



## Model-based directed drifter launches in the Adriatic Sea: Results from the DART experiment

A. C. Haza,<sup>1</sup> A. Griffa,<sup>1,2</sup> P. Martin,<sup>3</sup> A. Molcard,<sup>4</sup> T. M. Özgökmen,<sup>1</sup> A. C. Poje,<sup>5</sup> R. Barbanti,<sup>6</sup> J. W. Book,<sup>3</sup> P. M. Poulain,<sup>6</sup> M. Rixen,<sup>7</sup> and P. Zanasca<sup>7</sup>

Received 9 February 2007; revised 31 March 2007; accepted 19 April 2007; published 23 May 2007.

[1] A high-resolution numerical model of the Adriatic Sea is used to predict Lagrangian coherent structure boundaries, quantified by finite-size Lyapunov exponents (FSLE), for flow features in the region of the Gargano Peninsula during the course of the Dynamics of the Adriatic in Real Time (DART) observational program. FSLE fields computed from two-day model forecasts of the surface velocity indicate distinct regions of high relative drifter dispersion. Model predictions of such regions located on available ship-tracks were used to direct the launching of pairs of surface drifters on three days during March 2006, with the goal of maximize coverage of the sampling area. For two of the three launches, the observed trajectories separated at locations and along directions closely approximated by those predicted from the model FSLE fields. The third case acted as an inadvertent control experiment. Model predictions at release-time showed minimal FSLE structure at the launch locations and the observed drifter pair advected in a coherent fashion for two days. While there are considerable differences between individual drifter observations and trajectory envelopes computed from ensembles of synthetic drifters, the experiment confirms the model's ability to approximate the location and shape of energetic flow features controlling the near-time fate of quasi-Lagrangian particles. Overall, the combined use of FSLEs with realistic coastal circulation models appears to be a promising avenue to aid real-time-directed drifter launches in observational programs. **Citation:** Haza, A. C., et al. (2007), Model-based directed drifter launches in the Adriatic Sea: Results from the DART experiment, *Geophys. Res. Lett.*, *34*, L10605, doi:10.1029/2007GL029634.

### 1. Lagrangian Prediction Problem

[2] The combination of increased computational power, improved data assimilation techniques and both the quantity and quality of available observations has resulted in marked improvements in the ability to model ocean dynamics on regional scales. The increased realism of coastal and sub-basin scale models has naturally led to interest in using the latest predictive models to inform the design of observational programs.

[3] For Lagrangian based observations, however, model prediction is a challenging problem for two main reasons. First, model Lagrangian trajectories depend intimately on details of the Eulerian velocity field which inevitably contains a number of error sources. Forcing due to wind stress, heat flux, precipitation, evaporation, river input, and open boundary conditions introduce errors due to the sparseness in space and time of the observational data sets. Coastal models contain errors due to missing or parameterized processes, such as non-hydrostatic dynamics, details of air-sea interaction, and surface mixed-layer physics. The high Reynolds number of coastal flows implies that not all scales of motion and domain geometry are resolved. While observed drifter trajectories integrate the dynamics of the complete spectrum of spatial and temporal scales in the ocean, synthetic model trajectories contain errors associated with the effect of sub-grid scales on the resolved motion. These errors propagate from the Eulerian field forecast to the Lagrangian transport prediction and accumulate in time. Second, even the simplest time-dependent Eulerian velocity fields are non-linear in the spatial variables leading to *Lagrangian Chaos* in the particle trajectories with rapid error growth due to sensitivity to initial conditions and details of the Eulerian flow field [Aref, 1984].

[4] Nevertheless, significant progress has been made in Lagrangian prediction during the last decade. A number of new analysis methods based on dynamical systems theory have been put forth to identify so-called *Lagrangian coherent structures*, namely Lagrangian boundaries separating the domain into sets of initial conditions with different advective dynamics. Methods for identifying such structures, defined either directly in terms of distinguished flow invariants [Haller and Poje, 1998] or by ridges in spatial distributions of finite-time or finite-size Lyapunov exponents [Shadden et al., 2005] have been tested in a number of realistic ocean models [Kuznetsov et al., 2002; d'Ovidio et al., 2004]. The use of Lagrangian structure information in the context of directed drifter launch strategies has been studied in idealized model situations by Hernandez et al. [1995], Poje et al. [2002], and Molcard et al. [2005] with promising results.

[5] In this paper, we report the results from an effort to address the following questions: (1) Are current high-

<sup>1</sup>Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA.

<sup>2</sup>Istituto di Scienze Marine, Consiglio Nazionale delle Ricerche, La Spezia, Italy.

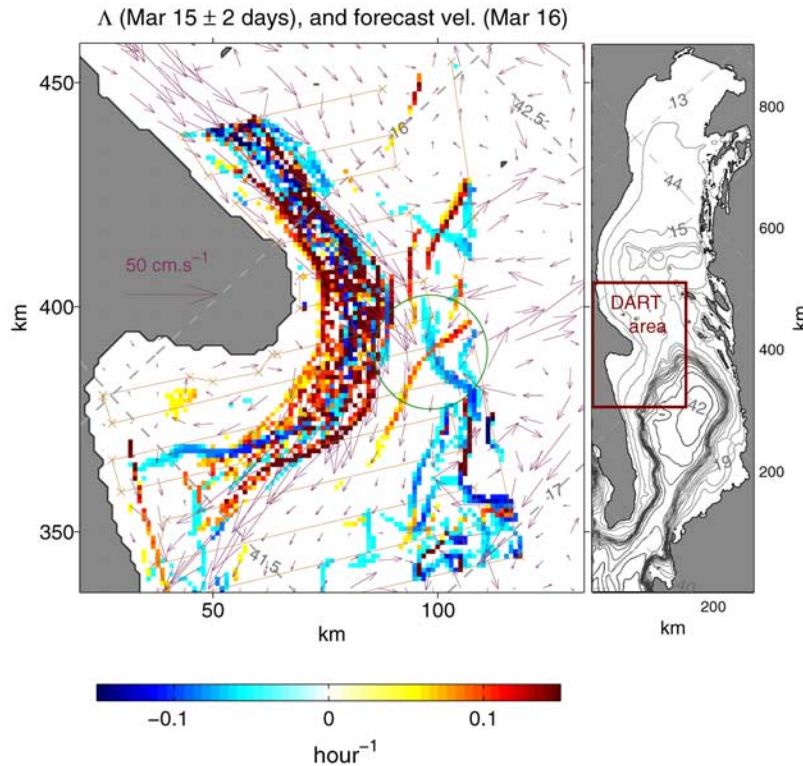
<sup>3</sup>Ocean Dynamics and Prediction Branch, Oceanography Division, Naval Research Laboratory, Stennis Space Center, Mississippi, USA.

<sup>4</sup>Laboratoire de Sondage de l'Environnement Electromagnetique Terrestre, Université de Toulon, Toulon, France.

<sup>5</sup>Department of Mathematics, College of Staten Island, City University of New York, Staten Island, New York, USA.

<sup>6</sup>Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Trieste, Italy.

<sup>7</sup>NATO Undersea Research Center, La Spezia, Italy.



**Figure 1.** (right) The location of the experimental domain within the Adriatic Sea and (left) the forecasted surface NCOM velocity field on March 15, 2006, in the DART region. Superimposed are the 2-day model based FSLE field (in  $\text{hour}^{-1}$ ,  $\delta_i = 0.45$  km,  $r = 15$ ), the ship track (regular line) and the location of a hyperbolic point determined by the intersection of inflowing/stable (blue) and out-flowing/unstable (red) FSLE branches (green circle).

resolution coastal ocean models able to capture and predict the main patterns of transport related to the Lagrangian structure of ocean flows, or does this remain a challenge for the future? (2) Can Lagrangian methods applied to the latest predictive coastal ocean models be used to direct real-time drifter launches in an observational program?

[6] We show results from launches of surface drifters during the DART experiment in the Adriatic Sea, a sub-basin of the Mediterranean Sea (Figure 1). DART involved two trials, namely DART06A in March 2006 and DART06B in August 2006. We focus on observations during DART06A here, concentrating on a set of surface drifters launched during a high resolution hydrographic ship survey. Drifter launches were specifically directed based on maxima of finite-size Lyapunov exponents calculated from the Navy Coastal Ocean Model (NCOM) configured in the Adriatic Sea to provide two-day hind and forecasts. The specific goal was to choose positions that would maximize the particle spreading and therefore the spatial coverage of sampling. To the knowledge of the authors, this is the first time that drifter launches during an observational program have been guided in near real time based on modern coastal model output and Lagrangian techniques.

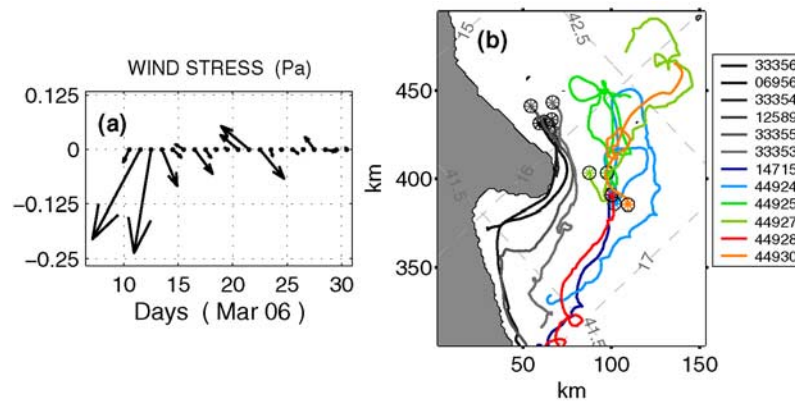
## 2. DART Program and Launch Protocol

[7] A main objective of the multi-institutional DART experiment in the coastal area of the western central Adriatic (Figure 1) is to study mesoscale instabilities arising in the Western Adriatic Current (WAC) near the Gargano

Cape. A suite of different measurements were used in conjunction with a real-time modeling effort. As part of DART06A, a total of 12 surface drifters (CODE and SVP types described by *Ursella et al.* [2006]) were successfully launched between March 11 and 23. During this period the weather was quite variable as shown by the time series of the wind stress vector (Figure 2a). A strong Bora (northeasterly wind) event occurred in the first few days of the experiment, followed by a period of relative calm from March 14 to March 20 and then by a Sirocco (southeasterly wind) event around March 20. During the calm periods, the surface circulation displays a state described by *Veneziani et al.* [2007] based on the analysis of historical drifter data.

[8] The mean flow is characterized by a well-established, stable WAC and both northern and southern cyclonic gyres which separate roughly at the Palagruza Sill extending offshore from the Gargano Cape. The inter-gyre region is populated by time dependent eddies and intense mesoscale variability. As shown in the snapshot of the model velocity in the circled region of Figure 1, the structure of pairs of liked-signed circulations often produces strong saddle-type stagnation points in the frozen-time flow field. Persistent saddle-type stagnation points may lead to hyperbolic trajectories in the Lagrangian frame. Such trajectories, which attract (repel) nearby trajectories along identifiable inflowing (out-flowing) directions, are known to organize the Lagrangian transport.

[9] The main sampling goal for the drifters was to achieve good coverage of the DART area. To this end, launches were planned in the two dynamically distinct areas



**Figure 2.** (a) Time-evolution of spatially-averaged ALADIN wind stress vector (in Pa). (b) Observed drifter trajectories (36 hour low-pass filtered). Circles indicate the launch positions.

namely in the WAC and along the inter-gyre boundary offshore from the Gargano Cape. The exact launch locations and times were constrained by logistical considerations including weather conditions and the pre-planned ship track. The launch locations in the WAC were determined a-priori based on historical information and required no real-time, model-based direction effort. Three directed launches were made targeting the region off-shore from the Cape. The launch locations and trajectories of all drifters are shown in Figure 2b for the period March 11–30. The drifters provide good coverage of the region, satisfying the general goal of the sampling strategy. This is in part due to directing drifter launches along the out-flowing branch of identifiable Lagrangian boundaries. As shown by *Molcard et al.* [2005], this strategy optimizes the relative dispersion of drifters, the overall data coverage, and the sampling of high kinetic energy features in the flow field. A prerequisite for implementing this strategy is a methodical identification of the Lagrangian features.

### 3. Identification of Lagrangian Features

[10] The Eulerian velocity field in the study region was obtained from NCOM. NCOM and its setup for the Adriatic are described by *Martin et al.* [2006]. The domain consists of the entire Adriatic Sea and includes the Strait of Otranto and a small part of the northern Ionian Sea. The horizontal grid resolution is 1020 m. The vertical grid consists of 32 total layers, with 22 sigma layers used from the surface down to a depth of 291 m and level coordinates used below 291 m. Daily boundary conditions were taken from hindcasts and forecasts of a global model [*Barron et al.*, 2004]. Tidal forcing was provided for eight constituents using tidal elevation and depth-averaged normal and tangential velocities at the open boundaries from the Oregon State University tidal data bases. Tidal potential forcing was used in the interior. Atmospheric forcing was obtained from the Aire Limitee Adaptation Dynamique development InterNational (ALADIN) atmospheric model run by the Croatian Meteorological and Hydrological Service. The NCOM sea surface temperature (SST) was relaxed towards a satellite SST analysis. River and runoff inflows for the Adriatic were taken from the monthly climatological data base of *Raicich*

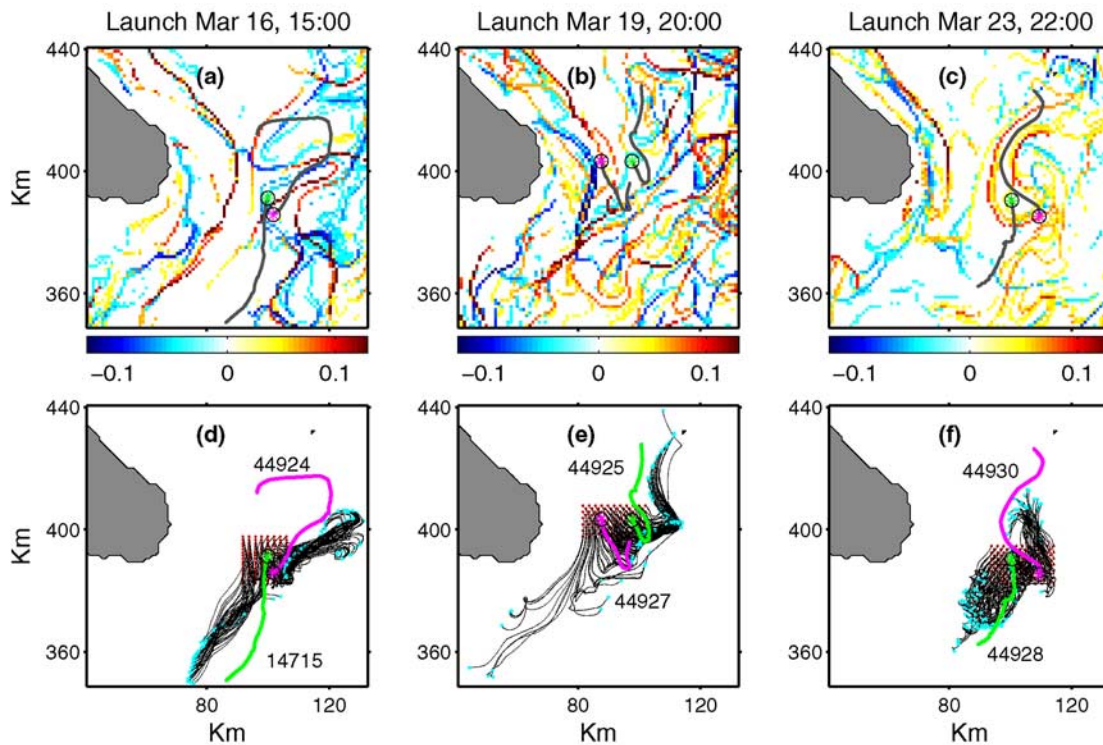
[1994], except for the Po river for which daily observed discharge values were used (courtesy of ARPA-SIM Emilia Romagna).

[11] Given the Eulerian model output, synthetic drifter trajectories were computed using standard particle advection techniques. A practical method to identify high-dispersion regions and mixing boundaries upon which to base drifter launch strategies is the computation of the Lagrangian spatial structures produced by the local, finite-size Lyapunov exponent (FSLE) [*Artale et al.*, 1997]. The FSLE is a measure of the time required for a pair of particles to separate a finite distance. The FSLE,  $\Lambda$ , is given by  $\Lambda(\mathbf{x}, t, \delta_i, r) = \tau^{-1} \log r$ , where  $\tau$  is the time required for a particle pair centered at  $\mathbf{x}$  with an initial distance  $\delta_i$  at time  $t$  to separate a distance  $\delta_f = r \delta_i$ .

[12] Model FSLE fields were calculated from sets of 5 synthetic trajectories centered at every grid point in the NCOM model. The FSLE map of the DART region at a particular day is obtained by advecting a total of 114,250 particles both forward in time from the 2 day-forecast velocities, and backward in time from the 2 day-hind-cast velocities.

[13] As explained by *d'Ovidio et al.* [2004] and *Molcard et al.* [2005], ridges in the FSLE field indicate potential transport barriers in the Lagrangian flow. The forward-in-time calculations approximate dynamically significant in-flowing Lagrangian structures while the backward-in-time calculations indicate the location of out-flowing structures. Hyperbolic regions of strong (near exponential) relative particle dispersion are evidenced by those locations where the in-flowing and out-flowing ridges intersect. Isolated intersections of FSLE maxima indicate the time-dependent location of hyperbolic trajectories in the flow. We refer to the coordinates of identifiable, isolated intersections of forward-backward FSLE maxima as hyperbolic points (HP) in instantaneous time-slices of the fields.

[14] The FSLE maps are used in conjunction with the daily velocity fields to locate persistent and isolated hyperbolic structures within the survey region. As seen in Figure 1, the high shear edge of the WAC is a region of intense foliation of Lagrangian structures shown by overlapping FSLE maxima. These mark the complicated pathways by which Lagrangian parcels are entrained and



**Figure 3.** The initial 2-day trajectories for real (gray in top panels, green and purple in bottom panels) drifters launched on March 16, March 19, and March 23 (launch position indicated by circles). Superimposed are (a, b, c) the FSLE ( $\delta_i = 0.45$  km and  $r = 40$ ) computed at launch time, and (d, e, f) synthetic drifters released in regular arrays. Red (blue) dots indicate initial (final) positions of the synthetic drifters.

detained from the boundary current. In this sense, the tangle of FSLE curves marks the spatial extent of the fluctuations in the WAC during the prescribed time interval. In contrast to the edge of the WAC, the FSLE calculations indicate a pair of semi-isolated intersections to the east in the interior region between the 2 cyclonic gyres. For the purposes of directing drifter launches, we concentrate on the area near the southern intersection, marked by a green circle in Figure 1, which lies along the predetermined ship track.

[15] Once the location of a strongly hyperbolic region was determined from isolated intersections of the FSLE fields from two-day NCOM forecasts and hind-casts, a subset of 10–20 synthetic drifters were launched in this selected area and advected by the 2-day-forecast fields as a preliminary test. Finally, 2–3 drifter launch locations were chosen to straddle the in-flowing structure and to lie as close to the out-flowing pathway as the ship-track would allow. These locations were then communicated to the ship on a real-time basis.

[16] Despite best efforts, practical constraints (weather, other observational priorities, etc.) affected the time between the launch prediction analysis and the actual time of drifter deployment. Also, model predictions of the location of strong FSLE maxima often occurred beyond the eastern boundary of the ship's predetermined track (Figure 1), further limiting number and duration of desirable spatial and temporal launch coordinates.

## 4. Results of Directed Launches

### 4.1. Launch Set 1: March 16, Buoys 14715 and 44924

[17] Due in part to the low-intensity winds (Figure 2a), the HP is particularly visible from the FSLE map (Figure 3a). Two locations are selected along the track corresponding to the out-flowing Lagrangian branches from the HP, based on the FSLE extrema. As a result, the drifters diverged immediately and propagated in opposing directions. The success of this launch is due in part to the nearly-stationary position of the HP over the following two days, and effectively real time implementation of the suggested launch locations. The synthetic trajectories also confirm the polarized nature of the Lagrangian dispersion in the vicinity of the launch, as all synthetic particles are transported along only two out-flowing branches (Figure 3d).

### 4.2. Launch Set 2: March 19, Buoys 44925 and 44927

[18] Launch locations were initially chosen based on the model-forecasted FSLE fields for March 17, to straddle an in-flowing branch of an identified Lagrangian structure boundary near a HP with the expectations of rapid divergence of the drifter pair. But, logistical problems delayed the actual drifter launch until March 19. As shown in Figure 3b, the model accurately predicts the rapid reaction of the flow to the changing wind conditions and the movement of strong intersections of FSLE maxima away from the previously determined launch locations. As such, the actual drifter launch occurred in a region predicted by the model to have minimal relative dispersion.

[19] The observed drifter trajectories shown in Figure 3b confirm the model predictions, showing little relative dispersion during the first 24 hours and reacting to the onset of the south-easterly wind stress by moving, coherently, to the North at later times. As seen in Figure 3e, synthetic drifters launched at the same time show a similar tendency to retreat to the North as the wind increases. As such, the results of Launch 2 support the converse to our proposed strategy. Drifters launched away from identifiable hyperbolic regions in the model do not exhibit significant amounts of relative dispersion on two day time scales.

#### 4.3. Launch Set 3: March 23, Buoys 44928 and 44930

[20] In this case, the deployment time was constrained by the finite extent of the observational program, with the latest possible launch date being March 24–25. While the model did not predict the presence of a strong, isolated, hyperbolic point along available ship tracks on March 23, Figure 3c indicates the presence of a Lagrangian structure boundary in the launch region as given by distinct maxima in the backward-in-time FSLE (the red curve). The actual drifter deployment placed one drifter in the interior of this structure and the other outside. This deployment leads to advection in nearly opposite directions and a rapid separation of the observed trajectories in keeping with the overall predictions of the model (Figure 3f). Drifter 44930 followed the pronounced northward pathway outside the model FSLE structure with remarkable accuracy (Figure 3c). Initially the other drifter, 44928, propagated southwards with the structure as predicted by the model. The observed drifter track shows appreciable slowing before further southern propagation due to the break up of the transport barrier blocking southward pathways one day after the launch (not seen in launch time FSLE plot). This change in structure and opening of advective pathways is presumably due to the influence of the Bora wind event.

[21] We emphasize the remarkable spatial complexity and rapid change of the model FSLE fields (Figures 3a, 3b, and 3c), forced and maintained mainly by winds and mesoscale turbulent coherent flow structures. While the envelope of synthetic drifter trajectories and the observed trajectories indicate significant differences, the model-derived FSLE fields (resulting from averages over both time and ensembles of trajectories) are apparently robust enough for accurate short-time prediction of the observations.

## 5. Summary and Conclusions

[22] Directed drifter launches were carried out in near real time during an observational program on the basis of identification of the Lagrangian structures using FSLEs from the output of a modern coastal model in order to maximize the relative dispersion of drifters. The model derived Lagrangian metric was capable of predicting the general fate of the observed drifter pairs. Overall, the accuracy of the surface Eulerian fields from state-of-the-art operational coastal models appears to have reached a level that is adequate enough for model-based Lagrangian

diagnostics to be used in real-time-directed drifter launches in observational programs.

[23] **Acknowledgments.** We are grateful to ONR via grants N00014-05-1-0094 and N00014-05-1-0095 (Haza, Griffa, Özgökmen), 0602435N (Martin, Book), N00014-03-1-0291 (Poulain), N00014-00-0019 (Poje), and to NSF via ATM-200102 (Poje). We thank Martina Tudor from CMHS for providing the ALADIN forcing.

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- R. Barbanti and P. M. Poulain, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante, 42/c, I-34010 Trieste, Italy.
- J. W. Book and P. Martin, Ocean Dynamics and Prediction Branch, Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS 39529, USA.
- A. Griffa, Istituto di Scienze Marine, CNR, Forte Santa Teresa, I-19036 La Spezia, Italy.
- A. C. Haza and T. M. Özgökmen, Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA. (tozgokmen@rsmas.miami.edu)
- A. Molcard, Laboratoire de Sondage de l’Environnement Electromagnétique Terrestre, Université de Toulon, F-83957 La Garde cedex, France.
- A. C. Poje, Department of Mathematics, College of Staten Island, City University of New York, 2800 Victory Boulevard, Staten Island, NY 10314, USA.
- M. Rixen and P. Zanasca, NATO Undersea Research Centre, Viale San Bartolomeo 400, I-19126 La Spezia, Italy.