Tracking the drift of a human body in the coastal ocean using numerical prediction models of the oceanic, atmospheric and wave conditions

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This paper describes the use of numerical models to infer the path of a floating human body in the Ligurian Sea (north-west Mediterranean) during the month of January 2001. The prevailing oceanic currents were obtained from a state-of-the-art real-time nowcast/forecast ocean circulation model, while the sea state was inferred from a numerical model of the surface gravity waves, both driven by regional atmospheric models. The surface currents (from the ocean model) and the drift ones at the ocean surface, as inferred from the wave model, were used to drive a Lagrangian model of the drifting body to deduce its plausible trajectory along the Ligurian coast. The inferred path is reasonably consistent with location and time of the discovery on the French coast. This note illustrates the utility of numerical prediction models at the disposal of modern forensic science in the fields of ocean sciences.

Este trabajo describe el uso de modelos numéricos para inferir el camino seguido por un cuerpo humano en el Mar de Liguria (Mediterráneo noroeste) durante el mes de Enero de 2001.Las corrientes oceánicas existentes se obtuvieron de un modelo de circulación oceánico de predicciones a tiempo y situación reales mientras que el estado del mar fue inferido de un modelo numérico de las ondas de gravedad de la superficie, ambos conducidos por modelos atmosféricos regionales. Las corrientes de superficie (del modelo oceánico) y las de deriva de la superficie oceánica, deducidas del modelo de olas, se usaron para construir un modelo de Lagrange del cuerpo a la deriva que permitiera deducir su trayectoria a lo largo de la costa Ligúrea. El camino deducido es razonablemente compatible con la localización y el tiempo de aparición en la costa francesa. Esta nota ilustra la utilidad de los modelos de predicción numérica a disposición da la moderna ciencia forense en el campo de las ciencias oceánicas.

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Introduction

In forensic science, there occasionally arises a need to infer the path of an object in a marginal or coastal sea. For example, the body of a person involved in an accidental drowning or a crime victim disposed of intentionally by dumping into the coastal waters. The trajectory, from point of origin to final destination, of an object suspended in the water column depends very much on the currents prevalent at the time. These currents include the oceanic currents from the circulation prevailing in the region, as well as the drift currents induced by winds and wind-generated gravity waves on the ocean surface. Since observations are seldom available to provide details of the spatial and temporal distribution of these currents, it was necessary to resort to dependable models of the oceanic state, the atmospheric state (principally the wind magnitude and direction) and the sea state (more specifically the surface wave field) in the region of interest. Fortunately, technological advances have put at our disposal numerical prediction models capable of providing the necessary information. In this way, it is not only possible to investigate likely scenarios in past incidents, but it is also possible to make predictions of the likely destination of the object in real time (with no time lag) or near real time (with some time lag).

It is beyond the scope of this article to go into the details of oceanic circulation and its dynamic causes. The reader is referred instead to standard oceanographic texts on dynamic oceanography [1–4]. Nor will we be able to describe the modern numerical models and techniques available to infer oceanic circulation prevailing in a region during the period of interest [5,6]. Suffice it to say that the ocean is primarily driven by the overlying atmosphere while tides and tidal currents are generated by luni-solar gravitational forces. The winds blowing at the surface of the ocean and the heat exchange between the ocean and the atmosphere set up large scale circulation patterns with features such as the Gulf Stream in the Atlantic Ocean off the east coast of the United States and the Kuroshio in the Pacific off the coast of Japan. Seasonally reversing monsoon winds in the North Indian Ocean are responsible for the complex circulation in that ocean. However, there is considerable variability superimposed on this scenario due to fluctuations in local winds and waves on a wide variety of time scales. Consequently, it is important to know what the ocean currents are during the time of interest. Because of the highly complex nature of the dynamics underlying the ocean circulation, not amenable to analytical solutions, it becomes necessary to use numerical (computer) prediction models to infer the oceanic state. Numerical ocean models, when driven by external forcing with appropriate spatial and temporal scales of variability, can account for the dynamical variability.

Even in the absence of any prevailing ocean currents, a floating object can be transported over considerable distances by wind waves generated elsewhere but travelling through the region. Ocean wind waves propagating over the surface induce a small but nevertheless significant drift current in the direction of wave propagation, named after Sir George Stokes, a 19th century British expert on fluid flows. This drift current needs to be taken into account in inferring the trajectory of the floating object and this requires, of course, knowledge of the wave fields prevalent at the time. We will not describe the many aspects of wind waves over the ocean here [7–9], but suffice it to say that wind waves generated by atmospheric winds blowing over the ocean surface can be simulated using sophisticated numerical models driven once again by wind fields obtained from numerical weather prediction models of the atmosphere.

Thus, the use of numerical simulations of the atmosphere, ocean and waves provided us with the capability to infer the currents responsible for transporting an object suspended in the water column, which includes, of course, a floating object. These simulations can be run for a period in the past (that are called hindcasts), or can be used in a forecast mode to make predictions (in analogy to weather prediction models). The latter can be used to predict the destination of an object (e.g. aircraft, helicopter) or body involved in a drowning accident, for more efficient and effective search and rescue operations. However, the infrastructure needed for this is considerable and comparable to that required for weather prediction, and so far only the appropriate government institutions have been able to undertake such tasks, that too only when necessity forces them to. For example, the US Navy makes routine nowcasts/forecasts of the atmospheric, oceanic and sea states over the Mediterranean Sea for operational use by its forces and NATO navies [10]. While regular weather forecasts are made by civilian government agencies and made available to the public without any restrictions, the operational products from the military are not generally available. This situation is likely to change in this century, principally because of the increasing importance of the oceans to human activities and welfare, and sea state forecasts may become available to the general public as routinely as weather forecasts now are. The application of the resulting knowledge will allow better and sustainable exploitation of ocean resources. In the current context, it makes available to forensic science the knowledge of the currents needed to track the path of a floating or submerged human body. It is the purpose of this note to describe such an application.

The case and the area of study

On 8 January 2001, an important Italian citizen disappeared from home in Portofino, Italy (Latitude 44.3°N, Longitude 9.17°E), on the Ligurian coast. The body was discovered 22 January 2001 on a French beach off Hyeres (Latitude 43.1°N, Longitude 6.3°E), more than 300 km from Portofino. Subsequent investigations concluded that there was a possibility that she fell off the steep cliff where his home was located. One important question in the investigation was whether the body could have travelled over that distance during the roughly two weeks between the time of disappearance and finding the body. This point was crucial in determining whether the body was introduced into the Ligurian Sea off Portofino or was disposed off elsewhere along the Ligurian/French coast. The answer to this question depends critically on the strength and direction of currents, winds and waves prevailing over the region during that period. The extreme sensitivity of the location where the body ends up to the details of the currents is obvious and well known. For example, a young man died after jumping off the 67 m high Tacoma Narrows bridge near Seattle in 1988 [11]. His body was found on a beach 32 km north of the bridge. However, careful simulations using a laboratory hydraulic model (a physical scaled replica, not a computer model) of the flow in the region near Tacoma Narrows bridge in Puget Sound established that because of the strong periodically reversing tidal currents, the body would have floated 10 km southward, if the jump had occurred a mere 1/2 an hour earlier, because of the change in the direction of tidal current just around that time. In a similar manner, depending on the prevailing conditions, the body found off the French coast could have originated anywhere on the Ligurian coast. To reduce this uncertainty, we used numerical models to explore the possible path of the body.

The Ligurian Sea is part of the Mediterranean basin and generally speaking, the prevailing winds in the region set up a counterclockwise circulation [12–15]. Strong currents along the Ligurian-Provencal coast of as much as 0.5 m/s flow southwestward [16–17]. It is therefore natural to presume that a body originating at a point along the Ligurian coast is likely to be transported toward the French coast. However, the magnitude and direction of the surface currents depend on the wind, wave and current conditions prevalent at the time. The tidal currents in the region are small (the barotropic component is less than 1 cm/s; we did include barotropic tidal currents in the simulation and found very little difference in the results) and can be disregarded except very close to the coast where shallow water and bottom channels can amplify these currents. In addition, this region has numerous canyons in the water along the coast that are likely to give rise to local circulation features important to the drift of the body close to the coast but difficult to reproduce in an oceanic model.

Numerical models of the ocean, atmosphere and waves

An example of the numerical ocean model useful for the application described here is the Mediterranean Forecast System Pilot Project (MFSPP, see http://www.cineca.it/~mfspp000), a European project for forecasting currents in the Mediterranean Sea using the Geophysical Fluid Dynamics Laboratory Modular Ocean Model (GFDL-MOM) [18], implemented on a regular 1/8˚ grid. The model is driven by meteorological data provided every six hours by the European Centre for Medium Weather Prediction (ECMWF). Another example is the Naval Oceanographic Office (NAVO) of the US Navy at Stennis Center, Mississippi, which runs operational nowcast/forecast models for various marginal seas around the world to produce current oceanic conditions as well as conditions for the next three days. The system is called Shallow Water Analysis and Forecast System (SWAFS). The Mediterranean Sea SWAFS has a 10 km horizontal resolution and assimilates available in-situ oceanographic data to produce realistic currents in the basin [10]. It is driven by a high resolution (1/4˚, less than 30 km at this latitude) regional atmosphere model called Coupled Ocean-Atmosphere Mesoscale Predction System (COAMPS) covering the Mediterranean Sea region, also run operationally every day at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) of the US Navy in Monterey, California. FNMOC also runs a high resolution (1/5˚, about 20 km at this latitude) operational Wave Model (WAM) driven by COAMPS. Thus at any given time, the atmospheric, oceanic and sea states in the Mediterranean Sea are known up to three days into the future. These products are useful in day-to-day naval operations as well as any special operations such as a search and rescue mission to retrieve a downed naval aviator. The latter requires forecasting the likely path of a floating object to ensure more efficient and effective search and rescue operations.

The GFDL-MOM and the Ocean Model developed at Princeton University [19,20] are widely used in the civilian community. Colorado University's version of the Princeton Ocean Model (CU-POM), [6] has been used to infer the circulation in the North Indian Ocean during 1993–1998 [21,22] and is currently used to make real-time forecasts of circulation in the Gulf of Mexico for operational use by the offshore oil industry [23]. It has also been used to nowcast/forecast currents in the Ligurian sea [24–25].

The prevailing winds, waves and currents were thus inferred every 12 hours from 8 January to 22 January 2001, on a 10 km grid covering the Ligurian Sea and used to drive the Lagrangian drifter trajectory model described below. Based on the post-mortem, the coroner determined that the body most likely floated in the water. Therefore, we assumed that the body was floating (a rather good assumption in most cases) and only surface currents (derived from NAVO SWAFS model archives) were used to infer the drifter trajectories, even though the currents were available in the entire water column. The currents in the top layer (whose thickness is proportional to the water column depth; 1.7 m thick where bottom depth is 1000 m) of the SWAFS model were extrapolated to the surface using the well-known logarithmic law of the wall in a turbulent boundary layer. SWAFS includes wind-driven mixed-layer physics through a turbulence closure model that accounts for wind and buoyancy flux-driven mixing in the top layers.

The Lagrangian drifter model

A Lagrangian drifter model developed at Institute for the Dynamics of the Large Masses (CNR-ISDGM), Venice, Italy, to compute the trajectory of an object in the water column, given the ambient currents as a function of time [26], was set up to compute the trajectory of the floating body in the Ligurian Sea, on the 10 km grid covering the region of interest. The ocean currents were available every 12 hours and so were the wave model results. These were interpolated to the Lagrangian model grid. For a monochromatic surface wave, the Stokes drift is 6.32

H^2/T^3, where H is the wave height and T is the period. However, the wind-generated waves cover a broad spectrum. But knowing the significant wave height H_s, the principal wave direction and the mean period of the waves T_m, it is still possible to compute the surface Stokes drift current produced by the waves: $U_d = 3.2\ H_s^2/T_m^3$. This was added to the ocean currents simulated by the model and used to drive the Lagrangian drifter model. This model calculates the distance and the direction travelled by the floating object every time step (12 hrs), so that starting from a given location at the initial point in time, the trajectory can be computed up to any given time afterwards. The model also accounts for unresolved current fluctuations by using a statistical random walk approach (similar to plotting the trajectory of a drunk, which consists of a mean trajectory with superimposed small deviations in various directions from this path due to the drunken man's inability to traverse a straight path). Briefly, this technique is equivalent to adding an additional but random displacement to each particle at each time step to account for the dispersion that exists at scales less than the model grid size, which cannot be resolved by the model. Because of this, different drifters released at the same initial point follow different trajectories, whereas if no random walk were implemented, all drifters released at the same initial point would follow exactly the same trajectory.

Figure 1 The bottom topography (contours are in meters). (a) Actual 1' values (b) and as used in the ocean model. The postulated origin of the body off Portofino, Italy, and the location where it was found off the French coast are denoted by triangles.

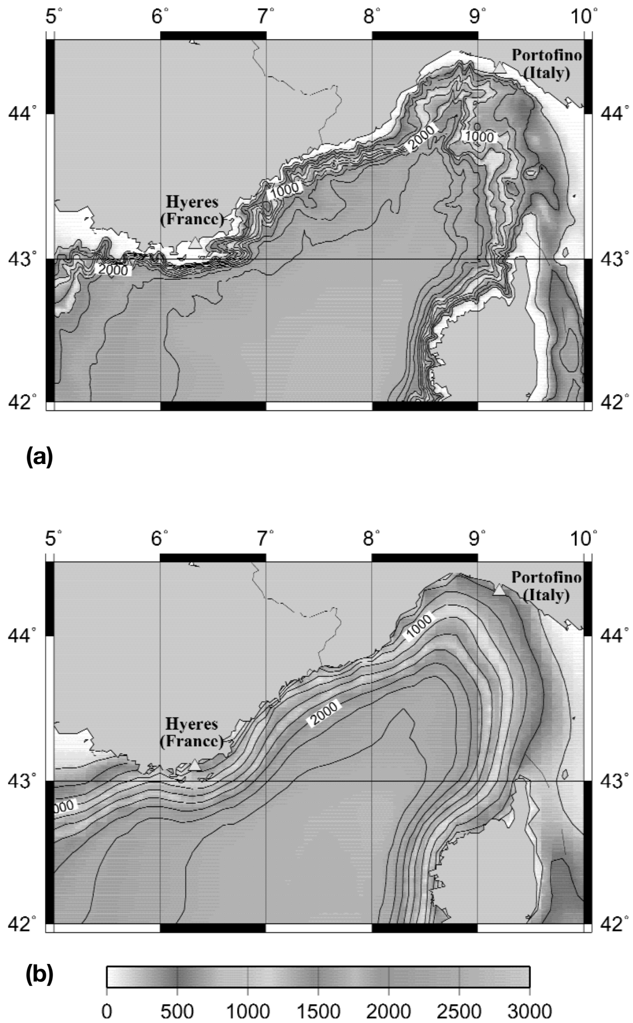


Figure 1a shows the study region, with the bottom depth derived from a bahymetry database of 1' (1.8 km) resolution. The white triangles denote Portofino, the likely point of origin of the body on 8 January, and the location where the body was found on 22 January. The numerous canyon-like features in bottom topography can be clearly seen: one such canyon is located approximately 10 km to the east of where the body was found and runs roughly east-west between the French coastline and an offshore island (Isle du Levante), located southeast of Cap Benat di Bormes (Hyeres). In principle, at least, a floating object transported by large scale currents to the vicinity of the passage east of the island can be transported in between the island and the coastline. Unfortunately, the relatively coarse (for coastal applications anyway) 10 km resolution of the ocean model and the smooth bottom topography used in the ocean model (Figure 1b) make it impossible to resolve these coastal canyons and hence the site-specific features of the local circulation very close to the coast. More specifically, the Isle du Levante and the channel behind it are missing in the ocean model. There is also a tendency to underestimate coastal currents because of the coarse resolution model's inability to resolve the very narrow shelf in this part of the world (less than 10 km wide). These are important points to remember in interpreting the results of the drifter trajectory model. A better approach, albeit time and resource-intensive, would have been to run a high resolution ocean model (say 2–3 km) that would be able to better resolve the coastal features, including of course the relevant processes at these spatial scales. Even then, very near-shore processes, namely wave and tide-induced circulation in the surf zone cannot be represented. Nevertheless, while the drifter trajectories could differ somewhat, the overall conclusions derived would not differ significantly from the current ones, since our intention is to show that the body drifted to the vicinity of the beach where it was eventually found, and not to trace it all the way to the beach.

Results and Discussion

The post-mortem examination of the body by the Italian coroner suggested that the body floated in the Ligurian sea. Therefore, the Lagrangian model was used to simulate the transport of the body by surface currents. In order to take into account the uncertainty in the time origin (since the exact time of entry of the body into the water on 8 January can only be guessed), 500 particles were released on 8 January noon (GMT), and 500 more

Figure 2 Ocean currents prevailing on model simulation days 9.5, 14.5 and 19.5 corresponding to noon 9, 14 and 19 January. Note the strong currents on 14 January. The currents are generally along the Ligurian coast to the southwest consistent with observations, but there is considerable variability in magnitude and direction from day to day and place to place.

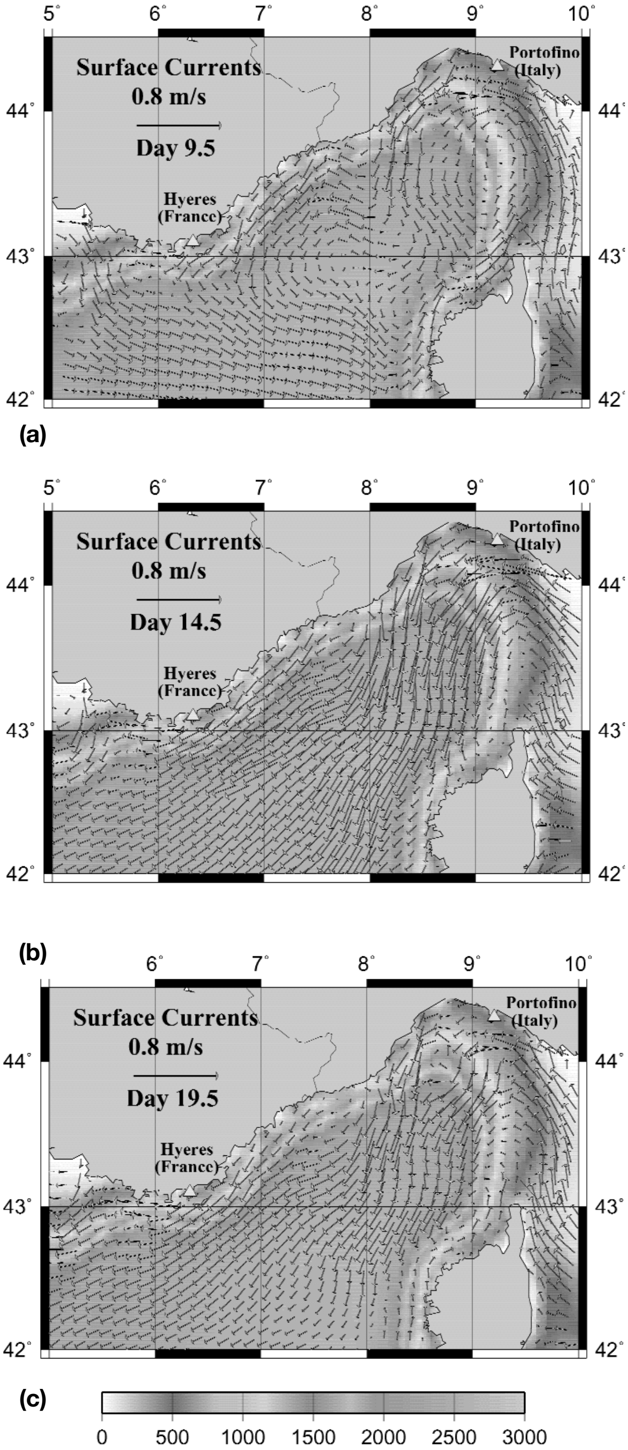


Figure 3 Wave-induced Stokes drift currents on model simulation days 9.5, 14.5 and 19.5 corresponding to noon 9, 14 and 19 January. Note the very weak currents on 9 January but strong ones on 14 January. The direction and magnitude are such that they significantly augment the drift of the body towards where the body was found. Omitting the Stokes drift and hence the influence of waves would lead to severe underestimation of the drift velocities.

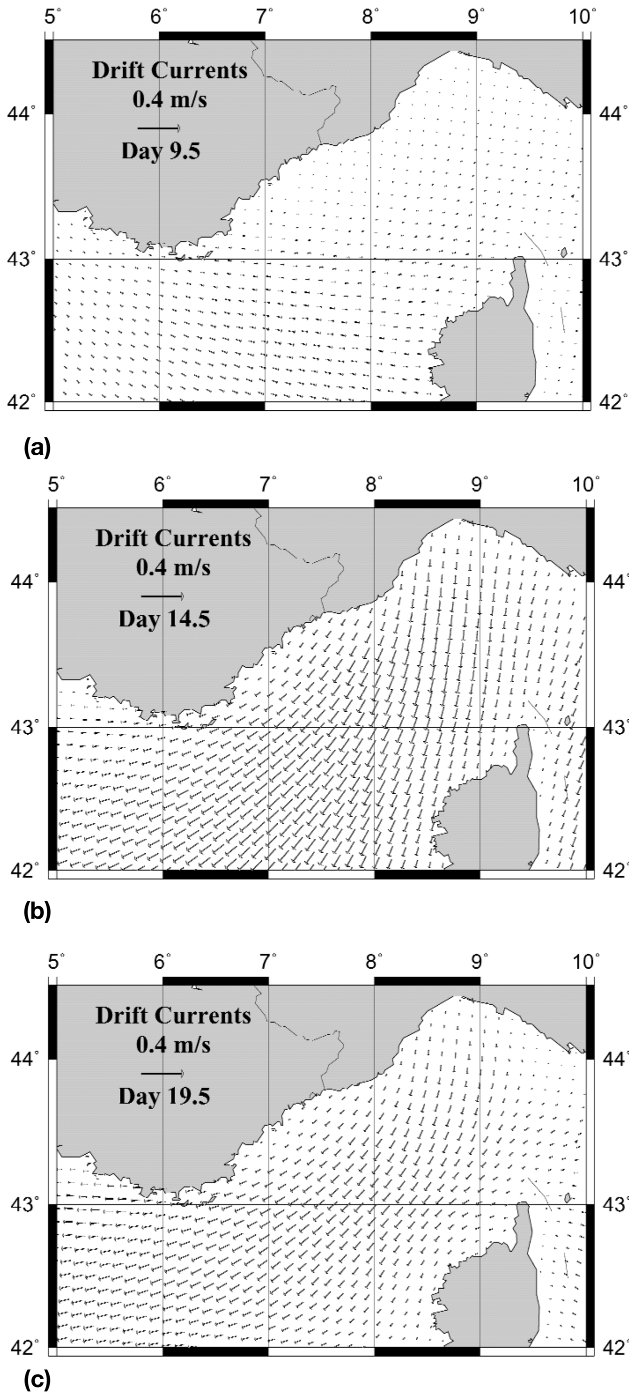


Figure 4 The stress exerted on the ocean surface by the prevailing winds on model simulation days 9.5, 14.5 and 19.5 corresponding to noon 9, 14 and 19 Janury. Note the very weak winds on 9 January but strong south-southwestward ones on 14 January. It is these strong winds that give rise to strong ocean currents and waves that transport the body into the Ligurian basin followed by southwestward transport to the French coast. Winds continue to be strong and in similar direction near the French coast on 19 January.

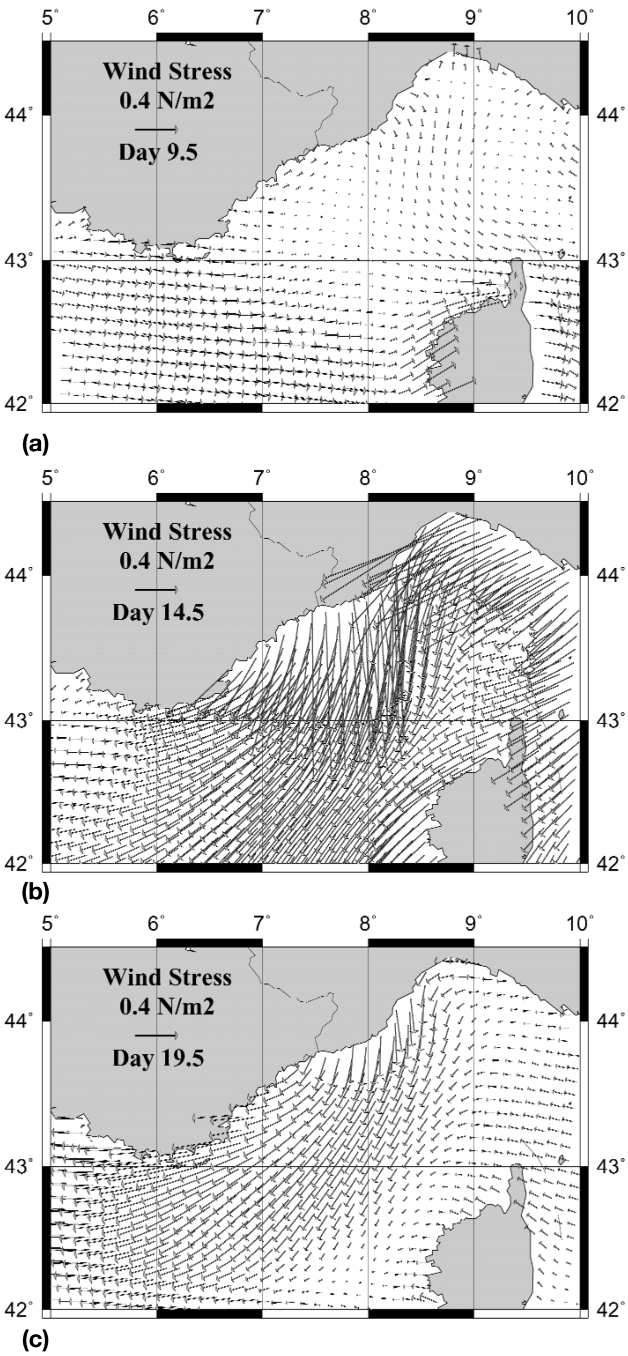


Figure 5 The cloud of particles (1000 in number) on model simulation days 9.5 and 14.5 corresponding to noon 9 and 14 January. Note that because of the weak winds, currents and waves intially, the particles have not travelled far from the point of origin on 14 January.

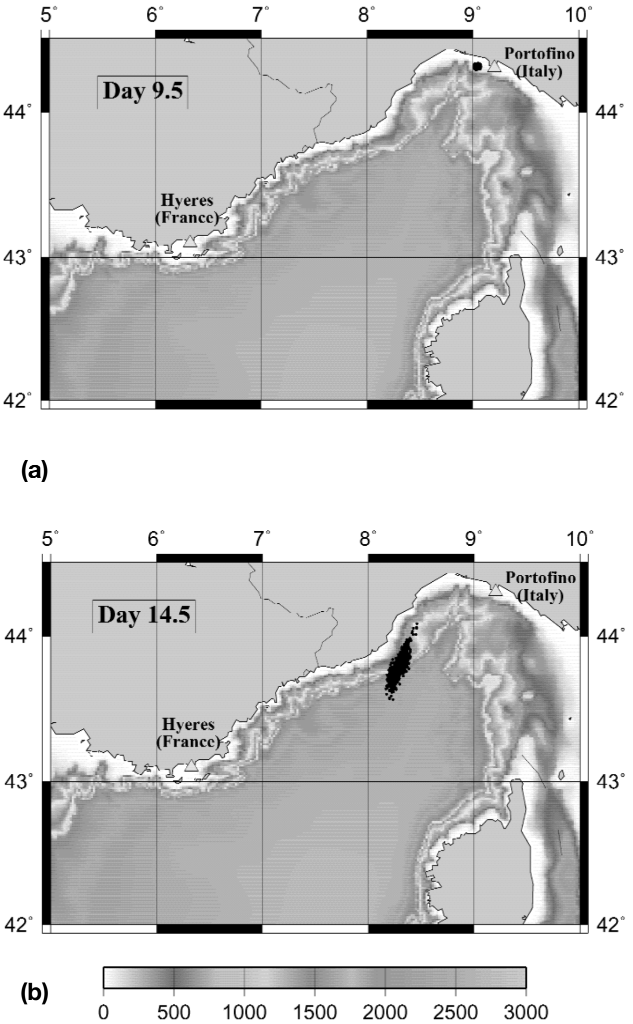
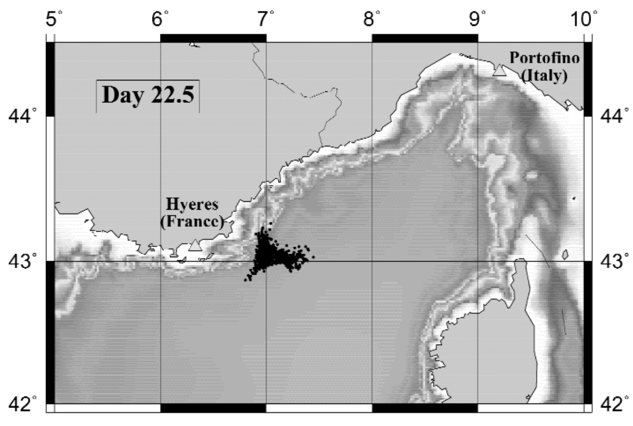
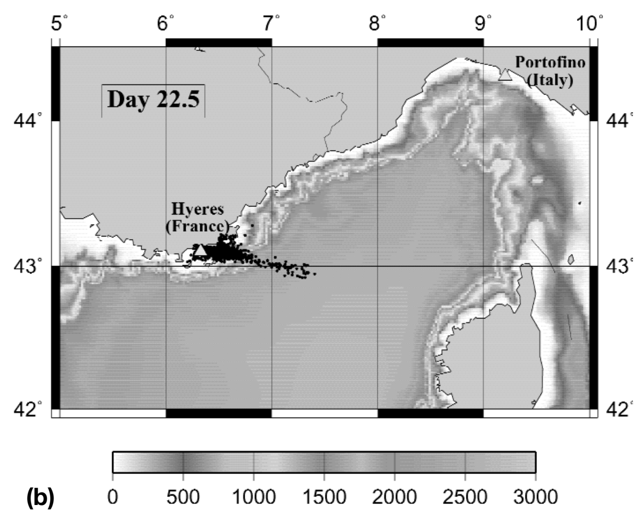


Figure 6 The cloud of particles (1000 in number) on model simulation day 22.5 corresponding to noon 22 January with and without the influence of local near-coast currents. Top panel shows the disposition of drifters without the influence of local near-coast currents. The bottom panel shows the disposition with local near-coast currents (see the text for description). Overall, the final disposition of drifters suggests that it is highly plausible that the body originating off Portofino on 8 January could have reached the French coast where it was found on 22 January.

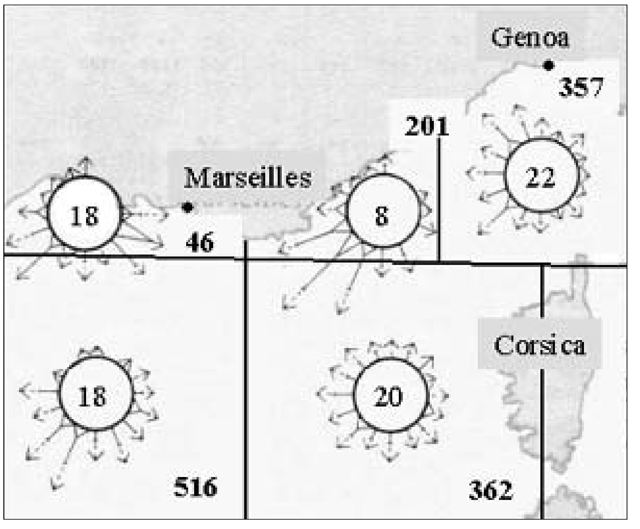


(a)



(b)

Figure 7 January surface current rises in various regions of the Ligurian Sea as inferred from observations (adapted from [17]). The numbers in the corner of each box denotes the number of observations, the circled numbers the percentage of measurement where currents had magnitude less than 12.75 cm/s.



on 8 January, 12 hours later. To account for the uncertainty in local near-coastal currents at the point of origin, which cannot be resolved by the 10 km resolution ocean model and which translate directly into uncertainties in the initial location of the body, the particles were released in a cluster of 2 km radius centered around the estimated point of origin of the body. As described above, each drifter is subjected to transport by the modeled currents as well as a randomly fluctuating (in both direction and magnitude) velocity derived from the random walk model. Thus the particles clustered initially in a tiny circle around the point of release disperse into a cloud of particles as time goes on. The centroid of this cluster denotes the likely final destination of the floating object, with the radius of the cluster providing a measure of uncertainty involved in the estimate of the final destination.

The prevailing conditions during the time the body was in the water is shown in Figures 2–4. Figure 2 shows the oceanic currents on 9, 14 and 19 January (noon GMT), while Figure 3 shows the drift currents induced by waves (interpolated from a 1/2° wave model) and Figure 4 shows the wind stress on the ocean surface (from a 1/4° model) on these days. Figure 5 and Figure 6a show the cloud of drifter particles on 9, 14 and 22 January. Note that the winds (and currents) were rather weak initially (a finding supported by meteorological observations at a small private observatory a few kilometers from Portofino) and the particles linger in the vicinity of Portofino. But the winds pick up dramatically after 13 January and this causes the particles to be transported rapidly southward into the Ligurian basin on 13 and 14 January. During these days and subsequently, the waves are towards the coast and hence the particles, by now at a considerable distance from the coastline, move west-southwestward towards the French coast. Around 19 January, both the winds and the waves relax significantly and the drifters travel more slowly. However, by 21 and 22 January, the particles are transported to the vicinity of the narrow channel betwen the island Isle du Levante, southeast of Hyeres and the French coastline. Simulations beyond 22 January show that the particles are transported mostly around the southern side of the island instead of into the passage between the island and the coast. This is principally because of the absence of the island, the canyon and the channel between the coast and the island in the numerical model and hence local circulation features in the currents simulated by the large scale model. The shelf is nearly absent at this location in the ocean model.

Thus the model deficiency in reproducing currents very accurately close to the coastline is most likely the reason for the particles not being transported in between Isle du Levante and the coast to the French beach, although errors in the estimation of prevalent wind and wave conditions cannot be ruled out. For example, a steady south-southeast wind or wave conditions during the last two days of the simulation would be capable of transporting the particles to the location where the body was found. Nevertheless, despite all these uncertainties, it is remarkable that the modeled currents depict the body being transported to the very near vicinity of where it was actually found and not elsewhere in the Ligurian basin (for example, the island of Corsica).

In an effort to include the local near-coastal circulation off Hyeres, we looked at climatological values for currents in the vicinity of Hyeres derived from historical records of measurements in this region [16,17]. The prevalent current direction in the area during January is SW-WSW, with 10% of the measurements bracketed within the range 0.25–0.5 m/s (Figure 7). Consequently, a local current of 0.25 m/s in the westward direction was added to the simulated currents only in the proximity of Hyeres and only after 21 January. As can be seen from Figure 6b, the particles then are transported to the location where the body was found (approx. Lat 43.1˚N, Long 6.3˚E). Thus a plausible scenario is that the large scale circulation and wave conditions in the Ligurian Sea proper transported the body to the vicinity of the channel between the mainland coast and the offshore island, and the local westward prevailing currents at the time pushed the body into the passage between and the body landed on a beach on the mainland coast.

Conclusions

Thanks to modern numerical prediction models, we were able to piece together the wind, wave and current conditions prevailing at the time when the human body was drifting in the Ligurian Sea. Inputting these into a Lagrangian drifter model, we were able to show that the body could have easily drifted from near Portofino to very near the channel between Isle du Levante and the French coast in the two weeks between the disappearance of the person and discovery of the body. We were further able to show that the local currents could have carried the body into the channel so that it could have ended up on the beach where it was found. Thus the results reported here are consistent with the postulated place and time of origin of the body of this unfortunate human being.

The application presented above illustrates additional tools that have become available to forensic science in modern times due to advances in science and technology over the previous decades. Clearly, mankind will need routine forecasts of oceanic, atmospheric and sea states in the coastal oceans for better use of the coastal seas and sustainable development of marine resources. An ancillary use of such operational simulations in the near future to satisfy the needs of forensic science in investigating incidents or crimes involving floating human bodies in coastal seas (and even ocean basins) is not hard to visualize and anticipate.

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