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The Poseidon Operational Tool for the Prediction of Floating Pollutant Transport

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In this work the development and the application of an operational management tool for the Greek Seas is described. This tool consists of a three-dimensional floating pollutant prediction model coupled with a weather, a hydrodynamic and a wave model in order to track the movements and the spreading of the pollutants and indicate those coastal areas which might be affected. The tool is part of the Poseidon system which has been designed to provide real time data and forecasts for marine environmental conditions in the Greek Seas. In this paper, we present four case studies based on realistic scenarios that show the value of the application for long-term strategic planning and short-term decision making in oil spill accidents. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: chemical pollution; tar balls; ecosystem management; environmental protection; mathematical models; oil spills.

Introduction

The annual maritime transport of crude oil and refined products within the Mediterranean Sea is estimated today at 360 million tonnes corresponding to approximately 20% of the total world oil maritime transport (IMO/UNEP, 1998). As a result, an amount varying between 0.5 and 1 million tonnes of oil per year is discharged into the Mediterranean Sea (Le Lourd, 1977). The continual release of oil into the sea from marine operations and land-based activities is considered to be a source of contamination more important than accidents involving large-scale oil spills in the sea (UNEP, 1988). Nevertheless, over the last 15 years more than 55 000 tonnes of oil have been spilled in the Mediterranean resulting from 242 accidents reported to the Regional Centre (IMO/UNEP, 1998). In the same period more than 12 major oil accidents have been reported from the Aegean and Ionian Seas while more recently a persistent tar contamination has been observed along the northern and western coasts of the island of Crete (Kornilios *et al.*, 1998). In addition tar deposition has recently increased in many coastal areas of the south-west Aegean and the south-east Ionian Sea. While shipments of early Azeri oil to the world markets through the Turkish Straits and the Aegean have already commenced, the recent discovery of large deposits of oil and natural gas in Azerbaijan, Kazakhstan and Turkmenistan is expected to increase the oil maritime traffic through the Aegean. The result could be an even higher risk of oil pollution, both intentional and accidental, and it is therefore in the interests of Greece and Turkey, to protect their coastal zones on which they largely depend for tourism and other human activities.

Spill simulation models are increasingly used to provide preventive measures and to assess risks, and generally to assist the development of strategies for oil spill contingency planning and response in the event of an accidental oil spill in the sea (Volckaert and Tombroff, 1989). In this paper the Poseidon pollutants transport model (PPTM) is described. It is a fully operational model, which efficiently simulates drift, spreading and weathering of floating chemicals, taking into account major physical and chemical processes. The application of the model in four areas of strategic interest with respect to present and future oil production and transportation as well as its sensitivity in the prediction of oil spill movement and impacts related to oil spill accidents is also presented. The model may be used either in hindcast mode for the tracing of the source of a spill, or in a forecast mode in order to predict the path, the

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horizontal extent, and the mass balance, assisting in this way in a real-time crisis management.

Materials and Methods

Studied area – data analysis

The application area covers the Greek Seas i.e. the Aegean Sea extending south to the north-west Levantine and the eastern part of the Ionian Sea. The Aegean is the third major sea of the Eastern Mediterranean, surrounded by the Greek and Turkish mainland. It communicates with the Black Sea through the Dardanelles, and water exchange occurs with the north-west Levantine through Kasos, Karpathos and Rhodes Straights and with the Ionian Sea through Kithira and Antikithira Straights. The Aegean Sea is characterized by a complicated coastline and also by the presence of more than 2000 islands scattered mainly in its central and eastern area. The Ionian Sea is marked by the presence of the deep Hellenic trench, lying along the western and south-western Greek coast and the islands of the Cretan arc, and characterized by depths generally greater than 4000 m, with a maximum depth of 5121 m south-west of Peloponnese (Stergiou *et al.*, 1997).

The Poseidon system is an operational monitoring, forecasting and information system for the marine environmental conditions of the Greek Seas (Soukissian *et al.*, 1999). The observational basis of the system is a network of 11 oceanographic buoys operating in the Aegean Sea since June 1999. Each 'Seawatch' buoy is equipped with meteorological and oceanographic sensors that measure the following parameters: wind speed and direction, atmospheric pressure, air temperature, wave parameters, current speed and direction, water temperature, salinity, dissolved oxygen, chlorophyll-a and radiation. Every 3 h, data are collected and automatically transmitted via INMARSAT-C satellite and GSM telephone to the operational centre of the National Centre of Marine Research (NCMR) in Athens. The data are used by a hierarchy of numerical models that daily provide operational forecasts covering the next 72 h. The atmospheric model provides high-resolution forecasts for the entire Mediterranean (20 km resolution) and the Aegean Sea (10 km resolution). The results are used as surface forcing by the offshore wave model and the hydrodynamic model that cover the Aegean Sea with a 5 km grid.

The PPTM receives information from the wave and ocean hydrodynamic prediction models and produces quantitative information of the pollutant under investigation (Fig. 1). The information produced by the offshore wind-wave model comprises the wave spectrum and all the derived operational quantities such as significant wave height, direction and period. It receives information from the surface wind prediction model in order to produce a realistic description of the wave-generating parameters. In addition, the model is linked with the ocean hydrodynamic prediction model in order to incorporate currents inducing refraction to the wave propagation. The hydrodynamic model used for the Poseidon system is the Princeton ocean model (POM) (Blumberg and Mellor, 1983; Blumberg and Mellor, 1987; Mellor, 1991). It is a three-dimensional sigma-coordinate primitive equation model with a free surface, that uses a time-splitting technique to solve both the depth integrated and fully three-dimensional primitive equations with different time-step and has been applied to both coastal and estuarine water bodies as well as to larger oceanic areas.

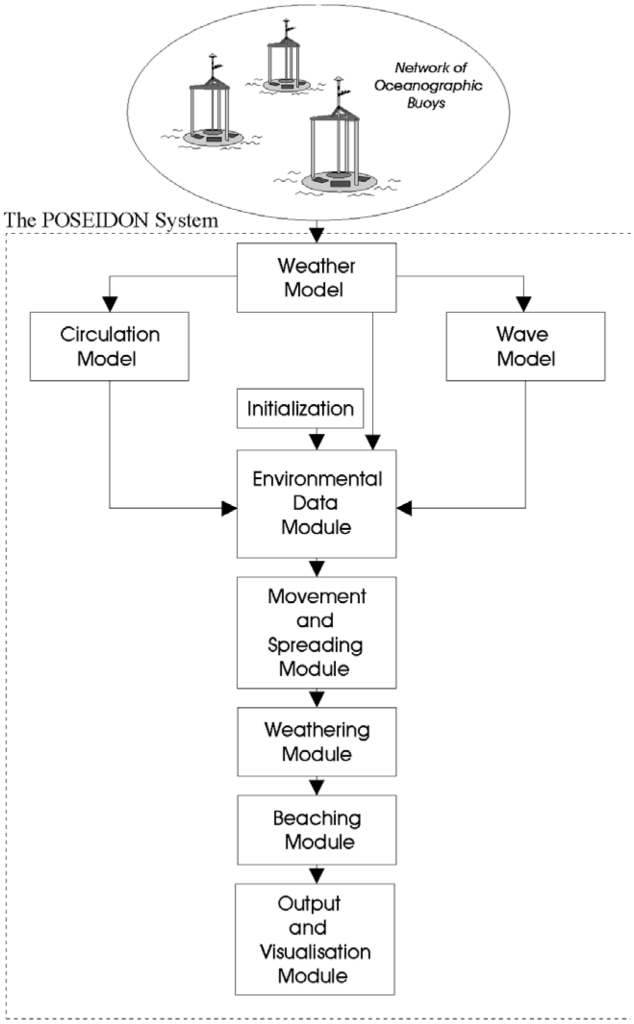

Fig. 1 The Poseidon system.

The Poseidon Pollutants Transport Model

Basic assumptions and initial spreading

PPTM has been based on the PARCEL model (Koutitas, 1988; Petihakis *et al.*, 2001). For modelling purposes, the whole mass of the oil slick is simulated with 'parcels', representing a large number of material particles, which are characterized by evolving physico-chemical properties and may represent, in reality, many cubic meters of oil, occupying a considerable space on the sea surface (Elliott, 1986; Johansen, 1985).

The position of every parcel is described by its coordinates x, y, z and by the parameters that attribute the physicochemical properties as the initial volume, the density, and the droplet diameter. In the operational system all the models use the same orthogonal lattice of points in the horizontal dimension. However, in the vertical dimension, PPTM uses a Cartesian system of reference, while the hydrodynamic model uses sigma coordinates.

In the case of an instantaneous spill the application of the Fay's law gives an analytical solution for the evolution of the radius and thickness of the oil slick in time, as functions of the mass and the other physical properties of the spilled oil (Rasmussen, 1985). Although the application of Fay's law on each oil parcel might lead to distortions, the radial spreading morphologically resembles the result of isotropic uniform diffusion, allowing the simulation of the oil slick on a circular shape with horizontal uniform radial diffusion rates during the time of mechanical spreading. A continuous spill is simulated by considering a sequence of a certain number of parcels (as a function of the evacuation time) released in the location of the accident.

Pollutants advection

The three-dimensional displacements of the oil parcels are calculated from the velocity field, produced by supplying the advective forces, caused by the water currents, and the wave drift:

$$\vec{v}_{\rm par} = \vec{v}_{\rm current} + \vec{v}_{\rm wave}.$$

The velocity components caused by the currents $u_{\rm cur}$, $v_{\rm cur}$ for each parcel are calculated from the velocities of the hydrodynamic model as follows. Using the sigma transformation $\sigma = (z - \eta)/(H + \eta)$, velocity values at the sides of the grid boxes of the oil spill model are assigned, where η is the water surface elevation above the mean, and H is the depth. Finally the local velocities at points with coordinates of those of the oil parcels are computed via linear interpolation from the velocity values on the sides of the meshes of the oil spill model grid. The wave drift is modelled as Stokes drift and is the net current speed caused by linear waves and has the same direction as the wind (Elliott, 1986). The vertical transport of the oil particles is caused by the hydrodynamic vertical velocity field as well as by the buoyancy velocity, which is a function of the density and the diameter of the droplet. The distinction between small and large oil droplets is based on the concept of critical diameter (Elliott, 1986).

Horizontal and vertical diffusion

Two very important processes, resulting from the turbulent nature of the current fields, are the horizontal and vertical diffusion. The vertical eddy diffusion coefficient consists of two components, the current and the wave component. For the current component the Mellor–Yamada 2.5 turbulence closure model (Mellor and Yamada, 1982) is used to calculate the vertical diffusion of the oil particles in the water column. This model characterizes the turbulence using equations for the turbulent kinetic energy $q^2/2$ and a turbulent macro scale l. The vertical mixing coefficient is defined as $K_{\rm vel} = lqS_{\rm vel}$, where $S_{\rm vel}$ is a stability factor which is a function of the Richardson number and depends on stratification. The turbulence length scale q^2l and the turbulent kinetic energy $q^2/2$ can be determined from the solution of two prognostic equations. A complete description of these equations can be found in Mellor and Yamada (1982). The wave component varies exponentially from the free surface extended to a depth of the order of the wavelength (L) with an upper limit of $z = -L/2$ (Johansen, 1985; Ichiye, 1967). The horizontal diffusion coefficient A_s is calculated according to Smagorinsky (1963) and is provided by the hydrodynamic model. Then, for each particle, an excursion is $d = (6D{\rm d}t)^{0.5}(2[R]_0^1 - 1)$ (Koutitas, 1988), where $[R]_0^1$ represents a random number in the range between 0 and 1. D describes the vertical or the horizontal diffusion coefficient. Horizontal advection and the combined effect of depth varying vertical and horizontal diffusion describe the entrainment and the dispersion of the oil slick. These processes form the specific oil slick elongation with thick surface head and a tail of particles distributed vertically along a certain depth.

Evaporation

Evaporation is a process influencing mainly the lighter fractions of mixture of hydrocarbons and can result in the transfer of 20–40% of spilled oil from the sea surface to the atmosphere, depending on the type of the oil (Gundlach and Boehm, 1981). The most volatile (low carbon number) hydrocarbons evaporate most rapidly, typically in less than a day and sometimes in less than an hour (McAuliffe, 1989). The rate of evaporation depends on surface area, thickness, vapour pressure, wind speed, temperature and mass transfer coefficient, which, in turn, are functions of the composition of the oil (Reed, 1992). It is quantitatively described by a function of the evaporative volume fraction as a function of time. Various forms of those functions are available. The approach used here to characterize evaporation of oil has been suggested by Stiver and Mackay (1984) and Stiver *et al.* (1989). In this model the oil is assumed to consist of a mixture of hydrocarbons of various densities, and the heavier fraction that can undergo evaporation is predetermined. It is checked whether the parcel under examination is on the surface and the slick thickness in the adjacent area of the parcel is computed, then the difference of the evaporated volume during the present time step, from the total evaporated fraction, is computed.

Emulsification

Emulsification is a process commencing after a predefined time since the generation of the spill and it affects the mixing of water in the heavier fractions of the hydrocarbons and leads to the formation of a 'chocolate mousse' with a tendency to remain on the surface as a thick layer. Factors that influence the emulsification process are wind speed, wave characteristics, make-up of the oil, degree of weathering of the oil, environmental temperature, local thickness, and time (Rasmussen, 1985). In the model the emulsification influences the hydrocarbon fractions with specific gravity bigger than a predetermined critical value. The emulsification process takes place after a time span longer than 4 h from the spill accident, for wave steepness greater than 0.028 mm, and for local oil slick thickness reaching at least a critical value of 0.75 mm (Koutitas, 1991; Riemsdijk van Eldik *et al.*, 1986). The fractional water content of an emulsion is calculated according to Mackay *et al.* (1980).

Beaching and Sedimentation

The oil behaves in a different manner when it contacts different types of the coastline. This can be described by a mechanical process called 'beaching' affecting the spatial evolution of the oil slick in coastal waters by defining the trapping time that the oil quantity remains on a specific type of coastline. The shorter time holds true for rocky cliff coasts while the longest is for marshland and tidal flats. PPTM following the approach of Gundlach (1987), permits the initial characterisation of the portions of the coastal boundaries with predetermined values of average beaching times (Petihakis *et al.*, 2001). As this is an average value, the exact time that each beaching oil parcel will remain on a specific type of beach is a stochastic magnitude following an exponential distribution with 50% value equal to the given average (Koutitas, 1991). After the expiration of that individual time, the parcel is reflected back to the sea. Note that the evaporation process continues during beaching time using the pre-existent film thickness.

Sedimentation occurs when the oil's specific gravity increases over that of seawater. Several processes may act on entrained oil and surface slicks to increase density weathering (evaporation, dissolution and emulsification), zooplankton ingestion and subsequent incorporation into faecal pellets, adhesion or sorption onto suspended particulate or detrital matter, or incorporation of sediment into oil during interaction with shorelines. The sedimentation process in the model is expressed as the trapping on the bed of those particles that reach the bottom of the sea. Those particles are excluded from the subsequent computations.

Results and Discussion

System applications

Initially, the stand-alone version of the oil slick model (not linked to the Poseidon system) had been applied and validated in Navarino Bay, Greece in connection with the 9th October 1993 oil spill accident (Petihakis

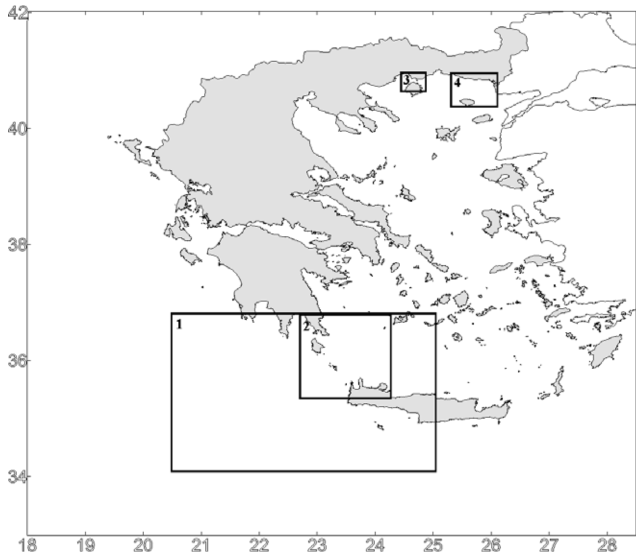

Fig. 2 Map of Greece indicating the study areas.

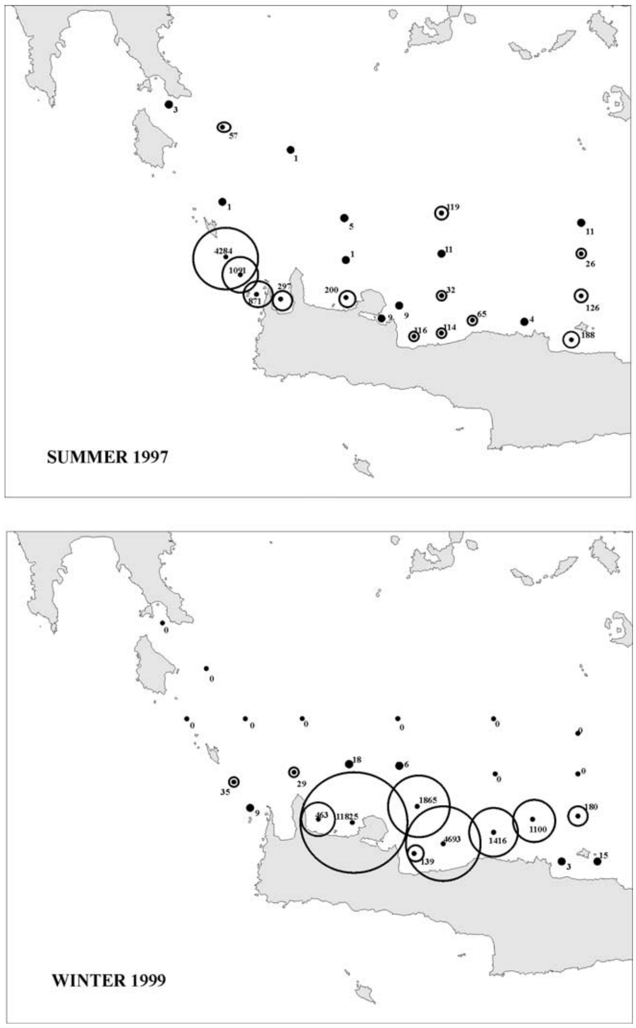

Fig. 3 Pelagic tar balls distribution in the Cretan Sea, according to Kornilios *et al.* (1998) and unpublished data from TALOS programme.

et al., 2001). In this paper, PPTM forced by the Poseidon's real-time data was used to examine four different cases to track the movement and spreading of a hypothetical oil spill in order to predict the pathway of the oil parcels and demonstrate possible effects on the coasts. Two of these cases were examined in the south Ionian Sea, one close to the area where oil-contaminated residue discharging was permitted in the past, and the other off Kithira island, an area characterized by heavy ship traffic connecting the Aegean and the Black Seas with the western Mediterranean Sea. The other two cases were examined in the north Aegean, one at the Prinos oil platforms off Thassos island and the other off the port of Alexandroupolis, an area which is expected to become an important terminal for crude oil and refined products (Fig. 2).

South Ionian Sea: tar balls entering the Cretan Sea through Antikithira Straight

According to Kornilios *et al.* (1998) considerable amounts of tar balls are found every year on the north and the west coasts of Crete, particularly during wintertime (Fig. 3). In order to validate the PPTM model and to find possible paths explaining such effects on the coasts of Crete, the assumption that tar balls were initially located between Crete and Sicily has been investigated. PPTM ran for 50 days starting from February 17 using Poseidon's data set for that particular period to track the movement and the spreading of 3000 tar balls.

Fig. 4 shows the floating parcels at the beginning of the simulation and after 50 days as well as the trajectory of the statistical centre of gravity depicted every 4 days, with part of the parcels reaching the west and north coasts of Crete. However, the main mass of the pollutants goes south into the Libyan Sea while another significant amount turns north-west heading towards the south coasts of Peloponnese. This is in a good agreement with the results reported by Kornilios *et al.* (1998) and Dounas *et al.* (1999).

South Aegean: oil accident at the maritime route close to Kithira Straight

In this experiment the deposition of oil on the shores of north-west Crete during summer was investigated. An oil spill of 3000 parcels of crude oil, representing a total volume of 10 000 tonnes was released instantaneously on the surface. The time of the accident is said to be 17th July. According to Poseidon weather data, on that day the wind was blowing from a north-west direction with a speed of about 3.5 Beaufort. Initially the spill was located at Lon. 23°.31E and Lat. 36°.19N. The simulation ran for 6 days and the model results showed that after 48 h the spill hit the coasts of Kithira and started to separate in two parts, one following a north and the other

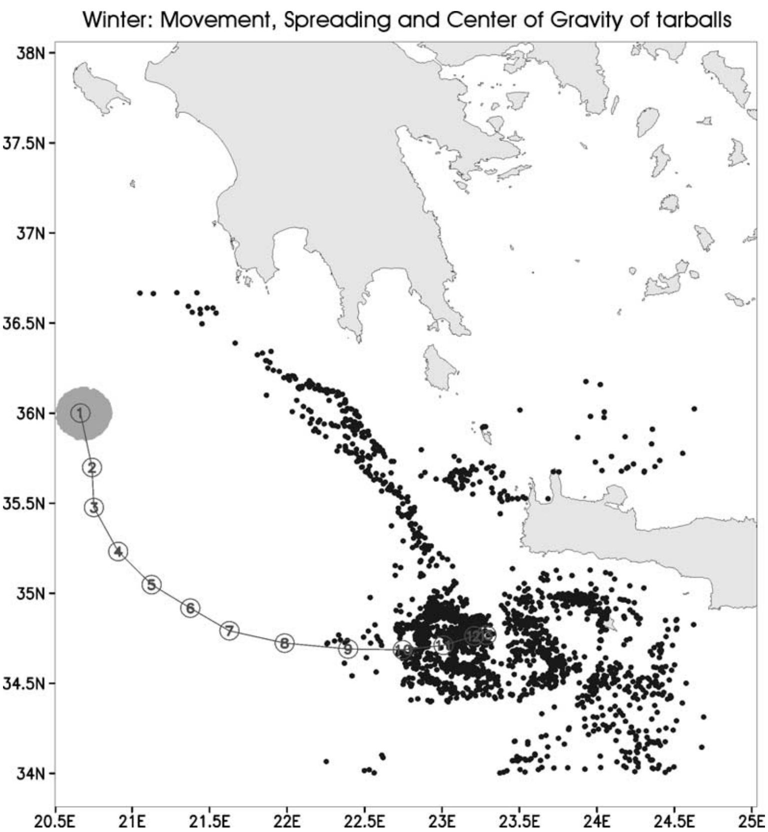

Fig. 4 Simulation results of tar ball distribution entering the Cretan Sea from the Antikithira Straight. Spill spreading is shown at the beginning of the simulation and after 50 days along with the trajectory of the statistical centre of gravity.

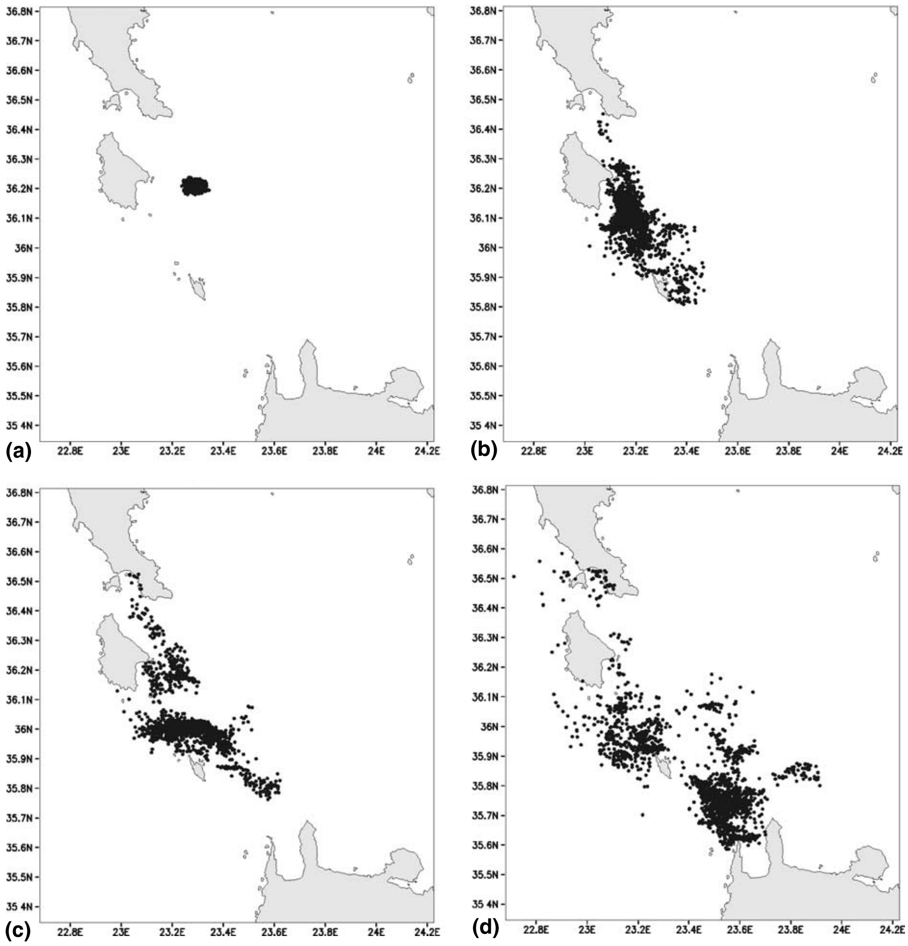

Fig. 5 Simulation results of the distribution of spilled oil in the Kithira Straight. Spill spreading is shown after (a) 6, (b) 54, (c) 72, and (d) 108 h.

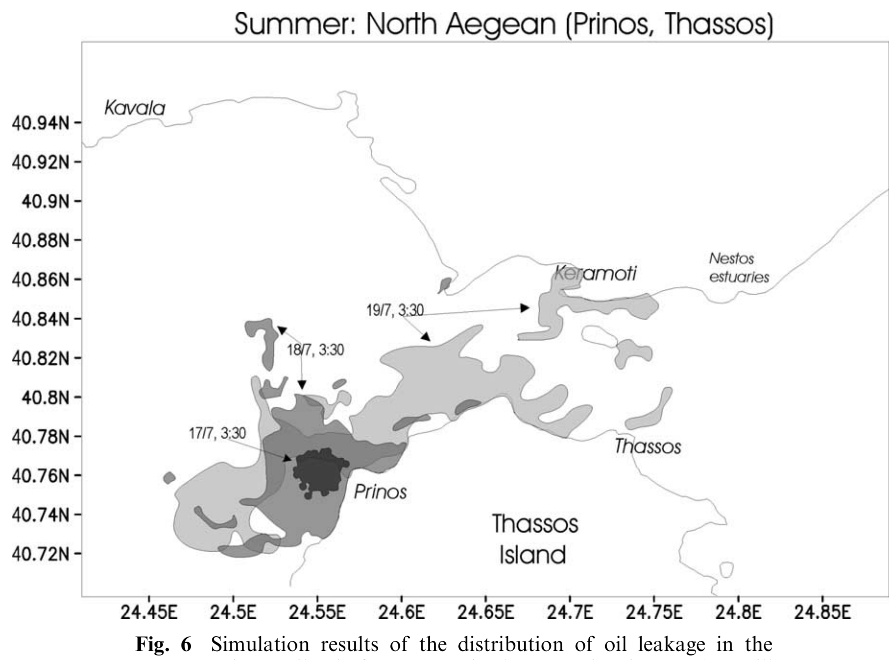

Fig. 6 Simulation results of the distribution of oil leakage in the Prinos oil platform (North Aegean–Thrasian Sea). Spill spreading is shown after 0.5, 24 and 72 h.

following a southerly direction (not shown). In the next 6 h the south-east shores of Peloponnese and the north shores of Antikithira island were affected (Fig. 5(b)). After 72 h the south part of the spill started having an elongated shape following a west to east direction while half of the beached parcels returned into the water (Fig. 5(c)). Twenty-four hours later, the south part of the spill separated again, with one part heading to the west of Antikithira island while the other, the densest, entered the Cretan Sea. In the next 12 h the west side of Antikithira and Kithira islands as well as the north-west shores of Crete were seriously affected (Fig. 5(d)). Finally, 150 h after the accident the area most affected was the Falasarna shore in the north-west part of Crete while the main mass of the oil was moving off the north coasts of Crete following a west to east direction (not shown). It is worth noting that the final developed front of oil parcels in north-west Crete might be related to the distribution of pelagic tar balls at the same area and season reported by Kornilios *et al*. (1998) (Fig. 3).

North Aegean: continuous oil leakage at the offshore production platforms of Prinos

An area of great environmental importance is Kavala gulf located in the North Aegean, characterized by extended wetlands and aquaculture activities. The Prinos oil field located in the area is at present the only national source of crude oil in Greece. In this experiment, em-

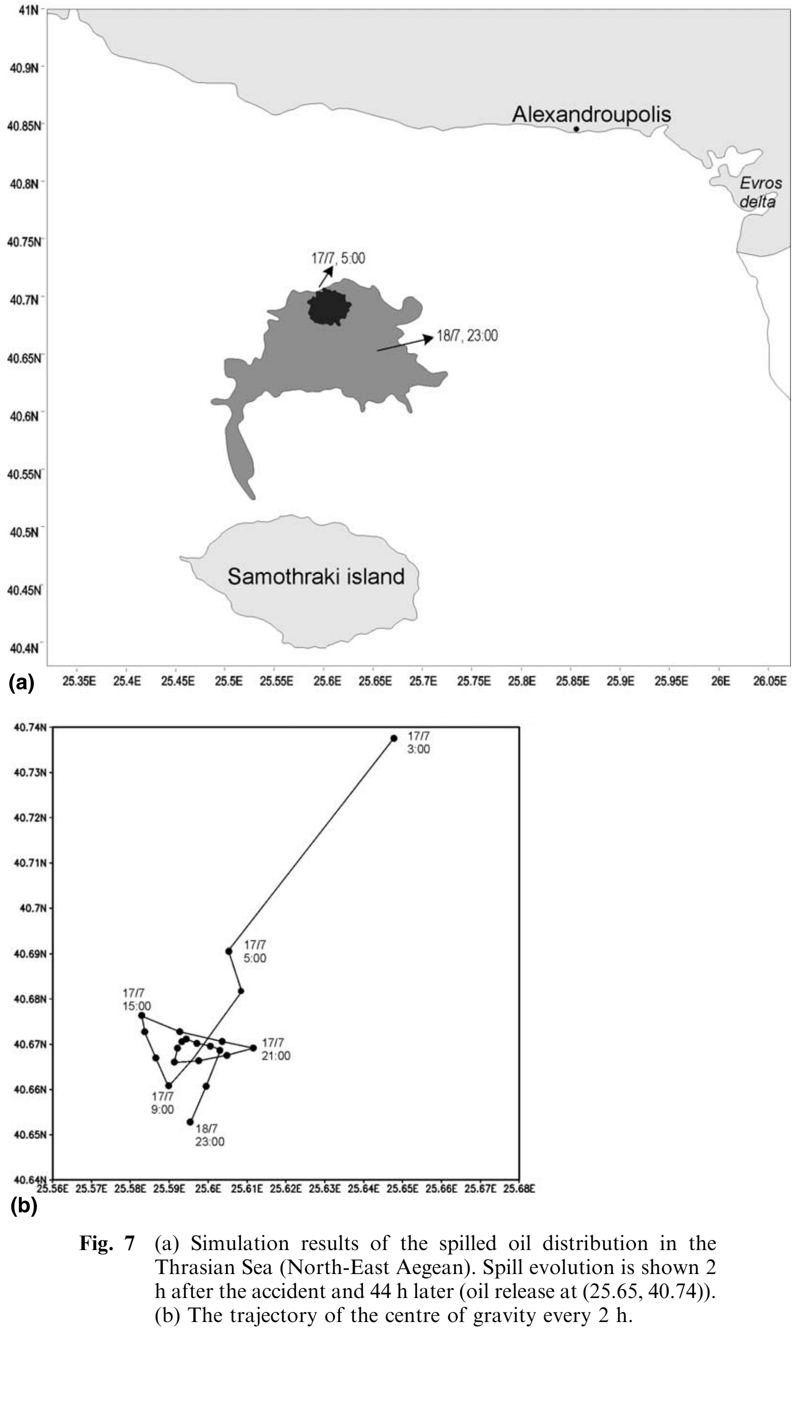

Fig. 7 (a) Simulation results of the spilled oil distribution in the Thrasian Sea (North-East Aegean). Spill evolution is shown 2 h after the accident and 44 h later (oil release at (25.65, 40.74)). (b) The trajectory of the centre of gravity every 2 h.

phasis is given to the advection and spreading of oil in the case of a leakage from an underwater pipeline at a depth of 30 m for 24 h.

Simulation of the oil spill is performed for 78 h in order to prevent or avoid potential environmental impacts in the area using Poseidon's data. At the time of the incident, July 17, the wind was blowing from northwest and locally west directions with an intensity of about 2.5 Beaufort.

Fig. 6 shows the simulated spreading of the spill after half an hour and after 24 h when the north-west coast of Thassos island starts to be affected giving a last chance to the crisis management team for an effective response in preventing further environmental impacts. After 48 h the spill expanded along the north shores of the island, and between 60 and 72 h (shown also in Fig. 6) hit the mainland affecting the wetland of Keramoti and the estuary of Nestos river, areas of high environmental importance protected by Ramsar convention. The model results show that a contingency plan should be activated in less than 24 h otherwise there the consequences at the social, economic and environmental level could be considerable.

Oil accident in the Thracian Sea

This experiment was triggered from the recent cooperation of the Greek, Bulgarian and Russian governments for the construction and operation of a pipeline that could potentially provide an alternative route for Caspian Sea oil export. A 300-kilometer pipeline is designed from Bourgas on the Bulgarian coast to an Alexandroupolis terminal on the North Aegean, having a potential to transport 35 Mt of crude oil annually. In the experiment a ship accident was assumed giving an instant spill of 50 000 tonnes of crude oil represented by 10 000 parcels. The accident takes place at Lon. 25°.65E and Lat. 40°.75N on July 7.

Total simulation run was for 44 h providing output results every 2 h. Fig. 7(a) depicts the dispersion of the oil parcels as predicted by the model 2 h after the start of the experiment and at the end of the simulation. The model predicts that the oil parcels do not hit any of the coasts of the north Aegean having a tendency to remain grouped moving slowly southwards. It is worth noting that during the first 6 h (locations 1–4, Fig. 7(b)) the oil moves by the dominant surface currents but afterwards the wind dies down resulting in the development of inertial currents. The spiral movement of the oil's statistical centre of gravity (Fig. 7(b)) may be attributed to the inertial currents occurring frequently in the area.

Conclusions

The Aegean Sea is characterized by extremely complicated coastal geomorphology exhibiting quite variable time-and-space weather and hydrodynamic conditions. Taking into consideration that an oil spill movement in a such variable environment, is highly dependent on the local weather and hydrodynamic regimes, the Poseidon system providing real time weather, wave and hydrodynamic data offers a unique opportunity for the operational use of oil spill models. The PPTM has been developed and applied to four different cases of particular interest in order to demonstrate specific environmental impacts resulting from accidental release of oil pollutants in the marine environment. The first two experiments possibly explain the appearance of significant amounts of tar balls in the north and west coasts of Crete. The last two experiments at the two high-risk areas of the north Aegean indicate the significance of immediate and direct response. The oil spill simulations performed here must be viewed as preliminary studies directed towards the understanding of the broad-scale transport of oil as well as the underlying dynamics involved in the oil physicochemical processes. The system outputs could be linked into the National contingency plan supplementary to other oil spill combating techniques, allowing risk management authorities an opportunity to respond rapidly to an incident and minimize the environmental impact of an oil spill.

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