

Oceanic

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## Real-Time Regional Forecasting

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### Abstract

An observational network, dynamical models and data assimilation schemes are the three components of an ocean prediction system. Its configuration for a regional real-time forecasting system proceeds in three phases, based on previous knowledge and experience of the area. In the initial (exploratory) phase, identification of dominant scales (synoptic, mesoscale and submesoscale), processes and interactions is obtained. In the intermediate (dynamical) phase, a clear resolution of the important dynamics and events must be reflected in the nowcasts and forecasts. This is carried out via energy and vorticity analysis (EVA). The third phase is designed to validate the predictive capability of the forecasts. Both qualitative verification and quantitative skill are utilized. At each stage, high quality data sets are required. Observing System Simulation Experiments are essential to the development of the regional ocean prediction system. Initializations and updates are obtained by the fusion of multiple data streams, i.e., the melding of feature models, previous data driven simulations and observations. Nowcasts and forecasts are generated via sequential assimilation combining ship-acquired and sensed remote data. Nested models and nested observations are employed for adequate resolution. The approach is illustrated with recent real-time experiences at sea in the Iceland-Faeroe frontal region, the Straits of Sicily and the Eastern Mediterranean basin.

### 1. INTRODUCTION

This chapter is concerned with the real-time nowcasting and forecasting of an arbitrary region of the ocean. The region may have both open and coastal boundaries and may be in the deep or coastal ocean or may straddle the shelf break. Ocean forecasting requires both observations and models. The three basic components of an ocean prediction system are: an observational network, a set of dynamical models, and a scheme by which the data are assimilated into the models. The observational network

can consist of a variety of sensors mounted on various platforms. The emphasis in this discussion will be on shipboard forecasts, carried out with data primarily gathered from the ship itself. The work reviewed will be real-time, regional forecasts carried out with the Harvard Ocean Prediction System. Although most of the effort has been directed towards the forecast of physical fields, fully interdisciplinary regional forecasts are now both feasible and important for acoustical, biological, chemical and optical variables.

From a scientific viewpoint, nowcasting and forecasting oceanic mesoscale variability is important to efficiently utilize research resources in the intermittent ocean. Such nowcasts and forecasts are essential for the rapid assessment of a region. General management and Naval operational applications are discussed by Durham and Lewis (1992) and Peloquin (1992) in introductions of the special issues of *Marine Technology Society Journal* and *Oceanography*, respectively, which provide good reviews of the subjects. The real-time shipboard problem is introduced by Robinson (1992). Although mesoscale forecasting research is only about a decade old (Mooers *et al.*, 1986), operational forecasts have been initiated for the Gulf Stream region (Clancy, 1992). This is the region where a relatively good quality data set (Lai *et al.*, 1994) has also been assembled for forecast and simulation validation; preliminary results are presented by Willems *et al.* (1994). Robinson *et al.* (1995a) present mesoscale regional forecasts carried out on shipboard in an operational mode. Lynch (1995) has edited a book, *Quantitative Skill Assessment for Coastal Ocean Models*, which is generally relevant to ocean prediction techniques.

In this chapter, we describe the nature of the problem of oceanic forecasting, introduce the stages (exploratory, dynamical and predictive; *vid* Section 2) involved in the development of a forecast system and discuss the approach taken for the Harvard ocean prediction system, detail methodology contained within the Harvard system and give specific examples of regional forecasting which have been performed.

The overall development of a regional forecast system is exemplified in the Iceland-Faeroe Front region. The dynamical phase experiment at sea was carried out during October 1992 and the predictive phase forecast experiment took place in August 1993. The Sicily Straits cruise of November 1994 initiated the exploratory phase for that region, chosen for its complex and steep topography and multi-scale circulation features, driven both regionally and remotely. The Eastern Mediterranean cruise may be regarded as contributing to the dynamical stage of the development of a regional forecast system for the entire Eastern Mediterranean basin and illustrates the use of such a prototype system for shipboard forecasting for real-time experimental guidance.

## 2. NATURE OF THE PROBLEM

The synoptic state of the open ocean is generally dominated by the energetic mesoscale, characterized by the Rossby internal radius of deformation (Robinson, 1983). In the multi-scale synoptic circulation, structures occur over a range of interactive scales, including jet-scale, subbasin-scale, and large-scale. Mesoscale variability is now known to be episodic and intermittent. Mesoscale interactions and synoptical dynamical events occur on space and time scales which are smaller and shorter than the scales for the evolution and propagation of mesoscale features. Such events include rapid

nonlinear cresting of meanders, ring births and reabsorptions, eddy-eddy interactions, streamers and filaments, and are often referred to as submesoscale processes. Event-scales range from  $O(1-10 \text{ km})$  and  $O(\text{days})$ , whereas mesoscales range from  $O(10-100 \text{ km})$  and  $O(\text{weeks-months})$ . The coastal ocean synoptic state is a multi-scale mix of forced responses and internal dynamical processes. These include wind, tide and boundary forced responses and mesoscale and event-scale processes analogous to those in the open ocean.

Faster and smaller phenomena may also be present and interactive, such as various types of waves, fine- and microstructures and turbulence. The partitioning of scales and phenomena between deterministic and statistical treatments, and between explicit resolution and subgrid scale parameterization must be done partly because of interest and partly because of necessity. Event-scale and submesoscale phenomena of interest require high resolution measurements and dynamical model grids, which are generally impossible to obtain and maintain over the entire region of interest. What is required is nested, high resolution domains, in both the observational network and the dynamical models. Scales smaller than those which can be resolved in the finest grid require subgrid scale parameterization. Forcing mechanisms include surface fluxes of momentum, heat, and fresh water, initial conditions and boundary conditions, which include a representation of larger than regional scales. The nature of the forecast problem is strongly influenced by the relative importance of the response to direct regional surface flux forcing, compared to the evolution via internal dynamics of fields remotely forced in space and time.

Although general processes occur throughout the world ocean, their mix, relative amplitudes and interactions are different in different regions. Regions have their own geometries, topographies and peculiarities. The region chosen for the development of a regional prediction system, may need to be considerably larger than the region of forecast interest for practical purposes, in order to include external influences efficiently. As many regions of the world ocean are still relatively unknown, we will discuss here the development of a regional forecast capability for a relatively unknown region. Better known regions will require less work. Desired forecast purposes (optimal use of research resources, coastal zone management, marine operations (including Naval), etc.), variables, duration and accuracies need to be quantified initially, but must be expected to be iterated and modified as regional predictability is determined. Regional predictability requires accurate estimates of actual ocean states and is influenced by many factors, including the development of instabilities and regional boundaries and boundary conditions.

There are three stages in the development of a regional forecast capability. The first phase is exploratory, the second phase is dynamical, and the third phase is predictive. The exploratory phase is descriptive and kinematical and involves the identification of regional scales, phenomena, processes and interactions. The dynamical phase must be definitive with regard to the determination of synoptic flow structures, regional synoptical dynamical events and interactions, and the elucidation of dynamical processes governing mesoscale evolution and submesoscale events. Dynamical processes such as wave generation and propagation, internal instabilities, dominant external forcings, etc. impose qualitative and quantitative requirements on the design of a regional prediction

system. Nowcasts and forecasts need to be carried out during all three stages. However, during the predictive phase the focus should be on forecast experiments. High quality data sets for forecast initializations, updating and verification are required. Oversampling is necessary in order to determine minimal data requirements for efficient forecasts of desired accuracies.

### 3. APPROACH

We now describe the general methods utilized for the application of the Harvard Ocean Prediction System (HOPS) to real-time regional forecasts. HOPS is a flexible, portable system whose modularity facilitates efficient configuration for specific applications. Figure 1a presents HOPS in its presently most comprehensive form, with all modules and models attached. Configured for a particular application, the system will generally be less complex. Products are indicated by the rectangles, while models and procedures are indicated by ovals. The 'star modules' represent specific start-up and updating modules (Figure 1b). Lozano *et al.* (1995) discuss the system in detail and Robinson (1995) reviews forecasting applications up to 1993.

From a scientific viewpoint, a central idea for nowcasting and forecasting the multi-scale ocean is to attempt to initialize the nowcast or forecast with the best possible estimate of the synoptic state of the system. This contrasts with the approach where a general circulation model may be initialized, e.g., with a mean climatology, and run forward in time in an attempt to develop the regional synoptic state via dynamics with data assimilation. Adequate high resolution and synoptic observations are seldom available for direct initialization so methods have been developed to meld the available synoptic data with synoptic state information from prior observations and dynamical studies. Such information includes prior estimates of the synoptic state of the region from measurements, assimilated observations and realistic regional data driven simulations.

The development of an efficient prediction system for a region thus involves the development of a forecast oriented, historical, synoptical, statistical data base. Statistical models for data reduction and downward extension of satellite data include empirical orthogonal functions in one to four dimensions. Error models, essential for data assimilation, require statistical models for correlation functions, structure functions, and so on. Of particular importance are feature models, i.e., statistical models of typical synoptic structures, a type of structured data model (*vid* Lozano *et al.*, 1995 and Figure 1b). A set of feature models for the dominant circulation structures of the region, kinematically linked via mass-conservation constraints, provides a powerful mechanism for regional initializations and updating. Multiscale linked feature models, developed for the Gulf Stream meander and ring region (Gangopadhyay *et al.*, 1995) have been used together with the primitive equation dynamical model to reproduce the statistics of meander growth and ring formation in the region (Robinson and Gangopadhyay, 1995) and for forecast verification studies (Gangopadhyay and Robinson, 1995). For shelf and coastal oceans, tidal models are necessary; statistical feature models can represent various types of waves, and feature model storms and weather systems can be useful.

## HARVARD OCEAN PREDICTION SYSTEM - HOPS

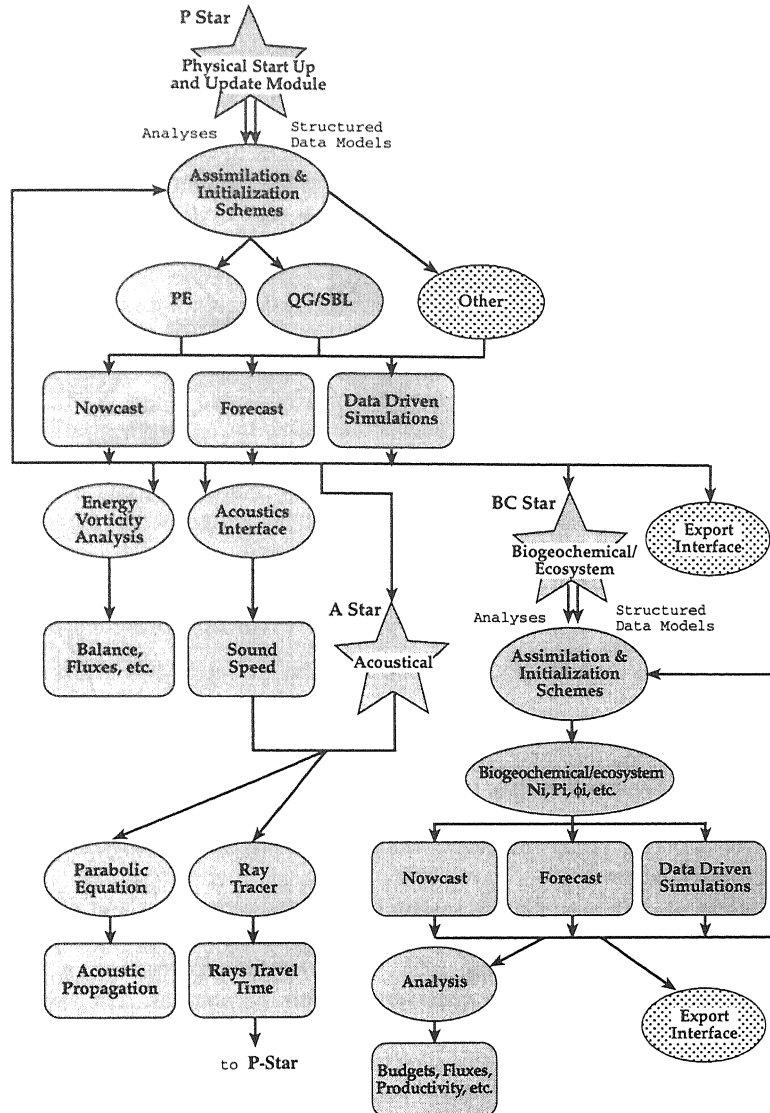


Figure 1a. Schematic of Interdisciplinary Ocean Prediction System. Overview.

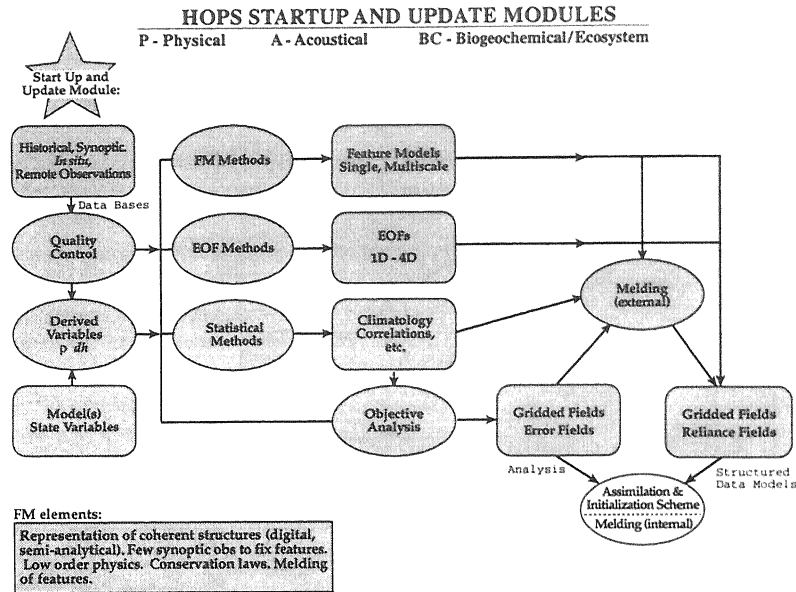


Figure 1b. Schematic of Interdisciplinary Ocean Prediction System. Start-up and update module.

The observational network of the regional forecast system must provide real-time input to nowcasts and forecasts. A mix of platforms and sensors with nested sampling is desirable to provide efficiently information over a range of scales. Coastal areas, ships, aircraft, satellites, moorings, freely floating and roving vehicles are now available as platforms. Dickey (1993) overviews the range of physical, biological and chemical sensors now available.

A variety of data assimilation schemes, based on estimation and control theory, are now available (Bennett, 1992) and methodological research is rapidly progressing (Malanotte-Rizzoli and Tziperman, 1995). For real-time forecasting, a filtering approach is indicated and efficiency considerations are paramount. For applications of the Harvard Ocean Prediction System (HOPS) to real-time regional forecasting, we have chosen a simple, robust optimal interpolation scheme (Lozano *et al.*, 1995). This choice was made not only for efficiency, but also to focus initially on the subtleties of forecast and predictability research rather than data assimilation methodologies.

Verification of a forecast system is an essential task requiring several steps. Prior to commencing forecasts in a specific region, a dynamic model for the region must be chosen and validated. This entails selecting adequately sophisticated physics for the phenomena and scales in the area (e.g., quasigeostrophic equations, shallow-water equations, primitive equations, etc.). The model must then be calibrated and tuned for the environmental, computational, and subgrid scale parameterizations (e.g., the

number of layers or levels, stratification strength, convection and mixing, etc.). The model must be able to capture the dynamics of synoptic events. Verification requires reproducing the statistics of past synoptic events and finally predicting, in real time, new events with qualitative and quantitative skills.

#### 4. SYNOPTIC SHIPBOARD NOWCASTING AND FORECASTING

In this section, we present a methodology to build up and maintain a synoptic description of a region by nowcasting and forecasting on board a ship, primarily utilizing *in situ* data obtained by the ship itself as it moves around the forecast region. The present method of *sequential updating* replaces our previous method of *sequential reinitialization*. In the sequential reinitialization method, a subregion of the entire region is first initialized when sufficient data has been obtained to make a reasonable nowcast and short forecast. With a dedicated research vessel taking hydrographic observations with a mix of CTDs and expendable probes, this is typically one day's (24 hours) worth of data. Then, on each successive day, the model will be reinitialized in successively larger subdomains until the entire domain is covered, at which time the entire forecast domain will be initialized on the central day of the data gathering time interval. In the sequential updating method, when the first subdomain data is available, the entire domain is initialized, using, in the data empty region, elements from the regional historical synoptical data base. On successive days, then, the new subdomain data sets are assimilated via optimal interpolation as they become available. In this way, the entire domain is built up with data being assimilated and evolving as synoptically as possible. As the ship continues to operate in the region, the sequential assimilation procedure is continued whenever sufficient data is obtained over a subdomain to make updating meaningful.

The sequential updating process for the Iceland-Faeroe Front (IFF) is illustrated in Figure 2. The ship is moving from east to west, gathering data along north-south sections separated by 25 km. There are three subdomains and it takes three days to cover the entire area. Initially, the central and western subdomains are initialized by invoking a feature model frontal jet along the climatological mean east-west frontal axis together with climatological mean stratification to the north and south. An objective analysis is made for the entire domain, adding the climatology and feature model data to the eastern subdomain observations. Figure 2 shows the three assimilations and the subsequent forecast via the Primitive Equation model. Figure 2a shows day 1, after the eastern data has been assimilated. Notice the synoptic scale meanders in the eastern part of the front and the contrasting flat feature model front (in its climatological position) to the west. In Figure 2b, another day has gone by and the central domain has been assimilated. The frontal meanders cover more of the domain and synoptic eddies appear. By day 3 (Figure 2c), all the 1992 data has been assimilated. The meanders and eddies now cover the entire region. Finally, an additional four-day forecast is made (Figure 2d). An identifiable, realistic front is present, as are other synoptic scale features.

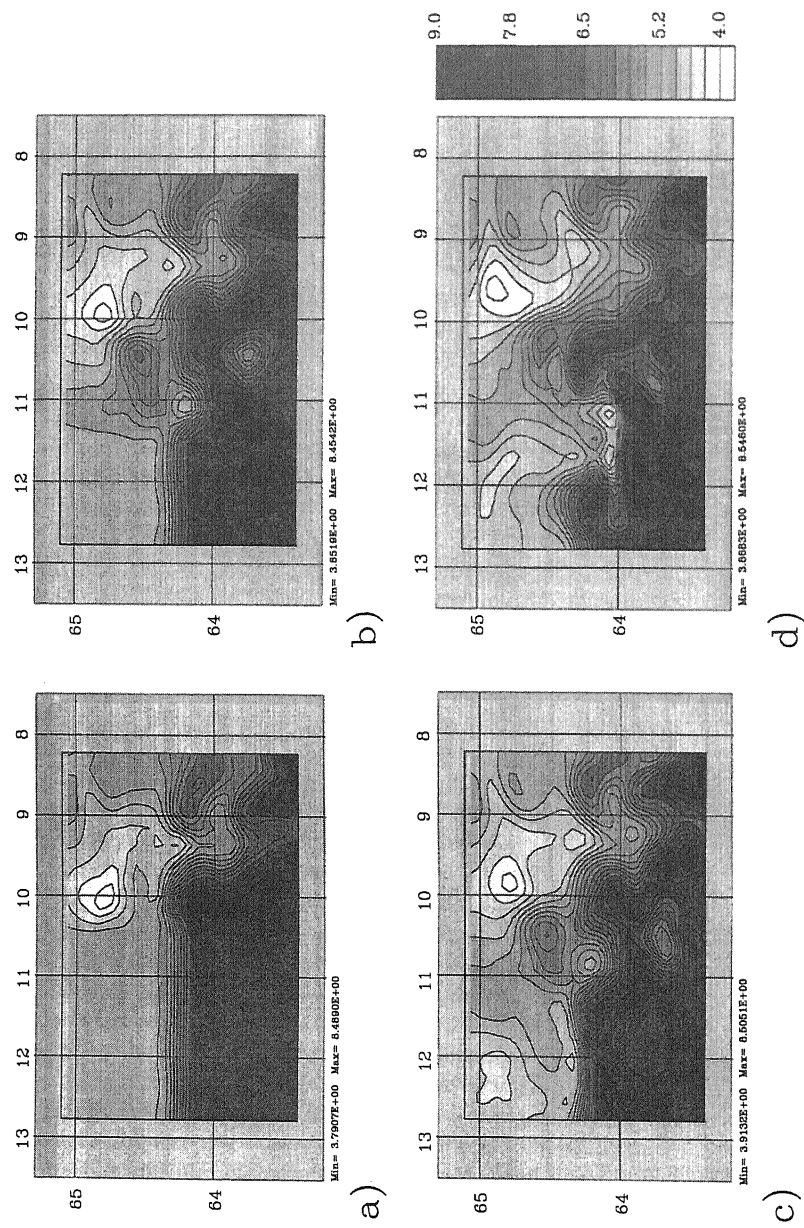


Figure 2. Observational System Simulation Experiment for IFF August 1993 cruise. 25 m temperatures at: a) Day 1, b) Day 2, c) Day 3, d) Day 7.



The illustration of Figure 2 is actually an Observational System Simulation Experiment (OSSE). It utilizes objectively analyzed (OA) data obtained during an October–November 1992 cruise. During the 1992 cruise, data was gathered in a west-to-east pattern. The logistics of current meter recovery and efficient data collection for model initialization and verification, dictated that, in 1993, data would have to be collected in an east-to-west fashion. The OSSE was necessary to validate the details of the data collection and assimilation scheme. The novel aspect of the sampling was moving the ship from east to west against the current. The sampling pattern of Figure 2 was subsequently carried out successfully during August, 1993, as discussed in Section 6.

## 5. EVALUATION METHODS

Here we describe in greater detail some of the aspects of the methodology which are necessary for the dynamical and predictive evaluation of the regional predictive system. In the exploratory phase of the development of such a system, the procedure is largely descriptive; determining features and process which exist in the region. During the dynamical phase, the strategy of energy and vorticity analysis helps to elucidate an understanding of the regional physics. The final predictive phase necessitates both a qualitative and quantitative assessment of regional predictive ability. Qualitative assessment can be based on measures such as feature location, shape, size, jet axes, eddy center and radii, etc. Specific quantitative skill measures are defined below.

### 5.1 Energy and Vorticity Analysis

During the development of a forecast capability for a new region, it is essential to understand the physical processes which control the dynamical variability, in order to improve the model physics (e.g., choice of eddy mixing coefficients), the model framework (e.g., the number of layers) and the model geometry (e.g., smoothing of topography). A useful strategy for interpreting the physics of quasigeostrophic (QG) and primitive equation (PE) flows has been energy and vorticity analysis (EVA), developed by Pinardi and Robinson (1986) and Spall (1989) through derivations of the QG and PE energy and potential vorticity equations (and PE divergence equation). Pinardi and Robinson analyzed several selected analytically tractable examples whose energetic and vorticity signatures thereafter form a set of physical benchmarks to which forecasts (or hindcasts) can be compared for insight into the dynamics. The goal is not only to characterize the dynamics of individual events, but also to identify generalizable dynamical processes after many cases have been studied throughout the world ocean.

In order to set the stage for the discussion of energetics of the Iceland–Faeroe Front later in this chapter, we now give a brief introduction to the techniques developed for energetic diagnostics; analogous derivations apply for the vorticity diagnostics which are not presented here. The derivation commences with the quasigeostrophic potential vorticity, written in nondimensional form with characteristic time,  $T$ , length,  $L$ , depth,

$H$ , and velocity scales,  $U$ , as,

$$\frac{\partial}{\partial t} (\nabla^2 \psi + \Gamma^2 (\sigma \psi_z)_z) = \alpha J(\psi, \nabla^2 \psi) + \alpha \Gamma^2 J(\psi, (\sigma \psi_z)_z) + \beta \psi_x + F_{pqr}. \quad (1)$$

Symbolically (1) can be written as

$$\dot{Q} = \dot{R} + \dot{T} = \Delta F_R + \Delta F_T + \Delta F_P + F \quad (2)$$

where  $\psi$  is the quasigeostrophic stream function,  $J(\cdot, \cdot)$  is the Jacobian operator,  $\nabla^2$  is the horizontal Laplacian operator,  $\alpha = TU/L$ ,  $\beta = \beta_0 TL$  and where  $R(= \nabla^2 \psi)$ ,  $T[= \Gamma^2 (\sigma \psi_z)_z]$  and  $Q$  are the relative, thermal and dynamic vorticity respectively. The  $(\dot{\quad})$  denotes the time rate of change and  $(\Delta F)$  denotes the advective flux divergence of  $R$ ,  $T$  and  $\beta y$ , the planetary vorticity. The subscripts on the filter have been dropped from (2).

The quasigeostrophic kinetic energy [ $K = (u^2 + v^2)/2$ ] equation consistent with equations (1, 2) can be written as

$$\begin{aligned} \frac{\partial}{\partial t} (K) = & -\alpha \vec{\nabla} \cdot (\vec{v} K) + \vec{\nabla} \cdot (\psi \vec{\nabla} \psi_t + \alpha \psi \vec{v} \cdot \vec{\nabla} \vec{\nabla} \psi + \beta \psi \vec{v} y) \\ & + \frac{\partial}{\partial z} (\Gamma^2 \sigma \psi \psi_{zt} + \Gamma^2 \alpha \sigma \psi \vec{v} \cdot \vec{\nabla} \psi_z) - \psi_z w + \mathcal{D}_K. \end{aligned} \quad (3)$$

For ease in subsequent referencing (3) is rewritten using a label for each term in the form:

$$\dot{K} = \Delta F_K + \Delta F_\pi^t + \Delta F_\pi^a + \Delta F_\pi^\beta + \delta f_\pi^t + \delta f_\pi^a - b + \mathcal{D}_K; \quad (3a)$$

or, more briefly, in the form

$$\dot{K} = \Delta F_K + \Delta F_\pi + \delta f_\pi - b + \mathcal{D}_K. \quad (3b)$$

The available gravitational energy [ $A = \sigma \Gamma^2 (\psi_z^2)/2$ ] equation is

$$\frac{\partial}{\partial t} (A) = -\alpha \vec{\nabla} \cdot (\vec{v} A) + \psi_z w + \mathcal{D}_A, \quad (4)$$

or

$$\dot{A} = \Delta F_A + b + \mathcal{D}_A. \quad (4a)$$

where again the symbols in (4a) correspond to the terms in (4). The nondimensional parameters are  $\Gamma^2 = f_o^2 L^2 / N_o^2 H^2$  and  $\sigma = N_o^2 / N^2(z) = -N_o^2 / g (\partial \bar{\rho} / \partial z)$ . In the above,  $f_o$ , and  $\beta_o$  are representative values of the local rotation rate and its latitudinal gradient.

The symbols representing the terms in (3, 4) are  $\Delta F_K$ , the horizontal KE advective working rate;  $\Delta F_\pi$ , the horizontal pressure working rate, which is further broken up into three terms,  $\Delta F_\pi^t$ , that due to acceleration of the geostrophic velocity,  $\Delta F_\pi^a$ , that due to advection of the geostrophic velocity, and  $\Delta F_\pi^\beta$ , that due to Coriolis acceleration;

$\delta f_\pi$ , the vertical pressure working rate, which is further broken up into two terms,  $\delta f_\pi^t$ , the vertical pressure energy flux divergence due to time changes in density, and  $\delta f_\pi^a$ , the vertical pressure energy flux divergence due to horizontal advection of density;  $b$ , the buoyancy working rate; and  $\Delta F_A$ , the horizontal AGE advective working rate. The  $\mathcal{D}_{K,A}$  are dissipation terms in the energy equations arising from the Shapiro filter operation on the vorticity.

A suite of simple solutions of the quasigeostrophic equations was examined to gain physical insight into expected spatial and temporal relationships among the dominant terms in (3, 4). The analysis included a simple baroclinic Rossby wave, the eddy baroclinic instability problem and a particular barotropic instability example. The Rossby wave example exhibits the benchmark interplay among the terms in (3, 4), with the two instability solutions revealing perturbations about that basic wave-like state. Simple propagation involves a periodic exchange of K and A through b, and the instability signals are usually asymmetries of the large propagation noise. In the eddy baroclinic instability model (pure vertical shear), buoyancy work is negative definite in the mid-depths of the water column, indicating a transfer of energy from AGE to KE. The source term for the AGE is the energy of the shear flow, arising through  $\Delta F_A$ . Besides the forcing through buoyancy coupling at mid-depths, the KE equation is driven near the surface and bottom through vertical exchange processes,  $\delta f_\pi$  in the baroclinically unstable case. The term  $\delta f_\pi$  drains the KE at mid-depth and drives the KE at the top and lower boundaries. In the barotropic instability model (pure horizontal shear) that they selected, the AGE equation is inconsequential. The dominant source term in the KE equation is  $\Delta F_\kappa$ , corresponding to a Reynolds stress effect drawing energy from the mean shear. Developing additional analytical or numerical basic examples to add to this list (e.g., topographic waves, radiating instabilities) is an important future direction for EVA.

Dynamical analyses of simulations and forecasts are required to understand processes. These are carried out via term-by-term balances. Consistent schemes have been developed for analyzing the potential vorticity, kinetic energy and available gravitational energy for the quasigeostrophic equations (Pinardi and Robinson, 1986) and the vorticity, divergence and energies for the primitive equations (Spall, 1989). QG dynamical studies have been carried out for the California Current (Robinson *et al.*, 1986), the North Atlantic mid-ocean eddy field (Pinardi and Robinson, 1987), the Gulf Stream (Robinson *et al.*, 1988) and the Eastern Mediterranean (Golnaraghi, 1993a,b) and the Iceland-Faeroe Front (Miller *et al.*, 1995a,b). PE studies have been carried out in the mid-ocean eddy field (Spall, 1989) and the Gulf Stream (Spall and Robinson, 1990).

## 5.2 Verification and Skill Assessment

A quantitative validation of forecast skill is highly desirable, but the difficulty of acquiring sufficient oceanic data for both initialization and validation means that convincing demonstrations of mesoscale ocean forecast skill are rare. Measures of forecast

skill we use are the pattern correlation coefficient,

$$\text{PCC} \equiv \frac{\langle \psi'_p \psi'_o \rangle}{(\langle \psi_p'^2 \rangle \langle \psi_o'^2 \rangle)^{1/2}} \quad (1)$$

and the normalized root-mean-square error,

$$\text{NRMSE} \equiv \frac{\langle (\psi_p - \psi_o)^2 \rangle^{1/2}}{\langle \psi_o^2 \rangle^{1/2}} \quad (2)$$

where  $\psi_p$  is the predicted variable (e.g., stream function),  $\psi_o$  the observed variable (e.g., dynamic height scaled to stream function), the primes denote removal of the spatial mean, and the angle brackets denote averaging over the specified horizontal area. The forecast variable  $\psi_p$  will apply either to the dynamical prediction or to using persistence of day 0 as the predictor.

Measures of quantitative dynamical forecast skill must first be gauged relative to persistence of day 0. Once that baseline is demonstrated, forecast models can be compared relative to each other. To attach statistical confidence to measurable skill of a forecast model, one would need many data sets with adequate initial and verifying data, and this is presently very difficult to realize for oceanic forecasting (Willems *et al.*, 1994; Lynch, 1995).

## 6. THE ICELAND-FAEROE FRONT

The Iceland-Faeroe Front (IFF) is located between Iceland and the Faeroe Islands in a region where the ocean bottom rises to within 400 m of the surface. The front forms the confluence of the warm saline North Atlantic water mass and the cold low salinity Arctic water mass. Strong currents and sharp temperature gradients are found in this area. A composite picture of the current structures has emerged that shows a flow along the frontal area with inflow from the North Atlantic along the southeastern Icelandic shelf. Some inflow of Arctic-type water occurs along the northeastern Icelandic shelf and merges with the North Atlantic water inflow at the frontal location off Iceland (Peggion, 1991). In the frontal region, a high degree of mesoscale and event-scale dynamical activity exists. Frontal meanders, cold and warm eddies are present. Atmospheric cooling, mixing of the upper ocean, internal tides and internal waves occur.

### 6.1 Forecast Experiments

This has been a particularly successful region for executing the previously described 3-phase strategy of regional forecast system development (Section 2). The forecast experiment cruises were carried out cooperatively by Harvard and SACLANT scientists aboard the *R/V Alliance* in October 1992 (Arango *et al.*, 1993), and August 1993 (Robinson *et al.*, 1994), but significant work had been achieved before those dates, in tuning both quasigeostrophic (QG) and primitive equation (PE) models for specific

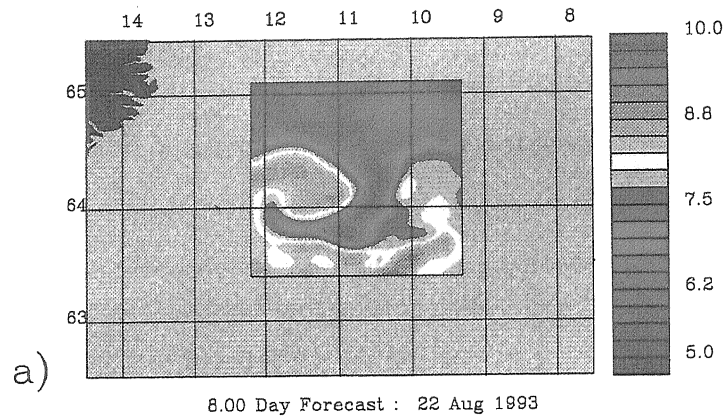
application to that region. Denbo and Robinson (1988a, b) had shown that QG physics were sufficient to capture many aspects of the natural variability of the IFF and a suitable set of model environmental parameters had been identified.

The October 1992 cruise to the IFF was designed to provide a hydrographic data set geared specifically towards initialization and validation of a forecast. It turned out that poor weather limited the data set in two ways. First, the initialization survey required 5.5 days to complete and therefore was not synoptic. Second, the validation survey was necessarily limited to a single criss-cross track over the model forecast region, rather than a complete resurvey of forecast fields. Nonetheless, the data set proved essential for tuning the dynamical models, for demonstrating qualitative forecast skill in the region, and for identifying underlying dynamical processes (Miller *et al.*, 1995a).

During the August 1993 cruise to the IFF, the tuned QG model and a primitive equation model, capable of handling steep and tall topography, were both used in real-time forecasts. Real-time, shipboard nowcasts and forecasts were used to define and predict regional structures and provide experimental guidance. As fine weather prevailed during the expedition, the forecasts were able to be validated quantitatively for skill in two separate initial states, i.e., at the beginning and the middle of the cruise. Both the QG model (Miller *et al.*, 1995b) and the PE model (Robinson *et al.*, 1995a) forecasts showed significant real-time quantitative forecast skill, beating the persistence of day-zero conditions to at least 3 or 4 days, with strong events occurring. A striking, deep-sock meander developed from an initial simple, gentle meander pattern. A PE model forecast (executed post-cruise in forecast mode with an improved model over that used at sea) for 25 m depth temperature shown in Figure 3a, exhibits submesoscale features that corresponds well to those observed in the satellite SST map (Figure 3b), which was obtained on a rare clear day. Quantitatively the at sea forecast was comparable but slightly better.

The observations and PE forecasts are summarized in Figure 4 in terms of the temperature fields at 125 m. Figures 4a, b, and c are objective analyses on the central day of three day regional surveys. The first and last were complete surveys, and the intermediate survey focussed on critical features with a zig-zag sampling pattern. Note that the inlet position of the front on the western boundary is nearly stationary throughout the experiment. On August 15 (Fig. 4a), the IFF was oriented eastward in a distinct meander pattern with a crest at about  $11.5^{\circ}\text{W}$  longitude and a trough at about  $11^{\circ}\text{W}$ . In the east, the flow broadens and bifurcates around a pair of eddies only partially contained within the domain. The upper frontal system evolved rapidly and changed qualitatively between each survey. By 19 August (Fig. 4b), the meander had disappeared and the straightened frontal stream had shifted to a southeastward orientation in the western domain and a northeastward orientation in the eastern domain. However, only three days later, on 22 August (Fig. 4c), the dominant synoptic feature was the large, cold intrusion, or deep sock meander, which had developed in the center of the domain (Miller *et al.*, 1995b; Robinson *et al.*, 1994, 1995a).

Nowcasts and forecasts were carried out using the sequential updating method initialized in the manner of the OSSE of Figure 2. The nowcast of Fig. 4d and the forecasts of Figs. 4e,f utilize data from the first 3-day survey only. Figure 4g has been updated with the intermediate survey data and Fig. 4h is the resultant forecast. Note,



NOAA11 AVHRR CH4, 22-Aug-1993 14:31 GMT

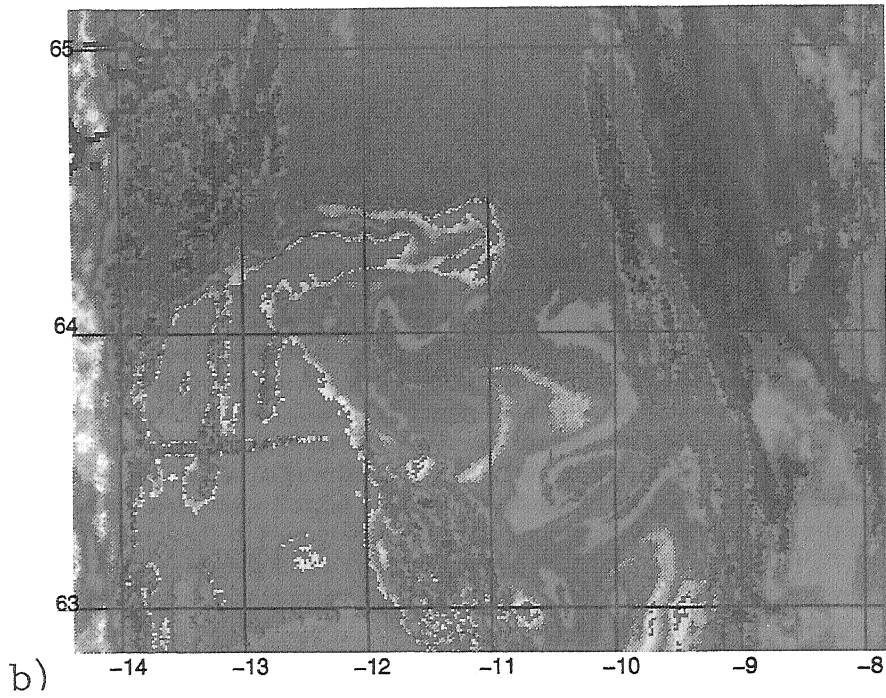


Figure 3. a) Primitive equation model 25 m temperature forecast for 22 August 1993. b) Sea-surface temperature from satellite IR for the same date. Modeling domains is outlined on b).

importantly, that dynamics successfully accomplish the straightening of the jet and its southward orientation (Fig. 4e) and also predict the deep sock meander.

The day-2 nowcast, Fig. 4d, has assimilated, via intermittent optimal interpolation in three daily cycles (sequential updating - Section 4), the entire initialization survey data set. It represents a field estimate in which day-2 synoptic data has been assimilated synoptically at the central day, and as a result of previous assimilations in the cycle, the data dynamically adjusted, dynamically interpolated, and dynamically extrapolated by the model. It should be compared with the objective analysis for the central day of the survey Fig. 4a. Although a time-dependent OA was used, since every region of the domain was sampled only once, the full domain maps for August 14, 15, 16 are essentially identical to the central day map (Fig. 4a). What differs from day to day are the maps of expected error of the analyses. The OA (Fig. 4a) and nowcast (Fig. 4d) estimates are very similar but there are significant differences. In the nowcast, the meander crest has smoothed and the trough has weakened and propagated westward. We believe that these dynamical adjustments are real and that the nowcast estimate based on synoptically assimilated data melded with dynamics provides the most realistic picture of the frontal system.

## 6.2 Event Dynamics

The dynamics of the flow fields involved in the occurrence of the major synoptic events, such as rapid shifts and deep meandering, have been studied. In each of the two cruises to the IFF, a strong internal instability event occurred. During October 1992, a cusp-shaped cold intrusion developed along an east-west oriented frontal current (Miller *et al.*, 1995a). During the August 1993 IFF cruise, a gentle meander pattern first straightened and shifted to the southeast, which was followed by the development of the deep sock meander (Figures 4a-b).

The instability processes which control current variations in the Iceland-Faeroe front (IFF) have been studied by Miller *et al.* (1995a,b) using the EVA diagnostics. Three mesoscale events occurred during two forecast expeditions to the IFF, and these were modeled successfully in their QG forecasting experiments. For each of the three synoptic events, a diagnostic breakdown of the AGE and KE equations revealed that energetic conversion processes are at work which are consistent with those that occur in a simple model of baroclinic instability (the eddy problem discussed in Section 5.1). The source term for barotropic instability was very small and inconsequential during these three events. Somewhat surprisingly, the baroclinic instability mechanism occurs for each of the three mesoscale events, suggesting the predominance of the mechanism, even though the spatial structure of the current variations differ considerably from case to case. A schematic of the basic energetic exchange processes which occurred for those three IFF synoptic events is sketched in Fig. 5, mapped in Fig. 6, and discussed more thoroughly in the next paragraphs.

The specific details of the energetic exchange processes are as follows. In October 1992 a cold tongue intrusion of the IFF grew as a wave-like meander on an east-west oriented frontal current. The EVA energetic breakdown showed that AGE was

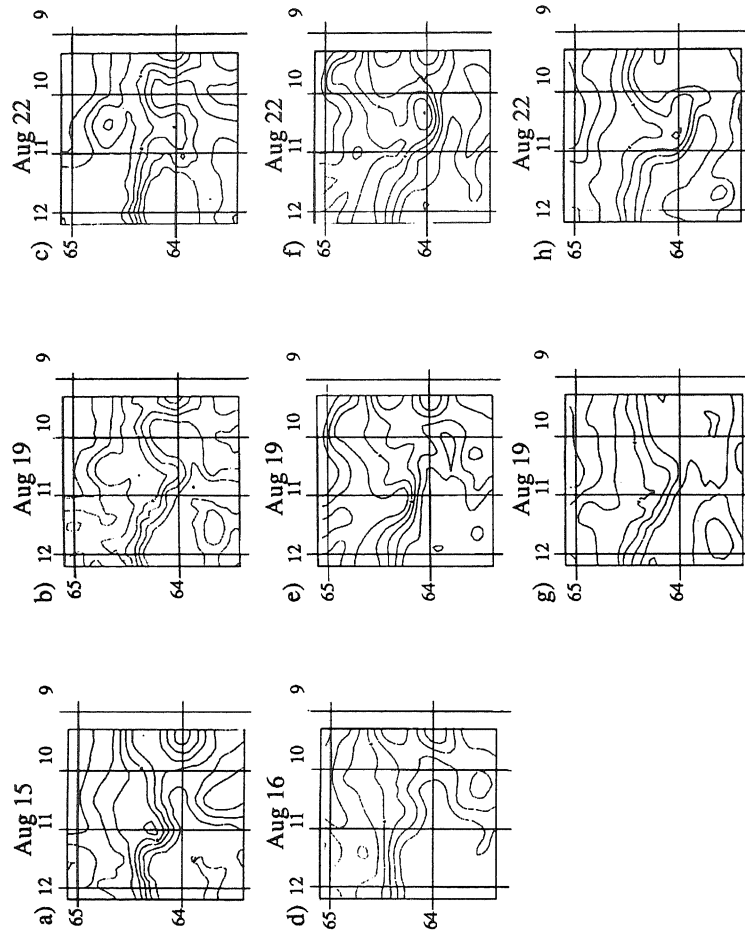


Figure 4. IFF primitive equation model forecast validation. 125 m temperatures. Contour interval is 1°C. a), b) and c) are objective analyses for Aug. 15, Aug. 19 and Aug. 22, respectively. d), e) and f) are forecast days 0, 3 and 6 for a forecast which does not contain the updating data from Aug. 19. g) and h) are days 3 and 6 for a forecast which contains the updating data from Aug. 19.



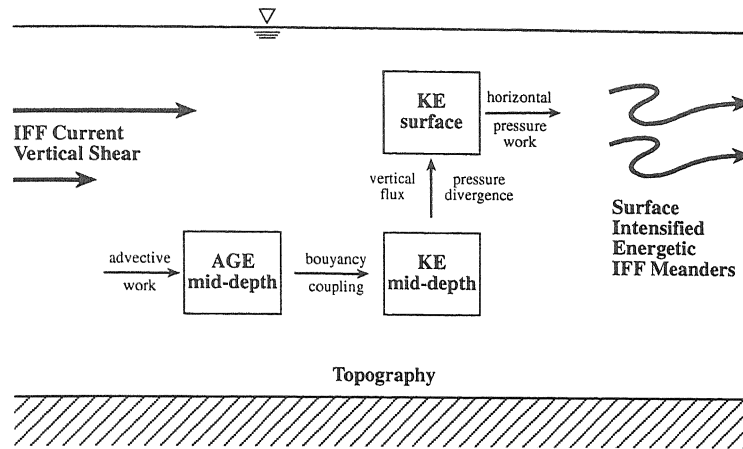


Figure 5. Schematic of energy processes in Iceland-Faeroe Front region.

converted to KE in the mid-depths of the water column from where it was transferred upward into the near-surface KE field yielding the surface current field associated with the cold tongue intrusion. The whole process required roughly 3-4 days to develop indicating the rapid exchanges of energy which can occur in this region (Miller *et al.*, 1995a).

A similar sequence of energetic transfers prevailed during the two synoptic events observed and forecast during August 1993 (Miller *et al.*, 1995b). In these two cases, however, the growing unstable perturbations were not wave-like, but rather occurred as localized disturbances which developed over 3-4 day time scales on a convoluted IFF current. From an initial meandering IFF current, the dynamics shifted the current to a southeastward flowing state through baroclinic instability processes similar to those described above. Likewise, the southeastwardly flowing initial current developed into an intense hammerhead intrusion along the IFF via the same dynamical process, the which is schematized in Fig 5, corresponding to day 3 (August 23, 1993) of the dynamical QG forecast. The velocity field at 250 m depth (Fig. 6a) is related to the hammerhead pattern in sea-surface temperature seen near the surface. At mid-depth (250 m), the advective working rate in the available potential energy (AGE) equation (Fig. 6b) indicates that a net transfer of energy from baroclinic shear flows occurs at the leading edges of the developing hammerhead. Mirroring that effect in sign, the net buoyancy working rate (Fig. 6c) shows that this energy is drained from the AGE and converted to kinetic energy (KE) in the mid-depths of the water column. The vertical pressure-working rate (Fig. 6d) reveals a net upward transfer of KE towards the vigorous current field of the surface layers. These processes of IFF current variability correspond remarkably well to the basic energy exchange patterns diagnosed from the very simple Eady baroclinic instability problem.

The surface-intensified nature of the baroclinic instability mechanism evidently

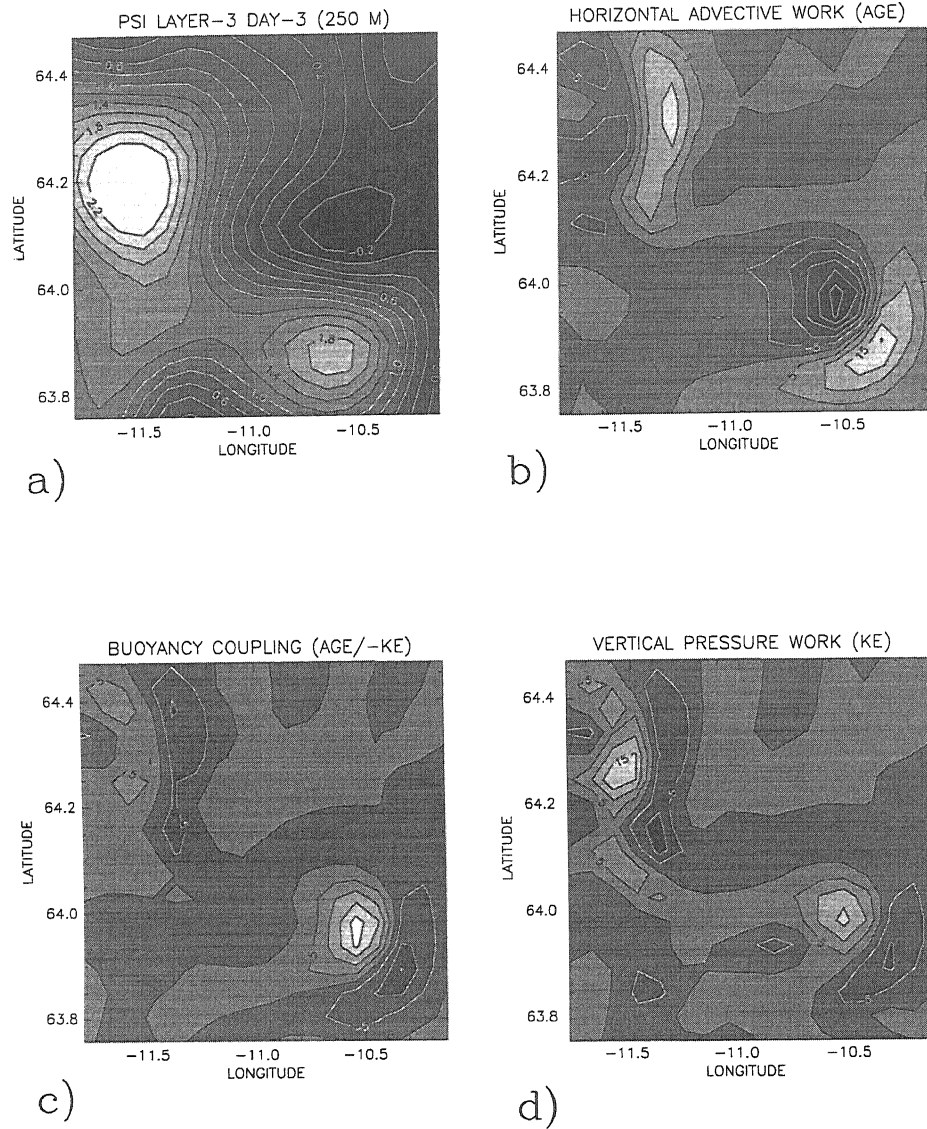


Figure 6. a) Forecast stream function at 250 m depth (QG model layer 3) for August 23, 1993, (forecast day 3). Contour interval is 0.25 nondimensional units. To redimensionalize to  $\text{m}^2/\text{s}$ , multiply plotted values by 4500. Spatial maps for the same day and layer of b) the horizontal AGE advective working rate c) the buoyancy working rate (oppositely signed in the AGE and KE equations) and d) the KE vertical pressure working rate. Contour interval is 5.0 nondimensional units. Unshaded areas lie between 0 and 5, lightest shading lies between 0 and -5.

helps to explain why the QG model (with a flat bottom) was able to adequately represent the explosive cold tongue and hammerhead intrusions in spite of the presences of very steep topography in the vicinity. A comparable energetics analysis of PE model forecasts, which can handle the steep bathymetry in this region, will provide more conclusive details of the physics, especially if forecast skill can be demonstrated beyond the 3-to-4 day range of the QG case.

### 6.3 Forecast Skill

Skill measures introduced in Section 5 are Pattern Correlation Coefficient (PCC) and Normalized Root Mean Squared Error (NRMSE). A positive PCC difference (or a negative NRMSE change) indicates higher skill for the forecast. Due to the existence of the front, correlations remain high even for persistence forecasts (e.g., typical values of the PCC exceed 0.6 for forecasts by persistence of day 0). It should be noted that even a slight improvement in PCC for a forecast can explain a fair percentage of additional pattern variance of the field. For example, if a forecast field has PCC = 0.85, representing an increase of 0.10 over a persistence forecast PCC = 0.75, 16 percent additional variance of the pattern of the field has been predicted, which is useful.

An oceanic data set adequate for quantitative skill assessment is provided by the August 1993 IFF experiment. The hydrographic data set consists of a complete initial survey (spanning 3 days), an updating assimilation zig-zag survey (over 2 days) and a complete validation survey (7 days later than the initial). The HOPS was invoked in several different forecast scenarios during that cruise, and significant quantitative skill scores have been obtained for both the PE model (Robinson *et al.*, 1995) and the QG model (Miller *et al.*, 1995b). A similar forecast by the PE model, which assimilated both the initial and the zig-zag surveys, successfully forecast middle and lower water column temperature better than persistence, increasing the PCC by more than 0.10 and reducing NRMSE by several tens of percent. In fact, the PE model captured the upper-water column structure of the observed hammerhead intrusion but forecast a hammerhead displaced slightly downstream of the observed, thus destroying the PCC. If that downstream shift (10 km) is accounted for by including a spatial lag in the PCC computation, the PE model PCC beats persistence by 0.14 and the RMSE is reduced by 0.15.

Skillful results were also obtained for upper-water column flows using the quasi-geostrophic forecast model (Miller *et al.*, 1995b), although the QG model was unable to capture the sharp and narrow features of the hammerhead structure. However, the QG model was validated against dynamic height while the PE model was validated against temperature. A direct comparison between forecast PE and QG current or dynamic height fields has yet to be carried out. But since both the PE and (flat bottom) QG models exhibited upper-ocean forecast skill, we note that topographic influence was minimal during the 3 to 4 days of the simulations because the modeled instability apparently was trapped in the upper part of the water column. Only the PE model was able to forecast with fidelity the deep flows around the IFF.

## 7. THE STRAITS OF SICILY AND IONIAN SHELFBREAK REGIONS

The region of the Straits of Sicily, the Ionian shelf break and the western Ionian Sea has a complex geometry and topography (Fig. 7a). In the Straits, there are shallow coastal areas with depths less than 100 m. Off Tunisia, there is a broad gentle slope region extending eastward. There is a central narrow passageway which is most restricted at the western end. Deep trenches exist in the middle and other regions of the Straits with depths of 300–1500 m. Along the eastern coast of Sicily and extending southward, there is a narrow Ionian shelf break, which fans out and broadens off the coast of Libya.

In the Straits of Sicily, the fresh Atlantic inflow and the salty Levantine outflow constitute a two-current system of the general circulation of the eastern Mediterranean. The Levantine outflow is located at depth and the Atlantic inflow is in the upper ocean. The Atlantic inflow, which marks the beginning of the Atlantic-Ionian Stream (AIS), flows past Malta and turns northward where, we believe, it was first identified as a local feature over the shelf break, the Maltese Front (Johannessen *et al.*, 1971). Subsequently, the AIS flows off the shelf into the upper, western Ionian Sea, with an intense looping northward meander, which generally decreases in amplitude during the winter. Various analyses of data gathered in this region (Grancini and Michelato, 1987; Moretti *et al.*, 1993; Manzella *et al.*, 1990) have described the Atlantic inflow as having a filamented but predominantly two-jet structure spanning the upper 100 m, with an associated salinity minimum, flowing closest to Tunisia and along the coast. This region contains a number of significant processes and phenomena. 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 topographical complexity, multiplicity of scales, and circulation currents and structures make the Straits of Sicily, the Ionian shelf break and western Ionian Sea a most challenging region for the development of a regional ocean prediction system.

In November 1994, Harvard University and the SACLANT Undersea Research Centre carried out their first exploratory phase research cruise for the development of a forecast system for the Straits of Sicily and the Ionian shelf-break region. The observations (Fig. 7b) were gathered in two phases: (i) a survey with mesoscale resolution over a large region; and (ii) a survey with submesoscale resolution over a mesoscale region in the region of the Maltese Front segment of the AIS over the sharp Ionian shelf break, as shown in Figs. 7c and 7d. Here we present preliminary results of analyses and sample nowcasts and forecasts carried out at sea. A second forecast experiment is planned for October 1995.

### 7.1 Descriptive Oceanography

Analyses to date have identified interesting aspects of the complex circulation and water masses of the region. A water-mass model was constructed from the hydrographic data collected during the cruise. The CTD and XCTD profiles were analyzed for water-

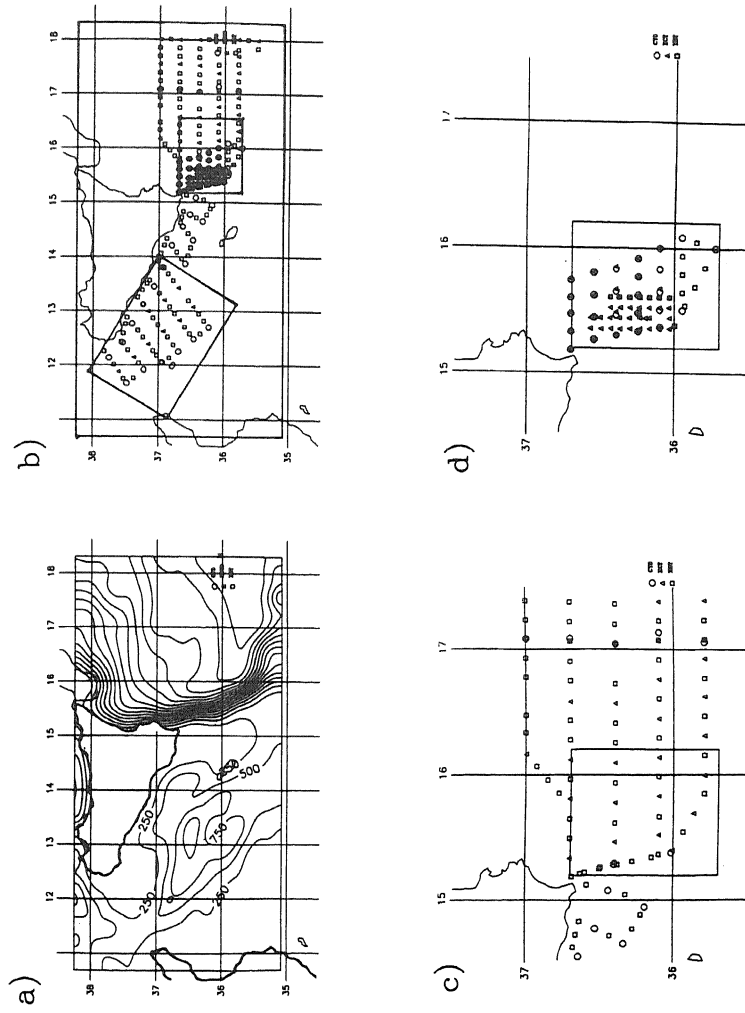


Figure 7. a) Bottom topography in Straits of Sicily and Ionian shelfbreak regions. Contour interval is 250 m. b) Hydrographic observations November 13–21, 1994. Indicated are the large and two nested modeling domains. c) and d) Observations in Ionian shelfbreak region at mesoscale and submesoscale resolution, respectively. For b), c) and d), XCTDs are indicated by circles, XBTs by triangles and XBTs by squares.

mass signatures. Seven water masses were identified among the measured temperatures and salinities, as sketched in Fig. 8. Moving from the Levantine water at the bottom towards the surface, one finds Transitional, Fresh, Mixed, (Modified) Atlantic, Upper, and Surface water masses. Not every water mass was found in the water column at every station. We comment briefly on the Atlantic water mass, as the kinematics and dynamics of the AIS were of special interest. It was found that the core of the Atlantic water mass was located below the mixed layer and spread throughout most of the survey region. In the center of the core, the salinities ranged from 37.4 to 38.0 PSU and temperatures from 16.5°C to 18.5°C. The thickness of the Atlantic layer ranged from 30 to 100 m, with center core depths 30 to 80 m below the surface. During the survey, the southwestern corner of the shelf break always contained a core of Atlantic water below the mixed layer. The rest of the shelf-break region exhibited variability in its upper layer Atlantic water content distribution. Research in progress includes horizontal mapping of the indices which characterize the depths of central and intermediate temperatures and salinities of the seven water masses (Fig. 8).

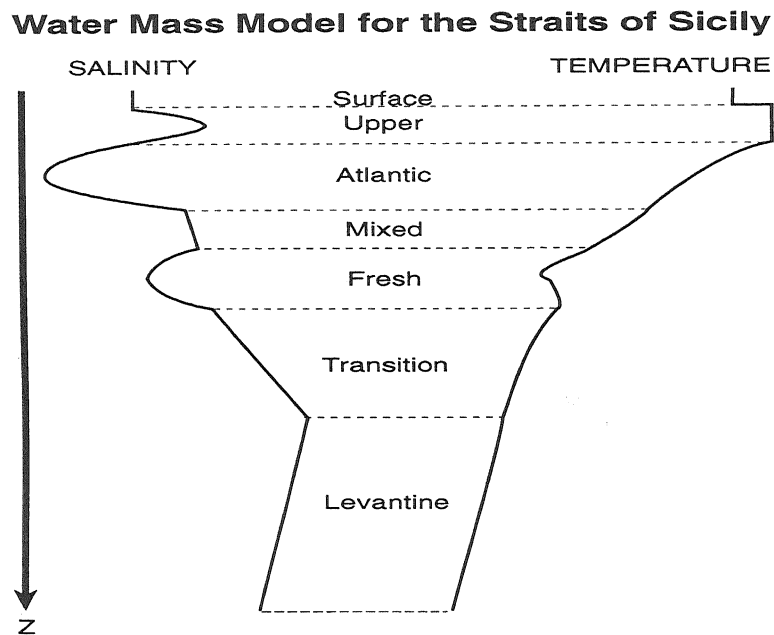
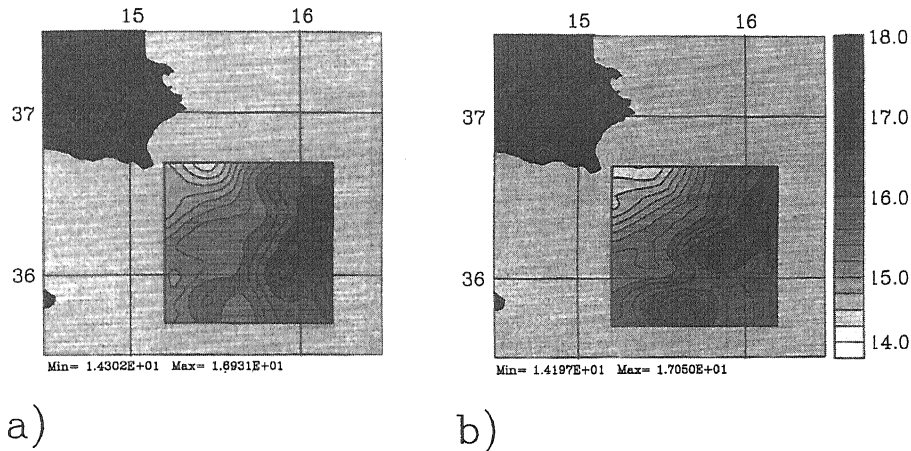


Figure 8. Water mass model for observations collected in Sicily Straits region in November 1994.

Figures 9a and 9b depict the temperature at 100 m on 16 and 19 November in the Ionian shelf-break region. These analyses reveal the rapid event-scale or submesoscale evolution which occur in the region of the shelf break. Clearly illustrated is the movement of mesoscale eddies just below the Maltese Front region of the AIS and lateral

shifts of 10–15 km in the frontal position over the brief interval of three days. This rapid evolution causes the accuracy of forecasts for small subregional domains to be highly dependent on boundary conditions.



Figures 9a and 9b. Objectively analyzed temperature at 100 m using the data from November 15–17 and November 18–21, respectively.

## 7.2 Nowcasts and Forecasts

The region has complex topography and a variety of phenomena which makes forecasting challenging. As a result of this, a nesting strategy is adopted for the nowcasting/forecasting of this region. The real-time modeling domains were selected to be congruent with the sampling strategy. There is a large domain which covers all observational areas and two small domains which encompass the Straits of Sicily and Ionian observations (illustrated in Fig. 7b). The large domain has a 7.5 km resolution, whereas the small domains are resolved at 5 km. Each domain is modeled with 14 terrain-following vertical levels. The small Ionian domain is a very difficult one, as it is located in an area of steep and tall topography with a slope of about 12%.

The large domain contains areas which are well sampled (as indicated by the station symbols) and other areas in which no data was collected (south-west and north-east corners). For this experiment, the ship was restricted to sampling only in Italian waters. In the data-poor areas, climatology, historical synoptic data, and feature models are used in combination (melded) to provide initialization data. The large domain is initialized and forced with the melded feature model and climatology and the observations from multiple data streams are assimilated using the sequential updating

approach. Initial and boundary conditions are then extracted for the small domains from the large domain. The synoptic sampling was designed to yield adequate coverage for nowcasts and short-term forecasts in the small domains at the southwest and east of Sicily shown in Fig. 7b.

A sequence of real-time shipboard nowcasts and forecasts were carried out in the large and in the nested domains to test and tune model and sequential updating strategies. Figure 10a shows the temperature field at 50 m from a forecast for November 24 two days after the assimilation of all the cruise observations. One of the most notable features is the flow northward of the Maltese Front section of the AIS along the Ionian shelf-break region. Due to the lack of observations (Fig. 7b) south of Malta the synoptic structure of the AIS could not be definitively determined there.

The nowcasts and forecasts show that important mesoscale circulation elements can reasonably be reproduced. For instance, Fig. 10b shows the velocity and salinity field at 50 m of a forecast for November 14 in the nested Sicily Straits domain, obtained by sequential updating. The observations are assimilated in two stages; tracks 1-3 (western half) are assimilated at day 1 and tracks 4-6 (eastern half) are assimilated at day 2. The Atlantic Ionian current along the southern boundary of the domain and the structure of the coastal currents are well defined in the velocity and salinity fields. This figure also shows the fresher inflow of Atlantic water with salinities less than 37.5. Hindcasting research is now in progress to elucidate the forecasting potential of the November 1994 data set and to input to the design of our October 1995 cruise.

## 8. THE EASTERN MEDITERRANEAN

In early 1995, a multi-ship, multi-national experiment was conducted by the POEM-BC (Physical Oceanography of the Eastern Mediterranean with Biology and Chemistry) group in the Eastern Mediterranean to study the preconditioning, formation and spreading of Levantine Intermediate Water (LIW). Real-time regional forecasting, both shipboard and laboratory, was an integral component of the experiment, providing guidance for real-time design and modifications of the experiment as it occurred. Here we report our real-time nowcasting and forecasting during the first cruise of this experiment on board the *F/S Meteor* (January 10 to February 3) (Robinson *et al.*, 1995b). This initial survey was designed to determine the general circulation pattern and identify synoptic features during the preconditioning stage of the LIW formation, in conjunction with a transient-tracer and deep water experiment (Roether *et al.*, 1995). In general, this experiment can also be considered as contributing to the development of a basin-scale Eastern Mediterranean regional forecast system in both the exploratory (identification of regional scales, phenomena, processes and interactions) and dynamical phases (determination of synoptic flow structures, regional synoptical dynamical events, evolutions and interactions). As significant progress via other POEM work in the region had previously been made in the exploratory phase, this experiment should contribute significantly to the understanding of the dynamics of the region.



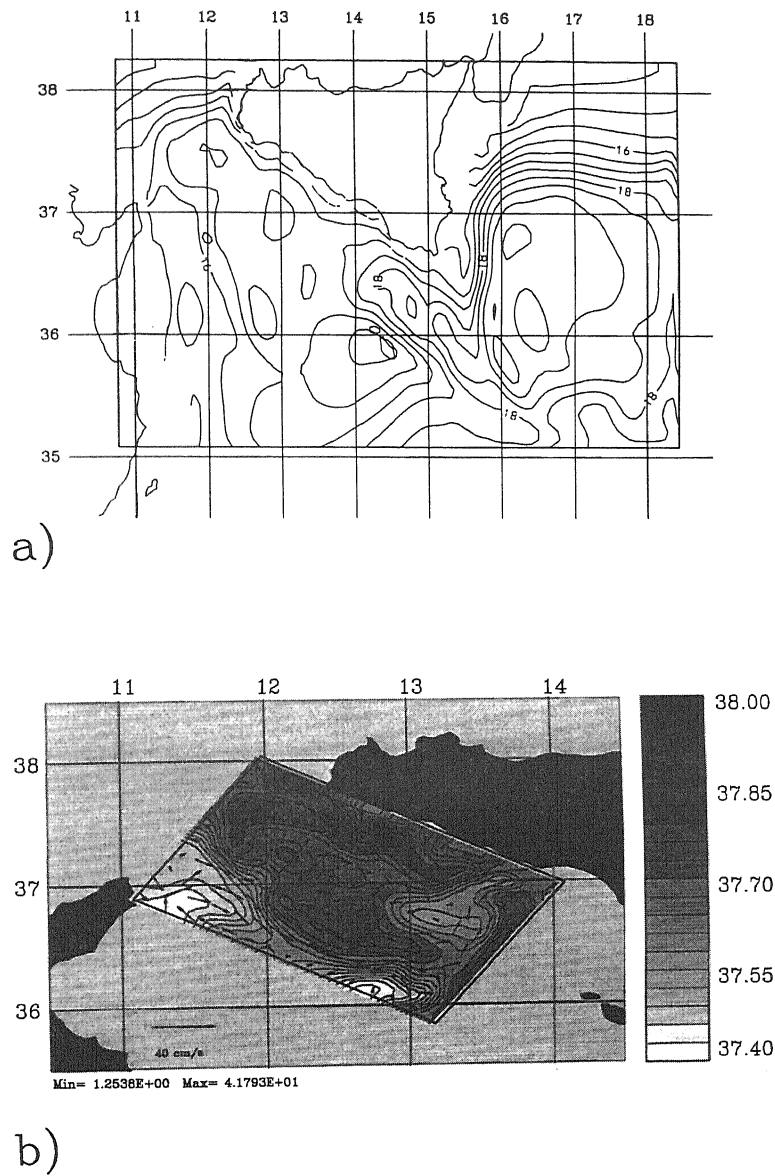


Figure 10. A four-day forecast in the Sicily Straits domain. The observations are assimilated in two stages; tracks 1–3 (western half) are assimilated at day 1 and tracks 4–6 (eastern half) are assimilated at day 2. Salinity at 50 m is mapped with overlying velocity vectors. b) Two-day forecast temperature at 50 m in large modeling domain after assimilation of all observations.

Figure 11a shows the positions of the *F/S Meteor* data stations. Nearly 600 observations were made with CTDs (circles) and XBTs (squares). Along-track distance between XBTs was nominally 15 km in the Ionian basin (approx. 10–23° East) and 10 km in the Aegean Sea and Levantine basins (approx. 23–34° East). Sections along the entrances to the Adriatic and Aegean were sampled at 5 km resolution. CTD station locations were based on the needs of the tracer circulation study, hydrographic analysis and intercalibration stations for subsequent cruises. In order to maximize the use of the XBT data, a technique was used to combine the XBT temperature observations with the CTD salinity data. This technique involved identifying the individual CTD which best represented the temperature profile of the XBT and adding the CTD salinity to the XBT (with appropriate density constraints).

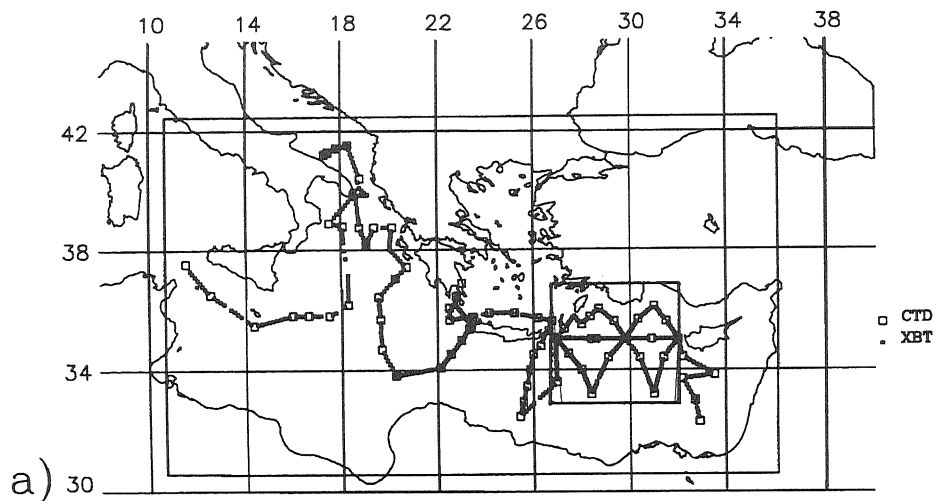
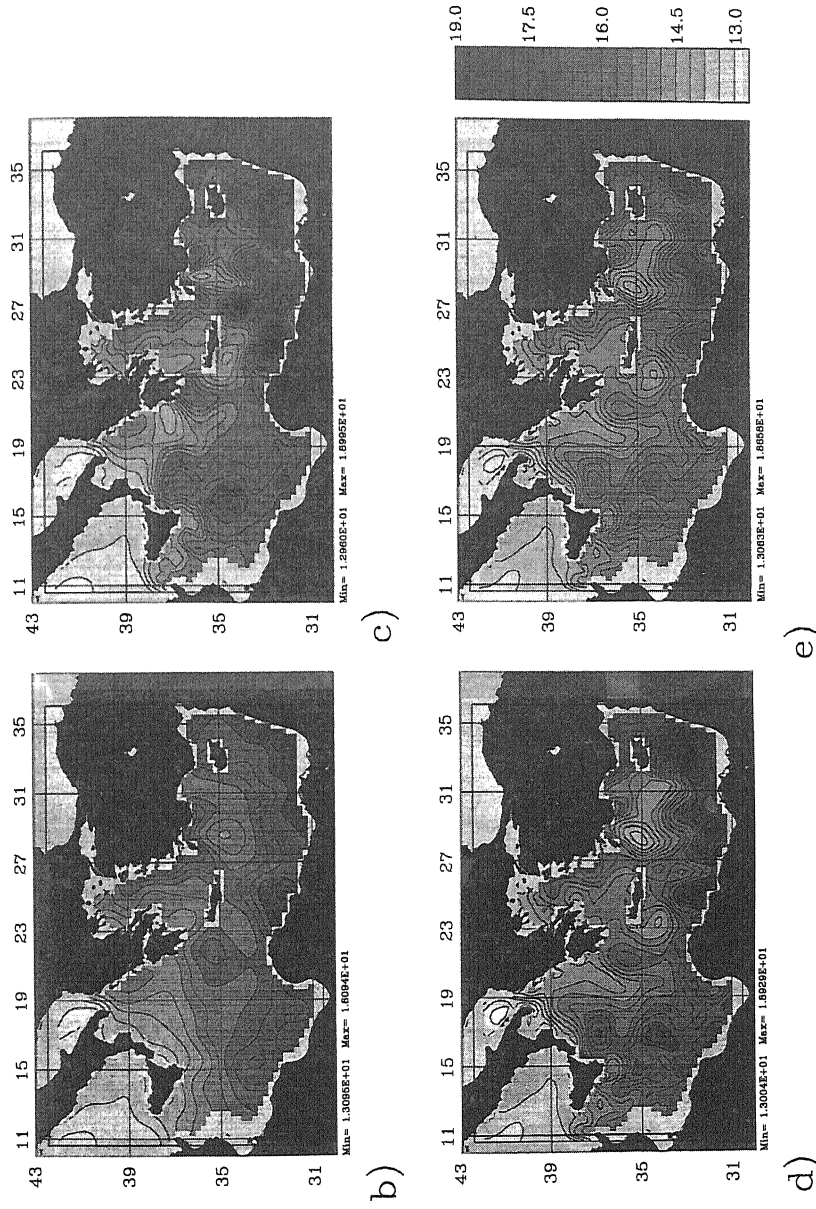


Figure 11a. Eastern Mediterranean CTD (squares) and XBT (dots) data collected during *F/S Meteor* cruise M31/1. Indicated are full Eastern Mediterranean and Levantine region modeling domains.

The modeling objectives for this cruise were to sea-test, in real-time, novel methods of nowcasting, forecasting and simulating real ocean multiscale synoptic fields involving: i) nested regions of high resolution within a full basin synoptic estimate; and, ii) the fusion of dynamics with various data types via multiple data streams, including historical synoptic realizations, climatologies and direct data streams acquired at sea. More specifically, the intent was to establish a synoptic circulation over the entire Eastern Mediterranean basin (the large box in Figure 11a), with an emphasis on the northwestern Levantine basin (the small box shown in Fig. 11a), where the LIW is thought to form.

The approach was to establish a background circulation which contained the major circulation elements in the basin and which could smoothly incorporate the ship



Figures 11b-d. Temperature at 125 m for: b) primitive equation model forecast initialization (day 0) from climatological data; c) forecast day 1, after the assimilation of two historical synoptic data sets; d) forecast day 11, after the assimilation of all but one day of *F/S Meteor* data; e) forecast day 12, after the complete assimilation of *F/S Meteor* data.

gathered observations. The process used to construct the model initialization fields is as follows. Selected elements of the regional, historical, synoptical, statistical data base (Section 3) were assembled. The Primitive Equation model was initialized with the Mediterranean Oceanic Data Base (MODB) (Brasseur *et al.*, 1995) winter climatology (Figure 11b). This provided a reasonable state for the time of year, but with smooth, broad features. Figure 11b shows the presence of the flow into the Eastern Mediterranean through the Straits of Sicily, the Pelops Gyre to the west of Crete, the Rhodes Gyre in the northwest Levantine, the Mid-Mediterranean Jet in the central Levantine and the general sense of the circulation in the Levantine. The model, forced with climatological wind stresses, was allowed to adjust, and then historical synoptic data was assimilated (Figure 11c). This data set included the November 1994 AIS data (Sicily Straits and Ionian basin east of Sicily; Section 7) and the December 1991 NAVO AXBT (complete Eastern Mediterranean; Horton *et al.*, 1994) data. The inclusion of this synoptic data introduces realistically structured conditions, tightens the fronts and reduces the size of eddies. There is no assumption that this synoptic data represents the oceanic structures of the period immediately prior to the present cruise. Rather, the introduction of this data creates a "typical" synoptic situation for this time of year. At this time, the circulation closely resembles the complex, linked, basin-scale circulation pattern (Fig. 12) which has been discovered by POEM research (Robinson and Golnaraghi, 1993).

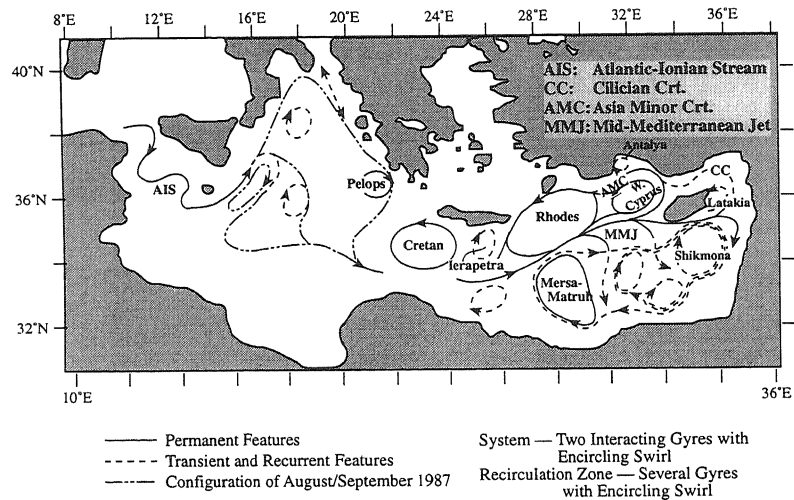


Figure 12. Schematic of Eastern Mediterranean circulation (after Robinson and Golnaraghi, 1993). Reprinted by the kind permission of Pergamon Press, Ltd.

The model is now in a state suitable for assimilating the 1995 *Meteor* data as it comes in. Figure 11d shows the model 11 days later, when almost all of the *F/S Meteor* data has been assimilated (only the final southeast leg is absent). Comparing with Figure 11c, we see that, along the ship's track, the synoptic features are corrected to their January 1995 locations. Features in the Ionian are adjusted and shifted, most notably in the western Ionian. The warm eddy at 37°N, 17°E is more clearly defined, as is the Pelops Gyre. Warm temperatures advance farther to the north and there is greater distinction between the waters of the central Ionian and coastal waters along the east coast of Italy. In the Levantine, however, the *Meteor* data indicates significant changes from the historical synoptic data. The Rhodes Gyre is considerably expanded and its borders well indicated. There is a strong temperature gradient from the eastern Aegean to the Rhodes Gyre. Figure 11e shows the final assimilation of the remainder of the *Meteor* data set (13 model days). The newest data is from the region south of Cyprus, towards Egypt (see Fig. 11a). While the west-east temperature gradient has been weakened somewhat, it remains intact and in place. This is an indication that the combination of climatology and historical synoptic data located reasonable features in reasonable places and that the *Meteor* data, in this small area, is providing only minor corrections to the initial and forecasted conditions.

The nested northwestern Levantine modeling domain, indicated in Fig. 11a, was initialized at day 11 from the field depicted in Figure 11d, providing a first guess to the circulation in the domain. Figures 13a and 13b show a two day forecast of temperature and density anomaly for this region. The cold core of the Rhodes Gyre is clearly defined. Analysis of the data and modeling results were sent from the ship to shore-based facilities in order to guide the design of subsequent cruises. Data gathered in the subsequent POEM LIW experiment cruises were essentially contained in this northwestern Levantine domain. The modeling research in progress involves nested domains, including the entire Eastern Mediterranean, the north-western Levantine and additional nested domains with mesoscale and submesoscale resolution using two way nesting.

## 9. DISCUSSION AND CONCLUSIONS

Modern research has revealed the synoptic states of the deep ocean and coastal seas to be a complex mix of interactive scales and circulation structures and variabilities. Thus the ocean prediction problem is complex and data requirements indicate that data assimilation is essential to the feasibility of nowcasting and forecasting. Unlike the atmospheric weather forecasting, ocean forecasting requires a regional approach, both from practical operational considerations and for the attainment of the accurate detailed realistic field estimates required for scientific research.

Regional ocean prediction system development involves three phases: exploratory, dynamical and predictive. General validation, regional calibration and qualitative verification are essential. The final system should be accurate and efficient with minimal observational resources, but such systems can only be achieved through forecast experimental oversampling. The approach taken with the Harvard Ocean Prediction System

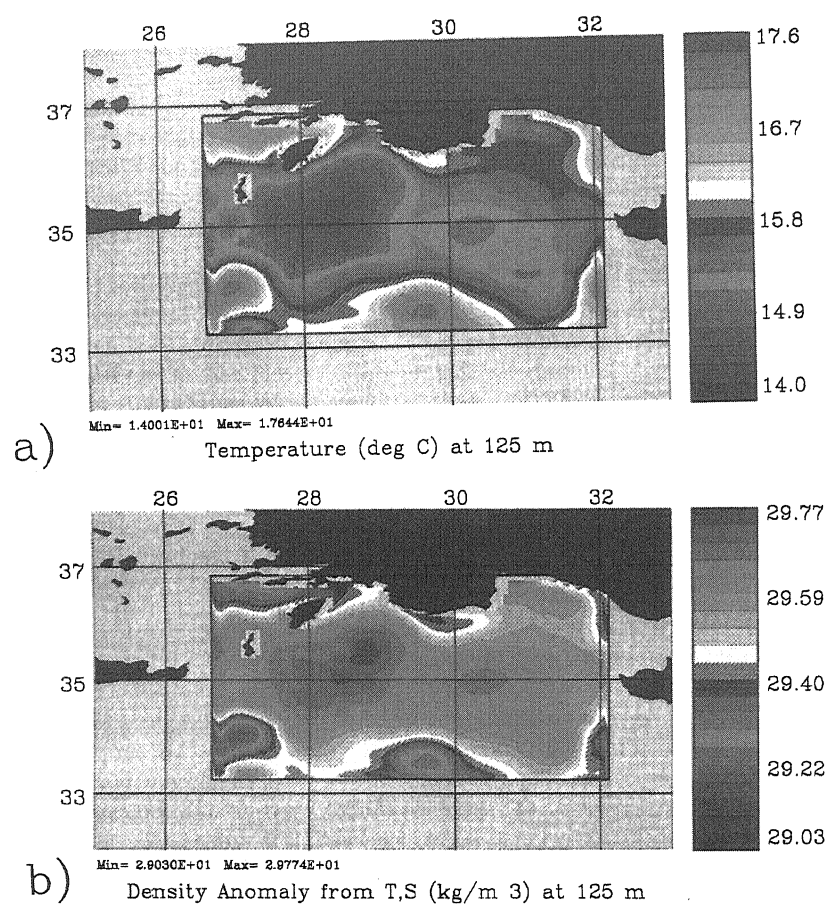


Figure 13. a) Levantine modeling domain day-2 forecast temperature at 125 m. b) As in a) but density anomaly.

(HOPS) involves initialization and assimilation of synoptic states constructed via the melding of multiple data streams, composed of real-time data streams, feature models, historical synoptic states, etc.. The synoptic accuracy of such states depends upon regional variabilities and the quantity of real-time data available, but, in any case, a reasonable and regionally typical evolving set of synoptic realizations is attained.

Recent real-time work at sea with HOPS has been reviewed and reported in the Iceland-Faeroe Frontal region, the Sicily Straits and the Eastern Mediterranean basin. The concept of an optimal synoptic representation of a region via the method of sequential updating has been proposed. This concept requires testing and development via the obtainment of truly regional synoptic time series which will require some mix of multiple platforms and remote sensing. Research is also required for an improved assimilation scheme for sequential updating to replace our simple optimal interpolation. Substantial further research is also required in the areas of nesting and multiple-data-stream melding, which have been initiated during these recent real-time shipboard nowcasts and forecasts.

Ocean prediction, in general, and regional prediction, in particular, are presently rapidly evolving. Indications are that ocean science and marine technology can benefit substantially in the near future by the practical availability, on a substantial basis, of realistic field estimates for operations, research and management purposes.

## 10. ACKNOWLEDGEMENTS

We thank Dr. Charles Horton (Naval Oceanographic Office) for providing the Eastern Mediterranean AXBT data. The CTD data set in the Eastern Mediterranean was obtained by Dr. Beniamino Manca (OGS - Trieste, Italy) aboard the *F/S Meteor*, as part of the POEM LIW experiment. We thank Prof. Wolfgang Roether for immediate access to this data, which facilitated the generation of nowcasts at sea; and his useful discussions with one of us (ARR). Special thanks to the Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg, Germany for making possible our participation in the M31/1 cruise on the *F/S Meteor*. The assistance of Dr. Pierre-Marie Poulain and Mr. Quinn Sloan at sea aboard the *R/V Alliance* in the Iceland-Faeroe Front and Straits of Sicily is acknowledged with thanks. On these cruises, the expertise and performance of both the technical staff of SACLANT Centre and the Captain and the crew of the *R/V Alliance* were essential for success. We thank Ms. Marsha Glass for the efficient logistics during our cruises. We acknowledge the Office of Naval Research for support of this research and enabling the acquisition of the XBT probes required for the mesoscale sampling conducted on the *F/S Meteor* (grants N00014-91-I-0577, N00014-90-J-1612, N00014-94-1-G915 and N00014-91-J-1521 (Ocean Educators Award)). Support from the National Science Foundation, grant OCE-9403467, is gratefully acknowledged.

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