# 11 Rapid Assessment of the Coastal Ocean Environment

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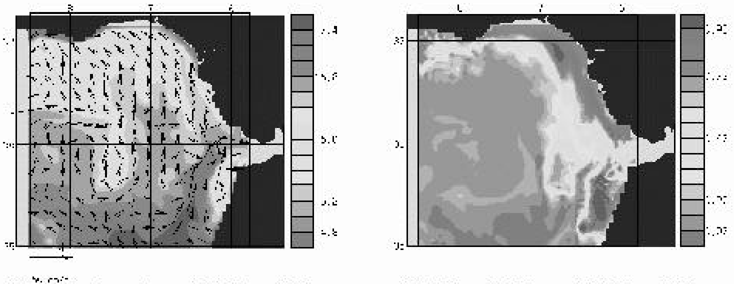
## 11.1 Introduction

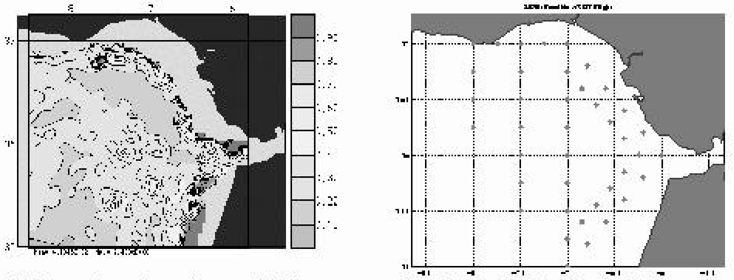
The concept of Rapid Environmental Assessment (REA) is to provide environmental nowcasts and forecasts accurate and efficient enough to support operational activity in any arbitrary region of the global coastal ocean, and to respond to operational assessment requests effectively on very short notice. Ocean science and technology today are rapidly evolving and recognized as generally involving interdisciplinary processes and interactions on multiple scales in space and time (Robinson et al., 1999a). To deal with the complex ocean forecasts and simulations required both for research and for operations and management, the concept of an Ocean Observing and Prediction System (OOPS) has emerged for assimilating data from the system's observational network into the system's forecasts models to generate requisite field estimates (Mooers, 1999; Robinson and the LOOPS Group, 1999). REA requires a rapidly deployable, generic, portable OOPS.

REA has been articulated in the context of NATO naval operations (Pouliquen et al., 1997) as "a new approach to environmental support, designed specifically to provide ... tactically useful environmental data in a tactically useable time scale" (Hammond, 1997) and US requirements have recently been articulated by Curtin (1999). The Harvard and SACLANTCEN oceanography groups have collaborated in recent years (Sellschopp and Robinson, 1997) in providing real time nowcasts and forecasts for a number of NATO REA exercises (Sellschopp, 1998; 1999). Fig. 11.1 , taken from an exercise operational web site, illustrates multiscale interdisciplinary forecast products for the Gulf of Cadiz for 21 March 1998 obtained by assimilating multiple streams of *in situ* and remotely sensed data. It will be discussed further below.

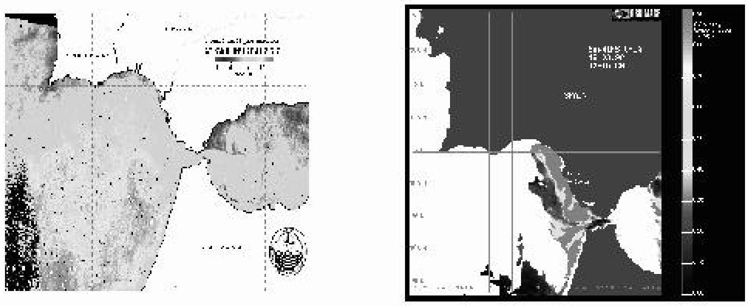
Section 11.2 discusses physical forecasting and section 11.3 the use of the physical forecast. The concept of an REA OOPS is introduced in section 4 and validation issues are presented in section 11.5. Section 11.6 overviews and evaluates experience gained in NATO Rapid Response REA exercises in 1996-1998. Sections 11.7 and 11.8 summarize and discuss prospects for improved REA respectively from an operational and research viewpoint.



(a) Temperature forecast 21 Mar. 1998 (b) Chlorophyll forecast 21 Mar. 1998



(c) Temperature forecast error (100m) (d) Adaptively designed sampling



(e) SST from AVHRR 17 Mar. 1998 (f) Chlorophyll from SeaWiFS 18 Mar. 1998

**Fig. 11.1.** Fig. 11.1a shows the melded estimate of forecast temperature from a real time multi-disciplinary forecast for the Gulf of Cadiz and Strait of Gibraltar with data assimilation, Fig. 11.1b shows the melded estimate of forecast chlorophyll with data assimilation, Fig. 11.1c maps the forecasted error associated with the estimated field of Fig. 11.1a carried out by ESSE methodology (Lermusiaux and Robinson, 1999; Lermusiaux, 1999), Fig. 11.1d depicts the sampling track adaptively designed from the forecast and forecast errors, Fig. 11.1e portrays a remotely sensed sea surface temperature field, and Fig. 11.1f illustrates a remotely sensed (SeaWiFS) chlorophyll field. The data from 11.1e and 11.1f were both assimilated into the multi- disciplinary real time forecast fields (Figs. 11.1a, b, c). Figs. 11.1a, b, c, d were displayed on the RR97 exercise web site.

This chapter is addressed to both ocean forecast scientific researchers and to applied REA managers and naval officers. Thus some material will be of more or less interest to each group.

### 11.1.1 Nowcasting and forecasting for REA

Mankind has learned to intuitively assess weather and sea conditions and to predict their likely development from observations. In the first place the experience of shepherds and fishermen is related to their home area and can only be relocated if the same physical processes are dominant in another area. Universal environmental assessment systems must include all physics of potential relevance. The theory of tides is an excellent example of a relocatable assessment system with long range forecast capability. Prediction of ocean features that are less deterministically forced, suffers from spatial scales being an order of magnitude smaller than in meteorology. While in meteorology a worldwide observational network has constantly been maintained, a comparable oceanographic eddy resolving observation system would still be too expensive. In oceanography detailed environmental information, though technically always possible, is only assembled in limited areas and for limited time periods.

Operational oceanography that sustains the comparison with atmospheric weather analysis and forecast must be based on a relocatable ocean assessment system that yields results within short time (order of a day) and, besides a description of the present status, predicts changes in the ocean. As noted above, an ocean assessment campaign that meets these requirements is called Rapid Environmental Assessment (REA).

An REA operation is required whenever necessary information cannot be obtained from available sources. Pre-existing information usually provides good estimates of ocean depth and climatological means of parameter fields such as temperature, salinity or nutrients. Even though for many applications this information might already be sufficient, there are cases where small discrepancies between climatology and actual fields create large errors in a derived quantity. The requirements for parameter accuracy and spatial or temporal resolution depend on the final products that are desired. They control the measurement strategy and the numerical assessment and prediction tools to be applied.

### 11.1.2 Naval REA

Navy vessels are more affected by environmental conditions than merchant ships. Currents and waves would impact navy ships or soldiers the same as in the civilian world. However, certain specific environmental parameters have a meaning only in a military scenario. Sonar range, e.g., confines the ability to fight or protect against an invisible enemy. Navy ships do have limited capability for environmental *in situ* measurements that can be combined with *a priori* knowledge.

Single point measurements however do not give full insight into the environmental situation. On the contrary, the melding of a point measurement with climatology can in some conditions be worse than the climatological database alone.

In military operations, there is room for improvement by REA (Sellschopp, 1999). In many cases, overt REA operations may be carried out without antagonist interference. To give an example: In an oceanographically active region, the safest route may be found by REA to bring a convoy across. Survey results will be kept secret for a few weeks, positions of survey deployments not. In a not totally unrealistic scenario, navy units are sent to an area that is close to a focus of mischief. Good knowledge of the littoral environment is eminent and can be obtained via REA, the results of which need not be classified.

In denied areas one would not deploy survey ships. Remote sensing from satellites and aircraft is primarily useful for the investigation of surface features. Except for visible light, electromagnetic waves are not appropriate for illumination below the sea surface. Surface signatures are, however, often caused by subsurface features, such as the transformation of surface waves by currents or bathymetry.

Air deployed autonomous systems are an alternative for ship measurements. Buoys may be moored or drift through a denied area and from time to time transmit data to an aircraft or satellite. For several weeks of continuous operation, a bottom deployed trawl-safe system can collect water column data; it can use a small pop-up buoy with an antenna to send the data at programmed intervals. Autonomous underwater vehicles are becoming increasingly important for underwater research and surveying. Their appropriateness for denied areas is coupled with high expenses for bridging the range from the deployment position. In summary, REA is aggravated but still feasible in a hostile military environment.

### 11.1.3 Civilian REA

At first glance it might seem that rapidity is not an issue in civilian environmental assessment except for standard products such as storm surge prediction. But there are scenarios, that would compel REA operations. An appropriate reaction on natural disasters or accidents might be impeded by lack of knowledge about environmental parameters such as mixing rates or time variable current fields. With an REA capability in place, it could be possible to close the knowledge gap in a timely manner. REA methodology should also be applied when management plans at-sea events such as byproduct dumping. Once an ocean area is sufficiently precisely modeled, variations of forcing fields will cost effectively yield the potential impact of the management event on the environment.

## 11.2 Nowcasting and Forecasting the Physics

The water column physical state variables associated with the circulation and its variabilities play a central role in the prediction of many REA parameters of interest. The fundamental physical state variables (velocity components, pressure, temperature, salinity, density) evolve in time according to the coupled conservation laws for momentum, mass, heat and salt, and the equation of state.

We will treat those scales and phenomena whose dynamics are adequately approximated explicitly by the almost incompressible and hydrostatic primitive equations (Cushman-Roisin, 1994; Robinson, 1996). Spatial scales are lower bounded by several hundred meters and temporal scales, by a few hours. Phenomena include, e.g., currents, meanders, eddies, fronts, jet filaments, topographic and coastline effects, surface and bottom boundary layers, upwelling, coastally trapped waves, barotropic and baroclinic tides. The effects of smaller scale and higher frequency physical processes (e.g. turbulence, tidal mixing) are parameterized in the primitive equations and referred to as sub-grid scale processes in accord with the numerical representation of the dynamical model.

The ocean evolves in time, both as a direct response to external, surface and body forces, and also via internal dynamical processes. The former include winds and surface fluxes of heat and fresh water. Where air-sea interactions are important, an accurate meteorological forecast is needed for the ocean forecast. Oceanic internal instabilities and resonances, which include the meanders of currents, frontogenesis, eddying and wave propagation, are generally analogous to atmospheric weather phenomena and are called the internal weather of the sea. The spatial scales of important internal ocean weather phenomena range from 0 (10 km) (submesoscale or synoptical dynamical event scale) to 0 (100 km) (mesoscale or evolutionary scale). These relatively short scales require ocean forecasts generally to be carried out regionally rather than globally. The regional forecast problem then has additional forces appearing as fluxes through horizontal boundaries, representing both larger scales of direct forcing, remote internal dynamical events and land-sea interactions in the littoral zone. The development of a regional forecast system and capability depends both upon the scales and processes of direct interest and the scales and processes that are dominant in the operational region and its surroundings. The forecast region or region of influence is often necessarily larger than the region of operational interest.

The ocean is intermittent, eventful, and episodic, and ocean circulation is characterized by very many dynamical processes occurring over a broad range of nonlinearly interactive scales in space and time. Intermittencies and multiscales have led to the concepts of adaptive sampling and nesting in ocean forecasting. Observations are used to initialize dynamical forecast models, and further observations are continually assimilated into the models as the forecasts advance in time.

Such observations are generally difficult, costly and sparse. If a region of the ocean were to be sampled uniformly over a predetermined space-time grid, adequate to resolve scales of interest, only a small subset of those observations would have significant impact on the accuracy of the forecasts. The impact subset is related to intermittent energetic synoptic dynamical events. For most of the energetic variability in the ocean, the location and timing of such events is irregular and not *a priori* known. However, a usefully accurate forecast targets such events and forms the basis for the design of a sampling scheme tailored to the ocean state to be observed. Sampling schemes can be determined subjectively by experience or objectively by minimizing a selected forecast error metric. Adaptive sampling is efficient, can drastically reduce observational requirements, and is essential for effective REA.

The smallest scales of operational forecast interest generally require compatible observational and modelling grids of too high a resolution to be practical for the entire forecast domain. Thus special interest regions are nested. Two-way modelling nests designed to run in parallel with equal elapsed computing times are efficient. Steep topographic slopes require careful treatment for accurate forecasts (Haidvogel and Beckman, 1998). Data assimilation (Malanotte-Rizzoli, 1996; Robinson et al., 1998) is essential to control phase and loss of predictability errors and to optimize forecast accuracies. A field estimate made by melding data and dynamics by a short dynamical adjustment model run, after assimilating data, is called a nowcast. The coupled system required for ocean forecasting composed of: an observational network; numerical dynamical models; and data assimilation, analysis and management schemes, is called an Ocean Observing and Prediction System (OOPS) (Robinson, 1999; Robinson and LOOPS Group, 1999). The OOPS concept is developed in the REA context in section 11.4.

## 11.3 Implications and Applications of the Physics

### 11.3.1 Interdisciplinary Processes

Ocean science and marine technology are inherently interdisciplinary subjects and physical forcing plays an important or dominant role in many aspects of, e.g., acoustical, biological and sedimentological dynamics in the sea. Thus there are a variety of scientific and practical applications of the forecast physical fields and many situations occur where coupled interdisciplinary simulations and forecasts are necessary. Recent rapid progress in understanding physical processes and in achieving realistic physical field estimation now makes feasible novel interdisciplinary prediction relevant both to climate, biogeochemical cycles, and ecosystem dynamics (Robinson et al., 1999a), and to the management of, and operations in, coastal oceans and multiuse Exclusive Economic Zones. Interactions and feedbacks occur among the physical- acoustical-optical-biological-chemical-sedimentological fields. Examples include living and other particulate control of incoming solar radiation, biological and chemical reactions during pollutant dispersion, motion induced bioluminescence, resuspension processes, the effects of temperature gradients on acoustic propagation and, inversely, the use of acoustic travel times to estimate temperature gradients.

### 11.3.2 Naval Applications

Navy interest in the ocean is due to the impact on system performance under different environmental conditions. Navy operations are usually categorized under warfare disciplines that, with some overlap, also reflect the water depth of the operations. There are three attack-defense pairs: Submarine operations and anti submarine warfare (ASW), mine warfare (MW) and mine counter-measures (MCM), amphibious warfare (AW) and coast protection. Both facets should be considered, when for simplicity only ASW, MW and AW are mentioned. Environmental conditions that favor the aggressor must be known to the defender and vice versa.

In an ASW scenario, the structure of the sound velocity field and its variability are most important. Sound radiated or reflected by a subsurface structure is nearly the only means for the detection of a submerged submarine. Under favorable conditions, sound can reliably be detected after thousands of kilometers. On the other hand, the noise produced by a modern coastal submarine often drops below the ambient noise level after only a couple of kilometers, and a sonar echo from its hull may not exceed the reverberation from the sea surface or bottom. The non-linearity of the relation between the depth dependent sound velocity and the detection range does not allow for a simple statement about the required accuracy of a modeled sound velocity field. An exemplary critical parameter is the sign of the sound velocity gradient in the upper layer.

Acoustical methods are also used for mine detection. Because of the limited range of detection systems, the necessary information on the sound velocity structure is fairly easily obtained by standard tools. In mine warfare, littoral ocean currents and their prediction play a dominant role.

On a sandy bottom in the presence of a sufficiently strong current, mines are buried by scouring. Mine divers are limited by a maximum current strength that obstructs swimming, and by a sediment load that reduces visibility.

Amphibious operations depend most critically on surf conditions. Together with the information on approaching deep water wave fields, accurate bathymetry is required for surf predictions. Near shore bathymetry can be modified by relocation of sand in the currents that are generated by a storm. REA should provide an update on coastal bathymetry, either by direct inspection or by calculation of the sand transport in a numerical model.

In a military REA operation, potential data sources reach from public databases over results from dedicated survey units down to sporadic measurements from navy ships. The information is merged at a data fusion center and made available for assimilation into models and for REA product generation (Sellschopp, 1998).

Oceanographic advisors and naval operations planners have environmental support systems and tactical decision aids at hand, that use environmental information for the benefit of the military task. Without REA, these tools have to rely on climatology or single measurements extrapolated over an area. REA for the first time offers the opportunity to use realistic physical fields in coupled tactical decision making models.

### 11.3.3 Fisheries and other applications

Advanced contemporary fisheries operations and management provides another example of environmental forecast fields coupled to strategic and tactical decision making models. Both governmental regulation of fisheries and commercial fishing are involved and subjective models are in the process of being augmented by quantitative numerical models. Fish spawning, larval survival and metamorphosis to adults (recruitment) affect inter-annual and longer variations in fishing stocks, and the migration of fish stocks over one or two weeks is of great importance to the fishing fleet. It is the latter forecasting problem which overlaps significantly water column REA forecasting requirements. Currents transport and entrap nutrients, phytoplankton, zooplankton and larvae, and the concentration distribution (mass abundance) of adult fish shifts to seek food (e.g., plankton, larvae) to remain in a comfortable environment (e.g., temperature, salinity), and to avoid predators.

This is only one example of many uses of REA involved in management and operations in a multi-use coastal ocean and extended EEZs. Planned operations, e.g. dredging, and sudden crises, e.g. oil spills, ship and aircraft crashes, represent events requiring REA. The ocean science and technology community is becoming increasingly aware of the advantages of dual use research and the development of dual use methodologies (military and civilian).

## 11.4 The REA OOPS (Ocean Observing and Prediction System)

### 11.4.1 The overall system and components

Purely deterministic processes such as the orbital motion of the planets can be predicted by integration of the governing physical laws, starting from precise initial conditions at a certain time.

In deterministic systems, inaccuracies of the initial conditions can in principle be decreased below any given value by repeated observations and backward modeling. Systems that are subject to stochastic influences, either implicitly through physical processes or by random forcing, can be predicted only with limited accuracy. In the model of a linear system, through its dependence on initialization and parameterization of the physics, the prediction error increases gradually with time. In a nonlinear system, predictions can degrade rapidly when nonlinear terms, including nonlinear transfer of error scales, amplify differences between predictions and reality.

The physical ocean is a nonlinear system with inherent stochastic processes and stochastic forcing. Physical laws are represented by the set of hydrodynamic and thermodynamic equations, which in general have no closed form solution. Numerical ocean models integrate simplified versions of the dynamical equations, that neglect physical processes having minor impact on the problem under consideration. The model formulation for an ocean circulation model, for example, would include gravity and friction forces and would omit density fluctuations that are responsible for sound propagation and vice versa.

A valid model, initialized with reasonable climatological fields and forced with accurate time dependent boundary conditions, can be expected to converge towards reality after a sufficiently extended spin-up period. Numerical calculations of this kind have been extensively used for studies of physical processes in the ocean, for the explanation of inter-annual changes and for climate predictions. Internal dynamics will produce meso-scale ocean features in an eddy-resolving model, if the resolution of the forcing fields in space and time is not too coarse. In this case, the statistical properties of meso-scale features may be correct, but their occurrence must not be regarded as a realistic synoptic prediction.

In an alternative and more realistic approach, real-time ocean assessment is initially based on observations, which are presumed to be essentially coincident in time, and with spatial resolution high enough to resolve the processes of interest. Ocean models initialized with the observations are then used to produce parameter fields that are consistent with the observations. This process, often called "nowcast", balances the fields in a way that they obey the laws of physics and therefore are more than just interpolations between observations.

Starting from the nowcast, the ocean model is integrated over a certain number of time steps, driven by its own internal dynamics and by predictions of the external forcing fields. Inevitably, the period for which reliable forecasts can be produced by this technique is limited by three factors: a) the quality and density of observations, b) the appropriateness of physical approximations in the forecast model and c) the quality and resolution of forecasts for the forcing fields. Before model results would degrade too much, model fields must be adjusted by new observations. The melding of new data into a model run is a non-trivial scientific issue, it is the third component of the ocean forecast system. An oceanographic observation and prediction system (OOPS) for REA thus consists of 1st an observational network, 2nd a numerical prediction model and 3rd a data assimilation scheme.

### 11.4.2 Data Acquisition and Management

In an REA scenario, very detailed results may be required for a small ocean area. Since the area of interest cannot be isolated from the surrounding ocean, the influences from outside must be taken into account by appropriate boundary conditions. A request for continuous in-situ measurements along the boundary would be unreasonable. Boundary conditions can instead be obtained from a larger scale model running on a coarser grid and either assimilated from time to time into the small scale model as if it were measured data, or the different scale models can be synchronized leading to frequent adjustments at the boundary of the small model domain. Synchronized models usually have the same number and vertical position of layers. Their horizontal grid spacing differs by a factor of 3 in order to obtain matching points on the staggered computation grid. Model nesting (recall section 11.2) may be carried out also with two-way data flow, thus improving the fields of the larger scale model with results from the more accurate small scale. The observational network required for nested models, includes an appropriate number of measurement stations in the outer domain in order to avoid discrepancies between water mass properties that might otherwise occur especially at depth. If climatological data is also used it must be checked and adjusted as necessary for compatibility with the new observations in both domains. Simple adoption of spun-up climatological data could result in unrealistic density driven currents.

Data acquired for assimilation into a model need not satisfy the conditions for sampling frequency in space and time that must be observed for initial conditions and forcing fields. Since they are only required for the compensation of developing model deviations, they are most effective in those parts of the parameter space that are most difficult to predict. The value of sparse observations may be extended by applying models that describe typical ocean features.

Data managers in an REA system are responsible for timely data transfers between the observational network, the assimilation and modeling effort and the users of observational and forecast products. Data formats should be pre-defined, but in the haste of real time operations, data cannot be guaranteed to be fully quality controlled. Data users, especially modelers, will check again. A single centralized authority for REA data management could slow down the final delivery. Collaborators should rather be connected in a network, preferably the Internet with data access restricted to authorized sites. Data originators or sub-nodes to which they report can keep the data on their computers and allow others to share the information. There should be a site that acts as an REA data fusion center. It has the responsibility to keep track of all information offered by participants, to maintain inventories and to establish links. A distributed system for data management is more flexible and potentially faster than a centralized solution.

The number of permanent platforms such as weather ships, tide gauges or wave poles, is very limited, and a sufficient number can hardly be expected in an area designated for REA. Quasi-permanent platforms are available through satellites that regularly look at the sea surface. Time intervals between repeated coverage of the same area ranges from hours for sea color and surface temperature to weeks for synthetic aperture radar imaging and altimetry. REA can take advantage of satellite data, but for littoral areas substantial information must come from dedicated smaller scale surveys.

Platforms used on demand are moored or drifting buoys, autonomous underwater vehicles, ships and aircraft. The most important *in situ* sensor in the assessment of the physical ocean measures temperature, electrical conductivity and pressure in the water column, which through the equations of thermodynamics also results in salinity, density and sound velocity. Conductivity-Temperature-Depth (CTD) sensors are lowered from a stationary ship, are towed in a yo-yo-ing underwater body or in a wide aperture multi-sensor chain. As expendables (XCTD), they are dropped from a ship or aircraft. Because of the costs, XCTDs are mostly replaced by expendable thermometers (XBT) and the data is assimilated without salinity or with an assumed relation between temperature and salinity, which is usually a good assumption in the open ocean but can be misleading in a littoral environment.

## 11.5 Forecast System and Predictive Skill Evaluations

### 11.5.1 Regional System Validation, Calibration and Verification

In the development of any regional forecast system, evaluation of the integrated system, the system components and the forecast products is of course essential. The development of a regional system is usefully conceptualized as having three phases, a *descriptive* phase, a *dynamical* phase, and a *predictive* phase (Robinson et al., 1996). In the descriptive phase the relevant circulation structures, their time and space scales and their variabilities need to be identified. Concomitantly, the forecast models must be *validated*, i.e., shown to be applicable to the relevant structures (e.g., a barotropic model is not appropriate for baroclinic structures) and observational requirements must be established. The extension to interdisciplinary phenomena is direct. In the dynamical phase, the specific dynamical processes responsible for i) the evolution of the circulation and its variabilities, and ii) for synoptical dynamical events must be determined. In this phase the models are *calibrated*, i.e., physical, domain and computational parameters tuned to the region and its phenomena by sensitivity analyses (Lermusiaux et al., 1999) and measurement requirements refined. Although forecasts are carried out in every phase, the predictive phase is devoted to forecast model and assimilation scheme *verification*. Real time forecasts with high quality data sets for initialization, assimilation and verification, obtained by oversampling, are required (e.g., Robinson et al., 1996). These data sets can then be used to design an optimally efficient observational network component for the regional forecast system.

The *predictive capability* of the regional system needs to be evaluated both qualitatively and quantitatively. Regional dominant variabilities need to be defined and used to characterize the forecast. Examples include: the number of branches present in a coastal current that may bifurcate or trifurcate; the existence or not of transient vortices; the location and shape of a permanent meander. Additionally, appropriate quantitative skill metrics need to be defined such as root mean square errors and pattern correlations (Miller et al., 1995 ; Robinson et al., 1996). The application of such metrics must generally allow for phase errors, i.e., errors in the location or timing of events. Predictive capability without data assimilation is ultimately limited by loss of predictability (Ehrendorfer, 1997; Goswami and Shukla, 1991; Houghton, 1991; Latif et al., 1998). Small differences in initial conditions after some time lead to reasonable but completely different synoptic states. In geophysical fluid dynamical systems, small-scale initial errors are non-linearly transferred to scales of operational interest. Error attribution (initial or boundary conditions, atmospheric forcing, model deficiencies) is important. It is desirable to forecast error fields as well as state variables, as is done, for example, in the ESSE method introduced in section 11.6.2 (Lermusiaux and Robinson, 1999). Automated objective adaptive sampling error minimization metrics can then be related to the quantitative forecast skill metrics (Robinson and Glenn, 1999). The topics discussed in this paragraph require extensive research efforts.

### 11.5.2 REA System Validation Issues

The sum of differences between validation measurements and model predictions has only limited value as a quantitative measure for predictive capability for operational applications. Capability assessment should comply with the requirements of the end user of the prediction, who is affected by certain deviations much more than by others. The end user cannot be convinced by a small rms error if erroneous predictions in a parameter subspace have high impact on operations. Depending on what the operations are, predictive capability would be estimated differently, obviating a general reliability assessment scheme. As a compromise, one might investigate the change of patterns and features and compare with prediction. At least the tendency, more pleasingly also the magnitude of changes, should match (Sellschopp and Robinson, 1997).

Processes with length scales comparable to or smaller than the cells in the numerical scheme cannot be forecasted. But also time and space resolution of the forcing fields, which is coarser than the grid of the ocean model, limit predictability. The reliability of forecasted atmospheric forcing fields can be of minor importance if internal dynamics exceed external forces, otherwise it has immediate influence on ocean prediction quality. If ocean internal dynamics is dominant, the somewhat longer ocean predictability time is then limiting.

Validation, calibration and verification of a generic REA system rapidly deployable in any region of the global coastal ocean is a challenging and demanding task. Curtin et al. (1993) advocate a series of Coastal Ocean Predictive Skill Experiments (CPSE), which are the essential elements of the predictive phase of regional forecast system development discussed above. Since REA predictive skill experiments must be designed to determine forecast skill on the basis of minimal and covertly attainable observations, they may be most efficiently carried out in the context of the definitive over-sampling provided by a series of regional CPSEs encompassing a broad range of coastal processes.

## 11.6 Illustrations from Rapid Response Exercises 1996, 1997, 1998

In three consecutive years from 1996 to 1998, REA exercises have taken place in, and at the entrance to, the Mediterranean Sea. They were connected with NATO naval exercises that succeeded the REA survey in the same areas. Up to 8 ships, 6 patrol aircraft and numerous institutions have been active in REA. For support of warfare commanders, data were collected, only part of which was oceanographic in a narrow sense. The rest was for sea bottom and beach assessment. Measurements for real-time analysis of the physical ocean consisted of CTD stations, XBT and XCTD casts from ships and aircraft, shipborne ADCP velocities, surface drifter deployments and satellite images. Self-recording current meters were used for a posteriori validation.

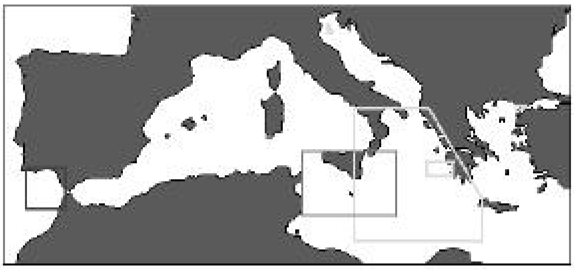


**Fig. 11.2.** The largest ASW domain for each Rapid Response exercise is shown (RR96 - red; RR97 - green; RR98 blue). Additional smaller MW domains for RR97 are also shown (in green).

Nowcast and forecast results from ocean modeling were delivered in a format suitable for the customer, who was most interested in surface currents and sound velocity profiles. Maps and vertical sections were produced as image files for electronic distribution. Profiles were reduced to inflection points coded in a special format for automatic insertion into navy environmental systems.

### 11.6.1 Location and Characterization of Operational Regions.

Rapid Response 1996 and its subsequent naval exercise (both referred to hereafter simply as RR96) took place in the Strait of Sicily and the adjoining western Ionian Sea from mid-August to early October. RR97 spanned the entire Ionian also from mid-August to early October a year later, followed by RR98 in the Gulf of Cadiz just west of the Strait of Gibraltar, only four months later in February and March. Nested modeling domains were utilized in all cases as appropriate for anti-submarine warfare (ASW), mine warfare (MW) and amphibious warfare (AW). Fig. 11.2 depicts the largest ASW domain for each exercise and also the MW domain off the western coast of Greece for RR97.

With respect to the phases of development concept for regional forecast systems these regions differed. During the 1980's Physical Oceanography of the Eastern Mediterranean (POEM) program (Robinson and Malanotte-Rizzoli, 1993) quasi-synoptic basin scale surveys of the Ionian Sea were carried out with the sub basin scale and coarse mesoscale resolution, and the circulation and water masses have been synthesized by Malanotte-Rizzoli et al (1997). Thus the 1997 exercise served as a predictive phase forecast verification experiment. Prior to RR96 our Harvard and SACLANTCEN research groups were collaborating in Strait of Sicily research and had carried out research cruises there with real-time at sea forecasting and data assimilation in 1994 and 1995 (Robinson et al, 1999b). A dynamical phase cruise was already planned for 1996 before RR96 was scheduled which was subsequently

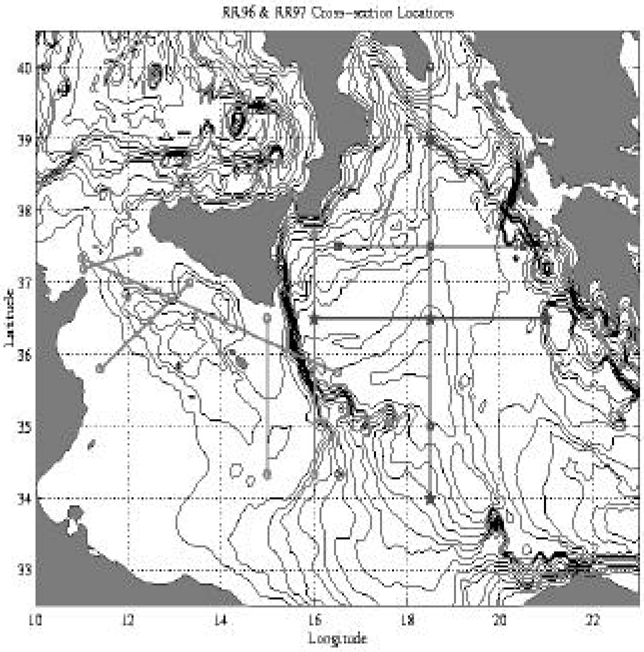


**Fig. 11.3.** Bottom topography for the RR96 and RR97 regions is shown. Contours are 250m. The red and blue lines indicate the positions of standard vertical sections for the real time forecast products.

carried out in conjunction. Thus excellent synoptic flow and water mass data was available for the region with mesoscale and submesoscale resolution (Robinson et al, 1999b; Warn-Varnas et al, 1999) and we regard RR96 as a combined dynamical/predictive phase exercise. The Gulf of Cadiz presented a complex and generally less well understood region for which we were not able to locate a prior synoptic mesoscale resolution regional data set. For our team, RR98 represented a challenging combined descriptive/dynamical/predictive phase effort, with little time for preparation. The full scope of phases of these three exercises provided a valuable range of REA experiences.

*The Strait of Sicily and the Ionian Sea* - The topography of this region is depicted on Fig. 11.3 . The choke point of the strait lies in the west to the northeast of 37°N, 11°W. There is a deep central trench in the strait and a narrow (broad shallow) coastal region off the Sicilian (North African) coast. The extremely steep and narrow Ionian Shelfbreak off the eastern coast of Sicily extends southward and fans out and broadens off the coast of Libya. The central Ionian basin and the Cretan

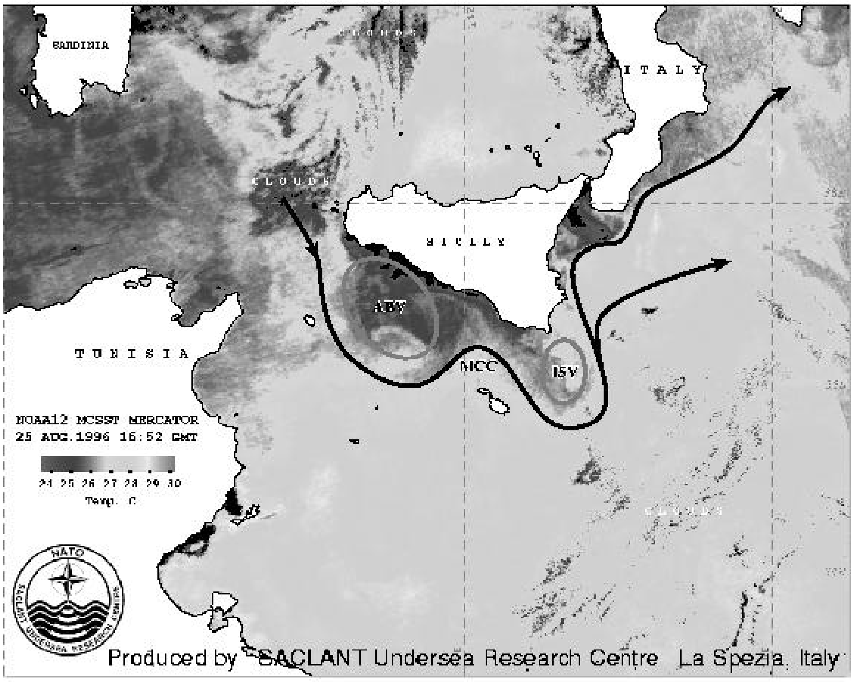


**Fig. 11.4.** a schematic of the near surface circulation and variabilities of the Strait of Sicily which was developed in real time during RR96 superimposed over an AVHRR image of the area for 25 August 1996. Features noted are: ABV - Adventure Bank Vortex; MCC - Maltese Channel Crest; and, ISV - Ionian Shelfbreak Vortex.

passage to the south of Greece have gentle slopes and lie between about 2500 and 3500m; there are steep narrow slopes off the west coast of Greece.

Fig. 11.4 presents a schematic of the near surface circulation and variabilities of the Strait of Sicily which was developed in real time during RR96. Fig. 11.5a is a similar schematic for the entire region based upon the POEM August-September 1986 data; Fig. 11.5b identifies the system of cyclonic and anticyclonic eddies and gyres present during RR97 in the Ionian.

In the Strait and the Ionian, the fresh modified Atlantic water flowing generally eastward and salty Levantine water flowing generally westward constitutes a two-current system of the general circulation of the western Mediterranean. The Levantine outflow is located at depth and the Atlantic inflow is in the upper ocean. The Atlantic inflow, the Atlantic-Ionian Stream (AIS) is an internal free jet controlled by topography and internal dynamics exhibiting variabilities. At the Ionian Shelfbreak, the AIS bifurcates (or trifurcates) into a branch that turns north and flows along the bathymetry before exiting into the Ionian, and one that proceeds directly east into the Ionian Sea. The strength and volume transports of the branches change considerably due to seasonal and ambient conditions. Mesoscale and sub-mesoscale eddies are always present in the Sicilian Channel and the mesoscale variability has been studied statistically by Lermusiaux (1999).

In addition to the general circulation, with its mesoscale variability, there are the wind-driven currents on the shelf from local and remote storms (including the Sicilian coastal current) and upwelling off Sicily. Tides, inertial, gravity, surface, and continental shelf waves occur. This region contains active water mass modification processes between the fresher and warmer Atlantic origin water mass and the saltier and colder Levantine water mass. The free jet filaments of the AIS in the Ionian Sea exhibit considerable variability in occurrence and location as they thread their way to the Cretan passage. In addition a number of (semi-) permanent and transient subbasin scale to mesoscale cyclonic and anticyclonic vortices occur which are interactive with the jets and each other. The variability of the circulation structures and subbasin scale features has been studied by Malanotte-Rizzoli et al (1999). Figs. 11.4 and 11.5 will be discussed in more detail below.

*The Gulf of Cadiz* - Fig. 11.1 , introduced earlier, and Fig. 11.6 present aspects of the circulation and topography of the Gulf of Cadiz. For our purpose we define the Gulf of Cadiz as the area east of 9°W and north of 35°N. To the north and east it is bounded by the Portuguese, Spanish and African coast. The western and southern boundaries are open; another narrow open boundary exists in the east at the Strait of Gibraltar. The west-east extension is about 270 km, in north-south direction it extends over about 250 km. Maximum water depth is about 3000m in the southwest corner. Interior to the Gulf, topographic slopes are gentle. The Gulf of Cadiz is incorporated in the eastern recirculation regime of the North Atlantic subtropical gyre (Siedler and Onken, 1996). It is located in the transition area between the Portugal Current and the Canary Current. A small fraction of the North Atlantic thermocline transport flows into the Strait of Gibraltar. Towards the southeast, the area is connected to the northwest African upwelling regime. The sill depth of the strait of Gibraltar is about 300m at the Camarinal Sill (5°45' W). The circulation in the Strait is characterized by a near surface inflow of low salinity Atlantic Water into the Mediterranean and an outflow of salty Mediterranean Water (MW) below. Mean transport rates of both flow components are on the order of 1 Sv, mean velocities are on the order of 1 m/s. After having passed the Camarinal sill, the high density MW slides down the continental slope and progresses further to the west while leaning against the Spanish/Portuguese continental slope. During these stages the MW is subject to strong mixing. The main spreading paths are confined to two warm salinity 'veins' at about 600m and 1100m depth, typical velocities within these veins are 40 cm/s or even more. The Gulf of Cadiz circulation is influenced by wind forcing and surface heat and water fluxes. In wintertime, the area lies close to the main storm tracks of the northern hemisphere, hence wind forcing may play a dominant role. The mean inflow/outflow situation in the Strait of Gibraltar is superimposed by strong tidal currents, the magnitude of which is on the same order as the mean flow. Hence, within a tidal

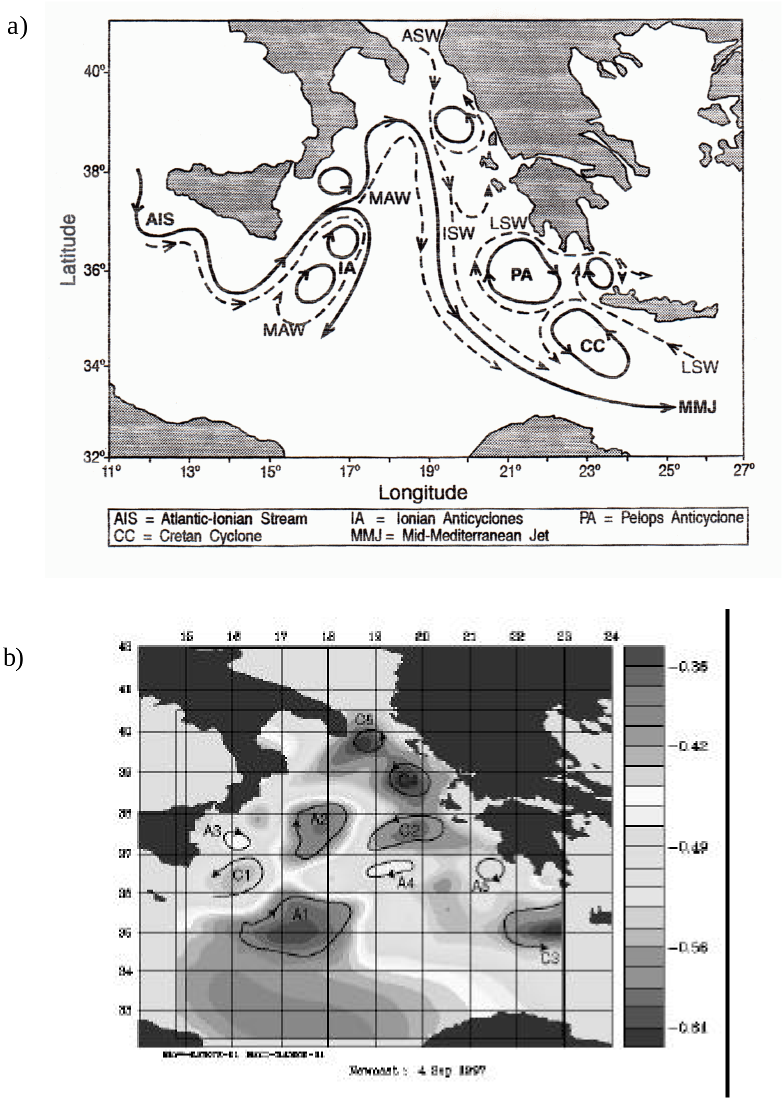


**Fig. 11.5.** a) a schematic of near surface (solid lines) and mid-depth (dashed lines) circulation for the Strait of Sicily and Ionian Sea based upon the POEM 1986 data; acronymous not identified in the figure legend include: MAW - Modified Atlantic Water, ASW - Adriatic Surface Water and LSW - Levantine Surface Water; b) identifies the system of cyclonic (C) and anticyclonic (A) eddies and gyres present during RR97 in the Ionian superimposed upon an analysis of dynamic height (5m/800m) for 4 September 1997.

cycle, inflow/outflow may be reversed. Strong tidal flow on the order of several knots prevails also in the Gulf of Cadiz, at least in the nearshore regions. Special features of the internal dynamics of the region involve the external effects of internal waves and hydraulic jumps occurring in the Strait of Gibraltar within a tidal cycle, the slope convection of MW west of the Camarinal Sill and the instability of the MW veins causing generation and detachment of meddies (Onken, 1998, personal communication).

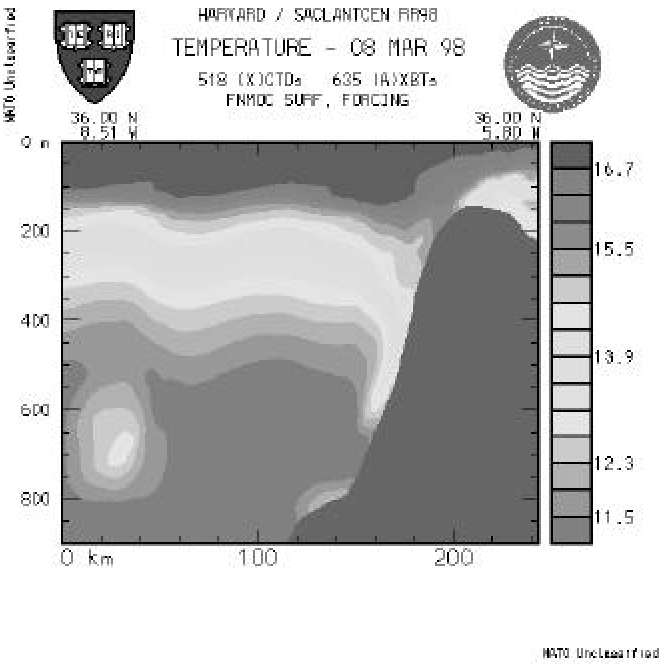


**Fig. 11.6.** A vertical section of temperature along 36N as taken from the RR98 operational web site. Data noted in the figure is from the RR98 exercise. The figure shows the outflow of Mediterranean water through the Strait of Gibraltar.

### 11.6.2 Methodologies: Initialization, Assimilation and Sampling

The Harvard Ocean Prediction System (HOPS) is a flexible, portable and generic system for inter-disciplinary nowcasting, forecasting and simulations. HOPS can rapidly be deployed to any region of the world's oceans, including the coastal and deep oceans and across the shelfbreak with open, partially open or closed boundaries. Physical, and some acoustical, real time and at sea forecasts have been carried out for more than fifteen years at numerous sites (Robinson, 1999) and coupled at sea biological forecasts were initiated in 1997. HOPS has been utilized during the Rapid Response exercises and the operational applications of the system are detailed in Haley, et al. (2000), which appears as a separate chapter in this book. The present system is applicable from 10m to several thousand meters and the heart of the system for most applications is a primitive equation physical dynamical model.

HOPS is used to build and maintain a regional synoptic description through nowcasting, forecasting and assimilation. The domain is initialized with the best possible estimate from historical synoptic data, climatology and feature models. Dynamical adjustment of synoptic conditions, not a spin-up from climatology, enables a rapid achievement of current conditions. Historical data can be thermodynamically and dynamically adjusted to match the present state. *In situ* or remotely sensed data, acquired via adaptive sampling designed to have optimal impact and control predictability is assimilated.

Data assimilation methods used by HOPS include a robust (suboptimal) Optimal Interpolation (OI) scheme with weights set by simple engineering-type assumptions and a quasi-optimal scheme, Error Subspace Statistical Estimation (ESSE). The advanced 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 (Lermusiaux and Robinson, 1999; Lermusiaux, 1999). Measurement models relate state variables to sensor data. Substantial real time efficiency is achieved by reducing the error covariance to its dominant eigendecomposition. Error propagation is estimated via an ensemble forecast using the full nonlinear model. The evolving error subspace is characterized by singular error vectors and values, i.e., time evolving three dimensional error empirical orthogonal functions (EOFs). Melding weights for assimilation are determined using a minimum error variance criterion. Importantly, melding occurs in the error subspace and is thus much less costly than a classical analysis with the full error covariances. The error subspace is updated at the melding step by combining the forecast principal errors, i.e., errors arising from the dynamical model and the loss of predictability, with the error covariances of the measurements. ESSE was utilized in real time for the first time during Rapid Response '96. The influence of historical synoptic data is reduced as data is gathered and eliminated when and if sufficient data is acquired.

During RR96, dynamically adjusted (heated while in dynamical balance) historical synoptic data from 1995 was used in combination with the Mediterranean Ocean DataBase (MODB) climatology. In RR97, quasi-synoptic data from the Physical Oceanography of the Eastern Mediterranean (POEM) cruise of 1986, along with MODB data, was used to formulate initial conditions. In the Gulf of Cadiz region (RR98), the MODB MED4 database, supplemented with data from the UK Hydrographic Office, the NODC CD-ROM and the SACLANTCEN web site, provided the basis of the initial conditions.

The Rapid Response exercises have generally provided extensive sampling during their duration and provide extremely rich data sets as a result. Fig. 11.7 shows the sampling patterns during RR97. Three panels (top left and right and bottom left) represent the data collected during the exercise; 5 ships and 17 aircraft flights acquired 416 CTDs and XCTDs and 975 XBTs and AXBTs during the period 18

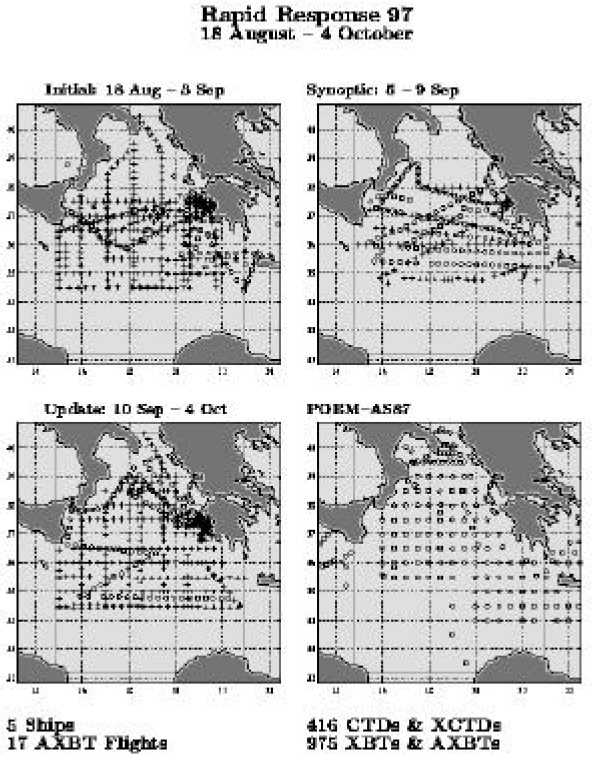


**Fig. 11.7.** Fig. 11.7 shows the sampling patterns during RR97. Three panels (top left and right and bottom left) represent the data collected during the exercise; 5 ships and 17 aircraft flights acquired 416 CTDs and XCTDs and 975 XBTs and AXBTs during the period 18 August - 4 October 1997. The sampling patterns were designed for maximum spatial coverage with constraints imposed by platform capabilities and mission needs. Some patterns were pre-planned while others were adaptively planned as forecasts and conditions dictated. The bottom right panel shows the data positions for the POEM 1986 data which formed the initial conditions for the RR97 forecasting. + signs indicate the position of XBTs and AXBTs. The small circles indicate the position of CTDs and XCTDs.

August - 4 October 1997. The sampling patterns were designed for maximum spatial coverage with constraints imposed by platform capabilities and mission needs. Some patterns were pre-planned while others were adaptively planned as forecasts and conditions dictated. The bottom right panel of Fig. 11.7 shows the data positions for the POEM 1987 data which formed the initial conditions for the RR97 forecasting.

Fig. 11.8 illustrates the effect of, and need for adaptive sampling. The left panel shows the expected error of an objectively analyzed data field after an AXBT

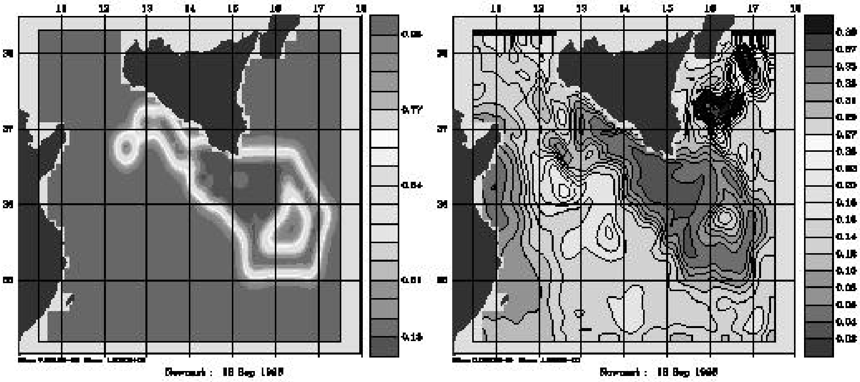


**Fig. 11.8.** The left panel shows the expected error of an objectively analyzed data field after an AXBT flight. The path of the aircraft is obvious and was adaptively designed to reduce model forecast error of the meandering stream. The right panel is the model forecast error (contours of 0.02) after the data collected was assimilated into the model. The reduction of model error in the region of sampling is indicated and the higher errors in other regions indicate the need for sampling at a future time.

flight. The path of the aircraft is obvious and was adaptively designed to reduce model forecast error of the meandering stream. The right panel is the model forecast error after the data collected was assimilated into the model. The reduction of model error in the region of sampling is indicated and the higher errors in other regions indicate the need for sampling at a future time.

### 11.6.3 Products

Operational products provided to naval operators have evolved during the Rapid Response exercises, as indicated by the needs of the operators. Primary products have included maps of surface temperature, salinity, mixed layer depth and velocity, maps of bottom velocity (for mine warfare), vertical sections of temperature along chosen paths, temperature profiles in standard naval JJXX format, maps of forecast error, tidal velocities and maps of surface chlorophyll (as a proxy for bioluminescence). The use of a central web site for product distribution has allowed for the release of products within a few hours after the completion of a forecast. Forecasts were issued, on average, at a 4-7 data interval. Fig. 11.9 represents a sampling of the products issued during RR97. Shown are maps of surface temperature and mixed layer depth for 30 September 1997 in the large forecast domain, a south-north vertical section of temperature along 18.5E for 30 September 1997 and a map of bottom velocity in the Mine Warfare (Kiparissia Bay) domain for 20 September 1997.

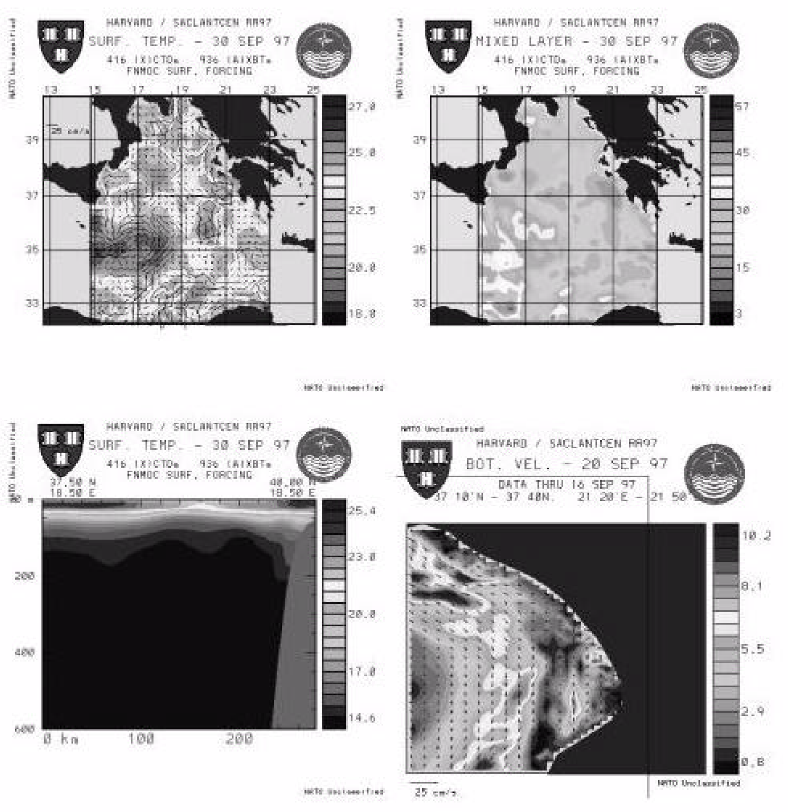


**Fig. 11.9.** Fig. 11.9 represents a sampling of the products issued during RR97. Shown are maps of surface temperature and mixed layer depth for 30 September 1997 in the large forecast domain, a south-north vertical section of temperature along 18.5E for 30 September 1997 and a map of bottom velocity in the Mine Warfare (Kiparissia Bay) domain for 20 September 1997.

### 11.6.4 Forecast evaluations

Subjective evaluations of the real-time forecasts during RR96 and RR97 are presented below. These rich data sets also provide the possibilities for quantitative hindcast studies and REA Observational System Simulation Experiments (OSSEs), some of which have been initiated. Quantitative skill metrics for objective evaluations of the real-time forecasts are under development.

A quick-look verification of predicted variations of features in the Sicilian Channel was performed for four dates during RR96 as the exercise proceeded. The satellite sea surface temperature images and the HOPS nowcasts and forecasts were selected and the position and shape of three dominant features were identified, as well as their development in time. These dominant features are presented in Fig.

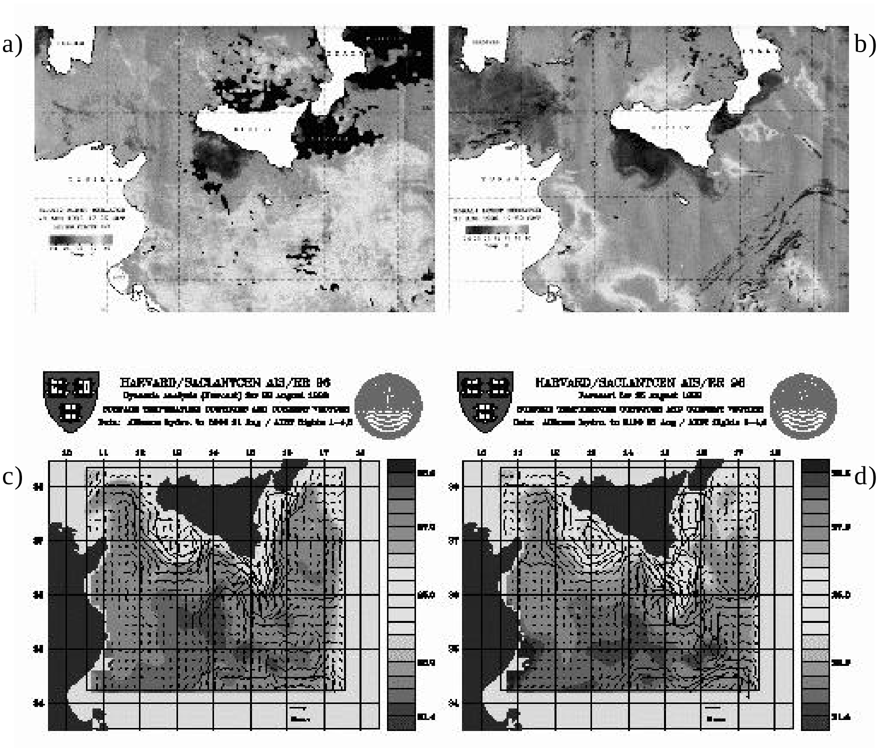


**Fig. 11.10.** Panels (a-b) show the satellite SST distributions for August 23 and August 25, 1996, respectively. Panel (c) shows the HOPS nowcast of the surface temperature for August 22, overlaid with surface velocity vectors (scale arrow is 25 cm/s). Panel (d) is as Panel (c), but for the forecast fields for August 25.

11.4 : ABV - Adventure Bank Vortex; MCC - Maltese Channel Crest; and, ISV - Ionian Shelfbreak Vortex. The satellite images were chosen with regard to percentage cloud cover. The quick-look comparison of actual development versus predicted development indicated that the HOPS forecasts predicted conditions at a success rate of approximately 70%. Fig. 11.10 depicts the type of comparisons made for the quick-look comparison. A subjective comparison of the SST distributions from AVHRR show excellent agreement with the HOPS nowcast and forecast fields shown below them.

Dr. K. Nittis, from the National Center for Marine Research (NCMR) of Athens, Greece, joined the Harvard/SACLANTCEN group for RR97 to provide expert knowledge of the circulation and processes present in the Ionian Sea. We summarize here his description and subjective evaluation of the RR97 circulation and forecasts. Fig. 11.5b illustrates the upper thermocline dominant circulation mesoscale and sub-basin scale features present during RR97. The most energetic features are the two anticyclonic eddies located in the central Ionian (A1 and A2). They can be easily observed in both altimeter and CTD (dynamic height) data. Between these two anticyclones we observe two cyclonic eddies, C1 and C2. The two eddies C1 and C2 occasionally appear as part of a larger cyclonic system that separates A1 and A2. Two smaller anticyclonic gyres are present in the same area, without being visible in most of the SSH images (probably due to their size). The first one (A3) is located west of. At surface and subsurface layers (0-100m) it appears to be connected with A2. The second anticyclone (A4) is located east of A2 and C2. All four anticyclones (A1-A4) seem to be part of the same system; the Ionian Anticyclone. In the eastern Ionian, along the coasts of Greece we observe the Cretan cyclone (C3), the Pelops anticyclone (A5), and two cyclonic gyres (C4 and C5). The Cretan cyclone is a permanent sub-basin scale feature of the East Mediterranean upper thermocline.

The model seems to reproduce the three phases of the Ionian Anticyclone: the 1st phase when the large scale circulation dominates and the anticyclones are part of the same system; the 2nd phase with i) the intensification of cyclones C1 and C3, ii) the weakening of the large scale circulation, iii) the intensification of A2; and the 3rd phase when A1 and A2 seem to merge again in large scale circulation. Finally, it is interesting to note that the model simulates the cyclonic circulation in the NE Ionian (C4 - C5) but the Cretan cyclone (C3) in the SE Ionian is not well represented at least during the first half of the period (up to Sept. 8).

### 11.6.5 Accomplishments and implications

The time evolution and thus the predictive capability (recall section 11.5) of regional circulation systems is driven by internal dynamical processes, inflow and outflow boundary conditions and surface atmospheric fluxes. Our knowledge of internal dynamical processes and boundary conditions is affected by the type, density, accuracy and collection strategy of environmental data and the calibration and tuning of the physical dynamical model. Rapid Response forecasts have proven to be usefully accurate. The predictability of the individual regions is limited: in weather prediction, to a few days by atmospheric internal non-linear dynamics, and, within the ocean, to a week or two by similar processes.

Each of the Rapid Response exercises provided new and unique opportunities. While many aspects of the REA process remained consistent between exercises, the variation in domains and dynamical processes contributed to differences between each operation. RR96 was our first experience in REA. Dialogs were initiated with naval officers and products tailored for specific warfare activities. The NRV Alliance served as a shipboard forecast center. HOPS utilized a novel synoptic initialization from warmed historical synoptic data. Aircraft adaptive sampling was initiated both subjectively and based on the first real time ESSE error forecasts.

In RR97, very efficient communications and data management procedures were established. A command ship (R/V Alliance) collected data from the survey fleet (vid Fig. 11.7 ) which was transmitted to a fusion center (SACLANTCEN) and a remote institutional forecast center (Harvard). An efficient website was central to the almost flawless communication of data and products. This exercise involved a unique preliminary forecast phase with historical synoptic data from the same season in 1987 (POEM) and data acquired from satellite and ships transiting to the preliminary briefing in Crete. New experience was gained in adaptive sampling from many simultaneous platforms and the assimilation of SSH. Nesting of operational domains was initiated and special products for the MW region developed. RR97 was a sustained exercise in a large region with known dynamics which allowed for attention to forecasting and expert qualitative evaluation.

RR98 proved especially demanding due to minimal preparation time in an unknown region with demanding physics. The physics included challenging forcing through the Strait of Gibraltar as well as from the NE Atlantic. Many new initiatives were brought forward during RR98, including: the coupling of physical and biological modeling, assimilation of sea surface color (SSC), the first prototype bioluminescence forecast and the first inclusion of tidal products to the forecast center.

The experience of these three exercises and the lessons learned provide the substantive basis for sections 11.7 and 11.8.

## 11.7 Organization, logistics and resources

As for any oceanographic field activity, the establishment of an ocean observation and prediction system (OOPS) for rapid environmental assessment has to be arranged within the constraints of limited resources and a given suite of measurement systems and platforms. A single laboratory is hardly able to provide all components of an OOPS by itself. In a cooperative program, laboratories should be tied together to provide the required mix of expertise, instrumentation and platforms.

### 11.7.1 Platforms and resources

In an early phase of military survey planning, it must be defined whether the process of data collection ought to be covert or overt. Remote sensing of the sea surface is the most obvious method for covert ocean measurements. It can provide the surface parameters: elevation, sea state, roughness, temperature and color, which to a certain extent allow conclusions to be driven for subsurface conditions also. With visible laser light and translucent water, also shallow water bathymetry can be obtained from distance. Currents can be measured by their impact on the velocity of surface waves and the Doppler shift of Bragg-scattered radar signals. Platforms for remote sensing of the sea surface are satellites, aircraft and radar towers.

Covert *in situ* measurements require a submerged platform to be deployed in the area of interest. The range of possible platform size is from a swimmer to a submarine. Autonomous underwater vehicles (AUV) will gain more importance even for overt surveys in future when the maximum range of small affordable units increases to operationally meaningful distances. For time series at fixed locations, bottom moored systems are appropriate, deployed from aircraft, ship or AUV. Following a pre-programmed sequence, they release a surface float with an antenna that transmits the most recent data via satellite to the laboratory (Tyce et al, 1998). Moorings of this kind are required also for non-denied observations because traditional moored instruments would store data during the full deployment period. Data are read out only after recovery and thus not available in time for ocean prediction.

Open military environmental investigations like any civilian ocean research activity mostly rely on ships as the main platforms. The expenses for ship time are easily compensated by the advantage of hands-on interaction with measurement systems. On a ship it is easier to meet the requirements for instrumentation, which need not be as complex and sophisticated as in remotely operated systems.

For the analysis of the physical ocean, the direct measurement of those quantities is most valuable that are represented in the fields of numerical models, namely temperature, salinity and water velocity. Temperature and conductivity below the sea surface require direct probing. The limitation to one-dimensional measurements when *in situ* probes are lowered from a ship, is overcome by towing undulating bodies or multi-sensor chains. Traditional current measurements at single fixed positions have been widely replaced by acoustic profiling current meters.

An optimal ocean observing and prediction system would continuously have access to real time data. Many measurement systems and platforms that are used for an REA campaign, are also suitable for permanent monitoring, and it is only the costs for maintenance and periodic replacement that prevents constant deployment. Sensor fouling can, however, severely degrade data such as electrical conductivity, with the consequence that the precision required for ocean modeling is not guaranteed after weeks of exposure to a shallow littoral environment.

### 11.7.2 Adaptive sampling and assimilation

In an REA operation, it is not totally predictable when and from what location updating measurements will arrive. This might put some strain on data assimilation procedures as compared with assimilation from fixed station networks. On the other hand, smart assimilation of data from changing locations has the potential for detection and refinement of structures that might fall through the meshes of an immutable observational scheme.

Free decision on the locations for the next day's measurements offers the opportunity for optimal track design. Ocean areas that are suspected or estimated to be incorrectly represented in the model results will be covered together with areas that have not been visited for a longer period. Adaptive sampling significantly reduces the demands for resources and the number of platforms, which otherwise would have to provide full area coverage with acceptable forecast degradation everywhere. Automated adaptive sampling, which is in its infancy, can be expected to impact the efficiency and effectiveness of REA very substantially (Robinson and Glenn, 1999).

### 11.7.3 Data fusion and communication

For successful cooperative adaptive sampling it is necessary that modelers are prepared to timely articulate their preferences for the next sampling locations and data types, and that reliable communication channels exist between modelers, survey planners and data providers. In a small experiment, when cruise management, data acquisition and processing, and ocean modeling is united on a single research ship, timely communication is purely a problem of persons working together. In a bigger scenario with several ships, aircraft and land based laboratories, technical installations for communication require major attention. Traditional ship to ship and ship to shore communication is at the best appropriate for short conversations. For data transfer from ships, high bandwidth satellite communication is preferable. Near to shore also cellular telephones with digital data capability are appropriate, since in most cases a data rate close to ten thousand bit per second will suffice.

Data at high rates can be exchanged between ships or with a land station in sight (15 km) using modern off the shelf spread spectrum radios. They are not standard on ships. Their installation requires a few months preparation time. Standard data transfer protocols are adapted from local area networks. Connections via spread spectrum radio can be virtually transparent for the user, whose computer becomes part of a larger network spread over several platforms.

On land it can be presumed that everybody involved in an REA operation possesses a connection to the Internet and the appropriate technology. Internet standard is appropriate for data exchange even if the data must not be shared with the public. Access control and encryption are in place that would keep unwanted recipients out. REA operations take advantage of the three main services on the Internet. Electronic mail is used for coordination, file transfer for data delivery and the web for distribution of results.

Relevant information for REA consists of databases, archived and actual data, that are likely spread over several agencies and data providers. To make the information usable for the development of derived products, format conversions and data transformations must be carried out for older data. For the expected real-time data, administration programs must be in place prior to the exercise. Paper products are a challenge for appropriate handling and therefore sometimes ignored. Fast delivery and processing requires information in electronic format.

Once the existing data have been determined, everything needed for forecasting is gathered by modelers. Entire databases need not, and the responsibility for data bases should not be transferred to the groups that perform the modeling. In the web structure of the Internet, data can be shared when they reside at different places. For atmospheric forcing fields, doubtlessly the atmospheric center takes responsibility for data presentation and administration. Also the responsibility for oceanographic input data should be with the organization that is closest to the originators.

A distributed data system for REA has to be better organized than ordinary information on the Internet. It is unacceptable for participants in an REA effort to regularly search through the offers of potential data providers and find out whether new information has shown up. There must be an element in the REA organization, called the Fusion Center, that either receives an REA data set as soon as it is generated, or is informed about its existence and the location from where it can be downloaded. The Fusion Center will set up an inventory of all existing data with pointers to the respective files. It generates maps, designs web pages and provides appropriate data search algorithms. Occasionally the Fusion Center can adjust data formats to a common standard. Data originators remain however responsible for data integrity. The Fusion Center provides service to participating groups who for product generation rely on other people's data, it creates and maintains an archive of contributions, and it finally places results to be browsed by customers.

### 11.7.4 Simple and complex systems for special purposes

The complexity of the distributed data management system and fusion center depends on the size of the REA operation. In the most simple case of a single platform for measurements and modeling, data collection on a computer with a clear directory structure and a few pages written in hypertext markup language (html) for descriptions and cross-links between data types would do. In a complex REA survey, data are physically organized relative to the different data providers. They keep their contributions together, either on an own Internet server or in a directory at the fusion center. The fusion center then creates tables that would combine links to a certain data type regardless of the originator. The distributed data archive thus gets a double structure: the physical placement of files and the menu-guided access to data can differ significantly.

In an REA operation, it is often required to establish a back-up for the data server or to save the complete server contents on a CD-ROM. This should be facilitated by a simple information format and server structure. Some of the modern techniques, that are widely used on Internet servers such as java scripts and database queries, are counterproductive in that respect.

Common formats for all data delivered for REA, though desirable, are unlikely accomplished. But care must be taken that data files are compatible between computer systems. Standard tools under the most frequently used operation systems, at least MS Windows and Unix, must be able to digest all files. Plain ASCII files with a simple structure are preferable. If binary data are more appropriate, platform independent formats such as Netcdf or Matlab save sets are recommended. For text and image data, standard file types of the world wide web (Internet) are preferred including the platform-independent document format (pdf) for vector graphics and formatted documents. Postscript (ps) format is also acceptable for documents that are anticipated for high quality printouts rather than for screen display.

Files generated with a typical office tool such as a spread sheet, presentation graphic or document writer, would require compatible software releases for ingestion, that are unlikely available under Unix and may not be present under Windows. Office file formats are therefore inappropriate for data exchange. By careful choice of the format of electronic products, especially of raster graphic images, the file size can often be remarkably decreased.

REA relies on state of the art communications technology and computer network software. The data flow from acquisition and primary data processing to the generation of derived products and further to appropriate presentation to the end user, cannot be expected to be defined in standard procedures yet. The construction of the data collection and distribution system requires expert knowledge of modern technology. At the same time, in-depth knowledge is required of the essence of the disseminated information. To make a REA communications system functioning, computer specialists, network managers and scientists work closely together. In a fully satisfying REA communications system, scientists have experience in the generation of electronic products, and network managers have a scientific background and a clear idea of the needs of the end users.

Feedback and continuing discussion guarantee for optimum results at the end of an REA communications chain. Data originators continuously monitor the product that is delivered to the end user and verify that the product is presented correctly without degradation by inappropriate integration into the context of other expositions. Data managers give advice on data formats that would comply with a general standard, increase readability or diminish the requirements for transmission bandwidth.

### 11.7.5 Distribution and impact of information

The final customer must be seen as part of the information chain. It is highly desireable that the customer takes part in the definition of data products and its presentation. Different from usual publications, which will sooner or later find the intended audience, REA products are available to a limited number of users who have the proper network connection. The suitable complexity of REA products very much depends on who the customer is and what capability he has for higher-volume digestion.

A major navy command being the customer of REA products likely has good communication channels and a staff of meteorology and oceanography experts who would be happy to receive detailed and complex environmental descriptions and predictions, even contradictory assessments from different origins. Smaller units and sub-commands that cannot spend time on environmental assessment need concise filtered products.

Security issues complicate data fusion and dissemination, if part of the information is to be released only to a subset of participants. Special password protection can be used to limit access only to authorized persons. By identity checks at login time, it can be decided by the data server which part of information is offered to a customer, who would not even get knowledge about the existence of denied products.

Data protection and restricted accessibility by selected members of an REA effort might be necessary in exceptional cases because of industrial proprietary issues. There is, however, no need for software protection. Essentially all software required for the management of a distributed network can be obtained from the public domain. The same is true for browsers, image viewers, document readers and geographic information system client software. As a precondition, originators of REA products must avoid the delivery of files that would require not freely available proprietary software for ingestion.

It is not suggested to publicly disseminate the entirety of information that is exchanged between participants of an REA operation because of the preliminary and provisional character of partial results. It is however a good idea to prepare a few pages with selected and possibly updated results on the unrestricted Internet for mitigation of the public that might be interested or have environmental concerns.

A visitors page on the Internet is also apt to gain credibility of the scientific community. Regular presentations of results demonstrate that REA is more than a vision. Scientific and logistic state of the art includes the competence for rapid assessment of the ocean environment.

## 11.8 Summary, conclusions and prospects

In this chapter we have presented the concept of rapid assessment of coastal ocean regions for the purpose of providing detailed synoptic environmental nowcasts and forecasts in support of a variety of naval and other operations. The general concept was illustrated and specific research and operational issues were identified and explored in the context of the NATO REA Rapid Response exercises 1996-7-8. The REA Ocean Observing and Prediction System requirements include importantly portability, flexibility, rapid relocateability, inclusivity with respect to coastal processes, and scalability with respect to hardware and software. Operational and system integration issues with respect to data acquisition and management and product design and dissemination have been discussed.

Scientific research areas which impact REA and provide the fundamental bases for advancement of the concept and capability include interdisciplinary coastal ocean science, ocean forecast science, ocean engineering sciences and information and complex system sciences. All of these sciences are evolving and growing rapidly and novel interdisciplinary interactions among them are being identified and researched. Rapid progress in rapid assessment of all regions of the global coastal ocean must be anticipated.

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