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ARGOMARINE: A NEW OIL SPILL EARLY WARNING SYSTEM INTEGRATING MODELING, *IN-SITU* AND REMOTE SENSING

FLÁVIO MARTINS
ISE/CIMA, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal

JOÃO JANEIRO
CIMA, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal

SURUJ BABWAH
CIMA, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal

NATHALIE VERELST
CIMA, University of Algarve, Campus da Penha, 8005-139 Faro, Portugal

MICHELE COCCO
Parco Nazionale Arcipelago Toscano, Via Guerrazzi 1, I-57037 Portoferraio, (LI)-Italy

INTRODUCTION

Short Sea Shipping is a central part of the logistics chain for transport in Europe, delivering nearly 40% of the total tonne-kilometres per year, only superseded by road transport with 44%, Ferraro *et al.* [1]. Between 1995 and 2004 the transport in this sector increased by 32% in EU-25 countries, and while increase in sea transport can be desirable from an economic point of view, it places a growing burden on the marine and coastal zone environment due to the risk of pollution. The Mediterranean Sea is particularly exposed due to its intense oil transport. It gives maritime way to Europe, for the oil produced in the Middle East, in Northern Africa and in the Caucasus. According to the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea [2], 360-370 million tons of oil and refined products is transported annually through Mediterranean Sea, representing 20-25% of the world total. Due to this the Mediterranean Sea is often quoted as one of the places in the world with the highest risk of oil pollution.

Decision-makers need efficient pollution monitoring and forecasting systems providing continuous and reliable real time access to all available observations as well as forecasts of sea variables and oil spill fate for the area of interest. These systems must seamlessly integrate all data and must have software for analysis, decision-support and intervention planning. The ARGOMARINE system is a pilot study implementation of this concept, currently under construction for the Tuscany archipelago (Italy). The top control is carried out by a Marine Information System (MIS) consisting of a network for data storage, data mining and analysis, decision-support, data warehouse and a web-GIS portal. The communication relies on an Integrated Communication System (ICS), developed to ensure reliable and efficient data transmission from different sensors and models to the MIS. When fully operational the system will be receiving data from the modeling system and also from Synthetic Aperture Radar (SAR) images, airborne Hyperspectral/Thermal Imaging, AUV/Glider mounted sensors and Electronic Noses. For this project a consortium was created consisting of nine top research institutions in Europe: National Technical University of Athens, Greece; National Research Council – Institute of Information Science and Technologies, Italy; Nansen Environmental and Remote Sensing Center, Norway; Environmental and Marine Research Center – University of Algarve, Portugal; Sciensive Technologies Limited, UK; National Maritime Park of Zakinthos, Greece; Joint Research Center – Institute for the Protection and Security of the Citizen; NATO Undersea Research Centre and National Park of the Tuscany Archipelago, Italy, the coordinator.

In this article a global perspective of the ARGOMARINE system is given, followed by a detailed description of the mathematical models being developed for sea and oil spill forecasts.

The ARGOMARINE SUITE OF SYSTEMS

Information and Communication Systems

The core of ARGOMARINE is the Marine Information System (MIS), it collects, converts, store and process data from a large set of different data sources, including remote sensing data, in situ data and mathematical model results. The communication network is managed by the Integrated Communication System (ICS) as represented in Figure 1.

The MIS possesses tools for data storage and retrieval, data manipulation and analysis, as well as for graphical presentation. The interface is divided in two parts: The HI (Human Interface) used by the operator and the DEI (Data External Interface), for interfacing the MIS with other networks/structures such as GMES services and systems. The DEI is developed using a web-based GIS portal. The main functions of the MIS are: analysis of signals coming from external data sources, data storage in data warehouse, GIS connection, data mining algorithms, management of a control console with interactive panels and implementation of decision Support System routines. MIS is being designed looking to a robust fault tolerance: some entry-level servers, distributed on the territory will enable a decentralization of the data storage and the calculation. The MIS decisional and storage architecture will be structured into levels: a first level allow the handling of global information, a second pre-computation level sorts which information has to be written in the data warehouse and finally a third “data warehouse” level extracts information by data mining techniques. This architecture will integrate robustness and reliable calculation and, in order to support catastrophic events, it will be parallel and redundant as well as able to reallocate computational tasks from one computer to other as a consequence of the workload, or drawbacks.

The ICS is a communication structure with the objective of transfer data between passive and active actors presents in the geographic area to be monitored. It will be structured as a network where the nodes that can be associated to the functions: informative Intranet flow, informative flow towards other nets and capability of simple elaborations of the collected data. This last function permits to use the net of the integrated informative system at its best as a nervous digital system able to adapt quickly to new situations and to send alarms in case of anomalies.

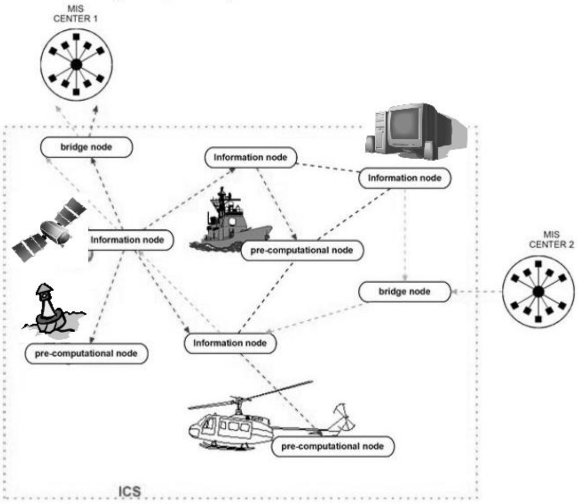

Figure 1: The ARGOMARINE global structure: Remote Sensing, In-situ Sensors and Mathematical Models connected through the ICS to MIS centers.

From a logical point of view, the pre-computational nodes are placed between the informative nodes and the bridge nodes. Pre-computational nodes will get raw-data flow from the informative nodes. They can be located in fixed or mobile positions, the last by a suitable data routing. The mobile nodes can be set up by portable devices like mobile phones, palm tops etc. or computers installed on jeeps, boats etc.

Remote Sensing

Synthetic Aperture Radar (SAR) images from many of the available satellites will be used (ERS-1, ERS-2, ENVISAT-ASAR, Cosmo-SkyMed, TerraSAR-X). Satellite SAR images can be obtained day and night and independently from the cloud coverage and weather conditions, furthermore they are capable of showing not only oil spills, but also ships. This capability will be exploited in combination with shore-based AIS to obtain a complete picture of shipping density and infer oil spill risks. Oil spills are obtained indirectly from SAR images by changes in sea roughness. However dark areas in the pictures may also be caused by other phenomena, like locally low winds, currents or natural sea slicks called “look-alikes”. The DopRIM model, Johannessen *et al.* [3], and the CDop model Collard *et al*. [4], will be implemented and results incorporated in the oil spill detection algorithm.

Hyperspectral Compact Airborne Spectrographic Imager (CASI) and Thermal Airborne Broadband Imager (TABI) will be mounted on helicopters and tested in the scope of ARGOMARINE. These RS systems cannot replace satellite platforms because they cannot be operated continuously but offer a highly detailed view over a specific area, complementing satellite imagery during surveillance and are crucial during accidents. The CASI hyperspectral sensor acquires digital spectral data in the visible and near infrared wavelengths. The method is based on the simultaneous use of spatial and spectral information by extended mathematical morphology operations. It also uses signal processing tools to correct aircraft position and movement errors. With this method CASI has proved to be capable of defining the shape of slicks with high contrast and spatial resolution, moreover it is also able to penetrate to depths of 20-30 m in clean water to see the submerged oil Salem [5]. The TABI sensors will acquire infrared images with refractive optics, uncooled and with a thermally stabilized micro bolometer, showing a resolution of 0.1ºC. Thermal imagery will be preprocessed, i.e. georeferenced, filtered, enhanced and transformed to equivalent temperatures. The resulting temperature differences will lead to potential oil spill formations and will permit to infer the thickness of the oil slick, Maya [6].

In Situ Data

Chemical (electronic nose) sensors are rather selective for hydrocarbons and oils Sobanski *et al* [7]. In ARGOMARINE a new type of sensor will be developed to rapidly detect volatile chemicals (VOCs) associated with oil and fuels in the sea water. A new version of the Scensive (Bloodhound® ST214) will be developed, it is a 14 sensor instrument (13 outputs and 1 internal sensor) with an integral flow system to allow sampling to be done in transient sniffing mode. The sensors are all pure semi conductive polymers deposited electrochemically on interdigitated gold on silicon transducers and the system is run by proprietary electronics.

The electronic nose sensors will be mounted experimentally in a fixed buoy for testing after which will be installed in an autonomous underwater glider. The glider will be of the Folaga type which combines gliding capabilities with active propulsion Alvarez *et al*. [8]. The system will be useful in two different types of missions: surveillance (patrolling) and accident assessment.

MATHEMATICAL MODELING

The modeling suite is composed by a 3D nested system of hydrodynamic models, a wave model and an oil transport and weathering model based on a Lagrangian transport model. The system is linked upstream assimilating data and receiving boundary conditions from external operational data products currently running for the global Mediterranean Sea: The system is linked downstream via the ICS to populate the MIS databases.

Hydrodynamic Model

The hydrodynamic model used is the “Hydrodynamic Module” of the MOHID modeling system Martins *et al* [9]. It is a 3D baroclinic model that solves the shallow water equations with the Boussinesq approximation:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial \left(u_i u_j\right)}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p_{atm}}{\partial x_i} - g\frac{\rho(\eta)}{\rho_0}\frac{\partial \eta}{\partial x_i} - \frac{g}{\rho_0}\int_{x_3}^{\eta}\frac{\partial \rho'}{\partial x_i}dx_3 + \frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j}\right) - 2\varepsilon_{ijk}\Omega_j u_k \tag{2}$$

Where u_i are the velocity vector components in the Cartesian x_i directions, η is the free surface elevation, ν the turbulent viscosity, and p_{atm} is the atmospheric pressure. ρ is the density and ρ’ its anomaly. The last term in equation 2 represents the Coriolis apparent force: Ω_j is the Earth rotation and ε_{ijk} the Kroneker operator.

Density is computed by the UNESCO EOS-80 equation of state from the salinity (S) and temperature (T) values computed by the model. S and T are transported using the same methods used for momentum.

The equations are discretized using the finite volume method on a structured grid and solved by the ADI semi-implicit technique. The vertical coordinate in MOHID is of a generic type, meaning that several types of coordinates can be used, such as sigma, Cartesian, Isopycnic or Lagrangian. This is accomplished directly by the use of the finite volume method instead of using coordinate transformations, as explained by Neves *et al.* [10]. Initial and boundary conditions will be obtained from currently running global Mediterranean operational models: Initial and Boundary values of S, T, u_i and u_j from the MFS model (http://gnoo.bo.ingv.it/mfs/) while meteorological will be imported from the SKIRON system (http://forecast.uoa.gr/). The initial free surface elevation η will be obtained from MFS and the boundary values from FES2004 (http://poc.obs-mip.fr/pages/research_topics/gravity_waves/waves.htm#fes2004). The boundary conditions will follow the general method proposed by Leitão *et al* [11], i.e. a Flow Relaxation Scheme is applied to S, T, u_i and u_j combined with a radiation scheme for η. The baroclinic mode use also a radiation condition with a constant celerity typical of the internal waves (obtained from the first baroclinic Kelvin mode).

Lagrangian and Oil Spill Models

The Lagrangian transport model computes the evolution of discrete water (or oil) masses (referred hereafter as particles), along lagrangian coordinates using the velocity fields produced by the hydrodynamic model, complemented by the wind and wave fields. Besides this direct influence of winds and waves in the particles movements they are also influencing indirectly the movement through the hydrodynamic fields. The turbulence contributes both to the displacement and to the spreading of the particles: the vortices larger than the particle (the Nyquist wavelength) will induce velocities while those smaller than the particle will contribute to its spreading. The implementation of the movement follows the method of Sullivan & Allen [12]. The Lagrangian model uses a multi-mesh approach, meaning that the lagrangian particles can move over all the computational meshes being computed at the moment. The nested meshes have a priority rank associated, to allow the particle to "choose" the best velocity field available in each position. The Oil Weathering Module uses variables from the hydrodynamics and the Lagrangian transport modules and computes oil density, viscosity, and the weathering processes. Weathering processes include oil spreading, evaporation, dispersion, sedimentation, dissolution, emulsification, degradation (biodegradation and photo-oxidation), oil beaching and removal techniques. The detailed formulation of these processes can be found in Janeiro *et al.* [13].

Preliminary Results

The modeling suite is applied to a computational domaincentered at the Pianosa Island in the Tuscany Archipelago (Italy), as shown in Figure 2. The bathymetric data was obtained from GEBCO (http://www.gebco.net/), a global 30 arc-second grid generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data. GEBCO data is then interpolated using a triangulation method to a 0.015° (aprox. 1500 m) 160x60 cells grid. A vertical discretization of the Cartesian type was chosen for the two domains. In this situation this is preferred for the other type of possibilities due to the sharp depth gradient close to the islands. A sigma coordinate for example would lead to excessive spurious errors in the baroclinic term (the so called "sigma error"). Twenty Cartesian layers are used, starting from 6 meters thickness at the surface and increasing using a double exponential law to a maximum of 128 meters at a maximum depth of 1287 meters.

In these first preliminary results the model is only simulating the external barotropic mode, being forced by free surface height at the open boundaries and wind stress at the surface. This configuration will not produce accurate results from the point of view of the water column velocity field but from the point of view of superficial oil spill movement it accounts for t most important mechanisms. The boundary values of the free surface elevation □ are obtained from FES2004 and the velocity field is obtained from the ISPRA-Civitavecchia operational buoy (http://www.mareografico.it). An instantaneous oil spill accident is simulated by discharging instantaneously 1000 particles with a total initial volume of 100 m^3 in a position 15 Km west off the Elba Island, which corresponds to a zone of intense traffic. The evolution is simulated for 5 days.

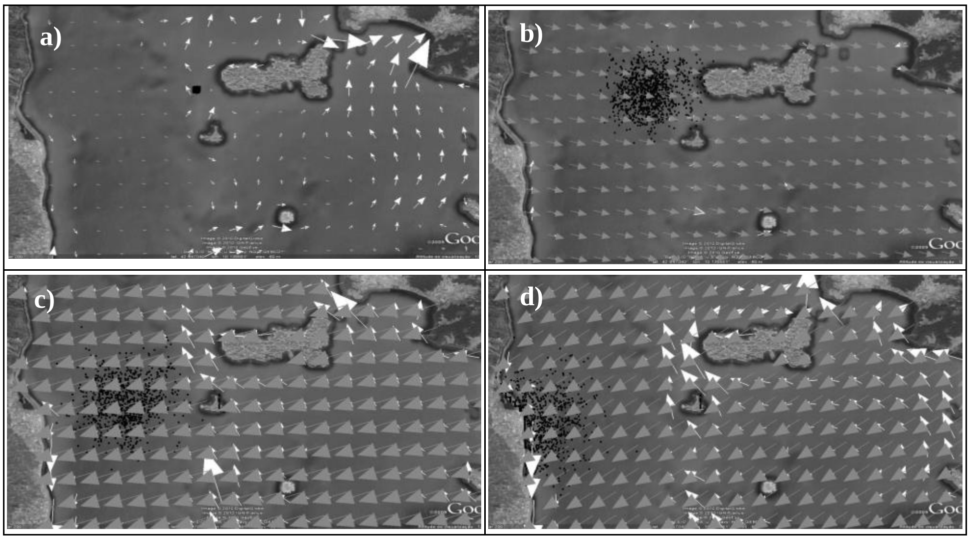

Figure 2:Wind fields (gray), velocity fields at the surface (white) and oil particles of a punctual discharge for the dates a) 12/11/2007-1:00; b) 14/11/2007-9:00; c) 15/11/2007-22:00; and d) 16/11/2007-15:00.

In Figure 2 the velocity fields and the particles positions are represented in 4 time instants subsequent to the discharge. It can be seen that the barotropic velocity field is much more intense in the shallow region between the islands and the Italian coast (East part of the domain) than in the deep region between the Elba Island and Corsica. This scenario is expected to change dramatically with the introduction of the baroclinic mode. Nonetheless the particles are much more influenced by the wind field than by the hydrodynamic field. The later only play arole during very low wind periods. The relative importance of the hydrodynamic field is expected to increase for sub-superficial oil spills, justifying the introduction of baroclinic forcing in future simulations. These are preliminary results and a full calibration procedure will be performed during the project's lifetime both for the hydrodynamic and for the oil spill model.

CONCLUSIONS

The ARGOMARINE concept for oil spill surveillance, early warning and management is presented briefly, in all its components, with a special focus on the mathematical modeling techniques. Preliminary results of oil spill simulations are presented to demonstrate the potentialities of the system.

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