MARINE ENVIRONMENT AND SECURITY FOR THE EUROPEAN AREA

Toward Operational Oceanography

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An assessment of the present European operational marine monitoring and forecasting systems shows how observations, atmospheric forcing fields and ocean models combine to make useful oceanographic products possible.

The Marine Environment and Security for the European Area (MERSEA) Strand-1 Project was established in January 2003 to conduct an 18-month preparatory study of the key issues in setting up the marine elements of the joint European Commission (EC) and European Space Agency (ESA) initiative on Global Monitoring for Environment and Security (GMES). MERSEA Strand-1 examined individually the capabilities and requirements for in situ observations, satellite ocean measurements, and ocean models able to analyze and assimilate satellite and in situ data. As such, it consolidated the European contribution to the Global Ocean Data Assimilation Experiment (GODAE) (www.usgodae.org/). Most importantly the project evaluated the capacity in Europe for creating an integrated ocean monitoring system, following the operational concept of the so-called GMES diamond (Fig. 1). This concept links the in situ and space-based observing

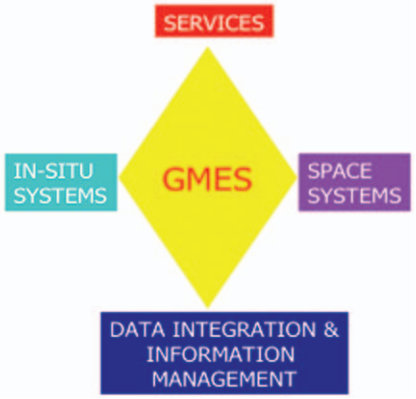

FIG. 1. The relevance of the MERSEA Strand-1 approach seen in the context of the GMES diamond.

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systems through a data integration, information, and management handling system that provides the backbone for effective operational services tailored to marine monitoring for environment and security. The MERSEA Strand-1 Project served as a preliminary step to the ongoing MERSEA Integrated Project, which is tasked with preparation of the operational system to be launched in 2008 (Desaubies 2005).

The motivation for the marine element of GMES arises from the wide range of international bodies, treaties, conventions, and organizations at global, regional, and national levels concerned with monitoring and protecting the marine environment in Europe. The United Nations Convention on the Law of the Sea (UNCLOS 1982) provides the regulatory framework at the global level for all activities at sea. Supporting this are the International Convention for the Prevention of Pollution from Ships (MARPOL 1973/1978), the framework for preventing dumping of pollutant material (London Dumping Convention 1972), and the International Convention on Oil Pollution Preparedness, Response, and Cooperation (OPRC 1990). These are complemented by specific conventions and agreements for particular maritime regions, such as the Oslo and Paris Commission (OSPAR) for the Northeast Atlantic and the European shelf seas, the Helsinki Convention (HELCOM) for the Baltic, the Barcelona Convention for the Mediterranean, and the Copenhagen and Bonn agreements. These legal frameworks set the foundation for policies on sustainable development and protection of the seas. Their overarching goal is to establish a sound balance between economic and social benefit on one hand and acceptable environmental impact on the other hand.

International agreements place obligations on nations to monitor the marine environment. GMES (www.gmes.info) is a response at the European level to provide a common infrastructure for meeting this need, while serving as the European contribution to the Global Earth Observation System of Systems (GEOSS) (www.geo.org/). With a target date of 2008 for operational implementation, GMES Marine Services are proposed to support and strengthen European capacities for

- verifying and enforcing international treaties, and informing the assessment of policies;
- enabling sustainable exploitation and management of ocean resources (offshore oil and gas industry, fisheries, aquaculture industry);
- improving the safety and efficiency of maritime transport, shipping, and naval operations, and supporting national security and reducing public health risks;
- anticipating and mitigating the effects of environmental hazards and pollution (oil spills, harmful algal blooms);
- advancing marine research for better understanding of the ocean ecosystems, their variability, and their contribution to climate change issues;
- contributing to seasonal climate prediction and mitigating its effects on coastal populations;
- supporting specific services for coastal management and planning.

MERSEA STRAND-1 GOAL. The MERSEA Strand-1 (www.nersc.no/-mersea) Project (Johannessen et al. 2003, 2006) responded to the GMES Action Plan (initial period 2001–03), drawing on many of the conclusions and recommendations from the OceanObs conference in 1999 (Koblinsky and Smith 2001) and the GODAE Strategic Plan (GODAE 2001). It attempted a trial integration of existing spaceborne observations with data from in situ monitoring networks, using ocean models and data assimilation. The specific objectives were to

- compare existing forecasting systems to check the quality and consistency of the products and information;
- deliver information products (physical, chemical, and biological) needed by users concerned with European marine environmental and security policies;
- report on the problems encountered and lessons learned in supplying this information;
- contribute to improving the knowledge, methods, and tools required for ocean monitoring, leading to the production of management support information and its delivery to users with responsibilities for marine environmental monitoring, management, and security.

The project achieved these objectives through three main activities. The first activity was the intercomparison and assessment of four different ocean forecasting and assimilation systems. The outcome of this is briefly reported in the "Ocean modeling systems" section. The second activity comprised a structured consultation between the model developers and those reviewing the existing and planned availability of satellite and in situ ocean monitoring systems, in order to identify the observational infrastructure that is needed to support a future European operational ocean forecasting system. This produced the recommendations reported in the "Operational oceanography data requirements" section. The third activity included a set of specific demonstrations of marine service applications that were made possible by integrating available observations and models. The results from these demonstration experiments are presented in the section titled "Service applications of the system." This is followed by consideration of major challenges in the "Challenges" section, and lastly a summary.

OCEAN MODELING SYSTEMS.

The primary numerical modeling systems evaluated for data assimilation were as follows:

(i) Towards an Operational Prediction System for the North Atlantic European Coastal Zones (TOPAZ), covering the North Atlantic, Nordic Seas, and Arctic Ocean. It uses a hybrid-coordinate (*z*, isopycninc, and sigma coordinate) ocean model (HYCOM) (Chassignet et al. 2005; Bleck 2005) with a grid size of 20–30 km and 22 hybrid layers in the vertical (http://TOPAZ.nersc.no/).

(ii) Mercator, covering the North Atlantic and Mediterranean. It uses a *z*-coordinate ocean model [Ocean Parallelise/Nucleus for European Modelling of the Ocean (OPA/NEMO)] (Bahurel 2005) with a grid size of 5–7 km and 43 vertical levels (www.mercator-ocean.fr/).

(iii) (Forecasting Ocean Assimilation Model (FOAM), covering the North Atlantic and Mediterranean Sea. It uses a *z*-coordinate ocean model with a grid size of 12 km and 20 vertical levels (Bell et al. 2005) (www.ncof.gov.uk/).

(iv) Mediterranean Forecasting System (MFS), covering the Mediterranean. It uses a *z*-coordinate ocean model with a grid size of 12 km and 31 vertical levels (Pinardi et al. 2003) (www.bo.ingv.it/mfstep/).

The systems were forced with atmospheric data from numerical weather prediction models. Satellite-derived sea level anomaly (SLA), sea surface temperature (SST), and sea ice fields were assimilated using either optimal interpolation (MERCATOR, FOAM, and MFS) or ensemble Kalman filter (TOPAZ), while the potential for ocean color assimilation was also considered. Profiling data from the Argo floats measuring temperature and salinity in the upper 2000 m were used for assimilation (FOAM system only) or for model validation. In addition, regular expendable bathythermograph (XBT) observations from volunteer observing ships (VOS) were used for validation.

Diagnostic fields were provided on a daily basis from 1 June 2003 to 31 May 2004 corresponding to three major categories:

- *Class 1:* This class comprised daily best estimates of 3D fields of temperature, salinity, and velocity, 2D fields of wind stress (τ_x, τ_y), total net heat fluxes, surface freshwater flux (E-P-R), barotropic streamfunction, mixed layer depth, and sea surface height. The fields were interpolated on a reference grid for the North Atlantic and the Mediterranean. In addition, the class included the best T0+6-day forecast fields.
- *Class 2:* This class comprised daily best-estimate fields of temperature, salinity, and velocity fields along predefined high-resolution sections and at mooring locations. Also for this class the best T0+6-day forecast was provided.
- *Class 3:* This class comprised daily volume transport through given sections, meridional heat transport, and overturning streamfunction.

Product exchange and distribution were facilitated by the application of both Open-source Project for a Network Data Access Protocol (OPeNDAP) and Live Access Server (LAS) (www.opendap.org) (http://ferret.pmel.noaa.gov/Ferret/LAS/ferret_LAS.html). The routine intercomparison and assessments of the output products from the core data assimilation system were based on an internal metrics (Crosnier and Le Provost 2005). Differences between models were considered in relation to choice of vertical coordinate system; spinup length; mixing parameterization; mean sea surface height; treatment of SLA data; surface flux parameterization; type of ice model; model resolution; and type of data assimilation scheme. For example, the impact of mixing parameterization and surface fluxes in the Mediterranean is shown in Fig. 2 for four selected local areas. The mixed layer depths are shallow in all areas during boreal summer and reach their maximum during the late boreal winter. Overall, the three systems display comparable temporal evolutions of the mixed layer depth but with noticeable differences when the mixed layer becomes deep. This suggests sensitivity of the mixed layer depth to the choice of turbulent mixing parameterization and heat fluxes. Assimilation of temperature and salinity profiles is therefore highly needed to ensure that the water masses are properly represented in the models (see next section).

The definition and use of the metrics allowed systematic and fast intercomparison of the modeling systems. This enabled problems and deficiencies to be

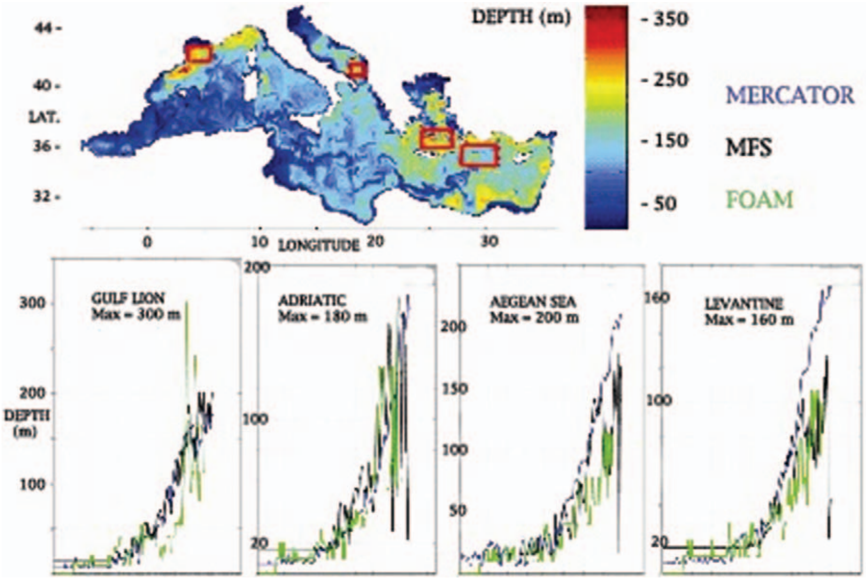

Fig. 2. (top) Impact of mixing parameterization in the Mediterranean basin at the four selected areas marked with red boxes. (bottom) The evolution of the mixed layer depth as a function of time (from 15 Jun 2003 to 15 Feb 2004) for the four selected areas resulting from Mercator (blue), MFS (black), and FOAM (green).

detected in near–real time and triggered immediate response with system upgrading whenever possible. The metrics concept has also been adopted by the participants of GODAE. Further details of the intercomparison results are reported by Crosnier and Le Provost (2006).

OPERATIONAL OCEANOGRAPHY DATA REQUIREMENTS. MERSEA Strand-1 provided a forum for collaboration, not only across various operational oceanography initiatives but also between different ocean science communities. It also capitalized on the consensus view on operational oceanography that has emerged from the OceanObs conference (Koblinsky and Smith 2001), the GODAE Strategic Plan (GODAE 2001), as well as the three EuroGOOS conferences in 1996, 1999, and 2002 (Stel et al. 1997; Flemming et al. 2002; Dahlin et al. 2003). Thus, constructive dialogue was facilitated between numerical modelers of the ocean and observational experts (both with respect to in situ and remote sensing), which allowed discussion about the type of observations that are required to initialize, force, constrain by assimilation, or validate operational ocean models. The desirable spatial and temporal resolution, accuracy, and timeliness of the observational data could also be specified as a realistic compromise, balancing the models' needs with the reality of what in situ and satellite measurement systems are available or can become operational within the next 5–10 years.

It emerged from these discussions and the systematic use of the metrics that all four of the evaluated model systems, irrespective of their slight differences of methodology and approach, have comparable core data requirements. These are outlined in the rest of this section, separately, considering altimetry, thermal and visible radiometry from space, Argo and XBT systems, the rapid dissemination of global ocean data from moorings, drifters and VOS, and the data needed for atmospheric forcing of ocean models. It was also noted that to help justify the investment in new observational infrastructure that is implied by some of these requirements, it would be desirable to perform model sensitivity studies that quantify the impact on ocean forecast quality when new or improved data sources are introduced.

Altimetry. After 2007 a high-inclination altimeter mission (post-Envisat) is needed to complement Jason-2 (planned launch in 2008) in order to constrain the open-ocean surface currents and their mesoscale variability. This will ensure adequate representation of ocean eddies and associated currents, that is, the "ocean weather" in models. Most operational oceanography applications require high-resolution surface currents that will not be adequately reproduced without a high-resolution altimeter system. The data assimilation systems are expected to show a significant degradation if the number of altimeters flying decreases after 2007 (Fig. 3). Le Traon et al. (2005) emphasize how the performance of the GMES marine element depends on the development of a high-resolution altimetry system, requiring a constellation of altimeters (up to 3 in addition to the Jason series). Operation of the Multi-Mission Ground Segment for Altimetry, Orbitography and precise Localisation/Developing Use of Altimetry for Climate Studies (SSALTO/DUACS) service (www.cls.fr/html/oceano/general/applications/duacs_en.html) should also be sustained to provide high-quality merged and intercalibrated altimeter data from the different altimeter sensors in real time and delayed mode. When the concept is demonstrated in the future, GMES will also benefit from wide-swath altimeter systems. An independent mapping of the high-resolution geoid also forms an essential component of the long-term altimetry strategy.

Thermal radiometry. High-quality and high-resolution SST measurements are needed beyond 2007. SST assimilation is essential to correct for the asynchronous coupling of the ocean models with atmospheric forcing, since the atmospheric fluxes use a different SST field, usually with much lower resolution and quality. Finescale features such as ocean fronts and eddies can be uniquely determined by daily SST data under cloud-free conditions. The methodology for harmonizing SST data from different sources before assimilation has been proposed by the GODAE high-resolution SST Pilot Project (GHRSST-PP) (www.ghrsst-pp.org) and implemented in Europe by ESA's Medspiration project (Robinson et al. 2005). The GHRSST-PP has emphasized the need to maintain at least one sensor in orbit having measurement stability and accuracy (especially in the event of a major volcanic eruption injecting ash into the stratosphere) equivalent to that of the Along Track Scanning Radiometer (ATSR)/Advanced ATSR (AATSR) series of sensors. This would provide an important complement to the optical and microwave sensors approved on National Polar-orbiting Operational Environmental Satellite System (NPOESS) and Meteorological Operational Platform (MetOp).

Visible spectrometry. Ocean color measurements from space allow chlorophyll to be derived. Two–three spectrometers [of the Medium Resolution Imaging Spectrometer (MERIS) and Moderate Resolution Imaging Spectroradiometer (MODIS) types] are needed to minimize the limiting effects of cloud cover impact, and thus ensure better conditions for near–real time data for validation of or assimilation into marine biogeochemical models. Suitable methods must be developed for blending data from different missions that use different wavebands and different algorithms for retrieving phytoplankton-related water constituents. In Case 2 waters it is also important to develop and validate reliable retrieval algorithms for suspended matter.

Argo and XBT data. The deployment and operation of Argo profiling floats (www.argo.ucsd.edu, www.coriolis.eu.org/) and XBTs should be sustained. These data provide important information on the suburface temperature (*T*) and salinity (*S*) structures and distribution of water masses. They are also importantly complementing SLA data to yield better representation of the subsurface stratification. The full implementation and maintenance of the global Argo array is therefore urgently required in this context. Class-2 diagnostics pointed out that the models fail at representing some mode water as well as some central water characterized by high salinity properties. On the other hand, these water masses will be resolved as soon as the models assimilate quality-controlled *T*,*S* profiles from Argo floats or *T* profiles from XBTs. Assimilation of *T*,*S* profiles is thus a key feature for reliable representation of water mass characteristics, especially in the upper 2000 m where most of the Argo profiles are available. This is illustrated with the FOAM model showing a magnification of the strength and westward extension of the deep salinity maximum in the tropical Atlantic after assimilation of Argo floats (Fig. 4). Without assimilation of these Argo float data, one notices that there is very little visibility of this westward extended deep core of saline water.

Moorings, drifters, and VOS data. The Coriolis system (www.coriolis.eu.org/) already harvests and processes in situ data from different sources (in situ

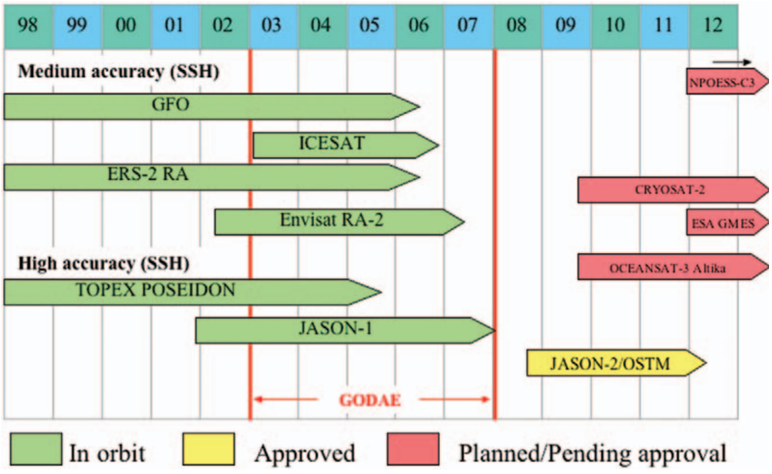

Fig. 3. Time line of the satellite altimetry missions in high- and medium-inclination orbit (green), approved (yellow) and planned (red) up to 2012. Note that the U.S. NPOESS-C3 altimeter launch is currently planned for 2013. The OCEANSAT-3 Altika is a joint French–Indian mission.

measurements from ships, moored, or drifting autonomous systems). It must be sustained. Moreover, there is a need to adapt and apply real-time processing, quality control, and dissemination methods [such as currently offered by, e.g., Argo, XBT, and the Tropical Atmosphere-Ocean Array/Triangle Trans-Ocean Buoy Network (TAO/TRITON; www.pmel.noaa.gov/tao/)] to other sources of in situ data (e.g., research vessels, underway datasets from VOS, data from drifters) to ensure the timely supply of consistent data needed by operational ocean forecasting systems. For the Mediterranean, a regional data service connected to the Coriolis system is being established that will serve the Mediterranean community, improving regionally the quality of the data service and the data collection.

Forcing fields. High-quality numerical weather prediction models are able to supply the surface forcing for ocean models. In addition, high-resolution measurement of wind vectors (25-km resolution and global daily coverage) by scatterometers should be made available in near–real time to complement the weather models and thus preserve more details of the wind field structures.

SERVICE APPLICATIONS OF THE SYSTEM.

The information products from these basin-scale assimilation systems were used as boundary conditions for a number of high-resolution (1–5 km) regional and local models nested inside them. The nested models and systems are tailored to the North Sea and Skagerrak (http://moncoze.met.no/), the U.K. shelf and coastal seas (www.pml.ac.uk/), the Baltic Sea (www.fimr.fi/en/itamerikanta/bsds/2056.html, http://ocean.dmi.dk/), the Aegean Sea (www.poseidon.ncmr.gr/), and the seas around Cyprus (www.ucy.ac.cy/cyocean/). The observational requirements to constrain and validate these local models are very demanding and require similar or eventually finer forcing field inputs as for the core models. Their capacities to deliver structured information on environmental stresses to the marine ecosystem were evaluated in the context of managing two problem scenarios:

(i) Harmful algae blooms (HAB) and eutrophication in the Baltic, Skagerrak, and North Seas.
(ii) Oil spills in the Baltic and North Seas, northwest European Shelf, and Mediterranean Sea.

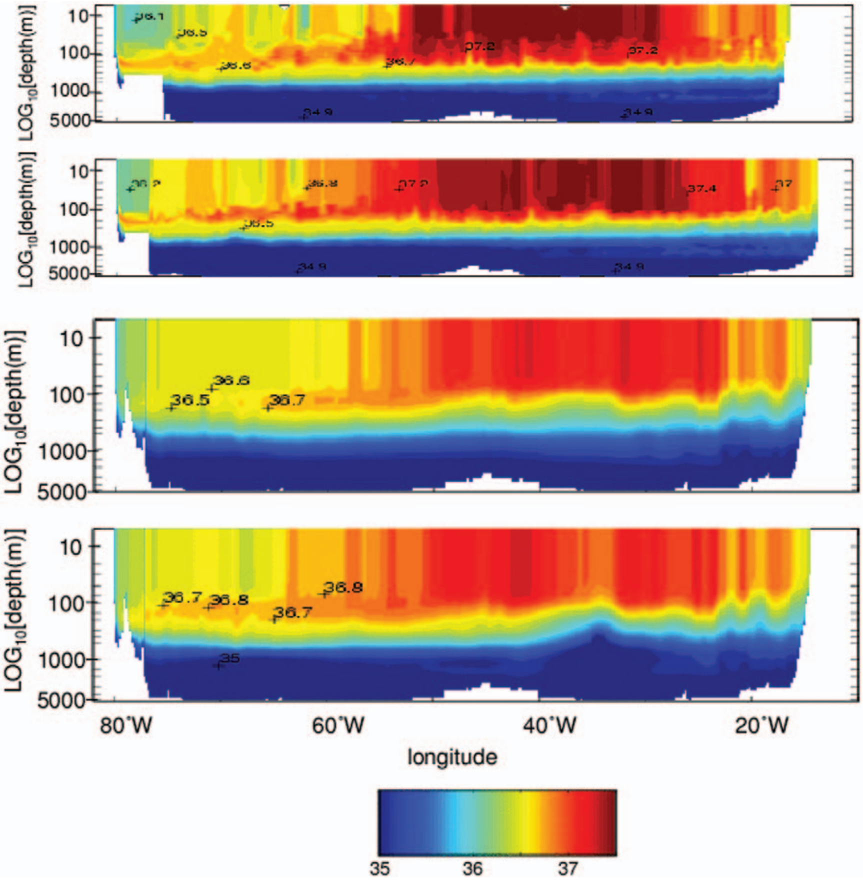

Fig. 4. Evidence of the impact from assimilation of Argo salinity profiles in FOAM. (top two) Salinity from the World Ocean Circulation Experiment (WOCE) sections along 26°N obtained respectively in 1992 and 1998. (third) The salinity structure along the same zonal section without assimilation of Argo. (bottom) The corresponding salinity structure after assimilation.

The HAB and eutrophication demonstration experiments. The main European Union (EU) instruments to combat eutrophication are the Nitrates Directive, the Urban Wastewater Directive, and the Water Framework Directive (WFD). Both OSPAR (under its strategy to combat eutrophication) and HELCOM stress the need to implement these measures and undertake to identify what additional measures would be required.

The coupled physics and marine biology models at lower trophic levels are capable of reproducing the observed spatial and temporal patterns in hydrodynamic properties, chlorophyll, and nutrients across most of the shelf areas. These models are effective at reproducing primary production and providing a closure hypothesis for zooplankton modeling. Their performance diminishes rapidly toward the coastal zone as these waters are more optically complex and land-derived inputs are poorly quantified (Nittis et al. 2006; Stipa et al. 2003). A number of shortcomings in the present observing capacity and in the coupled physical and biogeochemical models therefore emerged from the HAB and eutrophication experiments:

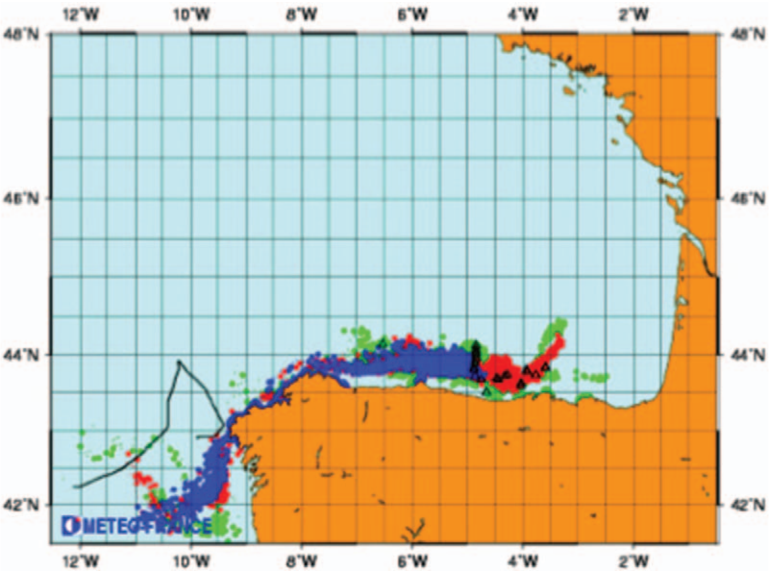

Fig. 5. Visual impact of the provision of 3D currents form the MERSEA Strand-1 Project for an operational oil drift dispersion simulation after the Prestige accident. The oil spill position on 13 December forecasted by the Météo-France Mothy oil drift model along the Spanish coast with the atmospheric forcing from the Arpege model (blue). Simulation extended with the additional inputs from Mercator currents (green) or FOAM currents (red). Observations of spill marked with black triangles. With the large number of particles used in these simulations, many symbols are overlaid and it is not possible to "see" the amount of stranded oil. Figure courtesy of P. Daniel (Météo-France).

- In situ marine biogeochemical measurements, which complement satellite observations, are essential for ecosystem monitoring, model validation, and assimilation. Improved observation technology, the ability to discriminate between different functional groups of phytoplankton, bacteria and zooplankton, biomass, and production, is highly desirable for further evaluation and development of ecosystem models.
- Operational high-frequency (daily) freshwater and nutrient river runoff data must be routinely measured and made available in near–real time.
- The shelf- and coastal-scale algae distribution and eutrophication levels are sensitive to the open boundary conditions from larger-scale models, particularly regarding the 3D currents and thermohaline conditions.
- The shelf and coastal biogeochemistry models may need input on biogeochemical state variables from larger-scale coupled models.
- Nutrient regeneration processes (pelagic and benthic) are important mechanisms that should be better understood and modeled.
- Atmospheric nitrogen deposition is an important mechanism that needs to be better monitored and parameterized.

The oil spill forecast demonstration experiments. The main activity in the EU on combating pollution at sea is the action program on controlling and reducing marine pollution by discharges of hydrocarbons and hazardous and noxious substances. The European Maritime Safety Agency (EMSA), created as a consequence of the Prestige oil spill accident, will play a fundamental role in this activity.

One of the oil spill applications examined during the project was the Prestige accident off the Iberian Peninsula in November 2002 (Hackett 2004). The simulations of oil drift patterns after the accident used daily mean fields from Mercator and FOAM and compared the results to that obtained with the standard numerical weather prediction oil dispersion model (Fig. 5). Mercator generally produces a more textured eddy field than FOAM due to the 5–7-km versus 12-km grid sizes. The two current models agree well on the gross features of the oil distributions, while differences in spatial resolution result in differences in the simulated oil drift, most notably regarding eddy trapping and site-specific stranding. Both models predict oil from the surface release phase moving into the Bay of Biscay and stranding along the north coast of Spain and west coast of France, and both agree that nearly all oil from the bottom release phase remains out at sea. In both simulations, the stranding increases episodically in time, reflecting onshore advection events. The main limitations identified by these experiments were the following:

- Oil spill weathering and fate forecasting is a problem that requires modeling of fully 3D hydrodynamics (see also Hackett et al. 2005). Systems based on 2D models can provide quite erroneous estimates, especially in the case of a deep oil release.
- Horizontal and vertical resolution of most model systems is inadequate when coastal areas and stranding of oil are considered. Complete downscaling from global to coastal high-resolution models should be used with increased vertical resolution in the upper few centimeters to meters.
- There is a need to develop methodologies for optimal estimate of surface (skin) currents from existing modeling systems as this has a profound impact on the spreading at moderate to strong winds.
- Real-time access to airborne surveillance in combination with satellite synthetic aperature radar (SAR) data optimizes the observation frequency for oil spill monitoring including determination of oil drift pathways.
- Modeling of long-term weathering processes, especially for oxidation and biogeneration, should be improved.
- Interfaces should be developed with coastal classification systems able to provide information for the geomorphology and ecological characteristics of the area. This would optimize modeling of stranding processes and complement decision support systems.

CHALLENGES. A particular concern relates to the integration that is needed between the open-ocean basin-scale models and the local and regional monitoring and modeling systems. It has already been noted that models at different scales have rather different requirements for assimilation or ingestion of measured data. It is equally important to acknowledge that these different scales of modeling systems have different relationships with their users. The basin-scale models, which have formed the focus for the MERSEA Strand-1 Project, are generating the synoptic initial ocean states that in turn can provide boundary conditions for nested models. Those working at the local scale already tend to have close relationships with their operational end users (who often provide the funding source for local observatories, tailored to meet very specific user needs). These end users are not necessarily aware of the benefits that will be achieved by integrating local systems within the larger-scale systems. Consequently, there is clearly a need for improved dialogue between the different players working at different scales. In parallel, new classes of users must be trained to benefit from the improved operational reliability and capacity of the data and products that should become available when the marine services of GMES start to be delivered. All in all, effective communication and involvement of the users is urgent, as it is through this approach that the whole enterprise for ocean forecasting can be justified.

In general, monitoring and modeling systems are more mature for ocean physics, while they are still at the research level for pollution and ecosystem monitoring and simulations (Blackford et al. 2004). There is a developing need to be able to measure pigments, nutrients, dissolved gases, and other biogeochemical properties in the sea at fine spatial and temporal resolution. Moreover, as the coastal systems reach finer spatial resolution, the need for validation becomes more constrained by lack of data. It is apparent that satellite data alone are not able to make up the deficit of timely observational data needed for the coastal systems.

The execution of the focused application demonstration activities identified particular need for sustainable observatories within the European shelf seas and coastal regions. The development and operation of integrated observatories at selected tie points is an essential approach to secure regular and sustained in situ monitoring for environment (physical, biogeochemical) and security (oil spills, red tides, toxic algal blooms). Sustainable observatories including moorings and drifters should also incorporate repeat hydrographic and water quality (e.g., continuous plankton recorder) observations from ferry lines and the Ship-of-Opportunity-Programme (SOOP), and enable near-real-time data flow. In addition, there is a need to advance the availability of surface current data product for model validation and for serving applications. The number of operating short- and long-range high-frequency (HF) radar systems should therefore increase (today, three systems are operating in Europe). There is also an urgent requirement for a routine monitoring system of freshwater volume and nutrient discharges from rivers into coastal seas.

The optimum performance of the marine GMES will only be achieved when there is an effective two-way integration between the regional to local-scale observations and models and the basin-scale forecasting system. Observations made locally need to be fed back in a timely way to constrain the behavior of the basin-scale model system and thus improve its performance. Data network systems must thus ensure rapid transmission of very high rates of raw data to processing centers and derived products to operational users.

In parallel to this there is also a regular demand for systematic examinations of the performances of operational forecasting models that quantify their dependence on the availability, timeliness, and quality of measured ocean data from satellites and in situ systems. This involves improvements in data assimilation techniques, for example, integration of fully multivariate assimilation schemes, needed for a better use of all observation data, as well as development of objective measures of predictive skill.

SUMMARY. The MERSEA Strand-1 Project initiated a series of multidisciplinary activities regarding the assessment of the current capacity for marine GMES in Europe. In so doing, the project provided opportunities

- to intercompare and evaluate operational ocean models and data assimilation systems;
- to examine the operational oceanography data requirements;
- to enable execution of demonstration application experiments with relevance and importance to the public.

In finalizing the project, a number of valuable achievements and findings regarding basin-scale operational oceanography have been accomplished and projected onto the functionalities and integration of the four corners of the GMES diamond (see Fig. 1). In line with these achievements and the execution of several demonstration application experiments, specific recommendations for cost-effective and sustainable solutions to obstacles encountered for the development and implementation of a fully basin-to-local operational oceanography system beneficial to GMES have been delivered. The assessment of the observing system, data and product flow and dissemination, intercomparison of the assimilation systems, and execution of the application experiments are also importantly forming the platform for the consolidated European view and contribution to GODAE (GODAE 2001). Similarly, the MERSEA Strand-1 Project has also importantly contributed in pushing the consensus view on operational oceanography within the Global Ocean Observing System (GOOS) (http://ioc.unesco.org/goos/) and EuroGOOS (www.eurogoos.org).

There has been a gradual accumulation of expertise and knowledge to design, implement, and operate operational ocean forecasting systems in Europe over the last 5–10 years. This is extremely timely in view of the full execution of GMES in 2008. The provision of observational data and forecasting system outputs as freely available public goods will ensure wide applications in a variety of existing and new public and private sectors, and may also stimulate development interests within the commercial value-added sector. In the 2008–10 time frame a European Ocean Forecasting System of Systems may emerge with a global core component that provides downscaling to a series of regional systems that cover the open ocean and shelf seas from the Arctic Ocean to the Black Sea (Desaubies 2005). Local, high-resolution systems could then in turn be nested to these regional systems. Aspects of sustainability and associated institutional, governmental, and international organizational involvement and integration are currently being explored in this context. Recent and future advances in operational oceanography are therefore greatly stimulated by the joint ESA/EC GMES initiative. In parallel to this, a dedicated curriculum in operational oceanography at universities around Europe is needed to meet the expected demand for operational oceanographers that can secure adequate and timely analyses of the large amount of regular quality-controlled information products.

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