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Existing operational oceanography

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Abstract

This paper reviews operational systems used for real-time prediction of tides, surges and waves in northwest Europe. The review takes the form of a ‘snapshot’ of models, related observing systems and dissemination procedures in use early in 1999. A brief account of surge, tide and wave dynamics and factors influencing them combined with regional factors such as water depth, shallow water extent, exposure (fetch), etc., provides a basis for understanding the diversity in design and implementation of the different national systems. It is shown that the systems in the different coastal states have evolved to address the needs of their own coastal and marine environments; take account of relevant processes and dynamics; and employ technologies such as data assimilation where appropriate. As a result, there are areas of common interest and overlap. Possibilities for rationalising systems or enhancing benefits by sharing of forecast products and data are discussed. Improved communication among operational agencies, perhaps using the PROMISE web pages (http://www.pol.ac.uk/promise/) to facilitate exchange of information on systems, operational developments and experience, is suggested as a means of encouraging collaboration and dissemination of new techniques.

Keywords: Operational oceanography; Surges; Tides; Waves

1. Introduction and background

Knowledge of and the ability to predict variations in sea level and sea state are essential for those living and working on or near the sea. Changes in sea level are due, predominantly, to the tides generated by the variations in the gravitational attraction of the sun and moon, and to the effects of storms. Winds and variations in atmospheric

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pressure associated with a storm can raise or lower sea level by several metres over a period ranging from a few hours to 2 or 3 days, producing a 'storm surge'. Winds also generate waves, with periods up to perhaps 25 s and wavelengths of 10–1000 m. Such waves may be large enough to threaten ships and offshore structures and to damage and breach coastal defences, allowing inundation of low-lying coastal land.

Forecasts of sea levels, currents and sea states are commonly made using numerical models and most countries in northwest Europe have developed and/or operate model-based systems. Progress and developments in storm surge modelling were reviewed recently by Bode and Hardy (1997). Komen et al. (1994) describe the state-of-the-art in spectral wave modelling. At present, separate models are generally used for routine prediction of storm surges and waves. However, the generation of waves and surges is closely related and there are several mechanisms by which waves and the mean flow or water level associated with tide and surge interact, each component of the total motion affecting the others (Wolf et al., 1988). This has led to the development of coupled models for waves, tides and surges and for waves, ocean and atmosphere, e.g. in ECAWOM (MAST II Project MAS2-CT940091) based on more complete physics. Although some interaction processes have been shown to produce a significant effect, a clear demonstration that coupled models give consistently better results than tuned separate models is required to persuade operational agencies to adopt them (Ozer et al., 2000).

Observational networks of tide gauges and wave buoys provide data in real- or near-real-time to support the predictions. The data are used for assimilation into the models to improve the initial conditions for forecast runs, and to validate and check the model predictions. Such networks are operated in most countries and constitute an essential component of the prediction systems. The usefulness of such data extends beyond national boundaries and some ad hoc transfers have been carried on for many years. Initiatives to extend these by providing a framework linking national networks are continuing. A notable example is 'SeaNet' (van der Poel and Rozema, 1997).

'ECOMET', an Economic Interest Group formed in 1995 by European national meteorological services, also provides a mechanism for dissemination of observational data and model products aimed at private sector service providers. Its objectives include promoting greater availability of data and products, increasing data use, and improving distribution of data, products and services. The ECOMET catalogue consists mainly of meteorological parameters, although a number of centres provide oceanographic data and products from their wave and surge forecast models. Products and data are available locally from national meteorology services. Charges are levied for the information and data delivery.

The third important, but sometimes neglected, element comprises the post-processing or interpretation of output from the prediction system to suit user needs, the associated infrastructure (data communications, etc.) for dissemination, and response procedures. These depend on applications and on national or local responsibilities and arrangements. Applications include flood warning, operation of barriers and similar defence structures, navigation (ship routing; in addition to waves and possibly adverse currents which may cause delays, negative surges can reduce water depth enough in approach channels to ports to ground large vessels), coastal works, shellfish farming, etc. Data archived from operational model and observational networks also provide climatologies for use in, e.g. calculating extreme conditions for the design of structures, risk assessments, etc.

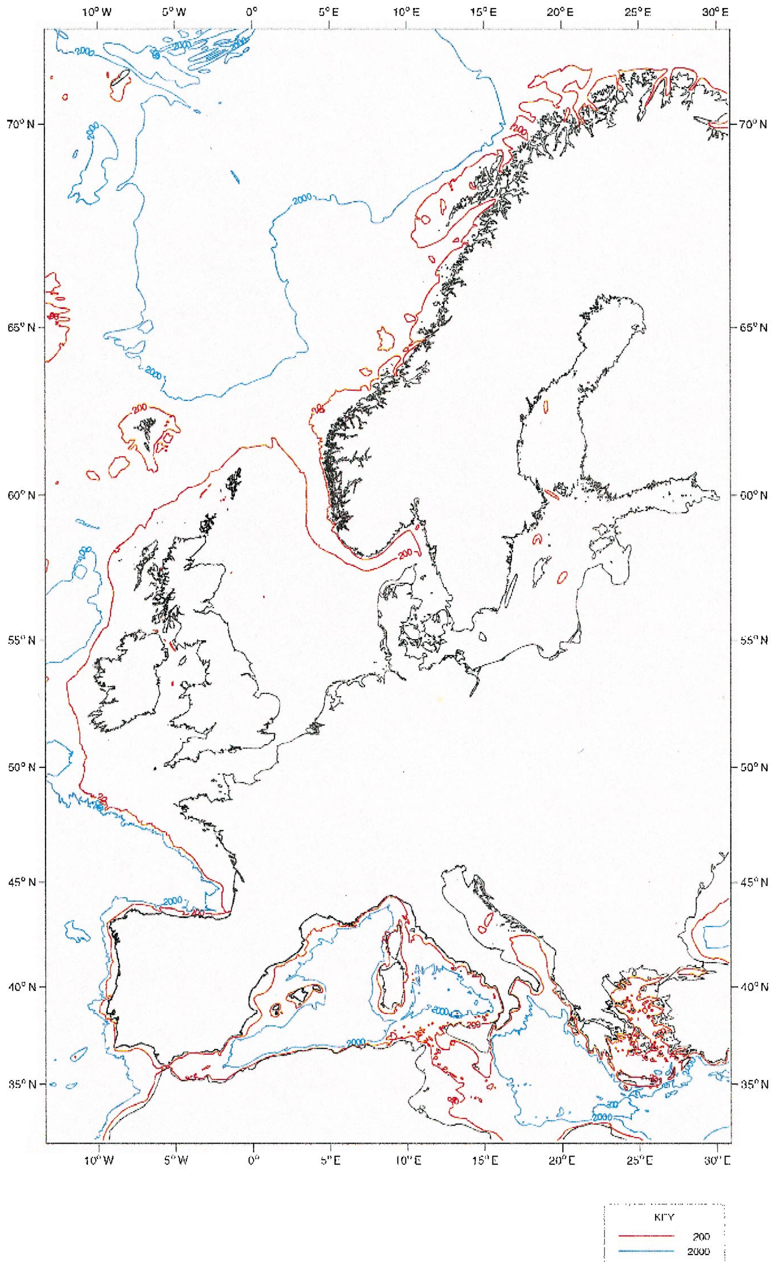

Fig. 1. Map and bathymetry of northern and western Europe with depth contours at 200 and 2000 m, showing the main shelf (depth < 200 m); shelf slope (200 m < depth < 2000 m); and deep water (> 2000 m) areas.

The PROMISE project included a basic task to rationalise existing operational models. Of these, models for wave and sea level prediction are most widely used and form the heart of the Service Module of GOOS (Komen and Smith, 1999). A survey sponsored by EuroGOOS (Davies, 1997) identified as many as 30 operational models of different kinds covering the southern North Sea. About half of these were wave or tide–surge/current models, though not necessarily intended specifically for this area. It is natural, therefore, to ask why there are so many models?

The present paper attempts to answer this question by providing an overview of systems operational in northwest Europe. Fig. 1 shows a map and bathymetry for the region. Many reports and papers describe the development and application of individual systems and models, but no overall picture is available. Therefore, to complement the detailed accounts, we present a 'snapshot' of real-time prediction of tides, surges and waves early in 1999. We attempt to highlight special features of the systems in place and to identify problems requiring further study. Our aim is to understand and clarify the reasons why there are so many and diverse systems, providing a rational basis for future development and identifying possibilities for enhancing European capabilities by mutually beneficial collaboration.

In order to achieve this, some background information is necessary. The region contains a wide range of oceanographic regimes with differing tide, surge and wave behaviour. Aspects of tide, surge and wave dynamics needed to understand this are briefly reviewed in Section 2. A 'snapshot' of operational systems is provided for each country or region in Section 3. Discussion and conclusions follow in Section 4.

2. Tide, surge and wave dynamics

Tides and storm surges are described by the 'long wave equations' (see, e.g. Bode and Hardy, 1997). A fundamental assumption is that wavelengths are large compared with the water depth. Tides are generated by gravitational forces acting over the whole water column in the deep ocean. They propagate as waves, predominantly as Kelvin waves, and are dissipated by bottom friction in shallow water on continental shelves. Local enhancements can occur due to resonance producing very large tides.

Storm surge generation is represented by two terms in these equations: wind stress/water depth, and ∇p_{msl}, the horizontal gradient of atmospheric pressure at the sea surface. The wind effect depends on water depth and increases in importance as the depth decreases, whereas the pressure effect is independent of depth. The most important mechanism for surge generation is wind stress acting over shallow water. Surges are, therefore, large and dangerous where storms impact on large areas of shallow continental shelves. In deep water, surge elevations are approximately hydrostatic; a 1 hPa decrease in atmospheric pressure gives about 1 cm increase in surge elevation.

Surges are superimposed on the normal astronomical tides. Where the tidal range is large, the relative timing of a surge peak and tidal high water is critical. A moderate surge at high tide may cause flooding, whereas a large surge may go unnoticed if its peak occurs at low water. In addition, non-linear processes become important in shallow water, modifying the storm surge and causing interaction between it and the tide.

In contrast, surface wind waves have wavelengths which, except on beaches, are small or comparable with the water depth. They are generated by winds, which typically produce waves with a spectrum of frequencies (or wavelengths) and propagate in a spread of directions. The magnitude depends on the distance over which the wind acts, known as ‘fetch’. Locally generated components, containing generally higher frequencies, are called ‘wind sea’. Non-linear interactions among wave components result in a transfer of energy from high to lower frequencies and the resulting longer period waves can travel very large distances, when they are known as ‘swell’. In shoaling water, the wave orbital velocities reach the seabed and their propagation slows, causing refraction and dissipation of energy by bottom friction. Wave energy is also dissipated in deep water by white capping and ultimately by breaking at the shore. Wave conditions at a point therefore depend on fetch, wind duration, exposure to incoming swell, and (local) bathymetry. For coasts of northwest Europe, swell generated in the Arctic and western or tropical Atlantic can be important.

Interactions also occur between the surge–tide motion and waves (Ozer et al., 2000).

Northwest Europe (Fig. 1) contains a wide range of oceanographic regimes. Resonance produces large tides in the Bristol Channel, the Gulf of St. Malo and the eastern Irish Sea, which dominate their dynamics, whereas tides in the Baltic and Mediterranean are small. The North Sea is large enough to support propagating tides (as long waves) and storm surges. Surges generated north and west of Scotland can travel into the North Sea, south along the east coast of England returning along the Dutch, German and Danish coasts. These are known as externally generated or ‘external’ surges. Extensive areas of very shallow water susceptible to large locally generated (‘internal’) storm surges occur in the German Bight. In contrast, the Iberian peninsula has narrow shelves bounded by deep ocean so surges contain a significant hydrostatic-pressure-generated component modified by the local effects of coastal winds.

Some west- and north-facing coasts are exposed to swell and have long fetch, producing large and long period waves. The Irish Sea is relatively enclosed, fetch lengths are relatively short and so waves are not so large and have shorter period. Extensive shallow water dissipates wave energy and so reduces extreme wave heights, e.g. in the southern North Sea and German Bight.

The above overview of dynamics and the bathymetry (Fig. 1) provide a basis for understanding the systems described below.

3. Overview of operational systems

3.1. Norway

3.1.1. Tides and storm surges

At the Norwegian Meteorological Institute (DNMI), the three-dimensional ocean model ECOM (Estuarine, Coastal and Ocean Model), a version of the Princeton Ocean Model, is used to forecast storm surges and currents (Engedahl, 1995; Martinsen et al., 1997). The model is run on a 20-km Cartesian grid on a polar stereographic projection covering most of the northwest European continental shelf, the eastern Norwegian Sea, and the Barents Sea. For storm surge prediction, ECOM is run in 3D barotropic mode (with 12 ‘sigma’ levels in the vertical); a 3D baroclinic run with 17 sigma levels provides currents (mainly for input to an oil drift model), together with sea surface elevation, temperature and salinity. Runs are carried out twice a day, at 00 and 12 UTC, to produce forecasts to $T+48$ h. The forcing consists of fields of 10 m wind and atmospheric pressure at MSL (mean sea level) provided six hourly at 50 km resolution by the operational HIRLAM weather prediction model at DNMI. Each forecast is preceded by an 18-h hindcast forced by six hourly analysed fields from HIRLAM, giving a total simulation time of 66 h/run.

On lateral open boundaries, both model runs are forced by multi-year monthly mean climatological fields of sea level and currents. At present, the tides are not included. The 3D baroclinic run is also forced by climatological salinity and temperature at the boundaries, and includes monthly mean fresh water inputs from the Baltic and the major European rivers. To prevent the model results from becoming unrealistic, the prognostic fields of salinity and temperature are relaxed towards the climatological mean in the deeper parts (below approximately 500 m). At the surface, the fluxes of salinity and temperature are controlled by relaxation (nudging) using climatological mean surface values. All operational forecasts are run on sequential or parallel (CRAY J90/CRAY T3E) computers in Trondheim.

3.1.2. Waves

In February 1999, the WAM spectral wave model replaced the earlier model WINCH in operational use at DNMI. WAM is run on a rotated latitude–longitude grid with resolution 0.45° (approximately 50 km) covering the northeast Atlantic Ocean and the North, Norwegian, Greenland and Barents Seas. Two-day forecasts are run twice each day with wind forcing (50 km resolution) from HIRLAM. In addition, forecasts to 7 days are run once a day driven by forcing data from the European Centre for Medium-Range Weather Forecasts (ECMWF). Sea ice cover, which inhibits wave growth, is updated weekly. The model is run on a parallel computer, a CRAY T3E. The output from WAM is two-dimensional wave energy spectra and the full spectra are stored for selected grid points. Wave parameters computed from the spectra, such as significant wave height, mean and peak wave period, mean and peak wave direction, are stored for all grid points. The parameters are computed for total sea, wind sea, and swell.

An oil spill model (NOROIL) driven by outputs from ECOM and WAM has been implemented for the area of the 20-km version of ECOM. Analysed fields from HIRLAM and ECOM are maintained for the last 7 days to allow calculations of spill history, and input model forecasts are extended to 5 days during a spill. The system provides a rapid response, with first oil drift forecast within 30 min of spill report.

The Marine Forecasting Centre at DNMI Bergen issues warnings when there is a risk of water level above given criteria. Warnings are sent to responsible organisations, e.g. harbour authorities, local authorities and police stations at about 100 addresses along the coast, and to national and local radio and TV stations for inclusion in weather reports. The Norwegian Hydrographic Office (SKSV) operates a network of tide gauges, and work on real-time transmission of the data to DNMI is in progress. Floods due to high water levels are most common on the west coast, but the infamous storm of October

16–17, 1987 flooded parts of Oslo. The Marine Forecasting Centre also issues daily wave forecasts for the oil industry, and wave forecasts are included in the radio weather reports three times every day. A special wave warning system operates for shipping in the Stad area. Current forecasts have also been issued for special operations, e.g. tow out of platforms and drilling at locations in deep water.

Several improvements to the operational model system are under test. These include a version of ECOM (3D baroclinic) with tides and extending to the east coast of Greenland and two nested fine grid (4 km) versions covering the shelf area off the west coast of Norway, and the Skagerrak and Kattegat. A special nested fine mesh (0.8 km) version for Oslofjord is run in connection with an annual regatta. By Autumn 1999, DNMI intends to initiate operational forecasts using ECOM with a coupled chemical/biological module for mapping transports of contaminants; a 20-km grid will cover the North Sea, with a nested 4 km refinement in the Skagerrak and Kattegat. Longer-term plans include a coupled sea ice model, presently under test, and assimilation of in situ and remotely sensed observations.

3.2. Denmark

3.2.1. Tides and storm surges

Since 1990, the Danish Meteorological Institute (DMI) has run a nested system of 2D models based on 'System21', developed at the Danish Hydraulics Institute. This covers the North Sea, Skagerrak, Danish Belts and the Baltic with grid resolutions of about 18, 6 and 2 km (Fig. 2). Forecasts covering the period $T+00$ to $T+36$ h are run twice each day to predict sea levels for coastal flood warning along the Danish coast (in particular

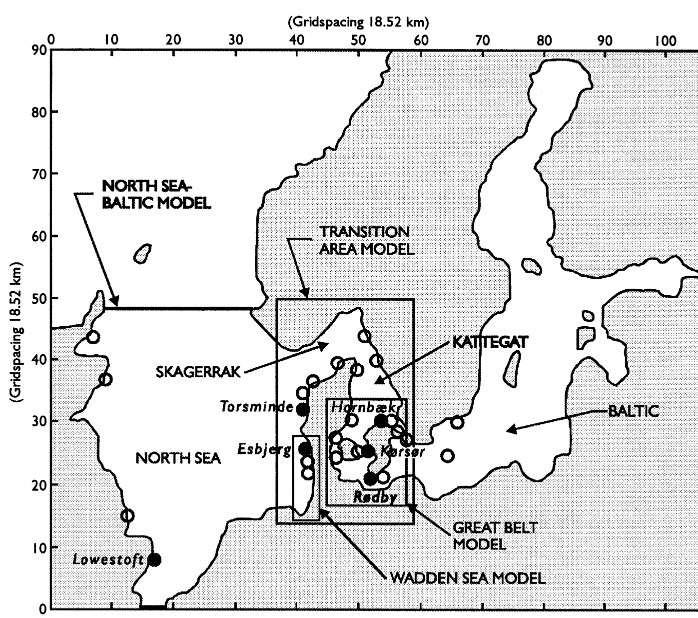

Fig. 2. Overview of the DMI operational models.

the Danish Wadden Sea). Forecasts start at $T = 00$ UTC and 12 UTC and are preceded by a 24- or 36-h hindcast starting at 00 UTC on the previous day. Extended water level and current prediction runs for $T + 00$ to $T + 120$ h were carried out during construction of the Great Belt Link. The 36-h forecasts are driven by 10 m winds and MSL atmospheric pressure from the DMI version of HIRLAM, with 0.15° and 1 h resolution, but for the extended 5-day forecasts, UKMO (UK Meteorological Office) Limited Area Model (LAM) data at 1.25° and 6-h resolution are used.

On open boundaries (Scotland to Norway and in the Dover Strait), 10 tidal constituents (no surge) are introduced. Twenty-two Danish tide gauges provide data for validation. In addition, data from four British and six Swedish stations are used for monitoring and calibration. Vested et al. (1995) describe the system and accuracy achieved. Average RMS (root mean squared) errors over all stations and for operational forecasts 6–18 h ahead are about 15 cm. Experiments with data assimilation using the Kalman filter approach developed by Heemink (1988) have also been carried out. Assimilation can improve the first few hours of the forecast (Vested et al., 1995).

The network of tide gauges in Denmark is operated collaboratively by DMI, the Royal Danish Administration of Navigation and Hydrography (RDANH), and the Danish Coastal Authority. RDANH is responsible for navigational safely and maintains 13 water level stations, established between 1991 and 1994, and oceanographic stations, established 1994–1996, with ADCP and temperature–conductivity chains providing information in the Belt seas (Buch, 1997).

The 'Maritim' service, operated by DMI, RDANH and the Danish Coastal Authority, provides tide predictions, forecast results and measurements in digital and graphical form, updated every few minutes, in real-time on the Internet (http://www.dmi.dk/). Fig. 3 shows an example of real-time observed water levels at Danish stations.

At present, real-time wave predictions are not run in Denmark, but a system using the WAM-cycle4 spectral wave model is being developed and expected to be operational from the end of 1999.

3.3. Germany

3.3.1. Tides and storm surges

Since 1983, the Bundesamt für Seeschiffahrt und Hydrographie (BSH) has developed and run a system of 3D baroclinic models covering the North Sea, Baltic and English Channel (Kleine, 1994; Dick, 1997) and a new version was introduced at the start of 1999. Nested grids are used with resolution of ~ 10 km in the whole region, and 1.8 km in the German Bight, Kattegat and western Baltic (Fig. 4). The models are forced by meteorological forecast data from global and local area models of the Deutscher Wetterdienst (DWD) (resolution: 30 km/15 km), transmitted to BSH each day. Boundary inputs include tides (14 harmonics), external surges calculated by a 2D Northeast Atlantic model, and river runoff. For the advection of temperature and salinity, an algorithm has been developed which gives low numerical diffusion (Kleine, 1993). Heat fluxes between atmosphere and sea surface are calculated to simulate realistic water temperatures in the surface layer. Since the density distribution and currents are also influenced by the ice distribution, an ice model computing ice thickness and compact-

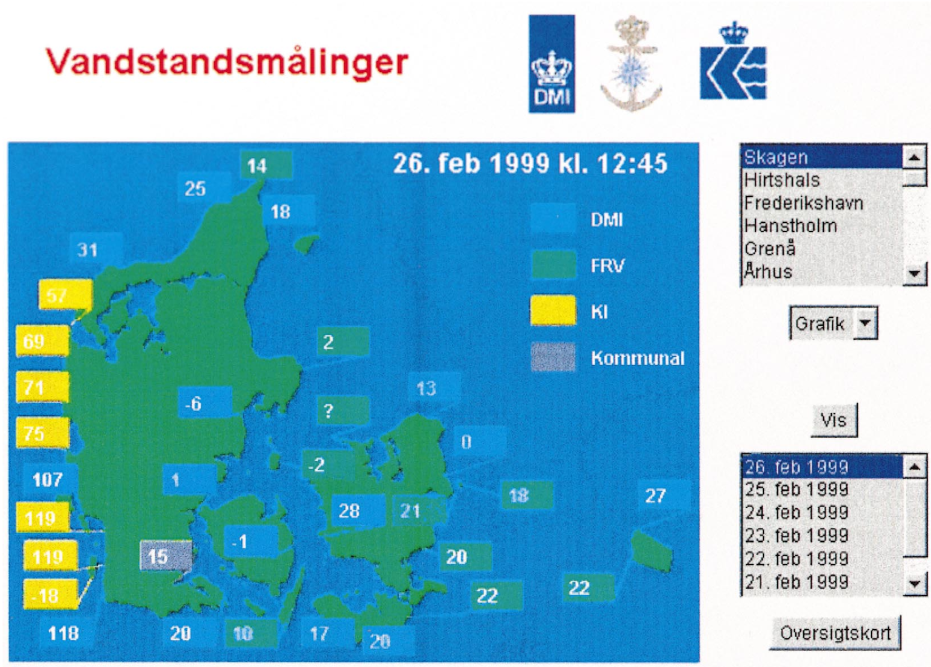

Fig. 3. Display of real-time observed water levels at Danish stations from the web page of the 'Maritim' service, updated every few minutes, on http://www.dmi.dk/. Menus also provide access to time series of tide predictions, model forecasts and measurements in digital and graphical form.

ness has been included, accounting for ice dynamics and thermodynamics as well as wind- and current-induced ice drift. Data from a DWD wave forecast model are used to account for the influence of waves on water levels and currents in shallow water, in particular, effects of radiation stress producing wave-induced currents and wave set-up and set-down. Forecasts covering $T+12$ to $T+60$ h are run once each day (during the night), with initial data from the model fields at $T+12$ h of the previous forecast. Water level, currents, salinity, temperature, density and the ice distribution are predicted, with output fields stored every 15 min.

Results can then be used in dispersion and transport models (e.g. for pollutants, oil spills and tracking drifting objects). The water level forecasts, together with real-time data from the German, Dutch and UK tide gauges networks, and other tools are used by the water level prediction and storm surge warning service. The accuracy of high water level prediction by the baroclinic circulation model for different German stations is between 10 and 20 cm (RMS); standard deviation is between 15 and 25 cm.

Especially for the water level prediction service of BSH, a 2D tide–surge model has recently been implemented for surge prediction. This model covers only the North Sea with 10 km resolution and is forced by tides and DWD meteorological forecasts. Two runs are carried out, the first with tide and meteorological forcing, the second run with tide only. By subtracting 'tide' from 'tide + surge' solutions, surge values for German

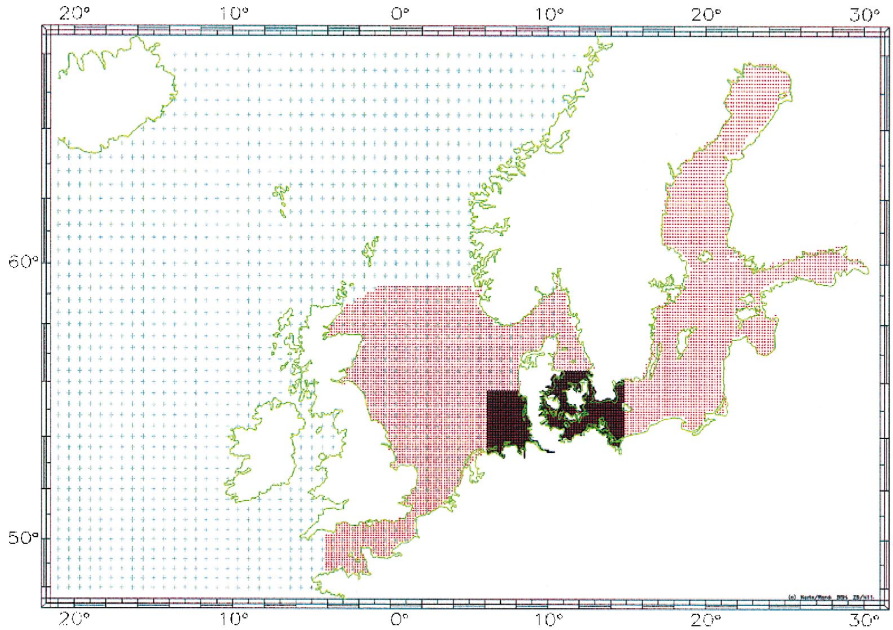

Fig. 4. Grid plots of tide–surge and transport models operated by BSH.

stations are determined. The 'surge model' runs much faster than the 3D baroclinic model, so that two forecast runs covering $T + 00$ to $T + 84$ h can be computed each day. The accuracy of the 'surge model' is also higher than that of the 3D baroclinic model because errors in the models tide predictions are, to a large extent, eliminated. In operational use, the mean absolute deviation between measured and modelled high water and low water surges is between 10 and 15 cm, the standard deviation is about 15 cm. Fig. 5 shows a frequency distribution of differences between measured and modelled surge values for all high waters in 1998 at Cuxhaven. Generally, good agreement is obtained with occasional large errors, up to -80 cm, which can cause problems for flood warning. This is typical of most operational surge models.

For water level predictions in the River Elbe, two regional models are run at BSH: a 2D model developed by Hydromod (see below), and an inverse 1D model including data assimilation of water levels.

An operational 3D model for the Elbe estuary, originally developed in the EUREKA–EUROMAR project 'OPMOD' (OPerational MODelling of Regional Seas and Coastal Waters), has been run routinely by Hydromod in Wedel since autumn 1994 (Nöhren et al., 1995). The model area extends from the tidal weir at Geesthacht (east of Hamburg) to the outer estuary west of Cuxhaven and includes a large area of ecologically important tidal flats, which are part of Wadden Sea national parks (Fig. 6). Driven by meteorological and hydrographic data from larger-scale forecast models and field stations, the operational system produces three-dimensional hydrodynamic fields (currents, water level, salinity, water temperature) on a 250-m horizontal grid with a mean

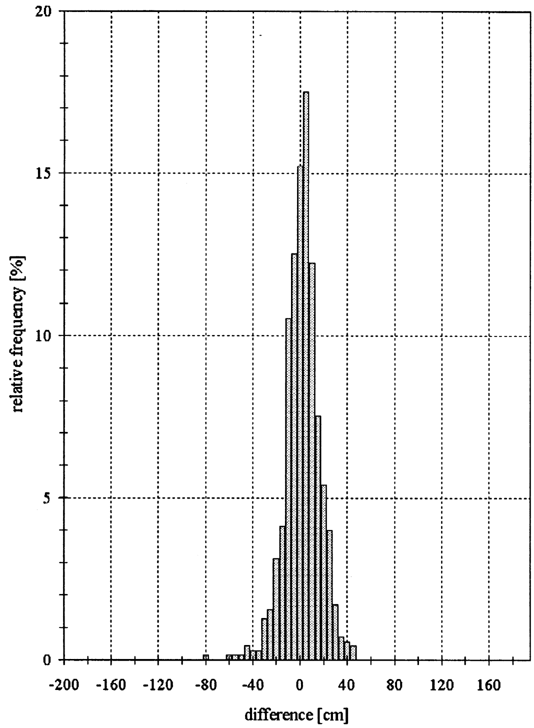

Fig. 5. Frequency distribution of errors (model observed) in surge elevation at high water during 1998 at Cuxhaven.

vertical resolution of 2 m every 3 min. Output fields and mesoscale model input have been stored since 1995 for statistical analysis and environmental monitoring.

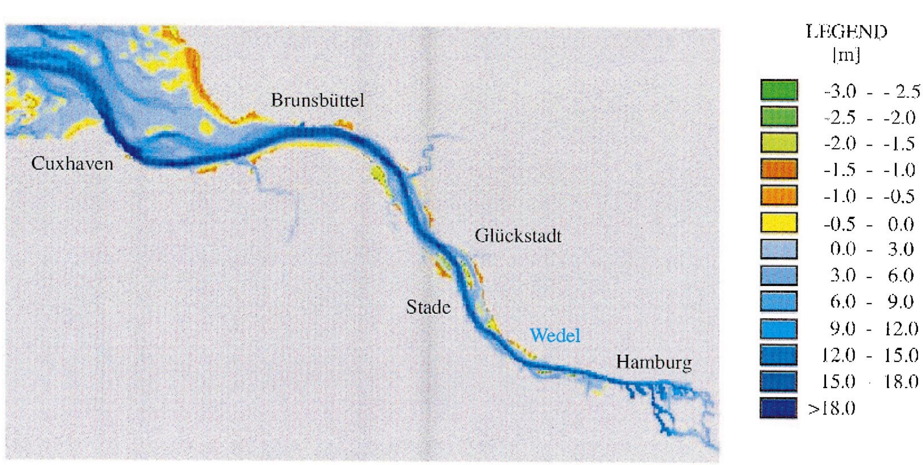

Fig. 6. Bathymetry and extent of the Hydromod operational 3D model of the Elbe estuary.

The system is used both for short-term forecasts and medium-term monitoring purposes in the Elbe estuary. For the latter applications, water temperature and salinity especially are of great importance. Information about salinity, water temperature, and water level at the model open boundaries in the German Bight, discharge and temperature information for tributaries and the upper Elbe at Geesthacht as well as global radiation, wind speed and direction over the whole area is essential for accurate forecasts. For model validation and additional environmental assessment purposes, useful hydrographic and meteorological data from field measurement stations along the river are available.

3.3.2. Waves

A wave forecast system based on the second-generation HYPA and HYPAS (S meaning shallow) models (Günther and Rosenthal, 1983; Günther et al. 1979) has been operated by DWD since June 1992 (Behrens and Schrader, 1994). The system has three components. A deep water version run on a 150-km North Atlantic grid provides 7-day forecasts driven by winds from the DWD global atmospheric model. A shallow water version on a 30-km grid covering the northwest European Shelf and eastern Norwegian Sea and a shallow water version covering the Baltic on a 16-km grid provide 3-day forecasts. The shallow water versions are driven by winds from the DWD European atmospheric model. Two runs are carried out each day, taking account of ice distributions from the BSH Ice Service. Boundary input is passed from the North Atlantic to the Northwest Shelf model, which in turn provides boundary input for the Baltic model. Behrens and Schrader (1994) outline the system and verification against ERS-1 altimeter and scatterometer data.

At end of 1999/2000, the HYPA models will be replaced by WAM in a global version on a 60-km grid and a local version covering the North Sea and the Baltic. The local wave model will be forced by a new DWD local atmospheric model (7 km resolution), whereas the local wave model grid is that of the BSH 3D baroclinic model (10 km resolution), to facilitate the data exchange between wave and current models. The operational schedule of the old wave forecast system will be retained.

3.4. Sweden, Finland, Poland, Germany and Denmark — Baltic collaboration

Within the framework of EuroGOOS, a development plan for operational modelling of the Baltic Sea has been established (Dahlin, 1997; Woods et al., 1996, p. 112; Woods et al., 1997, p. 13). The partners are the Swedish Meteorological and Hydrological Institute (SMHI), the Finnish Institute of Marine Research (FIMR), the Polish Maritime Institute in Gdansk, BSH in Germany, and RDANH Denmark. The main aim is to establish a common operational system for all states surrounding the Baltic Sea.

Central to this is a high-resolution baroclinic ocean model of the Baltic (HIROMB) developed by BSH and SMHI and based on the 3D model of BSH (see above). This is a 3D primitive equation model with 24 ‘layers’ increasing in thickness from 4 m for the surface mixed layer to 60 m for the deeper layers. It includes one equation boundary layer dynamics and a viscous–plastic ice model. A system of nested grids, designed to meet the requirements of all partners, is used with resolution ranging from 12 nautical miles ($\sim$ 22 km) for the North Sea reducing to 3 nautical miles ($\sim$ 5.5 km) east of 6°E and covering the eastern North Sea, the Skagerrak, Kattegat and Baltic Sea. Interaction between the two grids occurs at 6°E where flux, temperature, salinity and ice properties are interpolated and exchanged. As in the BSH scheme, a coarse grid storm surge model for the northeast Atlantic supplies the water level at the coarse grid open boundary between the Atlantic and the North Sea. Forcing consists of atmospheric pressure, wind speed and direction, humidity, temperature and cloud coverage from HIRLAM and fresh water inflow is given at 80 major river outlets. Wind waves enhance mixing and mass transport (Stokes' drift) in the surface layer and this is accounted for using outputs from the HYPAS wind wave model.

HIROMB was originally set up at SMHI in the summer of 1994 and has run in pre-operational mode since the summer of 1995, making daily 48-h forecasts of sea level, current, temperature, salinity, and ice conditions.

Wave conditions in the northern Baltic are characterised by complicated fetch geometry and bathymetric effects (focusing, etc.). The importance of wave forecasts in the area was highlighted by the 'Estonia' disaster in 1994. The HYPAS wind wave model is run at SMHI for the North Sea (including part of the Norwegian Sea) and Baltic, providing wave forecasts and inputs to HIROMB.

Daily forecasts from HIROMB are transmitted to all partners and are available, along with wave forecasts from HYPAS on the Internet (password protected pages at http://www.smhi.se/). HIROMB is currently being moved to a fully operational environment.

The Baltic countries also operate observational networks. For example, the Sea Level and Wave Information Service of FIMR operates a network of tide gauges, 12 of which provide real-time data used to provide hindcasts and forecasts (Grönvall, 1997).

3.5. The Netherlands

3.5.1. Tides and storm surges

Since 1990, KNMI has run the Dutch Continental Shelf Model (DCSM), a 2D tide–surge model based on the 'WAQUA' system developed by Delft Hydraulics and Rijkswaterstaat (Gerritsen et al., 1995; Phillippart and Gebraad, 1997). The present operational model covers the northwest European Shelf with resolution 1/4° in longitude by 1/6° in latitude, ~16 km. Ten tidal harmonics and surge elevation, assumed hydrostatic, are introduced on the model open boundaries. Since 1993, the DCSM has been driven by 10 m wind and surface pressure from the KNMI HIRLAM atmospheric model. Forecasts extending to $T+48$ h are run every 6 h, four times per day. The model is used to compute the storm surge component of sea level by subtracting model-generated tide predictions, derived from 'offline' simulations, from the 'tide + surge' real-time runs. Best estimates of total sea level are then obtained for tide gauge sites by adding the model surge to the more accurate local tide predictions produced by Rijkswaterstaat using the standard harmonic method.

A special feature of DCSM is the use of 'state-of-the-art' optimal methods, specifically an adjoint model for calibration (e.g. Phillippart et al., 1998) and since 1992, assimilation of real-time measurements from tide gauges using a steady-state Kalman filter (Heemink, 1988). Assimilation can improve forecasts on the Dutch coast during the first 10–11 h, compared with equivalent deterministic forecasts (see Fig. 7; Hans de

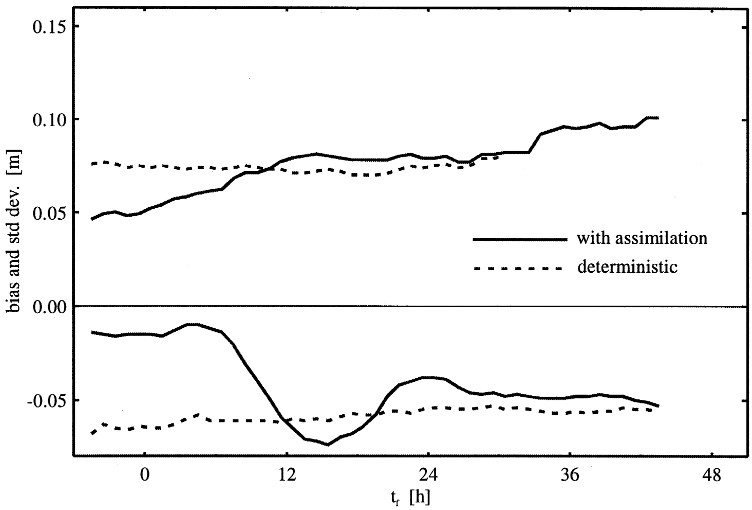

Fig. 7. Mean error statistics (bias and standard deviation in metres) for high water as functions of warning interval (t_f in hours) at Hoek van Holland during March–May 1998, from the Dutch CSM run at KNMI. Dashed lines are deterministic forecasts and continuous lines equivalents using assimilation of tide gauge data.

Vries, 1998, personal communication). This time scale is, presumably, determined by the surge propagation from northeast Scotland to the Dutch coast. Thereafter, results may be less accurate than deterministic equivalents. Also, the success of the assimilation procedure depends on high-quality data being used. For these reasons, model results with and without assimilation are produced and disseminated.

Outputs are supplied to the Hydro Meteo Centres in Hoek van Holland and Middelburg for use in flood warning. Information about the Dutch Storm Surge Warning Service (SVSD), status of coastal sectors and flood barriers can be found on the Internet (http://www.waterland.net/). Fig. 8 shows an example.

3.5.2. *Waves*

Wave forecasting for the North Sea area at KNMI began in 1977. Since 1990, forecasts have been produced using 'NEDWAM', a limited area version of the third-generation WAM spectral wave model (Komen et al., 1994; Voorrips et al., 1997) on a ~ 32 km grid covering the North Sea, the Norwegian and Greenland Seas and the eastern English Channel. The model is driven by 10 m winds from the KNMI HIRLAM atmospheric model (present operational resolution 50 km). A 12-h hindcast and a 48-h forecast is run every 6 h, producing wave parameters for the North Sea and off the Dutch coast. Model wave analyses and forecasts are monitored and verified on a daily basis using real-time data from ships, buoys and satellites.

Assimilation of spectral buoy data has been included since late 1998. Without data assimilation, typical RMS errors in predicted wave height in the southern North Sea range from 25 cm (at $T + 00$ h) to 40 cm (at $T + 48$ h). A large part of the error is normally due to errors in the forcing wind field. Problems in the wave model with

Fig. 8. Status of coastal sectors and flood barriers from the Dutch Storm Surge Warning Service (SVSD) web page, http://www.waterland.net/.

propagation of swell, which is attenuated far too much, also contribute. With assimilation of buoy data, the model accuracy in the first 12 h of the forecast can be enhanced significantly, mainly due to improved description of low frequency swell.

For lead times 48–120 h, a statistical forecast model is used, based on ECMWF model forecasts and MOS regression equations (Wijngaard and Kok, 1997).

Wave outputs are supplied to the Hydro Meteo Centres for use in storm and flood warning systems and for coastal zone management (e.g. in the procedures for access to Rotterdam harbour). Wave forecasts are also supplied to shipping and offshore companies for both safety and economical purposes.

The limited resolution of both the wave model and wind input limits accuracy near the coast, where interaction between waves and the strong tidal currents is also significant. Extensive tests are now being carried out with a nested high resolution ($\sim$ 8 km) wave model for the southern North Sea, forced by winds from a nested (11 km) version of HIRLAM. This produces a significant improvement in accuracy for small storm systems and sharp gradients close to the coast. Plans for comparing, or possibly coupling, this high-resolution NEDWAM model with the shallow water SWAN model (Ris, 1997) are under consideration.

3.6. Belgium

3.6.1. Tides and storm surges

Since the late 1970s, MUMM (Management Unit of the North Sea Mathematical Model) has run a 2D vertically integrated hydrodynamic model, covering the North Sea

(Adam, 1979). The horizontal resolution was 20′ in latitude and longitude in the northern part of the domain and ~7 km in the southern North Sea. In 1998, a new 2D model covering the whole northwest European continental shelf was introduced for operational use at MUMM and at AWK (Afdeling Waterwegen Kust; Ministry of the Flemish Government) (Ozer et al., 1997; van den Eynde et al., 1998). The new model uses a uniform horizontal resolution (2.5′ latitude, 5′ longitude).

Surface wind and pressure forcing is provided by the UKMO for both models. Tidal forcing, with eight tidal harmonics, and surge elevation (assumed hydrostatic) are introduced along the model open boundaries. The models are run, automatically, twice each day as soon as the meteorological data are available. Forecasts cover a period of 4 days. Typical accuracy of sea surface elevation (level including model tide) is about 15 cm (RMS). Variability between successive forecasts can be, in some circumstances, relatively high due to changes in meteorological data.

Results of the North Sea model at Ostende are available on the Internet in tabular form at http://www.mumm.ac.be/docs_en/forecasts/mops/ostend.html). The user interface for the continental shelf model is implemented in HTML, providing an easy access to the model forecasts. A similar user interface for the North Sea storm model is also being implemented.

3.6.2. Waves

Since 1992, both MUMM and AWK have also run the second-generation wind wave model HYPAS, developed by GKSS, in operational mode (van den Eynde, 1992). A refraction module has been developed at MUMM and is used for Belgian coastal waters, accounting for the effects of water depth changing with time due to varying tide and surge elevations. UKMO winds are used as forcing. Two runs per day are carried out.

The model has been validated by the use of buoy data and of ERS-1 altimeter data (Ovidio et al., 1994). The accuracy of significant wave heights is typically 40 cm (RMS), indicating a scatter index of about 35%.

A user interface, implemented in HTML, is being developed at the moment to provide an easy access to the model forecasts.

Wave predictions at Westhinder are available on the Internet in tabular format (http://www.mumm.ac.be/docs_en/forecasts/deining/deining.html).

Plots of the significant wave height predictions at different stations are available at http://www.mumm.ac.be/docs_en/models/deining/prepoi.html.

An observational network, Meetnet Vlaamse Banken, provides, in real-time, observations of sea surface elevations and wave parameters to check and validate forecasts.

3.7. United Kingdom

3.7.1. Tides and storm surges

The Meteorological Office has run 2D tide–surge models developed by the Proudman Oceanographic Laboratory (POL) routinely since 1978 (Flather, 1979; Flather et al., 1991). The present model, CS3, introduced in 1991, covers the northwest European shelf (12°W to 13°E, and 48° to 63°N) with resolution 1/6° in longitude by 1/9° in latitude, ~12 km. It has open boundary input of 15 tidal harmonics and an external surge component, assumed hydrostatic. Tide-generating forces and the drying and flooding of intertidal areas are accounted for. The model is driven by wind and surface atmospheric pressure data from the Met. Office's limited area atmospheric model (LAM), with resolution of about 50 km and 1 h. Two runs are carried out each day, comprising a hindcast from $T-12$ to $T+00$, and a forecast covering $T+00$ to $T+36$ h. The hindcast runs are forced by met data from the atmospheric model assimilation cycle, incorporating met observations. (In mid-July 1999, the LAM forcing was replaced by data from a new mesoscale atmospheric model on a rotated latitude–longitude grid of 0.111° [$\sim$ 12 km]. Four surge model runs per day are carried out, each comprising a 6-h hindcast + 36 forecast.) The model is used to predict the storm surge component, accounting for interaction with the tides, by subtracting the model predicted tide from the tide with surge solution. This is added to the harmonically predicted tide based on tide gauge observations to estimate total water level.

Results are used by the UK Storm Tide Forecasting Service and the Environment Agency (EA) as the basis for flood warnings on the coasts of England and Wales. The UK National Tide Gauge Network consists of gauges at about 35 sites, from which data are retrieved in near real-time to check forecast accuracy and for assimilation. The model forecast accuracy achieved varies for different parts of the coast — typically $\sim$ 10 cm (RMS).

Additional models have also been introduced to address specific problems. Shelf-scale models did not provide useful surge forecasts for the Bristol Channel, with its large tidal range and strong interactions. This led to the development of a system of one-way nested local models with 4 km and 1.3 km grids linked to a 1D model of the River Severn. These models use boundary tidal input of 26 harmonics and surge components interpolated from the shelf model. Because the tide–surge interactions are so strong, separation of the surge component is difficult. The resulting surge in the upper channel also exhibits rapid changes around the time of tidal high water, causing problems with interpretation of the results for flood warning. Tuning of the models (Amin and Flather, 1996) provided accuracy for tidal prediction comparable with that of the harmonic method and allowed the models to be used to predict directly total water levels.

To provide surge forecasts necessary for operation of the Thames Barrier, a 2D model of the southern North Sea and eastern English Channel, linked to a 1D model of the River Thames, was set up by POL in 1989 and is run by the EA at the Barrier site. Open boundaries are at 55°N, 5°E, and at 2°W. A simple non-optimal assimilation scheme — the 'boundary correction method' (Flather, 1984) — uses data from the tide gauges at North Shields and Newhaven to correct errors in open boundary surge input taken from operational shelf model runs carried out at the Met Office. This gives a useful improvement in surge forecast accuracy during the $\sim$ 9 h propagation time from the boundary to the barrier — the lead-time required for decisions on closure.

A larger English Channel–North Sea model (ECNS) uses a similar approach to assimilate data from the tide gauges at Aberdeen and Newlyn. This model has been run at the Met. Office for the last 3 years.

The UK has a long coastline with varied tide and surge conditions. Further local models for complex sections have been developed but not yet implemented operationally. Major surge events are generally well handled and moderate surges on large spring tides cause more forecast and warning errors. Some cases, with external surges travelling south along the east coast of England during periods of southwesterly winds, have been problematic. Fig. 9 shows predictions of a typical external surge in November 1998 from the UK operational model archive. Flather and Smith (1993) investigated the causes of a significant underprediction of surges on the east coast and in the Thames Estuary in January 1993. They showed that a small perturbation near The Wash in the southwest winds was not forecast by the atmospheric model. As a result, model offshore

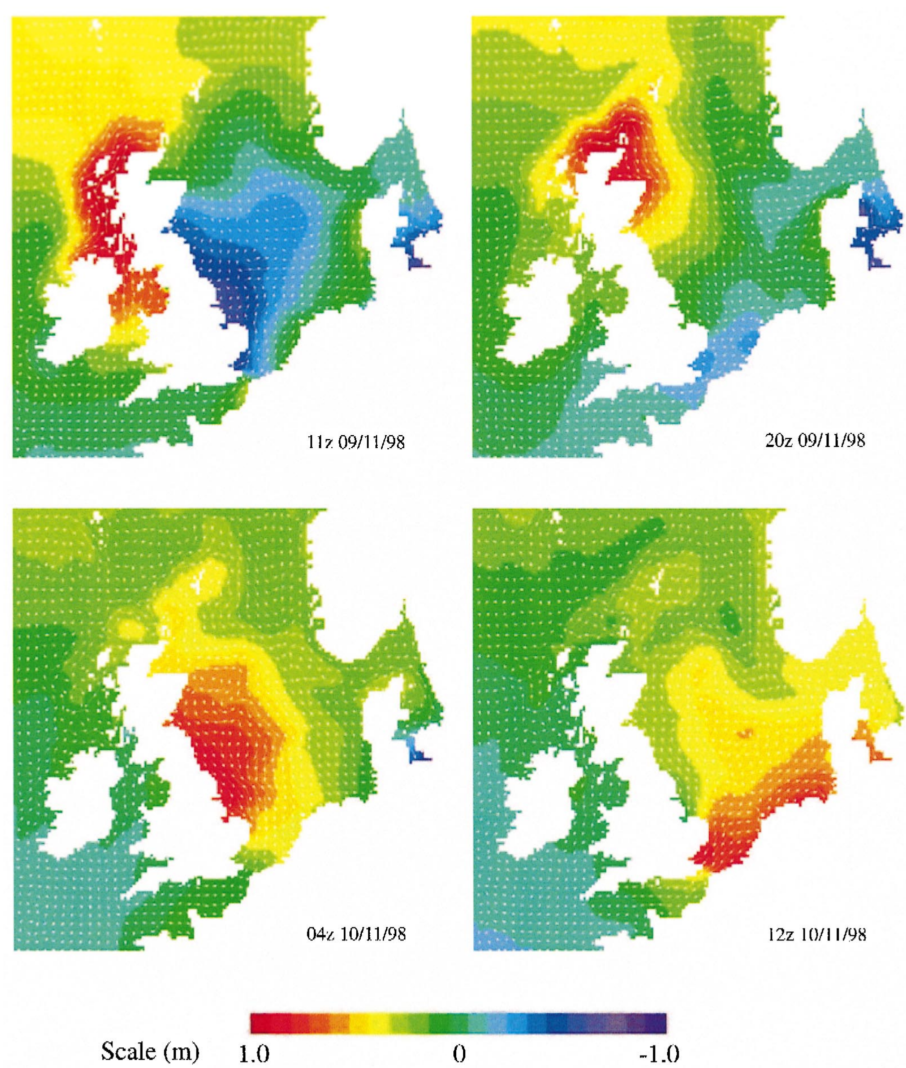

Fig. 9. A typical external surge event from the UK operational storm surge model archive, showing surge generation west of Scotland, followed by propagation around the north of Scotland and southwards along the east coast of England into the southern bight of the North Sea.

winds were too strong and the predicted surge was too small. In this case, the error was generated within the forecast, not from initial conditions, and reached coastal points within a short time. Such errors are difficult to correct. Even the most sophisticated assimilation schemes may be ineffective in such situations.

3.7.2. Waves

The UK Met. Office run a second-generation wave model based on Golding (1983) and updated by Holt (1994). The model includes shallow water physics (shoaling, bottom friction and refraction) in depths less than 200 m and is run both globally and regionally.

The global model is implemented on the same $0.833° \times 0.56°$ grid (~ 60 km in mid-latitudes) as the global numerical weather prediction (NWP) model which provides surface wind forcing, and assimilates ERS-2 radar altimeter wave data (using the altimeter surface wind speed). The model is run twice daily, from data times of 00 UTC and 12 UTC, and produces a 5-day forecast. The model runs take place at around 0430 and 1630 UTC. The time at which the latest forecast is produced can be an important issue for some applications, requiring the best prediction at a critical time.

The regional model covers the northwest European shelf, the Mediterranean, Baltic and Black seas, on a grid of $0.4° \times 0.25°$ (~ 30 km). This regional model is also run twice daily, at approximately 0230 and 1430 UTC, producing a 48-h forecast forced by winds from the preliminary run of the global NWP model and with boundary input provided from the previous run of the global wave model. This forecast is later extended to 5 days, using winds from the main global NWP run and boundary input from the new global wave model run when these become available. The regional model does not include data assimilation.

Both wave models provide gridded output of integrated parameters in the form of values of significant wave height, up-crossing period, and direction, for each of total sea, wind–sea and swell. The forecast wave energy spectrum is also an output. Applications include ship routing, offshore operations, coastal flood warning, and sea state-sensitive offshore heavy lifts. A recent development has been to link the predicted spectrum to a response amplitude operator (RAO) to predict the motion of a semi-submersible rig. A grid point archive of the frequency spectrum, starting from October 1986, provides data for design and consultancy studies.

Future plans are to introduce a version of the wave model on the same (~ 12 km) grid as the operational storm surge model. This will give a better definition of the coastline, and will also permit calculation of the effect of wave–current interactions on the wave spectrum. This version of the model is scheduled for operational implementation in 2000.

3.8. Ireland

Tides and storm surge models are not run operationally in Ireland.

3.8.1. Waves

Met Éireann run a version of the WAM spectral wave model on a 25-km grid covering the sea area around Ireland (48–57°N and 0–15°W). The model calculates the

2D wave energy spectrum in 25 frequency $\times$ 12 directional bins, covering wave periods from 2.4 to 23.0 s and giving 30° directional sectors. The directional bins are rotated by 15° relative to the coordinates to correct a numerical problem in the standard version of WAM causing artificial shadowing effects behind islands and headlands, (identified by P.A.E.M. Janssen). Wind forcing is provided by the Met Éireann version of HIRLAM (resolution is 33 km in space and 3 h in time). Open boundary wave input, essential to account for swell propagating into the area from the Atlantic, is taken from a global version of the WAM model run daily in ECMWF. Forecasts to $T+48$ h are run twice each day (starting at 00 Z and 12 Z), with initial data taken from $T+12$ of the previous run. Outputs are hourly integrated parameters (for the total sea state and separately for wind sea and swell) and six hourly 2D wave energy spectra. The model does not, at present, include tidal effects.

Verification is carried out against observational data supplied by the ERS-2 satellite, the UKMO array of moored buoys around Ireland, and observations from voluntary observing ships passing through Irish waters. Fig. 10 shows a comparison of ERS-2 altimeter wave heights with 24-h forecast results along the satellite track from the Met Éireann wave model during the period January 5–April 1, 1999. Generally, wave heights are slightly underpredicted (by about 10%), but the largest waves are not well forecast 24 h ahead.

Model results are used by forecasters in Met Éireann and made available through its Weatherdial system in a form tailored to the needs of fishermen, recreational users

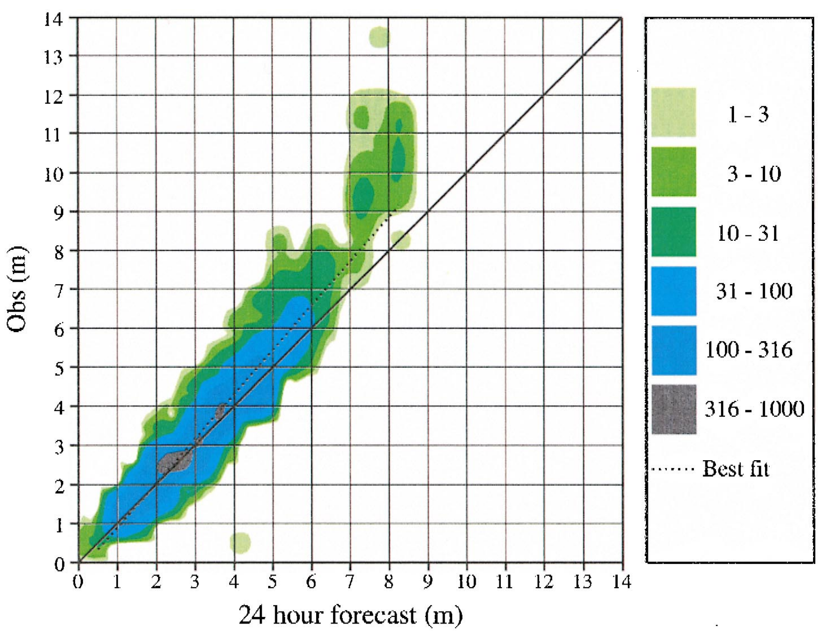

Fig. 10. Comparison of ERS-2 altimeter wave heights with model 24 h forecast results along the satellite track in the area of Ireland during the period January 5–April 1, 1999, showing good agreement with a slight tendency to underpredict.

(surfers) and others. For specific needs, spectral data are also provided in components (frequencies/periods), e.g. for use in oil rig operations where data at the rig's resonant frequency may be required.

3.9. France

3.9.1. Tides and storm surges

Météo France has developed a 2D storm surge model configured as a 'stand-alone' system to predict surges generated by tropical cyclones. Forcing is provided as a small number of cyclone parameters (position, intensity and size) using an empirical–analytical model. Systems are operational in the French Antilles, New Caledonia, French Polynesia and in La Reunion (Daniel, 1997). At present, surge models are under development for the coasts of France. The first, covering the Channel and Bay of Biscay (43°N–52°N, 8.5°W–4°E) with a 5′ latitude/longitude grid and open boundary input of 16 tidal harmonics, will be operational by the end of 1999. A second model for the Mediterranean coast will follow in 2000. The Météo France mesoscale atmospheric model will drive the models.

3.9.2. Waves

The numerical deep water wave model, VAG, runs operationally on the super computer of Météo France, producing daily forecasts over two domains: the North Atlantic (VAGATLA model) and the Western Mediterranean (VAGMED model). VAG is a second-generation 'coupled discrete' model, in which interactions between components of the wave spectrum are parameterised, derived from that of Golding (1983).

A new and improved 1° global version of the VAG model with nested 'zooms' for regions of interest, assimilation of wave data from the ERS-2 satellite, an enhanced propagation scheme, a sea ice mask updated daily and shallow water physics is now ready for implementation.

3.10. Spain

3.10.1. Tides and storm surges

The 'Nivmar' storm surge prediction system, developed and run at Clima Marítimo, predicts sea level for Spanish coasts. It is based on the HAMSOM ocean circulation model (Backhaus, 1985; Alvarez Fanjul et al., 1998) applied in 2D vertically integrated mode on a grid with resolution reducing to 1/4° in longitude by 1/6° in latitude. The model is driven by surface wind and pressure fields from the HIRLAM atmospheric model run by the INM (Instituto Nacional de Meteorología). Two runs are carried out per day, each consisting of a hindcast from $T-12$ to $T+00$ forced by analysed meteorological data, and forecast to $T+48$ h. Since the continental shelf is narrow, with shallow water confined to a coastal strip, atmospheric pressure effects dominate the sea level response to storms. Also because the water is generally deep, interactions between tide and surge components are weak and can be neglected. Thus, the model is used to predict the surge component driven by meteorological forcing only. Water levels are computed as the sum of model predicted surge and tide predicted using the harmonic method from analyses of data from tide gauges of the REDMAR network (Perez and Rodriguez, 1994). Predictions are stored and distributed via the Internet (http://www.puertos.es/Nivmar). Fig. 11 shows an example.

A more complete description of the system, developments in progress and future plans can be found in Carretero Albiach et al. (2000).

3.10.2. Waves

A wave forecasting system developed to predict waves at the coast is run on a twice-a-day cycle by Clima Marítimo. The system is based on two implementations of the WAM-cycle4 model (Komen et al., 1994): one for the Atlantic Ocean and one for the Mediterranean Sea. WAM provides boundary conditions for a high-resolution wave model of the Strait of Gibraltar based on WAVEWATCH (Tolman, 1991, 1992) and for a phase-averaged monochromatic wave propagation model, PROPS (Garci, 1996; Rivero and Arcilla, 1993). To provide high resolution close to the Spanish coast without resorting to high resolution in the deep ocean, a two-way nesting scheme for the WAM model has been developed and implemented at CM (Gomez and Carretero, 1997). For WAM and PROPS coupling, a new and efficient approach based on linear theory has been developed, providing solutions only at points of interest.

The system is driven by wind fields supplied by Oceanweather (OWI) and is designed to provide wave forecasts for ports on the Atlantic and Mediterranean coasts of

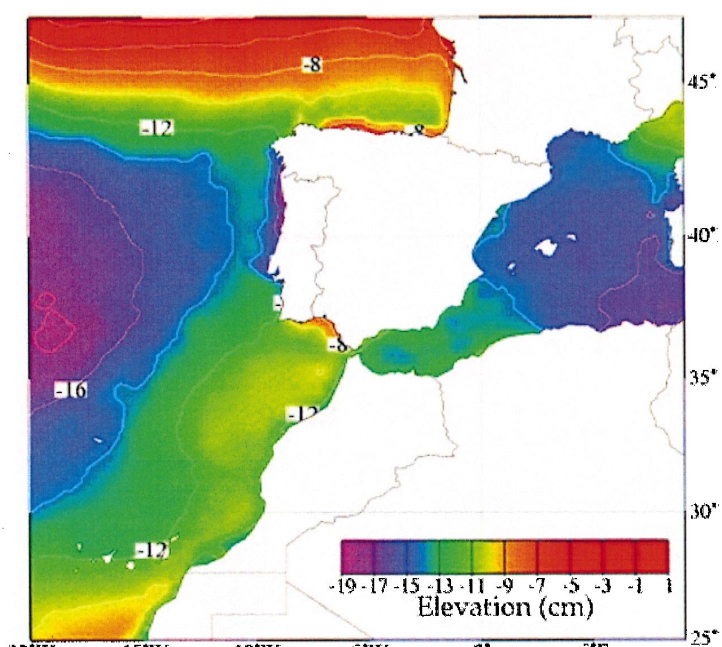

Fig. 11. Predicted surge residual at 0600 GMT December 8, 1999, produced by the Nivmar surge forecast system at Clima Marítimo. Note the rapid variation in surge on the narrow continental shelf.

Spain. Analysed and forecast wind and waves along with other information such as an alert system, real-time verification with measurements from the Spanish buoy network, etc., are available to the users through the WWW (access restricted to authorised users). See Carretero Albiach et al. (2000) for more details.

3.11. Portugal

There is, as yet, no operational model in Portugal. Models developed by Instituto Superior Técnico (IST), Lisbon, and applied in estuaries have all the necessary characteristics for being operational. This is a goal of IST in the project ‘OPCOM’ (http://www.hydromod.de/projects/). Portugal has tide gauges but no real-time transmission of data is carried out. Tidal harmonics derived from the observations is used as input data to run ‘pre-operational models’.

4. Discussion

The above overview of systems, which are actually operational early in 1999 for northwest and western Europe, shows a diversity of methods, models and approaches. Clearly, the operational systems in the different coastal states have evolved to address the needs of their own coastal and marine environments, taking account of relevant processes and dynamics, and employing technologies such as data assimilation, where appropriate, to best the advantage.

The main requirements for success are much as one would expect. Accurate meteorological forcing with resolution in space and time defining the important features generating and modifying surges and waves is fundamental. The UK experience shows that very small meteorological features such as secondary depressions or wave developments on fronts, can in some circumstances have a much greater influence on the accuracy of surge (or wave) predictions than might be expected. The response and general trend is to drive surge and wave models with forcing data from atmospheric models of higher resolution. Developments such as HIRLAM are clearly having a big impact, providing the key meteorological forcing at resolutions of 20–30 km for many systems, and with plans for further refinement.

Remarkably, despite the technological developments in hydrography and surveying, bathymetry (or its availability to those who need it) remains a major problem.

Variations in model physics mainly reflect different regional priorities determined by dynamics. For example, neglect of tides is acceptable and a useful simplification in some regions but would be completely inappropriate for others. Most surge forecasts are still produced by 2D models. These vary in formulation, even when applied to the same or very similar regions, e.g. including, or not, tide-generating forces, wetting and drying of intertidal areas, differing numbers of tidal harmonics, alternative formulations for the surface and bottom stresses, and so on. The 3D models, e.g. in Norway, Germany and Sweden, are mainly run to provide additional information such as currents vertical structure, and/or additional variables — such as temperature and salinity. Ice is important and must be taken into account in the Baltic and, for some purposes, in the Greenland and Norwegian Seas, since it constrains wave growth and changes fetch.

For waves, the WAM model, which incorporates more complex physics than earlier generations of wave model, is finding increasing use. It approximates the non-linear interactions responsible for redistributing wave energy in the spectrum and so makes no prior assumptions about spectral shape. However, it is not entirely without problems. Many of these, in particular those limiting its use on fine grids and coastal areas, have been investigated and solved in the PROMISE project (Monbaliu et al., 2000) and code updates are available. Another third-generation model, WAVEWATCH, is already used on a ~ 1 km grid for the Strait of Gibraltar by Clima Marítimo. Other improvements for waves can result from improved spatial resolution or increased resolution of the 2D frequency–directional energy spectrum. One question is whether better value is gained from running a simpler model at higher resolution than a more complex model on a coarser grid; i.e., is it better to use computer resources to improve physics or resolution?

Boundary inputs are another aspect in which there are variations even between similar models applied to the same region. For surges on the northwest European shelf, a hydrostatic assumption seems reasonable and is applied, e.g. in the Dutch and UK schemes. However, this does have some drawbacks, which are being addressed. One alternative, employed at BSH, is to use a large coarse-grid northeast Atlantic model to provide external surge input to a refined North Sea model. Some other North Sea models presently omit this external surge component entirely.

Real-time observational data also play a vital and increasing role: in improving model predictions by assimilation techniques; providing checks on model predictions; and as a basis for those responsible for warnings to assess their reliability. The data may come from networks of tide gauge and wave buoys or, for global and large scale models, from satellites. Many countries operate buoy networks and major operational centres receive satellite data. In many cases, data observed by one country or group would be useful to others, but the logistics, bandwidth of connections, compatibility of systems and formats, and issues of data ownership can inhibit exchange. Such issues are being addressed, e.g. in SeaNet.

A striking aspect of the final link — delivery of results to users in a format that suits their requirements — is the increasing use of the Internet. Many operational agencies provide subsets of the output from their operational systems via links accessible through their web pages; in some cases, access is ‘free’ and in others is restricted by password protection. Some examples are noted above.

Overall, it is clear that there are areas of common interest and overlap. For example, several countries operate models to predict storm surges and waves in the North Sea. This could be considered wasteful, offering scope for rationalisation, or healthy, offering potential benefits to all.

Taking the first viewpoint, larger-scale models meeting the communal need could be run by one authority and results transmitted to national (or regional) centres which could use these as boundary inputs for refined models providing the detailed information needed for their own vulnerable coasts. This looks efficient and would save computing time, etc. On the other hand, the networking and communications must be efficient and robust to ensure that the vital data would reach national users reliably, even during severe weather which could impact on power supplies, etc. Those responsible for running the models would be remote from the local needs of users who have important knowledge and experience of their own coast. So, overall cost savings may actually be modest.

Taking the opposite view, it could be argued that the diversity is healthy and could benefit all. The possibility of several more or less independent forecasts being available to those in national centres would be very useful, e.g. when the meteorological development may be difficult to predict. The degree of agreement or disagreement between equivalent forecasts from different systems provides an indication of the consequent uncertainty in surge or wave predictions, which would be valuable for those responsible for warnings and action to prevent damage or loss of life. Provided outputs are accessible to all, diversity can also imply robustness.

Speculating on future developments, the author is of the opinion that improved communication in all senses is the key. More accessible and open information on what is done, where, and by whom, such as summarised in this review, would be useful to all involved with operational systems. Operational systems change constantly, but a simple catalogue could be maintained, e.g. on the PROMISE web pages. More fundamentally, some concerted action to set up the exchange of model products between appropriate agencies would allow all to benefit from the existing diversity. This would encourage collaboration and dissemination of worthwhile techniques and system improvement. In time, sharing or rationalisation might result; though it seems unlikely that the agencies operating major centres with commercial interests and responsibilities for public safety would wish to concede their autonomy.

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