FORECASTING SYNOPTIC TRANSIENTS IN THE EASTERN LIGURIAN SEA

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Abstract

Oceanographic conditions in the Gulf of Procchio, along the northern Elba coast, are influenced by the circulation in the Corsica channel and the southeastern Ligurian Sea. In order to support ocean prediction by nested models, an initial 4-day CTD survey provided initial ocean conditions. The purposes of the forecasts were threefold: i) in support of AUV exercises; ii) as an experiment in the development of rapid environmental assessment (REA) methodology; and, iii) as a rigorous real time test of a distributed ocean ocean prediction system technology. The Harvard Ocean Prediction System (HOPS) was set up around Elba in a very high resolution domain (225 m horizontally) which was two-way nested in a high resolution domain (675 m) in the channel between Italy and Corsica. The HOPS channel domain was physically interfaced with a one-way nest to the CU-POM model run in a larger Ligurian Sea domain. Eleven nowcasts and 2-3 day forecasts were issued during the period 26 September to 10 October, 2000 for the channel domain and for a Procchio Bay operational sub-domain of the Elba domain.

After initialization with the NRV Alliance, CTD survey data adaptive sampling patterns for nightly excursions of the Alliance were designed on the basis of forecasts to obtain data for assimilation which would most efficiently maintain the structures and variability of the flow in future dynamical forecasts. Images of satellite sea surface temperature were regularly processed and used for track planning and also

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for model verification. Rapid environmental assessment (REA) techniques were used for data processing and transmission from ship to shore and vice versa for model results. ADCP data validated well the flow in the channel. Additionally and importantly, the direction and strength of the flow in Procchio Bay were correctly forecast by dynamics supported only by external observations. CU-POM model hydrographic and geostrophic flow data was assimilated successfully on boundary strips of the HOPS domain. Flow fields with/without CU-POM nesting were qualitatively similar and a quantitative analysis of differences is under study. A significant result was the demonstration of a powerful and efficient distributed ocean observing and prediction system with in situ data collected in the Ligurian Sea, satellite data collected at SACLANTCEN, forecast modeling at Harvard University and the University of Colorado, and adaptive sampling tracks designed at Harvard. The distributed system functioned smoothly and effectively and coped with the adverse six-hour time difference between Massachusetts and Italy.

1. Introduction

The island of Elba lies off the western coast of Italy in the Corsican Channel, which connects the Ligurian Sea to the north and the Tyrrhenian Sea to the south (Fig. 1). The dominant large scale general circulation features of these two seas in late September 2000 are indicated in the sea surface temperature of the figure as an elongated cool pool of water (Ligurian Sea cyclonic gyre) and a pair of cool (cyclonic) and warm (anti-cyclonic) gyres in the Tyrrhenian. The circulation and variabilities of the Corsican Channel are driven interactively by the circulation and variabilities of the south-eastern Ligurian and northern Tyrrhenian, as well as by direct local atmospheric fluxes.

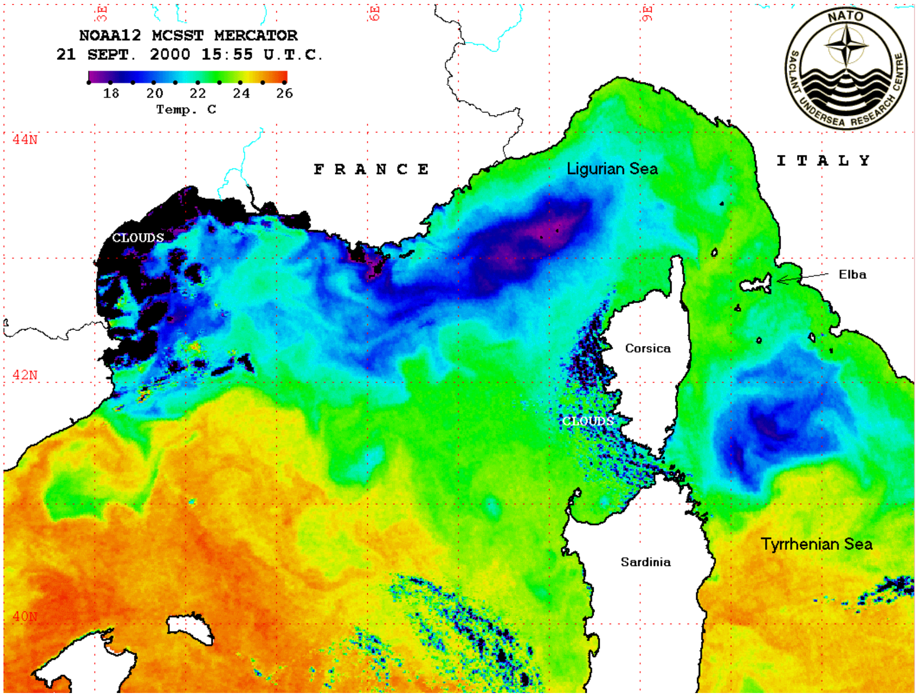

Figure 1 *Satellite sea surface temperature in the Ligurian-Provencal Basin and the Tyrrhenian Sea during the initialisation survey.*

In the early fall of 2000, the Harvard Ocean Prediction System (HOPS), schematized in Fig. 2 [1], carried out real time ocean forecasts for the Corsican Channel with a focus on the Gulf of Procchio, an embayment of approximately 2km x 4km located along the northern coast of the island of Elba. During the forecast period, experiments on the use of autonomous underwater vehicles (AUVs) in the littoral environment were conducted in Procchio Bay by scientists from the NATO SACLANT Undersea Research Centre (SACLANTCEN) co-operatively with partners from several countries. The purposes of the forecasts were threefold: i) in support of the AUV exercises; ii) as an experiment in the development of rapid environmental assessment (REA) methodology; and, iii) as a rigorous real time test of our distributed ocean prediction system technology.

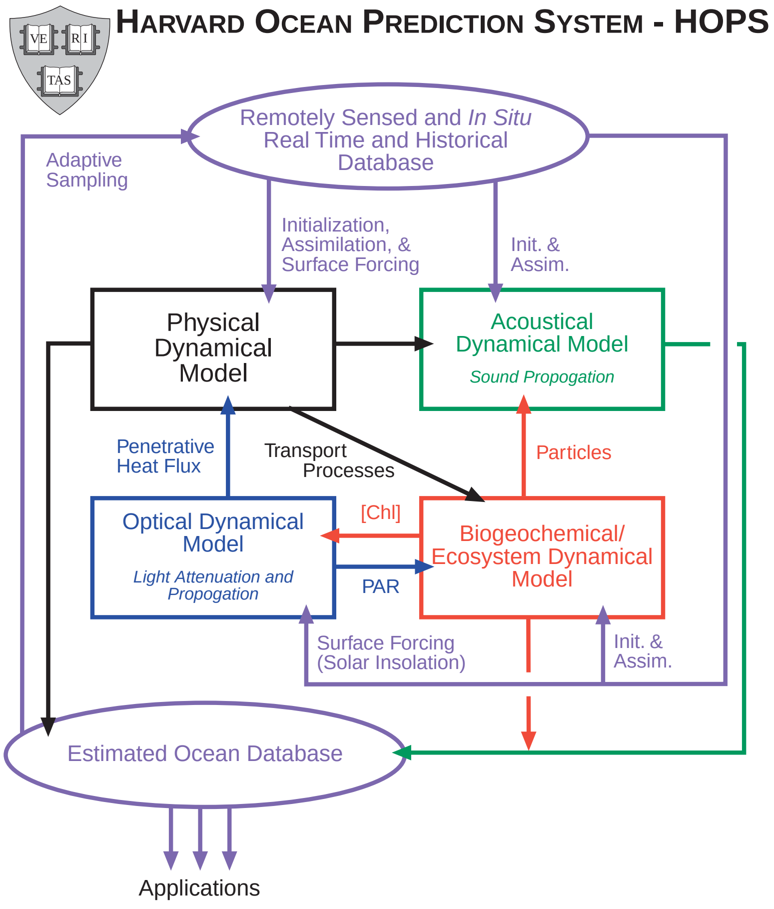

Figure 2 *The Harvard Ocean Prediction System (HOPS).*

The AUV experiments, which included engineering trials and novel operational methods, were related to mine counter-measure applications and carried out in the context of a research project dedicated to Generic Oceanographic Array Technology Sonar (GOATS). Specific tasks accomplished during the exercise are: underwater navigation, bottom mapping, object detection and classification and the operation of multiple vehicles in a network [2].

The NATO rapid environmental assessment concept involves the development of a capability to set up a portable and generic ocean observing and prediction system in any region of the world ocean efficiently in a short time [3] and is relevant to numerous civilian applications, such as crisis response and temporary marine operations. The Harvard and SACLANTCEN team have carried out a number of REA exercises together in a variety of regions over the past five years [4]. A novel aspect of the present forecasts is the forcing of the Corsica Channel region by the external general circulation and the concomitant forcing of the Procchio Bay operational domain by the Channel circulation. Thus this forecast experiment was named multiscale environmental assessment studies (MEANS). The HOPS forecast modelling domains (Fig. 3) consisted of a very high resolution Elba domain two-way nested in a high resolution Channel domain with open boundary conditions to the north and south. Additionally, the HOPS Channel domain was also nested in a larger Ligurian-northern Tyrrhenian domain (Fig. 3) in which forecasts were carried out with the Colorado University-Princeton Ocean Model (CU-POM). The one-way nesting provided boundary conditions from CU-POM by interpolation to the HOPS northern and southern boundaries. Furthermore, boundary conditions for the CU-POM forecasts were provided by the routine ongoing forecasts from the US Naval Oceanographic Office Mediterranean Sea general circulation model (Shallow Water Analysis and Forecast System (SWAFS) [5]). This note presents results from the HOPS Channel and Elba domain forecasts. Comparison with the HOPS nested in CU-POM forecasts will be presented elsewhere by a different set of authors.

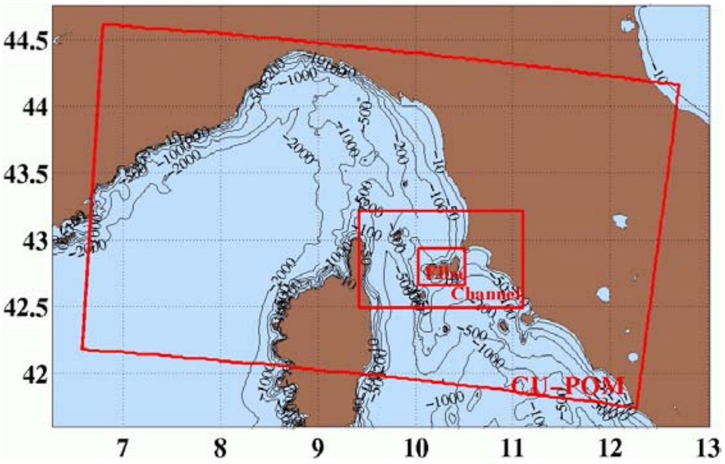

Figure 3 *HOPS and CU-POM modelling domains.*

Data for forecast model initialization was obtained by the NATO research vessel *Alliance* during a four day hydrographic survey covering a uniformly spaced mapping grid (Fig. 4). Subsequent data for updating assimilation was obtained via sampling patterns adapted to optimize data impact according to the ongoing forecasts. As the NRV *Alliance* supported AUV operations during the day, the update excursions took place at night, with Procchio Bay fixed as both a starting and ending point, which imposed a severe restriction on adaptive sampling design. Through modern communications and Internet technology, a distributed system was established which separated data acquisition and processing, which took place aboard the NRV *Alliance*, from dynamic analysis, data assimilation, forecasting and adaptive sampling design, which took place at Harvard University in Cambridge, Massachusetts. The distributed system functioned successfully and efficiently, although the logistics of assimilating yesterday's data today for tomorrow's adaptive sampling, which are always demanding [6], were exacerbated by the six hour time lead of Italy relative to Massachusetts.

During the period 25 September through 9 October 2000, 11 sets of model forecast products were issued. These products included nowcasts and forecasts of fields of temperature, salinity and current velocity for the surface and 50m in the deep ocean domain and at the surface for the shallow domain. Additional data acquired on NRV *Alliance* or other platforms such as AUVs, buoys, bottom moorings and satellites were used for model verification rather than assimilation into the model run. The comparisons with satellite sea surface temperatures and ship-borne Acoustic Doppler Current Profiler (ADCP) data are most striking. A noteworthy result was the ability to forecast the Procchio Bay circulation by assimilating into the dynamical model only data external to the Bay. These forecasts with data assimilation provide a more detailed picture of the circulation and variabilities of the Corsican Channel than previously available. The Capraian Eddy, a mesoscale anti-cyclone around Isola Capraia was not, to our knowledge, previously identified in the literature.

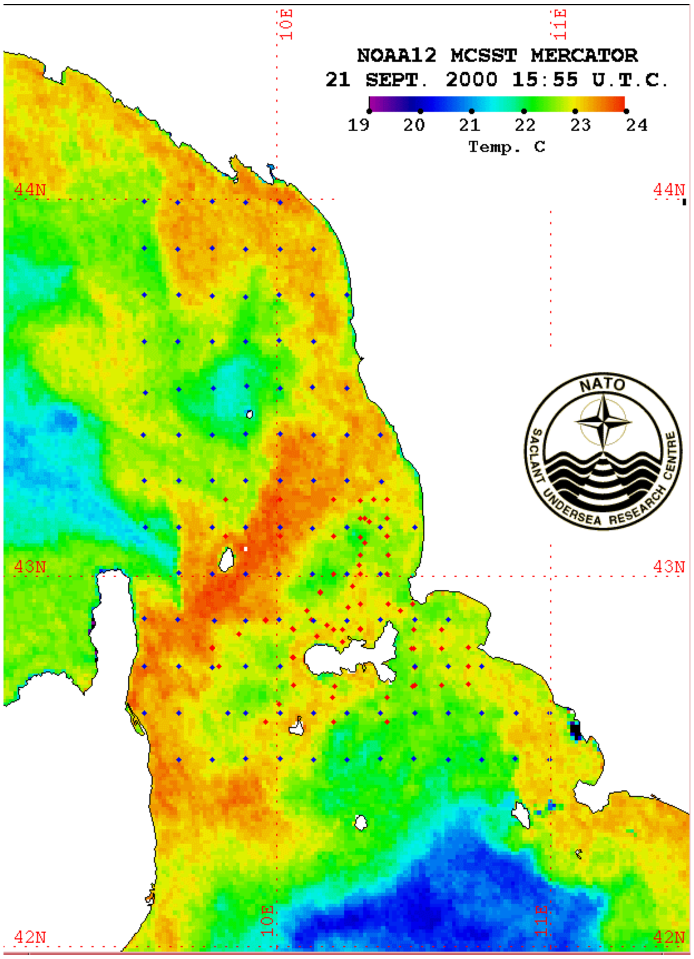

Figure 4 *Eastern Ligurian Sea with locations of CTD stations during the initial survey (blue symbols) and update excursions (red symbols). The satellite sea surface temperature image is a magnification from Fig. 1.*

Subsequent sections describe: data indications, forecasts, adaptive sampling, forecasts validations, the Capraian Eddy, the distributed system and conclusions.

2. Direct data indications

The satellite sea surface temperature image of 21 September 2000 (Fig. 1) is consistent with previous knowledge about the general situation in the Ligurian and northern Tyrrhenian Seas. In a season with a pronounced thermocline, local low temperature signatures at the surface can indicate phenomena such as: a different water type advected from somewhere else, higher wind stress that through stronger turbulence increases mixing with the underlying colder water mass, or a shallower thermocline in the centre of a cyclonic eddy or in another upwelling situation, which under unchanged wind conditions favours the cooling of the mixed layer by erosion of the underlying colder water.

Bonifacio Strait, between the islands of Corsica and Sardinia, is famous for strong wind [7]. Also, directly east of the strait, westerly wind is stronger than in the shadow of the islands. An area of enhanced turbulence is reflected by lower temperatures. The prevailing westerly wind through the strait induces a pair of eddies in the northern Tyrrhenian Sea [8]. The cyclonic eddy in the north lifts up the thermocline with the consequence of a cool surface signature (e.g. [9]). On both sides of Corsica currents are directed to the north [10,11]. North of Corsica, the combined flow sets along the Riviera coast, thus closing the loop for the Ligurian Sea cyclone [12].

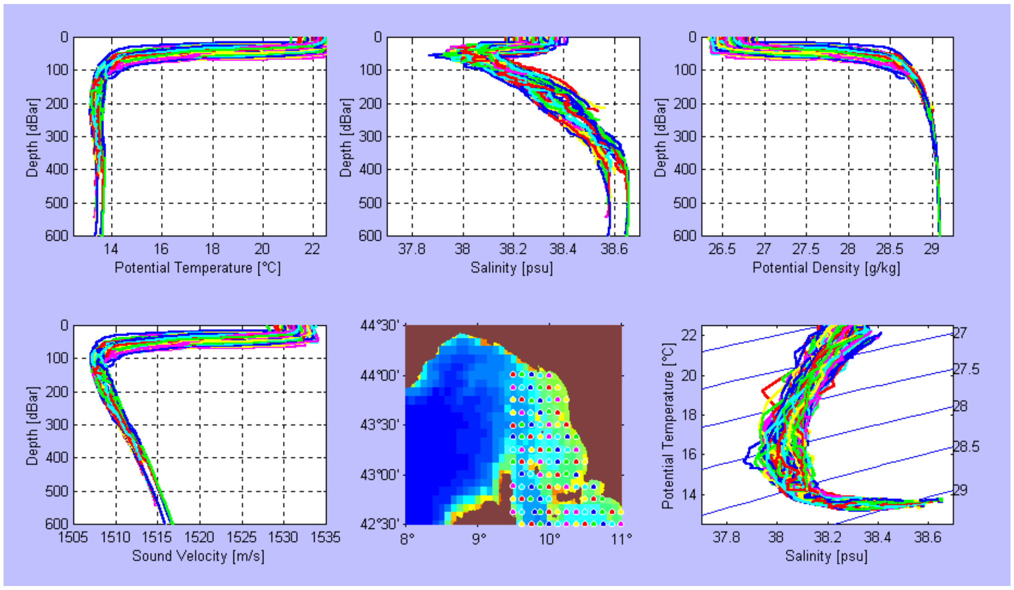

Figure 5 *CTD stations of the initialisation survey. Profiles of salinity, density anomaly and sound velocity are calculated from measured parameters. The two branches in salinity below 400m mark the difference between Ligurian and Tyrrhenian Sea intermediate water.*

Compared with the northern Tyrrhenian and western Ligurian Seas, the area north of Elba seems to be dynamically quiet. Figure 5, which shows all the CTD profiles of the initial survey of the *Alliance*, gives an impression of the data spread. Below 400m, which is the sill depth of the Corsica Channel, the profiles separate into the Tyrrhenian and Ligurian branches of Levantine intermediate water (LIW). The LIW of the Ligurian-Provencal Basin is fresher and cooler because of the deep convection that takes place in the Gulf of Lyon in winter [13]. Differences between the actual situation during the MEANS survey and climatology are exemplified in Figs. 6 and 7. Measured profiles are compared with GDEM [14] profiles for approximately the same location. At the western boundary of the survey area, the measured profile is cooler and denser than GDEM in the depth range from 50 to 300m, but GDEM lies well within the variance of all profiles. At the southern boundary in the Tyrrhenian Sea, GDEM temperature matches the measured profile quite well, but salinity differences cannot be overlooked, especially below the depth of the sill to the Ligurian Sea.

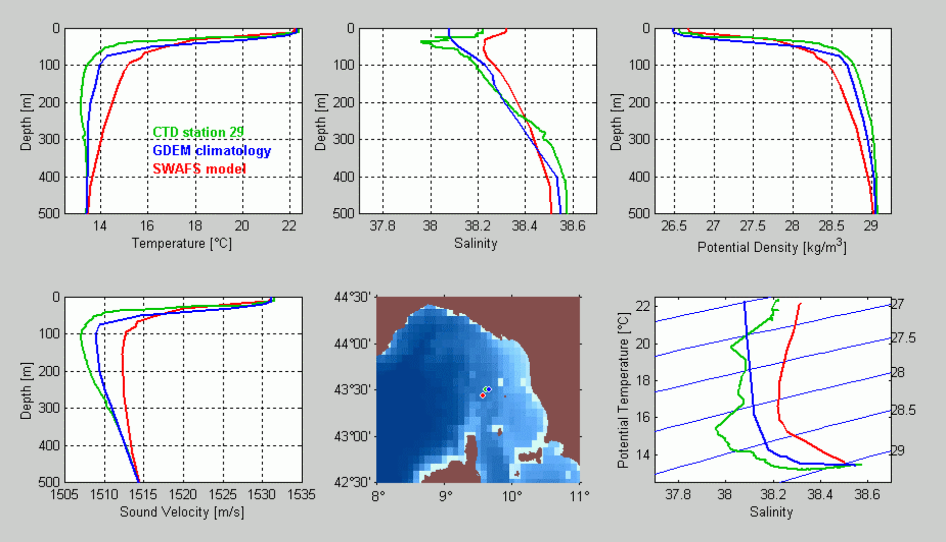

Figure 6 *A measured CTD profile (note the red dot on the map) at the western survey boundary in the Ligurian Sea compared with a mean profile from climatology. The transitional water between 50 and 300m depth is significantly colder than climatology. Also shown is a profile from an operational navy model run, which was used a boundary condition for the CU-POM model.*

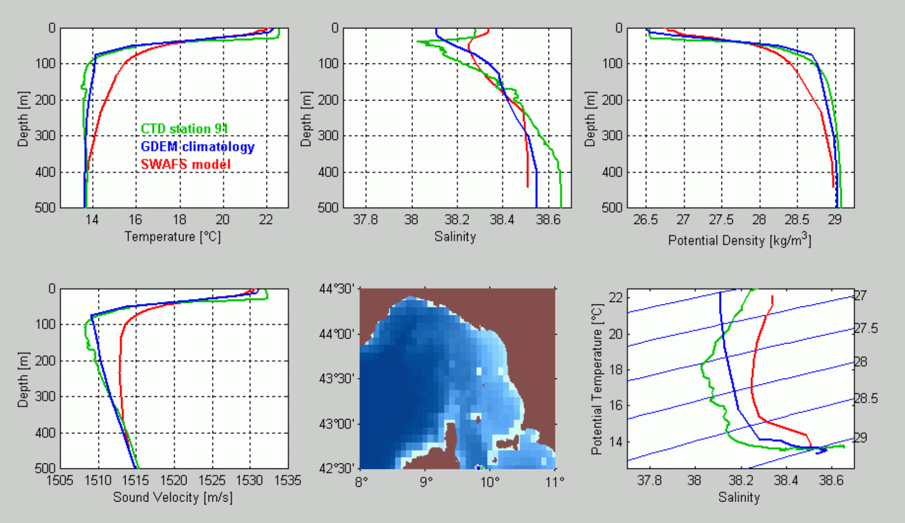

Figure 7 *A measured CTD profile (note the red dot on the map) at the southern survey boundary in the Tyrrhenian Sea compared with a mean profile from climatology. Climatology does not reflect the higher salinity in Thyrrhenian Sea intermediate water. Also shown is a profile from an operational navy model run, which was used a boundary condition for the CU-POM model.*

The sea surface image of the survey area (Fig. 4), which shows the positions of the CTD profile measurements, is displayed with an enhanced temperature scale. A pool of cool water is located in the eastern Ligurian Sea. It is correlated with a local minimum of the thermocline depth defined by the 18º C isotherm (Fig. 8). The uplift of the thermocline suggests a cyclonic eddy being present in this location. The East Sardinia Current carrying warm surface water would be steered towards the Italian coast. This assumption is supported by salinity at the 28.5 kg m^{-3} pycnocline which, because of its origin in the Tyrrhenian Sea, is 0.1 units higher below the warm surface streak than in the intermediate water to its left.

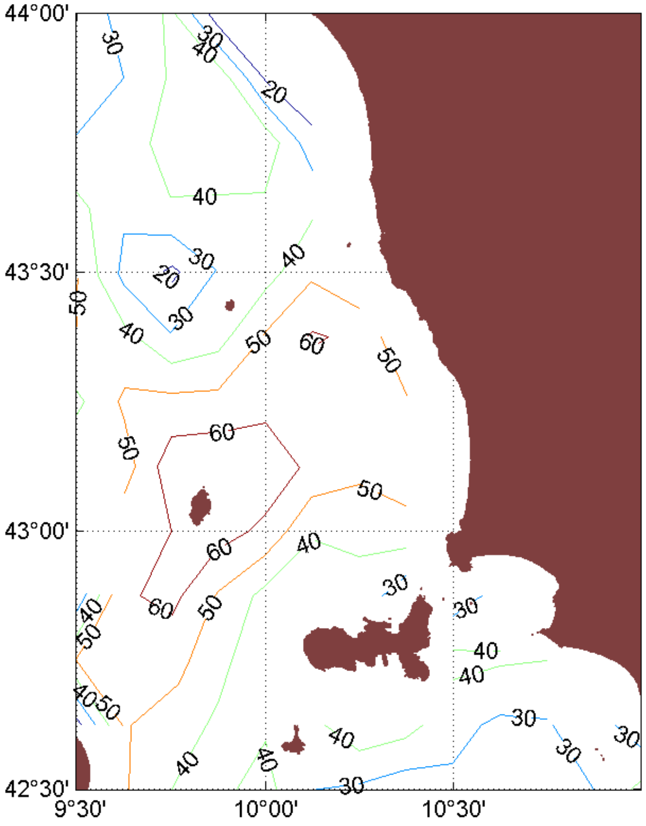

Figure 8 *Depth of the 18º C temperature plane representing the thermocline during the initial survey.*

One week later surface warming has diminished the signature of the cyclonic eddy in the eastern Ligurian Sea in the satellite image of sea surface temperature (Fig. 9). The warm band north of Elba has now, however, assumed the shape of a disc, which could be an indication that it was transformed into an anti-cyclonic eddy. Accumulated along-track ADCP current measurements in the same time period show, in fact, an anti-cyclonic eddy in exactly the indicated position (Fig. 10). The anticyclone is present for the rest of experiment, slightly changing position and strength. Figure 11 shows along-track current measurements a week later than for Fig. 10.

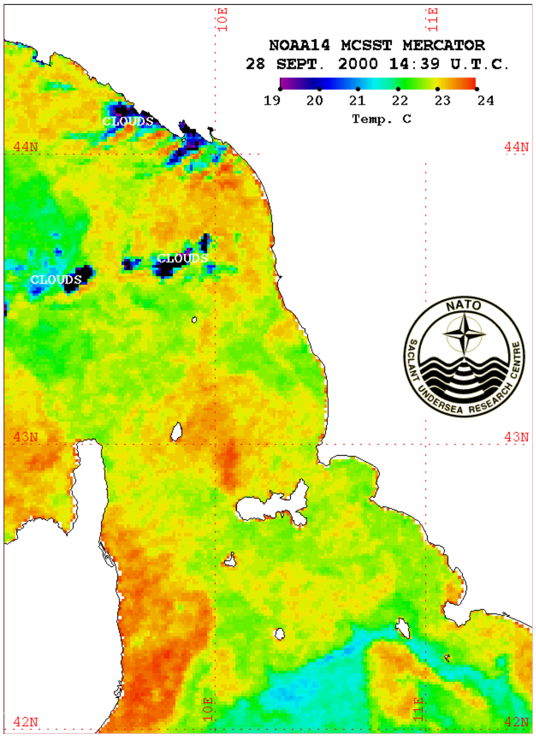

Figure 9 *Satellite sea surface temperature in the eastern Ligurian Sea one week after the initialisation survey.*

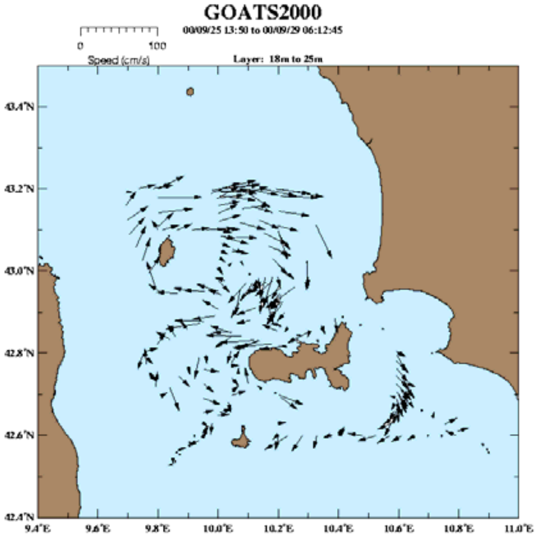

Figure 10 *Currents measured by NRV Alliance with the ship-borne ADCP during the first update surveys. Data of 4 consecutive nights are merged. The SE current in the south-eastern corner is due to high wind force.*

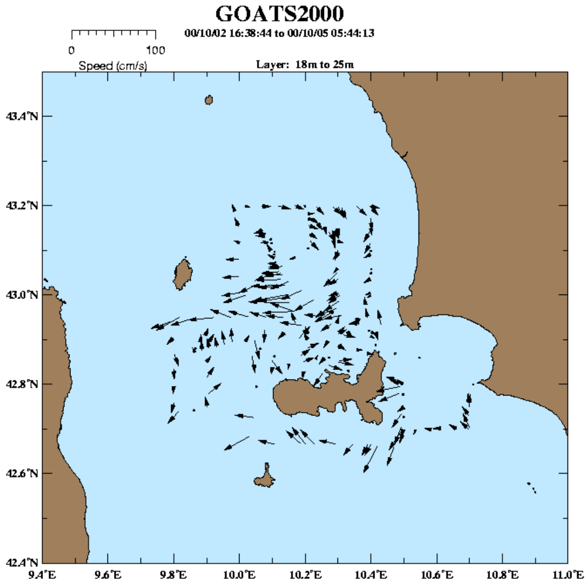

Figure 11 *Currents measured by NRV Alliance with the ship-borne ADCP during update surveys in early October. The anti-cyclonic eddy has shifted towards the north.*

The southern edge of the anti-cyclone reaches to the north coast of Elba. It can therefore be assumed that the experiment area in the Gulf of Procchio is under the influence of a westward current. Very close to shore, an upward looking ADCP was moored in 10m water depth. In Fig. 12, current vectors are plotted for all 30cm depth intervals within the current profile. Vectors of the sequential 90-second record intervals continuously appended to a virtual track, give an impression of the flow at the current meter position, although real tracers would deviate from the tracks in the figure because of the inhomogeneity of the current field. In 3 days, a mean vector velocity of 1 cm/s would displace a tracer 2.6km from its origin, which is close to the distances in the figure. The indicated displacements suggest velocities of approximately 0.4 to 1.3 cm/s. In the upper water column, currents are pointing to the west-southwest. The shoreward component is compensated by outflow to the northwest close to the bottom.

Autonomous underwater vehicles (AUV), which were used for bottom mapping during the GOATS experiment, were also tasked to collect oceanographic data. Only very short sample tracks were realised. Continuously ascending and descending, the AUV collected temperature and salinity. The example of Fig. 14 was measured on the track across the entrance of the bay indicated in Fig. 13. Since the track does not intersect potential water mass boundaries, the temperature is quite homogeneous with only 0.2° C difference across the front. Because of the slower temperature sensor in comparison with pressure, the front appears shifted up and downward in the ascending and descending cycles.

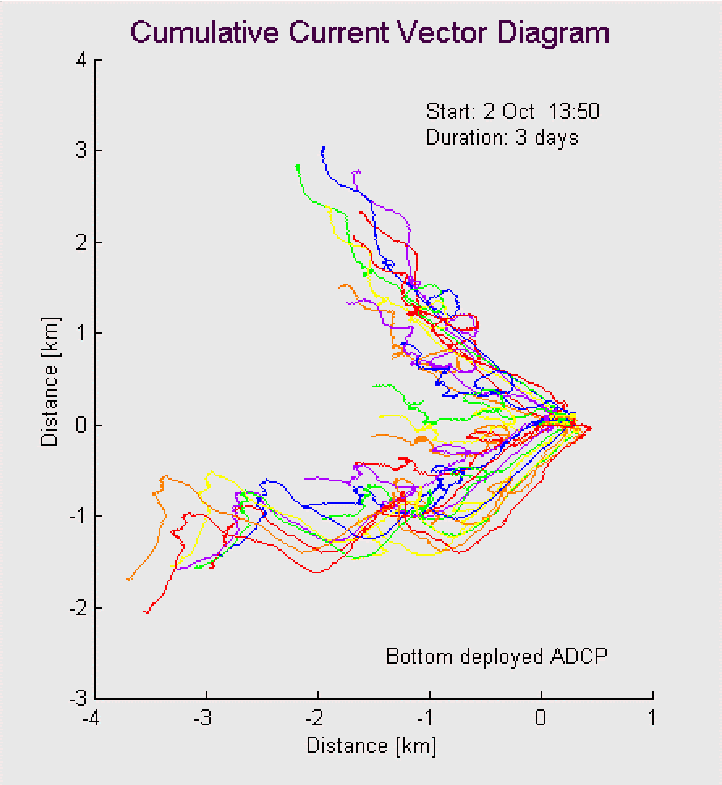

Figure 12 *Current measurement at the north coast of Elba. For each 30cm depth interval (bin), current vectors measured by an Acoustic Doppler Current Profiler are accumulated. Curves of bins close to the surface point to WSW, close to the bottom to NW.*

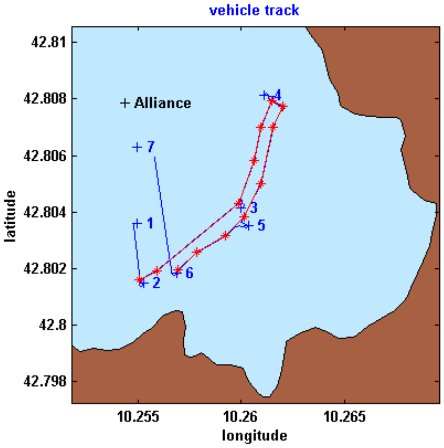

Figure 13 *Track of an autonomous underwater vehicle (AUV) north of Elba. The AUV samples temperature and salinity while it ascends and descends along its track. At the positions marked with an asterisk the AUV surfaces and updates navigation by the global positioning system (GPS).*

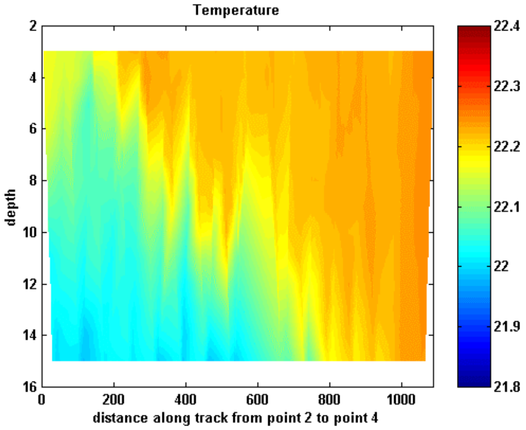

Figure 14 *Temperature measurement by the AUV between the endpoints of the track in Fig. 13. Temperature values are interpolated between upward and downward profiles. The apparent oscillation of the front is an artifact caused by different sensor response times.*

3. Data assimilation, model nowcasts and forecasts

3.1 Forecast methodology

The Harvard Ocean Prediction System (HOPS, Fig. 1) consists of data analysis and assimilation schemes, and a suite of coupled interdisciplinary (physical-acoustical, biogeochemical-ecosystem) dynamical models [1,15]. HOPS employs a primitive equation (PE) physical dynamical circulation model. Boundary layers (top and bottom) and isopycnal and diapycnal turbulence are modeled through process parameterization, turbulence closure schemes, or scale-dependent filters. Multiple sigma vertical coordinates are calibrated for accurate modelling of steep topography. Multiple two-way nests are an existing option for the horizontal grids.

HOPS was used to build and maintain a regional synoptic description through nowcasting, forecasting and assimilation. An initial synoptic field was constructed by global objective analyses of the data taken during the experiment. The data set from 19 to 24 September 2000 for model initialisation consists of 107 CTD profiles over the region 42.5-44^{o} N, 9.5 - 11^{o} W (Fig. 2). During night-time surveys from 25 September to 9 October, another 77 CTD profiles were obtained. This data, acquired via adaptive sampling designed to have optimal impact and control predictability, was assimilated. In addition, 44 expendable CTD profiles (XCTD) and 75 expendable temperature profiles (XBT) were collected. Unfortunately, due to general unreliability of the upper layer (~ 40m) salinity of the XCTDs, and the lack of salinity from the XBTs, these profiles could not be assimilated for modelling purposes in the real-time operation. The profiles were used for model verification.

HOPS data assimilation, which melds observations with dynamics, provides the most feasible basis for obtaining accurate synoptic mesoscale realizations over the space-time scales and domains of interest [16]. Data assimilation methods used by HOPS include a robust (suboptimal) optimal interpolation (OI) scheme as well as a quasi-optimal scheme called Error Subspace Statistical Estimation (ESSE) [17,18,19]. The ESSE method determines the nonlinear evolution of the oceanic state and its uncertainties by minimizing the most energetic errors under the constraints of the dynamical and measurement models and their errors. Real-time efficiency is achieved by reducing the error covariance to its dominant eigen-decomposition. Data assimilation is utilized for a variety of purposes. Among them: control of predictability error; correction of model dynamical deficiencies; parameter estimation; process studies; simulations, Observation System Simulation Experiments (OSSEs) and sensitivity analysis.

Atmospheric forcing for HOPS was acquired from the US Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC). The products, including 00Z and 12Z nowcasts and forecasts for up to 144 hours on a 1-degree or 2-degree resolution grid, are downloaded via the internet. The model and analysis fields were generally produced on a one-degree grid, with the exception of relative humidity and cloud cover. FNMOC fields include surface pressure, air temperature, 12-hour forecast precipitation, surface winds, relative humidity, cloud cover, sea surface temperature and mixed layer depth. These gridded fields were interpolated in space and time onto the model grids by HOPS and are used to compute fluxes that drive the HOPS models at the surface. Flux analyses were used whenever possible and forecast fluxes replaced by the analyses as those analyses became available.

Each working day, data was analyzed and gridded into fields, model runs performed, adaptive sampling plans designed and disseminated, and nowcasts and forecasts issued via the GOATS web site. The HOPS modelling was performed under the guideline: "assimilate yesterday's data today for tomorrow's forecast". In other words, each morning, data collected during the previous day and night was available to be processed and analyzed. The data was utilized in model runs that produced nowcasts and forecasts to be issued the next day. The HOPS model system was run at Harvard University on a set of Sun Ultra-80 quad-processor workstations. In addition to the HOPS modelling, a form of the Princeton Ocean Model (POM) was being run at the University of Colorado under the guidance of Prof. Lakshmi Kantha. Model results from the CU-POM were used to provide boundary conditions for the HOPS model as a demonstration of inter-model nested operations.

3.2. Modelling domains and products

The design of the modelling domains was accomplished by first reviewing the dynamical processes in the region and examining the topographic influences on these processes. These issues are balanced against the computational resources required for the simulations. The model system was tuned by investigating objective analysis (OA) parameters in local (such as around Elba) and far-field (in the Ligurian Sea) regions, temporal correlation parameters, various dynamical model parameters, assimilation criteria, vertical resolution, assimilation methodologies, etc, through a series of OSSEs. The domains were further refined based on these results and the sensitivity studies redone until a robust oceanographic observation and prediction system (OOPS) emerged. The model tuning was validated by comparing model output fields with objective analysis maps of data, AVHRR imagery, and documented circulation patterns in the region.

The operational nested modelling domains for real-time nowcasting and forecasting were known as the "Channel" and "Elba" domains. These HOPS domains are pictured in Fig. 15. Figure 16 depicts the process of the two-way nesting. At each time step, independent estimates are made in each domain. The left-hand panel indicates how the coarse grid (green circles) is interpolated using bi-cubic interpolation onto the fine grid boundaries (green highlighted plus signs). The right-hand panel demonstrates how the fine grid data (plus signs) is averaged onto a coarse grid node (red circle). Collocation of the two grids simplifies navigation between the coarse nodes and supporting fine grid nodes. A 3:1 horizontal resolution ratio is used for scale matching. The "Channel" domain was centred at 42.85°N, 10.26°E. The domain included 203×120 horizontal grid points at 675m resolution. The physical extent of the domain, therefore, was 136×80km. The "Elba" domain was centred at 42.80°N, 10.27°E. The domain included 173×138 horizontal grid points at 225m resolution. The physical extent of this domain was 39×31km. Each modelling domain included 20 vertical sigma levels. The bottom topography of this region was particularly challenging due to locations of very rapid changes in bottom depth.

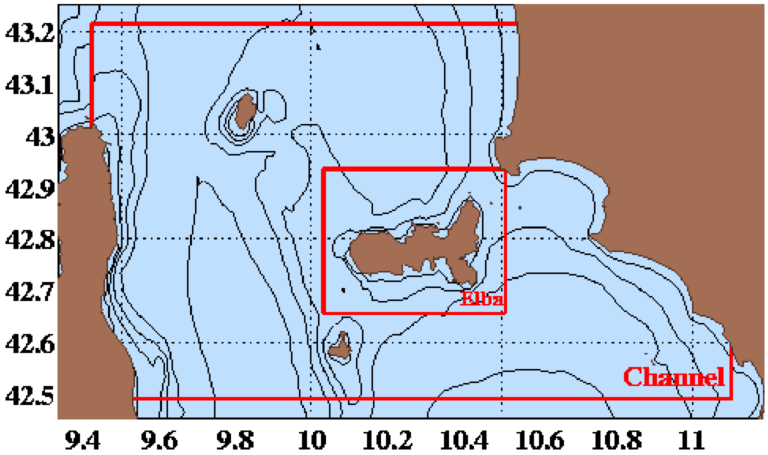

Figure 15 *Schematic of the HOPS operational nested modelling domains.*

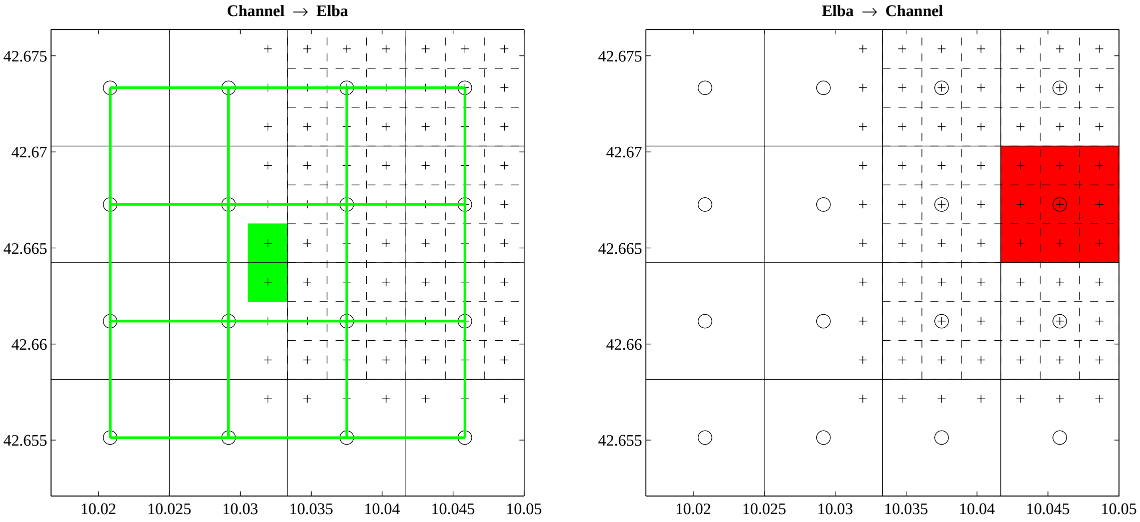

Figure 16 *2-way nesting for modelling domains. (left) Channel to Elba (coarse to fine), (right) Elba to Channel (fine to coarse).*

Products were issued for the entire "Channel" domain and for a sub-region of the "Elba" domain that included only the area of Procchio Bay. This Procchio Bay product focused on the AUV area of interest and operations.

The standard suite of GOATS/MEANS products included:

- A description of the forecast products
- A discussion of the current model forcing (e.g., winds, oceanographic features) and the analysis/forecast fields
- Comments on forecast methodology
- Synoptic (nowcast) maps for:
    - Temperature (surface and 50m)
    - Salinity (surface and 50m)
    - Current speed (sub-tidal velocity vectors at the surface and 50m)
- Twenty-four (24) and 48-hour forecast maps for:
    - Temperature (surface and 50m)
    - Salinity (surface and 50m)
    - Current speed (sub-tidal velocity vectors at the surface and 50m)

3.3 Forecast results

During the period 26 September through 9 October 2000, 7 sets of products were issued for the Channel Domain. In addition to the GOATS web site, the products were (and are) available from a Harvard web site (http://www.deas.harvard.edu/~robinson/GOATS/index.html). The dates of the product releases are: 26, 27 and 28 September, 1, 4, 5 and 9 October. As mentioned above, each of these products included a nowcast and one or two-day forecasts of the physical conditions in the model domain. Figure 17, a nowcast for 28 September and a forecast for 29 September, provides an example of the type of product issued. The Channel Domain provided the external influence for the finer resolution Elba Domain. Within this domain the upper water column responded rapidly and properly to strong wind events, as exemplified in Fig. 16. ADCP measurements provided independent verification of the Channel Domain forecasts including: a mesoscale anticyclone north of Elba; flow into Procchio bay from the northeast; northward flow between Corsica and Isola Capraia; westward flow south of Elba (probably the northern edge of a cyclonic structure in the Tyrrhenian Sea); robustness of forecasts after strong wind events (e.g. 30 Sept. - 1 Oct., 8-9 Oct.) - i.e. the system returns to the background dynamical state after the passage of a storm.

Three sets of Procchio Bay products were issued from a sub-sample of Elba Domain forecasts via the GOATS web site from 4-10 October 2000. As for the Channel Domain, the products are also available from the Harvard web site. Figure 18 is an example of the Procchio Bay products, showing plots of surface temperature and sub-tidal velocity for 9 October. The Elba Domain was a demonstration of nested modelling for forecasting in shallow waters and the ability to combine dynamics and data external to the area to achieve proper results. The importance of adaptive sampling was demonstrated by the design of tracks for AUVs in Procchio Bay after data and model analysis concluded that original sampling plans were not optimal for the synoptic conditions. Once again, ADCP measurements provided independent verification of the forecasts including: larger velocities outside of Procchio Bay as compared to inside the bay; and, a flow of 0.5 - 1.5 cm/s to the west-southwest inside of Procchio Bay. Note, however, while the model forecast of currents compares well with data at the surface, forecasting accurately both speed and direction, the deeper estimates of velocities do not correspond as well to the ADCP measured velocities to the northwest.

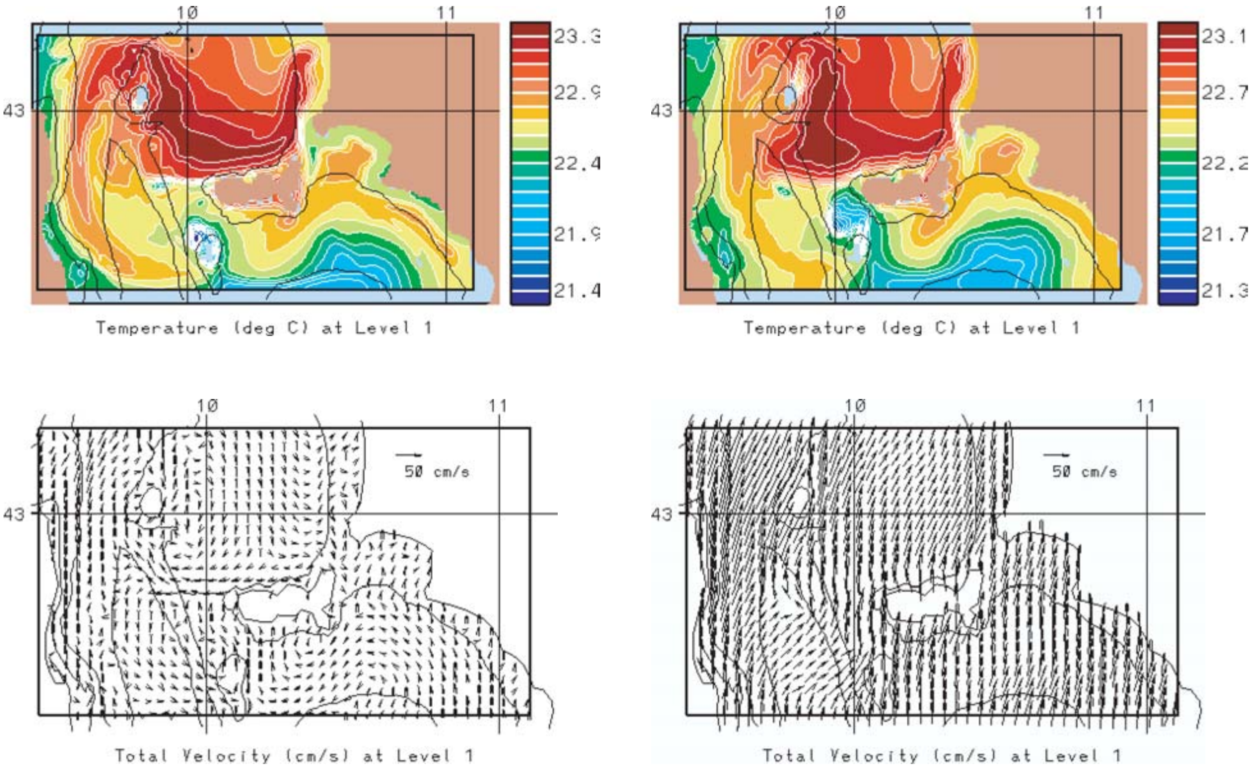

Figure 17 *Example HOPS product from the Channel modelling domain.*

As mentioned above, in addition to the HOPS modelling at Harvard, a form of POM was run at the University of Colorado. Ligurian Sea fields from CU-POM were used to provide boundary conditions for the HOPS Channel Domain model as a demonstration of inter-model nested operations. Proper utilization of the model results necessitated studying issues of model compatibility, including physical parameterization, domain mismatch. The CU-POM fields were utilised in HOPS via time intermittent assimilation and the direct assimilation of temperature and salinity at open boundaries. Velocity fields were not assimilated. There was general qualitative agreement between the CU-POM and HOPS models. Causes and the details of the differences remain to be attributed, based on data. Figure 19 shows the HOPS and CU-POM fields for 4 October 2000. The warm patch at the northeast corner of the domain was the most readily identifiable difference between the model fields and appears, at this time, to be a model artifact.

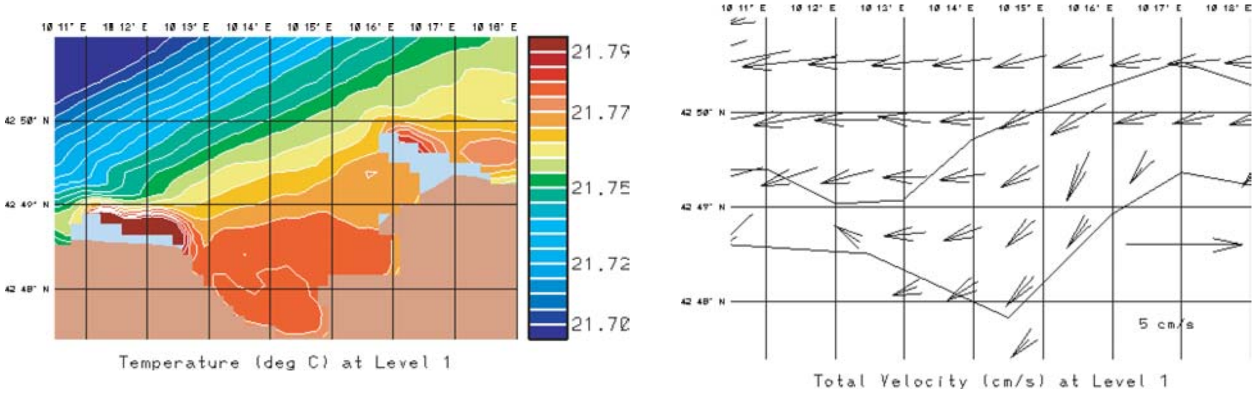

Figure 18 *Example HOPS product from the Elba (Procchio Bay) modelling domain.*

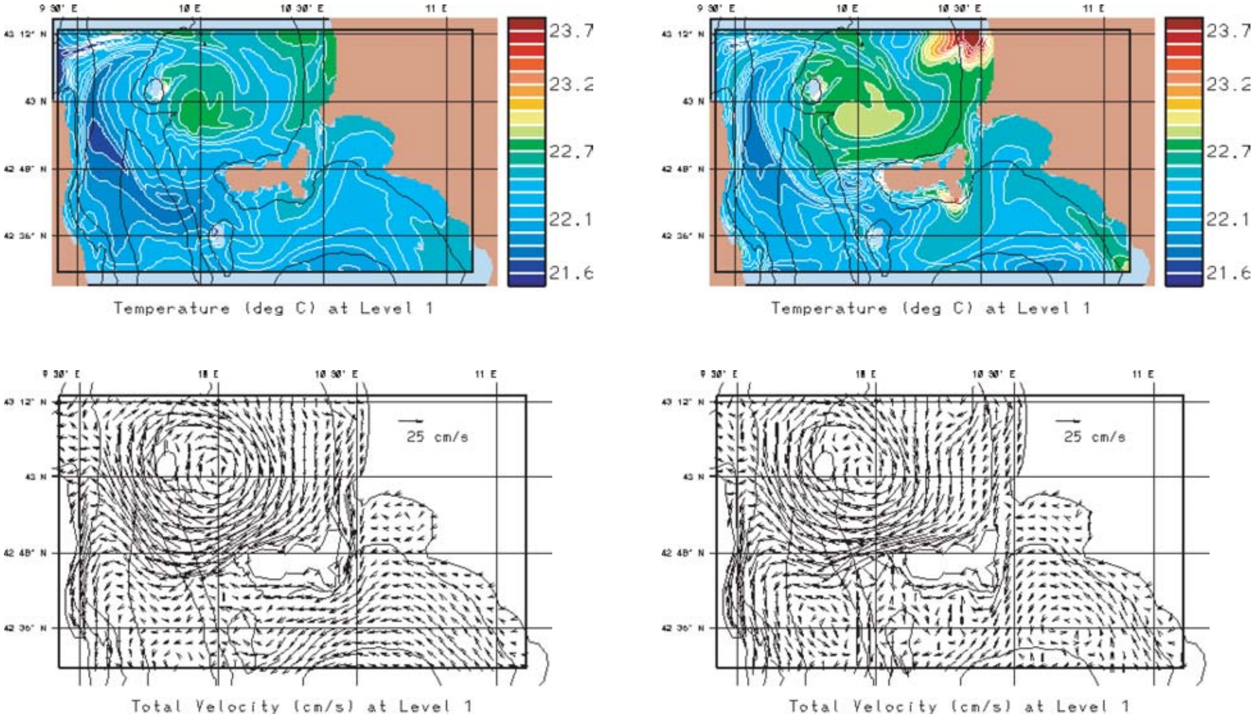

Figure 19 *A comparison of HOPS (left) and CU-POM (right) results for 4 October 2000.*

4. Adaptive sampling

Uniformly sampled observations are generally utilized for initialization and assimilation as forecasts advance in time. Sampled uniformly over a predetermined space-time grid, these observations are usually adequate to resolve most scales of interest. However, only a small subset of the observations has a significant impact on the accuracy of the forecasts. The impact subset is related to intermittent energetic synoptic dynamical events. *Adaptively sampled* observations are preferable for initialization and assimilation as forecasts advance in time. The sampling scheme is tailored to the ocean state to be observed based on knowledge of the ocean state from ongoing observations, nowcasts and forecasts. Adaptive sampling targets observations that will have the greatest impact on knowledge, resolve scales of interest, and improve forecast accuracy. Efficient adaptive sampling can reduce observational requirements by one or two orders of magnitude.

Adaptive sampling schemes can be either subjective, objective or a combination of both. Sampling can be based on environmental forecasts or error forecasts. Forecast information is combined with *a priori* experience to intuitively choose future sampling. Objectively, the forecast serves as input to a quantitative sampling criterion whose optimization predicts the adapted sampling. A goal is automated objective adaptive sampling.

Specific goals of the adaptive sampling for GOATS/MEANS included: specification of the sampling patterns for the AUVs; sampling in regions not yet covered to locate local structures; sampling in regions not recently covered to understand the evolution of structures; sampling to determine the strength and structure of the anticyclone north of Elba; sampling to determine the general nature of the flow in vicinity of Procchio Bay (e.g.. is it from the north or the result of flow through the Corsican Channel from the Tyrrhenian turning around the island?); sampling to evaluate the structure and evolution of the flow between Corsica and Elba; sampling to determine the impact of the flow between Elba and the coast of Italy; and, sampling to determine the nature of conditions in Procchio Bay.

The adaptive sampling patterns (Fig. 20) were designed on a nearly-daily basis based on the goals described above and sent to the NRV *Alliance*. Patterns were designed both for large scale adaptive sampling carried out by the *Alliance* and for the AUV sampling in Procchio Bay. The efficacy of the distributed system discussed in Section 6 is illustrated by the fact that scientists local to the sampling area and on board the vessels performing the sampling requested adaptive sampling patterns from scientists located thousands of kilometers away who were performing the detailed studies of the fields and their evolution.

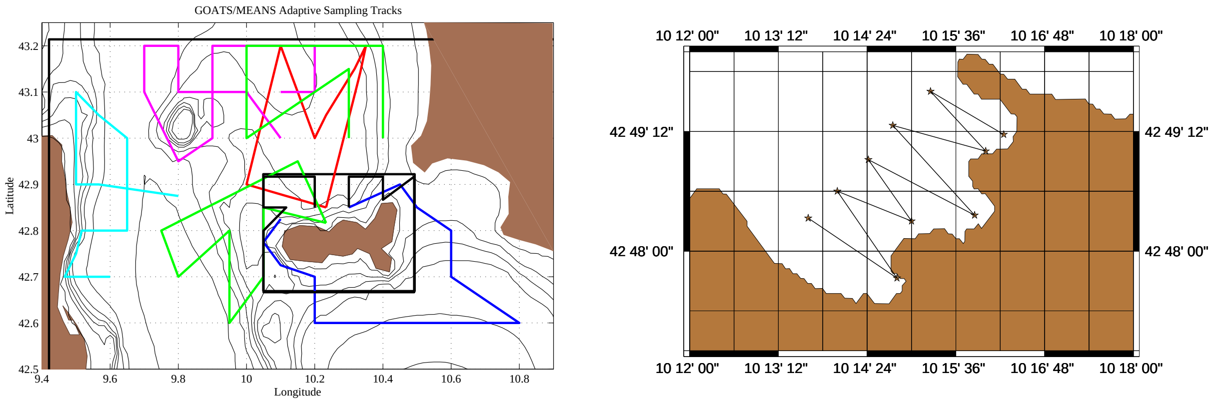

Figure 20 (a) *Adaptive sampling tracks designed on a real-time basis. (b) Adaptive sampling track for the AUV in Procchio Bay.*

5. Data - comparisons and forecast validations

Independent data, that have not been used to adjust the model fields, can be used for comparison with dynamic analysis and forecast. But also the same data that are assimilated into the numerical model can be used to validate previous forecasts. Independent data sets are mainly satellite sea surface temperatures and ADCP measurements. Here we restrict ourselves on the comparison with these two data types.

The first example of ocean analysis (Fig. 21) shows a model result for 26 September, four days after the initialization survey. As expected, the surface temperature in the model compares well with a satellite temperature image of the same day (Fig. 22). The challenge of real time modelling is to maintain accuracy during the subsequent period when the validity of the initial data decreases and the model relies only on internal dynamics, atmospheric forcing and a small number of assimilated profiles. After two days the agreement between the model surface temperature (not shown) and a satellite image (Fig. 9) is again very good. The strong current west of Elba, which had created the cold tongue in Fig. 21, has subsided in the model (Fig. 22). ADCP measurements from the *Alliance* during the same period (Fig. 10) verify the model currents of Fig. 23.

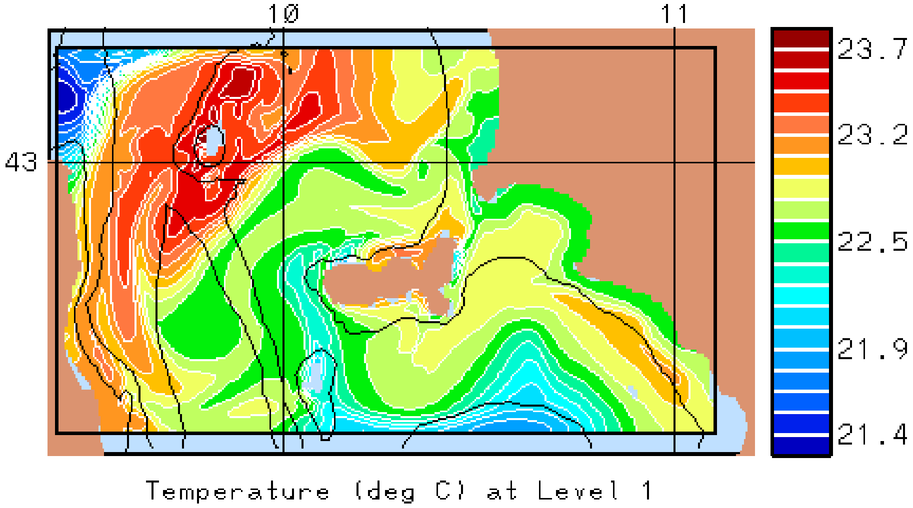

Figure 21 *Surface temperature after 4 days of model run on 26 September. Overlaid on the temperature field are the 50, 200 and 500m isobaths.*

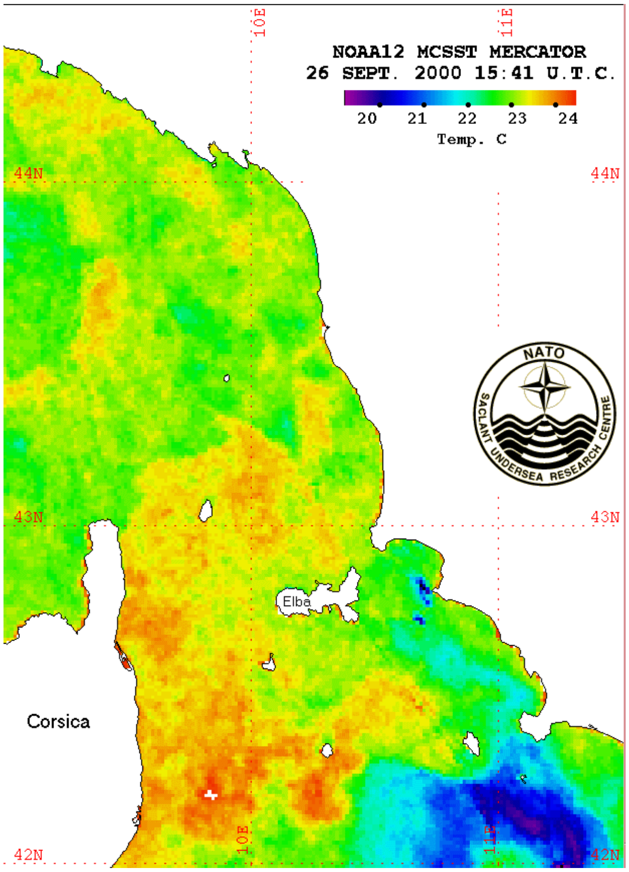

Figure 22 *Satellite sea surface temperature on 26 September.*

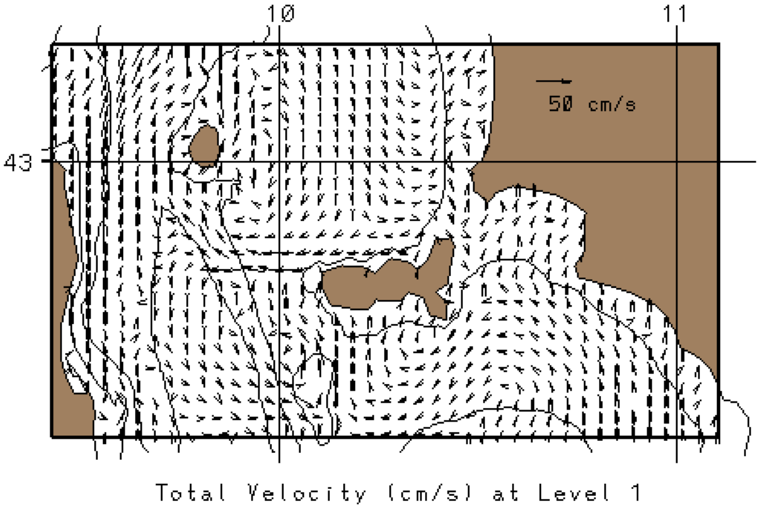

Figure 23 *Surface current from the ocean model on 28 September.*

On 3 October, the last usable sea surface temperature image (Fig. 24) was obtained from satellites, before clouds permanently hid the area. Temperature differences in the area of interest are very small. In the model result (Fig. 25) the range of the color scale is only one degree, so that verification of surface structures by the satellite image can hardly be expected. Nevertheless, the warmer patch north of Elba still exists and has the same position in both images. Surface currents calculated by the model (Fig. 26) indicate that the anti-cyclonic eddy north of Elba has moved north. This outcome of the model is verified by current measurements of the *Alliance* (Fig. 11) in the same period.

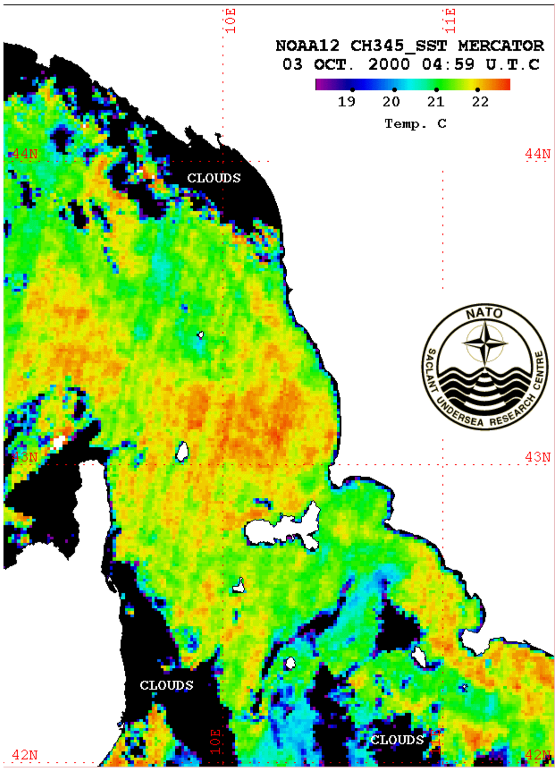

Figure 24 *Satellite sea surface temperature on 3 October.*

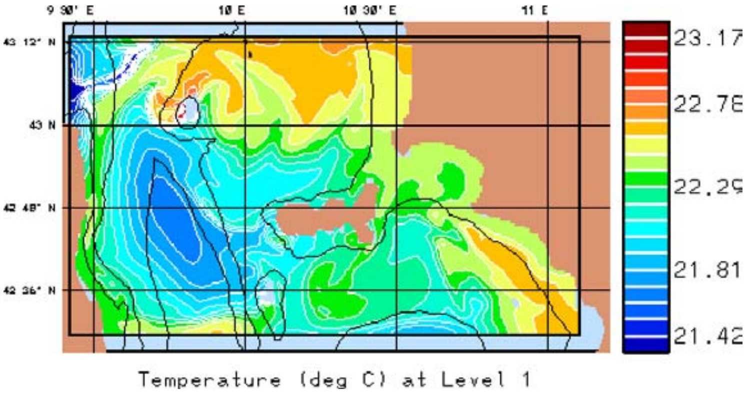

Figure 25 *Surface temperature from the ocean model on 3 October.*

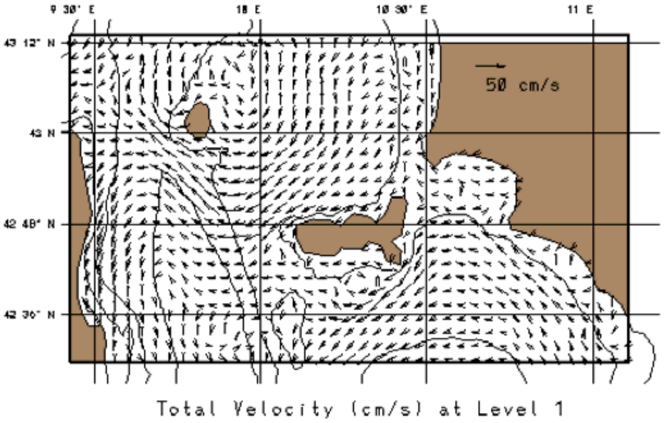

Figure 26 *Surface current from the ocean model on 3 October.*

6. Capraian Eddy

As has been described above, an anti-cyclonic eddy develops to the north of Elba and the east of Isola Capraia during the experimental period. This feature is well documented by hydrographic profiles, ADCP measurements, AVHRR observation and model results. The eddy appears after the initialization survey and develops during the updating portion of the exercise. The dynamics of this eddy are under study.

7. Distributed systems and logistics for MEANS

Data from two external sources are required by ocean modellers for real-time operations: atmospheric analyses and forecasts are crucial for surface boundary conditions, and *in situ* measurements of temperature and salinity are essential for initialization and data assimilation. Ideally the modelling effort should take place where there is fastest access to both data types. Atmospheric forecast fields from FNMOC can be downloaded at any place with an Internet connection, while *in situ* measurements are acquired on board the research vessel. In any case the gap from ship to shore must be bridged by a radio link at least for one data type. Since NRV *Alliance* was also the customer of ocean model predictions, embarkation of the modelling group would have required the least communications effort. Limited space for embarked personnel prohibited this solution.

A distributed system relying on the Internet and satellite communication between NRV *Alliance* and SACLANTCEN was established [4]. Processing of the measured ocean profiles was collocated with data acquisition on board. A dial-up satellite connection with a computer at SACLANTCEN was used to send and receive electronic mail and to store processed data on an Internet server, from where exercise participants would download. The server examines the authorisation of connecting computers and persons, before it provides access to its contents.

The ship data were acquired during the night and after processing transferred to shore before noon. The time difference between Europe and New England allowed the modelling team to find the data on the server early in the morning for assimilation into the model run. Model results were required by early afternoon in order to arrive on *Alliance* in the evening together with a suggested station plan for sampling during night. Graphical representations of the model output were incorporated into pages with the pertinent documentation and uploaded to the server at SACLANTCEN for access by trials participants.

Table 1 shows the daily time-table for the time critical activities on *Alliance* and at Harvard.

Elba time	**Activity**	**Boston time**
11:00	Transmit data of the night survey	05:00
	Final editing of input data	06:00
	Process data received overnight	09:00
	Plot and analyze completed forecast	10:00
	Grid data, prepare for assimilation into HOPS run	10:00
	Begin HOPS run	11:00
	Plan adaptive sampling tracks	12:00
19:00	Transmit forecast and sampling plan	13:00
20:00	Start CTD survey on *Alliance*	
	Apply CU-POM boundary conditions	16:00
	Continue HOPS forecast to completion	17:00
00:00	Replace CTD by XCTD and XBT	
04:00	Continue with CTD	
08:00	Survey ends close to Elba	
08:00	Process data of last night	
11:00	Transmit data of the survey	05:00

8. Conclusions

In the early fall of 2000, the Harvard Ocean Prediction System carried out real time ocean forecasts for the Corsican Channel with a focus on the Gulf of Procchio. The purposes of the forecasts were threefold: i) to support AUV exercises; ii) as an experiment in the development of rapid environmental assessment methodology; and, iii) as a rigorous real time test of distributed ocean prediction system technology. During the period 25 September through 9 October 2000, 11 sets of model forecast products were issued for two modeling domains in real-time via the web. These products included nowcasts and forecasts of fields of temperature, salinity and current velocity for the surface and 50m in the deep ocean domain and at the surface for the shallow domain. Comparisons with satellite sea surface temperatures and Acoustic Doppler Current Profiler data show excellent agreement. These forecasts with data assimilation provide a more detailed picture of the circulation and variabilities of the Corsican Channel than previously available.

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