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Operational ocean modelling with the Harvard Ocean Prediction System

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Operational ocean modelling with the Harvard Ocean Prediction System

Operationeel oceanografisch modelleren biedt de mogelijkheid om voorspellingen te doen van de maritieme omstandigheden. Op basis daarvan kan de inzet van sensoren, personeel en materieel beter gepland en uitgevoerd worden. Dit rapport geeft inzicht in de werking en toepassing van een oceaanmodel dat door TNO gebruikt wordt.

Probleemstelling

Kennis van de omgeving is van cruciaal belang bij militaire operaties. In het geval dat de zee een rol speelt bij operaties, zoals bij vrijwel alle activiteiten van CZSK, is het noodzakelijk van tevoren te kunnen inschatten in welke mate de omstandigheden de inzet van materieel, sensoren en personeel gaan beïnvloeden. Operationele oceanografie behelst het verzamelen en integreren van metingen tot bruikhare informatie, en het doen van voorspellingen over die omstandigheden. In dit rapport beschrijven we één van de tools die daarvoor ter beschikking staan: een numeriek model voor de oceaan.

De werkzaamheden zijn uitgevoerd voor DMO in het programma V512 'Sonar en onderwaterpropagatie'.

Beschrijving van de werkzaamheden

TNO heeft de afgelopen jaren de ontwikkelingen hinnen de operationele oceanografie gevolgd, en heeft een actieve rol gespeeld bij oceanografische experimenten van het NATO Undersea Research Center (NURC). In nauwe samenwerking met een team van Harvard University (later Massachusetts Institute of Technology) is het Harvard Ocean Prediction System hinnen TNO beschikbaar gekomen. Dit oceaanmodel biedt de mogelijkheid op basis van metingen tot een beschrijving van de toestand van de oceaan te komen, en die te voorspellen. Met dit model is ervaring opgedaan tijdens de experimenten van NURC. Het oceaanmodel is gekoppeld aan ALMOST, waardoor naast oceanografische ook akoestische voorspellingen gedaan zijn.

Resultaten en conclusies

Het oceaanmodel is geïnstalleerd hinnen TNO. Dit rapport legt details van het modelleerproces vast, en de keuzes die in dat proces worden gemaakt. De lezer wordt inzicht geboden in de consequenties van die keuzes. In 2007 is aangetoond dat de gehele keten van het doen van metingen, het verwerken tot een totaalbeeld van de waterkolom in een gebied, en het doen van voorspellingen omtrent water en akoestiek thans tot de mogelijkheden behoort. Daarvoor is input van buitenaf nodig, zoals een goede weersvoorspelling. In veel gebieden is het nuttig te kunnen beschikken over een grootschalig oceaanmodel, dat de randvoorwaarden levert voor het in meer detail te modelleren operatiegebied. Hiermee is ervaring opgedaan, maar de infrastructuur om op korte termijn te kunnen voorzien in operationele voorspellingen is nog niet aanwezig. De samenwerking met MIT en NURC levert een nuttig platform voor een goede blik in de wereld van de operationele oceanografie. Zonder in Nederland alle benodigde kennis en infrastructuur zelf op te bouwen, heeft dit project handvatten geleverd voor verdere uitbouw van toepassing van operationele modellen binnen de Nederlandse krijgsmacht.

Voor snelle operationele voorspellingen is in veel gevallen inbreng van internationale partners nodig, maar de basis is gelegd om met kennis van zaken, en een op bepaalde terreinen unieke eigen innovatieve inbreng, deze partners tegemoet te treden. Hierop bouwen we voort in het nieuwe programma V931 'Omgeving en onderwater-beeldopbouw' dat in 2009 van start gaat.

Toepasbaarheid

De recente ervaring met oceaanmodellering kan worden ingezet om voor relatief kleine gebieden op hoge resolutie voorspellingen te maken van de oceaancondities. Met de verkregen inzichten kan worden gewerkt aan betere inschatting van de te verwachten prestaties van akoestische sensoren, en de inzetbaarheid van mensen en materieel.

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1 Introduction

For some time, TNO has maintained a close eye on operational oceanography. TNO follows trends and developments in this field, with a focus on the military context, by maintaining contacts with universities and research institutions nationally and internationally, and by collaborating within international experiments conducted annually and coordinated by the NATO Undersea Research Centre in La Spezia, Italy.

Operational oceanography comprises the observation, analysis, interpretation and prediction of the state of the ocean, with the aim of assisting users who have a stake in knowing their marine environment. For the seagoing parts of the armed forces, it is of prime importance to have information on the maritime conditions under which their missions are planned. It is for this reason, that military applications have long been important aims of the operational oceanographic community.

Integrating observations towards a description of the environment, and forecasting those conditions within the near future, is done in operational oceanography with the aid of computer models. These have many similarities to the models used for meteorological forecasting. To keep in touch with this scientific branch, TNO has chosen to build up and maintain the knowledge and infrastructure needed to apply one such model. The model used at TNO is the Harvard Ocean Prediction System, which was developed originally (during the cold war) at Harvard University with the aim of contributing to the anti-submarine activities in the Gulf Stream region off the American coast.

In close collaboration with the developers of this model, now housed at the Massachusetts Institute of Technology (MIT) in Boston, USA, TNO has contributed to the NURC experiments of 2003, 2004 and 2007. The contribution of TNO has grown from assisting the American team in producing their ocean predictions, through coupling of the HOPS ocean model to the acoustic prediction software ALMOST, to the independent setup of a complete flow from in-situ measurements to ocean forecasts and the acoustic predictions that are derived from those.

In this report we describe some of the basics of ocean modelling in general (Section 2), and specifically of the HOPS[1] (Section 3), and the TNO experience with operational modelling (Section 4). We concentrate on the different steps to be taken to go from the collection of in-situ measurements to the final prediction of environmental parameters (Sections 5 and 6). We also discuss military applications and the outcomes of ocean modelling in Section 7, and an outlook on future work is given in Section 8.

The coupling of ocean modelling with acoustic models such as ALMOST and the effects of range- and azimuth-dependent environmental information that is delivered by ocean models, are discussed in a companion report titled '*Range dependent acoustic modelling*' [1]. A broader overview of operational oceanography discussing also observations and operational applications of other models (such as wave models), can be found in a third report titled '*Operationele oceanografie en 'Rapid environmental assessment*'' [2]. We conclude this report by an outlook on future developments in ocean modelling. There we discuss possible improvements in the ocean modelling done at TNO itself, but also the steps that can be taken towards operationalization of the

[1] In 2008, the HOPS model has been incorporated in a new structure maintained at MIT: MSEAS.

capacities in this field, and towards making available its results to the Dutch armed forces. Thereby, we discuss how the present successful approach within V029, 'Onderwater Propagatie en Doelresponsie', will be continued within V931, 'Omgeving en onderwater-beeldopbouw'.

2 Introduction to ocean modeling

The ocean is never at rest. Gravity, the earth's rotation, and forces acting from the outside, primarily at the surface between water and air, are the main driving forces of the motion of the water. These outside forces include the winds, the incoming radiation from the sun, but also other weather related forces such as evaporation at the surface. Other effects are heating at great depths due to geothermal activity, and river inflow of fresh and relatively warm surface water along the coast. On a very local scale even human activities such as fortification of the coastline or construction of built objects in the sea may play a role.

When a forecast of the state of the ocean at some point in the future is required, one has to take into account at least the dominant effects. The physical equations describing the motion and properties of the seawater as a function of the dominant mechanisms are the Navier-Stokes equations. These equations describe -in principle- the motion and thermodynamics of the ocean at all scales, ranging from the basin scale at several thousand kilometres, to the smallest sub-centimetre scales of local mixing and individual surface waves. This all-inclusive nature immediately brings out the main weakness of the Navier-Stokes equations: they will only generally hold when all scales are included. They are so general that inclusion of all factors and scales quickly leads to an unsolvable problem.

2.1 Resolved scales and parameterization

Only with assumptions on the relevant scales in time and space, and parameterization of the important processes on other, unresolved, scales, the problem becomes treatable. A parameterization implies that one is able to predict the combined effect of the unresolved scales (often the smaller) on the resolved scales (the larger), without precisely modelling the smaller scales. One assumes that by knowing the larger scales, it is possible to quantify the effect of the smaller scales on those larger scales.

With knowledge of air pressure at two locations, one can make a statement on the average wind in the region between those locations, but not on the precise characteristics of this wind. One may be able to give the general direction and wind speed, but the precise characteristics of the wind cannot be given: near high buildings wind speed may be enhanced, whereas bushes may reduce the wind. The effect of both buildings and bushes on the larger scale can be rationalized as reducing the overall energy in the wind (by drag, as the bushes obviously provide), or as introducing a certain vertical mixing of momentum (as the building seems to bring some of the energy from above down to the surface). These effects can be modelled as somehow dependent on a parameter which could be called 'surface roughness'. In this parameter information on the smaller scales is converted to a number that can be used to describe the effects on the larger scales.

Parameterization is not a problem in itself. For a good local weather forecast the exact timing of a raindrop or wind gust need not exactly be predicted. As long as average wind speed, temperature and total precipitation are adequately modelled, most users are satisfied. Extra information on the character of the precipitation or the variability in the wind can in some occasions be useful, depending on the situation of the end-user.
For an ocean-forecast similar considerations hold: not on every occasion full

information on all phenomena is required. Depending on the situation and scenario, one can assess the scales on which one needs the information (both in time and space). The resolution of the prediction can be tailored to the required level of detail.

The exact formulation of parameterizations is, however, a complicated and often nonexact science. Parameterizations lead to a substantial list of numbers, for which the 'realistic' range is rather wide, and which can be set and adjusted according to the situation at hand. Experience and iteration are important in this procedure.

2.2 Resolution and area covered

A forecast for the state of the atmosphere or ocean is nowadays made using numerical models. Such models divide the atmosphere or ocean in small (usually rectangular) blocks with assumedly homogeneous characteristics. Choosing the size of these blocks, the resolution of the computational grid, implies determining the scales of the resolved phenomena, and thereby determining to which extend certain phenomena will have to end up in the parameterizations rather than being explicitly modelled.

Often, models at several resolutions are used. Lower resolution is then used for regions further away from the region of immediate interest, and resolution is increased towards this focal region. For weather forecasting on a European scale, the European Centre for Medium-Range Weather Forecast (ECMWF) uses a global model with a resolution of about 25x25 km. For the Netherlands, the Royal Netherlands Meteorological Institute (KNMI) increases the resolution of their forecast, and thereby the level of detail in the predictions within the Netherlands, to about 5x5 km. The higher resolution has only a regional coverage, but uses the results of the global ECMWF model along its edges.

For operational ocean modelling often a similar procedure is followed: a large region is modelled with coarser resolution, and higher resolution models covering smaller regions are placed within this larger model, providing higher resolution where necessary. The size of the total area covered by the model determines -in part- the forecast skill. When processes somewhat further away are adequately resolved, the forecast may stay reliable somewhat longer as phenomena at a certain distance may not be of immediate importance, but will likely be so in the foreseeable future.

Another factor determining the size of the region covered by a model is the availability of adequate measurements to assure that not only a larger region is covered by the model, but that also the phenomena present in that region are correctly represented in the model. We will come back to this issue when the initialisation of the model is discussed.

2.3 History of ocean modelling

The most widely used class of ocean models nowadays is that of the models based on methods of finite differences. On a fixed grid, the relevant physical quantities and their spatial derivatives are computed. From these, the time derivatives can be computed which allows for a small step in time to be taken. The length of this time step may vary between seconds or minutes for high resolution models used for operational oceanographic of meteorological purposes, to hours, days or longer for coarse resolution models used in climate studies. The resolution is the most important parameter in determining the time step. The length of the time step is important as it determines the number of steps needed to simulate the state of the system a certain period ahead. The higher the resolution of a model, the shorter the time step can be. The dependence on the resolution becomes not just squarely proportional (as the number of grid points over a rectangular region increases with the square of the number of points per kilometre). The proportionality involves a third power of the resolution, as the time step is roughly inversely proportional to the grid size. The computational resources available thus in part determine the resolution that can be obtained.

Bryan and Cox were the first scientists experimenting with ocean models of this kind, developed in the 1960's at the Geophysical Fluid Dynamics Laboratory in de VS [3,4,5]. At this institute similar models for the atmospheric circulation had been in use for some time, and the step to the ocean was a logical one, considering the degree of similarity in the physics of ocean and atmosphere.

Since this pioneering work, ocean modelling has quickly matured. With the availability of much more computational power, and quick progress in the area of theory and implementation of numerical schemes and parameterizations, ocean models have grown from experimental tools to full-blown ocean prediction systems. On various levels numerical models of the ocean are used, from global climate scenario studies, via seasonal weather forecasting and operational models capable of capturing the mesoscale (several 100 km) phenomena of the ocean, to very locally focused high-resolution models for detailed forecasting in specific regions. In this last category we find the most applications of the model used by TNO, the Harvard Ocean Prediction System (HOPS) developed over several decades at Harvard University (Boston, USA), and currently maintained and under development at the Massachusetts Institute of Technology (MIT), also located in Boston, USA.

2.4 Important remarks

The state of ocean and atmosphere can in principle be described and predicted by physical laws. However, the wide range of scales that is present, combined with the strong and complicated interaction between these scales limit the predictability of both atmospheric and oceanic systems.

Predictions are made with numerical models. These models resolve certain scales, and use parameterizations for the unresolved scales. The choice of parameters is not trivial and subject to subjectivity. This makes modelling and prediction a venue that requires skill, experience, and knowledge of each specific situation. There is no 'fits-all' solution or choice of parameters.

The size of the region covered by a model and the resolution of the model determine the computational load and thereby the time needed to produce forecasts. A small increase in resolution can strongly increase the time needed to compute a forecast.

The length of the period about which one can produce reliable forecasts is determined by the size of the region covered, the availability of measurements, and the local characteristics of the circulation. Knowledge of the local situation can be used to optimise the model setup and can be used to most effectively plan the number and locations of in-situ observations.

3 Harvard Ocean Prediction System (HOPS)

During the eighties, the Harvard group headed by prof. Allen Robinson created a model called the 'Harvard Open Ocean Model'. This name indicates its main area of use: in open ocean settings. This model was successfully applied to the Gulf Stream and its meanders and rings, during an extended observational and model analysis/verification campaign, consisting of seven real-time forecasting experiments. An early version of the HOPS model was then set up to provide nowcast and forecasts for the Gulf Stream position and the birth and reabsorbtion events of Gulf Stream Rings (see Figure 1). The model, then called the 'Gulfcast system', combined infrared sea surface temperature observations and altimeter derived sea surface height observations into a quasigeostrophic model (using simplified dynamics) [6, 7].

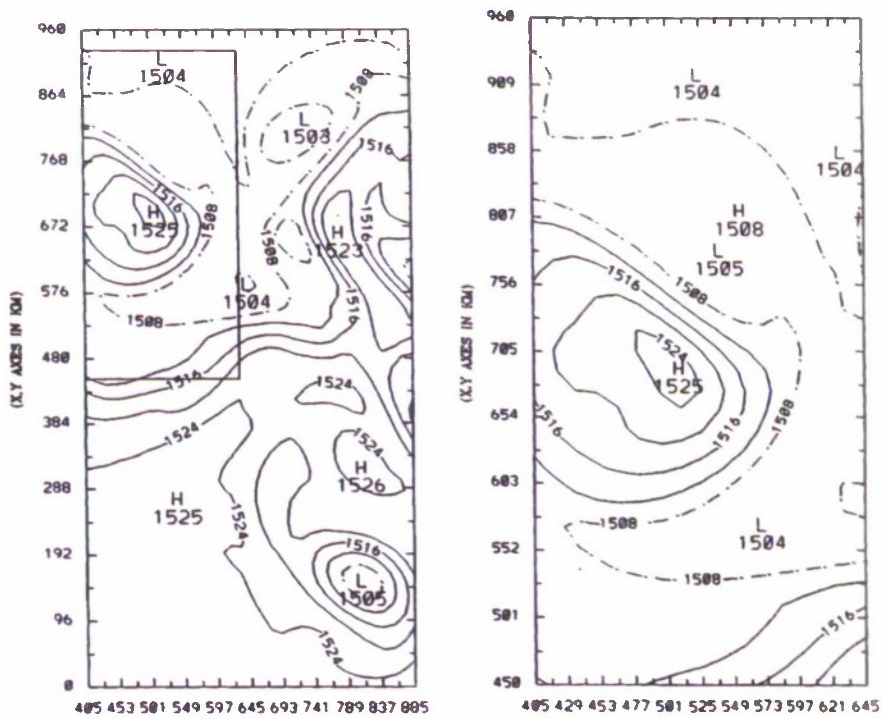

Figure 1 An example of sound speed at 120 depth for a 480 x 960 km area the Gulf Stream region (left panel), with a zoom in on the north-western part, containing a split off warm core Gulf Stream eddy north of the current proper.

Results from these campaigns were used to assess the acoustic implications of oceanographic phenomena in the Gulf Stream region, with application to anti-submarine warfare [e.g. 8]. The strong fronts in temperature found at the Gulf Stream and its rings and eddies were known to strongly influence the acoustic visibility of submarines. As is illustrated in Figure 2, the position of the Gulf Stream and its associated fronts is highly variable.

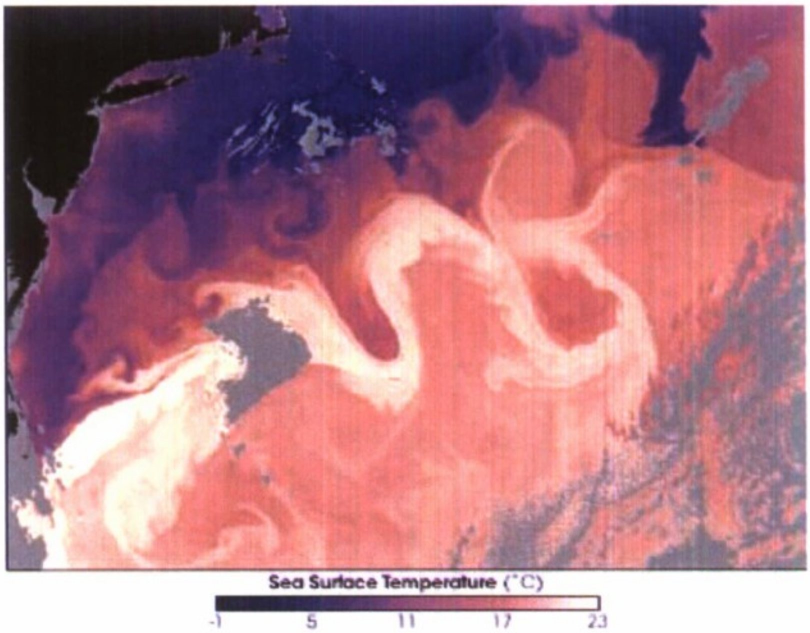

Figure 2 A snapshot of surface temperature on April 18, 2005, made by infrared measurements from a satellite. In the left side of the figure the US East Coast is visible. The Gulf Stream is clearly visible by its warm water content. The meanders and eddies of the current may inhibit the acoustic observation of submarines.

In the following years, this dedicated model was transformed into a portable forecasting system, allowing for quick setup in arbitrary locations. The model suite has a modular setup which allows for the attachment of biochemical, ecosystem, optical and acoustical components. Input and output has been generalized and conformed to the widely used and computer-architecture independent NetCDF format, which strongly enhances the ease of communication between different systems and allows for relatively simple assessment and exchange of the model output.

The HOPS suite of ocean modelling tools comprises not only a numerical model, but also separate tools to create ocean fields from irregularly spaced observations using so-called 'objective analysis'. These fields can then be used as a starting point for the model (as initialisation fields) or to keep the model constrained to observations during a model run (as assimilation fields).

A schematic of the interactions between different components of the HOPS modelling approach is given in Figure 3. The physical dynamical model is at the heart of this schematic, but the links between observations, applications and other component models are of prime importance to ensure proper embedding with other components and sources of information.

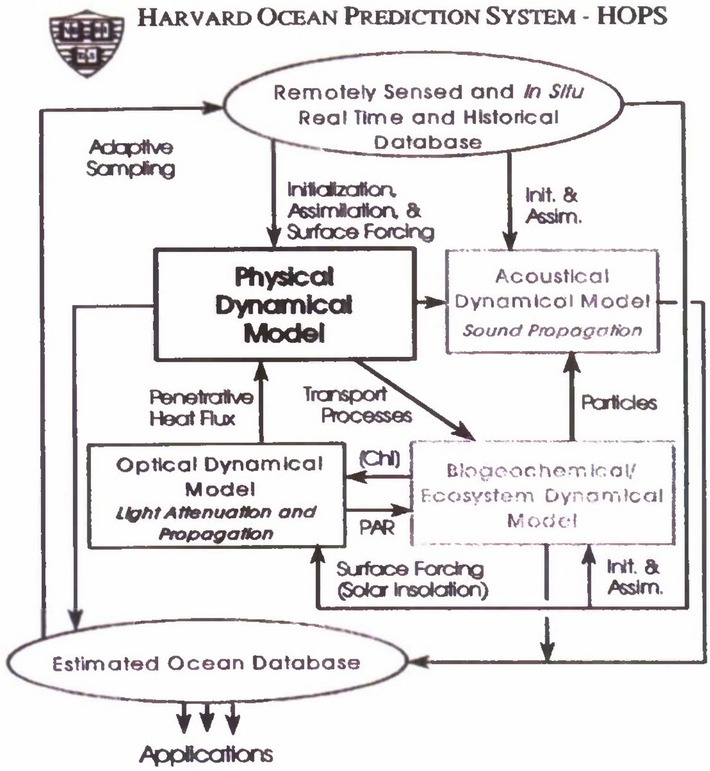

Figure 3 Embedding of the physical dynamical ocean model in a suite of model components, with links to observational systems and end-user applications.

The portability of the HOPS model is evident from its wide range of applications all over the global oceans. In Figure 4, an impression is given of the application regions, which range from a considerable part of the Southern Ocean in a Drake Passage model, to very small regions in the Mediterranean where very high resolution simulations of small-scale phenomena were produced.

These high-resolution local-scale models are the currently most often used applications of the HOPS modelling system. In civilian, scientific or military settings, but often in various combinations of the three, the model is implemented to assist in the investigation and forecasting of the local acoustic environment, evaluate and predict local oceanographic conditions, or predict the development and spreading of pollutants in or on top of (in the case of oil spills) the water. The focus has in many cases shifted from open ocean settings to the littoral, which provides the forecaster with often very different challenges.

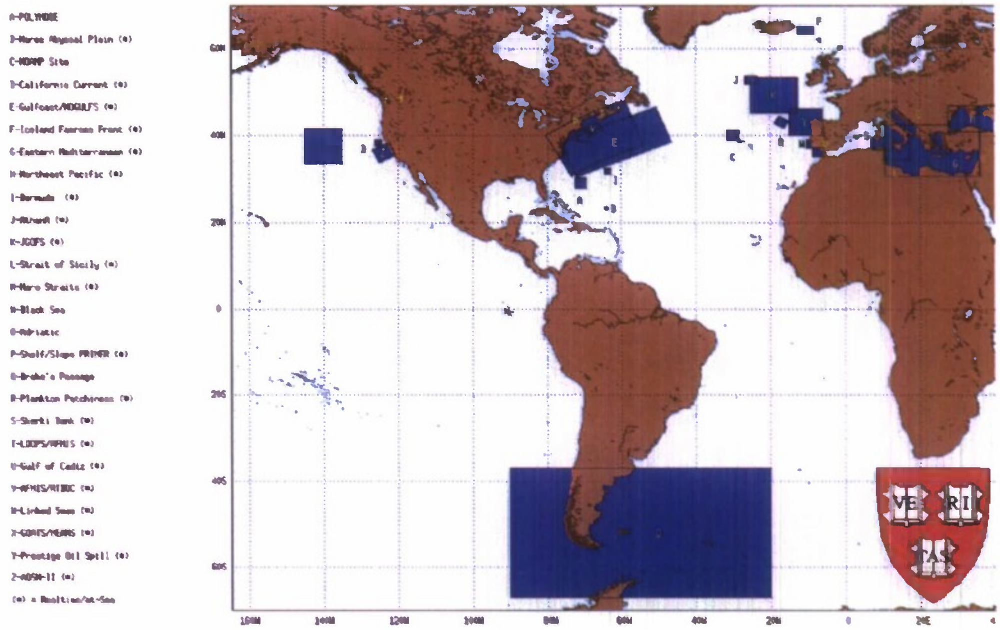

Figure 4 Map of a part of the globe, with the locations of recent HOPS-deployment indicated by dark rectangles. The vast majority of these applications were real-time forecasting trials, where data collected at sea was applied in near-real time to an operational model, providing forecasts a few days ahead.

4 TNO experience with operational oceanography

Within the last decade, TNO has had a continuous interest in operational oceanography with an emphasis on the use of operational oceanographic techniques in a military setting. In collaboration with the NATO Undersea Research Centre, the Netherlands Navy, and scientists based at Harvard and later MIT (both Boston, USA) TNO has participated in three recent sea trials focussing on Maritime Rapid Environmental Assessment (MREA). In 2003, the NATO/NURC coordinated trial MREA03 took place in the Mediterranean Sea near Elba, in Italian waters. In 2004, the MREA04 trial was held off the coast of Portugal in the Atlantic. TNO scientists took part in both of these trials. In 2005 and 2006 trials were held in the Adriatic Sea, but without TNO participation. In 2007, a strong Dutch contribution was made to MREA07, with the participation of HNLMS Snellius in the sea trial MREA07, again near Elba.
TNO participated in several components of the first part of the trial which was coordinated by scientists from NURC and the Royal Navy Academy of the Netherlands (KIM/NLDA, Den Helder).

4.1 MREA 2003: Northeast of Elba

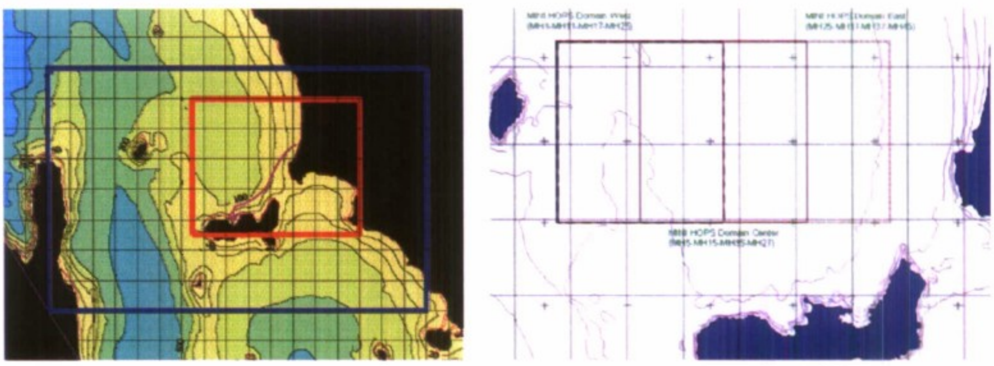

Figure 5 Model domains during the MREA 2003 trials. In the left panel, the mesoscale model domains are plotted in blue (Channel domain) and red (Elba domain). In the right panel, the three overlapping sub-mesoscale model domains of the west, central and east mini-HOPS models are depicted.

During the MREA 2003 campaign a multiscale model approach was demonstrated, with HOPS models at three levels: a channel model with a horizontal resolution of 1 km and a smaller Elba model at three times the resolution (333 m) were run at Harvard University. Nested within the Elba domain were three sub-mesoscale models with another zoom factor of three (111 m horizontal resolution), all of which are shown in Figure 5. The innermost models were run aboard the NURC vessel Alliance. TNO was involved in the operational part of performing the mini-HOPS model runs, and was present onboard Alliance with one scientist, who participated in the team of NURC/Harvard numerical ocean forecasters.

Other components of the interdisciplinary MREA03 trial included beach monitoring, surf forecasting, AUV operations to demonstrate covert beach reconnaissance capabilities involving mine burial potential, and high-frequency acoustic variability assessment.

4.2 MREA 2004: Southwest of Portugal

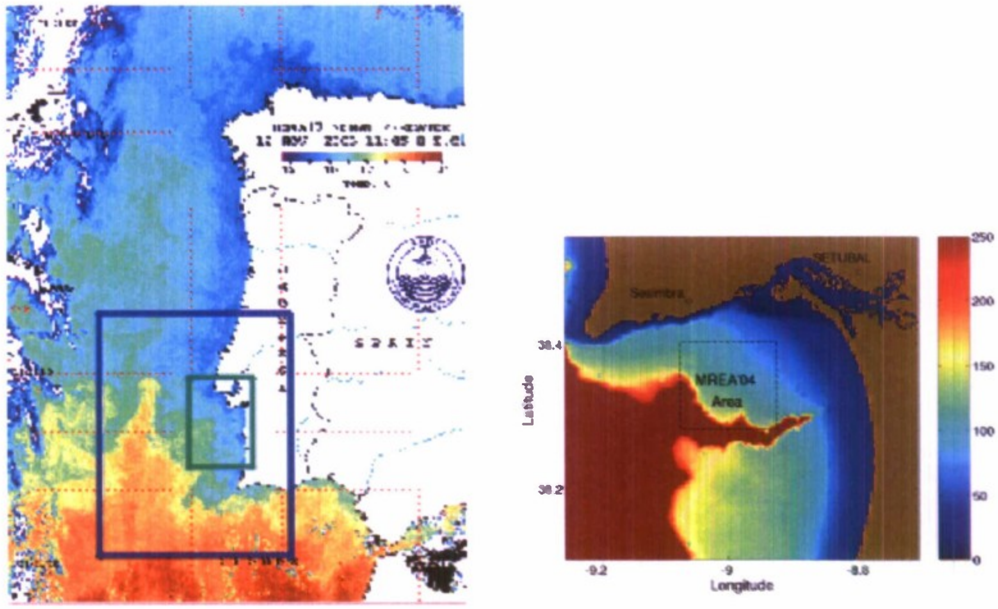

Figure 6 Overview of the region where the MREA04 trial took place in April-May 2004. The left panel shows a snapshot of sea surface temperature, with the mesoscale HOPS-model regions depicted in blue and green rectangles. The right panel shows a zoom-in of the bottom topography of the focal region of the acoustics campaign, which contained a steep underwater canyon.

During the MREA 2004 campaign, the TNO contribution went one step further in providing a link between the oceanographic modelling and acoustic modelling. An anti-submarine warfare (ASW) scenario was assumed and probability of detection for a submarine was modelled using the ALMOST package, which was linked to the oceanographic forecasts to demonstrate the temporal and local variability in the acoustics propagation and attenuation. TNO provided the trial-partners in near real-time with forecasts of the sonar performance, based on the ASW-scenario and the HOPS-forecasts of the mesoscale variability.

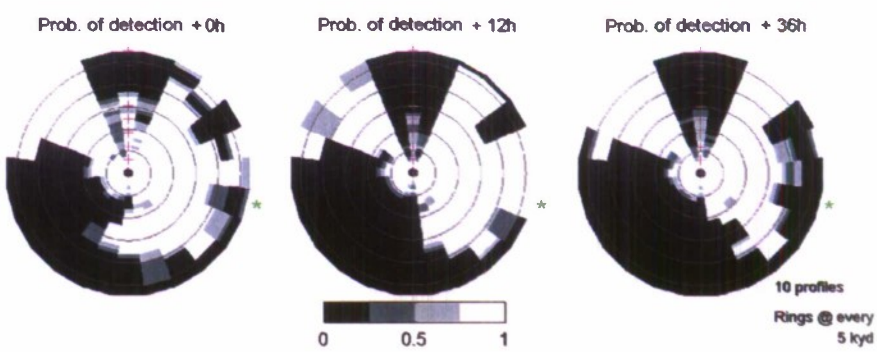

Figure 7 An example of two sonar performance forecasts from the MREA trial in 2007, East of Elba Island in the Mediterranean Sea.

4.3 MREA 2007: South of Elba

The most recent TNO activities with HOPS ocean modelling were within the MREA 2007 campaign, during which we went through the complete chain of data collection, initialisation of the model, forcing by output from high-resolution atmospheric models, data assimilation, and provision of (tactical) products to the partners within the trial. The HOPS model was now run on board the Snellius with support from the MIT team of developers [12].

The process is schematically shown in 8. In the first column, the chain of the meteorological modelling and forecasting is presented, from meteo-observations which are done globally, through the numerical models that provide weather forecasts which can be translated into tactical products. In the central column, a similar procedure for the oceanic products is presented. Input from the meteorological column was obtained through a wireless internet connection on the ship. The third column of this diagram is that of the acoustical assessment, part of which was done similarly within the MREA03 campaign.

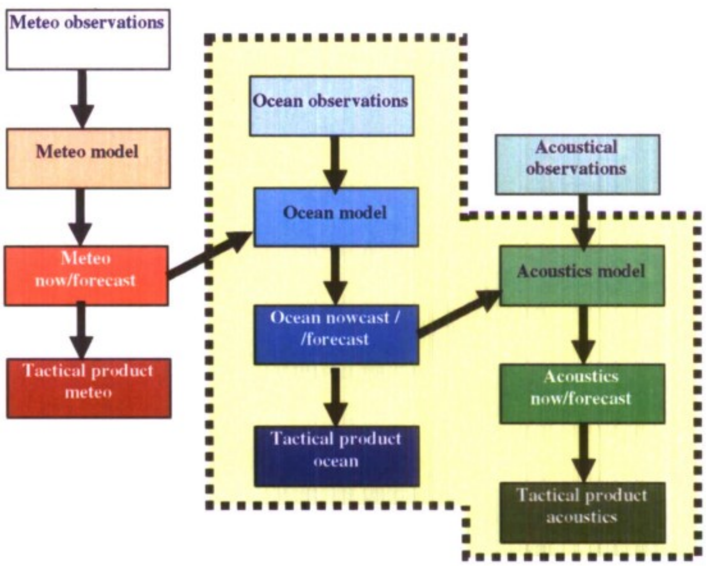

Figure 8 Process chain starting from observations of meteorology, oceanography, and acoustics, which, using various models, can be used to produce forecasts. These in turn should be converted into tactical products. The activities within the yellow box, were performed during NATO/NURC trial BP07 onboard of HNLMS Snellius.

Besides the modelling component of this trial, TNO contributed also by providing the trial partners with high-resolution sea surface temperature images acquired by satellite (an example of which is shown in Figure 10), by observing air-sea interface parameters relevant to the modelling of the optical instrument performance, and by providing a towed acoustic sub-bottom profiler (the X-STAR) which was used for bottom profiling close to the coast.

5 Anatomy and methodology of HOPS

In this part of the report, we will give a detailed description of the work flow associated with the application of HOPS. Starting with the selection of model domain parameters, grid definition and bottom topography setup (5.1), we then move to the collection of in-situ observations and inter- and extrapolation of the data to create model fields (5.2). The collection of forcing fields is a crucial component of the modelling effort, and is treated in section (5.3). The actual running of the model is treated in section 5 where also the application of assimilation data is discussed. The final analysis of the results is discussed briefly in 6. We also go into more detail of the analysis, and discuss the relation between model output and tactical products.

5.1 Grid and model domain

The first fundamental choices to be made when setting up an ocean forecasting system is the design of the domain and grid dimensions. As discussed before, there are several factors to be included in the decision making at this stage of the process, such as the user demands (for which purposes is the model intended; which scales and processes will have to be resolved?), the local, regional and possibly larger scale dynamics (dynamics of which area may influence the situation in our focal region, and on which timescales do we expect this influence to become important?), the availability of meteorological forecasts, and oceanographically observations (some of which may be available from third parties, others may have to be collected in-situ), and the available computing resources (which is rapidly becoming less of an issue as computer power is rapidly increasing).

Taking these factors into consideration, the vertical and horizontal grids may be defined. As the most important input, one needs an adequate description of the seafloor topography (bathymetry). On a global scale, such data are available on rather crude resolution (several km). For high resolution modelling, these datasets may not be accurate enough, and local high resolution datasets may be needed. As an example, during the MREA 2007 trial, several partners provided high resolution seafloor data, and datasets at four resolutions were compiled (see Figure 9). Adequate bottom bathymetry data are an important prerequisite for an ocean model, and are part of an early stage of REA/REP acquisition.

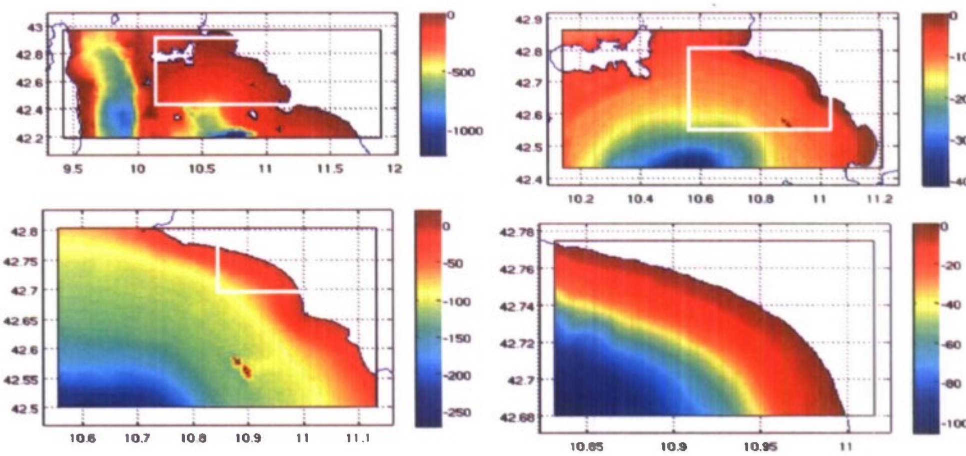

Figure 9 Increasingly high resolution bathymetry datasets for a region near Elba in the Mediterranean Sea, compiled for use during the MREA07 trial.

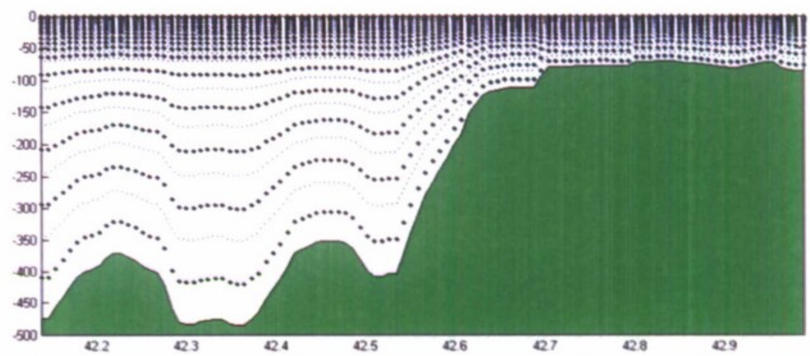

Figure 10 An example of the vertical grid of the HOPS model. The sigma-coordinates follow the bottom topography, providing higher vertical resolution in shallow regions, and a smooth transition towards the open ocean. In this case, a number of flat layers are defined in the top of the water column, to ensure adequate resolution in the mixed layer, even over deep regions.

With an available bottom topography dataset, a HOPS model grid can be generated. The procedure followed by the HOPS developers is described in some detail in their documentation, and is briefly summarized below. The process involves at least three steps, and several iterations of these steps may be necessary to develop a stable model. At MIT, considerable time and effort is put into grid development. This investment pays off during the operational use of the model, when imperfections in the model grid can lead to instabilities of the model. When such problems are prevented, their impact is smaller and at a more convenient time (preparation phase instead of the operational phase).

Grid extraction

The first step in grid generation is to extract a model bathymetry from the given bathymetric data. Given location, size of the domain, and the grid resolution, the program 'grids' extracts and interpolates depths at the horizontal locations.
With knowledge of the parameters used for the vertical grid to be created, the vertical layer positions are determined from these depths.

Land/sea masking
Secondly, an interactive routine 'PE_mask' is used, to fine-tune the coastline to the resolution of the model. A bay consisting of a single point may cause the coastline to be followed most accurately, but the model will not be able to simulate the currents within such barely resolved features. With the interactive tool, such points are removed by hand. Also, the in- and outflow at the model boundaries should be made such, that the coastlines are not blocking this inflow within the first or second row of points.
The coastline should be tuned such, that there are at least two water points in the direction of the inflow. Isolated ocean points, caused by interpolation or actual inland lakes should be removed at this stage.

Conditioning
As a third step, the topography should be checked for unreasonably steep bottom features. Given the model resolution, not all bottom features can be resolved. Too steep features often lead to instability and blow-up of the model runs. A Matlab script 'Cond_Topo' evaluates the steepness of the bottom topography, and smoothes where necessary.

With the model grid defined, the first tests can be performed with artificial or climatological data. It is highly recommended that such runs are performed, as problems with the model grid are best resolved before in-situ measurements are processed. Also, computational problems arising from the grid definition can be diagnosed and solved before more time-critical operations are commenced.

5.2 Preparation of ocean fields

To initiate the model, a starting condition has to be defined. The initial fields for the oceanic parameters (temperature and salinity, together defining density, but also velocity at all levels in the water column) have to be somehow defined from prior knowledge. There are several options from which to choose, all with their benefits and drawbacks.

When new data become available during the model run, this information can be used to improve the forecasts and bring the model closer to reality. The addition of new data is called 'assimilation'. This procedure comes down to balancing the model forecasted state and the observed data, and producing a 'best estimate' based on both.
Several techniques have been developed to achieve such best estimates; HOPS uses one of the more time-consuming techniques, with the benefit of producing smooth datasets, which make optimal use of the available information.

The initial conditions may be obtained
- from an earlier model run with the same model;
- from a different model;
- from climatological data;
- from synoptic data obtained by in-situ measurements;
- from synoptic data obtained by remote sensing techniques.

Some of the main differences are tabulated below. We will discuss them briefly.

Table 1

		Same model	Other model	In-situ observations	Remote sensing	Climatological data
Observables						
• Matching grid/coast/bathymetry?		yes	no	no	no	no
• Watermass parameters available?	(temp.)	yes	yes	yes	surface only	yes
	(salinity)	yes	yes	often yes	no	yes
• Velocities available?	(baroclinic)	yes	yes	yes	no	yes
	(barotropic)	yes	yes	no	No*	no
Data coverage / synopticity						
• Is the complete model region covered?		yes	yes	no	surface only	yes
• Are the data synoptic?		yes	yes	more or less	yes	no
• Are the relevant scales resolved by data coverage?		yes	depends	depends	yes	no
• Do the data agree with the real situation?		unknown	unknown	yes	yes	no

* To some extent, surface velocities can be deduced from altimeter observations of the sea surface elevation.

Matching grids/coastline/bathymetry?
When the same model is used to provide initial conditions, a major advantage is that the fields provided are completely consistent with the model. No further modifications, interpolations and interpretations are necessary, and all information can be one-to-one provided to the new model simulation. When other types of data are used, some or all of these steps may be necessary to translate the data into model fields.
A difference in grid-resolution requires interpolation or subsampling, subtle differences in the resolved coastline or bathymetry may lead to unexpected problems arising from extrapolation or removal of the original data. Several choices can be made regarding interpolation/extrapolation techniques, resolved scales and the level of smoothness enforced on the resulting fields. These choices strongly influence the results from the model run, especially when there is no spin-up towards an equilibrium model state.
In the case of high-resolution local modelling such as that usually done with the HOPS model, there is no complete equilibration and the runs often simulate a period of no

longer than a few days. The initial conditions are then of prime importance to the quality of the forecasted results.

Watermass parameters available?
The most important water mass parameters determining both the dynamics and acoustical propagation properties, are temperature and salinity. The quality of the observed fields (used for initialisation and later assimilation) for these parameters is a determining factor for the quality of the model predictions. When using model results as initial fields (either from the same or a different model), these fields are always available. When using observations, this is not always the case. The standard in-situ oceanographic observations are made using conductivity-temperature-depth (CTD) sensors, which measure profiles of these two quantities. Another frequently used means of observation is by expendable bathythermographs (XBT's), which do not measure conductivity/salinity. One may be able to reconstruct some of the salinity information using prior knowledge of the covariation between temperature, salinity and depth, which is related to the watermasses present below the surface, and the (seasonal) variations in the upper layers. Such reconstruction must however be done with great care.
Satellite remote sensing techniques can produce very detailed observations of the surface structures of temperature. Satellites, however, can not look below the water surface, and the surface information may only be representative of for a depth range somewhere between a few millimetres (in the case of surface warming during the afternoon for example) and a few meters (in the case of mixing by wind and waves. Observations of sea surface temperature (SST) have been successfully assimilated into ocean models, but such can only be reliably done when accompanying in-situ observations are available. These observations can give information on the status and depth of the mixed layer and the representativeness of the surface information for the near-surface layers below.
Remote sensing techniques capable of measuring salinity are not routinely available yet, although they may be so in the foreseeable future. Measurement techniques based on radar signature of the ocean surface are under rapid development although they are still in an experimental state.

Velocities available?
When using an initial field based on model results, the current velocities from these models can also be used to provide an initial state for the complete fields within the model region. Also, and more importantly, the boundary conditions along the edges can be provided. This is an important advantage over determination of the flow from observations, which are often limited along the edges of the domain.

Current velocities can not be directly measured by traditional oceanographic techniques. Acoustic Doppler current profilers (ADCP's) and current meters can be moored to fixed locations to provide time series of water velocity, and drifting buoys or floats can provide somewhat integrated measurements of the water flow. However, these observations are very local, and include all components of the flow, not all of which may be successfully reproduced by the model. Inclusion of such components may then destabilize the model run.

Baroclinic velocities are velocities that are non-uniform over the vertical extent of the water column. Examples are the major ocean currents such as the Gulf Stream and most other stable surface currents. They are strongest at the surface, and reach to several hundred meters depth, but not all the way to the ocean floor. Such vertically nonuniform velocities can be estimated when the density gradients (hence the distributions of temperature and salinity) are known. From observations, the baroclinic velocities may thus be determined. Variations in the baroclinic flow are seen on the somewhat slower timescales of several hours and days to years.

The barotropic velocity is the velocity component that is constant over the water column[2]. The most important example of barotropic currents are the tides.
Also tsunamis, and the first adjustment to changes in external forcing are associated with barotropic flow. Tidal and other barotropic currents are experienced throughout the water column. The timescales associated with barotropic currents are much shorter than those associated with the build up of baroclinic flow, and are expressed in minutes and hours.
Estimating the barotropic component of the flow from observed data means solving an underdetermined system of equations, which implies a large uncertainty of the outcomes, and an important role for fine-tuning and outside information.
Here, knowledge of the oceanographic setting around the region of interest is crucial. When in- and outflow through the edges of the domain are to some extent known (e.g. the total transports) these can add constraints to the determination of the barotropic flow. We will come back to this in the subsection on the production of oceanographic fields for initialisation or assimilation.

Data coverage, synopticity and representativeness
In Table 1, four bullets are given on data coverage and synopticity. As these four are very much interrelated, we discuss them together. Ideally, one would wish to have a snapshot of the complete circulation as it is in reality, with a resolution covering the full spectrum of scales resolved by the model. In practice, no such thing is available.
Data coverage is ideally over the full vertical and horizontal extent of the model domain. By synopticity of the data we denote the degree to which the data represent a single moment in time. By representativeness, we denote the agreement between data and reality.

Model results (from the same or a different model) can give a snapshot, but the portrayed situation need not resemble the truth very accurately. Model output can be very useful, but it can not provide estimates of how close to reality the output is.
The grid resolution and dynamics of the model where the output originates put a limit on the resolved scales, but at least this limit is well known. So coverage is good, synopticity is very good, but representativeness is very questionable.

In situ observations made from a ship or other moving platform give a very accurate description of the ocean at a certain location at a certain time. The spacing between observations puts a limit on the scales resolved, and the region covered by observations is often limited by the available ship time. The synopticity is compromised by the time it takes to acquire a full dataset. Observations made by a ship can take hours or even up to several days or weeks. When compiling a dataset takes several days, a daily cycle, which is often found in, for example, the surface temperatures, is not resolved and may lead to unrealistic features: temporal variability on timescales shorter than the observation period will map into erroneous spatial variability when the dataset is assumed to be synoptic.

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[2] This definition is somewhat simple, and does not cover the physical meaning of the barotropic component completely. A complete explanation is given in [13].

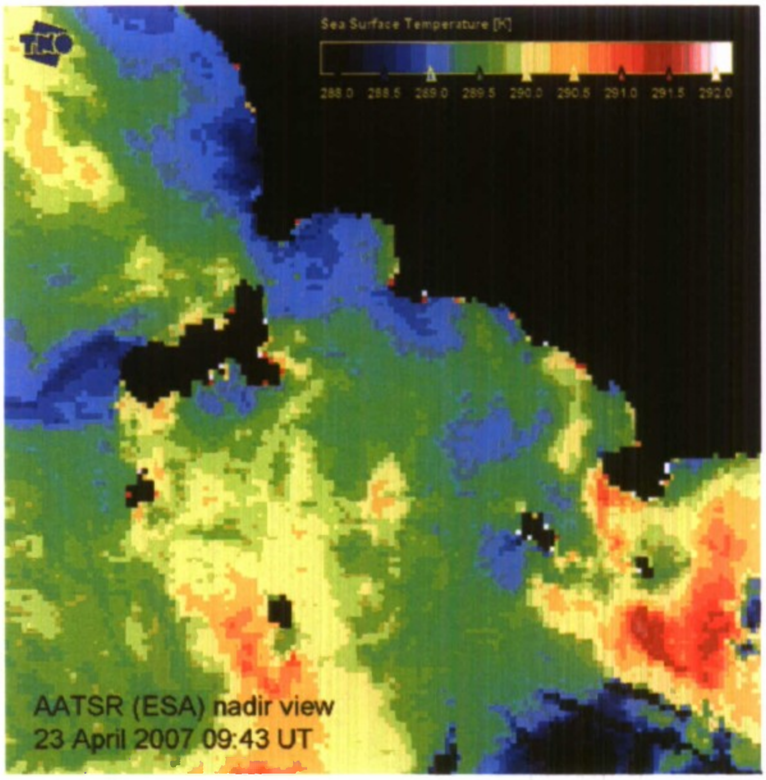

Figure 11 Example of an SST snapshot of the sea surface temperatures near Italy and Elba. The region shown here is about 100x100 km, and small scale features of about 1 km are clearly resolved.

Satellite observations (mostly of sea surface temperature, see Figure 11 for an example) offer very good synopticity as they form a true snapshot of the ocean. However, only the surface is portrayed and the representativeness for anything below the upper few mm is unclear without further information. With limited ground truth in-situ observations, however, the fields can add strongly to the level of detail that can be provided to the model, and thus strongly enhance short-term predictions.

In practice, usually a combination of the above techniques is used. For example, one could use in-situ observations for the larger subsurface structures and mesoscale variability, use an independent model of a larger region for the boundary conditions on the total transports, and include SST satellite information to enhance detailed representation of surface structures and fronts. Such combination of different data flows requires careful balancing of the relative weights of each, good quality control (as especially satellite images may contain outliers due to processing and clouds), and careful examination of each of the individual datasets and their compatibility.

5.3 Generation of ocean fields for HOPS

Ocean model fields for the HOPS model are created in two steps. First, the available data are interpolated and extrapolated onto the model's horizontal grid points. At depths chosen by the user, complete fields for temperature and salinity are constructed.
Next, from these interpolated fields, a vertical interpolation is performed onto the model levels. From these model grids of temperature and salinity the initial velocities are computed.

Objective analysis
The horizontal interpolation is done with an 'optimal interpolation' or 'objective analysis' scheme, which is an application of a technique known as 'kriging'. Optimal interpolation is optimal in the mathematical sense that knowledge is assumed of the true scales that are to be found. The downside of this method is the high computational burden and the involved computational time, which may take up to several hours for a set of complete fields. Based on these scales, the decorrelation distances in both directions can be estimated. A decorrelation distance of 10 km, for example, implies that a measurement is able to tell you something about a region with a 10 km radius. Beyond that radius, the measurement point has little meaning as prior knowledge tells you that the scales in the region are about that size. With knowledge of the decorrelation scales, we can compute the 'optimal' value for each grid point by weighting the measurements. The closer a measurement is, the more weight it is given.

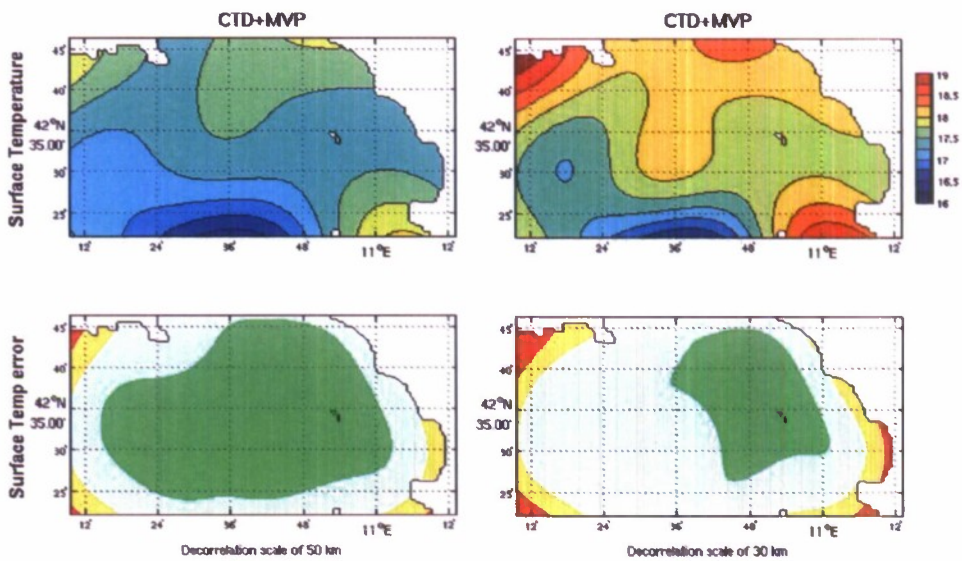

Figure 12 The influence of the decorrelation scale is illustrated here by an example from the BP07 trial near Elba island (upper left of the maps). The upper two panels show two realisations of an optimal interpolation of the available initialisation data, interpolated with decorrelation scales of 50 km (left panel) and 30 km (right panel). The smaller decorrelation scale clearly permits somewhat sharper gradients. In the lower two panels, an estimate of the interpolation error is given for the two interpolations. The region with low estimated error (which means that it is well-sampled, denoted by green colour) is much larger in the case of larger radius of assumed influence of an observation point. The observations are concentrated in the north-eastern part of the domain.

The decorrelation scales are estimated both in time and space. It can be intuitively understood that a measurement very close to a grid point, but measured rather long ago, may be given less weight than a somewhat further located measurement obtained just minutes ago. An investigation of the dominant processes in the model region can give valuable information on how to choose the decorrelation scales for time and space. However, one is usually strongly limited by the available data: when measurement points are sparse, a very small decorrelation scale will not lead to more detail in the interpolated result. On the other hand, when a large decorrelation scale is chosen, a very high resolution dataset may be strongly smoothed. An example of the effect of changing decorrelation scales is shown in Figure 12 where the initialisation data from the BP07 trial in May 2007 were interpolated using different length scales for the spatial decorrelation. With a realistic estimate of the scales present in the region under investigation, one can use the interpolation error to assess the adequacy of the observations in different parts of the domain.

In HOPS, the horizontal interpolation using the objective analysis technique is implemented in the program OAG, (Objective Analysis – Global) which does a global inversion of the data. This can be used when the number of data points is not too large, and computing power and time is not a limiting factor. When OAG is too slow or memory demanding, a local approximation of the objective analysis can be used. The program OA is very similar to OAG, but uses data points restricted to a user defined radius around the grid point in the inversion. This can speed up the process considerably. When the model region is well covered by measurements, and the horizontal decorrelation scales are small compared to the 'looking window' of the approximated OA, the difference in the results is negligible. In other cases, the differences may be considerable.

Vertical interpolation and velocity estimation
When the horizontal fields are ready they should be checked to capture the dominant variability in the vertical. In the top of the water column, the mixed layer will have to be present with much more detail than the deeper layers. In many cases, more than half of the levels are in the upper 100 m of the water column, and many of those in the upper 30 m. The definition of these levels is best based on a critical examination of the data that goes in: when CTD-profiles are processed, one should first analyse the temperature/depth and salinity/depth profiles and identify the critical levels where information should be maintained. A good method of checking this afterwards, is by plotting the original T/S diagram (an example is shown in Figure 13), and overlaying this by the T/S points taken from the interpolated dataset at the locations of the CTD stations.

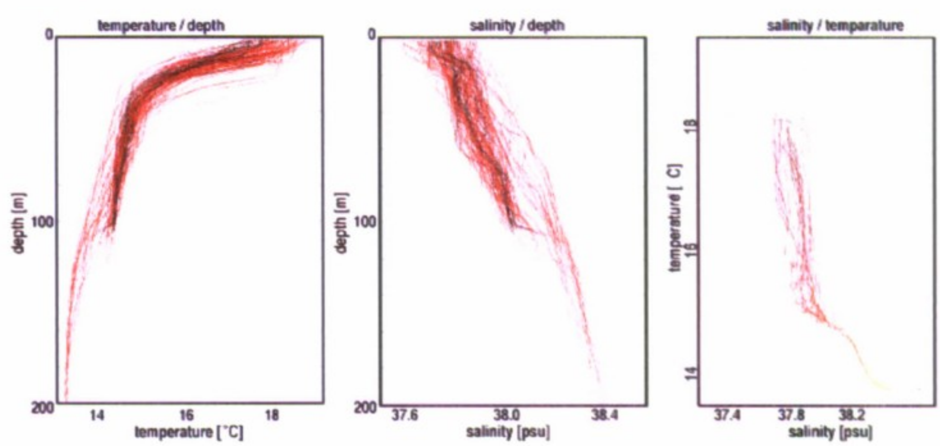

Figure 13 CTD profiles collected during BP07. (Left) Temperature vs. depth. (Centre) Salinity vs. depth. (Right) Temperature vs. salinity.

When a satisfactory representation of the data is given by the horizontally interpolated fields, the vertical interpolation at each grid location to the local terrain following coordinate levels is done by the program PE_initial. Velocity fields are then computed using geostrophy. The barotropic component of the velocity is not defined by the observations, and further information is needed here. First, one has to choose an initial 'level of no motion' where the ocean is assumed motionless. In many cases, this level is assumed to be at the bottom, but in general no single level is realistic, and it is best to try several levels, compare surface fields for the resulting solutions, and run the model

to check whether strong adjustment in the beginning of the run is needed.
Strong adjustment is seen in the beginning of the run as a large number of iterations is needed for the barotropic velocity solver. When too many iterations are needed, the solution (when one is found) is clearly too far from the estimated initial condition, and the initial condition may best be changed. Changing the level of no motion may in some cases solve such issues.

5.4 Collection of forcing fields

The ocean is forced by fluxes of momentum (by wind stress between the atmosphere and the ocean), heat (as the sum of incoming and outgoing radiation) and freshwater (as the difference between precipitation and evaporation). All these fields have to be provided from meteorological models or climatology, interpolated to the model grid, quality controlled and combined into a forcing format that the model can use.
This requires considerable preprocessing of the forcing fields (combining the fields into the three integrated fluxes of momentum, heat and freshwater).

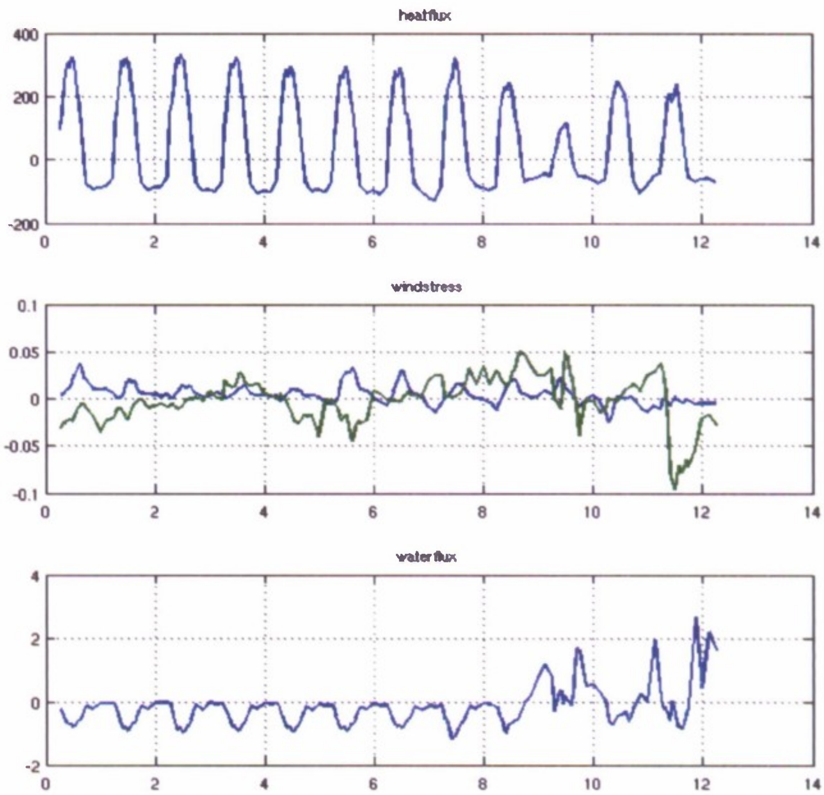

Figure 14 For the BP07 sea trial, the surface forcing in the middle of the domain is plotted. The daily cycle clearly shows warming (positive heat flux) during daytime (with accompanying evaporation visible as negative water flux). Towards the end of the series, some showers are seen as positive freshwater fluxes, and reduced solar heating during the day. The wind stress is depicted by the two components (eastward and northward wind stress in blue and green).

The preprocessing has to be done outside the HOPS model, and is dependent on the format in which the data are delivered. Standard formats for meteorological models are the GRIB and NetCDF formats. For both, several tools are available to read, select and process flows of information.

Special care has to be taken with the land/sea mask of the meteorological model. In most cases, the meteo-data are on a coarser resolution than the ocean model, and in most cases, the grids are very different. In the translation between the meteo and ocean model grids, one should be careful not to use data that are over land in the meteo model, and apply them to the ocean model. The interactions between land and atmosphere are very different from those between ocean and atmosphere, and careless translation of the meteorological data may lead to unexpected and wrong results near the transitions between land and water.

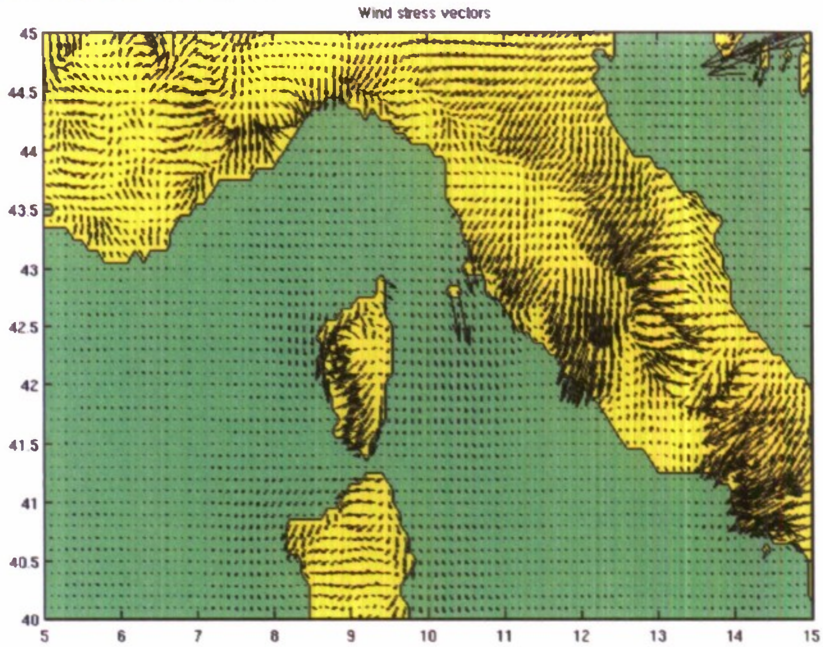

Figure 15 An example of the wind stress vectors (April 15, 0300 AM). As can be seen here, topography (see e.g. the mountains on Corsica and the Apennine Mountains in central Italy) and the transitions between land and sea (e.g. Elba and the northern tip of Corsica) are important regions for the wind stress. These stresses, however, are relevant only from an atmospheric perspective, as they occur between air and land. For oceanographic application, the forcing of the model should not be contaminated with these land-effects.

This is most clearly seen in the case of wind stress data. As the wind over the ocean is relatively free to move, stresses between the atmosphere and the ocean are relatively low. When the wind blows towards the coast, it is blocked by the landmass which stands out above the water. Strong stresses occur due to this blocking. Wind speed may be similar, or become smaller above land, which is not so for stress. This stress, however, is between atmosphere and land, and not between atmosphere and ocean. For the atmospheric model, the difference is not very relevant, but when these strong stresses are applied to an ocean model, strong effects near the coast will arise. An example of wind stresses in the Mediterranean region west of Italy is shown in Figure 15, where the blocking effect of the landmasses is clearly visible. One should carefully remove the wind stress grid points that are modelled in the meteorological model as 'land', before interpolating the fields to an ocean grid.

Similar effects are seen for the various components of the heat- and freshwater fluxes, which behave very differently over water and land. An example of all components of the fluxes is shown in Figure 16.

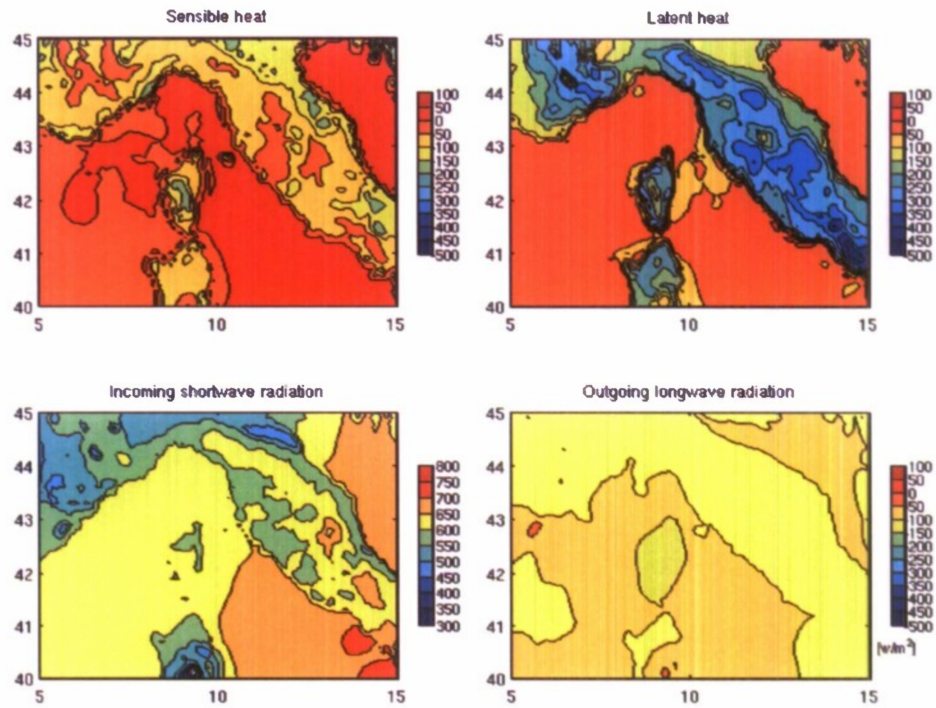

Figure 16 The four components of the heat flux. The incoming and outgoing radiation are related to sunshine warming the ocean surface and the water radiating with its surface temperature. The Sensible heat is related to the temperature difference between water and atmosphere, and the latent heat flux concerns the energy that is released when surface waters evaporate. Clearly, the land and water masks are important, as all of these components strongly differ between land and sea.

Once well-behaved forcing fields have been compiled, they have to be transformed into a single forcing file, in the HOPS familiar NetCDF based file format. This is done by the HOPS program PE_forcing. In the input file to this program, a conversion factor may be given to change between whatever units were used by the meteorological model, and the units assumed in HOPS. It takes no explanation that these conversions should be done carefully, as large errors can be generated which may go unnoticed for quite some time, when e.g. the heat fluxes are a factor of 100 too small. Another notable point is in the definition of the air/sea fluxes of heat and freshwater: positive values may be from atmosphere to ocean from an ocean perspective, but a meteorological model may well use the reverse perspective.

6 Running the HOPS model

In this section, we describe the actual running of the model: from the processed field and the external forcing, new fields at future time steps can be derived. During the run, some parameters of which are treated in 6.1, new data can be used as assimilation data, to keep the model constrained to the observed situation. We discuss assimilation in 6.2. In 6.3, the model setup is discussed for the situation when nested grids are employed.

6.1 Run parameters

When an initial field has been generated, and forcing fields have been compiled, the model can be run. Numerical ocean models can go from one ocean state to another, by evaluating the trend for the active parameters at each location. This trend is a function of the state of the ocean at the location itself, and in locations around it. The forcing from the outside (at the surface and possibly the open boundaries) adds to these trends.

The trend is considered to be constant for a small period in time. By adding the trend multiplied by this small time step, the model goes ahead in time. The trends are then evaluated again, and the process is repeated. The time step for a high resolution model is measured in seconds. For the HOPS model, with a typical resolution of a (few) hundred meters, time steps are in the order of 30 seconds. To simulate one day, thus takes 2880 time steps.

The number of time steps, and the length of a time step, are some of the important parameters to be chosen when running a model. Other important parameters include:

- Basic diagnostics. How often should output be generated? Which output should be saved, for which levels, locations and time steps? How often should complete fields be saved? The latter cannot be done too often as it leads to huge output files, but a complete model state is needed to restart the model when new data become available. Also, when it is as yet unclear which output are needed for further analysis, one may need to resort to the full fields.
- Which fields should be diagnosed? Standard output fields include temperature, salinity, velocity, and sea surface height. Other possible parameters include different components of the velocity and energy terms.
- Special diagnostics. Should sampling instruments be simulated? Drifters can be added to the model, which then are evaluated at each time step, so that the most accurate description of their trajectory can be simulated. Also, at discrete locations moored instruments can be simulated, with profiles or point-measurements being saved at specified intervals.
- Horizontal mixing parameters. Mixing of tracers (e.g. temperature and salinity, but also user-specified tracers or biologically active tracers can be added) can be modelled using several mixing schemes. Mixing of momentum and vorticity is modelled likewise. For each, the mixing scheme and associated parameters have to be specified.
- Vertical mixing and mixed layer depth parameters. In the vertical, also momentum and tracers are mixed. Various options for the vertical mixing schemes are available. These are important parameters as to adequately simulate the mixed layer processes and formation. The mixed layer depth is determined by the stratification, but also by the effects of wind and waves. Minimum and maximum mixed layer

depths can be set, as well as the parameters which relate the mixed layer depth to these determining factors.

- Friction along the boundaries, coast and bottom. Coastal friction, other than that introduced by the no flow condition which is implemented at the coast and propagated into the basin through horizontal mixing of momentum, and bottom friction can be used to control the flow over and through shallow or narrow passages.
- Boundary conditions. Along the boundaries of the domain which are not blocked with land, the interaction with the rest of the ocean is modelled through boundary conditions. For tracers, velocity, and total transport, the boundaries can be set as closed, provided for in the boundary data files, or one of several radiation conditions which allows waves and other variability to leave the domain without being reflected at the boundaries.
- Biological models. HOPS can be attached to several biological models, to produce forecasts of primary production, fish populations, different types of plankton concentrations, and biological tracers such as nitrates.

With all parameters chosen (and most of them do not change between model runs), the model input file further needs the locations of the preparatory files to be read (initialisation fields and forcing fields), and can be started. As a time step takes anywhere between less than a second and several seconds, the timescale for a typical run comes down to several hours.

6.2 Data assimilation

A way of keeping the model in touch with reality, is by periodically adding, or assimilating, new data. When observations are available for a period that is somewhere during a model run, these data can be processed into data fields very similarly to the preparation of initial fields. The fields will have similar accompanying error fields, which are then used to determine the degree to which the data are weighed with respect to the model prediction: when for a certain moment a good observation is available, at a location close to a grid point, the assimilation data set will have a very small error value there. In that case, the information of the assimilation field weights in rather strongly, and the model is 'pulled' towards this observed value. When data is further dislocated in time or space, the error becomes larger and the effect on the model state becomes smaller.

Figure 17 contains an example of the data acquisition, and part of the model run scenario used in the 2007 Battlespace Preparation sea trial near Elba, Italy. Along the bottom is the time line of the trial. The light grey blocks denote observation periods, during which data fields are observed using CTD and other techniques. From these observations, one initial field was formed with heavily smoothed features. As the initialisation period was about a week long, this smoothing was required to prevent artificial structures to be caused by daily and short timescale variability.
To regain a more detailed ocean structure, the model was run from this initialisation field for the full length of the initialisation period (model runs are denoted by the darker grey blocks). During this initialisation run, subsets of the first dataset were added as assimilation fields, but now processed with different decorrelation scales: a much shorter decorrelation scale was used to select only the observations within a specific period, and a much shorter horizontal scale was used to limit the effect of the assimilation data to only those regions where the observations were in fact obtained.

Using this procedure, applying the same observations twice but processed very differently, several benefits were gained. The model could be started with a relatively smooth field, nonetheless based on the actual vertical stratification and some of the larger features of the general circulation present. This was necessary as the other model data that were available, which could potentially have been used for initialisation, were too far off the in-situ observations (temperature differences of over 1 degree Celsius were common) for a combination of the two to be permitted.
The second application of the initialisation data is to constrain some of the smaller scale features within the region of strongest interest to the actually observed situation.

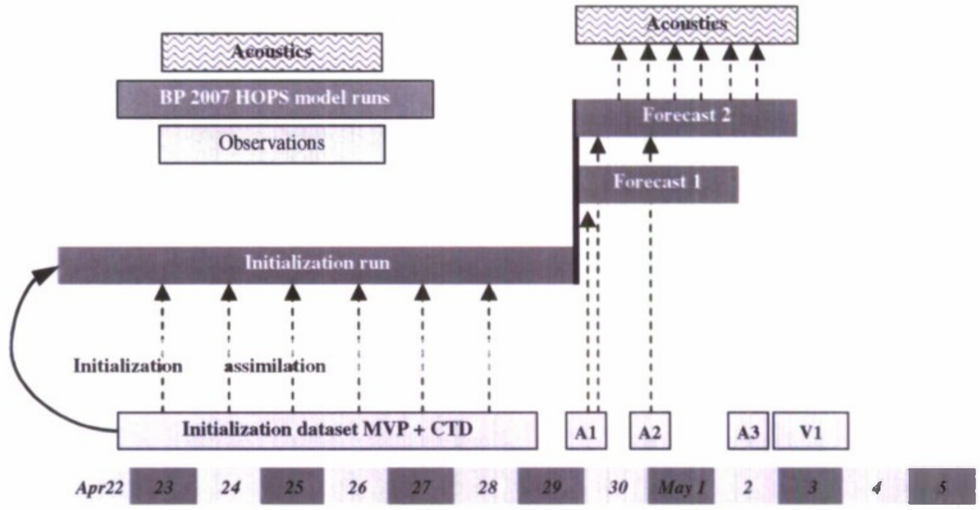

Figure 17 Along the horizontal axis in this schematic is the timeline of the BP07 exercise. Above it, the different layers of activities are drawn, with the observational level, the oceanographic modelling levels, and the acoustic forecasting level on top.

6.3 Nested models

The HOPS model has been specifically designed to allow for multiple model nests with the possibility of two-way interaction. Within a course resolution model, a smaller model with higher resolution can be nested. The resolution ratio is fixed at 1:3, so three grid points of the inner model agree to 1 grid point of the outer model. Within the inner model, further nesting is permitted.

Each of the nested models runs on its own as a separately compiled and stand-alone program. They need not run on the same computer, but can communicate over a network. All communication is done automatically once the communication framework is set up well. The framework chosen is that of the Parallel Virtual Machine (PVM), an open source and well-tested flexible framework that allows machines of various types and operating systems to communicate easily. The PVM framework is also needed when two models run on the same machine.

When several models run parallel, they can only go as fast as the slowest of the group. At fixed points during the run, fields along the common boundaries have to be communicated and therefore have to be available in both models. Therefore, it is advisable to have both models run at comparable speeds, and thus be of comparable size.

The setup of nested models requires careful setup of the grids, as the bottom topographies, coastlines and land/sea masks should not contradict each other at the boundaries. Apart from these difficulties, and a bit of added bookkeeping, running nested models is not more complicated than running single models. On machines with multiple processors (or several computers in a network) the running speed of the individual models is not significantly reduced by adding nests.

7 Outcomes

7.1 producing output

During a model run, the HOPS model writes its output to standard formatted NetCDF data files. These files have the strong advantage that one is able to access the file before it is completely finished. This means that as soon as the run has started and produced its first results, one may start analysing and checking for possible errors and other unwanted effects.

To ensure timely production and presentation of the outcomes, the analysis, plotting and publication procedures should be available beforehand. As was discussed in section 3, a distinction should be made between ocean model output and tactical products.

Ocean model output is a more or less direct representation of the outcomes of the model into figures, tables or maps or graphics. Parameters to be shown here are temperature, sound velocity, sea level, current strength and direction. At this level of presentation, no further conclusions are drawn and no additional information is needed. The units of presentation are usually the physical units used by the model, or an equivalent (current velocity in m/s or in knots, temperature in degrees Celsius).
HOPS has a built-in structure for routine creation of plots of all modelled quantities. Horizontal and vertical sections to plot can be predefined and created during the model run. Alternatively, one can use external procedures to access the model results while they are created. When external programs are used, one is somewhat more flexible in which plots are created. On the other hand, the routine plotting ensures the fastest possible and most consistent flow of output.

The production of tactical products requires further information on the goals and requirements of the modelling effort. An extra layer of interpretation is added to the model results, which makes them more suitable for quick decision making. A number of parameters that may be of importance is listed below, ordered according to their importance for three types of operations.

Mine Counter Measures (MCM)	Mine Drift Velocity and direction
	Bottom currents
	Diving conditions
Anti Submarine Warfare (ASW)	Tactical Sonar Range
	Counter Detection Range
	Propagation Losses
	Reverberation Losses
	Shadow Zones
Amphibious Operations (AO)	Beach gradient and accessibility
	Water temperature
	Wave conditions
	Near shore current velocity and direction

Not all the above parameters can be provided for using numerical modelling techniques. However, for all of the above parameters information on the water column is a prerequisite. The more accurate this information is, covering both temporal and spatial

variability, the more details can be provided on the relevant tactical products.
The aforementioned products are still somewhat intermediate level products, as for example 'beach accessibility' can be classified as 'favourable', 'neutral' or 'unfavourable' for a certain predefined vehicle when its characteristics are known.
A similar translation of 'temperature' into 'diving favourability' or 'landing conditions' can be made.

When detection is the endpoint of the prediction chain, as might be the case in ASW scenarios, model quantities such as temperature and salinity can be translated into intermediate, but still physical quantities 'sound velocity' or 'reverberation losses'. These quantities can be combined with scenario specific information such as information on the available sonar systems and submarine specifications, into a tactical product such as 'probability of detection'.

7.2 Ocean model output

In this section we give some examples of the typical direct output of ocean models (Figures 18-21). The figures show examples that were generated using the BP07 campaign in 2007.

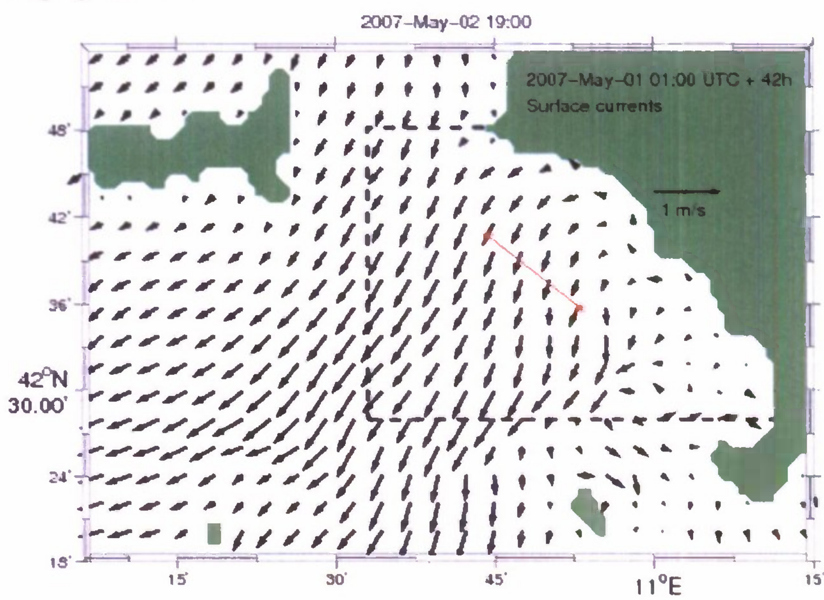

Figure 18 An example of surface velocity.

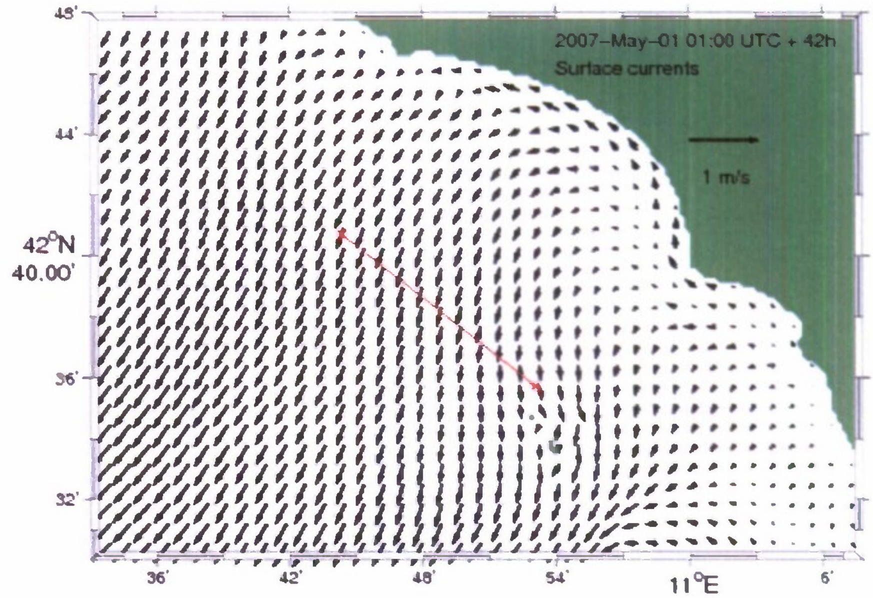

Figure 19 Example of surface velocity given by a nested high resolution model within the model shown in the picture above.

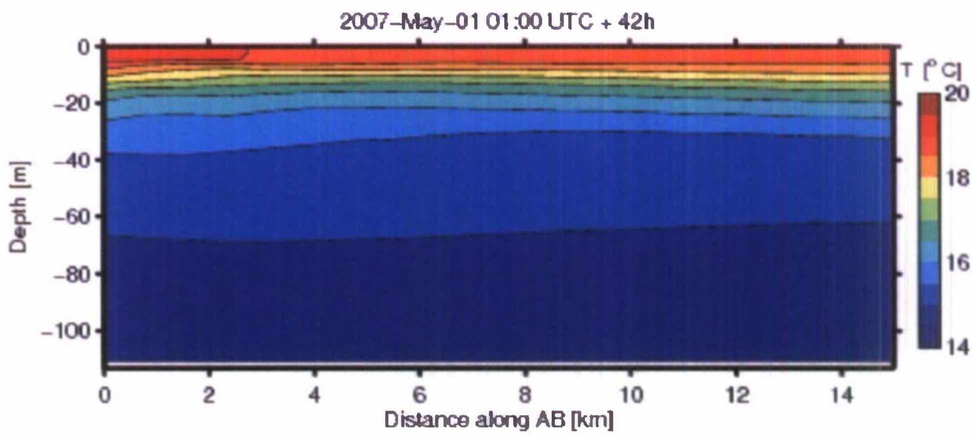

Figure 20 Example of a temperature section.

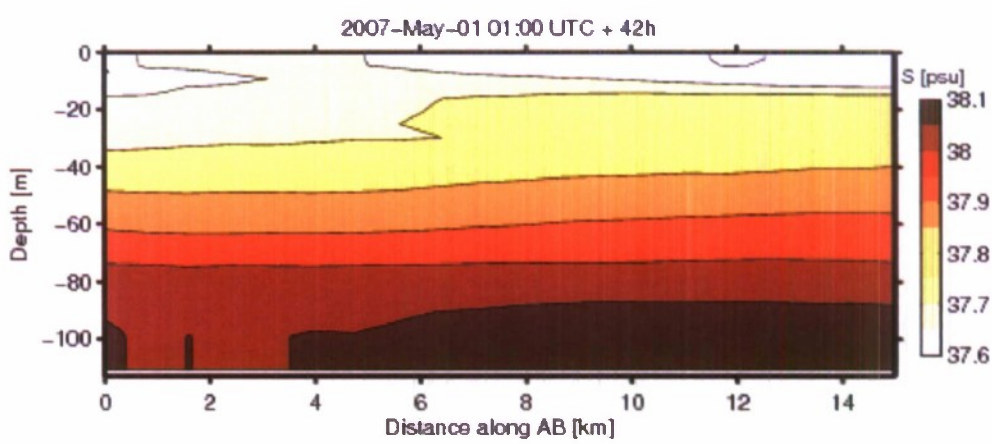

Figure 21 Example of a sound velocity section.

7.3 Conversion to tactical products

7.3.1 ASW

TNO has produced submarine detection probability forecasts during several sea trials, using an ASW scenario and the ocean forecasts produced with the HOPS ocean model. Below is an example of a sound velocity profile (Figure 22). When such profiles are extracted in all directions from a single point, a two-dimensional picture (see Figure 23) can be made with the 'Probability of Detection' for a submarine at all locations in a circle with a certain radius (Figure 24).

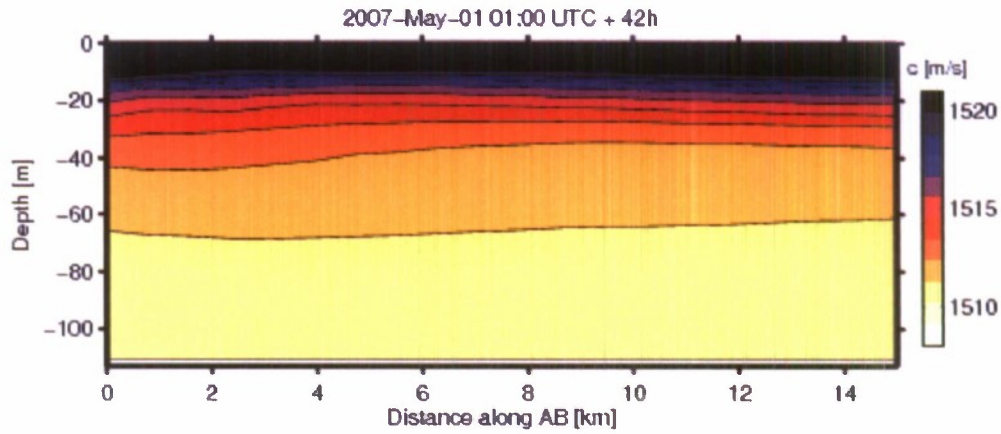

Figure 22 As Figure 21, but for predicted sound velocity along a section. From such sections, acoustic scenarios can be computed.

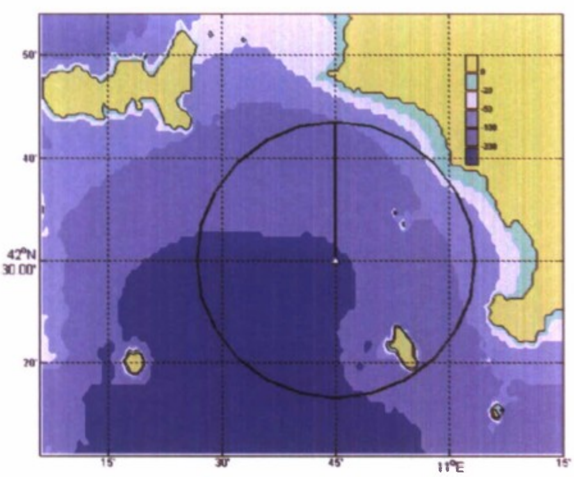

Figure 23 Region for the acoustics evaluation, with the black circle representing a sonar image of a ship travelling Northward, which was the scenario used for our ALMOST computations.

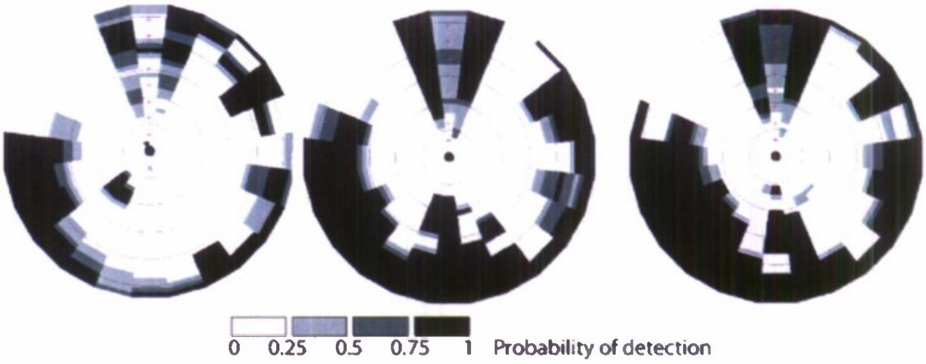

Figure 24 Detection probability forecast examples for the region shown in Figure .

7.3.2 *Amphibious Operations*

Surf zone products include significant wave height, wave direction, and wave induced residual currents. Other important quantities for amphibious operations are coastal current velocity and water temperature. These quantities can be given by ocean models like the HOPS.

HOPS is not a surf zone model, and cannot produce forecasts for surface waves. An example of surf zone modelling tactical products [10], which is a good example of how ocean modelling output can be translated into tactical products, is given in [2].

7.3.3 *AUV mission planning*

AUV mission planning is an increasingly important area of application for ocean models. As a rule of thumb, it seems that the ocean current field becomes an important factor in mission planning, when current velocities exceed half of the AUV self-propelled velocity. In such cases, the straight line between start en end-point is usually not the most energy-efficient solution [11]. Not only the radius of operation is considerably influenced by the environmental conditions, but also the operation of acoustic instruments is affected by the background flow.

8 Outlook

In this report we have given an overview of the components and procedural steps involved in the workflow of the HOPS ocean model. Here, we give some recommendations on steps to be pursued in the future.

The ocean model formerly known as HOPS, has been renamed into MSEAS in 2008, and has undergone substantial improvement. One of the more prominent features that have been added to the model is the inclusion of a free-surface formulation. Physically, this implies that a different range of phenomena are allowed in the model dynamics. The most important of these phenomena is that of the barotropic tides. Tidal dynamics could be added artificially to the pre-2008 HOPS model, but with the free-surface formulation, they can be modelled explicitly. In November 2008, we intend to visit the HOPS developing team headed by prof. P. Lermusiaux in Boston, and acquaint ourselves with this improved model.

In 2008, M. Borja Aguiar González, PhD candidate from the Canary Islands worked at TNO for about six months to familiarize himself with the basics of ocean modelling and HOPS. He will continue his PhD studies in 2009, and continuation of this cooperation is envisioned. His work will include data analysis of the MREA04 campaign near Portugal, and modelling of the dynamics in this region. His work can act as a test bed for the new model version including tidal dynamics, as this region has strong tidal currents.

Tidal activity is also an area of possible scientific collaboration with the MIT group. In the Netherlands, a strong theoretical community is present at NIOZ (Texel) and IMAU (Utrecht University). Already existing connections to the activities of these institutes can be used to leverage the scientific work.

To make HOPS a more readily available tool, a framework around the model is needed, which may enable swift application of the model in new regions. One approach that can be followed to pursue such operationalisation is to provide a standardized link to an existing global model, from which then boundary conditions for a more detailed regional simulation can be obtained. The UK MetOffice provides model forecasts up to 10 days ahead, which makes it a suitable candidate for such embedding. A similar approach to a continuously available meteorological forecast should be pursued.

The connections between HOPS and acoustic models are well-established, and relatively simple. From the HOPS-output, the information needed by the acoustic models can be easily extracted. As more information becomes available on the exact nature of the interactions between acoustics and ocean dynamics, it may be worthwhile to investigate the uncertainty of the model simulations by running several slightly perturbed simulations. At NURC, MIT and also at the Naval Research Laboratory and the Office of Naval Research, USA, such approaches are becoming more and more widely used for planning of observations, and uncertainty assessment. Also, the planned high-resolution modelling by HOPS can be used to gain some insight in the stochastic behaviour of sound propagation, as small scale features of the density distribution reduce the coherence of acoustic signals.

We also plan to further exploit the operational possibilities of ocean modelling in other situations than acoustic performance forecasting. Modelling of sea water temperatures and currents near-shore and in open water can be important to many other applications.

The collaboration with the international community working on military application of operational oceanographic modelling is to be continued, as the efforts involved in providing stand-alone solutions are too large to be implemented on a national level. With our emphasis on providing added value in certain (sometimes overlooked) aspects, such as the thorough investigation of tidal dynamics and the operational link between ocean and acoustic forecasts, the Dutch contribution to this network is significant and internationally recognized. TNO is too small to incorporate the complete process, but the close links to the military and focus on operational application make the TNO contribution well-recognized. We intend to continue this within the new program V931 'Omgeving en onderwaterbeeldopbouw'.

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10 Signature

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In close collaboration with a team of Massachusetts Institute of Technology an ocean forecasting system has been made available within TNO. The Harvard Ocean Prediction System (HOPS) is a large numerical ocean simulation system which produces forecasts for the maritime environment. This report documents the process of large scale ocean modelling and explains the choices that have to be made during this process. The consequences of these choices are discussed, as well as the operational uses of the model outcome.

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