# *FORECASTING OCEAN AND REGIONAL SEA-STATE*

# Real-time Marine Monitoring Systems

The seas are being monitored, from satellite observations of the ocean surface to the growing number of in-situ measurement networks. The amount of information being generated is huge and should ideally provide a consistent 3D picture of ocean-state, including temperature fields and current structures. Indeed, this is the expectation of a wide range of organisations and individuals engaged in coastal and offshore activities, who would prefer such forecasts to be in the shape of a synoptic overview of present conditions augmented by prediction of two or three weeks. In order to merge all past information and produce a forecast, models of ocean dynamics are required.

A real-time assimilation system has been established for the Atlantic and Arctic Seas that couples a thermodynamic sea-ice model to an ocean circulation model with a resolution of 20-30km. Driven by atmospheric forcing, the system monitors and predicts the main current patterns and provides boundary conditions for nested high-resolution models.

Integrated Monitoring Systems
The provision of observational data, both satellite and in-situ based, and their integration into appropriate models of the Earth system are of paramount importance for monitoring the state of the marine environment, notably waves, currents, temperature, mixed-layer depth, algae concentration, primary production, oil pollution, etc. The reliability and utilisation of these products depend not only upon the performance of the models and assimilation tools but also on the availability and quality of the observations, data access, processing and distribution, rapid information integration, and flow and services. Users range from the research community via operational applications to commercial customers and governmental entities. Very often their common need is for a synoptic overview of the present state in addition to outlook and forecast for the coming ten days.

Ocean Models
Ocean characteristics such as temperature, salinity and current velocity can be estimated in space and time by computer model simulation across a numerical ocean model grid. This means that one can get a fully 3-dimensional image of the ocean, as shown in Figure 1. Models can operate in Ã”hindcastÃ• mode to simulate historical time-series of past conditions and also in Ã”nowcastÃ• and forecast mode for operational applications.
Models run at basin scale are used to represent circulation of large oceanic water masses, whereas at Ã”nestedÃ• regional or local scale with higher spatial resolution they provide finer detail, for example where eddy resolution is required. A nested model means that a high-resolution regional model receives boundary conditions from an outer model with lower resolution. In this way one can ensure proper representation of the general circulation into the regional area.

TOPAZ: Arctic and Atlantic Model
A real-time forecasting system has been established for the Atlantic and Arctic basins that involves the coupling of a thermodynamic sea-ice model to the Hybrid Coordinate Ocean circulation Model (HYCOM). The model is forced with atmospheric fields provided by the European Center for Medium-range Weather Forecasting (ECMWF). The grid covers the Arctic and Atlantic basins at a resolution of approximately 20-30km. The TOPAZ system is intended to monitor and predict the main current patterns of the Atlantic Ocean and provide boundary conditions for nested high-resolution models, as illustrated in Figure 2.

North Sea Nested Model
Boundary conditions from the large-scale Atlantic model TOPAZ are imposed on a regional model covering the North Sea and Skagerak. This North Sea model has a resolution of about 4km, which means that it can resolve mesoscale dynamics such as eddies. The model is forced with atmospheric fields and includes tidal forcing and river input. The current system in the northern North Sea is characterised by a southward inflow of Atlantic water and the northward flowing Norwegian coastal current. As shown in Figure 3, the model is able to reproduce this complex current pattern with meanders and eddies.
When model simulations are compared with data from ship cruises (as in Figure 4) it is seen that the model is also doing a good job in correctly representing water masses. The North Sea model produces 10-day forecasts every week and the results are distributed via a public website, http://moncoze.met.no.

Data Assimilation
Though a model can reproduce realistic ocean-current fields and their variability, it cannot without additional information provide accurate locations of current features such as eddies and current fronts. To obtain accurate forecasts, a procedure called data assimilation, which makes use of recent observations, needs to be undertaken. Introducing observations into numerical models, however, is not a trivial task. Only a small part of the ocean is observed on a regular basis, such as the surface from satellites and vertical profiles from XBT and ARGO floats. The state of the unobserved portions of the ocean has to be estimated based on existing observations in a manner consistent with the dynamic balance of the system. The methodology chosen to properly achieve this has to account for ocean modelling, spatial statistics and optimal control aspects, and requires strong collaboration between the remote-sensing, oceanographic, ocean modelling and statistical communities.
In the TOPAZ system a single assimilation method is used, namely the Ensemble Kalman Filter (EnKF), designed for application to strongly non-linear systems such as is characteristic for ocean dynamics. It assimilates satellite-measured sea-surface temperatures, sea-surface heights, sea-ice concentration and extent and in-situ measurements from Argo profiling floats and XBTs, all provided in near real-time.
Advanced data assimilation methods can in a single step provide the best estimate of ocean variables and the associated estimation of uncertainty. EnKF handles this joint estimation by generating a relatively large ensemble of model states (a set of approximately one hundred states has been shown to be satisfactory for current applications).

Future of Monitoring Systems
The system briefly described here contributes to monitoring and reporting in support of protection of the marine environment. This concerns a wide range of international bodies, treaties, conventions and organisations at regional and national levels. As regards offshore and coastal engineering, companies are more than ever demanding site-specific forecasts to plan critical operations. Accurate three-dimensional forecasts of currents out to two weeks are therefore urgently needed. These added-value services are starting to be provided by small to medium enterprises such as Ocean Numerics Ltd, (www.oceannumerics.com).
The TOPAZ system development and operation is moreover part of the international Marine Environment and Security in the European Area (MERSEA) project under the joint EU/ESA Global Monitoring for Environment and Security programme. MERSEA (http://mersea.nersc.no) is undertaking the necessary measures towards implementation and operation of a European global operational oceanography system by 2008.
As forecast systems are validated and examined by practical users, we anticipate the following developments in the next decade:

- Ensemble forecasts: A single Ã”bestÃ• estimate is often perceived as the truth but it is generally not much help to decision-makers needing a quantitative assessment of the respective costs of different possible events. In this context, several equally likely forecasts often help better in quantifying the forecast uncertainty and making the right decision. Data assimilation methods based on ensembles such as the EnKF provide a convenient framework for these types of products
- Data assimilation methods:
  Data assimilation developments need multidisciplinary collaboration and research so that the mathematical models used to incorporate the observations are in best agreement with the physical models that produce the forecast. Data assimilation is also useful in assessing gaps in the observational network and deciding the optimal location for future observations
- Model developments: Forecast reliability is directly related to the abilities of the numerical model that produces it. Ocean-circulation models have gained a high level of flexibility over the last ten years and will continue to be improved, both in terms of better representation of physical processes and underlying numerical schemes
- The observational network: The forecasting systems are successfully using satellite observations. Important efforts are also being invested in in-situ measurement programmes such as Argo, and in making in-situ measurements publicly available in near real-time. These efforts will together result in better coverage of the world oceans and improved forecasting capabilities

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