Integration of an Oil and Inert Spill Model in a Framework for Risk Management of Spills at Sea – A Case Study for the Atlantic Area

Rodrigo Fernandes, Ramiro Neves and Cláudia Viegas
Instituto Superior Técnico - MARETEC
Lisbon, Portugal
Rodrigo.maretec@ist.utl.pt

Paulo Leitão
Hidromod, Lda.
Lisbon, Portugal

Abstract

The integration of multiple information layers from different regions in a common framework is particularly relevant when dealing with interregional and transnational pollution problems, very common in the Atlantic area. An integrated framework for the support of modeling fate and behaviour of oil and inert spills was designed in EASYCO, ARCOPOL and ARCOPOL+ EU research projects, where various metocean forecasting systems from different institutions were integrated in a common polycentric approach.

This paper describes recent updates of the oil and inert spill modeling component of MOHID model, including interfacing with EASYCO metocean data and the integration with novel Decision Support Systems (DSS) also presented here. MOHID updates include: a) an innovative multi-solution approach to dynamically integrate available information from multiple metocean forecasting solutions available for each model simulation; b) a new approach for the simulation of drifting buoys with subsurface drogues and floating containers; c) backtracking modeling; d) coupling to wave models and inclusion of Stokes drift; e) vertical movement of entrained oil; f) review of oil weathering processes including a new approach for emulsification.

Several case studies highlight the new capabilities of the MOHID model and the implemented DSS. Developments show increasing versatility for application in a wider range of situations, including improved simulation of drifting buoys or pollution source tracking. The multi-solution feature, included in particle transport module, also increases versatility when dealing with different metocean data sources with different scales. This is especially useful when processes studied (like marine pollution) can assume an interregional or transnational dimension – like the EU Atlantic Area. The DSS also show strong potential to be used in different areas and applications.

1 Introduction and Background

The increasing predictive capacity of environmental conditions and fate or behaviour of pollutants spilt at sea or costal zones combined with monitoring tools (e.g. vessel traffic control systems) can provide more robust support for decision-making in emergency or planning issues associated to pollution risk management.

Over the last few years, a new generation of different oil and inert spill decision-support systems (herein referred to as DSS) is being designed and developed by government agencies and private industry, aiming to provide a more detailed and realistic support to the prevention and response teams. When compared with the old generation systems, these were either too simplistic or too complex and slow.

This new generation of DSS is now pushing monitoring and modeling efforts forward, creating synergies that provide mutual benefits for the creation of innovative software technology, and also for the stimulation of research and development around modeling and monitoring activities.

In the early 90's, one of the most relevant DSS became popular due to its simplicity, speed (very fast), availability (publicly available), and extensive oil products database – ADIOS (NOAA, 1994). This software has been continuously updated, and ADIOS 2 was released in 2000 (Lehr et al., 2002). Even today, ADIOS (2) is widely used as an extensive oil products library and as a first test of the expected behaviour of the oil. It is also used as a reference weathering model, being compared with other new models, when ground-truth weathering data is not available (Berry et al., 2012). However, ADIOS does not simulate oil spill trajectory.

Meanwhile, other DSS started to be developed in order to provide a more accurate and detailed analysis and prognosis, often including a graphical user interface with typical GIS support. Several examples of these tools became commonly used around the world by private oil companies, consulting engineering firms, research institutions and government agencies. GNOME (although this one with limited weathering processes) (Beegle-Krause, 2001), SLROSM (Belore, year unknown), OILMAP (ASA, 1997; ASA, 2004), OSCAR (Reed et al., 1995a; Reed et al., 1995b; Aamo et al., 1997; Reed at al., 2001), OSIS, GULFSPILL (Al-Rabeh et al., 2000), or MOHID (which is used and developed in this work; Fernandes, 2001; Janeiro et al., 2008; Mateus et al., 2008; Leitão et al., 2013) are some relevant examples. At this stage, the inclusion of variable metocean / environmental data as input for oil weathering tools started to be possible for the end-user, although these data should be pre-formatted and manually added to the system. These tools are very relevant on planning stages and studying different spill scenarios, since different sets of metocean conditions can be imposed to the models.

Recent operational oceanography and meteorology and the advances in terms of computational technologies lead to the development of new desktop or web-based operational products, capable of automatically and seamlessly integrating data sets from forecasting systems. Among them are MOTHY (Daniel, 1996; Daniel et al., 2003), OILMAP evolution + OILMAPWEB + SARMAP, POSEIDON OSM (Pollani et al., 2001; Nittis, 2006), MEDSLICK (Zodiatis et al., 2012) / MEDSLICK II (De Dominicis, 2013 – part one and part two), Met.no's OD3D (Hackett et al., 2006) + LEEWAY (Breivik et al., 2008; Breivik et al., 2012), OILTRANS (Berry et al., 2012), BSHmod.L (Broström, 2011), SEATRACK Web (Ambjorn et al., 2011). These tools are in general non-commercial solutions, mainly used and maintained at an operational basis, by prevention and response authorities. Moreover, most of these tools were created to specifically answer the questions raised by those end users and, therefore, focused in well-defined geographical areas. They are also limited to the use of a small number of operational solutions (often only one) for each needed metocean property. An exception is the ASA's commercial products - OILMAP / OILMAPWeb / SARMAP, which can be coupled to a large set of operational forecasts from several different data providers, through their aggregated environmental data solution server - *EDS*.

A synthesis of the processes modeled in the systems mentioned above is presented in Table 1.

Table 1 – Processes presently modeled by examples of referenced oil or inert drift modeling systems

	ADIOS	GNOME	OILMAP / SARMAP / OILMAPWEB	OSCAR	MOTHY	POSEIDON OSM	MEDSLIK	MEDSLIK II	SEATRACK WEB	OILTRANS	BSHmod.L	SLROSM	OD3D + LEEWAY	GulfSpill	MOHID
Advection	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Diffusion	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Wind drift	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Stokes drift	-	-	-	+	+	+	-	+	+	+	+	-	+	-	+
Floating objects	-	-	+	-	+	-	+	+	+	-	+	-	+	-	+
Backtracking	-	-	+	-	+	-	+	-	+	-	-	-	-	-	+
Stranding	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Spreading	+	-	+	+	+	+	-	-	+	+	+	+	-	+	+
Evaporation	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Emulsification	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+
Natural Dispersion	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+
Vertical Movement	-	-	+	+	+	+	-	-	+	-	+		+	-	+
Dissolution	-	-	+	+	-	-	-	-	-	-	-	-	-	-	+
Sedimentation	-	-	-	+	+	+	+	+	+	-	+	-	-	-	+

ADIOS | GNOME | OILMAP / SARMAP / OILMAPWEB | OSCAR | MOTHY | POSEIDON OSM | MEDSLIK | MEDSLIK II | SEATRACK WEB | OILTRANS | BSHmod.L | SLROSM | OD3D + LEEWAY | GulfSpill | MOHID

(Note: the information sources for this table were mainly obtained from the references and bibliography cited in this paper; MOHID already includes developed processes described in this paper)

Summarizing, this wide panoply of DSS seems to give a positive answer to many different end users involved, operating with user-friendly interfaces, providing GIS outputs from model results, and most of them (with a few exceptions) making use of state-of-the-art equations and processes for the simulation of oil and inert trajectory and behaviour. However, some of them are not prepared or have a limited capacity to backtracking mode or to include wave-induced transport (Stokes Drift). Furthermore, some of them are not able to reproduce the vertical movement of oil droplets or to make use of 3d hydrodynamic fields (usually using only one layer, either the surface or an integration of the water column). Also none of them have the possibility of integrating different metocean forecasts for different regions in the same simulation. This issue can become more relevant when managing potential transnational or interregional accidental pollution spills. Additionally, recent advances and massification in operational oceanography and meteorology forecasting systems are generating many metocean solutions at different scales, from the global scale till the very high resolution level.

DSS and numerical models for the assessment of accidental pollution should be able to take advantage of the different solutions provided without being constrained to one solution per simulation, or using only one vertical layer for hydrodynamics and water properties. They should also allow backtracking mode, which is in general a powerful tool helping to track spill origins.

In the present work, an integrated framework of DSS properly supported by an adapted MOHID oil and inert drift component has been implemented, in order to reduce the main gaps mentioned above.

2 Methods

2.1 Integrative framework for Risk Management: The EASYCO-polycentric Approach / Environmental Conditions

The high heterogeneity of operational systems available in the Atlantic zone, with strong overlapping of several different forecasting systems, and focusing on various types of solutions, models, scales, and areas, can be seen as a potential problem to emergency response or risk management tools, due to the large amount of information available in critical management systems, as discussed in this paper. However, it can also be seen as a good opportunity to take advantage of the different operational systems, usually focused and validated on specific spatial scales and zones with different resolutions (from local to global scales), integrating and promoting the harmonization of those model results.

The proposed approach was the development of a harmonized polycentric solution, where any or many of the model results can be visualized, and also used as environmental data in the oil & inert drift modeling system (herein referred to as OIDM). This polycentric approach can then easily facilitate intercomparison exercises, boost the development of common interfaces or web software systems, as well as improve efficiency in response activities for management of transnational and interregional pollution episodes.

Two different solutions can be adopted for dealing with all these data layers: using a centralized server (automatically downloading metocean model results to a central server, which then will be able to feed different DSS) or a distributed approach (DSS will use directly the metocean model results from the multiple data providers).

Several inconveniences were found in a distributed approach. If oil and inert drift simulations have to be executed in a matter of seconds, the process of downloading and interpolating metocean data from remote servers on-the-fly can be unstable. Moreover, most of the oil spills can have a significant variation due to vertical movement (entrainment / sinking / rising). Therefore, all of the 3D layers from hydrodynamic model results should be defined as possible input. This increases substantially the amount of information being used by the OIDM, reducing the possibility of downloading information on-the-fly.

In relation to a centralized server, the main disadvantages can be found in the creation of an additional data layer, instead of directly using outputs from the data provider. The other disadvantage is the storage of a high volume of information. Since the proposed approach was mainly to deal with prevention and response to emergency situations of accidents at sea, the storage of historic data can be discarded. Also fast 3D simulations were required, and accessing distributed remote servers for acquiring metocean data during the simulation process could become a bottleneck.

Based on these requirements, the centralized server was implemented and tested.

EASYCO data server automatically downloads and converts multiple metocean data sources (Download & Conversion Service) to be ingested by the different DSS developed and the OIDM as well, indexes those files (using Apache Lucene), stores these results on the server during a period of 15 days, then it is able to provide multiple remote downloads of these files upon request (EASYCO Data Service); lastly, MOHID Web Service runs the OIDM by request.

Although the Download Service is able to be configured and adapted to different types of data sources and services (OPENDAP, FTP, HTTP), a common EASYCO methodology was proposed for model output files in order to facilitate exchange of information between partners and the integration with downstream services, as the DSS. The common methodology proposed was based on netcdf file and takes CF conventions (Eaton et al., 2011) as a standard. The recommended method for publishing model data to be used by EASYCO server was THREDDS data server.

Mohid Web Model Service was developed to perform automatic particle tracking model runs with MOHID OIDM, based on a submitted xml string or a query string with a list of origin locations, and returning a xml string with MOHID data grid results.

The generated EASYCO data service is available online and can be used to feed different software applications (local or remote), such as Web GIS visualization systems, or DSS as described in the next chapters.

MOHID Web Service can also be automatically requested by different software tools.

2.2 DSS Developed

Different type of model-based software applications were developed, in order to show the versatility of the polycentric approach being tested, and also forcing MOHID OIDM to be adapted to fulfill the needs of those applications.

All the tools developed were mainly prototypes and demonstration tools for short-term accident pollution prevention and response activities.

2.2.1 EASYCO WBT

The EASYCO Web Bidirectional tool consists in a demonstration website built in a WebGIS environment that provides metocean results from the different operational systems, allowing:

a) to visualize metocean forecasts at different vertical layers;
b) to simulate on-demand inert and oil spills in a matter of seconds
c) to simulate on-demand displacement of Harmful Algal Blooms as well

On-demand simulations run in server (with MOHID), and results are displayed on the website after a few seconds, depending on the number of lagrangian particles used. The on-demand simulations can use constant user-defined values for environmental parameters, or a group of available metocean solutions selected and sorted by the end-user. Model results and simulations are available in a 15-day history.

The information displayed to the user is read by the web interface as a WMS client, and can also be exported to an external WMS server, increasing the interoperability of the system.

2.2.2 ARCOPOL Offline Spill Simulator

The ARCOPOL (CETMAR, 2013) Offline Spill Simulator (herein referred to as OSS) was designed to work in a desktop / laptop environment, in order to give more detail, options, interoperability (like exporting spill results to kml - Google Earth format or ESRI shapefile) and stability for simulation and results visualization, compared to the web-based interface. The idea behind this concept was to demonstrate the possibility of creation and design of an advanced and fast simulation tool, using best available metocean solutions for the Atlantic zone (supplied by EASYCO data service). Hence, main purpose was to run oil & inert spill simulations in MOHID disconnected from the internet, in order to increase the operationality during crisis or situations of imminent risk. Spill simulations can also be executed considering only constant metocean data conditions (instead of using space and time varying data). An exhaustive database of oil products was included, based on ADIOS 2 internal database.

A model download service was implemented and configured, in order to select and schedule the automatic downloading of metocean model solution(s) needed and defined by the end-user.

This tool can also be used as a visualization tool of the downloaded metocean model results.

2.2.3 Dynamic Risk Tool

This system provides:

a) coastal pollution risk levels associated to potential (or real) oil
b) spill incidents, taking into account regional statistics information on vessel accidents history and coastal vulnerability indexes (Environmental Sensitivity Index and Socio-Economic Index, determined in EROCIPS project),
c) real time vessel information (positioning, cargo type, speed and vessel type) obtained from AIS, best-available metocean numerical forecasts (hydrodynamics, meteorology - including visibility, wave conditions) and
d) simulated scenarios by the oil spill fate and behaviour component of MOHID Water Modeling System (here referred to as MOHID OIDM).

Different spill fate and behaviour simulations are continuously generated and processed in background (assuming hypothetical spills from vessels), based on variable vessel information, and metocean conditions, and results from these simulations are used in the quantification the consequences of potential spills.

This system was initially implemented in Portugal as a prototype.

2.3 Oil and Inert Spill Modeling System

The different DSS implemented in this study are supported by an OIDM capable of simulating the trajectory & behaviour of oil pollutants, drifting buoys, or floating containers. This model is a component of MOHID Water Modeling System (Instituto Superior Técnico, 2013; Neves, 2013), integrated on MOHID lagrangian transport module, with simulated pollutants or objects represented by a cloud of discrete particles (or super-particles) advected by wind, currents and waves, and spread due to random turbulent diffusion or oil mechanical spreading. The super-particles also contain information about the oil rheological properties (density, viscosity) and main weathering processes (spreading, evaporation, emulsification, natural dispersion, sedimentation, dissolution) (Mateus et al., 2008).

This model has the ability to run integrated with hydrodynamic solution, or independently (coupled offline to metocean models), being this last one the option for the developed operational tools (to reduce computation time, taking advantage of metocean models previously run).

MOHID lagrangian module has been widely used in different types of studies and applications, not only in oil spills, but also in sediments transport, harmful algal blooms (Mateus et al., 2012), fish larvae (Nogueira et al., 2012), residence time in estuaries (Braunschweig et al., 2003), faecal contamination in bathing waters and plume diffusion and dispersion (near and far field) in water column from submarine outfalls or rivers (Miranda et al., 1999; Viegas et al., 2009; Viegas et al., 2012).

This integrated OIDM was initially developed and implemented in 2001 (Fernandes, 2001), and in the last years it has been successfully applied and validated in different applications (Balseiro et al., 2003; Carracedo et al., 2006; Janeiro et al., 2008; Mateus et al., 2008; Pierini et al., 2008; Fernandes et al., 2012). Oil spill simulations have been used since *Prestige* Oil Spill (2002), where oil spill trajectory forecasts were effectively generated, having successful results. Forecasts were generated in the early stages of the oil spill, and predictions were initially validated in-situ by the response team, afterwards, by remote sensing, and at last, by aerial observations. Since then, MOHID has been used operationally in other real accidents and in spill exercises performed by Portugal and Spain, always generating satisfactory results.

During the execution of this work, MOHID OIDM was also updated and applied in the simulation of deep water blow out of oil spills (Leitão et al., 2013).

2.3.1 Updates in MOHID Oil & Inert Drift Model

The updates in processes and features performed during the execution of this study were needed to fulfill the final purpose of building modeling software capable of responding to the high demands proposed for the development of an innovative and complete risk management infrastructure for spill incidents, composed by the previously referred DSS being developed.

2.3.1.1 Backtracking Mode

This feature allows performing model simulations of the trajectory of particles, running backwards (advection and diffusion processes are both included, but oil weathering properties are not simulated in backtracking mode). This means the model is now able to simulate possible sources or past trajectories based on an actual oil slick / inert object position, which is an added value in emergency response activities, or in the identification and tracking of potential pollution sources (e.g., vessels responsible for illegal discharges).

2.3.1.2 "Multi-solution" Approach

In the scope of the EASYCO project's predecessor (EASY project), MOHID lagrangian transport module started to be updated to include a multi-mesh functionality, allowing particles to move along different model domains / grids. The main advantage on this approach is the possibility of take use of high resolution models when and where available. Advantages of this functionality become even clearer when studying oil or inert drift incidents in interregional or transnational areas (very common in Atlantic Area, e.g. *Prestige* accident), where several different metocean model results are available in different regions. In these cases, the integrated use of metocean model results can become an advantage, increasing the coverage of the whole area. Other application for this multi-solution approach implemented in lagrangian module is the simulation of water quality (coliform bacteria) involving nested models for bathing waters, where usually a very high resolution grid (dx = 30m) is needed (Viegas et al., 2012). The approach gives the possibility of transporting the modeled lagrangian properties along the different nested models, instead of being confined to a single nested domain (which usually covers a small area). The execution of this feature implied an integrated grid interpolation for the whole domains used at the beginning of the simulation.

During EASYCO project, this feature has been improved and optimized, in order to increase operationality and execution performance. Hence, MOHID lagrangian module was updated to compute the needed interpolations on-the-fly, and limit these interpolations to a specific spatial area where lagrangian particles are present (instead of interpolating wide spatial domains).

This new development was rather important to the execution of the initial idea behind the polycentric modeling framework, in order to take advantage of several different operational modeling systems, and use them in an integrated way, feeding the different DSS already presented, and allowing the execution of the internal OIDM in a very short period of time (in a matter of seconds).

2.3.1.3 Floating Containers

A drift modeling of inert cargo containers was implemented on MOHID modeling system. The approach derives from the analytical solution of the basic movement conservation equation, as proposed by Daniel et al. (2002):

$$m\frac{\partial \vec{V}}{\partial t} + mf\vec{k}\Lambda\vec{V} = \vec{F}_a + \vec{F}_w + \vec{F}_r \qquad (1)$$

t denotes time, m the mass of container, V the horizontal velocity of the container, f the Coriolis parameter, k a unit vector in the vertical, F_a the wind drag, F_w the water drag, and F_r the wave radiation force.

Model only considers containers that do not sink, and assumes that containers are flat in the water and aligned with the wind.

Assuming a steady state, and neglecting the Coriolis parameter and wave radiation force, in the end MOHID computes the container's velocity from the analytical solution of previous equation, as implemented on a model developed by Météo-France (Daniel et al. 2002), but without assuming null water current (which means that the physics of the container simulated by MOHID takes into account the hydrodynamics on the submerged part, and the wind action on the emerged surface):

$$\rho_a C_a (100 - I)\left|\vec{V_a} - \vec{V}\right|(\vec{V_a} - \vec{V}) + \rho_w C_w I\left|\vec{V_w} - \vec{V}\right|\left(\vec{Vw} - \vec{V}\right) = 0 \qquad (2)$$

where ρ_a is the air density, C_a is the drag coefficient, V_a is the wind velocity. ρ_w is the water density, C_w is a drag coefficient, and V_w the water velocity. The end-user only has to define the immersion rate, water drag coefficient and air coefficient rate. These coefficients are based on experimental work (Daniel et al, 2002).

2.3.1.4 Drifting Buoys with Subsurface Drogues

MOHID lagrangian transport module was only prepared to simulate the behaviour of standard floating substances or substances that move in the water column based on density differences between the substance and the surrounding ambient (water). In order to simulate the movement of the drifting buoys with underwater / subsurface drogues more realistically, lagrangian module was updated, being now possible to define in MOHID a constant depth (which should be the depth of the drogue) relatively to the free surface, and simultaneously include a wind drag coefficient, which will be applied at the corresponding surface. Thus, MOHID is now able to simulate the transport of tracers / buoys influenced by the currents at a constant depth relatively to the free surface, and by a wind drag force applied at the surface. This update allows studying the trajectory of several types of buoys deployed around the world, which usually have drogues associated, in order to study the currents at specific depths. The referred feature can then be useful to better validate hydrodynamic models based on buoys trajectories coming from different sources, like ARGOS buoys.

2.3.1.5 Coupling to Wave Models and Horizontal Velocity due to Stokes Drift:

The coupling with wave models is relevant since some oil weathering processes can depend directly from wave properties (e.g. vertical entrainment / natural dispersion). Hence, "offline" coupling of MOHID lagrangian model with wave model results were made possible, using wave height, wave period, wave direction, or even wavelength. Following this, the Stokes drift component was also included in the modeling system. Stokes drift velocity (or mass transport velocity) is the average velocity of a particle due to the orbital motions induced by waves (Stokes, 1847), in the direction of wave propagation. This velocity is calculated for each particle, and velocity components are then added to the horizontal velocities of the particle calculated in MOHID.

The determination of the Stokes drift velocity (u_s, in m/s) in MOHID is mathematically represented as (Daniel, 2003; Longuet-Higgins, 1953):

$$u_s = a^2 \cdot \omega \cdot k \frac{\cosh\left[2 \cdot k (z-h)\right]}{2 \cdot \sinh^2 (k \cdot h)} + C \tag{3}$$

Where h (m) is the water depth, z (m) is the depth below surface, a (m) is the wave amplitude ($a = H/2$), ω (rad/s) is the wave circular frequency ($\omega = 2\pi / T$) and k (m^{-1}) is the wave number ($k = 2\pi / L$) for waves with height H (m), period T (s) and wavelength L (m). C is a depth independent term:

$$C = -\frac{a^2 \cdot \omega \cdot \sinh(2 \cdot k \cdot h)}{4 \cdot h \cdot \sinh^2(k \cdot h)} \tag{4}$$

The wavelength can be read from a wave model output, or manually defined by end user. Otherwise, MOHID internally calculates wavelength based on an explicit approximation of the wave dispersion equation, proposed by Hunt's method (Hunt, 1979).

The direction of the Stokes' drift is set equal to the local wave direction. If wave parameters H and T are not available from a wave model, they can be defined by the end-user, or calculated inside MOHID, using simplified internal models based on wind, previously implemented.

2.3.1.6 Vertical Movement of Entrained Oil:

Although a major number of oil spills take place at the surface, after the accidents the oil can be pushed down into the water column by the energy of breaking waves. Since its implementation, MOHID OIDM is able to compute the entrainment rate using Mackay, 1980 approach, or the classic method from Delvigne and Sweeney, 1988.

If the oil penetrates the water column after a surface spill, this means that oil will be subject to a vertical velocity, depending on the density differences and oil droplets diameter. The correct modeling of these processes forces the implementation of a three-dimensional modeling approach.

The first process to model is the entrainment of an oil tracer in the water column, which will be based on a random procedure. The probability of a tracer being entrained in the water column due to breaking waves is obtained from the instantaneous model "entrainment deficit" - difference between the theoretical fraction of dispersed oil estimated by one of the dispersion formulas previously implemented in MOHID, and the global mass fraction of entrained oil particles. Thus, the probability of a tracer entraining the water column is greater when the entrainment deficit is greater, i.e., when the difference between the global dispersion fractions obtained by the theoretical equations and the mass fraction of oil droplets in the water column is greater.

Once a particle is on the water column, the second process to compute is the specific depth position. The particle's depth is randomly determined between surface and the intrusion depth $D_i = 1.5\ H_b$. (D_i is the intrusion depth, and H_b is the breaking wave height) (Tkalich and Chan, 2002).

The next step is to decide the droplet diameter associated to the particle. Ideally, each surface particle entrained in the water column should then generate new entrained particles with different diameters following a droplet size distribution (Delvigne and Sweeney, 1988). For computational reasons, the surface particle, once in the water column, has only one diameter. One of three different methods can be chosen by the user for the determination of droplet diameter:

a) each particle is assumed to have a typical user-defined diameter (default option = 0.05 mm, as proposed by Delvigne and Sweeney, 1988);
b) each particle is assumed to have a constant diameter equal to half of the mass median droplet diameter (d_{50}) (as proposed by Spaulding et al., 1992)
c) a diameter is randomly assigned to each submerged particle based in the droplet size distribution profile. Five different droplet size classes equally spaced between a minimum and maximum droplet size are considered. Corresponding entrainment rates are then determined as proposed by Delvigne and Sweeney, 1988. In this approach, droplet sizes that tend to resurface in a short period of time, usually greater than the maximum droplet diameter (assumed to be d_{50}) are not considered. Also droplets below minimum droplet diameter (assumed as 10% of the diameter d_{50}) are neglected due to relatively small size.

Mass-median diameter can be determined as follows:

$$d_{50} = 1818\ E^{-0.5}\ (\mu/\rho_o)^{0.34} \tag{5}$$

Where E is the energy's dissipation rate per unit volume (J/m^3·s) (according to Delvigne and colleagues values are between 10^3 and 10^4). A value of 5000 was adopted. μ is the viscosity (mPa/s), and ρ_0 is the density of the oil (g/cm^3).

With this approach, at a given moment, an entrained particle will have a larger tendency to belong to a droplet size class with a higher entrainment rate.

The last step is the computation of the droplet buoyancy. The rising velocity will be based on the assumption that oil particles can be represented as spheres of given diameter and density. Thus, buoyancy velocity w_s will depend on density differences, droplet diameter d and water kinematic viscosity ν, as well as critical diameter d_{crit} (Soares dos Santos and Daniel, 2000).

$$d_{crit} = \alpha \frac{\nu^{2/3}}{|g'|^{1/3}}, \tag{6}$$

where g' is the reduced gravity (buoyancy)

$$g' = g\left(1 - \frac{\rho_P}{\rho}\right). \tag{7}$$

If the particle's diameter is greater than d_{crit} then

$$w_s = \frac{g'}{|g'|}\sqrt{\beta\, d|g'|} \tag{8}$$

else

$$w_s = \frac{g'}{|g'|}\left(\frac{d^2|g'|}{18\nu}\right). \tag{9}$$

The values for α and β defined by default are 9.52 and 8/3, respectively, as proposed by (Soares dos Santos and Daniel, 2000). However, β is probably too large, overestimating buoyancy velocity for larger diameters (Zheng and Yapa, 2000). Thus, a value of 0.711^2 can optionally be used for β, and since parameter α is directly obtained by solving equations (9) and (10) for d, in this case, a value of 5.47 is used for α (Liungman and Mattsson, 2011). Additionally to this two-equation approach, a new integrated approach (Zheng and Yapa, 2000) considering three different regimes (small spherical droplets, intermediate ellipsoid bubbles and large spherical cap bubbles) is presently being included in MOHID.

The droplet buoyant velocity is then integrated with the vertical advection and diffusion components (the advected vertical velocity – from the hydrodynamic solution – and the vertical turbulent diffusion velocity component). This means that in waters with higher turbulence, the buoyant velocity becomes less important.

2.3.1.7 Review on Formulations for Weathering Processes:

Although the update and review on formulations for oil spreading and weathering processes in MOHID is still a work-in-progress, at the moment of the edition of this work, a new additional method has been included for the simulation of emulsification process. Emulsification is responsible for the incorporation of water droplets in oil, changing substantially the oil viscosity and therefore its behaviour at sea. In fact, after evaporation, emulsification can be considered the most important transformation process (Fingas, 2008). Emulsions had been studied extensively in the laboratory and field, thus many facets of their formation are now known, and the basics of water-in-oil emulsification are finally understood and well-established (Fingas and Fieldhouse, 2006; Sjöblom et al., 2003). The new method adopted in MOHID was proposed and detailed in Fingas, 2011, and already implemented in (Berry et al., 2012). The approach is based on the determination of stability class from extensive empirical data obtained in previous studies, and then related to an emulsion state (stable emulsion, meso-stable emulsion, entrained water and unstable mixture). The proposed model has the oil starting viscosity, its asphaltene and resin content and its density as the most mathematically relevant factors when determining stability class. This formulation is considered to be very much more accurate than the old methods (Fingas, 2011).

3 Applications and Results

In this section, different types of examples can demonstrate the capabilities of the updated MOHID OIDM, and also how this model, integrated with the developed polycentric framework, can improve the operational capacity in prevention and response strategies in the Atlantic zone.

3.1 Simulating Drifting Buoys in the Tagus Estuary Mouth

Drifting buoys were released in Estoril Coast. This is a mixture area within the Tagus estuary, with several stream discharges, small harbours and marinas, tide, ocean and river influence, generating specific hydrodynamic circulation patterns and providing different water quality and hydrodynamic fields along space and time (some of them can change in tide based regime) – see Figure 1 and Figure 2.

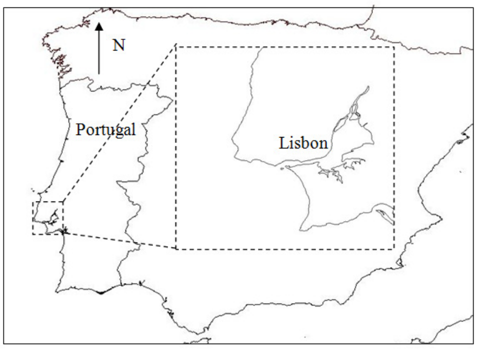

Figure 1 - Iberian Peninsula highlighting Tagus estuary location near Lisbon

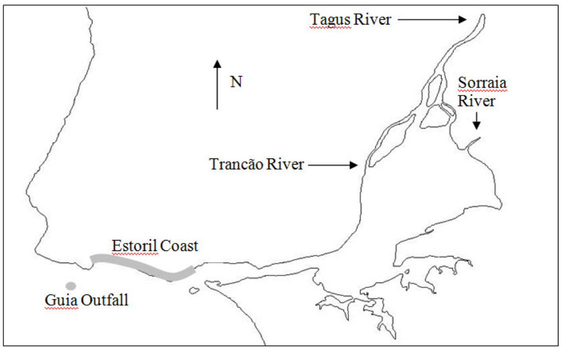

Figure 2- Tagus estuary and the Estoril Coast

Due to its location and proximity to the open ocean waters, the water residence time in Estoril Coast can be considered small. Inside Tagus Estuary the residence time is in the order of one month, but in the case of the area of study (at the estuary mouth) it can be in an hourly scale and change with a tide cycle. Due to this short residence time in the area of study, surveys were done with a continuous in-situ monitoring, avoiding that buoys got overtaken on fish nets, or got out from the study area (to the Atlantic Ocean waters).

The metocean data used was available from other ongoing projects and research activities, where high resolution models were implemented and validated for that site (Viegas et. al., 2009; Viegas et al., 2012).

The drifting buoys used were MD02 surface drifters developed by ALBATROS Marine Technologies, Palma de Mallorca, Spain. They are small and security oriented buoys, having flexible closed cell PE foam buoyancy. Being a coastal buoy, its position is obtained by a GPS module, and it has a GSM data transmission system. In these field exercises, a drogue with different sizes was attached to the drifter. This drogue was kept underwater at a constant depth, depending on the size of the drogue. The purpose of this drogue was to reduce the direct influence of wind on the buoys trajectory (see Figure 3). Therefore, the application of a drogue minimizes the wind drag effect on the surface buoy.

Figure 3 – drifting buoy with underwater drogue

The operational drift modeling system / OIDM was used as a tool to simulate and fit the modeled trajectories to the ground truth trajectories from experiments, and also to prepare and select release locations and time periods for buoys and dyes. Different scenarios and release points for each survey were simulated in a matter of seconds. During this model simulation analysis, it was possible to observe that small differences on time and local releases could have different results. A delay of 10 minutes or a deviation of one or two hundred meters from the planned point could be enough to produce a different behaviour of the buoys, which supports the idea of “Lagrangian chaos”.

The influence of buoys configuration and ocean-meteorological conditions in the buoys trajectory were also tested. Several different drifting buoys were released under different meteorological and hydrodynamic conditions. Hence, the field work performed was used to model calibration and validation. In the experiments performed, an optimal wind drag coefficient between 1 and 2% was found (Figure 4).

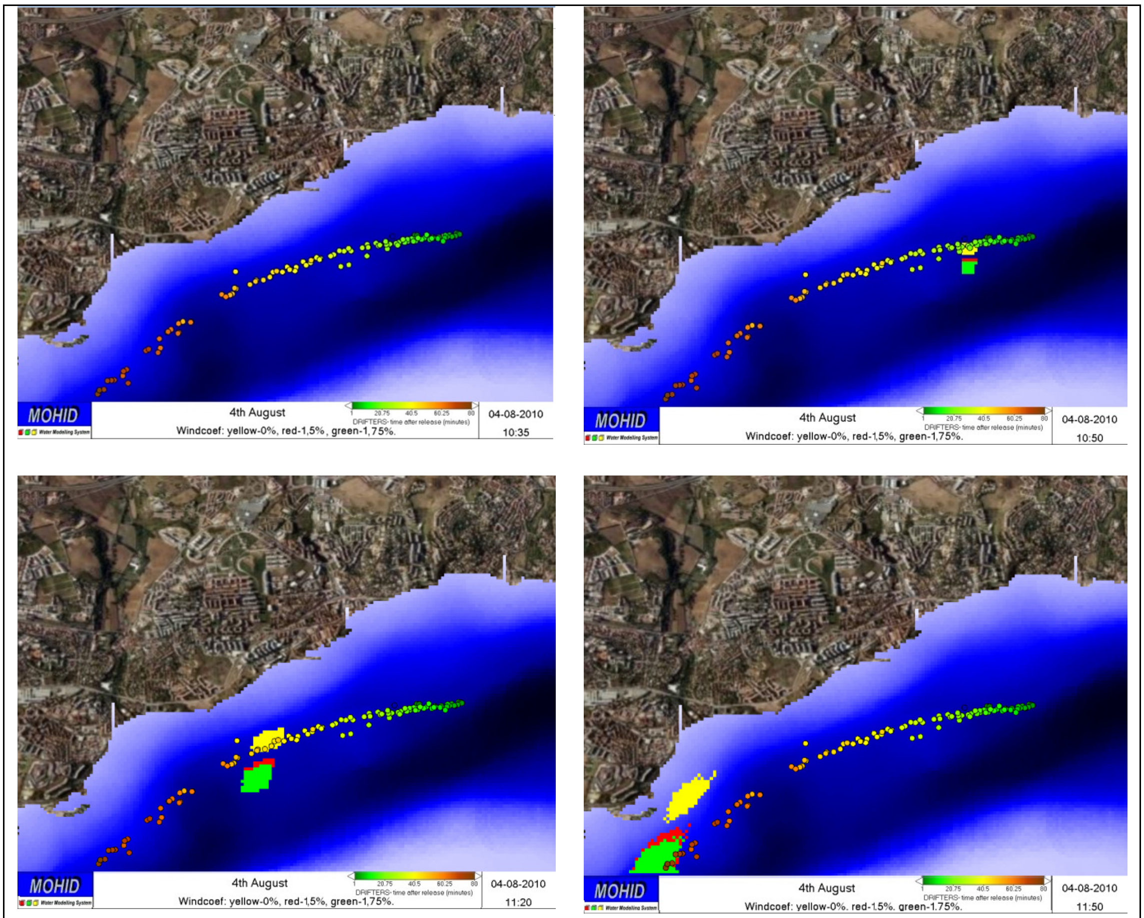

Figure 4 - Buoys survey, on 4th August 2010: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations in 4 different instants, considering different wind drag coefficients: 0% (yellow polygons), 1.5% (red polygons), 1.75% (green polygons)

Data from 4th August survey were additionally used to test and compare backward and forward model runs against measured drifter data (Figure 5). As can be seen, both model runs present similar average positions, but they differ in particle “cloud” areas due to turbulent diffusion, increasing more in backtrack run, near the buoys release position (as a result of higher current velocities at this point). Initial and final positions of backward and forward model runs are coincident with measured data, although the trajectories have some differences.

Figure 5 - Buoys survey, on 4th August 2010: black dots - measured buoys position along time; red polygons – particles from backward model run; green semi-transparent polygons – particles from forward model run

Drift model results using atmospheric models with different spatial resolutions were also compared (Figure 6). Two different scenarios were analysed considering the two different atmospheric forecasting models available: MM5 (with a resolution of 9km), and WRF (with a resolution of 3km). Both atmospheric models are implemented by IST to the study case site. Significant differences were found between the two atmospheric models evaluated. Drift model results compared better with data using WRF – 3km, as expected.

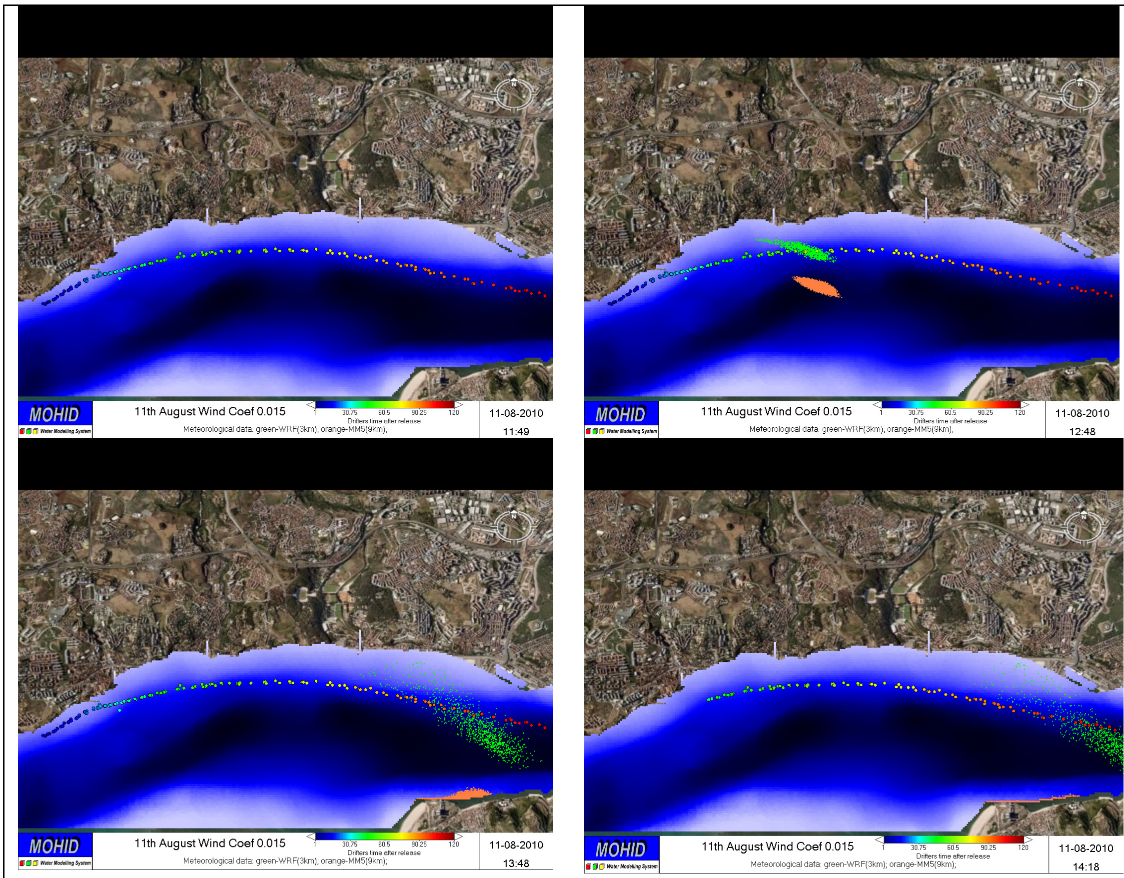

Figure 6 - Buoys survey, on 11th August 2010: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations at 4 different instants, considering wind forcing: WRF (3km) in small green dots, MM5(9km) in small orange dots

Several other exercises were successfully performed in order to calibrate the particle turbulent diffusion based on the "spreading" of a number of drifters initially released at the same time and location.

Another interesting result was the validation of buoys under a water mass front episode (fresh water coming from Tagus river, and salt water from open sea). Buoys tend to drift along the front, explained by the differences in density between both water masses, generating a tidal convergence front which "traps" the buoys there – Figure 7.

Figure 7 – Convergence of different water masses, recorded on 27-8-2010, with buoys "trapped" in the water-mass front

Since a local 3D hydrodynamic model was used to feed the drift model, it was possible to evaluate the ability of both models to reproduce this front. In terms of hydrodynamic modeling, results appear to simulate the front in agreement with the drifting buoys position (Figure 8). This was only possible due to the fact that this is a 3D fully baroclinic model, with a very high spatial resolution.

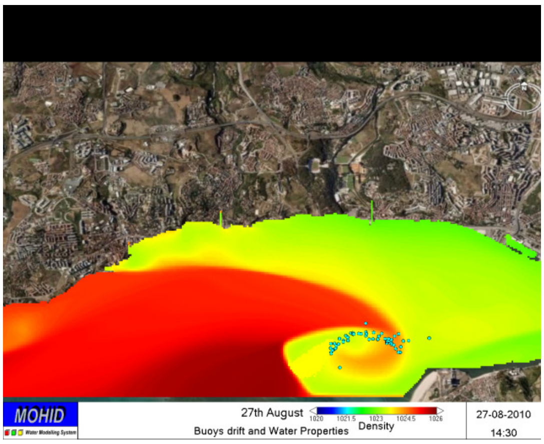

Figure 8 – Instant drifting buoys position and modeled water density during the front

In terms of drift modeling for this specific field experiment, results also showed a good agreement between observed and modeled trajectory (Figure 9). Modeled results were based on different particle turbulent diffusion velocity parameters (*VARVELHX*, as is called in MOHID, which is a water velocity multiplying dimensionless factor, in order to parameterize a correct standard deviation of the particle random movement velocity). At the beginning of the exercise the differences were small, but from the second hour on the difference became visible, and it was possible to see that larger diffusion lead to a larger simulated plume. For this survey, the value for turbulent diffusion parameter that better represented this behaviour is the 0.02 for *VARVELHX* (orange in image). However, 0.03 also seemed to be in good agreement with data, especially for the first moments. Greater values usually create an overestimated dispersion not observed in the developed surveys; smaller values produce a tracers "cloud" area too small to represent the variability of the drifter's behaviour.

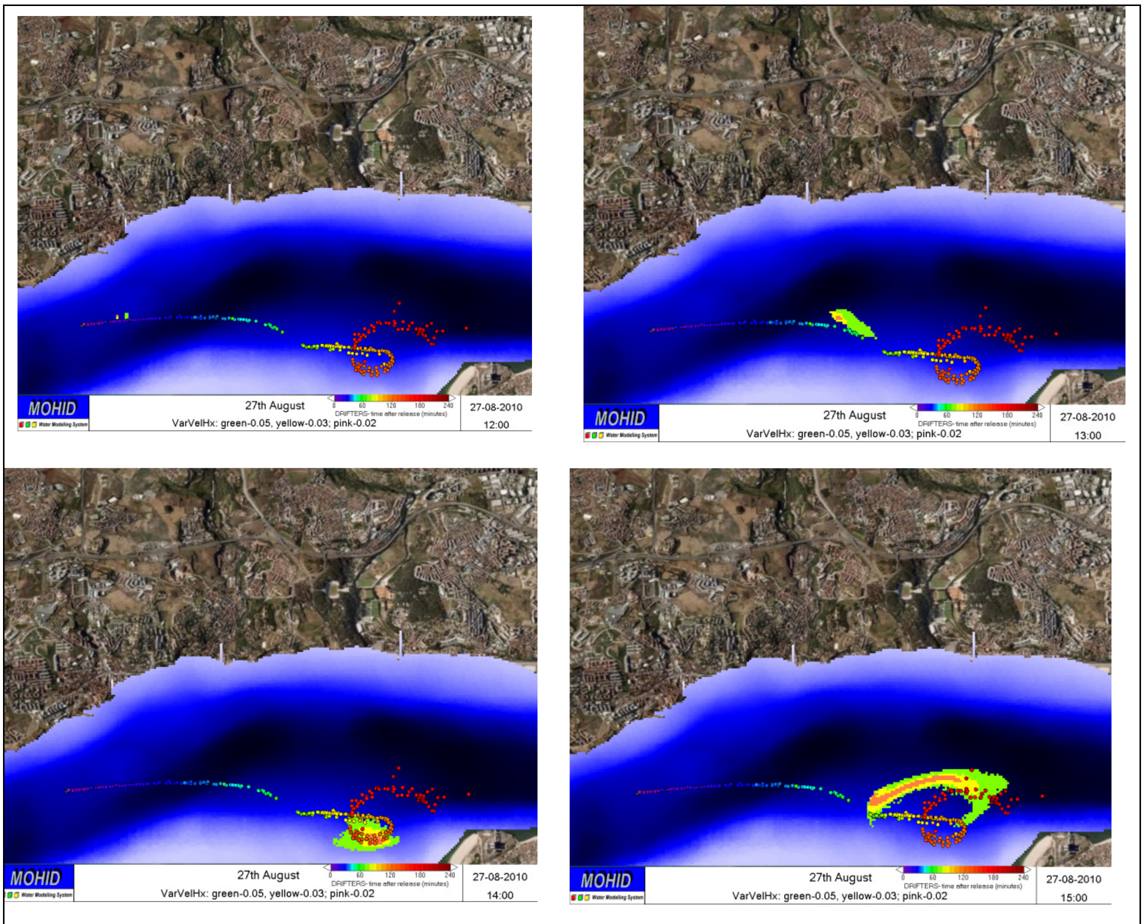

Figure 9 - Buoys survey on 27th August: measured data (buoys position represented by markers with color scale representing time after release – dark green is immediately after release) vs. MOHID drift simulations at 4 different instants considering different diffusion coefficient *VarVelHX*: 0.02 (orange polygons), 0.03 (yellow polygons), 0.05 (green polygons)

More field surveys were analysed and tested for different turbulent diffusion conditions, all of them leading to the same values and conclusions for the turbulent diffusion.

3.2 Oil Spill Exercise in Sesimbra (South of Portugal)

On 9th May 2012 a marine pollution response exercise "Xávega 2012" was held off Sesimbra, Portugal. The exercise was organised by the Portuguese National Maritime Authority (Autoridade Marítima Nacional-DGAM), with the aim of ensuring the measures in place - search and rescue, assistance for ships in distress, maritime pollution prevention. The scenario created was a ship-to-ship collision between two merchant vessels followed by a crude spill.

MOHID OIDM was applied in forecasting the scenarios considered, including a 500 m^3 oil spill (IFO 180). Different simulations were made, considering different wind drag parameters (Figure 10). Metocean data used was derived from the data sources made available at EASYCO data Service. In this case, different wind drag coefficients did not produce significant differences in model results, as modeled oil tracers seemed to appear almost in the same position. This was in fact explained by low wind (below 3 m/s) forecasted for this day, which was in fact confirmed during the exercise.

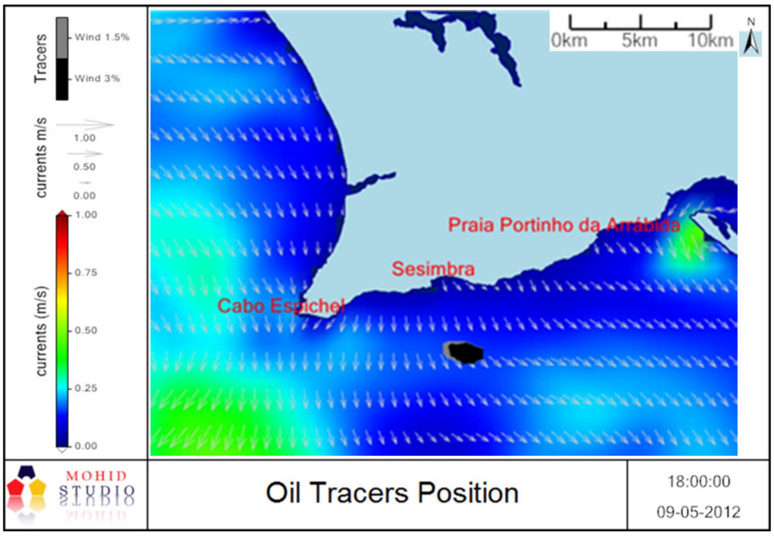

Figure 10 – Modeled oil tracers instant position: tracers with different wind drag coefficients showing similar positions (3% = black polygon; 1.5% = grey polygon)

3.3 Using MOHID Oil / Inert Spill Model Together With the Decision Support Systems

MOHID OIDM was effectively integrated in the different developed DSS. Most of the DSS became operational in 2012.

EASYCO web bidirectional tool was published in the project website (Instituto Superior Técnico, 2012a), and the EASYCO Data Service is now composed of several different data providers for the Atlantic Zone (
Table 2 and Figure 11). Figure 11 shows a visual representation of sea surface temperature simulations from different data providers, studying different areas in different scales. A continuity in temperature can be seen in the different models, and the visual differentiation is possible due to different opacity levels for each model.

Table 2 – List of operational modeling data sources included in EASYCO data service

Institution	Model & Domain	Institution	Model & Domain
IMI	ROMS – NEAtlantic	IST	MOHID – Portuguese Coast
IMI	ROMS - Connemara	IST	WW3 - Portugal
IMI	SWAN – NEAtlantic	IST	MOHID – Tagus Mouth
IFREMER	MARS – Biscay Bay	IST	MM5 – Portuguese Coast
Puertos del Estado	POLCOMS - Iberia	IST	WRF – Tagus Mouth
Meteogalicia	WRF – Galicia	IST	MOHID –Madeira
Meteogalicia	WW3 - Iberia	IST	WRF - Madeira
Meteogalicia	WWE - Galicia	Azores Univ.	MOHID – Azores Central Group
MERCATOR	OPA – N. Atlantic	Azores Univ.	MM5 - – Azores Archipelago
NOAA	GFS - World	Azores Univ.	MM5 – Azores Central Group

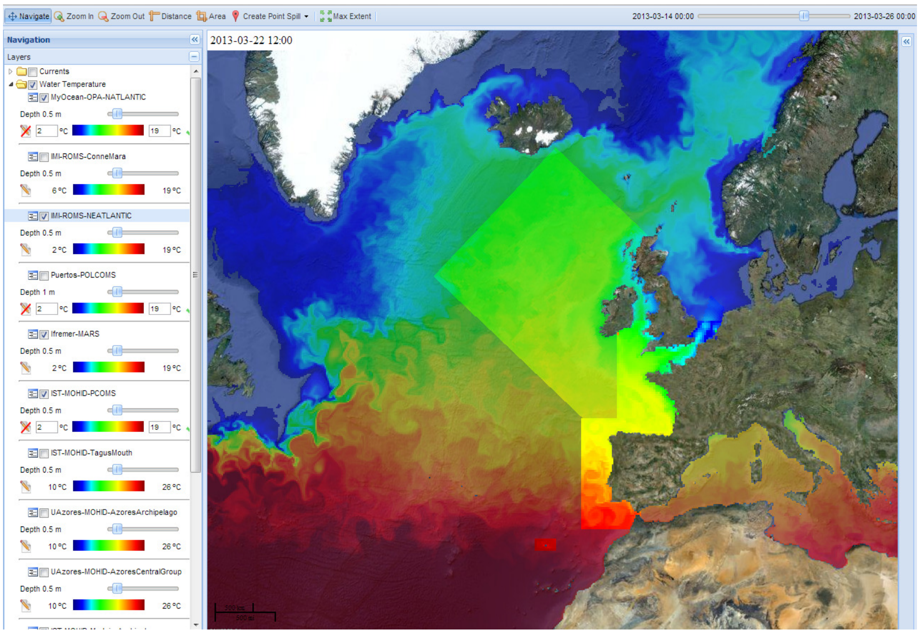

Figure 11 –Visualization of sea surface temperature of global and regional models from different data providers in EASYCO Web Bidirectional Tool. Same color scale is used, with different opacity levels.

The same methodology and web interface was applied with other metocean data remote services (and not only with EASYCO Data Service) and in other regions, namely the Brazilian coast – (Instituto Superior Técnico et. al, 2012b), in a joint effort promoted by IST, Hidromod and the Azores University. The web bidirectional tool has revealed to be a powerful integrative WebGIS tool to visualize and explore 3D model results.

In the first year of implementation (

Table 3) specifically, between 9th February and 24th October 2012), in general, the success rate of the different procedures involving EASYCO server was reasonable, although the downstream procedures that were executed (as the generation of data, which feeds directly EASYCO WebGIS) usually had lower success rate, mainly because they depend on the success of prior processes. The high number of files and data sources processed in EASYCO server also increases the possibility of execution errors.

Table 3 – EASYCO Server performance for the different procedures involved, during 2012-02-09 and 2012-10-24

EASYCO Server Procedure	Performance
Server State	95%
Data Service State	81%
Execution of Download & Conversion	79%
Effective period with model data	72%
Generated data	52%

Server state failures (5%) were motivated by low disk space. Although the system has been developed to continue working even when upstream procedures have failed, if any execution fails when downloading, converting, or simply because data providers don't provide models when expected, effective period with model data is reduced, and then, consequently the generated data to supply WebGIS is even worse.

No monitoring activities have been reported in the Brazilian WebGIS application, but users have experienced much lower failure rate, mainly because server procedures are better isolated, with significantly less number of files and data sources to be managed.

In relation to OSS, this software was released to partners during ARCOPOL project, and presently software interface is being under updates and improvement in terms of new features, design and correction of bugs, under the scope of ARCOPOL PLUS project. This software is also using the developed MOHID OIDM and EASYCO data service. Apart from an initial testing stage where some problems were found in the download from internet connection to EASYCO Data Service, the system is now running stable. Meanwhile, it has been designed to allow connection to other metocean data remote web services as well. The most recent version of this software – now called Aquasafe Oil Spill Simulator (although is not limited to oil spills) – has been recently implemented by Hidromod in different regions, including an operational oil spill forecasting system for the Strait of Malacca, in the scope of a demonstration project promoted by IMO. Indeed, both DSS previously mentioned are now fully integrated in Aquasafe Platform (Hidromod, 2013; IWA, 2009).

This system is revealing a good stability (due to the fact that it is a desktop / laptop application) and strong performance in visualization and running MOHID OIDM (Figure 12). Since this software has advanced options in the visualization and analysis of results related to oil weathering processes and properties, as well as an exhaustive oil products database (based in ADIOS 2 internal database), this DSS has shown that it is well suited for technical and professional uses, like decision makers in oil spill prevention and response activities.

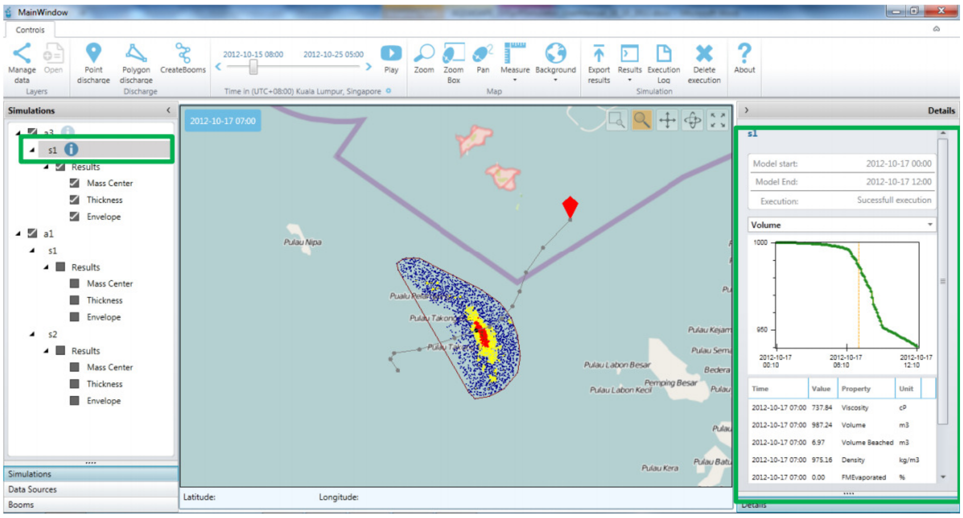

Figure 12 – OSS: example of displaying oil spill results –particles instant oil thickness (here displayed in a discrete color scale), instant slick envelope, center mass trajectory (in grey color) and oil weathering properties and processes evolution.

In relation to Dynamic Risk Tool implementation, this risk management tool was operationally applied as pilot project in the Portuguese Continental Coast, also making use of metocean data sources used in EASYCO data service. In this case, only one data source per environmental property is used. Presently, the application is configured to import data from IST's meteorological model in MM5, IST's wave model in WW3, and IST's Portuguese Coastal Operational System (PCOMS) in MOHID. Risk levels are generated in real-time, and the historic results are kept in a database, allowing later risk analysis or compilations for specific seasons or regions, in order to obtain typical risk maps (Figure 13).

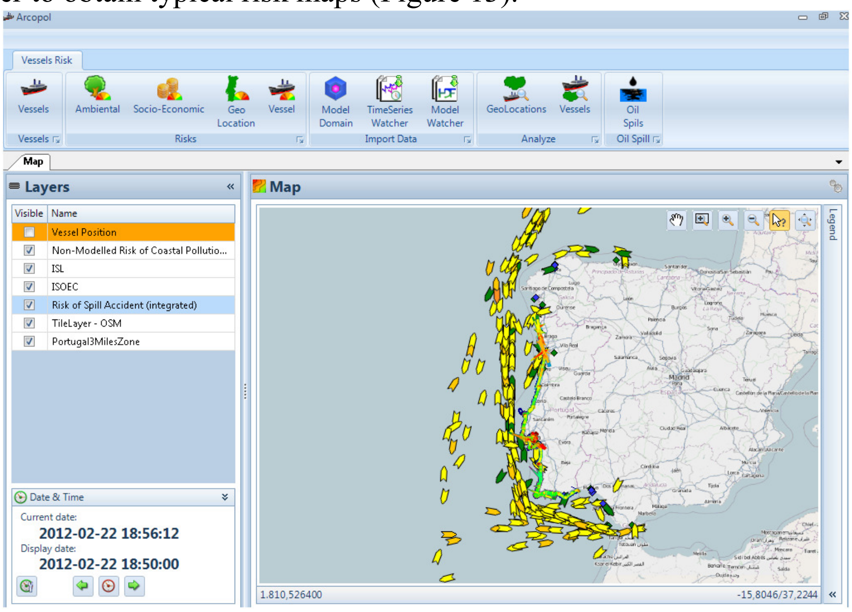

Figure 13 – Dynamic Risk Tool: Integrated Risk of Spill Accident represented in the vessels (green color = low risk; red color = high risk); Shoreline contamination risk represented by a line in the shore (green line = low risk; red line = high risk)

With the possibility of analyzing real time risks generated by a specific vessel, or finding the vessels posing higher risk to a specific site, this application can be used in the risk monitoring on a specific site (e.g. a port). This software can also be used to monitor and isolate risks coming from specific vessels (Figure 14).

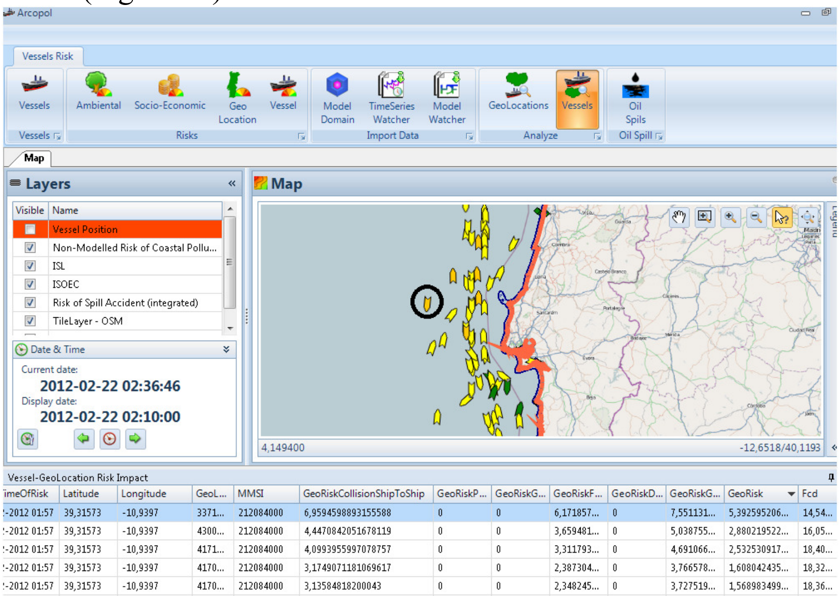

Figure 14 – Dynamic Risk Tool: Integrated Risk of Spill Accident represented in the vessels (green color = low risk; red color = high risk), and table representation of shoreline contamination risk values posed by one particular vessel selected

3.3.1 Operational Support to Incidents

All the developments pursued in this work have been followed by Marine Pollution Response Service from Portuguese Maritime Authority (DGAM), where active cooperation has been helpful for a better understanding of their needs, or even finding eventual software limitations and improvements. During this cooperative approach, an incident came up on 6th March 2013, involving *Harbour Krystal* tanker. This vessel suffered a fire & explosion 13 miles off the Portuguese Coast, Southwest from Cape Espichel, when it was carrying 8000 tons of naphtha. After the incident, a crew member of the vessel was missing, although no spill was recorded.

Since this incident occurred in the area of implementation of the modeling infrastructure in the Atlantic, generation of spill forecasts in real time using OSS was possible, and results were exchanged with the Portuguese Maritime Authority. Simulated forecasts for a possible naphtha spill have shown approximation of the coast (although most of the product would rapidly evaporate and disperse in water column), should there be a spill (Figure 15). In a case like this, diverting the vessel to take shelter in a port of refuge can be a wise solution. Indeed, after technical inspections, Harbour Kristal received the authorization to take shelter at Setúbal Port on 7th March.

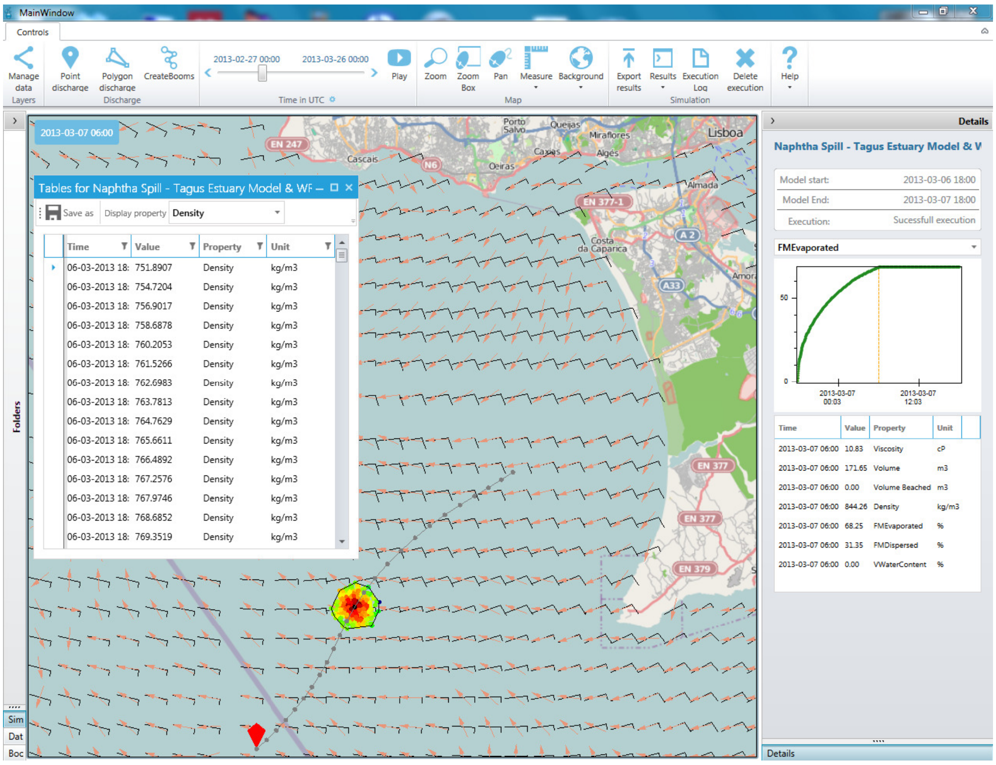

Figure 15 – Simulation of *Harbour Krystal* eventual spill (naphtha) using OSS

Nevertheless, after the implementation of the developed system (since 2012), no data (aerial observations or satellite imagery) was obtained for possible validation of the tools implemented, in respect to the oil spill modeling system.

4 Discussion and Outlook

The approach followed in this work regarding the multi-solution feature in lagrangian particle transport module, has been tested in the different DSS. Its major advantages are related to the increase of versatility in MOHID particle tracking system when dealing with integrated metocean data with different scales (like nested models). This can be interesting in areas where several different metocean forecasting systems are available, and processes studied (like marine pollution) can assume an interregional or transnational dimension – like the EU Atlantic Area.

Since MOHID OIDM has been successfully integrated in several different operational DSS, some of the updates in model were already successfully tested in a few real situations and real time forecasts. Assessing these systems performance in real situations, is always desirable in order to verify their adaptability to new situations. Every incident always presents something new and unexpected in terms of modeling approach, putting existing models on test, and pushing forward research and development activities. Hindcasting and then showing accurate simulations for past incidents where final results are already known is sometimes the only possible way to properly validate a model, but the million dollar question is: will the modeling system be prepared for the next real accident?

During the *Prestige* accident, MOHID forecasted simulations were an example of real time “blind” validation, and where model adaptability and interoperability was put on test against ground truth data. However, some of the latest updates in MOHID presented in this paper require much more testing and validation when possible. This applies mainly to floating container modeling, and some oil processes, such as vertical movement of entrained droplets, or the new implemented emulsification algorithm. Active work is already in progress, regarding the calibration and validation of MOHID's hydrodynamic, turbulence and oil weathering processes, with specific exercises conducted in a meso-scale flume tank. Nevertheless, probably only real time forecasts of future incidents will be able to effectively check performance of MOHID OIDM as an operational modeling system supporting DSS.

The field exercises with drifting buoys highlighted the importance of using high-resolution and quality metocean modeling data as input to the oil and inert drift models. The same applies to atmospheric models: significant differences were shown in model simulations with different atmospheric forcing (MM5 9km vs. WRF 3KM), which was probably increased by the fact that the case study was near a complex urban area. Particles turbulent diffusion and influence of wind drag coefficient in model results were also studied, where low wind drag coefficients were found for the studied case (1-2%), probably due to a good vertical discretization in the surface layers, in the hydrodynamic model used. Backtracking feature was also tested and compared with field exercises, showing good agreement with forward running model.

The overall performance of the EASYCO Sevice has been positive, although experience has shown that it can be better in web servers with less workload (as the case of the Brazilian WebGIS application). EASYCO webserver has to download, convert, index and generate several different types of data sources. The way to avoid failures maintaining the same polycentric modeling infrastructure would be to improve server hardware performance, increase log and report automatic procedures, implement redundant services, or simply reducing the number of server procedures involved. This could be achieved if some of server procedures were distributed by local servers, or data providers.

OSS is revealing strong potential to be used in different areas and applications. This DSS was also tested in an emergency incident, where simulations were possible and timely exchanged with responsible maritime authorities. Integration of WebGIS application and OSS with Aquasafe platform will probably increase significantly the future number of end-users. Current developments integrated in ARCOPOL PLUS include the possibility of import satellite-detected oil slicks under EMSA's CleanSeaNet operational service (CleanSeaNet is a near-real-time satellite-based oil spill and vessel monitoring service operated by EMSA) (EMSA, 2011), and being able to run simulations forward and backwards based on the detected slicks.

The Dynamic Risk Tool has been tested and used several times in real time. However, further work will include sensitivity analysis to different environmental conditions, ship traffic conditions, and drift modeling options. This system is also being updated in the scope of ARCOPOL PLUS where among other things, a post-processing system / hindcasting module will be included (exactly to simulate different past scenarios), as well as a possible incorporation of individual ship information (increasing accuracy in the quantification of probability of spill accident) from EMSA's Ship Risk Profile in THETIS system. This system will also be installed and applied in the Galician Coast.

Finally, all these decision support systems, and MOHID OIDM itself, provide a "best guess" solution / trajectories. In the future, efforts should be done to quantify model uncertainties under stochastic methods, being able to, in the end, supply decision makers with "minimum regret" solutions, as well as probability maps for the modeled scenarios.

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