS (Global Forecast System). Forecasts such as air temperature, wind speed, surface humidity, and mean sea level pressure are obtained for the 3 days following the beginning of simulation and updated 4 times per day (0, 6, 12 and 18h UTC) (Trancoso, 2012). The MOHID-PCOMS results are continuously validated and the results archived. The validation is performed by daily comparisons of:

- SST fields with remote sensing data from ODYSSEA Global SST (http://ghrsst.jpl.nasa.gov);
- Temperature and salinity profiles against Argo floats;
- Currents, water level and field data

In this study MOHID-PCOMS was used as a boundary condition (Ballent et al., 2013; Pando et al., 2013). Other study areas requiring local high resolution models application have been simulated using a nesting configuration such as in the Tagus estuary (Campuzano et al., 2012), Ria de Aveiro, Viana do Castelo and Leixões ports, and the Memória and St. Amaro de Oeiras beaches (Mateus et al., 2013).

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Chapter 2

Application of a lagrangian transport model to organo-mineral aggregates within the Nazaré canyon

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Abstract

In this study, a hydrodynamic model was applied to the Nazaré submarine canyon with boundary forcing provided by an operational forecast model for the west Iberian coast from the spring of 2009. After validation, a lagrangian transport model was coupled to the hydrodynamic model to study and compare the transport patterns of three different classes of organo-mineral aggregates along the Nazaré canyon. The results show that the transport in the canyon is neither constant, nor unidirectional and that there are preferential areas where deposited matter is resuspended and redistributed. The transport of the larger class size of organo-mineral aggregates (2000 μm and 4000 μm) is less pronounced, and a decrease in the phytodetrital carbon flux along the canyon is observed. During the modelled period, the Nazaré canyon acts as a depocentre of sedimentary organic matter rather than a conduit of organo-mineral aggregates to the deep sea, as has been reported by other authors. The results of this study are crucial for the understanding of the oceanic carbon sequestration at the continental margin, and therefore important for evaluating the role of submarine canyons within the global carbon cycle.

2.1 Introduction

Understanding the exchange of energy and matter between the shelf and the open ocean has been the focus of several European research programmes such as OMEX (Wollast and Chou, 2001), EUROSTRATAFORM (Weaver et al., 2006) and HERMES (Weaver and Gunn, 2009). Most recently the HERMES and HERMIONE programmes have addressed the distribution of organic matter, carbon flow and biodiversity in European continental margins (e.g. García et al., 2007; Ingels et al., 2009; Van Oevelen et al., 2011). In these studies submarine canyons are identified as important transport systems of sedimentary organic matter from the continental shelf to the deep ocean (Monaco et al., 1999; Schmidt et al., 2001; Canals et al., 2006), as important depocentres of sediments and organic matter of often higher quality (Epping et al., 2002; Van Weering et al., 2002; De Stigter et al., 2007; García et al., 2008, 2010) as well as hotspots of biodiversity (Ingels et al., 2009; Tyler et al., 2009; Cunha et al., 2011). Consequently, the transport of organic particles in submarine canyons is relevant in terms of global carbon budgets (Thomsen et al., 2002; Accornero et al., 2003; Masson et al., 2010).

Most of the present understanding on the transport of organic particles within submarine canyons has been derived from field observations which have subsequently been summarized in conceptual models of canyon dynamics. The downward transport and the redistribution of sediments and organic particles is controlled by hydrodynamic processes interacting with the bottom topography, such as internal tide circulation, internal waves, the formation of nepheloid layers, down and along slope bottom currents, intermittent gravity flows or the cascading of dense water (e.g. Van Weering et al., 2002; Canals et al., 2006; De Stigter et al., 2007). Hence, submarine canyons which are dominated by the formation of nepheloid layers and internal tides circulation, for example, should mostly concentrate organic material close to the canyon walls; while canyons dominated by down canyon circulation or cascading should mostly transfer organic particles to greater water depths.

The Nazaré submarine canyon is the largest canyon adjacent to the Portuguese coast and has been extensively studied in terms of its geomorphology and sedimentology (Schmidt et al., 2001; Van Weering et al., 2002; De Stigter et al., 2007; Oliveira et al., 2007; Arzola et al., 2008; Lastras et al., 2009), geochemistry (Epping et al., 2002; García et al., 2008; García and Thomsen, 2008) and biology (García et al., 2007; Koho et al., 2007; Ingels et al., 2009; Amaro et al., 2009; Tyler et al., 2009; Cunha et al., 2011). The bulk of the organic matter within the canyon is derived from terrestrial sources (Epping et al., 2002). The oceanographic regime favours the sedimentation of suspended material and burial, which explains the high organic contents and faster depositions in Nazaré canyon (Schmidt et al., 2001; Van Weering et al., 2002; Epping et al., 2002; De Stigter et al., 2007; García et al., 2008). The lateral transport of organic particles through the benthic boundary layer (BBL) is via both aggregation and disaggregation processes as the material is transported in resuspension loops (Thomsen, 1999; de Jesus Mendes et al., 2007) where aggregates are re-shaped and modified into organo mineral aggregates (OMAs) (de Jesus Mendes et al., 2007).

The characteristics of marine aggregates collected from depth have been determined for the Iberian continental margin (Thomsen and Gust, 2000; de Jesus Mendes and Thomsen, 2007) but have not been used to date for numerical modelling. The application of lagrangian transport models linked to hydrodynamic models has a high potential to predict various environmental scenarios. At the western Iberian margin, lagrangian transport models have been applied to the Galician coast (Carracedo et al., 2006), Ria de Vigo (Huhn et al., 2012; Abascal et al., 2012), Rio Lima estuary (Vale and Dias, 2011), Ria de Aveiro lagoon (Dias et al., 2001), Óbidos lagoon (Malhadas et al., 2009), and Tagus estuary (Braunschweig et al., 2003). The operational model MOHID-PCOMS (MOdelação HIDrodinâmica Portuguese Coast Operational Modelling System) (Mateus et al., 2012) runs in full operational mode for the western Iberian coast with daily hydrodynamic and ecological results. The model adequately represents the hydrodynamic features of the region and the seasonal variations in the dynamical processes. In this study, the MOHID model simulated the dispersion of OMAs within the Nazaré canyon by coupling the hydrodynamic model to a lagrangian transport model. The simulations in this current study cover several months of the spring, a period during which surface phytodetritus production and subsequent transport to benthic communities is of ecological interest. The numerical model was assessed to determine whether it agreed with the flux passing through the upper and middle part of the canyon as described by the current conceptual model of organic matter transport. Lastly, the hypothesis that the Nazaré canyon acts as a conduit for OMAs, and therefore an enhanced carbon flux, was tested.

2.2 Methods

2.2.1 Study area

The western Iberian shelf and slope are intersected by several submarine canyons. The Nazaré canyon is the largest of these extending ~210 km offshore, from the Nazaré beach running down to 5000 m depth (Tyler et al., 2009). According to Lastras et al. (2009), the canyon can be divided into three sections based on the hydrography and its physical characteristics. The upper section embraces a V-shaped valley incised into the shelf starting at the canyon´s head and extending to a depth of 2700 m and is branched by a short side valley called Vitória tributary. The middle section is characterized by a broad meandering valley with terrace slopes descending from 2700 m to 4000 m depth and the lower section, a flat floored valley which descends to a depth of 5000 m. The canyon cuts the entire Portuguese continental shelf and slope. The hydrodynamic processes are intensified by the rugged topography because the internal waves are preferentially formed in the canyon (Quaresma et al., 2007) and trapped as internal tidal energy. This mechanism is responsible for sediment resuspension and transport at the shelf (Quaresma et al., 2007) and in the upper section of the canyon (De Stigter et al., 2007). Martín et al. (2011) analysed the near bottom particle dynamics for the upper and middle Nazaré canyon and determined two contrasting dynamic environments. In the upper section (1600 m depth) high current speeds with spring tides up to 80 cm s^{-1} were registered and also high mass fluxes of particulate matter (mean 65 g m^{-2} d^{-1}; maximum 265 g m^{-2} d^{-1}), while at the deepest station (3300 m) the mass fluxes were below 10 g m^{-2} d^{-1}. The authors also concluded that storms can trigger sediment transport at the middle Nazaré canyon.

2.2.2 Organo-mineral aggregate data

The dispersion patterns, residence time estimation and travel trajectories of organic particles of different sizes under spring hydrodynamic conditions were studied. The OMAs of three different size classes (i.e. 429 μm, 2000 μm and 4000 μm) were sampled during OMEX I, OMEX II, EUROSTRATAFORM and HERMES cruises to the northeastern Atlantic continental margin (RV Pelagia 1995, 1998, 2004, RV Meteor 1998/1999; Thomsen et al., 2002; de Jesus Mendes and Thomsen, 2007). The 429 μm aggregates belong to a dominant class of aggregates with the same median aggregate parameter size observed at the western Barents Sea, the northeast Greenland Sea, the Celtic Sea, and the Nazaré and Setúbal canyons (Thomsen and Graf, 1995; Thomsen and Ritzrau, 1996; Thomsen and Van Weering, 1998; de Jesus Mendes and Thomsen, 2007). Frequently these aggregate sizes were found at the shelf and at depths >2500 m, while aggregates with larger dimensions (> 900 μm) were found at 3400 m depth at the Northwest Iberian continental margin (Thomsen et al., 2002). The median aggregate sizes (429 μm) were constituted of organic matter (≤ 80% wt) and lithogenic material (≥ 20%) while the aggregates with larger dimensions (2000 μm, 4000 μm), also known as fluffy phytodetrital aggregates, were constituted of small amounts of lithogenic material and were highly transparent (> 80 % organic matter).

Critical shear velocities (U^*_{cr}), critical deposition velocities (U^*_d) and particle settling velocities (Ws) were determined for the three different aggregate sizes (Thomsen et al., 2002; Table 2.1). These velocities were mandatory for the lagrangian model and their units were converted into the model requirement units.

Table 2.1: OMA characteristic data used in the model simulations: aggregate size d (μm); settling velocity Ws (cm s^{-1}); critical and depositional velocities U^*_{cr} and U^*_d (cm s^{-1}); critical and depositional bottom shear stresses τ_{cr} and τ_d (N m^{-2}) (Thomsen et al., 2002; de Jesus Mendes and Thomsen, 2007).

d [μm]	Ws [cm s^{-1}]	U^*_{cr} [cm s^{-1}]	τ_{cr} [N m^{-2}]	U^*_d [cm s^{-1}]	τ_d [N m^{-2}]
429	0.001	0.72	0.050	0.058	0.003
2000	0.303	0.61	0.038	0.500	0.030
4000	0.477	0.50	0.026		0.020

2.2.3 MOHID model

2.2.3.1 Hydrodynamic module

A high-resolution hydrodynamic model was used to simulate the evolution of the 3D physical structure of the Iberian coast, and its influence on OMA transport to and within the Nazaré canyon. The model is an open source software under continuous development, named MOHID Water (http://www.mohid.com), and a component of the MOHID Water Modelling System (MWMS), an integrated water modelling software that simulates water dynamics in water bodies, porous media and watersheds (Mateus, 2012). The MWMS is able to simulate broad processes and scales in marine systems ranging from coastal areas to the open ocean (Coelho et al., 2002;

Santos et al., 2002, 2005; Mateus et al., 2012). The hydrodynamic model solves 3D incompressible primitive equations considering hydrostatic equilibrium and the Boussinesq approximation, and its description can be found in Martins et al. (2001). The turbulent vertical mixing coefficient is determined using the General Ocean Turbulence Model (GOTM).

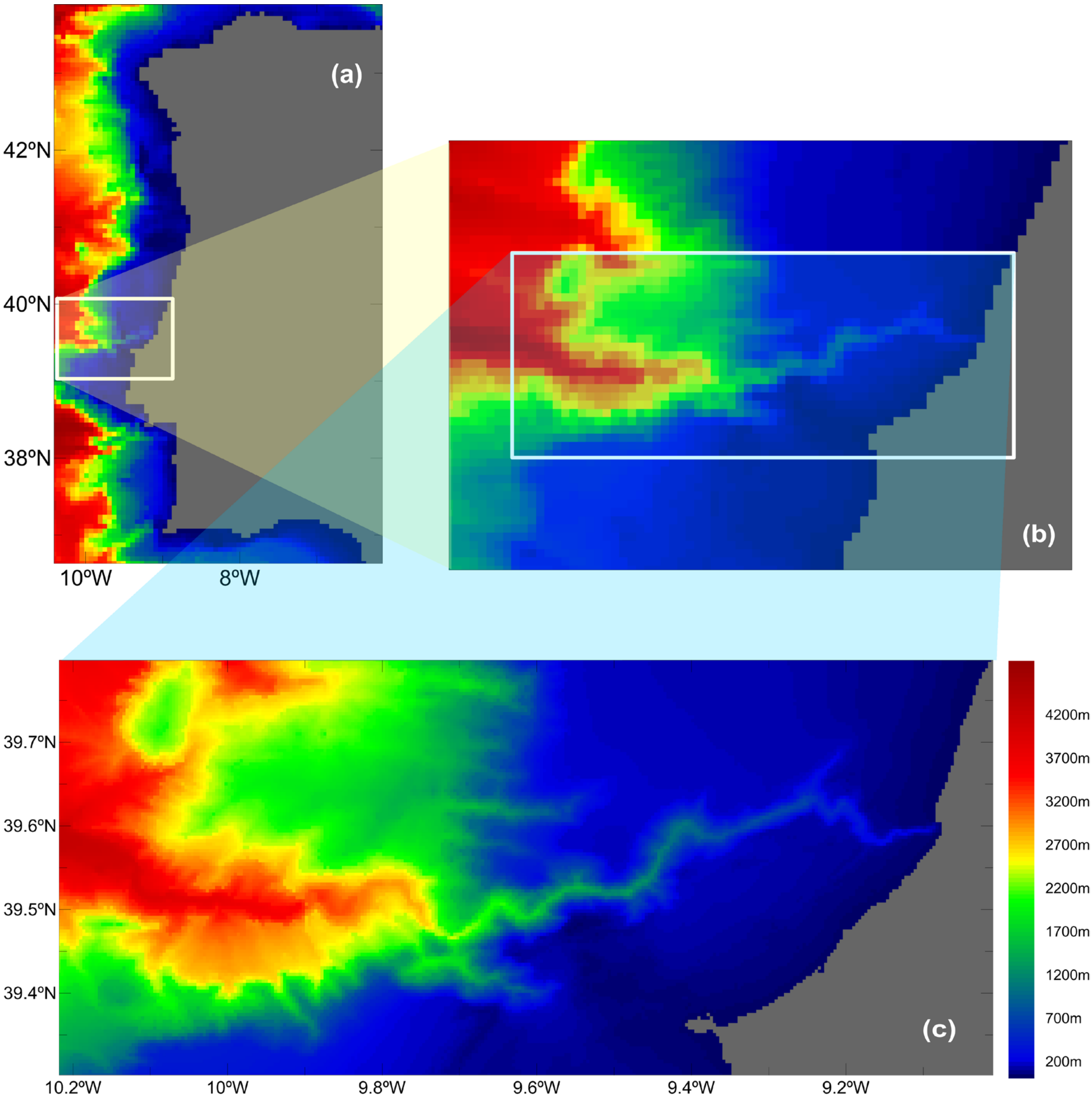

Figure 2.1: Nazaré canyon location at the western Iberia margin. The nested domains: (a) first level: MOHID-PCOMS; (b) second level: Figueira da Foz - Peniche; (c) third level: Nazaré canyon.

2.2.3.2 Lagrangian transport module

The lagrangian transport module of MOHID was used to simulate particle transport following the methodologies proposed in previous works (Braunschweig et al., 2003; Saraiva et al., 2007; Malhadas et al., 2009). The lagrangian module simulates the movement of aggregates located at specific water depths using the current fields calculated by the hydrodynamic module, thus solving the equation of transport independent of momentum balance equations. The lagrangian module derives the hydrodynamic information (current fields) from the system and updates the calculations without having the need to solve all variables at the same time. It uses the concept of passive tracers, characterized by their spatial coordinates, area and others properties such as settling velocities, and critical and depositional bottom shear stress (Table 2.1).

In our study, the model simulates the OMA trajectories using the concept of settling velocity, and each particle is assigned a time to perform random movement. These particles are placed at origins which emit the tracers at a specific depth and at one instant in time. The dispersion and distribution field of the particles is monitored using monitoring boxes to compute their residence time. For this project we use the term “residence time” for the temporal interval required by the OMAs to leave each monitor box. This is a new and alternative approach to the previous concept proposed by Braunschweig et al. (2003). The lagrangian results to characterize the OMA behaviour showed the average distance, displacement and velocity of OMAs of different sizes for each box (Figs. 2.8 - 2.10). The distance was related to the total length that the OMAs travelled (km); the displacement was the difference between the initial and final position of the OMAs (km) and the velocity of the OMAs (km y^{-1}).

2.2.4 Model set-up for the Nazaré canyon

The domain configuration of the Nazaré canyon includes three levels of nested models using a one-way coupling (Fig. 2.1, Table 3.2). This nesting methodology is described in Leitão et al. (2005). The first level covers the west coast of Iberia between 5.5º-12.6º W and 34.4º-45.0º N with a resolution of 5.6 km. The boundary conditions of this level are provided by the 3D operational model MOHID-PCOMS (Mateus et al., 2012). The operational model is forced by data from PSY2v2 Mercator Ocean solution for the North Atlantic and by MM5 atmospheric forecast model with 9 km resolution operated at IST (http://meteo.ist.utl.pt). Tide is imposed from

2-D barotropic model forced by the FES2004 global solution.

The second level covers the stretch from Figueira da Foz to Ericeira between 8.86°-10.38° W and 39.02°-40.08° N with a constant grid spacing of 2 km. The third grid has a resolution of 400 m for the Nazaré canyon area between 9°-10.22° W and 39.3°-39.8° N. The vertical resolution of the three different levels adopted in this one-way nested modelling scheme is with 50 vertical layers, 43 Cartesian coordinates on the bottom and 7 sigma coordinates on the upper 10 m.

Table 2.2. Percentage of OMAs escaping from the monitor boxes predicted by the model.

Box	Depth [m]	429 μm [%]	2000 μm [%]	4000 μm [%]
1	59	8.38	0.05	0.75
2	262	29.74	6.04	22.31
3	357	2.05	1.75	1.65
4	575	1.60	0.95	0.95
5	331	3.90	3.30	3.30
6	945	2.30	1.70	1.70
7	1498	7.73	3.54	8.87
8	2077	16.24	2.99	27.25
9	2657	14.36	2.49	39.38
10	3189	21.68	10.87	48.85

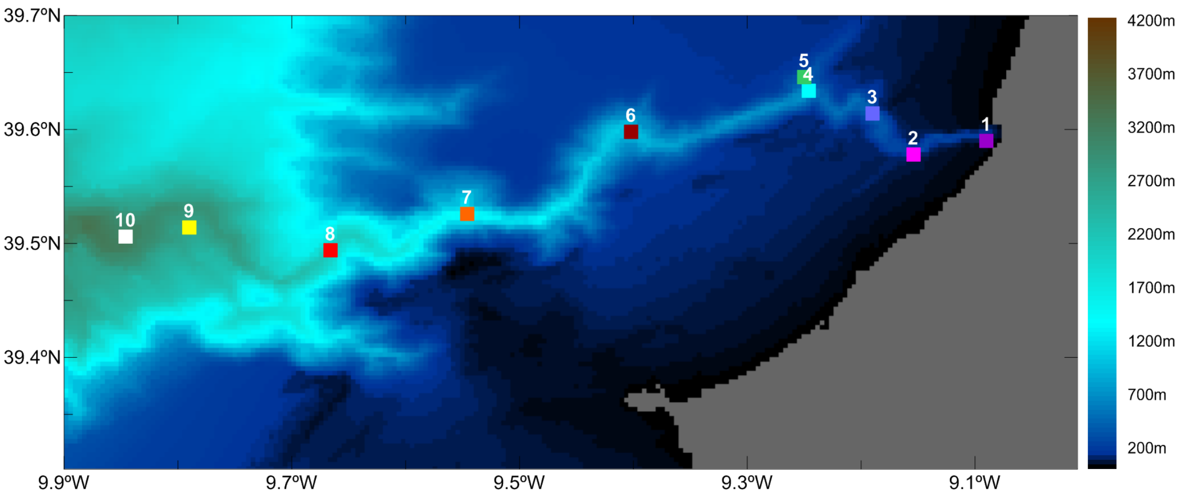

Figure 2.2: Location of the 10 monitor boxes. The monitor boxes are set at increasing depths from box 1 to box 10: 59 m, 262 m, 357 m, 575 m, 331 m, 945 m, 1498 m, 2077 m, 2657 m, and 3189 m.

The bathymetric data for the levels construction were provided by the National Oceanography Centre, Southampton (NOCS), and the Portuguese Hydrographic Institute (IH). To cover the main period of phytoplankton production, the simulations were conducted to cover a period of the spring season. The model runs from 1 March to 1 July 2009 in order to achieve a proper circulation pattern of the canyon dynamics. The simulations had a time step of 15 s and a horizontal viscosity of 10 $m^2\ s^{-1}$ for the third level. The first and the second level had a time step of 900 s and 60 s and a horizontal viscosity of 30 $m^2\ s^{-1}$ and 20 $m^2\ s^{-1}$, respectively.

The lagrangian module was run with tracers originating from 10 boxes of same dimensions distributed along the Nazaré canyon area at water depths between 59 and 3189 m (Fig. 2.2, Table 2.2). Each box corresponds to a geographic domain of 3×3 cells of the model grid leading to a total of 1.44 km^2. The boxes were filled with aggregates at a height of 0.5 m from the sea floor. While applying the module, properties such as the monitor box area and spatial coordinates, OMA settling velocities, critical and depositional bottom shear stress were taken into consideration. For the OMAs of three different size classes, the settling velocities (Ws) increased with increasing aggregate size, while the critical shear velocities (U^*_{cr}) decreased over the same aggregate size spectrum. However, the depositional bottom shear stress (τ_d) is highest for the medium-sized aggregates (2000 µm), and has lower values for the 429 µm and 4000 µm aggregates (Table 2.1). The boxes were located in the upper (canyon head - 2700 m) and middle (2700-4000 m) part of the Nazaré canyon according to Lastras et al. (2009). The first box was located at the canyon´s head (59 m) and box 2 at the shelf break. The third box was located at 357 m while boxes 4 and 5 were at Vitória's tributary and located at 575 m and 331 m respectively. Boxes 6 and 7 were placed at 945 m and 1498 m where the Nazaré canyon dynamics are controlled by the Mediterranean Outflow Water (MOW). Boxes 8 and 9 were located close to the boundary between the upper and middle part of the canyon (2077 m and 2657 m respectively). The last box was located in the middle part of the canyon at 3189 m. The boxes were filled with ~2000 aggregates of which part escaped from the box depending on the hydrodynamic conditions affecting the box. The validation of the hydrodynamic model was performed with the validation of the MOHID-PCOMS model (Mateus et al., 2012). The following nested levels, including the Nazaré canyon, were also validated allowing the linkage with the lagrangian transport model.

2.3 Results

2.3.1 OMAs residence time dynamics

The residence time of the three OMA classes inside each box for spring 2009 is shown in Figs. 2.3 - 2.5. The oscillation pattern of the three different OMA sizes for box 1 (59 m) to box 5 (331 m) follows the sinusoidal shape of the tide oscillation, being more intense within box 1, located at 59 m depth and smoother in the other boxes (Figs. 2.3 - 2.5). The 429 µm OMAs at box 1 show transport after 60 days of the simulation period (Fig. 2.3), while the phytodetrital aggregates (2000 µm and 4000 µm) remained in the box without being transported (Figs. 2.4 and 2.5). Box 2 at the shelf break showed an abrupt depletion due to transport of the phytodetrital aggregates (2000 µm and 4000 µm) after a period of four days (Figs. 2.4 and 2.5), whereas the 429 µm OMAs continuously decreased with time inside the box (Fig. 2.3). The OMAs in boxes 3, 4, 5, and 6 had high residence times, indicating a reduced transport of aggregates in this part of the canyon. Box 7 at 1498 m showed a decrease in the residence times particularly for the 429 µm and 4000 µm (Figs. 2.3 and 2.5). The model predictions for boxes 8, 9, and 10 located offshore showed a very active transport for the OMAs of different size classes. After 74 days, there was a sudden decrease in OMAs escaping from box 8, and this loss was more pronounced for the 429 µm (Fig. 2.3) and 4000 µm (Fig. 2.5) than for the 2000 µm OMAs (Fig. 2.4). The residence times of the 4000 µm showed a significant depletion in box 9 (Fig. 2.5). On the 46th day of simulation, there was an abrupt decrease of aggregate fraction followed by another significant escape on the 74th day. The 429 and 2000 µm OMAs however showed a gradual and less pronounced depletion with time (Fig. 2.3 and 2.4). Box 10 at 3189 m depth showed a significant depletion in the residence time of the 4000 µm OMAs on the 74th day (Fig. 2.5), whereas 429 and 2000 µm OMAs presented a gradual and less pronounced depletion as was the case of box 9 (Fig. 2.3 and 2.4).

2.3.2 OMA dispersion patterns

A higher percentage of OMAs escaped from the shelf break box 2 and from the offshore boxes 8, 9, and 10 for size classes 429 and 4000 µm when compared to the 2000 µm size class (Table 2.2). Very few 2000 µm OMAs escaped from the boxes along the canyon axis depth gradient, with box 2 and 10 showing a slightly higher escape percentage.

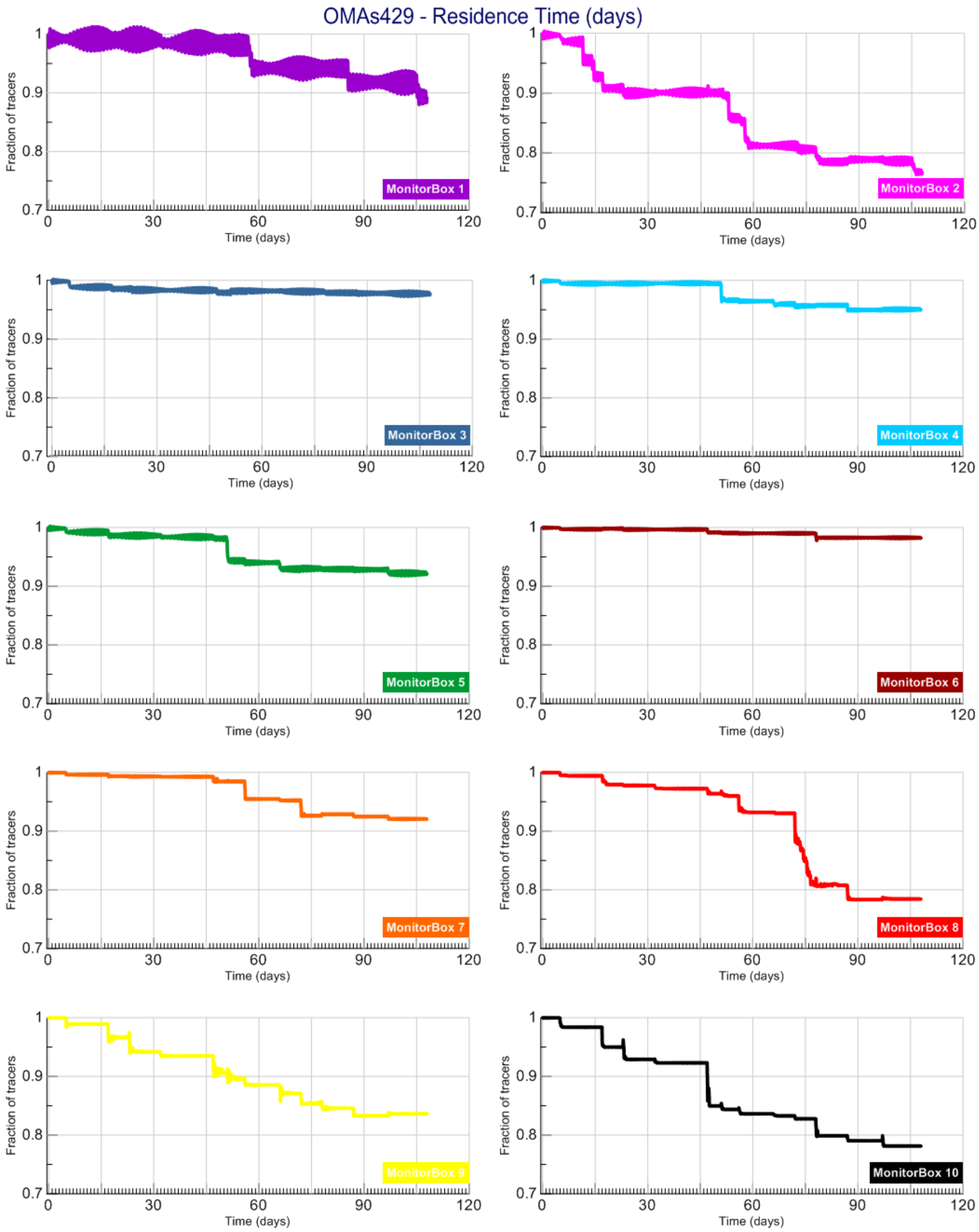

Figure 2.3: The residence time of the 429 μm OMAs in each monitor box over the simulated period. The monitor boxes are set at increasing depths from box 1 to box 10: 59 m, 262 m, 357 m, 575 m, 331 m, 945 m, 1498 m, 2077 m, 2657 m, and 3189 m.

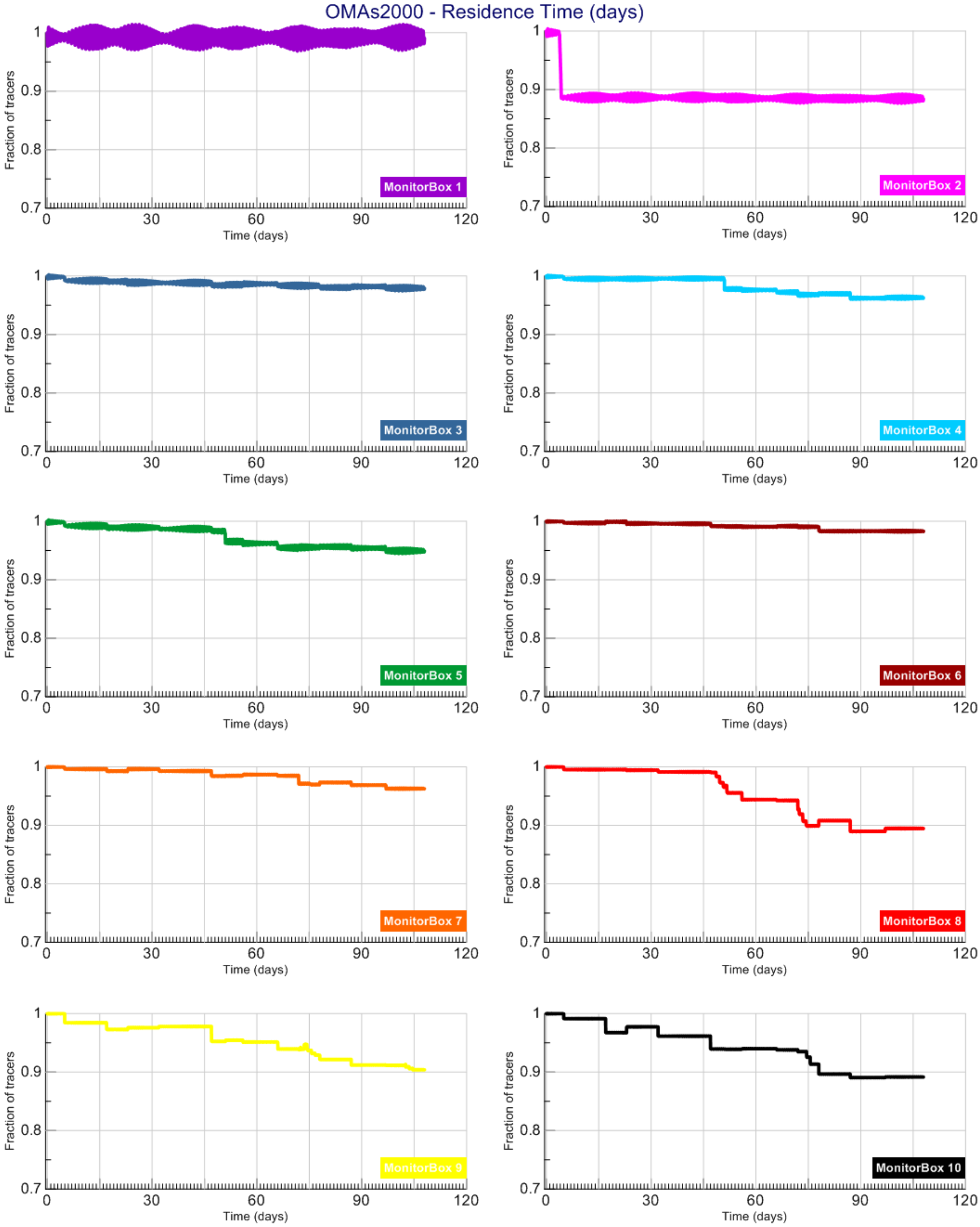

Figure 2.4: The residence time of the 2000 μm OMAs in each monitor box over the simulated period. The monitor boxes are set at increasing depths from box 1 to box 10: 59 m, 262 m, 357 m, 575 m, 331 m, 945 m, 1498 m, 2077 m, 2657 m, and 3189 m.

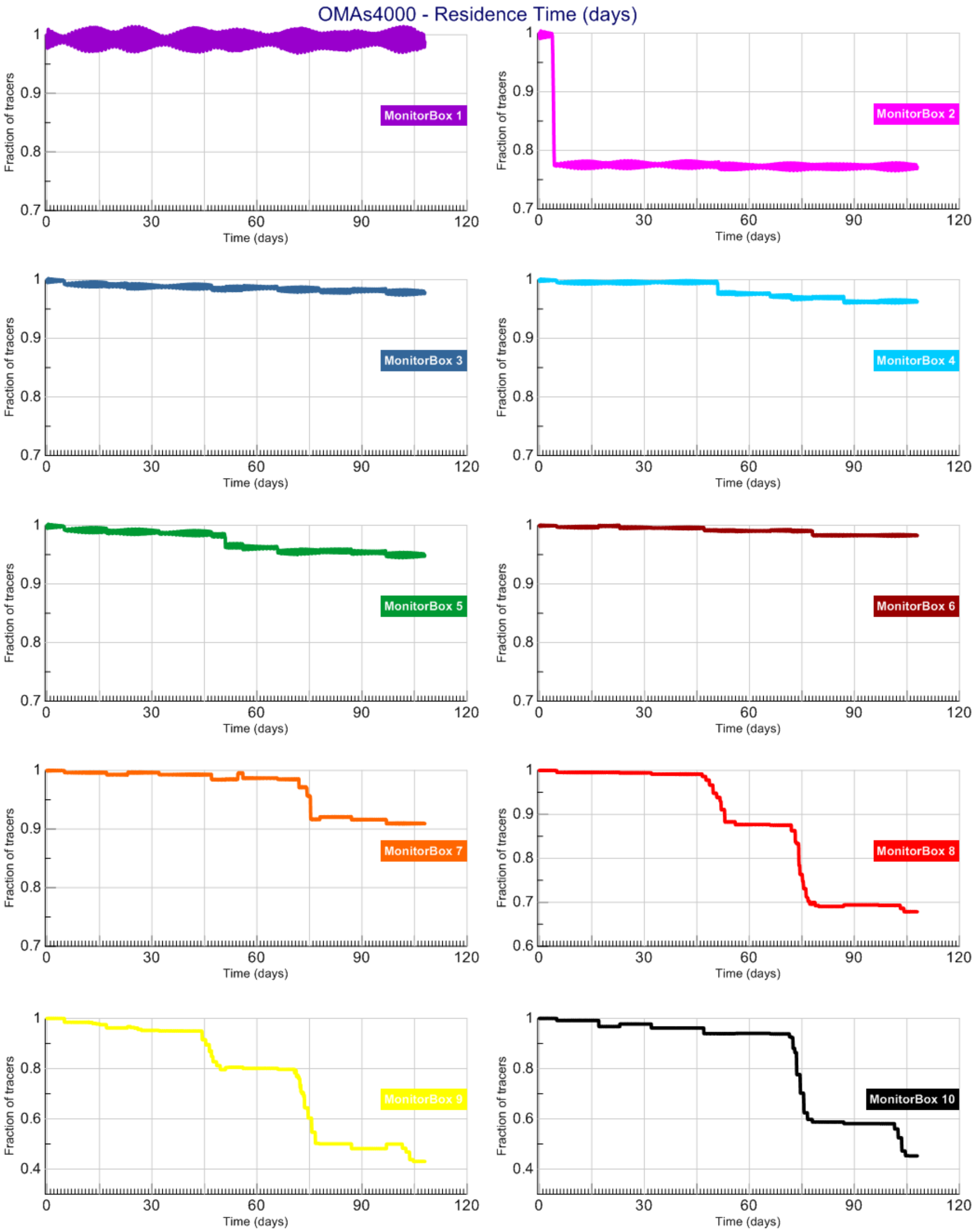

Figure 2.5: The residence time of the 4000 μm OMAs in each monitor box over the simulated period. The monitor boxes are set at increasing depths from box 1 to box 10: 59 m, 262 m, 357 m, 575 m, 331 m, 945 m, 1498 m, 2077 m, 2657 m, and 3189 m.

When comparing the 429 µm and 4000 µm OMA size classes, a higher percentage of 429 µm OMAs escaped from box 1 to 6, while from box 7 to 10 the 4000 µm OMAs showed higher percentages of escape (Table 2.2).

Figure 2.6 and 2.7 represent the dispersion patterns for the 429 µm and 4000 µm OMAs in each box predicted by the model for an initial period of 22 days, which is the half-life of fresh phytodetritus (Sun et al., 1991). The figures show the aggregate trajectories along the depth gradient during that period. The 429 µm OMAs from box 2 at the shelf break were dispersed and transported in different directions (Fig. 2.6). OMAs travelled southward along the coast with the Portugal current, up-canyon in the direction of the coast and down-canyon (Fig. 2.6).

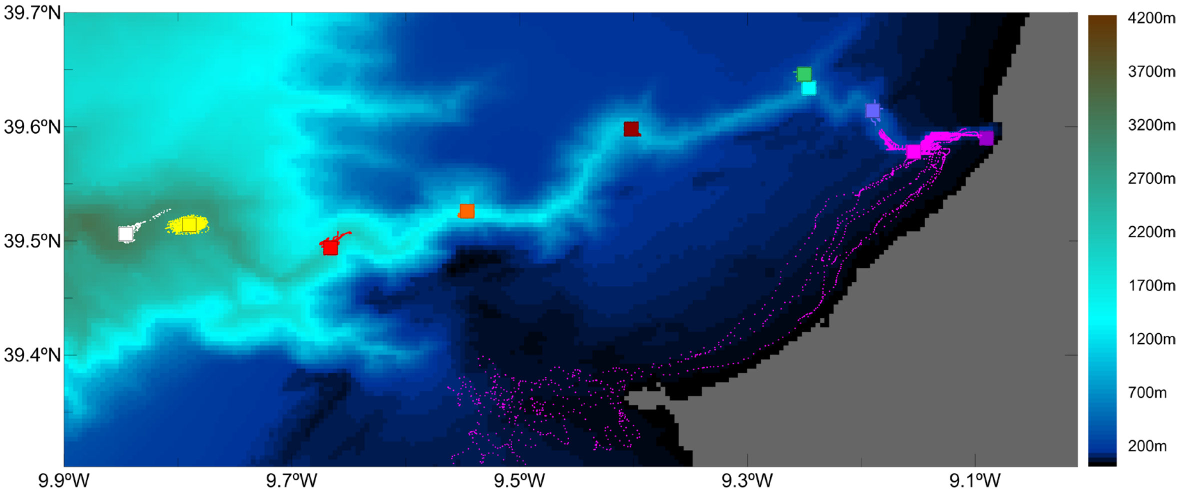

Figure 2.6: Snapshot of the 429 µm OMA dispersion patterns after 22 days of simulation.

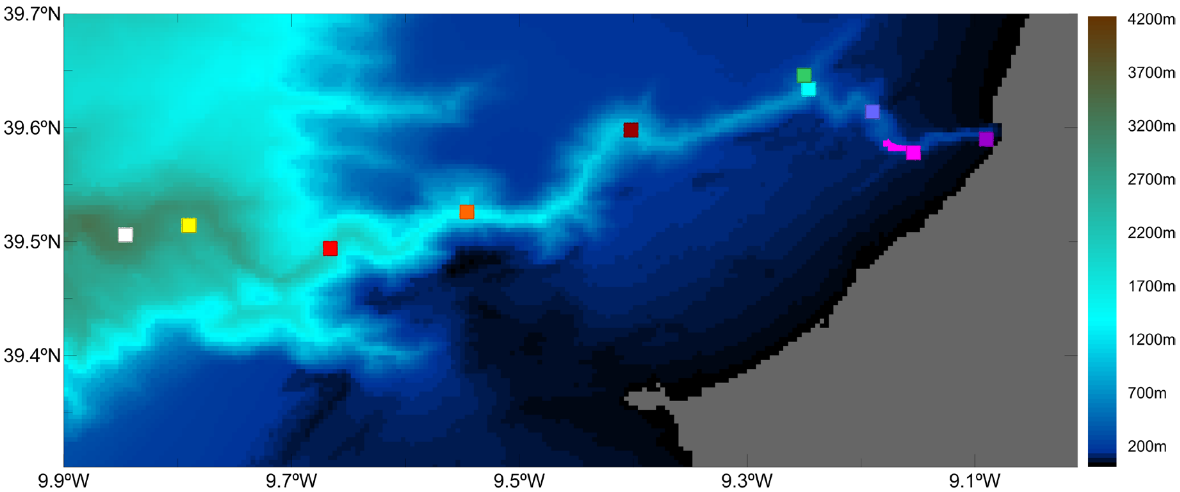

Figure 2.7: Snapshot of the 4000 µm OMA dispersion patterns after 22 days of simulation.

The 4000 µm size class OMAs were only dispersed down-canyon (Fig. 2.7) for the first 22 days simulated. Within the lower canyon region, the 429 µm OMAs from boxes 8 and 10 were mainly dispersed up-canyon after 22 days, with those from box 9 showing a symmetric dispersion on the up-down canyon direction (Fig. 2.6). The dispersion of the 4000 µm OMAs from the same boxes was not appreciable when compared with the 429 µm OMAs (Fig. 2.7). Boxes 1, 3, 4, 5, 6, and 7 for both 429 and 4000 µm OMAs did not show considerable dispersion.

2.3.3 OMA behavior

The 429 µm OMAs at the shelf break (box 2) and in the lower region of the canyon (boxes 8, 9, and 10) travelled longer distances (Fig. 2.8) and at higher velocities (Fig. 2.10) than the 2000 µm and 4000 µm OMAs. The highest distance value for the 429 µm was in box 2, while for the two classes of phytodetrital aggregates it was in box 9 (Fig. 2.8). The displacement was higher in box 2 for the 429 and 2000 µm size classes and in box 2 and 9 for the 4000 µm size class (Fig. 2.9). The velocities of phytodetrital aggregates were higher in box 9, while for the 429 µm in box 2 (Fig. 2.10). The 2000 µm OMAs travelled the shortest distance and at the lowest velocities. On average the 429 µm OMAs travelled 2.5 times farther away and with a speed 8 times higher than the 2000 µm and 2.2 times farther away and 7 times faster than the 4000 µm OMAs. In terms of displacement, the 2000 µm travelled a net distance 0.34 km and 0.47 km less than the 4000 µm and 429 µm OMAs respectively. OMAs at the remaining boxes generally showed short travelling distances, displacements and velocities.

2.4 Discussion

The conceptual model of OMA transport drawn from the model results mostly agrees with what other authors have described for the Nazaré canyon. This holds especially true for the 429 µm sized particles. In comparison to the transport of small lithogenic particles (De Stigter et al., 2007), large aggregates do not travel over long distances due to their different transport behaviour. The different sections of the canyon show different patterns of resuspension, transport and deposition of OMAs.

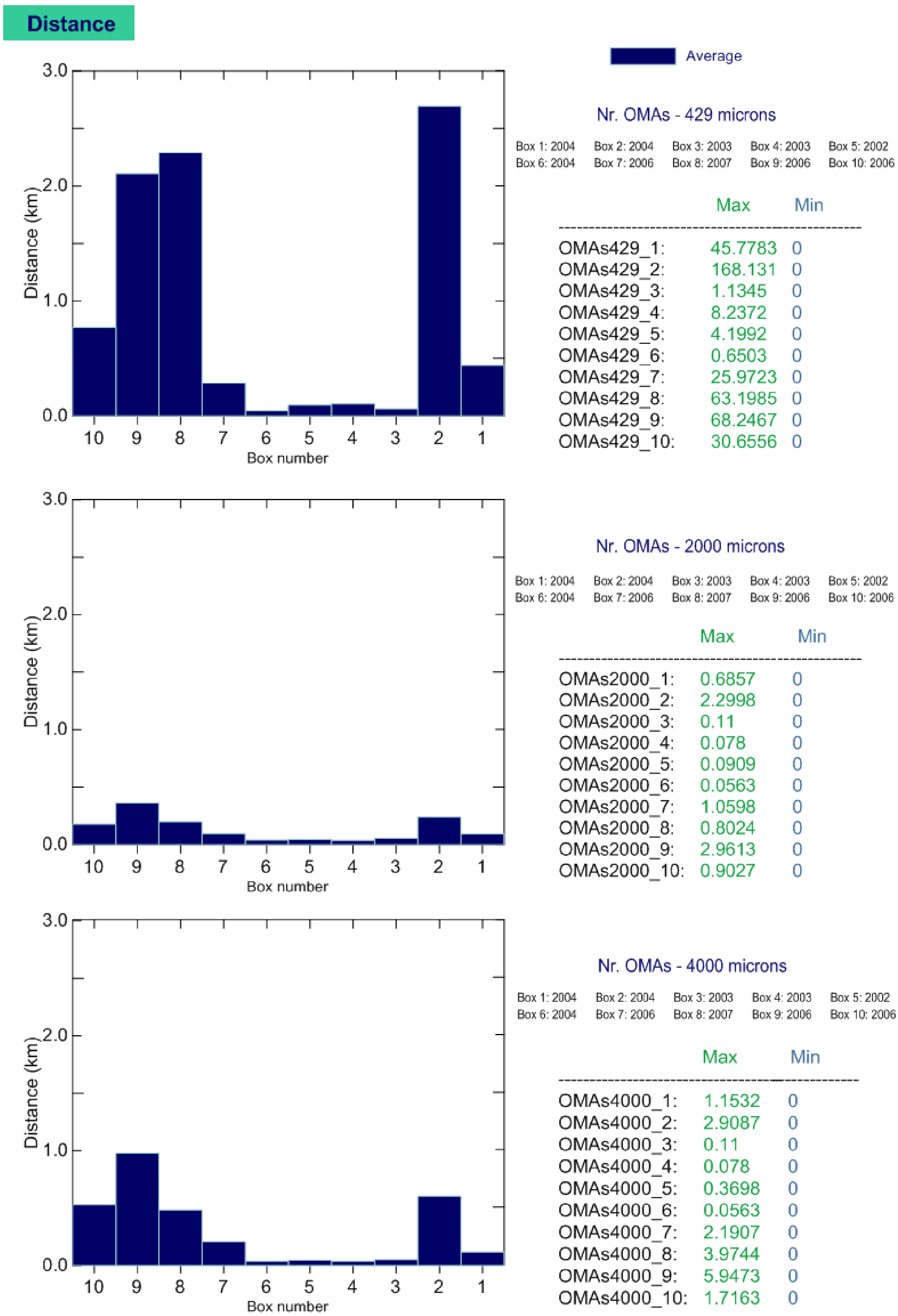

Figure 2.8: Distance predicted by the model for the three classes of OMAs.

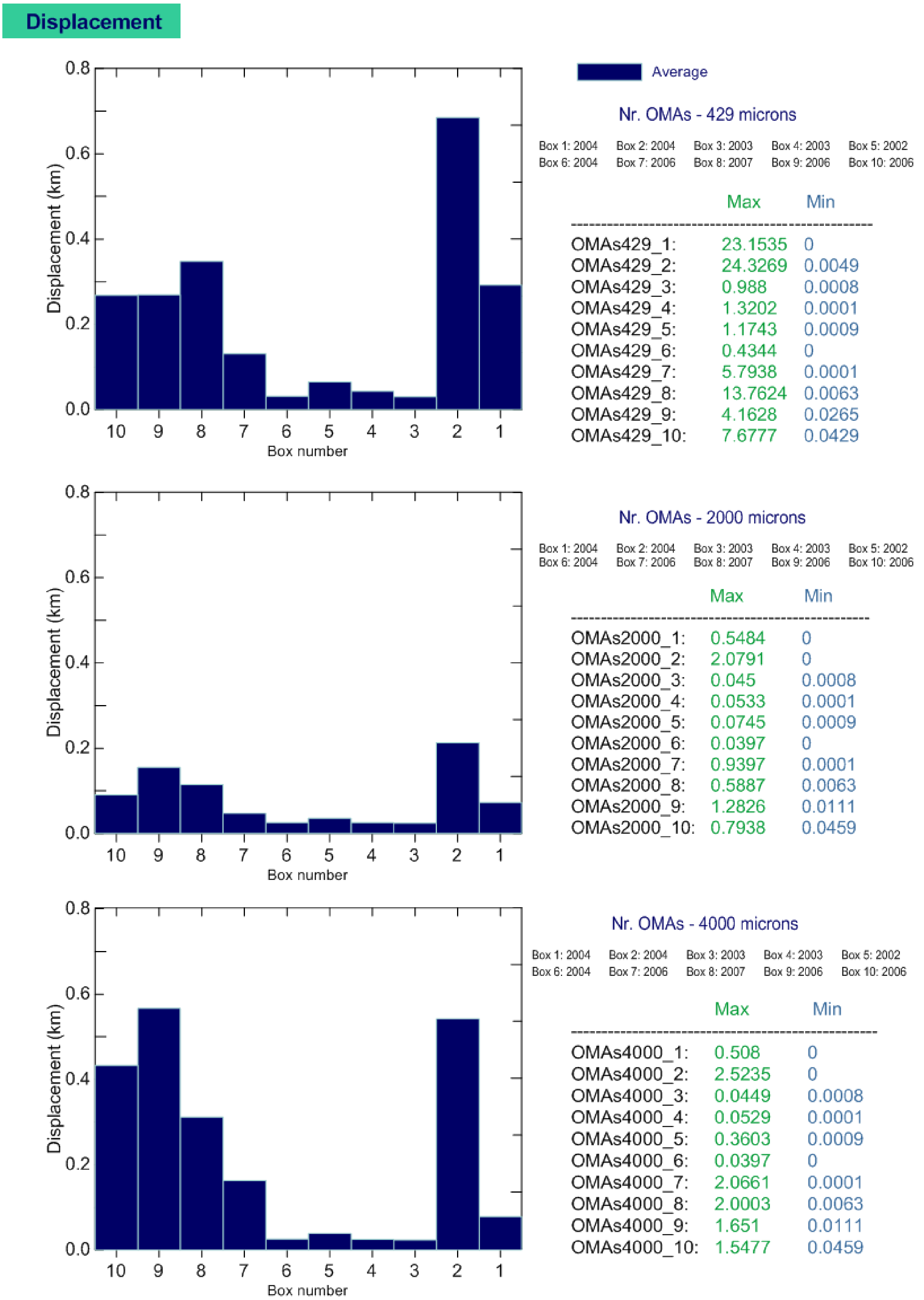

Figure 2.9: Displacement predicted by the model for the three classes of OMAs.

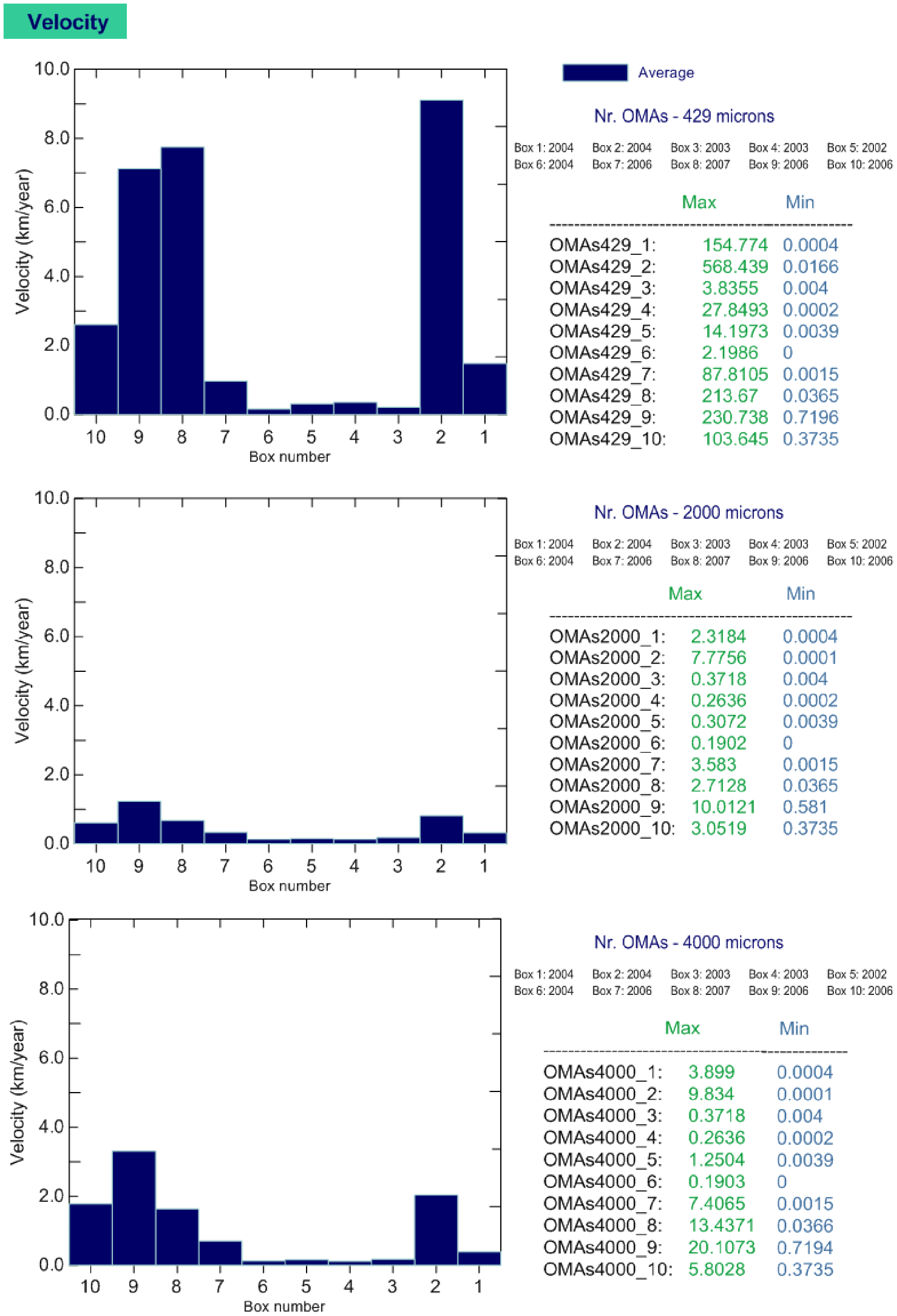

Figure 2.10: Velocity predicted by the model for the three classes of OMAs.

From the upper to middle canyon regions, tidal currents are an important mechanism of resuspension and transport of sedimentary particles (De Stigter et al., 2007), and the residence time of the OMAs showed a sinusoidal pattern for boxes 1 to 5 at the upper canyon (Figs. 2.3 - 2.5), also indicating a close match with the semidiurnal peaks of the tides (Vitorino et al., 2002).

The canyon head was characterized by active transport of OMAs, particularly the 429 µm size class. Larger amounts of OMAs escaped from box 2 (Table 2.2) and travelled up to 168 km (Fig. 2.8), and at maximum velocities of 568 km y^{-1} (Fig. 2.10). Here, longest displacements (Fig. 2.9) and dispersion were observed within the canyon, up and down the canyon, as well as southwards along the coast (Fig. 2.6). A large percentage of the 4000 µm size class OMAs also escaped from box 2, and showed long displacement (Fig. 2.9) and some dispersion down canyon (Fig. 2.7). However, these OMAs travelled at much lower velocities with maximum distances of 9.8 km y^{-1} and for much shorter distances of maximum values of 2.9 km. At the canyon head, the 429 µm OMAs exhibited the highest lateral carbon flux with the 4000 µm class being the next. This active lateral transport could be associated with the formation of nepheloid layers at these depths (Van Weering et al., 2002; Oliveira et al., 2002; De Stigter et al., 2007).

In the middle of the upper canyon (from box 3 to 6), OMA transport slowed down as indicated by the small percentages of the three OMA classes escaping from the boxes (Table 2.2), the very high residence times in the canyon (Figs. 2.3 - 2.5), the lack of dispersion (Fig. 2.6 and 2.7), and no appreciable travel distances (Fig. 2.8) and displacements (Fig. 2.9), which occur at the slowest velocities (Fig. 2.10). Hence, the large amounts of OMAs remaining in the boxes and the lack of lateral transport indicated that the transport of OMAs in this region is dominated by short travel times followed by rapid deposition due to their increased settling velocities. This supports the idea that this section of the canyon is a deposition area of sedimentary organic matter (Schmidt et al., 2001; Van Weering et al., 2002). The OMAs with the highest residence times were the 2000 and 4000 µm sizes (Figs. 2.3 - 2.5), which barely moved as indicated by their extremely short distances, displacements and velocities (Figs. 2.8 - 2.10). Hence, these large phytodetrital aggregates are the major contributors in terms of carbon flux to the sediments at this region of the canyon, which may fuel the benthic communities with a food source. Although faunal abundances and biomass generally show a decreasing trend with increasing water depth, higher amounts of fresher phytodetritus and labile organic matter characterize this region of the canyon (García and Thomsen, 2008; Pusceddu et al., 2010), where the higher faunal abundances and biomasses have been found (García et al., 2007, Koho et al., 2007).

Farther down, also within the middle upper canyon, the model simulations show a slight increase in the lateral carbon fluxes at box 7 at 1498 m depth. This box showed a slight increase in velocities (Fig. 2.10), displacements (Fig. 2.9) and distances (Fig. 2.8) of particularly the 429 μm and 4000 μm OMA size classes, and a slight increase of the percentages of particles escaping from the box (Table 2.2). We barely identify dispersion of OMAs though (Fig. 2.6 and 2.7), and the aggregates with 2000 μm systematically show low travelling velocities, displacements, distances and box escape percentages. We therefore conclude that this region acts as a transitional zone and is mostly characterized by a depositional regime, but where a certain amount of lateral transport occurs. Indeed, favourable conditions for sediment resuspension have been described for this region of the canyon (De Stigter et al., 2007; Oliveira et al., 2007; Martín et al., 2011). High current speeds have been observed at ~1600 m depth in combination with high mass fluxes of particulate matter (Martín et al., 2011), which may explain the slight increase of lateral transport in our results. The model simulations were only carried out for a spring period and do not consider the possible role of intermittent sediment gravity flows in the transport of material. Thus the OMA transport predictions could be underestimations. If the highly energetic winter conditions were taken into account, enhanced resuspension and transport of OMAs through this part of the canyon might have been more conspicuous. This could be further evaluated in future model simulations.

The offshore region of the canyon was characterized by resuspension of OMAs and acceleration of the transport. At boxes 8, 9 and 10, the OMA residence times were low (Figs. 2.3 - 2.5), accompanied by high escape percentages from the boxes, particularly of the 4000 μm size class (Table 2.2). There was an increase in OMA travelling distances (Fig. 2.8), displacements (Fig. 2.9) and velocities (Fig. 2.10) that reached similar values to the ones observed at the canyon head (box 2). The 429 μm size class was again the driver of the particle flux reaching maximum velocities of 230 km y^{-1} and distances of 68 km in box 9 (Fig. 2.10 and 2.8). The phytodetrital aggregates, particularly the 4000 μm, showed also an active transport but not as pronounced as the 429 μm. Box 10, located in the middle canyon (3189 m), showed a slight decrease in the carbon flux with average velocities ranging from 2.6 km y^{-1} to 0.6 km y^{-1} (Fig. 2.10) and average distances ranging from 0.8 km to 0.2 km (Fig. 2.8) for the three different OMA classes. These boxes were located between 2077 and 3189 m water depth in a steep section of the canyon under the influence of high bottom currents and internal waves (De Stigter et al., 2007; Martín et al., 2011). High current speeds and variable seasonal fluxes were observed in spring-summer at ~ 3300 m (Martín et al., 2011), which would explain the more active nature of this part of the canyon in terms of sediment resuspension and horizontal carbon flux.

2.5 Conclusions

Exploring the potential of the operational modelling, the MOHID-PCOMS was used to give the necessary boundary conditions to apply a hydrodynamic model in the Nazaré canyon. A lagrangian transport model was successfully coupled to the MOHID model, giving an overview of the OMA transport patterns along the Nazaré canyon bottom depth. The model simulations were performed during the spring season when phytodetritus production is high. With respect to our original hypothesis, the model results show that, during the specific time of investigation (spring 2009), the canyon did not function as a conduit of organo-mineral aggregates to the deep sea. Rather, it acts as a temporary depocentre of sedimentary organic matter during spring conditions. Previous studies (De Stigter et al., 2007; Martín et al., 2011) indicate that this may not always be the case, and the canyon is an active conduit of sediment transport to the deep sea. The model results show that the carbon flux in the canyon is not constant and unidirectional within areas of resuspension, transport and deposition. For instance, large, carbon-rich aggregates with their specific transport behaviour are not exported but rather remain in a given area for long periods of time. These aggregates, however, are frequently resuspended into the BBL and therefore allow mineralization to occur under turbulent conditions of the BBL. This is in agreement with other studies carried out within the canyon. The differences between transport patterns of the median OMAs and phytodetrital aggregates were also predicted by the model, and the lateral transport of the larger OMAs is less pronounced than for the median OMAs resulting in the carbon deposition. On the other hand, the model results did not include the possible role of sediment gravity flows, and therefore may underestimate the rates of OMA transport. Nevertheless, the model could also be applied to evaluate the transport patterns of other substances in the canyon such as pollutants. Further studies are required to analyse the differences in the carbon flux transport in an autumn-winter season and the impact of the river discharges on the increasing carbon fluxes in Nazaré canyon.

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Chapter 3

Modelled transport of benthic marine microplastic pollution in the Nazaré Canyon

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Abstract

With knowledge of typical hydrodynamic behavior of waste plastic material, models predicting the dispersal of benthic plastics from land sources within the ocean are possible. Here we investigated the hydrodynamic behavior (density, settling velocity and resuspension characteristics) of non-buoyant preproduction plastic pellets in the laboratory. From these results we used the MOHID modelling system to predict what would be the likely transport and deposition pathways of such material in the Nazaré Canyon (Portugal) during the spring/summer months of 2009 and the autumn/winter months of 2011.

Model outputs indicated that non-buoyant plastic pellets would likely be transported up and down canyon as a function of tidal forces, with only a minor net down canyon movement resulting from tidal action. The model indicated that transport down canyon was likely greater during the autumn/winter, primarily as a result of occasional mass transport events related to storm activity and internal wave action. Transport rates within the canyon were not predicted to be regular throughout the canyon system, with stretches of the upper canyon acting more as locations of pellet deposition than conduits of pellet transport. Topography and the depths of internal wave action are hypothesized to contribute to this lack of homogeneity in predicted transport.

3.1 Introduction

Marine microplastic pollution in the forms of preproduction pellets, fragments, filaments, films and foams originates from direct spillage and breakdown of plastic debris (Moore et al., 2011) and synthetic materials with densities ranging from ~0.9 - 1.4 g mL^{-1} (Morét-Ferguson et al., 2010; Andrady, 2011). Plastics of higher density (HD) than seawater are concentrated in marine and fluvial benthic environments (Galgani et al., 2000; Claessens et al., 2011; Costa et al., 2011; Mordecai et al., 2011). Data on sub-surface microplastic abundance and distribution within the marine environment is limited in comparison to data on neustonic microplastics, due to the inefficiency of benthic and pelagic sampling in collecting such small material in conjunction with the remoteness and size of the benthic and pelagic habitat which may be affected. Furthermore, mechanisms of benthic and below-surface transport of microplastics are not well understood. Coupling the intrinsic physical properties of microplastics with the ability to simulate hydrodynamic processes in the laboratory and with computer modelling techniques may greatly improve our understanding of the transport pathways of sub-surface microplastics, and likely locations of accumulation. The need for a better means of estimating sub-surface microplastic transport is growing as plastic production levels increase (PlasticsEurope, 2010) and plastic debris accumulation increases worldwide (Barnes, 2009; Wright et al., 2013). Models may help identify and predict regions where ecological communities and fishery-dependent coastal societies are more vulnerable to the potential consequences of plastic pollution, such as associated toxicity to marine organisms and a decline of marine ecological services (Derraik et al., 2009; Lithner et al., 2009, 2011).

Approximately half of all manufactured plastics have a higher density than seawater (USEPA, 1992; Morét-Ferguson et al., 2010). HD microplastics are found on beaches, in river and estuary sediments, on continental shelf slopes and in deep-sea benthic environments (Cole et al. 2011). Despite a number of recent studies on benthic plastic pollution, these rarely include information on microplastics due to the difficulties of sampling this size class of material in the deep-sea (Claessens et al., 2011). One extensive study covering European shelf areas reported spatial densities of 0.064 – 2.63 plastic pieces (<2 cm diameter) per hectare (Galgani et al., 2000). On the California continental shelf, benthic trawls collected microplastics in spatial densities of 6.5 and 1.5 pieces m^{-3} before and after a storm, respectively (Lattin et al., 2004). Recently, in a study supported by the HERMIONE program, remotely operated vehicle (ROV) video surveys of benthic marine litter in the submarine canyons off the coast of Portugal reported the highest abundances in canyon heads located off the coast of populated cities (Mordecai et al., 2011). Submarine canyons are known to be conduits for sedimentary material (Monaco et al., 1999; Schmidt et al., 2001; Canals et al., 2006), transporting organic and lithogenic particles from shallow shelf areas to the deep sea via various hydrodynamic processes such as internal waves, tidal circulation, bottom currents, and occasional sediment gravity flows (Van Weering et al., 2002; Canals et al., 2006; de Jesus Mendes and Thomsen, 2007; De Stigter et al., 2007). In light of this, submarine coastal canyon systems may also function as dispersal and transport conduits for benthic microplastics of coastal and fluvial origin (Mordecai et al., 2011).

In this study, we attempt to predict possible microplastic debris transport pathways and likely sites for deposition in a submarine canyon by integrating experimental density, critical shear stress values, and settling velocity properties of preproduction HD plastic pellets into a numerical model. The triple layer nested model used here was set up with boundary conditions provided by an operational circulation model and an atmospheric forecast model, and utilized a new residence time concept for analysis of the lagrangian results. Modelling benthic microplastic dispersal from a point source (e.g. river delta, sewage drain etc.) may be useful in determining the extent and depth to which certain ecosystems are affected, depending on local plastic concentrations, discharge volume, and hydrodynamic conditions. It may also serve political purpose by guiding the development of plastic disposal policy, such as Total Daily Maximum Loads for debris in urban runoff (Moore et al., 2011).

3.2 Methods

3.2.1 Microplastic hydrodynamic behavior determination

Experimental tests were conducted to determine the average density, settling speed, bed load transport, critical and resuspension shear stress thresholds of HD black preproduction pellets from a sample collected in Los Angeles County, California (received from Algalita Marine Research Institute). The average spatial dimensions of the pellets were assessed using the software application ImageJ (Rasband, 2012). The average Feret's diameter, defined as the "maximum distance between two points on the selection boundary" (Ferreira and Rasband, 2011, p. 123), of the pellets (N=350) was measured from photographs modified with a color threshold to allow easy edge determination. The average density of the pellets was determined by measuring the weight of random pellet subsamples (N=5) and the water displacement of each subsample using distilled water and a graduated cylinder. Average settling velocity of the pellets (N=50) was determined by video analysis. We extracted a JPG still image each second from the collected video, to allow computation of the velocity of pellets sinking through a 1 m still saltwater column with salinity 36 (PSS), following the method described in Pabortsava et al. (2011). A 20 cm erosion microcosm (Thomsen and Gust, 2000), capable of simulating various benthic shear environments was used to determine the flow velocities at which bed load transport, resuspension, and deposition of pellets (N=300) occurred. Four replicate runs were conducted according to a predefined calibration table relating rotor angular speed, pump flow and the resultant flow velocity (U*). Experiments were run in a stepwise manner, in which bottom shear was manually increased over seven, 2-minute duration steps (Table 3.1). Shear at which 50% of the particles rolled, slid or saltated was defined as bed load shear velocity U^*_b. The critical erosion velocity, U^*_{cr}, was defined as the shear velocity at which 75% of the particles were suspended in the water column. U^*_d, the depositional shear velocity, was defined as the flow velocity at which all pellets had settled from suspension. Using water density, the shear velocity values were converted to shear stress values, τ_b, τ_{cr} and τ_d [N m^{-2}] using Eq. (1),

$$\tau = (U^*)^2 \times \rho \qquad (1)$$

where τ [N m^{-2}] is shear stress, U* [m s^{-1}] is shear velocity, and ρ [kg m^{-3}] is the density of seawater (Thomsen et al., 2002). Experiments were filmed to allow for better analysis of particle behavior in laminar flows.

3.2.2 Modelling approach

MOHID Water is a high-resolution numerical model included in the MOHID Water Modelling System, which has been used to model a range of marine environments from coastal areas to open ocean regions (Santos et al., 2002; Braunschweig et al., 2003; Carracedo et al., 2006; Mateus et al., 2012), and which can be used to integrate different oceanographic processes, scales and systems. In this study the model was implemented to simulate the transport patterns of HD black pellets within the Nazaré Canyon. We applied the MOHID hydrodynamic model (Martins et al., 2001; Mateus et al., 2012) to represent the main oceanographic features of the canyon, and coupled it with a lagrangian model (Braunschweig et al., 2003; Malhadas et al., 2009; Pando et al., 2013) to simulate the transport of the pellets over time.

Table 3.1. Resuspension steps of shear velocity for bedload transport, resuspension and deposition within erosion microcosm containing saltwater of density ρ = 1026.20 kg m^{-3}.

Step	U^* [cm s^{-1}]	τ [N m^{-2}]
1	0.37	$1.4 \cdot 10^{-2}$
2	0.58	$3.5 \cdot 10^{-2}$
3	0.76	$5.9 \cdot 10^{-2}$
4	0.92	$8.7 \cdot 10^{-2}$
5	1.07	0.12
6	1.21	0.15
7	1.33	0.18
6-	1.21	0.15
5-	1.07	0.12
4-	0.92	$8.7 \cdot 10^{-2}$
3-	0.76	$5.9 \cdot 10^{-2}$
2-	0.58	$3.5 \cdot 10^{-2}$
1-	0.37	$1.4 \cdot 10^{-2}$

The model was adapted for the HD black pellets from one used previously in the modelling of organo-mineral aggregate transport (Pando et al., 2013). The hydrodynamic configuration applied in the Nazaré Canyon included three levels of nested models (Fig. 3.1, Table 3.2) with one-way coupling as described by Leitão et al. (2005). The three levels each had a vertical resolution of 50 layers; the bottom 43 layers using the Cartesian coordinate system and the top 7 layers using the Sigma coordinate system. The first nested level corresponded to the largest domain, and covered the Western Iberian Margin with a spatial grid resolution of 5.6 km. The second level had a spatial grid resolution of 2.0 km and covered the continental shelf area between Figueira da Foz and Ericeira on Portugal's coastline. The third level, and smallest domain, focused specifically on the Nazaré Canyon area at a spatial grid resolution of 400 m. For the model setup, the boundary conditions were provided by the MOHID-PCOMS regional forecasting system (Mateus et al., 2012), forced by the Mercator Ocean PSY2v2 and linearly composed with the global tide model FES2004 and the atmospheric forecast model MM5 (Dudhia et al., 2005). The physical properties of the operational circulation model were validated on a systematic basis by comparison with satellite remote sensing of the sea surface temperature (SST) data and by deep profiling (Argo) floats data.

Table 3.2. Main characteristics of the hydrodynamic nested models including coordinates, dimension, resolution and time step used in simulation of HD black pellets in the Nazaré Canyon.

Resolution Level	Coordinates	Dimension (dx/dy)	Resolution [km]	Time step [s]
1st level	34.4º - 45.0º N 5.5º - 12.6º W	72 * 122	5.6	900
2nd level	39.02° - 40.08° N 8.86° - 10.38° W	76 * 53	2.0	60
3rd level: Nazaré canyon	39.3° - 39.8° N 9° - 10.22° W	303 * 125	0.4	15

To determine whether transport patterns differed by canyon region, the lagrangian model was used to predict transport of pellets from four 1.44 km^2 monitoring boxes placed within the upper part of the canyon (at depths of 59 m, 262 m, 331 m and 2657 m, Box 1-4 respectively) (Fig. 3.1). Vertical displacement of each box was 0.5 m above the canyon floor and locations of the boxes corresponded to the canyon's head (Box 1), the section of the canyon in line with the shelf break (Box 2), Vitória's tributary (Box 3), and the lower section of the upper canyon (Box 4). Using the results of our experimental investigations of the behavior of the HD black pellets (see Sect. 3.3.1) and designating the spatial density of the tracers (N= 2000 pellets per box), the model was run for two distinct periods. The model simulated 101 days of the spring/summer period from 1 March 2009 to 24 June 2009 and 101 days of the autumn/winter period from 1 September 2011 to 10 December 2011. The predicted transport and distribution of pellets was computed as the residence time, defined as the temporal interval required by the tracers to leave each monitor box (Pando et al., 2013).

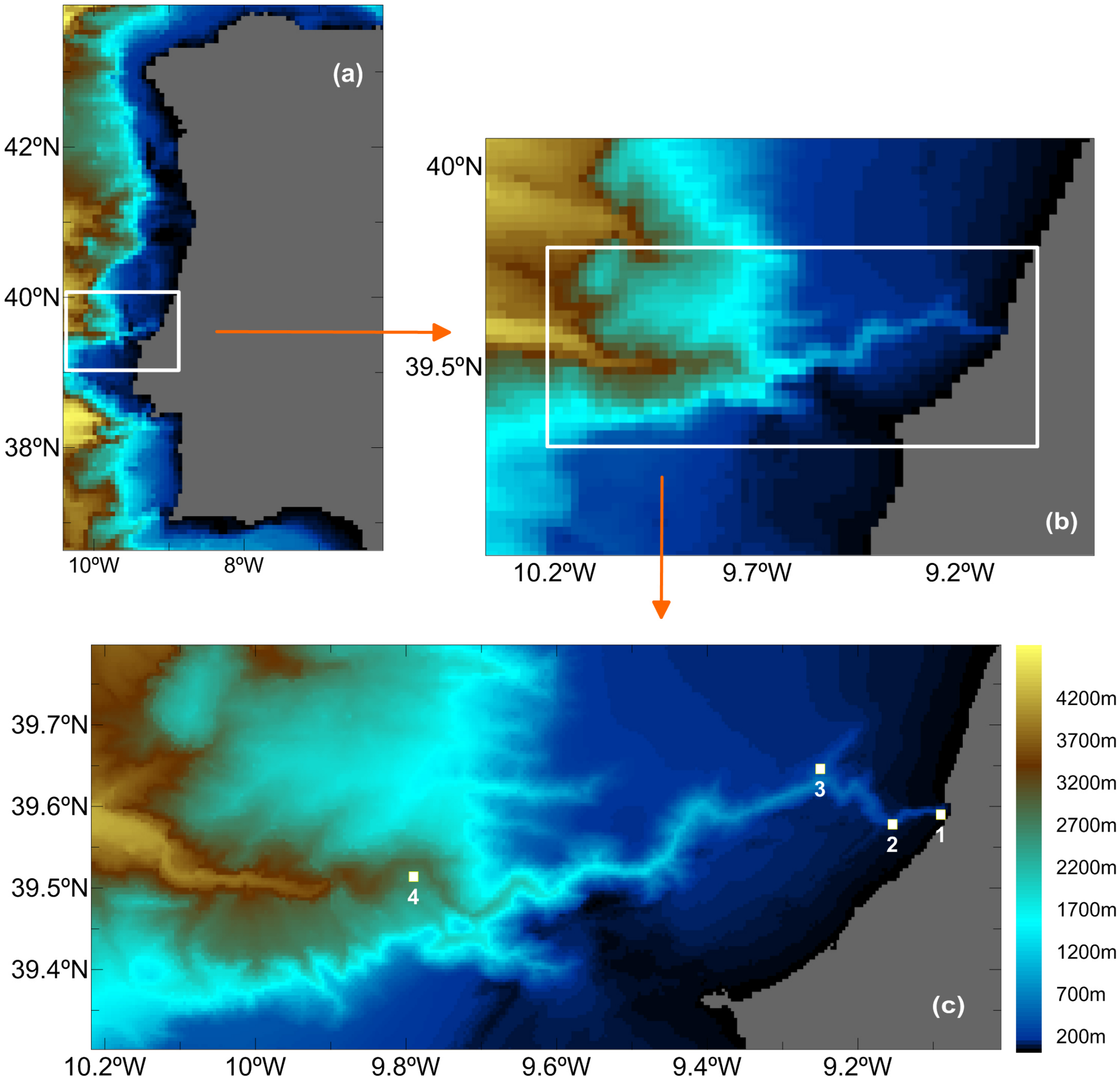

Figure 3.1: The nested domains of the hydrodynamic model used in the simulation of the dispersal of plastic preproduction pellets in the Nazaré Canyon on the Western Iberian Margin: (a) first level: MOHID-PCOMS; (b) second level: Figueira da Foz-Peniche; (c) third level: Nazaré Canyon and the locations of the monitor boxes 1-4 at depths 59m, 262m, 331m and 2657m along the canyon axis.

3.3 Results

3.3.1 Laboratory experimentation

Average HD black pellet density was 1055 ± 36 kg m^{-3} (Table 3.3), approximately 3% greater than the density of both the seawater (ρ = 1026.69 kg m^{-3}) used in the laboratory experiments and the seawater (ρ = 1025.1 – 1027.9 kg m^{-3}) modeled in the Nazaré Canyon. Accounting for the standard deviation in pellets density, the densest pellets may be up to ~7% denser than typical seawater (Table 3.3). Settling velocity of pellets was approximately 28 mm s^{-1} with little variability between individual pellets (Table 3.3). HD black pellets displayed uniform resuspension behavior. Bed load transport commenced at shear-stresses of 0.014 N m^{-2} and approximately 50% of pellets were in bed load transport at ~0.025 N m^{-2}. 75% of pellets were in suspension at a shear stresses of ~0.14 N m^{-2} and pellets were re-deposited at shear stresses of ~0.087 N m^{-2}. Shear stress values in Table 3.3 were approximated from direct observation and video analysis and averaged across replicates. Accuracy of the erosion stress threshold determinations was low due to the slow response time of pellets to changes in flow velocity, and slight differences in individual particle properties (i.e. shape, size, density, degree of bio-fouling). Distinguishing saltation from suspension was also problematic, given the high velocities required to transport the material and the rotational motion of pellets within the chamber.

Table 3.3. The mean Feret's diameter and density ρ of HD black pellets from the Los Angeles Beach sample. Settling velocity, bedload- (τ_b), critical- (τ_{cr}) , and depositional- (τ_d) shear stress of the HD black pellets as tested in saltwater of ρ=1026.69 kg m^{-3}. Mean diameter d_{50}, density, settling velocity, critical and depositional shear stresses of BBL aggregates reported from Thomsen et al., 2002 and de Jesus Mendes and Thomsen, 2007 for comparison to HD black pellets. Standard deviations (± SD) indicate differences between measurement replicates.

	Feret's Diameter [mm] (mean ± SD)	ρ [kg m^{-3}] (mean ± SD)	Settling Velocity [mm s^{-1}] (mean ± SD)	τ_b [N m^{-2}]	τ_{cr} [N m^{-2}]	τ_d [N m^{-2}]
HD black pellet	4.709 ± 0.333	1055 ± 36	28.20 ± 3.19	0.025*	0.14*	0.087*
BBL Aggregate	4.000†	1030	4.77	NA	0.026	0.020

† d_{50}
* Values are approximate and averaged across replicates.

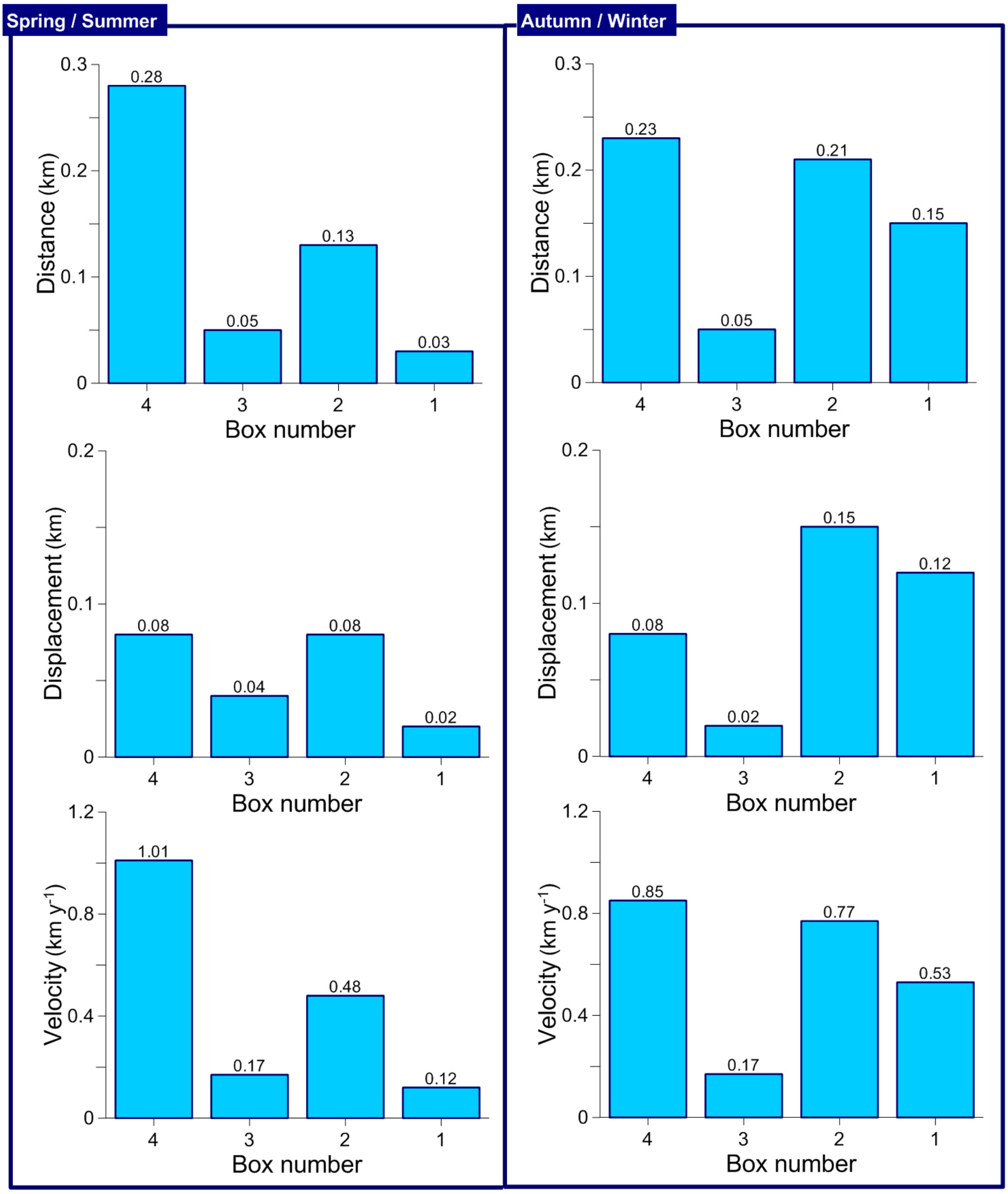

Figure 3.2. Average displacement [km], distance [km] and velocity [km yr^{-1}] of HD black pellet tracers (N=2000) predicted by the model for the spring/summer 2009 and autumn/winter 2011 model runs.

Table 3.4. Average distance, average displacement, average velocity of pellet tracers and percentage of pellet tracers transported from the monitor boxes by the end of each Nazaré Canyon model simulation (S/S Spring/Summer, A/W Autumn/Winter). N=2000 pellet tracers per monitor box.

Box	Depth [m]	Average Distance [km y-1]						Average Displacement [km y-1]						Average Velocity [km y-1]						Pellets Escaped [%]	
Modelled Period		S/S			A/W			S/S			A/W			S/S			A/W			S/S	A/W
		Mean	Max	SD	Mean	Max	SD	Mean	Max	SD	Mean	Max	SD	Mean	Max	SD	Mean	Max	SD		
1	59	0.035	0.11	0.02	0.150	0.76	0.16	0.017	0.07	0.02	0.120	0.62	0.15	0.12	0.41	0.08	0.53	2.76	0.59	0.05	0.20
2	262	0.130	0.67	0.12	0.210	2.05	0.37	0.084	0.41	0.08	0.150	1.74	0.29	0.48	2.41	0.42	0.77	7.47	1.35	0.65	2.35
3	331	0.047	0.13	0.02	0.047	0.23	0.03	0.037	0.11	0.02	0.022	0.18	0.02	0.17	0.46	0.08	0.17	0.82	0.09	3.35	2.45
4	2657	0.280	0.59	0.05	0.230	0.72	0.05	0.077	0.38	0.05	0.075	0.63	0.06	1.00	2.12	0.17	0.85	2.64	0.17	2.49	5.88

Additionally, the flow of the pump strongly influenced the instantaneous shear within the chamber, with slight fluctuations in pump flow resulting in abrupt changes in transport behavior of the pellets. Maximum shear stress generated in the chamber was limited to ~0.20 N m^{-2} by the maximum stable pump speed.

3.3.2 Model results

In addition to computed residence time in each monitoring box, three output parameters were used to characterize the pellet transport behavior in the Nazaré Canyon model simulation: distance (the total distance a pellet tracer traveled [km]), displacement (the net distance a pellet tracer was transported [km]), and velocity [km yr^{-1}]. The averages of each of these values, for pellet tracers from each monitor box (during both the spring/summer and autumn/winter modelled periods) are given in Fig. 3.2. Mean, maximum and standard deviations of modelled values, along with an alternative proxy for overall pellet transport (percentage of pellet tracers which escape each monitor box during modelled period) are given in Table 3.4.

3.3.3 Residence times of pellets

The residence times of the HD black pellets in each monitor box are depicted in Fig. 3.3 as the fraction of pellet tracers remaining inside the monitor box over time. In all cases of the both spring/summer and autumn/winter model runs, ~90-100% of the pellet tracers were not transported outside their monitor box at the culmination of the 101 day model run period. Extrapolating these data, using an average of 95% of pellet tracers remaining at the end of 101 days, allows the average monitor box residence time for microplastics in this study to be estimated at ~5.5 years. The minimal removal of tracers from monitor box 1 indicates that residence times close to shore may be on the decadal scale, assuming hydrodynamic conditions to be similar to those modelled for the entire duration. In contrast, pellet tracers from monitor box 4 (from which >5% of the pellet tracers were modelled to be transported during the 3 month autumn/winter period modelled), the residence time can be estimated to be shorter, at ~3.5 years. Integrating over the entire 200 km long canyon system (Tyler et al., 2009), and assuming relatively constant hydrodynamic conditions, the results suggest benthic microplastic transport from the canyon head to the abyssal plain would take place on the centennial or longer scale, if at all.

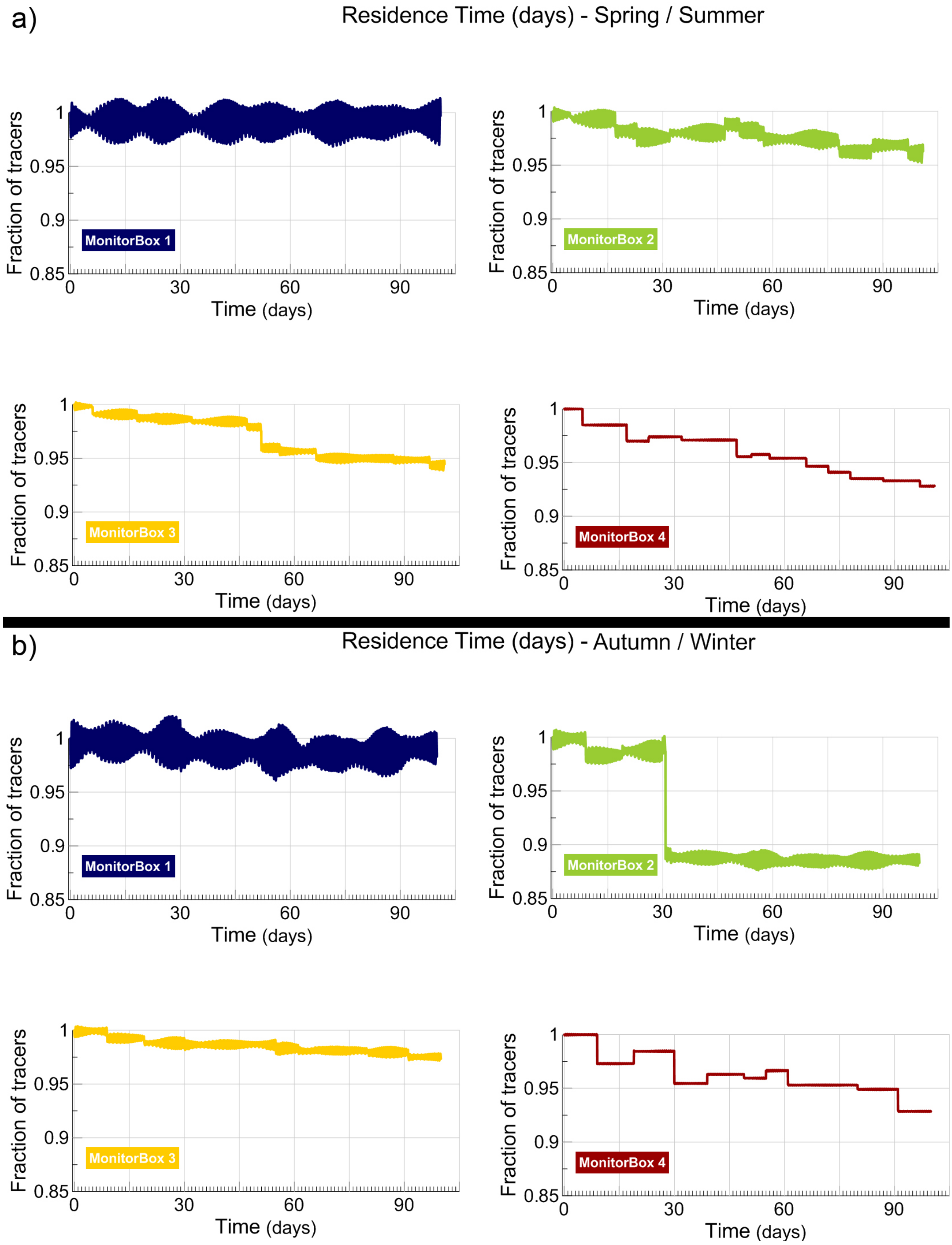

Figure 3.3. The residence times of the HD black pellet tracers in each monitor box of the Nazaré Canyon model simulation in (a) the spring/summer 2009 model run and (b) the autumn/winter 2011 model run.

Two signature patterns can be observed in the residence time plots; first, the regular sinusoidal oscillations of the pellet tracers and second, the irregular occurrence of distinct transport events where the fraction of pellets in a monitoring box decreases or increases abruptly (Fig. 3.3). The regular pellet fraction fluctuations correspond with the diurnal and semi-diurnal component of the tide observed in the Iberian margin region. These sinusoidal fluctuations indicative of tidal forces are observed at all depths for the duration of both simulation periods, but are particularly evident in the shallower monitor boxes 1 and 2 and decrease consistently in amplitude with depth. However, regardless of depth, the tidal water movement appears to have very little effect on modelled net displacement of pellet tracers. Rather, sudden changes (primarily decreases) in the fraction of tracers in monitor boxes suggest transport occurs primarily within the canyon during occasional periods of elevated oceanographic flow conditions, e.g. sediment gravity flows or internal waves which are reported to occur in the canyon (De Stigter et al., 2007; Quaresma et al., 2007; Muacho et al., 2013). These sudden transport events often occurred simultaneously in each box, signifying that these pellet tracer movements were likely the result of a large-scale event, rather than small-scale surface disturbances.

One exceptionally strong transport event can be seen in Fig. 3.3b, where 10% of pellets were transported out of box 2 on 1 October 2011 of the autumn/winter model run. To analyze the cause of this strong dispersion event, which was identified to occur between 18:00 and 19:00 UTC, we investigated the model input data for several days preceding the event. As wind shear stress could influence pellet transport at 262 m depth, wind patterns were analyzed but these did not show any significant change in direction or intensity. River discharges have been reported to influence current regimes on the western Iberian margin (Oliveira et al., 2007; Martín et al., 2011), however, flow data provided by the hydrometric stations (www.snirh.pt) from the Douro, Mondego and Tagus rivers near the canyon head showed that the contribution from those rivers' discharges was not significant during this period. Lastly, the modelled bottom currents in box 2 were analyzed and these showed a consistent pattern in the area during this period, with peak horizontal and vertical velocities in the bottom layer. The horizontal and vertical velocity modulus along the canyon axis for the time period between 17:00 and 20:00 UTC on 1 October 2011 is plotted in Fig. 3.4. Velocities up to 0.3 m/s were modelled to occur in the bottom layer in box 2, which are sufficient to suspend and transport pellets. Bottom shear velocities near box 2 during this time period were a factor of 3 times higher than those used to suspend

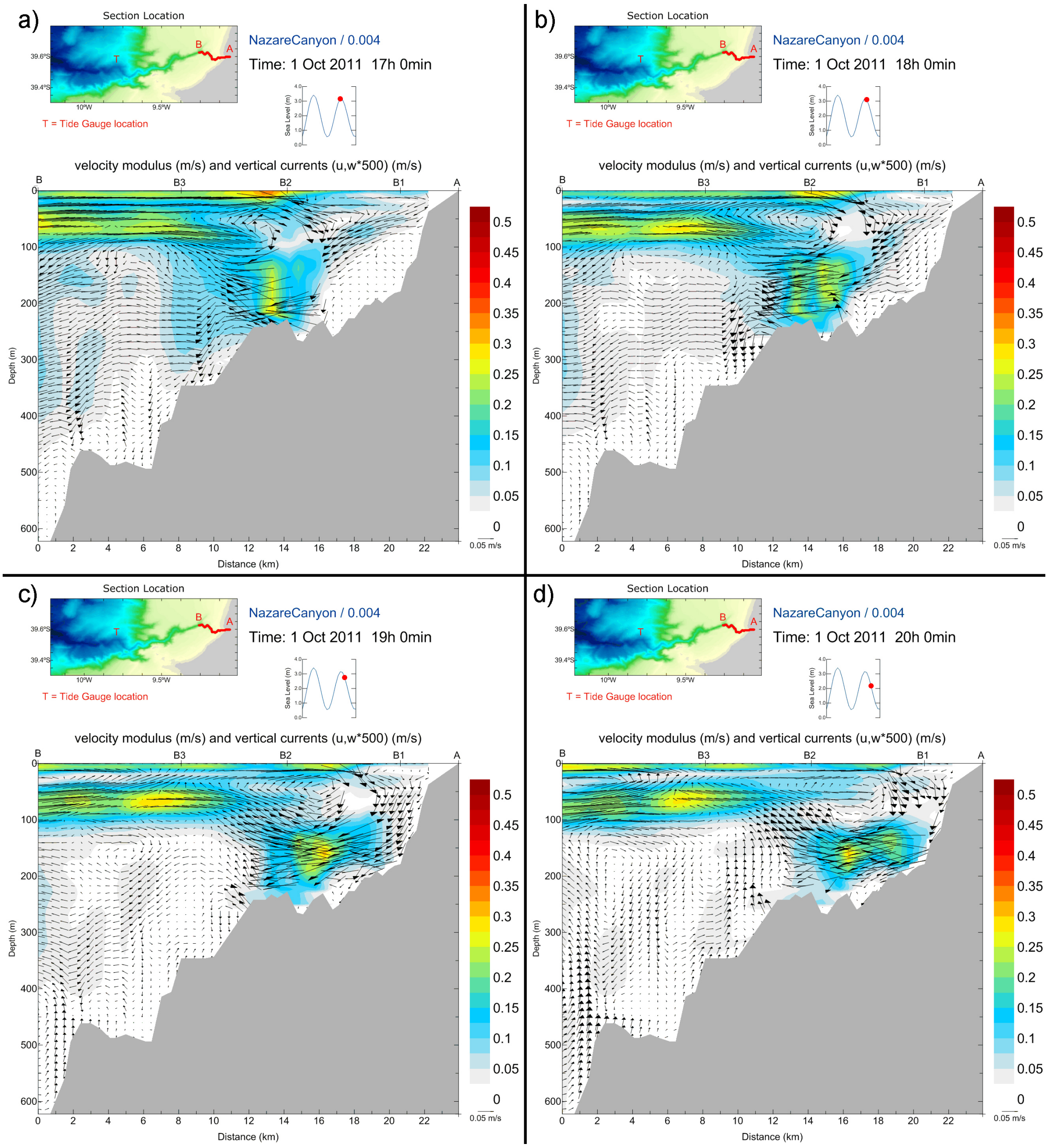

Figure 3.4. The velocity modulus * vertical currents (m s^{-1}) are plotted hourly from 17:00 to 20:00 UTC (a-d, respectively) for 1 October 2011, along the Nazaré Canyon axis (red curve on top), during which a large export of pellet tracers was observed in monitor box 2.

HD black pellets during laboratory experimentation (Tables 3.1 and 3.3). Considering water density (ρ=1026.69 kg m^{-3}) used in laboratory simulations are similar to modelled water density at box 2 (σ_T ~27 kg m^{-3}) the shear stresses experienced by the pellets in the model should be comparable to laboratory experimentation. To determine whether or not the increased current velocity was an artifact of an internal wave, we plotted the isopycnal surfaces, σ_T [kg m^{-3}], throughout the water column and along the axis of the canyon, arraying a series of plots for the same time period on 1 October 2011 (Fig. 3.5). The propagation of an internal wave with amplitude up to 200 m is visible approaching and breaking within the upper canyon. To further verify that the pellet transport was caused by the passing of the internal wave, we compared the mean isopycnal surfaces and mean velocity modulus along the canyon axis between the 1 October and a day during which pellet transport was modelled not to occur: 19 October 2011 (Fig. 3.6). The increased bottom shear stresses near box 2 at the shelf break coincide with the development of an internal wave at the head of the canyon (Fig. 3.4 and 3.5). Investigation of the bottom current velocity and isopycnal surfaces on the 1 and 19 October 2011 suggest that mean current velocities are insufficient to induce unidirectional transport of pellets, but amplified current velocities due to large scale hydrodynamic events, such as internal waves, are sufficient.

3.3.4 Seasonal variability

As mentioned in Sect. 3.3.1, abrupt displacements of pellet tracers from monitoring boxes were more evident in the residence time plots (Fig. 3.3) during the autumn/winter model run than in the spring/summer run. The other modelled transport parameters (distance, displacement and velocity) also differed by season, particularly for the shallow monitor boxes. Distance and displacement values were consistently higher during autumn/winter, up to factors of 5 or 6 times higher for pellet tracers originating in boxes 1 and 2 (Fig. 3.2). The standard deviations in these values were consistently higher during the autumn/winter period, as were the maximum modelled values, a trend indicative of a more chaotic and variable hydrodynamic environment (Table 3.4).

Average pellet tracer velocities ranged between ~0.1 and 1.0 km yr^{-1} in the spring/summer period and ~0.2 to 0.9 km yr^{-1} in the autumn/winter period suggesting that pellet velocity did not change significantly between seasons (Table 3.4). However, the average tracer velocity in

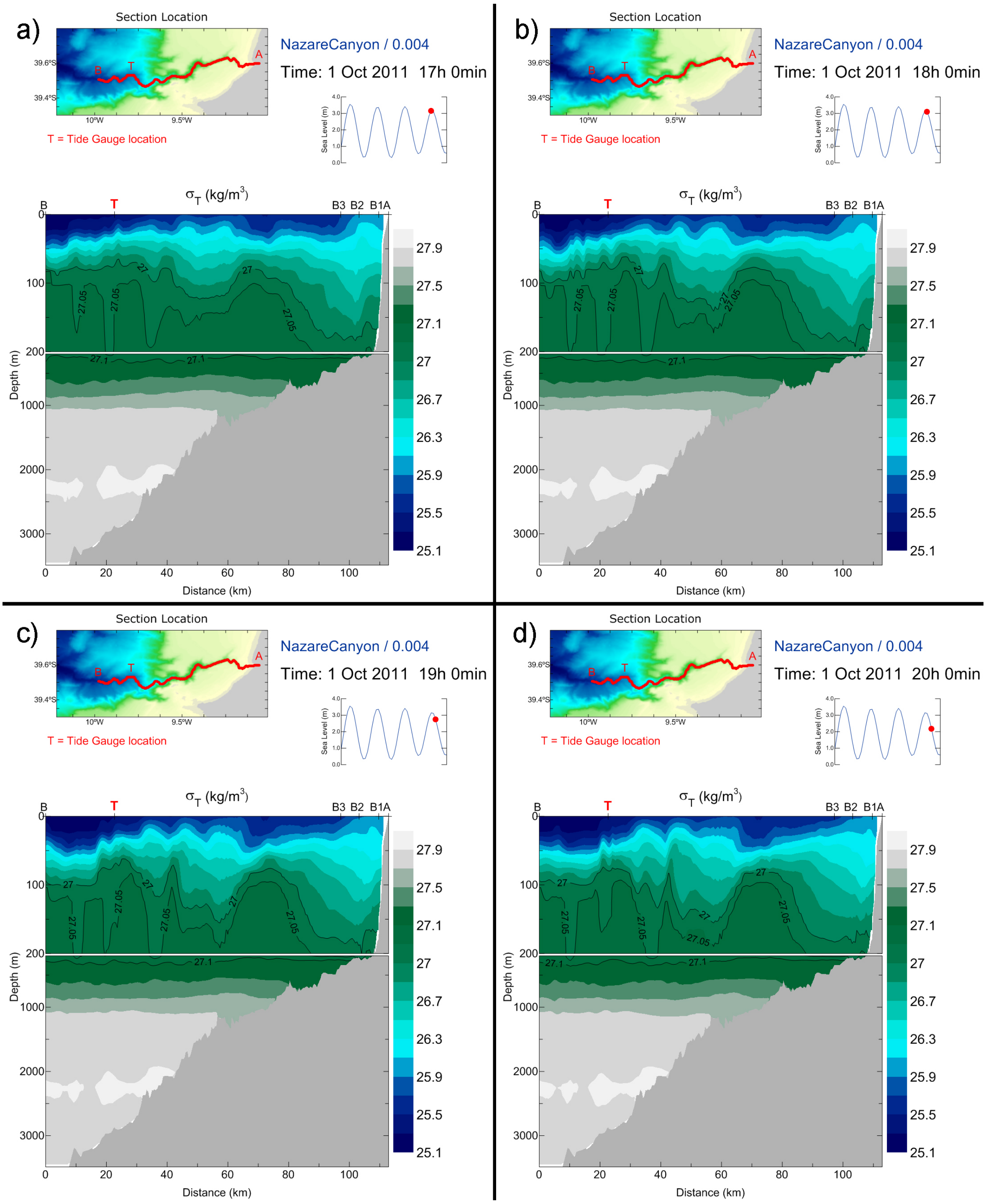

Figure 3.5. The propagation of a modelled internal wave hourly from 17:00 to 20:00 UTC (a-d, respectively) on 1 October 2011 in the Nazaré Canyon where the vertical distribution of water density, σ_T (kg m^{-3}), at depths up to 200 m varies rapidly along the canyon axis, particularly at the canyon head. The contour interval for the isopycnal surfaces (black lines) is 0.3 kg m^{-3} except for the range [27.0 – 27.1] where the step is 0.5 kg m^{-3}.

the autumn/winter (0.58 km yr^{-1}) was slightly greater than in the spring/summer (0.44 km yr^{-1}). As with the other modelled parameters, the maximum values and standard deviations making up this average were also higher during the autumn/winter period (Table 3.4).

In the model runs, large-scale transport events appear to occur more regularly and with similar impact in each monitor box in the spring/summer period as compared to the autumn/winter period. During the autumn/winter, when these sudden events were modelled to occur, they impacted pellet transport to different degrees in each monitoring box. For example, the large transport event modelled to occur on day 30 of the autumn/winter run effectively removed ~10% of pellets from box 2, but had only a minimum effect on concentrations within boxes 1, 3 and 4 (Fig. 3.3).

3.3.5 Differences in transport by canyon location

From the model output during both spring/summer and autumn/winter periods, pellet tracers throughout the canyon travelled greater distances than they were displaced (Fig. 3.2), further indicating the tracers were transported in an oscillating manner, up and down canyon repeatedly, as suggested by the pellet residence times shown in Fig. 3.3.

During the spring/summer period, boxes 1 and 3 exhibited similarly low displacements, distances and velocities of pellet tracer transport (Fig. 3.2), but had the largest difference in the percentage of tracers that ultimately escaped the monitor box (Table 3.4). Similarly, transport behavior of pellets in box 2 and box 4 was similar, but the percentage of tracers escaping from monitor box 4 was a factor of 3 times higher than that modelled for box 2. These incongruences suggest that pellet movement within and pellet export from the monitor boxes are not necessarily correlated. Alternatively to the spring/summer period, during the autumn/winter period, pellet tracers in boxes 1, 2, and 4 exhibited consistently high distance, displacement and velocity behaviors as compared to pellet tracers in box 3 (Fig. 3.2) but overall, the percentage of escaped tracers increased with depth in the autumn/winter modelled run, and, with the exception of box 3, in the spring/summer modelled run (Fig. 3.3, Table 3.4).

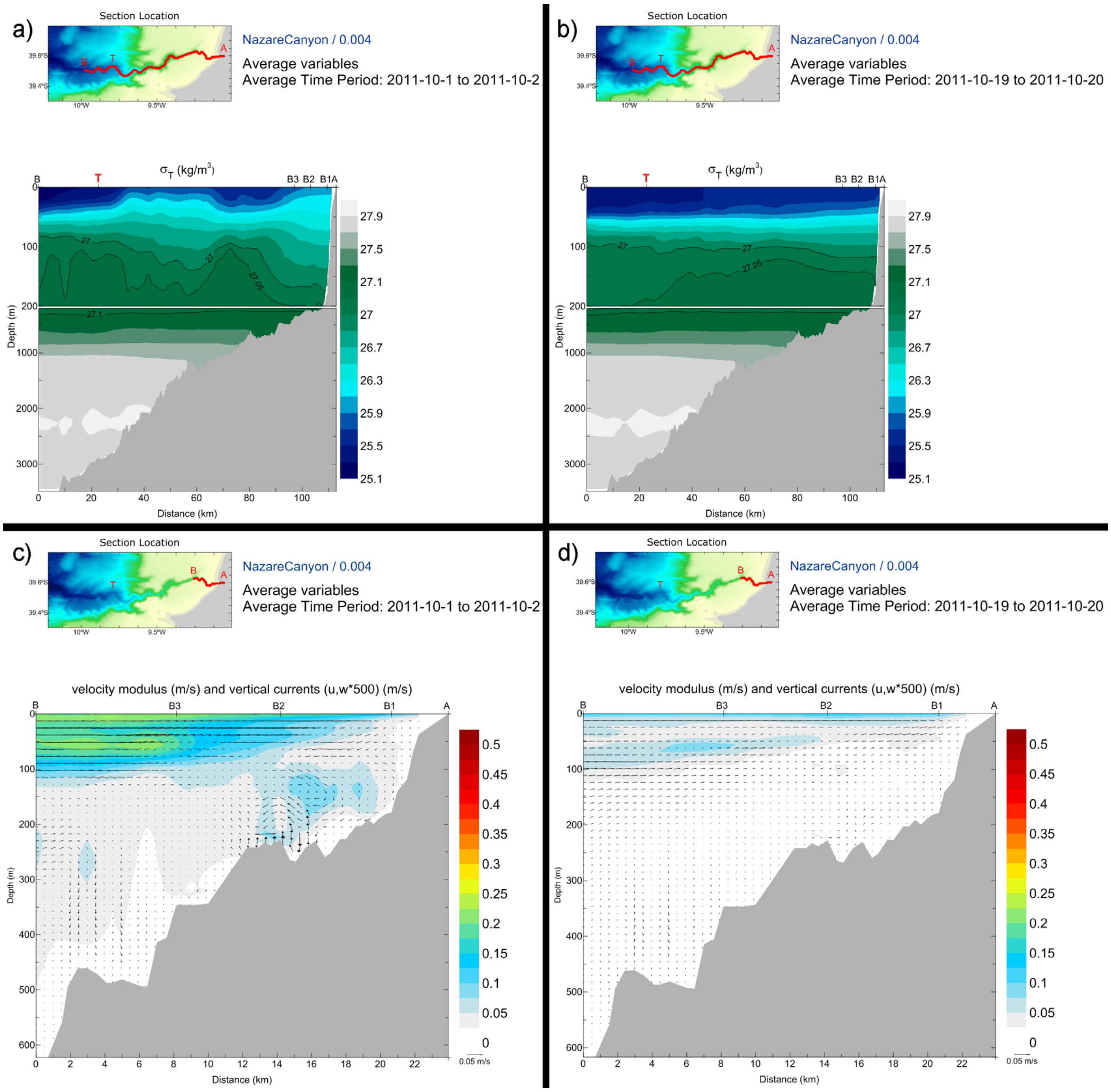

Figure 3.6. Comparison of vertical distribution of water density σ_T (kg m^{-3}) and velocity modulus * vertical current (m s^{-1}) averages for two days, 19 October (a and c) and 1 October (b and d) 2011, along the Nazaré canyon axis (red curve on top). In (a) and (b), the contour interval for the isopycnal surfaces (black lines) is 0.3 kg m^{-3} except for the range [27.0 – 27.1] where the step is 0.5 kg m^{-3}.

3.3.6 Canyon topography and flow

Cross sections through the canyon within each monitoring box, with average modelled flow velocities for 28 May 2009, are given in Fig. 3.7. As the figure shows, much of the modelled high velocity flow takes place in the shallow waters in monitoring boxes 1 and 2 for the day presented. Where the canyon starts to open up, near monitor box 3, higher velocity flows are modelled to occur at greater depths too. In box 4, where the canyon opens up considerably, chaotic higher velocity flows can be observed at various depths, particularly at around 1000 m.

In boxes 1 and 2, the cross canyon flow evident in the surface waters does not influence bottom flow, possibly constrained by the deep, narrow canyon topography. Alternatively, in boxes 3 and 4 where the canyon topography is of lower relief, near-surface flow patterns can propagate to deeper waters (in box 3, Fig. 3.7c particularly), potentially increasing the frequency of bottom velocities sufficiently high for pellet resuspension.

3.4 Discussion

The differences in pellet transport (both within and between seasons) modelled for each monitor box location reflect the changes in the hydrographic regime over time and the topography within the Nazaré Canyon.

The model simulations presented here indicate that the dispersion of ~5 mm diameter HD microplastic pellets through the Nazaré Canyon during typical spring/summer season conditions is likely slow, but may increase with the intensification of the hydrographic regime during the autumn/winter season. The model output suggests that topography restricts pellet movement at the head of the canyon making it a potential accumulation area for non-buoyant plastic debris, but allows escaped pellets to disperse more quickly at the shelf break and in deeper sections with the occurrence of large-scale hydrodynamic events due to the widening and deepening of the canyon axis. The canyon, situated on the western Iberian Margin of the eastern North Atlantic Ocean, is a hydrographic region characterized mainly by tidal currents, internal waves, and upwelling (Vitorino et al., 2002; Quaresma et al., 2007). Throughout the upper canyon, pellet movement appears from the model to be consistently affected by tidal forces as can be seen in Fig. 3.3; with predicted residence time of pellets fluctuating in a sinusoidal pattern characteristic of the peaks of the M2 tide. Recirculation of tidal currents within the canyon has been shown to actively resuspend organic and fine-grained lithogenic material (de Jesus Mendes and Thomsen, 2007; De Stigter et al., 2007). From our model, it appears that tidal bottom shear stresses may also be sufficiently high, not for resuspension, but for bed load transport of HD plastic pellets in the upper canyon and to a lesser degree in the lower canyon. Near the shelf break, (boxes 2 and 3 at ~300 m) where the canyon axis begins to deepen and widen (Fig. 3.7), the bottleneck shape (Fig. 3.1) of the canyon may be a source of higher current velocities and wave-induced turbulence, resulting in increased pellet transport, down-canyon. Tidally induced internal waves moving shoreward may amplify as they move into the shallow, narrow

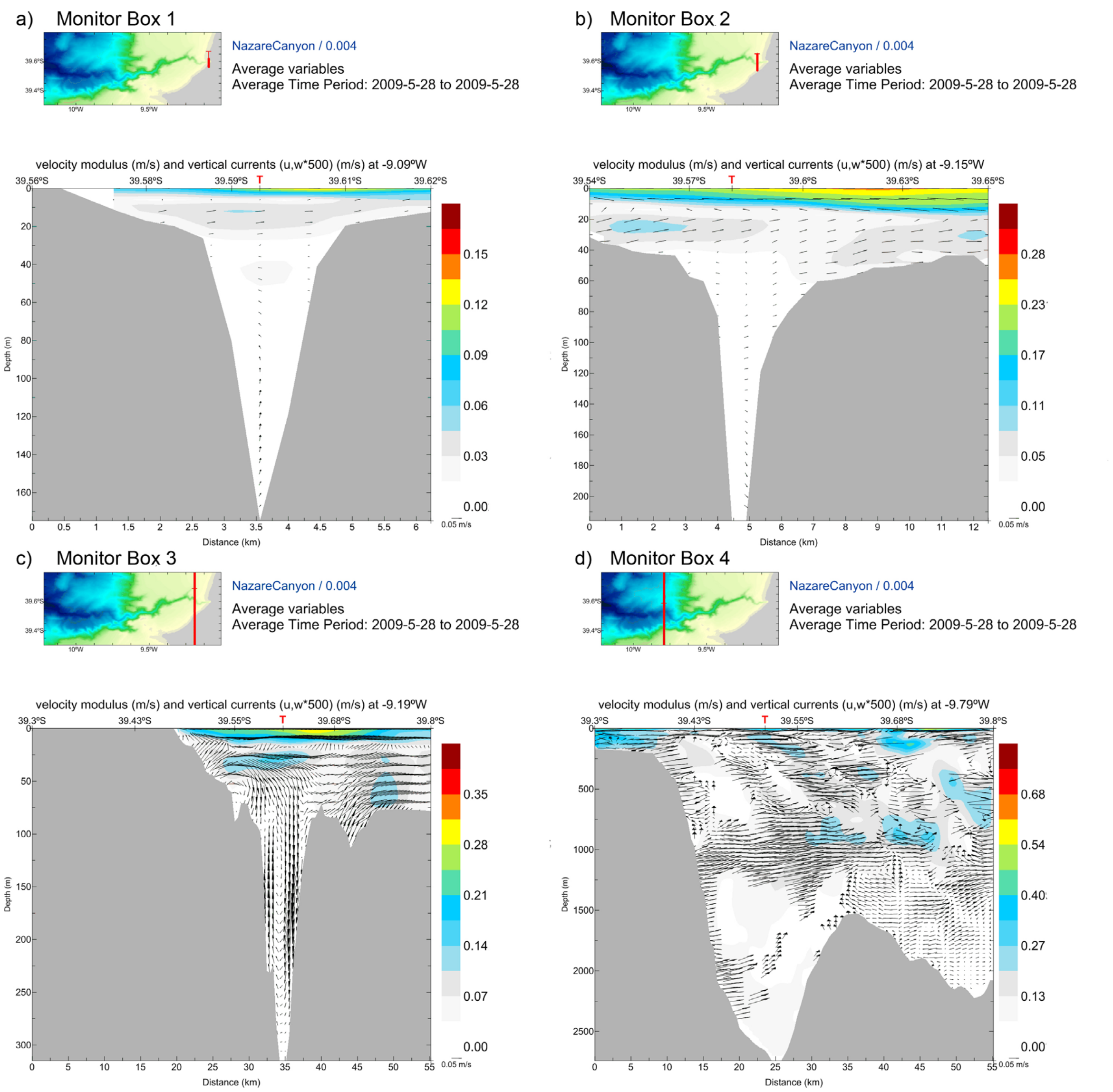

Figure 3.7. Average modelled flow data, velocity modulus * vertical current (m s^{-1}), for 28 May 2009, is plotted for the cross section through the canyon system at each monitor box location.

canyon head, causing them to destabilize at the shelf break (Fig. 3.4), generating turbulence and elevated bottom shear stresses sufficient to resuspend microplastic debris on the seafloor. The regular and synchronized occurrence of sudden transport events in the three deepest monitoring boxes suggests that these events correlate with a regular hydrodynamic event, such as tidally induced internal waves, with associated sediment gravity flows and resuspension of bottom material. The variable effect of such events on pellet transport in each monitor box indicates that the local canyon topography depth also affects the degree to which the large scale hydrodynamic disturbance can transport pellets down-canyon. Other similar phenomena, such as dense water cascades and turbidity flows, which can occur within canyon systems due to large scale hydrodynamic processes, are not considered here as they are not known to occur in the Nazaré Canyon on yearly timescales (De Stigter et al., 2007). The model run results support the hypothesis that in certain areas of the canyon internal waves are likely significant contributors to resuspension and mobilization of deposited materials, such as microplastics.

Sedimentology within the Nazaré Canyon, and specifically transport of organo-mineral aggregates (OMAs) of various size classes, has been thoroughly investigated (Schmidt et al., 2001; Thomsen et al., 2002; Van Weering et al., 2002; De Stigter et al., 2007; Oliveira et al., 2007; Arzola et al., 2008; Lastras et al., 2009; Pando et al., 2013). Comparing simulated pellet transport to OMA transport in a comparable model study in the Nazaré Canyon (Pando et al., 2013), indicates that microplastic pellets were modelled to behave more similarly to OMAs of size classes 2 mm and 4 mm than those of 429 µm. Modelled transport predictions also indicated that pellets were transported for shorter distances than OMA aggregates, likely due to the considerably higher settling velocity and critical erosion shear stress values of the pellets. In Table 3.3, the physical parameters of comparably sized OMAs from the Iberian continental margin are listed for comparison to HD black pellets (Thomsen et al., 2002; de Jesus Mendes and Thomsen, 2007). The pellets have a settling velocity 7 times greater and erosional shear stresses approximately 5 times greater than OMAs. In Fig. 3.8, the erosional shear stress of the pellets and OMAs are plotted on a quartz erosion curve as taken from Thomsen et al. (2002). The position of the pellets on the curve indicates that they can be expected to behave more similarly to compact, high-density medium-grain sand particles (d50 ~ 600 µm) than to loosely packed, low density benthic boundary layer aggregates of 4 mm size when under the influence of bottom currents. This is in agreement with the model results, where average pellet velocities are <1.0 km/year. Given that the length of the canyon is ~200 km (Tyler et al., 2009), transport of benthic microplastics from the shelf area to the abyssal plain would not occur during the time scales modelled here, unless greatly enhanced by large sediment gravity flow events.

During autumn and winter seasons, storms may cause sporadic sediment gravity flow events and higher river discharges (Martín et al., 2011), neither of which were specifically included in the model parameters. Such events, observed to occur on yearly scales, may transport high volumes of fine-grained sediment and debris from the upper to the middle and lower canyon. Sediment gravity flows strong enough to transport sandy sediment likely only occur only on centennial time scales (De Stigter et al., 2007), and following such events, plastics not wholly transported from the canyon would likely be buried within deposited sediment, further increasing residence time in the canyon system (Galgani et al., 1996; Mordecai et al., 2011). The rarity of flows of such magnitudes suggests that microplastics will accumulate within the upper canyon, assuming that the majority of plastic waste comes from land, a hypothesis supported by in situ data collected by Mordecai et al. (2011) wherein a correlation between macro-debris and distance from the coastline in the Lisbon and Setúbal submarine canyons is reported.

Benthic debris may also accumulate in certain zones of the canyon where further transport is inhibited by benthic topography, as suggested by Galgani et al. (1996) and Mordecai et al. (2011). Models could be used to locate and identify such depositional areas given that high-resolution physical oceanography and topography data is available. Additional field data (e.g. plastic counts from box core sediment samples and near bottom sediment trap samples) should be used to validate dispersal and depositional predictions.

Critical erosion values in this model were determined in a laminar flow environment by simulating the benthic boundary layer velocities found in deep sea environments (Thomsen et al., 2002).

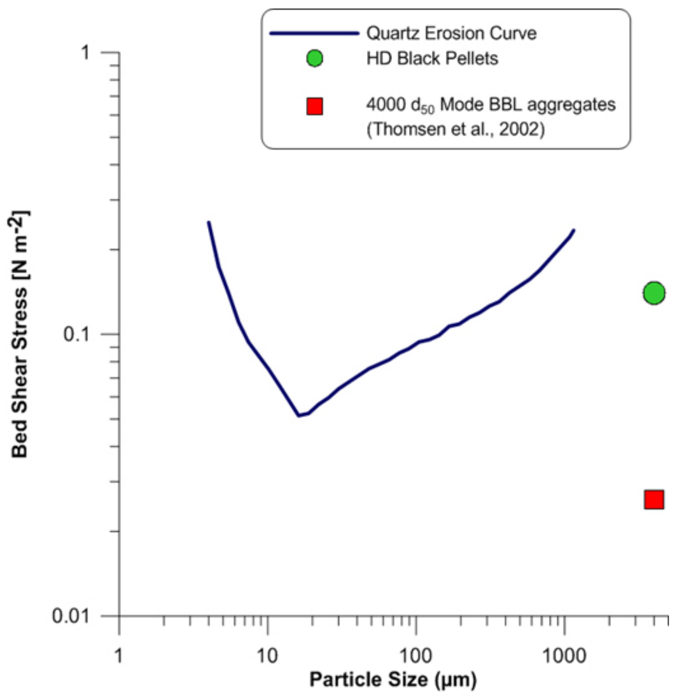

Figure 3.8. The critical bed shear stress erosion curve for quartz relates particle (sediment) size to critical shear stress, τ_{cr}, and includes average diameter (d50) 4000 µm benthic boundary layer aggregate data point (Thomsen et al., 2002). The mean HD black pellet size (d50 ~ 4700 µm) and τ_{cr} is plotted over the curve for comparison of aggregate and plastic erosional behavior.

However, flows generated by tides, waves and uneven bottom surfaces may result in turbulent conditions (De Stigter et al., 2007; Martín et al., 2011), and consequently a thinner benthic boundary layer and changes in the resuspension behavior of microplastics. Wave action, tides, turbidity flows and storm events may all induce turbulent bottom shears, particularly in shallow areas of a canyon system. Future research should incorporate both laminar- and turbulence-induced critical erosion shears, in connection with location and topography, to improve the accuracy of future model predictions of benthic plastic transport.

3.5 Conclusions

This investigation was an attempt to gauge the degree to which the intrinsic properties of plastic debris affect their transport within the sub-surface waters of a modelled marine canyon environment. It is crucial to understand how microplastics are transported below the surface to more accurately estimate global distribution, residence times, convergence zones and ecological consequences, which can be done using numerical models. The model presented here indicates slow transport of benthic microplastics in the Nazaré Canyon, implying long term exposure of benthic canyon ecosystems to plastics, but also suggests that large scale water movement, such as those associated with storms and internal waves may intensify down-canyon transport in episodic short duration events. Due to the long residence times for benthic microplastics indicated by our study, future investigations into the rates at which benthic microplastics degrade are important to better quantify realistic residence times. Potential changes in the intrinsic properties of microplastics as they degrade toward nanometer scale, may alter transport properties and, in turn, the results of long run-time transport models. Future research should also focus on the ecological consequences of plastic exposure in benthic environments, particularly in critical areas such as biodiversity hotspots, to allow the development of preventative measures and policy/legislation changes if required. Decreasing the amount of plastic debris originating from urban consumers would reduce exposure levels in many deep sea regions close to shore, such as the canyon ecosystems focused on in the current study.

With the culmination of this study, it is clear that further research is needed to accurately estimate the amount of plastic residing in the benthic oceans and to understand the subsurface behavior of non-buoyant microplastics and their sinks within the natural environment.

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Chapter 4

The Role of Nazaré Canyon on coastal upwelling enhancement: a numerical study

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Abstract

The narrow deep canyon of Nazaré (west Portuguese Coast) cuts the entire shelf to the coast line. The role of the canyon on the coastal upwelling observed in this area was analyzed using a 3D hydrodynamic numerical model forced by both regional operational and atmospheric forecast models. The model was validated using remote sensing data and Argo floats. The numerical model was assessed to explain how the presence of the canyon enhances upwelling. The remote sensing data obtained along the coast were applied to identify a sporadic upwelling event observed during spring of 2009.

A polarization of the currents along the axis of the Nazaré canyon was observed from a 2500 m depth up to the 150 m. The model results compared the canyon and the adjacent slope and confirmed that the presence of the submarine canyon enhances the upwelling. Comparing the canyon to the adjacent slope, it was evident that for the same time period the upwelling progressed inside the canyon but not on the slope. Upwelling at the canyon's head brings deeper waters, richer in nutrients, to a few meters away from the coast resulting in the enhancement of primary production. The upwelling has major importance to the trophic chain as it positively impacts socio-economic activities such as the fishing industry.

4.1 Introduction

The general ocean circulation pattern and consequently chemical, biological and geological processes are known to be modified in the vicinity of submarine canyons (Hickey et al., 1986; Durrieu de Madron, 1994; Monaco et al., 1999; Puig et al., 2003; Jordi et al., 2005). Several studies suggest that canyons affect the spatial pattern of regional upwelling and enhance the shelf-slope exchanges of water and material (Inman et al., 1976; Freeland, 1982; Hickey, 1997). As a result, submarine canyons have an important effect on the entire food chain of marine ecosystem, from phytoplankton to marine mammals (Hickey, 1995). Over the last few years, a number of studies have addressed the effects of cross-shelf submarine canyons on the dynamics of persistent flows on continental shelves (Freeland and Denman, 1982; Klinck, 1988, 1989, 1996; Huthnance, 1995; Allen, 1996; Hickey, 1997). Regional circulation attempts to follow the topography as it bends around the canyon at the shelf edge. How successful it follows the topography depends on stratification, vertical and horizontal structure of the incident flow, canyon width and Rossby number of the incident flow (Hickey, 1995). In a very narrow canyon with a width lower than the local internal radius of deformation, the flow in the canyon is parallel to the central axis and the bottom slope creates a strong vertical motion; whereas, in a very wide canyon with a width larger than the local internal radius of deformation, the current follows the isobaths without generating strong vertical motion (Freeland and Denman, 1982; Klinck, 1988). Another conspicuous feature of the flow patterns is the cyclonic/anticyclonic circulation related to left/right coastal bounded flows observed within some canyons and over their edges (Jordi et al., 2005). When the flow encountering the canyon is right-bounded with the coast to the right and looking downstream, it induces favourable conditions for downwelling motion within the canyon. On the contrary, when left-bounded, it induces favourable conditions for upwelling (Klinck, 1996). According to Skliris et al. (2002) and Skliris and Djenidi (2006), submarine canyons may have important implications on the dynamics of plankton ecosystems. The deflection of deeper offshore currents up canyon can induce a nutrient transport into the euphotic zone, on the continental shelf, leading to the enhancement of primary production. On the West Portuguese margin, the shelf circulation is strongly influenced by meteorological forcing which leads to a seasonal upwelling regime during summer and prevailing downwelling conditions during winter. The upwelling has been identified as the major source of seasonal and spatial variability of phytoplankton, associated with nutrient availability to the euphotic zone and alterations of the water column stability (Moita, 2001; Silva et al., 2009).

This study researches the role of the Nazaré canyon on upwelling by comparing two days; one with and the other without the occurrence of an upwelling event. Previous modelling studies performed by Pando et al. (2013) and Ballent et al. (2013) for the Nazaré canyon during spring 2009 consider it the period of increase phytoplankton production. In this work, a 3D hydrodynamic model was applied to the Nazaré canyon for spring 2009 where the occurrences of sporadic upwelling events were high. The boundary conditions for the hydrodynamic model were provided by a modelling system in full operational mode for the Western Iberian coast and by an atmospheric forecast model. Furthermore, the model was validated by remote sensing and Argo float data. The numerical model was assessed to evaluate and compare the upwelling event along the coast during spring 2009.

4.2 Methods

4.2.1 Regional setting

The Western Iberian Margin is characterized by a narrow shelf ranging from 25 to 50 km, with several canyons cutting the slope. The highly noticeable of these structures is the narrow deep canyon of the Nazaré, one of the largest canyons in Europe (Tyler et al., 2009) with a length of ~210 km. The Nazaré canyon is not connected to any river system and is divided into upper, middle and lower sections as described by Lastras et al. (2009). It consists of a largely single branch canyon, characterized by a narrow V-shaped upper section, steep walls and a meandering middle section with sedimentary terraces. Its broad lower section is U-shaped and stretches down to 5000 m water depth. For the last 15 years, the Nazaré canyon has been intensively investigated in the framework of some European research projects such as OMEX II (van Weering and McCave, 2002), EUROSTRATAFORM (Weaver et al., 2006), HERMES (Weaver and Gunn, 2009) and HERMIONE (Masson and Tyler, 2011). The vertical structure of the water masses of the West Iberian margin is quite complex. While the surface mixed layer can go down to around 100 m deep during winter, it reaches only around 50 m deep during summer as a result of a well-defined thermocline. Below the surface mixed layer, the salinity decreases up to 450 – 500 m depth marking the bottom limit of the Eastern North Atlantic Central water (ENACW) (van Aken, 2000). A distinct increase in salinity at about 500 to 1500 m depth, originating from overflow of saline and warm water from the Mediterranean Sea, marks the presence of the Mediterranean Water (MW). The deeper, colder, and less saline water masses below the MW comprise the Northeast Atlantic Deep Water (NEADW) below 2000 m, formed by mixing of Iceland-Scotland Overflow Water (ISOW), Lower Deep Water (LDW), Labrador Sea Water (LSW), and Mediterranean Sea Water (MW) (van Aken, 2000).

An important feature of the oceanography of the Portuguese margin is the seasonally variable circulation and wave regime on the shelf (Haynes et al., 1993; Vitorino et al., 2002; Coelho et al., 2002; Peliz et al., 2005) modulated by seasonally varying position and intensity of the Azores High and Iceland Low (Wooster et al., 1976; Fiúza et al., 1982). Typically from March to August, the Azores anticyclone moves along the 38ºW meridian from 27ºN until 33ºN. From November to February, it moves eastward, reaching 23ºN around January. This is a consequence of the winter atmospheric high pressures located in both Europe and Africa. This situation gives origin to weak West winds during the winter and relatively strong North and Northwest winds during summer. The local waves depend mostly on the wind intensity and wave's direction from N and NW and are frequent all year around (80%). The waves from other directions occur mainly during the winter and are almost absent during the summer months of June to September. Wave heights above 1 m are observed in the 95% of the year and above 4 m occur 5% of the year. As a result of this regime, the general circulation pattern is dominated by an equatorward flow on the continental shelf and slope; from the surface down to 500 m depth. The zonal gradient of atmospheric pressure established between the Azores anticyclone and the Iberian Peninsula during summer is reinforced by the development of an atmospheric depression over central Iberia, which drives a regime of sustained northerly, upwelling favourable. The northerly wind promotes an offshore transport in the surface Ekman layer, upwelling the cold sub-surface waters continuously and establishes a southward jet over the shelf (Vitorino et al., 2002). According to Mork and da Silva (1993) and Mendes et al. (2011), 35 h is the response to upwelling wind events development. After a 30 km width band, cold upwelled water extends along the Portuguese coast, particularly notorious at the canyon's head (Mendes et al., 2011). Spatial and temporal variability in the extent and intensity of upwelling off the Iberian Peninsula has been well documented by satellite imagery of sea-surface temperature and pigment concentrations (Haynes et al., 1993; Alvarez et al., 2005; Mendes et al., 2011).

4.2.2 Hydrodynamic model

The numerical model implemented is the MOHID Water included in the MOHID Water Modelling System (MWMS), integrated water modelling software that simulates water dynamics and biogeochemistry processes (Neves, 2013). It is an open source software (http://www.mohid.com) under continuous development at MARETEC, a research group from Instituto Superior Técnico (IST), Lisbon. The model has been successfully applied to study local processes in the case of the Nazaré canyon (Garcia, 2008; Ballent et al., 2012; Pando et al., 2013). In this study, the oceanographic features of the Nazaré canyon are simulated by the MOHID Water model. The hydrodynamic model is a free-surface, baroclinic model with Boussinesq approximations and considering hydrostatic equilibrium. It uses a finite-volume approach with a generic vertical discretization (Martins et al., 2001). The turbulent vertical mixing coefficient is determined using the General Ocean Turbulence Model (GOTM).

4.2.2.1 Model setup for the Nazaré canyon

The configuration applied in the Nazaré canyon included three levels of nested hydrodynamic models (Table 3.2, Figure 2.1) with one way coupling as described by Leitão et al. (2005). The vertical resolution of the three levels is with 50 vertical layers, with 43 Cartesian coordinates on the lower domain and 7 Sigma coordinates on the upper domain 10 m thick.

The first level covers the west Iberian coast and is forced by the MOHID-PCOMS regional forecasting system (Mateus et al., 2012). The boundary conditions for the operational model are provided by the PSY2v2 Mercator Ocean solution for the North Atlantic composed linearly with the FES2004 tide solution and by the atmospheric forecast model MM5 (Dudhia et al., 2005), operated at IST (http://meteo.ist.utl.pt). This level gives the boundary conditions for the second and third level (Table 3.2).The bathymetric data for the further levels construction was provided by the National Oceanography Centre, Southampton (NOCS) and by the Portuguese Hydrographic Institute (IH). The model runs from 1st of March to 1st of July 2009, with a 15 days "spin-up" period required to achieve a proper circulation pattern of the canyon dynamics. The simulated period cover several months of spring 2009, a period which is frequent the occurrence of sporadic upwelling events along the Portuguese coast increasing the nutrients availability in the euphotic zone.

4.3 Results and Discussion

From the simulations the model was capable of reproducing the upwelling process in the Nazaré canyon when compared to the remote sensing data of the sea surface temperature (SST). The results focus on the model validation of the three domains (Table 3.2) through comparison with observations from different days of spring 2009. At first, the first domain was validated with remote sensing data and Argo floats. Secondly, the circulation patterns within the canyon and adjacent slope were described by comparing and evaluating two distinct oceanographic situations driven by wind regime simulated by the model. Lastly, the model results assessed either the absence or the occurrence of a sporadic upwelling event in the Nazaré canyon.

4.3.1 MOHID-PCOMS validation

The physical properties of the first level were validated by comparing simulated SST to remote sensing data, highlighting the periods of high productivity. For the SST data, merged microwave and infrared sensor products were used because they provided more accurate information for that region. The products were acquired from the Marine Environment and Security for the European Area Integrated Project (Mersea Products & Services - http://w3.mersea.eu.org/). Likewise, comparisons between model results of temperature and salinity depth profiles and Argo floats were performed. The Argo data is available by the International Argo Project (http://www.Argo.ucsd.edu). In this study, statistical analysis parameters such as the root mean square error (RMSE), the bias and coefficient correlation were estimated to assess model performance by evaluating whether the model was over or underestimating the observations.

4.3.1.1 Model validation with Remote Sensing Data of SST

Following the same forecasted SST validation approach of the MOHID-PCOMS (Mateus et al., 2012), some examples of the first domain validation are shown in Fig. 4.1 - 4.4 for the days 6th May, 17th May, 15th June and 21st June, respectively. The common temperature gradient found along the Portuguese coast, characterized by lower temperature in the north increasing southward was observed. The pattern was also observed after comparing the measured and simulated temperature. Statistical analyses were calculated by averaging the entire modelled domain. Correlation coefficients, (R), greater than 0.7 were considered to possess strong statistical correlation. In this study, they ranged between 0.877 (Fig. 4.2) and 0.915 (Fig. 4.1). In May, the RMSE are 1.248 ºC and 0.835 ºC with bias equal to -1.06 ºC and -0.554 ºC, respectively (Fig. 4.1, Fig. 4.2). The RMSE and bias are lower (0.813 ºC and -0.43 ºC, respectively) on June 15th (Fig. 4.3) in comparison to the parameters observed on June 21st (Fig. 4.4; 1.391 ºC and -0.97 ºC). Based on the model observations, it was concluded that the simulated and measured SST presented a considerable agreement.

4.3.1.2 Model validation with Argo float data

Temperature and salinity profiles and a T-S diagram from model results including simple statistical analyses were compared to the data from Argo floats (Fig. 4.5, Fig. 4.6). The correlation coefficients of simulated and observed temperature and salinity profiles were high in both periods. However, in May (Fig. 4.6), the temperature and salinity profiles simulated and measured had a better fitting. The differences in real and interpolated topography in the model domains may explain the differences between the model and Argo data.

4.3.2 Circulation pattern within the Nazaré canyon and open slope

The horizontal distribution of instantaneous currents at different water depths in the canyon, and on open slope during absence, and occurrence of upwelling events, is highlighted by the different patterns on the circulation promoted by the canyon's presence. To represent the days with and without a sporadic upwelling event along the Portuguese coast, the SST maps on the 11th (Fig. 4.7) and 28th (Fig. 4.12) May 2009 were analyzed. Images of the horizontal distribution of the currents within the Nazaré Canyon and adjacent slope at different water depths were presented to show the absence of upwelling (Fig. 4.8 to Fig. 4.11), and sporadic upwelling (Fig. 4.13 and Fig. 4.14) . Velocities at four different depths (i.e. 0, 150, 1000 and 2500 m) illustrate the circulation pattern of the four water masses described on section 4.2. Figures 4.8 and 4.13 showed the surface layer flow where the wind effect on the current is maximal. Over the shelf at 150 m (Fig. 4.9, Fig. 4.14), the flow is occupied by the NEACW. Fig. 4.10 show the flow at 1000 m deep at the MW level and (Fig. 4.11) show the NEADW flow at 2500 m depth. The model results considered the peaks of low and high tide in order to observe the changes promoted by the tidal effect on the currents.

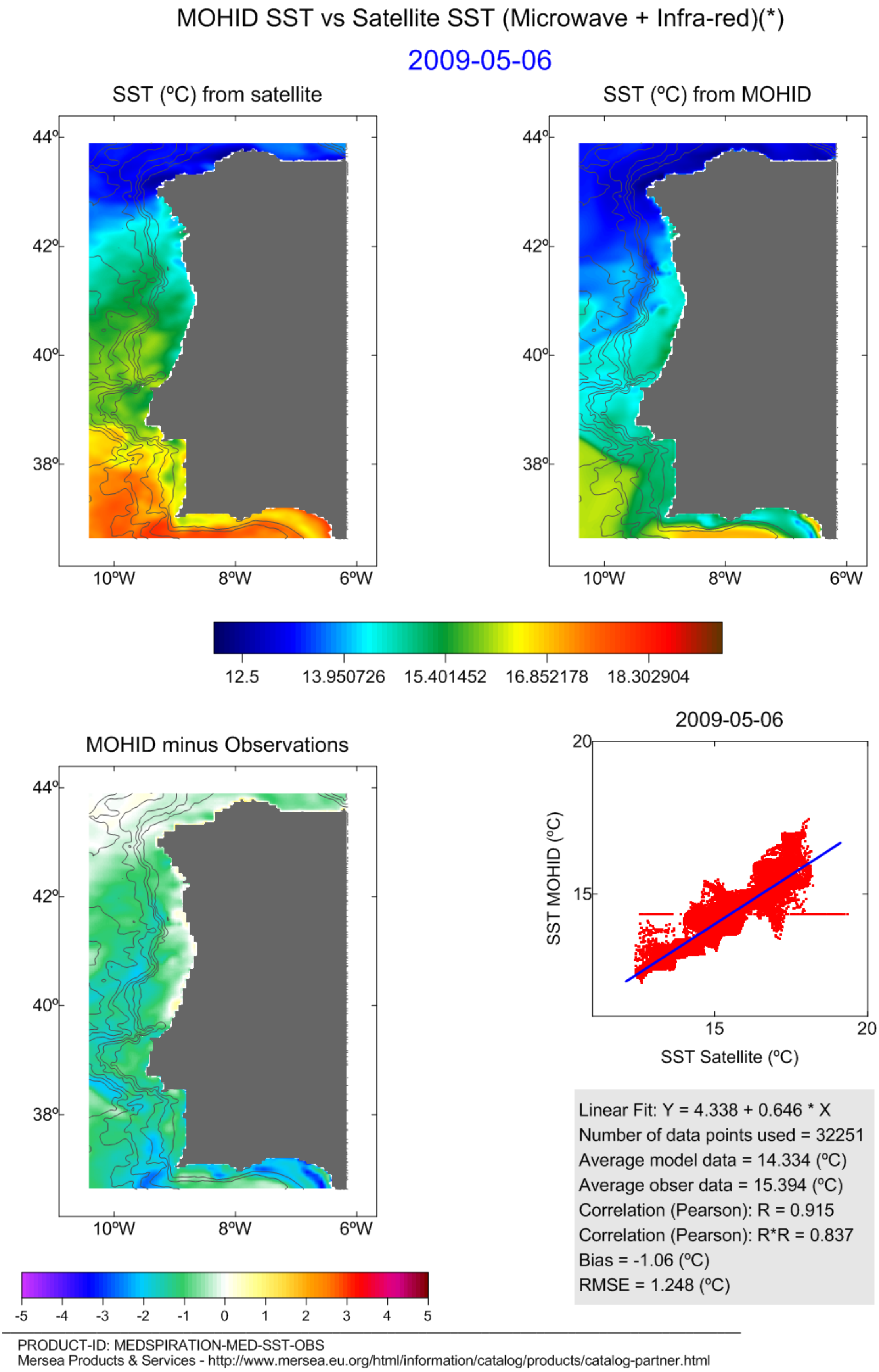

Figure 4.1 Sea surface temperature (SST) maps on 6th May 2009 retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between model and observed data, and results from basic statistical analyses are also shown.

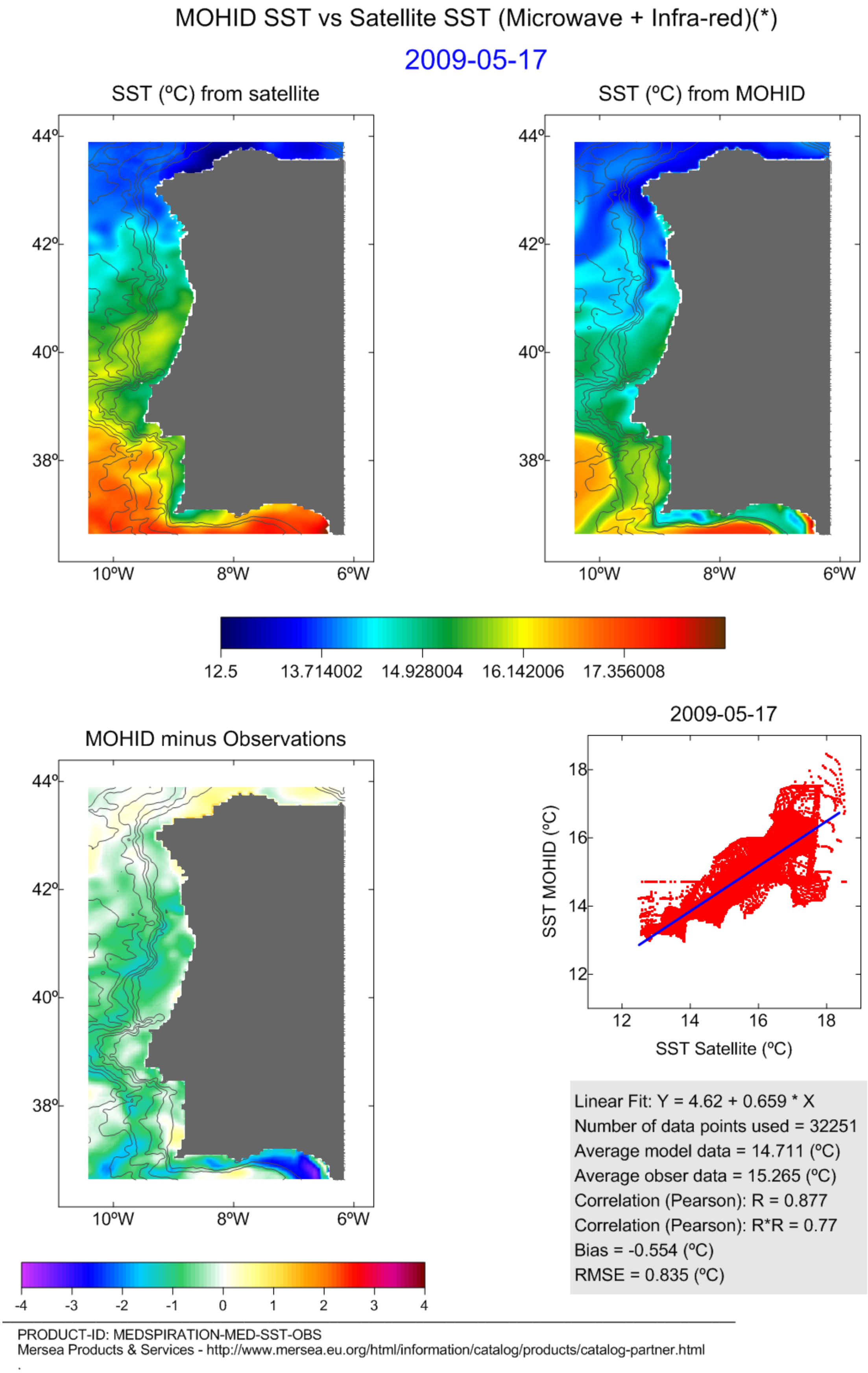

Figure 4.2 Sea surface temperature (SST) maps on 17th May 2009 retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between model and observed data, and results from basic statistical analyses are also shown.

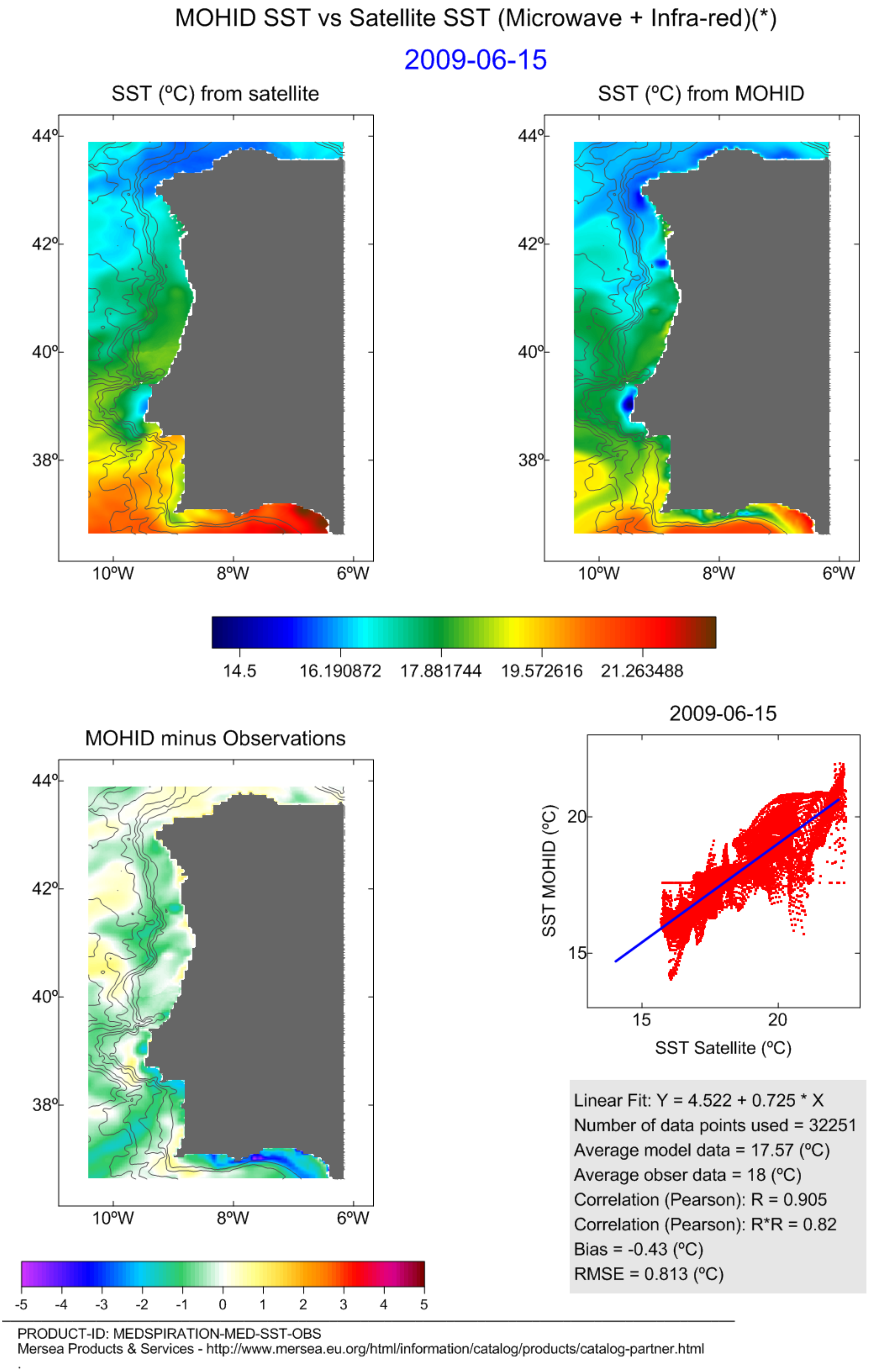

Figure 4.3 Sea surface temperature (SST) maps on 15th June 2009 retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between model and data, and results from basic statistical analyses are also shown.

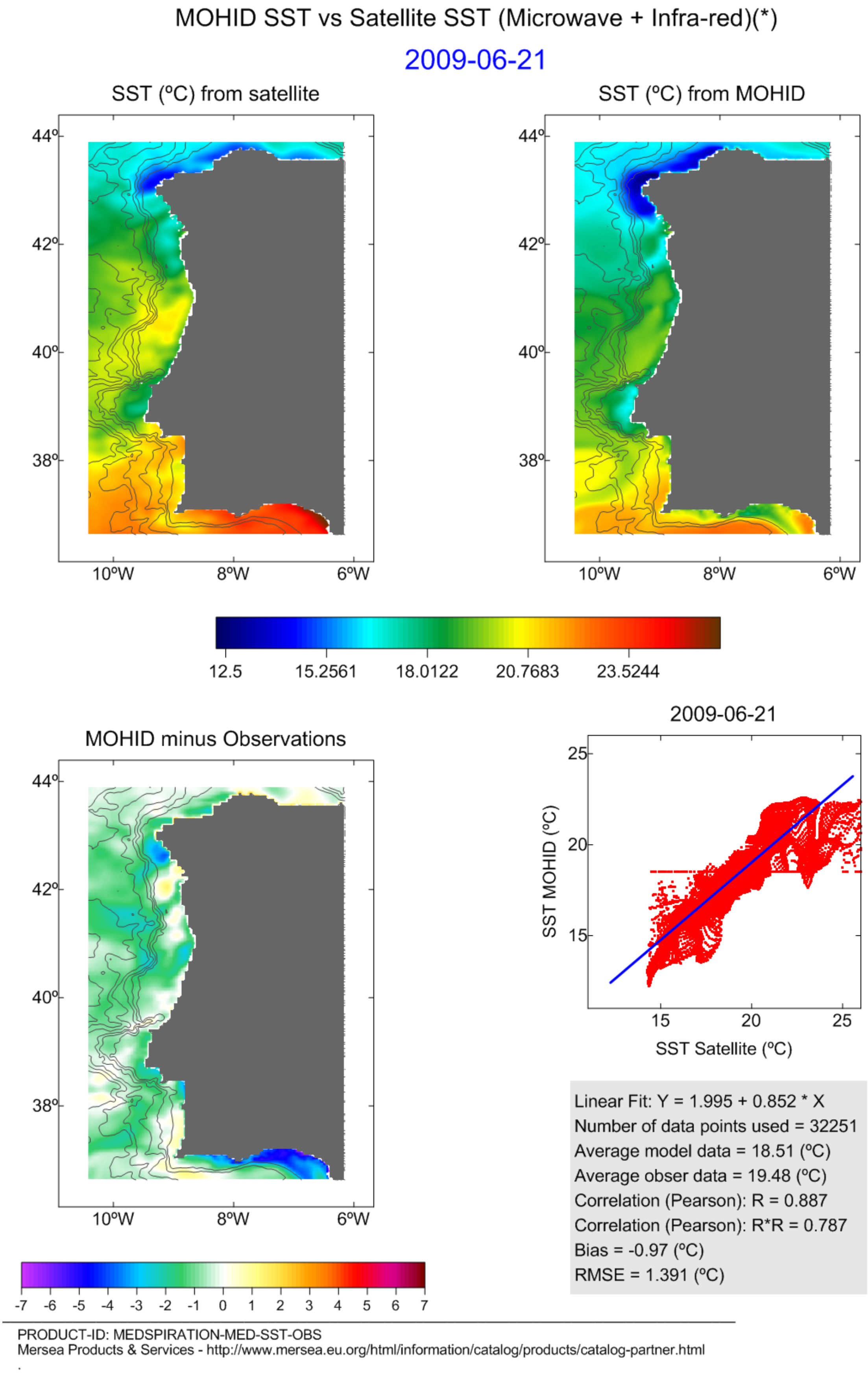

Figure 4.4 Sea surface temperature (SST) maps on 21st June 2009 retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between model and observed data, and results from basic statistical analyses are also shown.

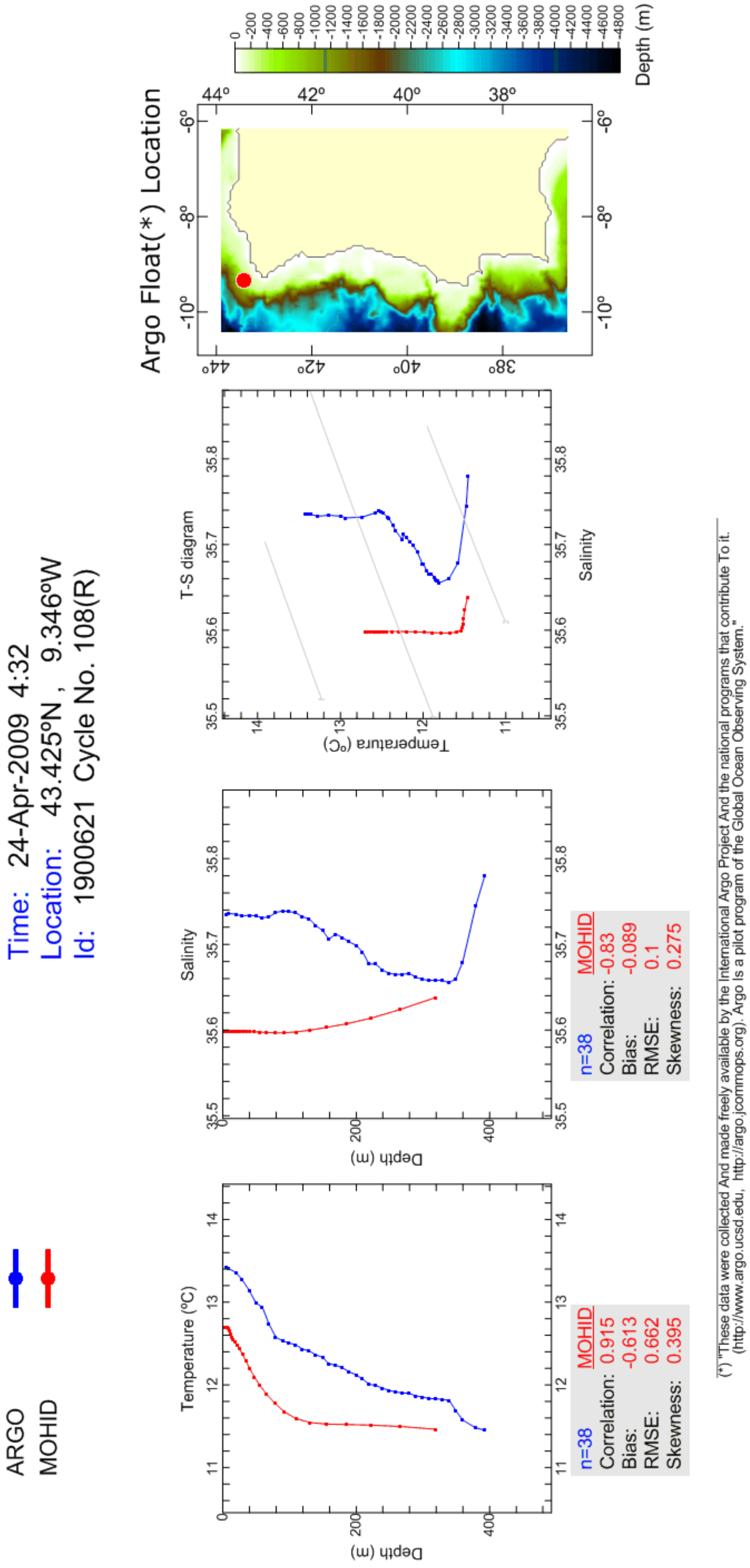

Figure 4.5 Simulated temperature and salinity profiles on 24th April 2009 compared with Argo data. The buoy locations are represented by a red circle in the maps. Statistical results are presented for each parameter.

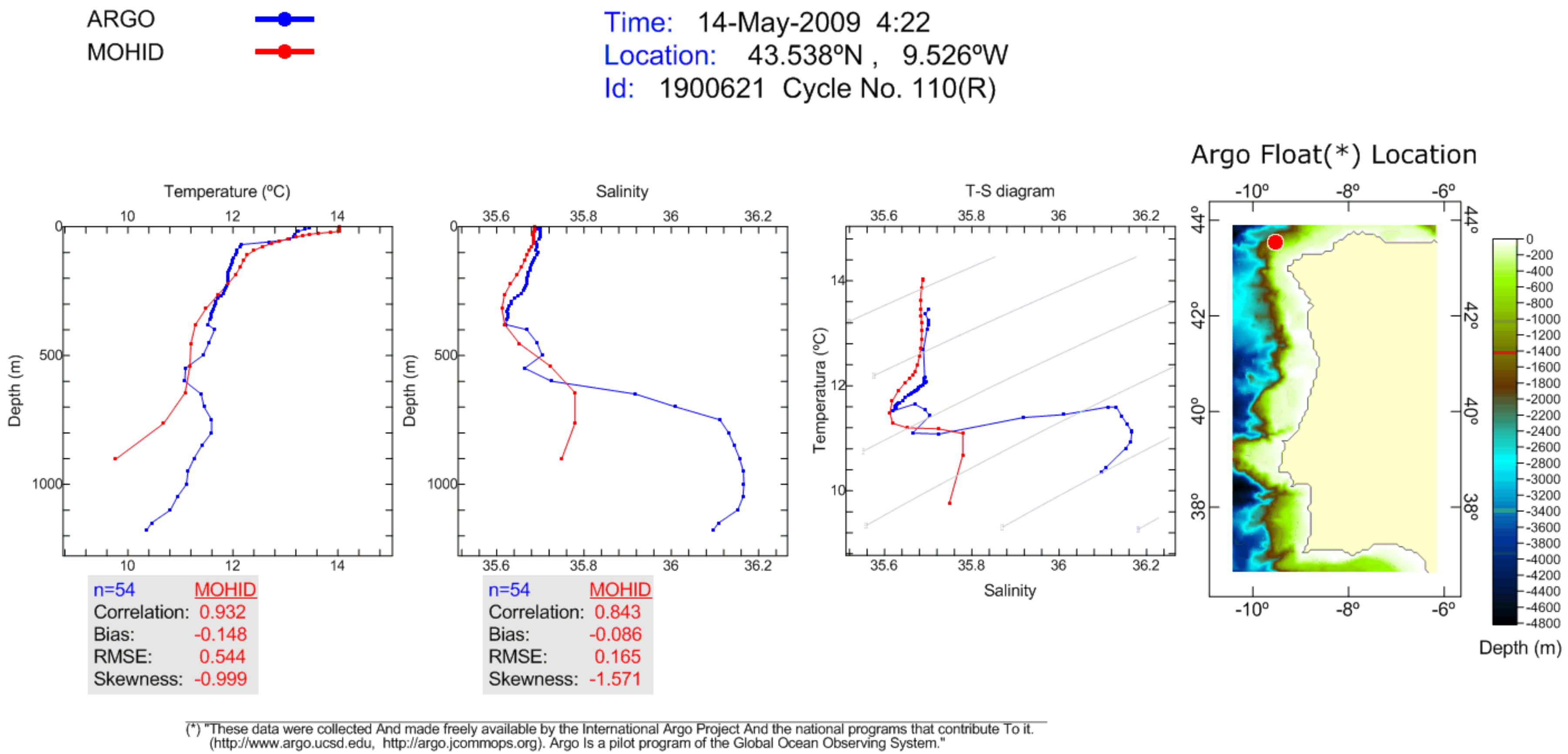

Figure 4.6 Simulated temperature and salinity profiles on 14th May 2009 compared with Argo data. The buoy locations are represented by a red circle in the maps. Statistical results are presented for each parameter.

4.3.2.1 Upwelling absence period

Figure 4.7 depict an upwelling absence period on May 11th. Good correlation was observed when simulated SST was compared to remote sensing data for that day (Fig. 4.7). The absence of upwelling is indicated by the inexistence of a longitudinal temperature gradient between offshore and the coast. Figures 4.8 to 4.11 analyze the circulation pattern within the canyon and slope for this specific day. At the surface, the wind regime was responsible for the circulation pattern (Fig. 4.8). The changes in the wind direction during this period under tide's influence were responsible for the undefined observed circulation pattern. Although it was not evident the connection between flow pattern and the wind for the same tidal period, the time delay between the onset of the wind and the response of the surface current direction should be considered. Field (Haynes and Barton, 1990; Vitorino et al., 2002; Peliz et al., 2005) and modelling studies (Coelho et al., 2002) performed in the West Iberian margin indicate the presence of a prevailing surface poleward flow, which is relatively narrow and weak. During summer upwelling season, this current can reverse inducing the development of equatorward jets (Vitorino et al., 2002) as a result of prevailing and persistent northerly winds. The model results supported their observations. At 150 m (ENACW) (Fig. 4.9), the offshore flow was not affected by the tide and near latitude 39.4ºN, the flow diverged northwards with a permanent vortex. Thereafter, it diverged southwards during low tide under the influence of the Estremadura plateau. At the shelf and on the northern part of the canyon, the effect of the tide and the presence of the poleward current were visible. In the upper part of the canyon, the flow tended to follow the isobaths, adopting an E-W direction with predominantly west direction independently of the tide effect. During low tide, at latitude 39.4ºN and 1000 m depth (MW level, Fig. 4.10) was observed the same influence of the Estremadura plateau as at 150 m depth (Fig. 4.9) with flow diverging southwards. It was also observed that part of the flow followed the isobaths and entered in the canyon while other flow diverged northwards. Contrary, during high tide, this effect of the circulation pattern was not so evident. A study performed by Frouin et al. (1990) using several arrays of current meters off Iberia concluded that most of the water column flows poleward. They also observed that the MW flows to the north along the continental slope as part of the undercurrent that probably extends from 1500 m to the bottom of the surface mixed layer. The results predicted by the model at this depth of the MW (Fig. 4.10) agreed with their observations and the poleward flow along the slope at MW level was observed even though the analysis of

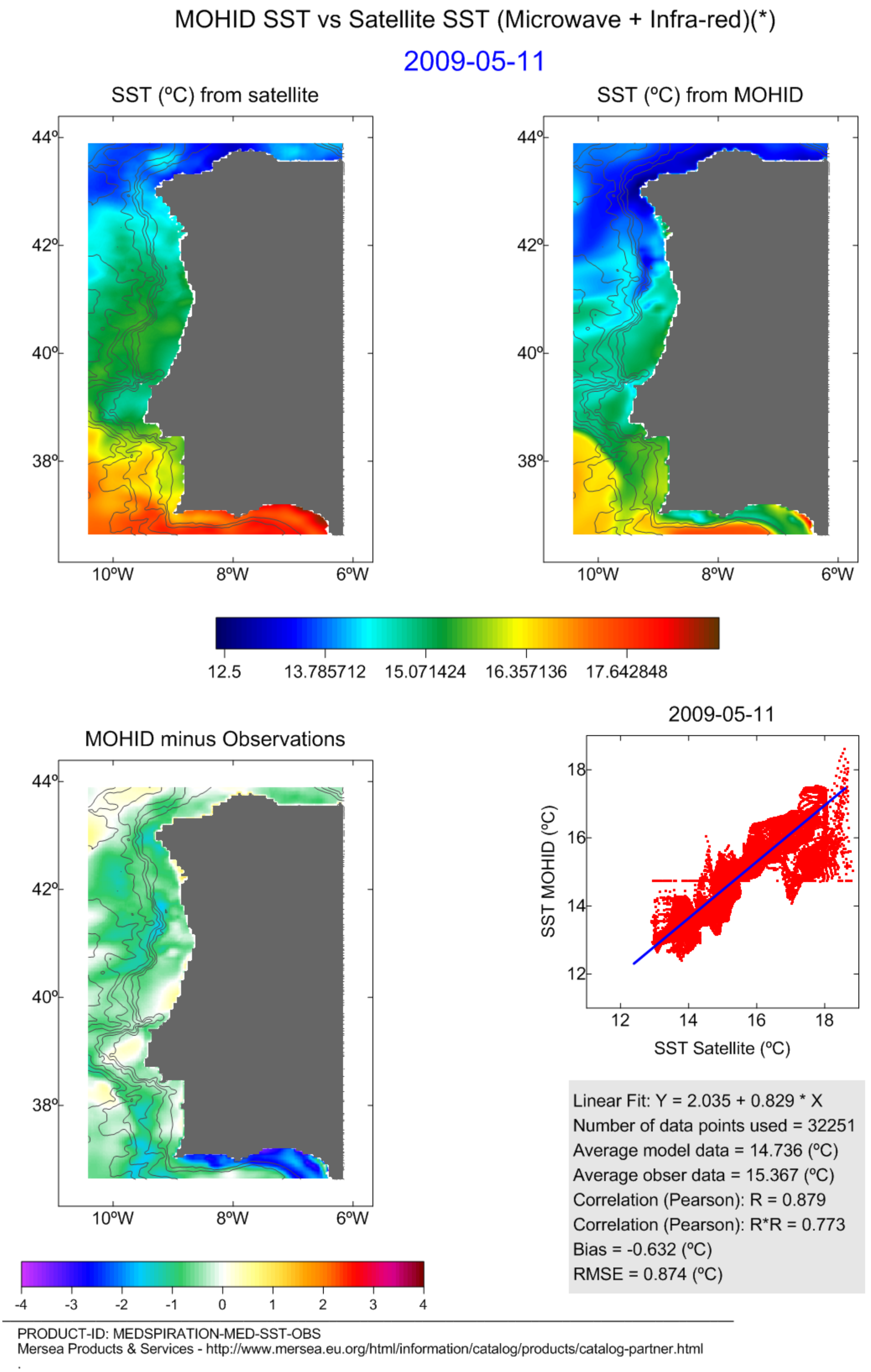

Figure 4.7 Sea surface temperature (SST) maps on 11th May 2009 with upwelling absence. Maps retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between the model and observed data, and results from basic statistical analyses are also shown.

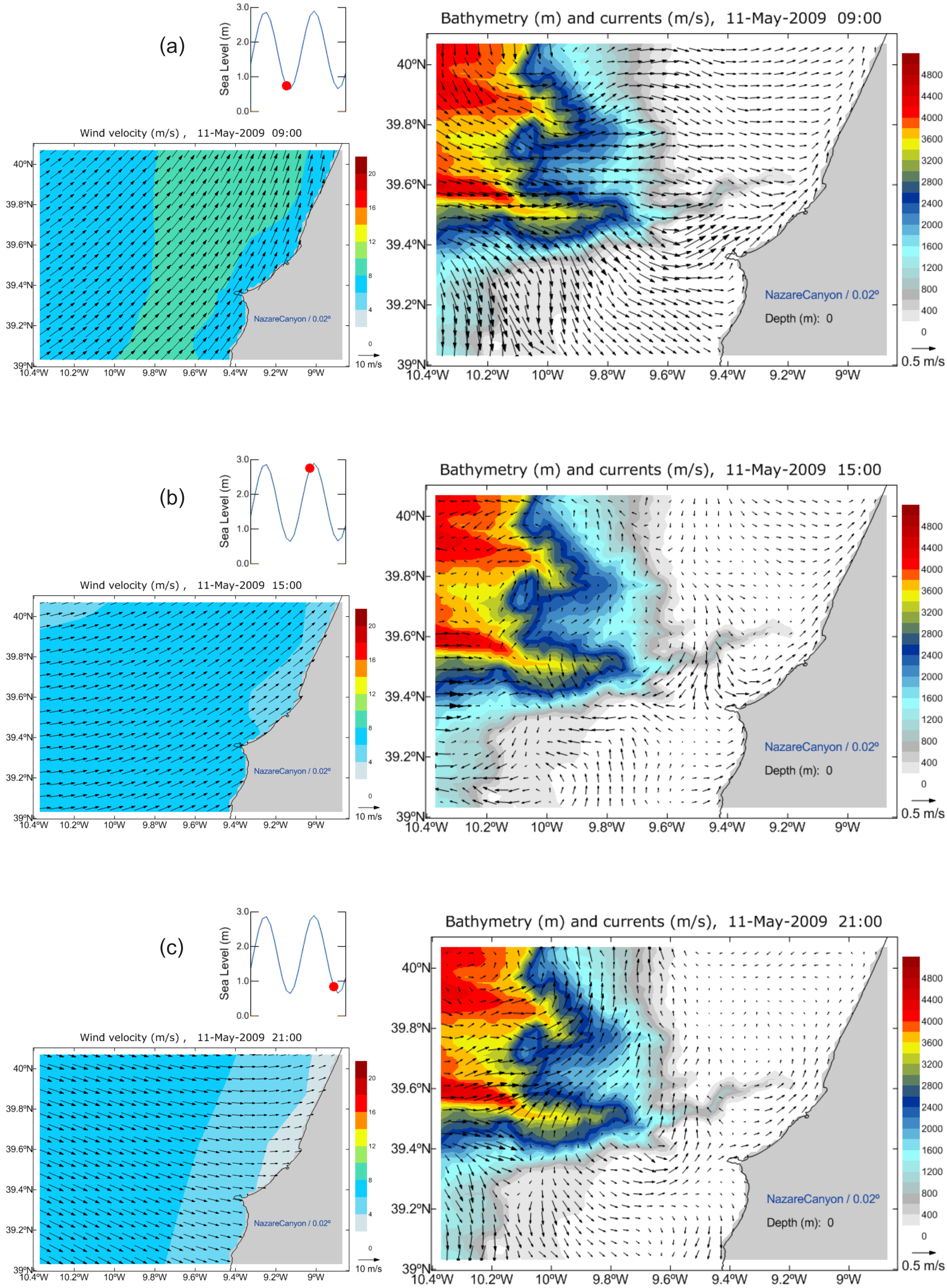

Figure 4.8 Snapshots of currents at the surface, tide oscillation and wind velocity predicted by the model for the second level: a) 11^{th} May at 9:00; b) 11^{th} May at 15:00; c) 11^{th} May at 21:00 without upwelling event along the Portuguese coast.

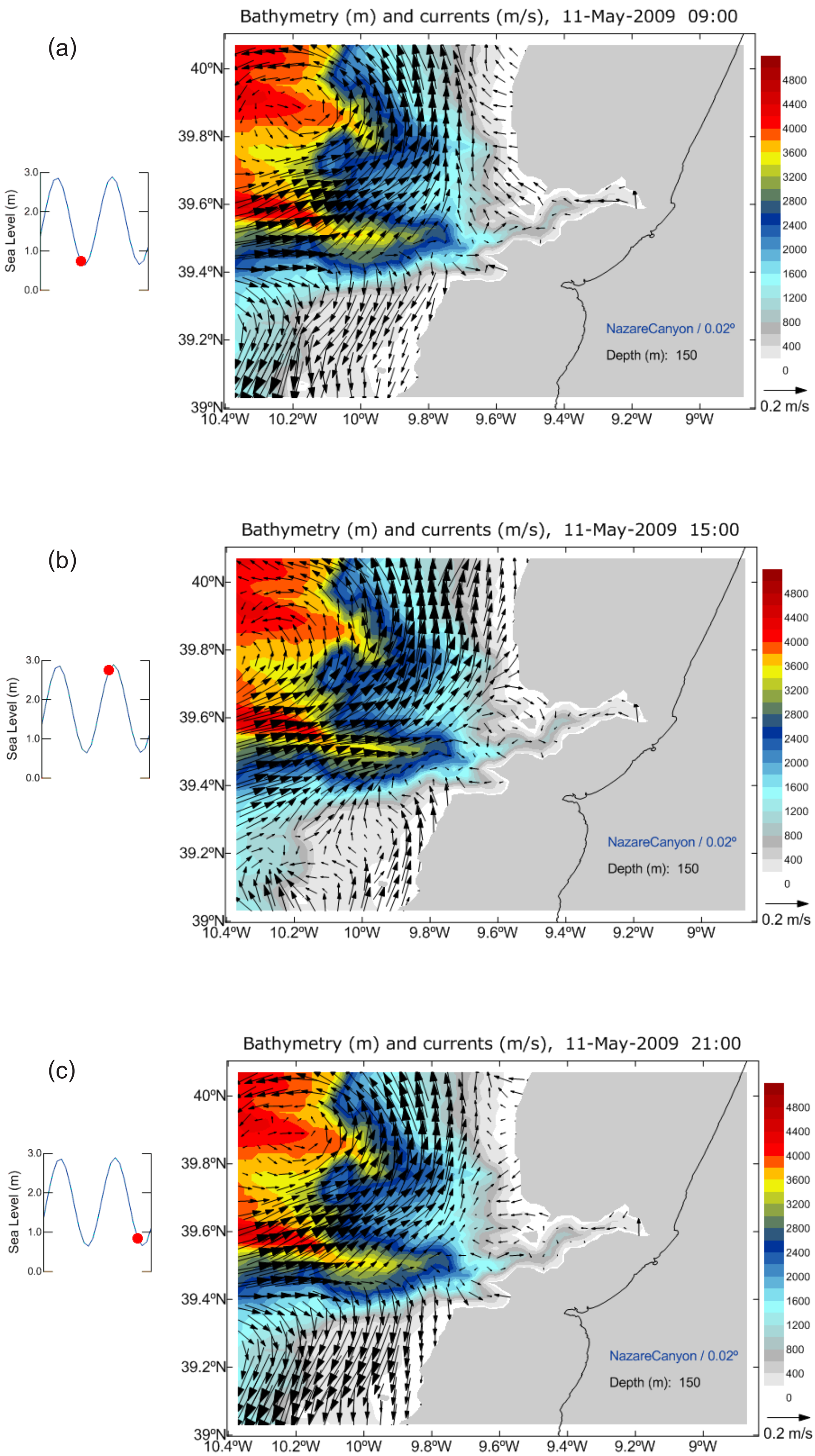

Figure 4.9 Snapshots of currents at 150 m depth predicted by the model for the second level: a) 11th May at 9:00; b) 11th May at 15:00; c) 11th May at 21:00 without upwelling event along the Portuguese coast.

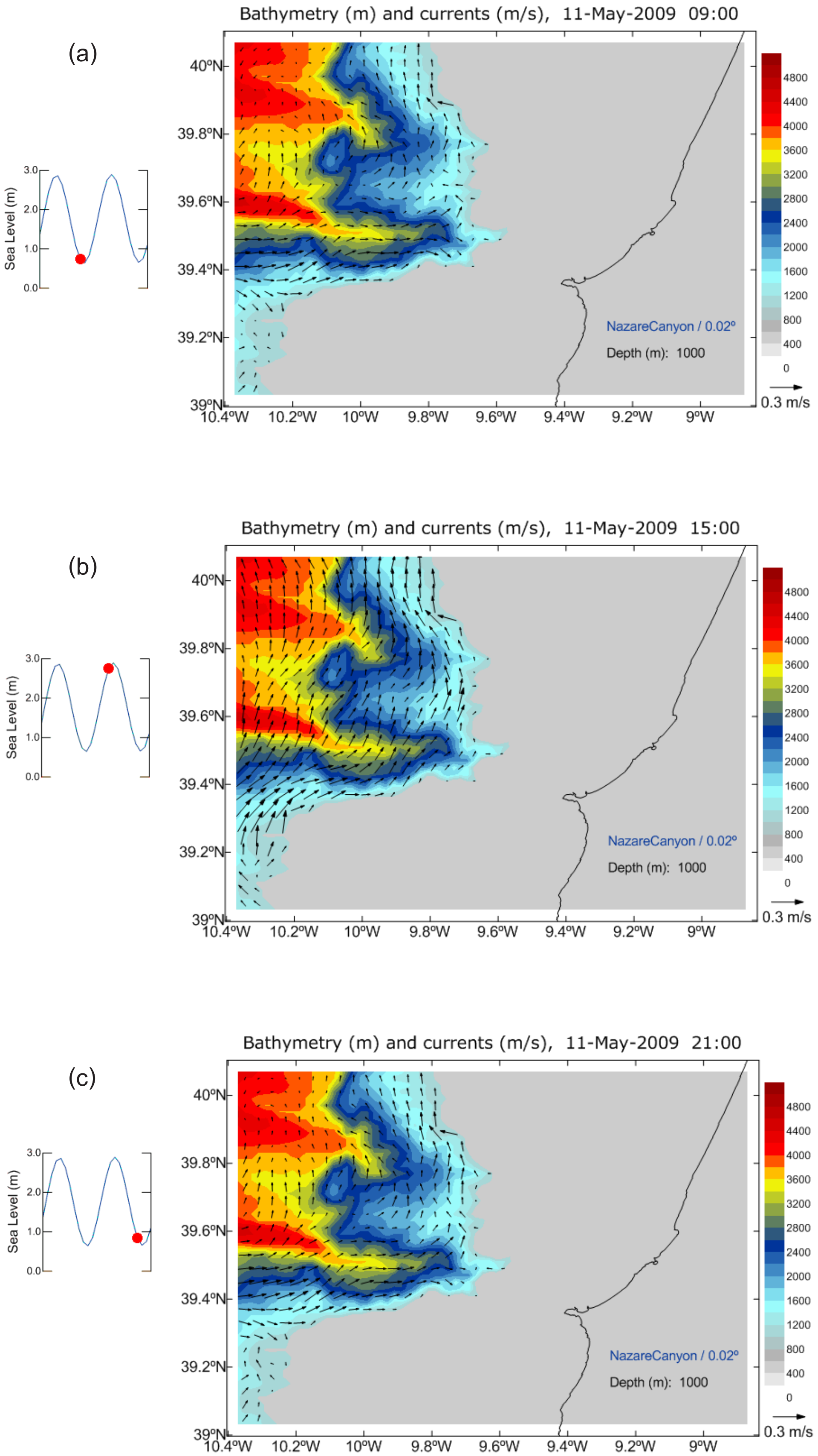

Figure 4.10 Snapshots of currents at 1000 m depth predicted by the model for the second level: a) 11th May at 9:00; b) 11th May at 15:00; c) 11th May at 21:00 without upwelling event along the Portuguese coast.

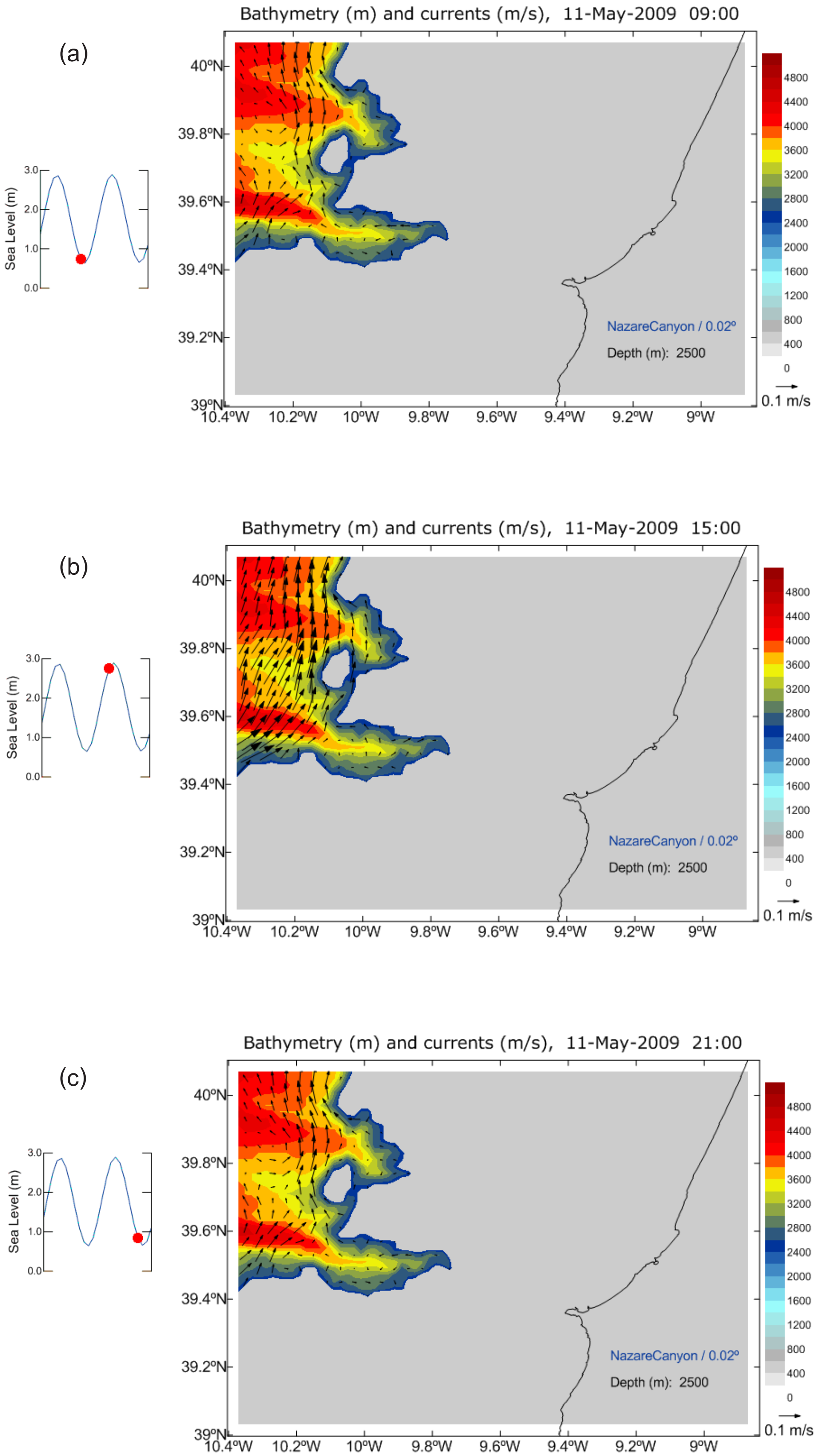

Figure 4.11 Snapshots of currents at 2500 m depth predicted by the model for the second level: a) 11th May at 9:00; b) 11th May at 15:00; c) 11th May at 21:00 without upwelling event along the Portuguese coast.

the figures did not permit a broader view of the circulation pattern along the entire coast. At the 2500 m depth a permanent poleward slope current was observed (Fig. 4.11). Mazé et al. (1997) explored a study using data from a hydrographic array off Iberian peninsula and concluded that the meridional transports in the 300 km wide boundary layer is northward at all levels, including the NEADW. The slope current at this depth flows inside the canyon adopting an E-W direction aligned with the canyon axis as observed in the top layers. The flow pattern inside the canyon indicates a low intensity eastward flow along the southern canyon slope and a westward on the northern side.

4.3.2.2 Upwelling occurrence period

Figure 4.12 depict a sporadic upwelling on 28th May observed along the Portuguese coast by remote sensing data. A good correlation was observed when simulated SST was compared to remote sensing data for this day. The colder water near the coast indicated the presence of an upwelling front (Fig. 4.12). Figures 4.13 and 4.14 showed the circulation pattern within the canyon and adjacent slope on that day.

Referring to section 4.2, during the summer, when the Azores high-pressure cell is located in the central Atlantic and the Greenland low has diminished intensity, the resulting pressure gradient forces the air to flow southward along the Iberian coast; a wind pattern is formed inducing upwelling and an associated southward circulation. The period between July and September is when presents intense and permanent upwelling regime (Fiúza et al., 1982), while in spring the occurrence of favourable wind condition promotes the development of dampened upwelling fronts. Similar results have been observed as the simulated graphics bears close resemblance to upwelling occurrence observed by remote sensing data. The differences in the current circulation pattern between the upwelling and the non-upwelling event only occurs until depths of 200 m since usually they are under the wind influence. The prevailing southerly winds observed during this period (Fig. 4.16) induce a persistent southward current in the same direction as the wind over the shelf (Fig. 4.13). Some local divergences can occur due to the effect of the coastal topography. At this level, no influence of the canyon on the circulation pattern could be observed. At 150 m depth (NEACW) (Fig. 4.14) insignificant differences on the current pattern offshore were registered. In the shelf north of the canyon, the influence of the wind inducing a southward current during low tide was evident.

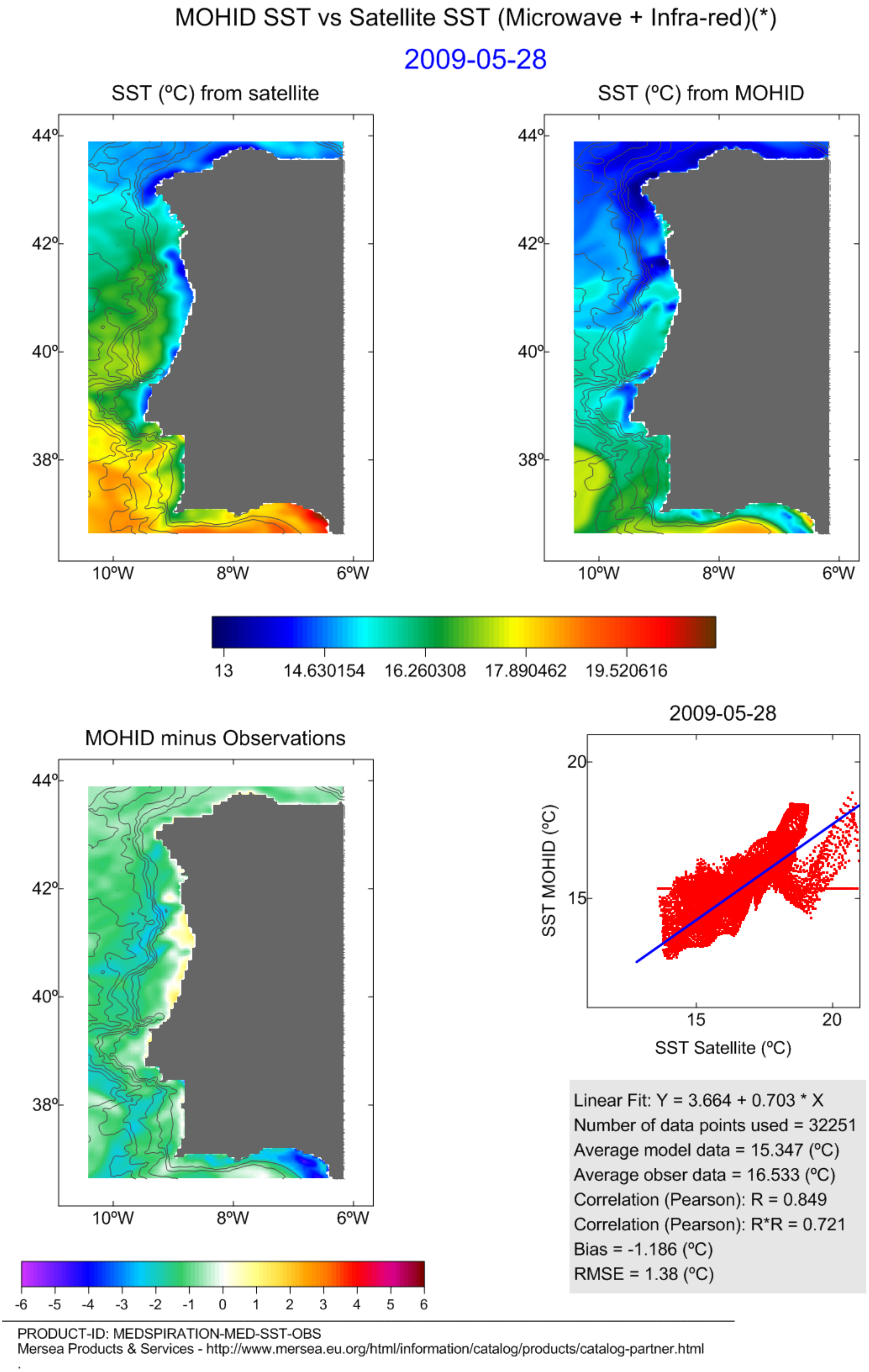

Figure 4.12 Sea surface temperature (SST) maps on 28th May 2009 with upwelling occurrence. Maps retrieved from remote sensing data (upper left panel), simulated by the model (upper right), and their difference (lower panel). Linear fit between model and observed data, and results from basic statistical analyses are also shown.

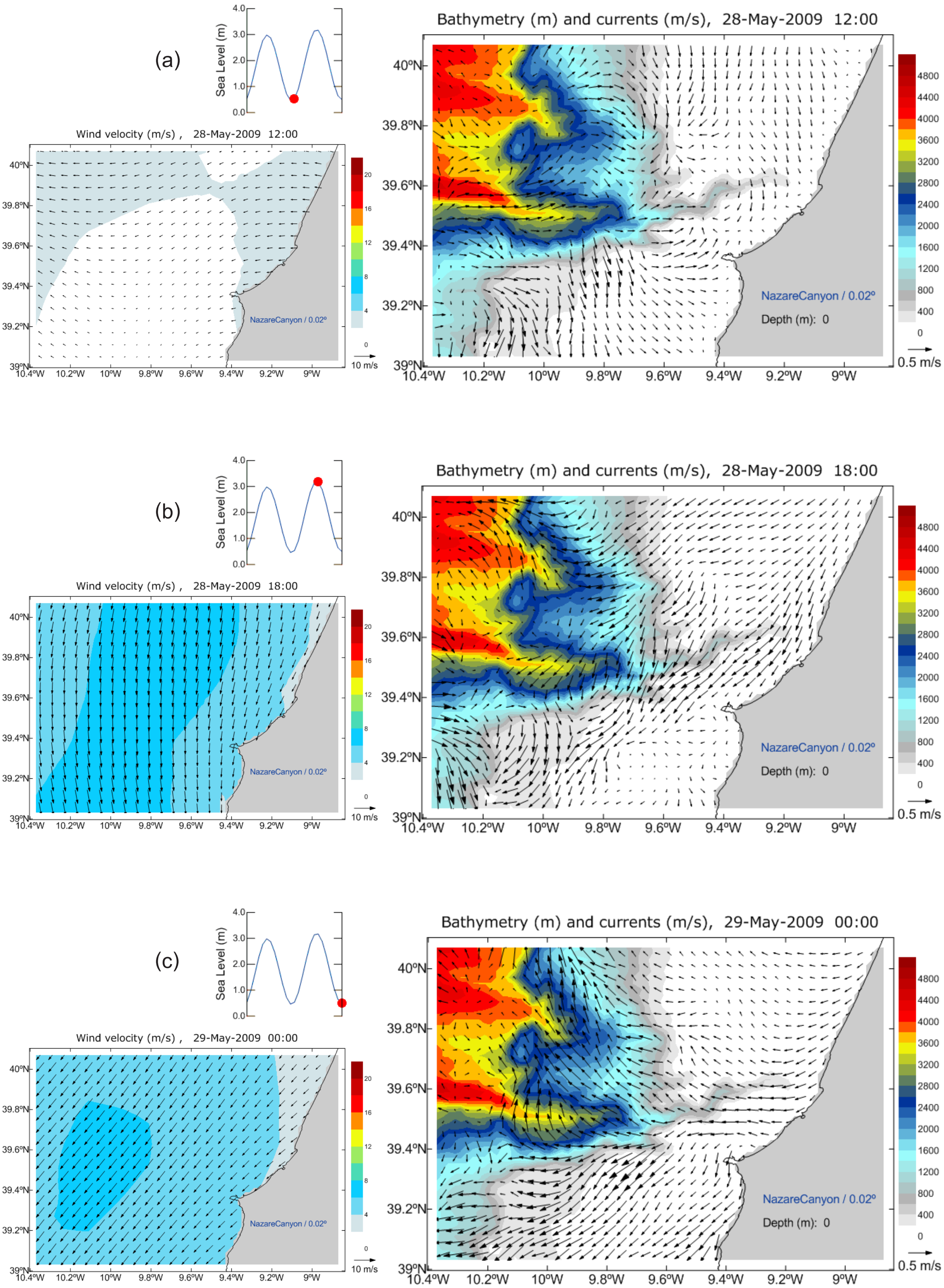

Figure 4.13 Snapshots of currents at the surface, tide oscillation and wind velocity predicted by the model for the second level: a) 28th May at 12:00; b) 28th May at 18:00; c) 29th May at 00:00 with occurrence of upwelling event along the Portuguese coast.

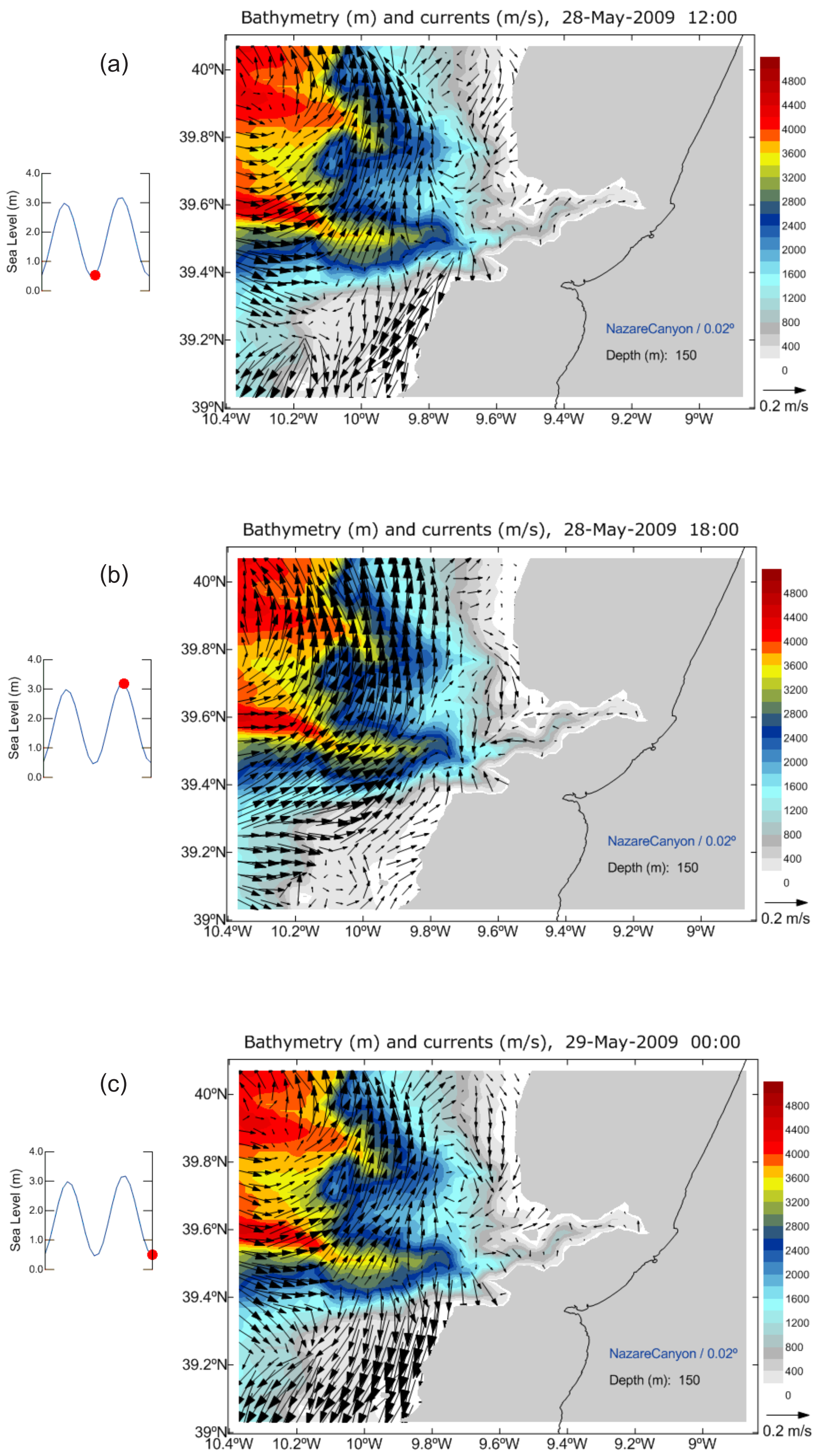

Figure 4.14 Snapshots of currents at 150 m depth predicted by the model for the second level: a) 28th May at 12:00; b) 28th May at 18:00; c) 29th May at 00:00 with occurrence of upwelling event along the Portuguese coast.

In the upper canyon, the currents are aligned with the canyon walls in an E-W direction with eastward flow during low tide and westward flow during high tide. These results seem to indicate that the canyon had an inverse response to tidal oscillation. In low tide, when the coastal waters withdraw, the canyon seems to induce an up-canyon flow bringing up to the surface deeper waters and the opposite is verified during high tide. Further studies are required to establish the canyon's response to the tides oscillation. The model results for the non-upwelling period showed a polarization of the current along canyon with E-W direction from the 2500 m depth up to the 150 m (Figures 4.8 to 4.11). Field results on near-bed current dynamics demonstrate the presence of moderate strong tidal currents in the upper and middle canyon, directed predominantly along the canyon axis and typically alternating in up-canyon and down-canyon direction with a semi-diurnal frequency (de Stigter et al., 2007). The currents polarization along canyon direction, particularly to the case of narrow canyons as is the case of the Nazaré canyon, has also been observed (Freeland and Denman, 1982; Klinck et al. 1988, 1996). According to these authors, the currents are forced by internal pressure gradients associated with the baroclinic tide that is generated in the surroundings, to create a substantial cross-shelf exchange.

4.3.3 Evaluation of the enhanced upwelling in the canyon by comparison with the open slope

The model results illustrated the comparison between upwelling (Fig. 4.15 and Fig. 4.18) and non-upwelling (Fig. 4.16 and Fig. 4.20) inside the canyon and on the open slope (Fig. 4.18 and Fig. 4.19). The model also displayed the time delay between the onset of the wind and the changes in the currents directions. The two time series at the canyon's head (B2 – 39.58ºN; 9.15ºW; 262 m depth) were compared. Figure 4.15 corresponds to an absent upwelling period from 10th to 14th May while Figure 4.16 corresponds to the sporadic upwelling period from 26th to 30th of May. In the shelf break, the model correctly reproduced the differences between the occurrence and the absence of upwelling (Fig. 4.15 and Fig. 4.16). The relevant differences were represented by the changes in wind direction and currents direction up to 50 m depth. In the non-upwelling period, weak southerly winds which induced northward currents prevailed (Fig. 4.15), while during the upwelling period such was not observed (Fig. 4.16). The wind blowing across the surface of the sea causes water displacement in that direction which was observe at 5 m depth. During upwelling, the model results showed the southward current accompanied by persistent northerly winds (Fig. 4.16). Also, the model correctly reproduced the systematic changes of the current directions at 5 m depth, in response to the wind forcing during non-upwelling (Fig. 4.15). As previously stated, the shelf current at the Portuguese West coast is a poleward current that during summer under long periods of intense and permanent northerly winds can reverse. The model illustrated that the northerly wind for that period was not enough to completely reverse the current and in both cases, a prevailing poleward current was experienced with high velocities than what was observed during the non-upwelling period.

The current patterns at 100 and 200 m depth show an E-W direction aligned with the canyon axis; with a tidal signal suggesting the absence of the influence of the shelf current inside the canyon. This effect was particularly noticeable in Fig. 4.17 which show a meridional transect through the canyon head with average values of salinity (psu) and density (kg m^{-3}) for the upwelling period (arrows represent the average values for the meridional (v) and vertical (w*500) velocity (m s^{-1})). In the shelf, the meridional velocity dominated, inducing a southward current due to the effect of the prevailing northerly winds. After reached the canyon rims and inside the canyon, the vertical velocity became dominant and aligned with canyon axis. The vertical flux indicated a down canyon flow at the southern flank of the canyon and an up canyon flow on the northern side, also visible by the inclination of the isolines (Fig. 4.17). This structure reveals the three-dimensionality of the circulation that has been identified in several canyons such as the Palámos canyon (Jordi et al., 2005) and the Calvi canyon (Skliris et al., 2002). The pattern consists of a cyclonic circulation related to left coastal bounded flows that is observed within some canyons and over their edges (Hickey, 1995).

To compare the processes within the canyon, transects were laid along the open slope for the two days representing the absence and occurrence of an upwelling event (Fig. 4.18 and Fig. 4.19). The average values of temperature (ºC), salinity (psu), and density (kg m^{-3}) for the period of 11th to 12th May (Fig. 4.18) and 28th to 29th May (Fig. 4.19) along a slope transect in the north of the Nazaré canyon were presented. The model managed to describe the entire water column from the surface to the bottom but in order to have a better definition at surface the scale was modified down to the 400 m depth. Through the analysis of temperature, salinity and density profiles, it was possible to identify the water column stratification with a stratified surface layer up to the 70 m depth, a more saline MW between the 500 and the 1200 m depth and the NADW below the 2500 m depth. The oscillation of the isolines patterns close to the coast were also characterized by the model. On a non-upwelling period, the isolines break strait into the

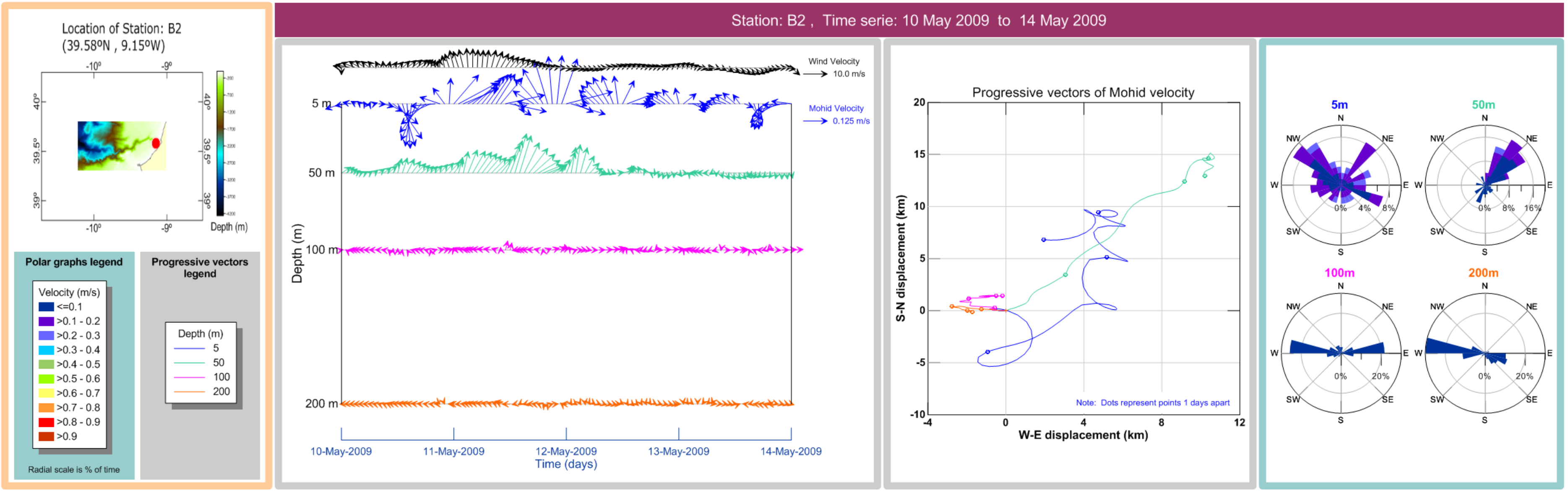

Figure 4.15 Time series of wind and currents predicted by the model during the non-upwelling period between 10th May and 14th May 2009. From left to right: a) stick diagrams of wind direction and velocity (black arrows), currents direction and velocities at 5, 50, 100 and 200 m depth (green, pink and orange arrows); b) Displacement of velocity vectors; c) Currents direction at 5, 50, 100 and 200 m depth.

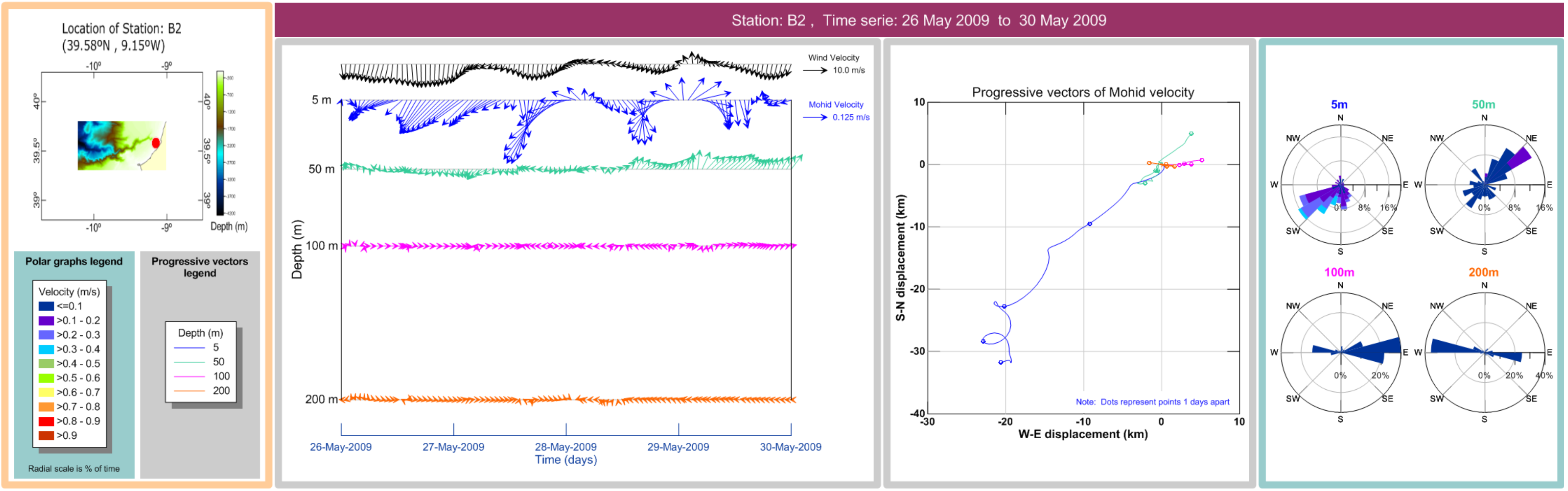

Figure 4.16 Time series of wind and currents predicted by the model during the sporadic upwelling event between 25th May and 30th May 2009. From left to right: a) stick diagrams of wind direction and velocity (black arrows), currents direction and velocities at 5, 50, 100 and 200 m depth (green, pink and orange arrows); b) Displacement of velocity vectors; c) Currents direction at 5, 50, 100 and 200 m depth.

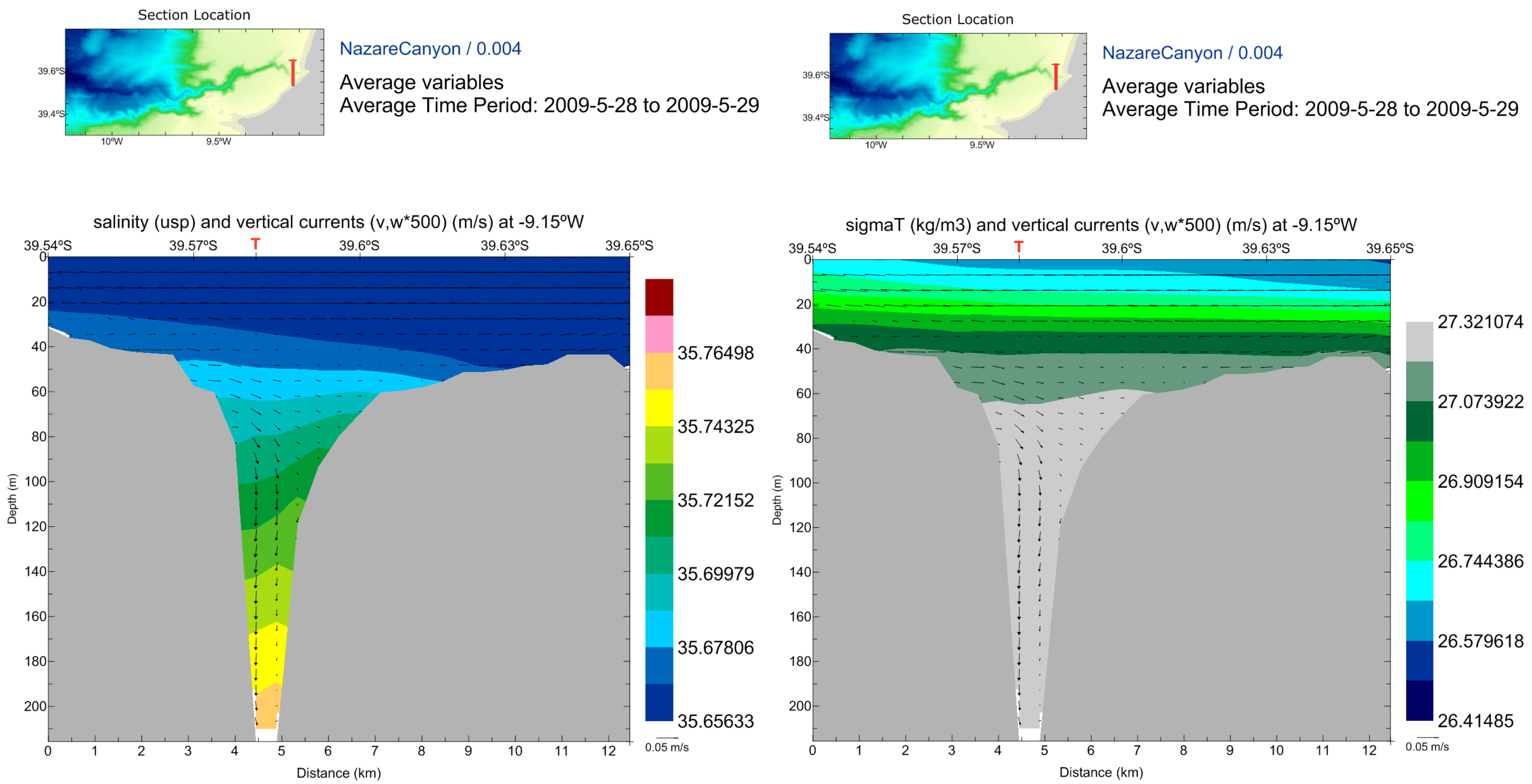

Figure 4.17 Meridional section within the canyon (from left to the right): Salinity and vertical currents, sigmaT and vertical currents predicted by the model. Occurrence of upwelling between 28th and 29th May 2009.

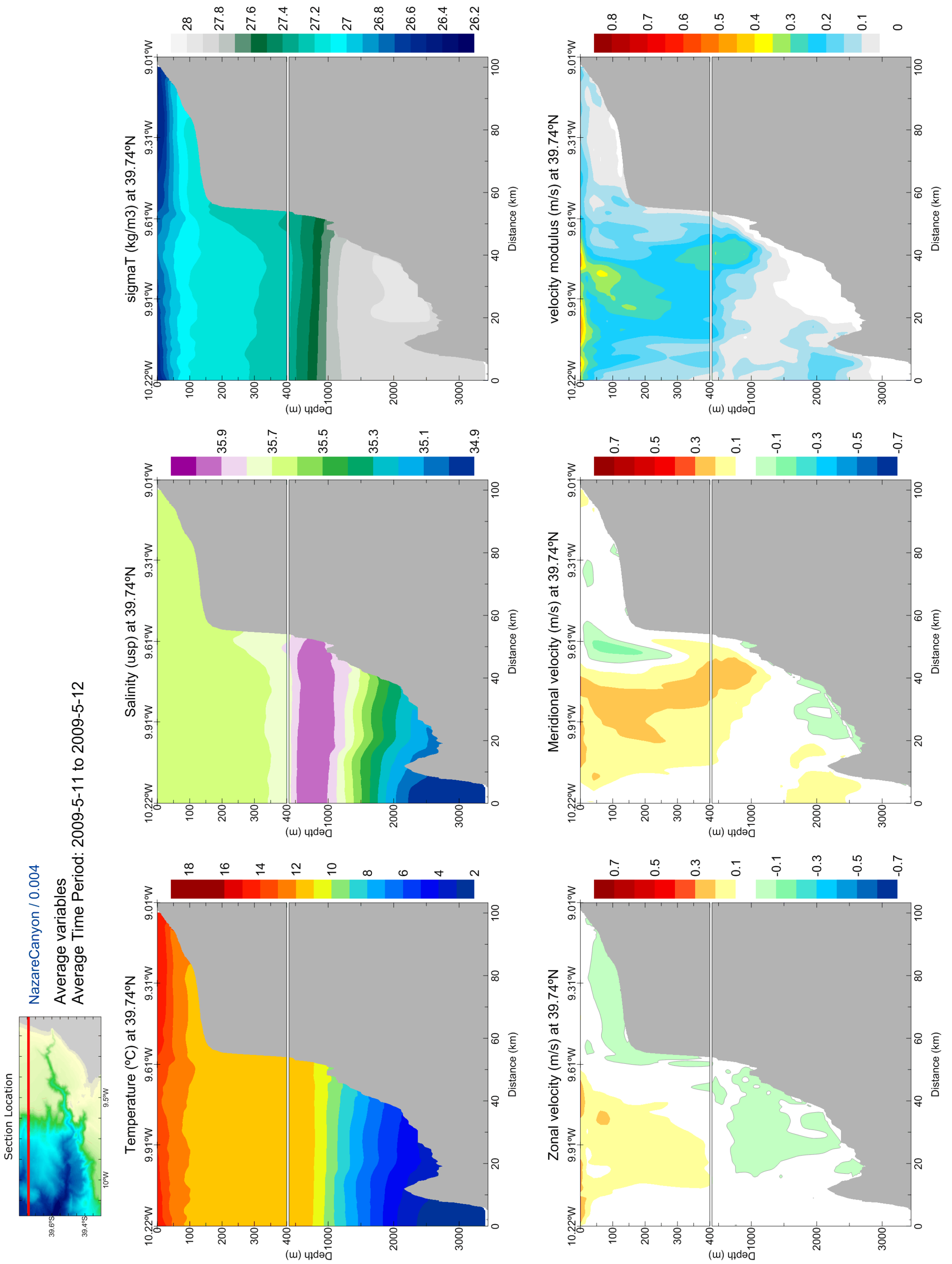

Figure 4.18 Zonal section along the slope of (from left to the right): Temperature, Salinity, sigmaT, predicted by the model. Absence of upwelling between 11th and 12th May 2009. The model results are continuous from the surface to the bottom but to have a better definition at surface the scale is modified down to the 400 m depth.

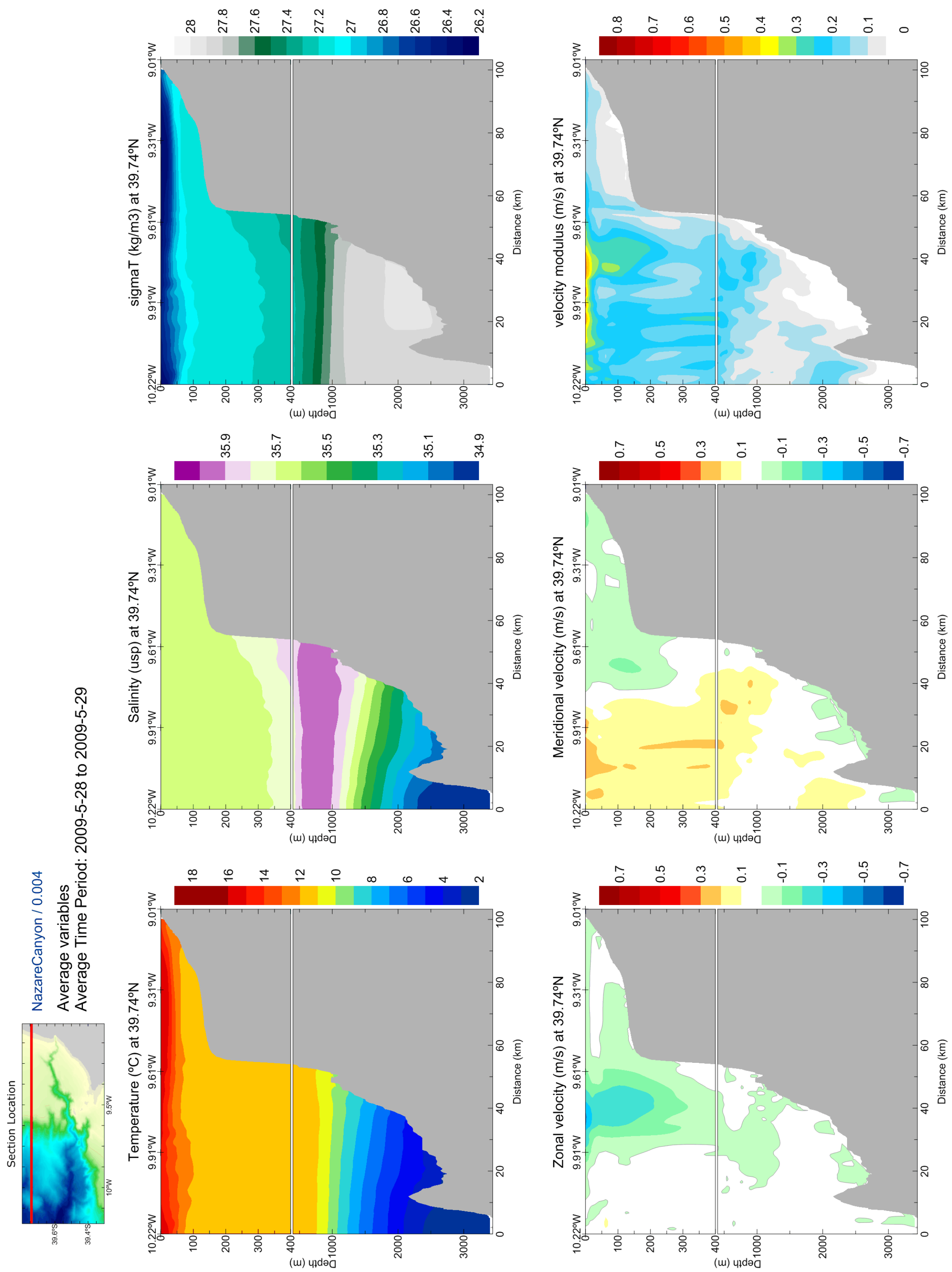

Figure 4.19 Zonal section along the slope of (from left to the right): Temperature, Salinity, sigmaT, predicted by the model. The occurrence of upwelling was simulated between 28th and 29th May. The model results are continuous from the surface to the bottom but to have a better definition at surface the scale is modified down to the 400 m depth.

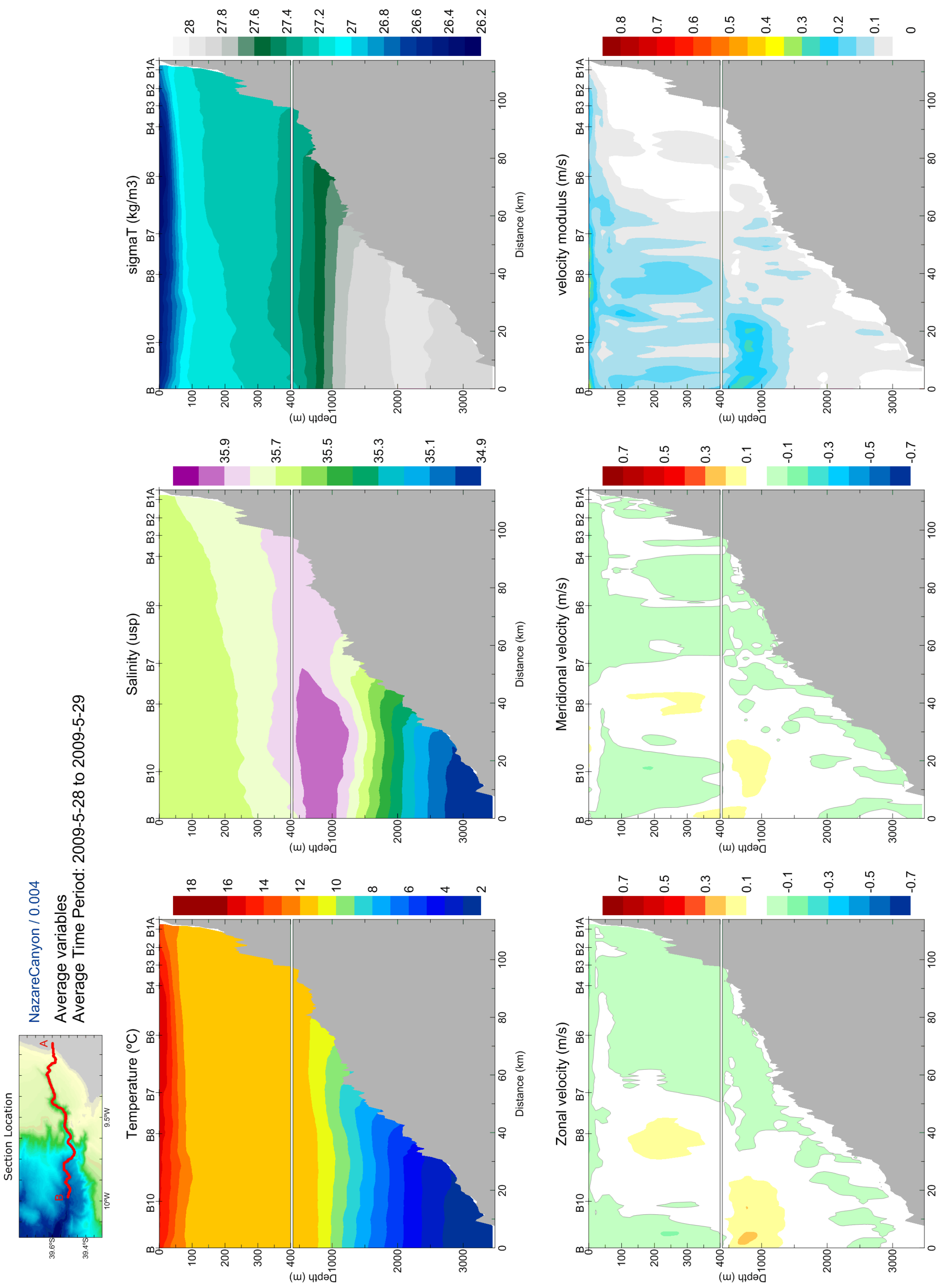

Figure 4.20 Zonal section within the canyon (from left to the right): Temperature, Salinity, sigmaT, predicted by the model. The occurrence of upwelling between was simulated between 28th and 29th May. The model results are continuous from the surface to the bottom but to have a better definition at surface the scale is modified down to the 400 m depth.

shelf (Fig. 4.18) while during upwelling the isolines bend upward toward the coast indicating the transport of deeper waters into the coast (Fig. 4.19). Comparing the slope transect (Fig. 4.19) with axis transect along canyon (Fig. 4.20) for the same upwelling event, the propagation of up canyon of the water masses along the canyon axis was notorious, bringing deep waters even closer to the coast. The effect was also evidenced by the bending up of the surface stratified layer isolines near the coast. As an example, considering the 35.7 isohaline, it reached approximately the shelf break depth on the open slope (Fig. 4.19) while on the canyon's transect it reached the coast. The model indicated that deeper and nutrient richer waters reached the coast due to the presence of the canyon, enhancing upwelling. This is of importance when considering that during the summer a persisting upwelling front for three months occurs along the Portuguese coast. A modelling study on circulation near a submarine canyon performed by Klinck (1996) conclude that, a narrow canyon, as is the case for the Nazaré canyon with left-bounded flow creates upwelling at canyon's head and a strong exchange between the ocean and the shelf. It was concluded that in these cases, dense water is pumped onto the shelf even during strong stratification. The head of the Nazaré canyon located up to 1 km southwest of the coast (Lastras et al., 2009) acts as a major source of nutrients for the coastal waters with a direct effect on the productivity and consequently an impact on the local economy.

4.4 Conclusions

In this study a hydrodynamic model was applied to the Nazaré canyon and adjacent slope with boundary conditions provided by a regional operational model for the west Iberian coast and forced by the atmospheric forecast model MM5. The model was validated with remote sensing data and Argo floats for spring 2009. The model adequately reproduced the wind forced circulation over the shelf and the main hydrological features of the canyon and adjacent slope. The model was able to simulate upwelling observed by the satellite images during spring 2009.

The model was able to illustrate the circulation patterns along the canyon's area as has been described by other authors. The circulation was modified due to the presence of the canyon and the flow tended to follow the bathymetry in and along canyon direction. The observed current polarization along axis direction is of major importance in the cross-shelf exchange processes.

Additionally, the model reproduced the upwelling usually observe in the summer. A comparison between the canyon and the adjacent slope confirm that the presence of the submarine canyon enhances the upwelling. After comparing the canyon with the adjacent slope, it was determined that upwelling was in progress inside the canyon but not on the slope. The Nazaré canyon being a narrow canyon with left bounded flow, upwelling is expected to happen at the canyon's head, bringing the deeper waters richer in nutrients to a few meters away from the coast thereby enhancing the primary production. Such a process is of major importance to the trophic chain as it increases the productivity in the area, impacting the socio-economic activities such as fisheries.

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Chapter 5

Conclusions and Future Plans

5.1 Conclusions

The work addressed in this thesis focused on the dynamics of the Nazaré canyon, relying on the application of numerical modelling tools. The application of a hydrodynamic model to a dynamic and complex marine ecosystem, the methods utilized to validate the model, and to represent particular features of the system such as upwelling events, have all combined as a new research field. Furthermore, based on the previous knowledge about the physical properties of OMAs and pollutants, the use of a lagrangian model in this work has broadened the fields of study which describe the spatial and temporal transport of any modeled particle, and includes a new approach to the residence time concept. The residence time concept was based on the temporal interval required by the OMAs and pollutants to leave each monitor box, and considered the area of the box and not the volume of water described in previous studies.

In terms of the objectives listed in the introduction, the modelling exercises were successfully able to reproduce the physical dynamics of the canyon, and represent the transport patterns of the OMAs and pollutants within the canyon. Additionally, model simulations allow for the comparison of empirical knowledge and data about the Nazaré canyon over the last 15 years, and are available in the published literature.

Manuscript I

The MOHID model was applied with a lagrangian transport model, thereby providing an overview of the OMAs transport patterns along the bottom depth of the Nazaré canyon. The model simulations were performed during the spring season when phytodetritus production was maximal. The model results demonstrated that during the specific time of investigation (spring 2009) the canyon did not function as a conduit of organo-mineral aggregates to the deep sea, but rather it acted as a temporary depocenter of sedimentary organic matter during spring conditions. Previous studies indicated that this may not always be the case and the canyon is an active conduit of sediment transport to the deep sea.

The model results showed that the carbon flux in the canyon was not constant and unidirectional within areas of resuspension, transport, and deposition. The large carbon rich aggregates with their specific transport behavior were not exported, but rather remained in a given area for long periods of time. These aggregates, however, were frequently resuspended into the BBL, therefore, allowing mineralization to occur under turbulent conditions of the BBL. These findings were in agreement with other studies carried out within the canyon. Additionally, the differences between transport patterns of the median OMAs and phytodetrital aggregates were predicted by the model, and the lateral transport of the larger OMAs was less pronounced than for the median OMAs, resulting in the carbon deposition.

Conversely, the model results did not include the possible role of sediment gravity flows; and thus the model may underestimate the rates of OMAs transport. Nevertheless, the model could also be applied to evaluate the transport patterns of other substances in the canyon such as pollutants. Further studies are required to analyze the differences in the carbon fluxes transport in an autumn-winter season and the impact of the river discharges to the increasing carbon fluxes in Nazaré canyon.

Manuscript II

This investigation was an attempt to gauge the degree to which the intrinsic properties of plastic debris affect their transport within the sub-surface waters of a modelled marine canyon environment. It is crucial to understand how microplastics are transported below the surface to more accurately estimate global distribution, residence times, convergence zones and ecological consequences, which can be done using numerical models.

The model results indicated slow transport of benthic microplastics in the Nazaré canyon, implying long-term exposure of benthic canyon ecosystems to plastics, but also suggested that large-scale water movement, such as those associated with storms and internal waves, may intensify down-canyon transport in episodic short duration events.

Due to the long residence times for benthic microplastics indicated by this study, future investigations into the rates at which benthic microplastics degrade are important to better quantify realistic residence times. Potential changes in the intrinsic properties of microplastics as they degrade toward nanometer scale, may alter transport properties and, in turn, the results of long run-time transport models.

Future research should also focus on the ecological consequences of plastic exposure in benthic environments, particularly in critical areas such as biodiversity hotspots, to allow the development of preventative measures and policy/legislation changes if required.

Decreasing the amount of plastic debris originating from urban consumers would reduce exposure levels in many deep sea regions close to shore, such as the canyon ecosystems. Additional investigation is needed to accurately estimate the amount of plastic residing in the benthic oceans and to understand the sub-surface behavior of non-buoyant microplastics and their sinks within the natural environment.

Manuscript III

The model was validated with remote sensing data and Argo floats during the spring of 2009, and reproduced adequately the wind forced circulation over the shelf and the main hydrological features of the canyon and its adjacent slope.

The model was able to represent the circulation patterns along the canyon's area, as previously published. The general circulation along the shore was modified by the canyon and the flow tended to follow the bathymetry, in and along canyon direction. This polarization of the current along axis direction is of major importance in cross-shelf exchange processes.

In the canyon area, the model was able to simulate an upwelling event observed by the satellite images during the spring of 2009. A comparison between the canyon and the open slope confirmed that the presence of the submarine canyon enhanced upwelling. When the canyon was compared to the adjacent slope, it was evident that during the same time period, the upwelling was in progress inside the canyon but not on the slope.

Considering the Nazaré canyon as a narrow canyon with left bounded flow, it is expected that upwelling at the canyon's head would bring the deeper waters richer in nutrients to the surface, thus enhancing primary production in the near-coastal area. The upwelling is important to the trophic chain as it increases the general productivity and impacts the socio-economic activities of the area, such as in the fishing industry.

The results achieved in the three manuscripts of this thesis allowed addressing the hypotheses formulated in Chapter 1.

Answer to H1 – The canyon did not function as a conduit of organo-mineral aggregates to the deep sea. Contrary, it acted as a temporary depocenter of sedimentary organic matter during spring conditions.

Answer to H2 – The carbon flux in the canyon was not constant and unidirectional within areas of resuspension, transport, and deposition.

Answer to H3 – The Nazaré canyon demonstrated a slow transport of benthic microplastics in the Nazaré Canyon, implying long-term exposure of benthic canyon ecosystems to plastics. The model also suggested that large-scale water movement, such as those associated with storms and internal waves, may intensify down-canyon transport in episodic short duration events.

Answer to H4 – The model was able to simulate the main oceanographic features within the canyon and represented the circulation patterns along the canyon‘s area. Due to the presence of the canyon, the flow tended to follow the bathymetry in and along canyon direction modifying the circulation.

Answer to H5 – The presence of the submarine canyon enhanced the upwelling. The upwelling started first in the canyon and later transitioned to the open slope.

5.2 Future Plans

Models are versatile tools that include existing quantitative knowledge about processes to provide an integrated overview of the system which would be difficult to achieve by the simple combination of available analytical methods. They are however limited by process knowledge and sometimes by data necessary to parameterize known processes. Despite the strengths shown by the model application, a number of limitations have made it difficult to address all the features of a canyon, and thus limits answering all the relevant questions regarding the impact canyons play in the ocean. For instance, the possible role of sediment gravity flows, and aggregation and disaggregation processes of the particles were not included. However, the model architecture makes it straightforward to either add other components or adapt and include existenting processes. Although the Nazaré canyon is not connected to a river system, the contribution from river discharges on the Portuguese continental coast can reach the canyon and are not included in the model. Currently, this feature is being improved by the inclusion of the river discharges along the coast in MOHID-PCOMS.

The importance of the processes or forcings not included in the model is assessed by comparing results with data (model validation). Model results are in good agreement with sediment dynamics data and contributed to explain it. However the quality of the hydrodynamic model results validation may be improved assessing the model results using observations from in-situ platforms and instruments located along the canyon, such those provided by the MONICAN project running at IH.

Considering the advantage of the MOHID system characteristics, the transport model is suitable for further applications. The lagrangian model can be applied to the Nazaré canyon when considering other hydrodynamic regimes and additional type of particles. For realize these extensions of the current MOHID system, it will be necessary to change the simulation period, parameters values, sizes, locations, and types of emissions. Following this methodology, a future study is underway, to track the transport of coccolithophores within the Nazaré canyon.

As it was mentioned on Chapter 1, the Portuguese continental margin is intersected by other canyons. Following the same approach for the Nazaré canyon, other canyons may additionally be modeled by benefitting from the boundary conditions provided by the operational forecasting model.

An additional step, which may also benefit the MOHID-PCOMS development, is to convert the Nazaré canyon model into an operational system. This will shorten costs of simulations and will increase results visibility creating conditions to demonstrate the potential of this predictive e.g. oil and gas industry. Recently, companies such as Petrobras, Galp, Repsol, and Partex have been exploring in the vicinity of the Nazaré canyon. The transport model applications would provide dispersion scenarios of oil spills, or simulate the transport patterns of aggregates discharged into marine environment during off-shore petroleum extractions.

This modelling system was designed to be applied in any canyon system using a downscaling approach. In fact canyons are small scale accidents that may amplify perturbations of the regional flow e.g. in the form of high internal waves. As a consequence the simulation of canyon dynamics requires the use of fine grids nested into regional circulation models forced by large circulation models. This downscaling process assures good resolution in the canyon and the inclusion of the general and regional scale processes in the local hydrodynamics. MyOcean or HYCOM are providing the general circulation data necessary to feed the system. The implementation of the Nazaré canyon as an operating forecast system and its extension to other Portuguese canyons will improve the MOHID model structure, while simultaneously enlarging the simulation scenarios for future potential studies.

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