G E O I N F O R M A T I O N S D I E N S T D E R B U N D E S W E H R

– Schriftenreihe –

Regional Ocean Prediction Models for Operational Use in the Navy

by

Uwe Paul,
Qualified Oceanographer,
German Navy Headquarters, Rostock,
Directorate Operations, Geoinformation Division,
Project 3310-0050-5570

Heft 1b, 2018

Herausgeber: Leiter Geoinformationsdienst der Bundeswehr
Bearbeitung und Herstellung: Zentrum für Geoinformationswesen der Bundeswehr Euskirchen 2019

ISSN 1865-6978
Druck: D01-IV.19-5-G191098

Table of Contents

Adress:
Uwe Paul
Marinekommando
Abteilung Einsatz UA GeoInfo
Kopernikusstraße 1
18057 Rostock

Abstract

The German Navy has a permanent and irrefutable need for reliable and assured oceanographic predictions, which are a prerequisite for providing mission-related advice for worldwide operations. The basis for these predictions are ocean simulations generated by running a numerical model on a computer. Due to the lack of reliable ocean model predictions for foreign operating areas,[1] e.g. the Horn of Africa/Somalia (EU Operation ATALANTA), the technical project "Regionales Ozeanmodell" ("Regional Ocean Model") was initiated at the Naval Office in Rostock on 31 January 2011. From 1 October 2012, the technical project was continued at the German Navy Headquarters[2] in Rostock before being completed in March 2015.[3] This report describes the entire technical project, from the preparation phase to the final outcome, including the operational use of all the ocean model nests and the further development phase. A prototype of an ocean model nest for the Ionian Sea was created during the preparation phase. With the experiences gained from this prototype it was possible to plan and implement the technical project. This facilitated the installation of another six fully-automated model nests at the German Meteorological Computing Centre (DMRZ), which have been in routine operation since March 2015: the Strait of Gibraltar, the Eastern Mediterranean Sea, the Western Black Sea, the Gulf of Aden, the East Coast of Somalia and the Strait of Hormuz. During the further development phase, another model nest, the Central Mediterranean Sea, was then put into operation. In total, there are eight model nests currently available.

This method of running high-resolution oceanographic prediction models to represent the Navy's foreign operating areas, similar to the long-established numerical weather prediction (NWP) models used at the DMRZ, is completely new, which should be reason enough to publish it in this document. The numerical model predictions generate valuable information for the provision of oceanography-based operational advice to the fleet. This report is aimed at current and future model operators, model developers, expert colleagues, advisers and, ultimately, anyone who is interested and wants to learn how numerical ocean predictions work and what benefit they offer. This report documenting the technical project can therefore also be used by the Bundeswehr Geoinformation Service.

All in all, this technical project can be regarded as a systematic continuation/extension of the family of oceanographic models (current and stratification, sea state and surge). After the author had made the first ocean model available for operational use by the German Navy in October 2010 (i.e. an installed and fully-automated model of the NATO submarine exercise area east of Sicily, Paul 2012), the experiences gained from this were used to implement the technical project including more models in accordance with the requirements of technical project publication 3310-0050-5577 (2011), p. 3.

Based on what has been achieved so far, completely new options arise which are to be implemented as part of further development and are therefore described in this report (see Chapter 5).

The ocean models currently use a standard prediction period of three days (72 hours) with prediction points at intervals of $\Delta t = 12$ hours.[4] The prediction period can be extended at any time and the interval (Figure 1a) decreased for the output file. The model output is a "5-dimension model ocean": (1) length/longitude x, (2) width/latitude y, (3) depth/height z, (4) time t, for each oceanographic parameter (5). Figure 1b shows the "3D ocean" of the Ionian Sea model for the temperature parameter at a selected point in time.

[1] Freely available information on the Internet is **not reliable**. Model predictions may be available on new websites that quickly disappear again. Furthermore, external sources like MyOcean/Copernicus cannot be accessed via the Internet, because the Bundeswehr network does not permit such access via the proxy server in Strausberg for IT security reasons. The technical project was therefore implemented at the Bundeswehr element of the German Meteorological Computing Centre (DMRZ).
The Federal Maritime and Hydrographic Agency (BSH) provides official ocean model predictions for the civilian sector, but only for the Baltic and North Sea up to the European North West Shelf, primarily in order to get reliable information for German territorial waters. For the military sector with its theatres worldwide, this is the responsibility of the Bundeswehr Geoinformation Service (GeoInfoDBw). Some of the information provided must be treated as sensitive or confidential to avoid putting operations, personnel or equipment at risk.

[2] The German Navy Headquarters were established in October 2012 from the Naval Staff, the Fleet Command and the Naval Office.

[3] Plans were made for a continuation of the technical project (FP 3310-0050-5570) on a research basis. In addition, substantial technical improvements could be made in 2017 as a result of a framework contract (EuMetSys project no. 217401.70) between the Bundeswehr and the company Ernst Basler & Partner Deutschland (Chapter 5, Further Development).

[4] The individually selected interval of 12h simply means that the calculated result is written to an output file (history.nc) every 12 hours. This way, the output file's size on the RELOC computer with its limited capacity is kept small. The time interval is not related to the internal numerical calculation interval. See Chapter 4.4 The ROMS model/CFL criterion.

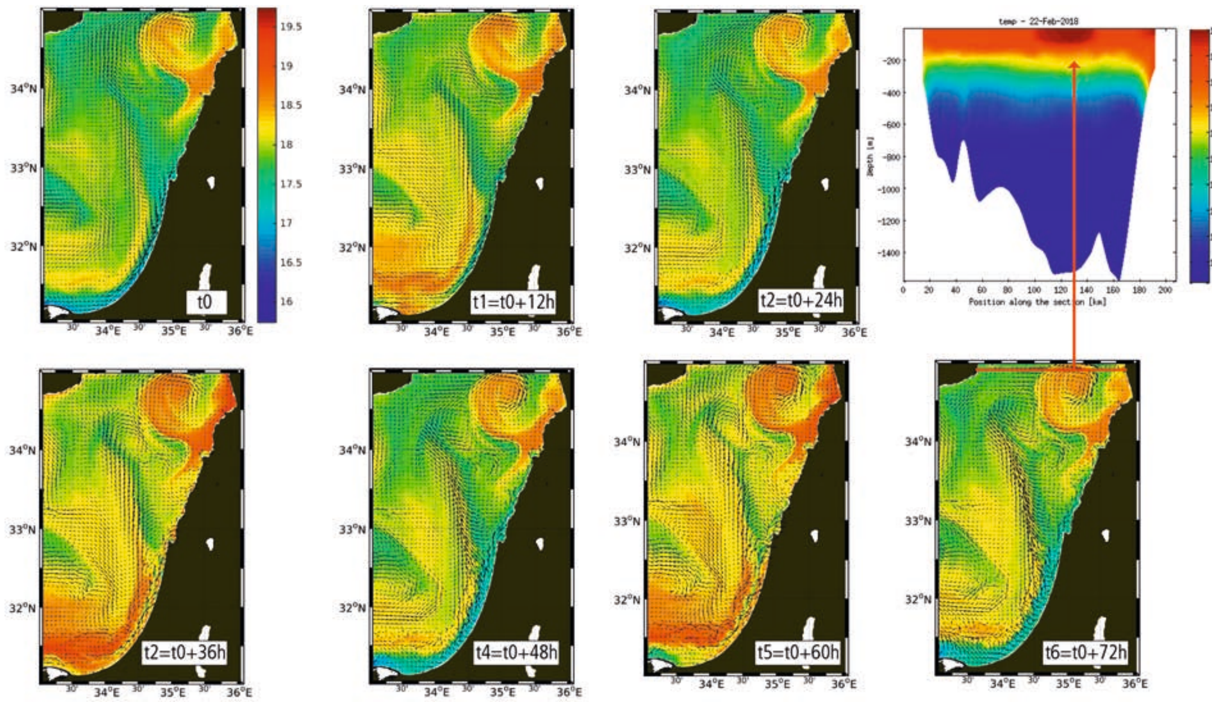

Figure 1a: *Example: Eastern Mediterranean Sea. Prediction points for the temperature parameter at the ocean surface over 72 hours. The northern boundary of the model area is shown as an example of a vertical section, from the island of Cyprus to Syria and from the sea surface to the sea bed. The distinctive vortex of warm water (red arrow) is found both in the vertical section and the horizontal representation.*

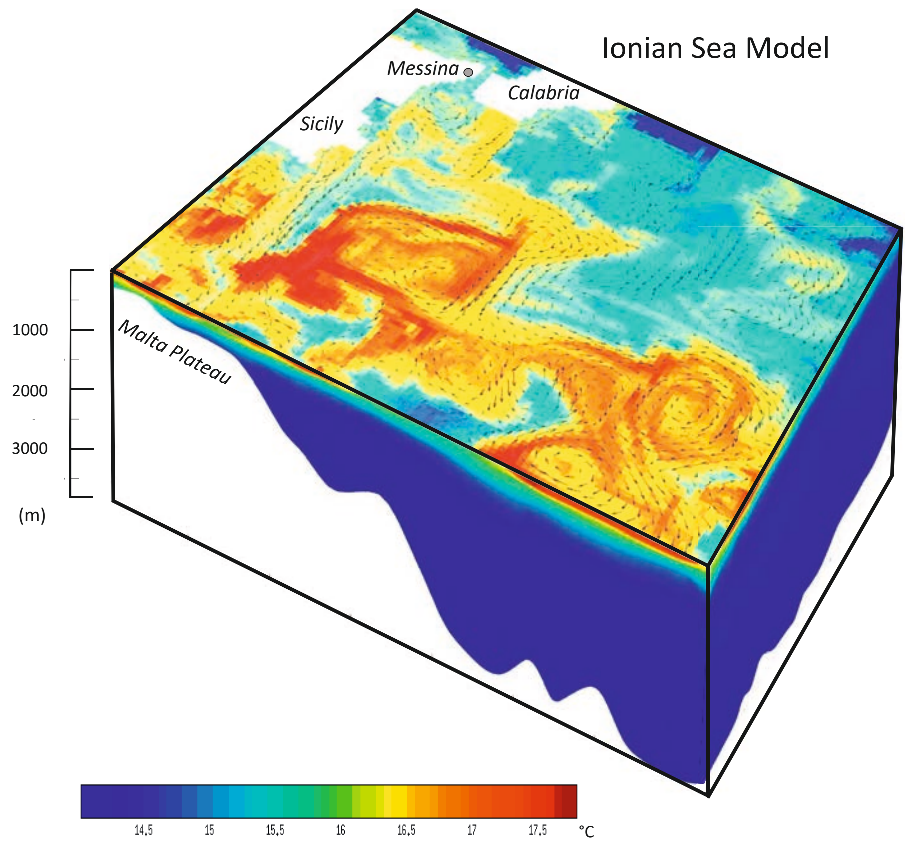

Figure 1b: *Example: Ionian Sea. At each time step t, there is a "3D ocean" for each oceanographic parameter. The image shows the temperature parameter: T = T (length/longitude, width/latitude, depth, time).*

Zusammenfassung

Die Deutsche Marine hat einen dauerhaften und unabweisbaren Bedarf an zuverlässigen und gesicherten ozeanographischen Vorhersagen als Voraussetzung für die missionsbezogene Beratung ihrer weltweiten Einsätze. Grundlage dafür sind Simulationen des Ozeans, die durch den Routinebetrieb eines numerischen Modells auf einem Computer gewonnen werden. Da für die außerheimischen Einsatzgebiete, z.B. am Horn von Afrika/Somalia (EU Operation ATALANTA) keine verlässlichen Ozean - Modellvorhersagen verfügbar waren[1], wurde bereits am 31.01.2011 beim Marineamt in Rostock das Fachprojekt (FP) „Regionales Ozeanmodell" initiiert, um diese Fähigkeitslücke zu schließen. Ab 01.10.2012 wurde dieses Fachprojekt dann beim Marinekommando[2] in Rostock (MarKdo) fortgesetzt und kam im März 2015 zum Abschluss[3]. In diesem Bericht wird nun das Fachprojekt in seiner Gesamtheit beschrieben, von der Vorbereitungsphase, bis zum fertigen Endergebnis, dem operationellen Betrieb aller Ozeanmodellnester und der Weiterentwicklungsphase. Während der Vorbereitung wurde der „Prototyp" eines Modellnestes für die Ionische See erstellt. Auf der Basis der dadurch gewonnenen Erfahrungen konnte das Fachprojekt geplant und realisiert werden. Dadurch konnten sechs weitere Modellnester vollautomatisiert am Deutschen Meteorologischen Rechenzentrum (DMRZ) installiert werden, welche seit März 2015 im Routinebetrieb laufen: Straße von Gibraltar, östliches Mittelmeer, westliches Schwarzes Meer, Golf von Aden, Ostküste von Somalia und Straße von Hormus. Während der Weiterentwicklungsphase konnte dann ein weiteres Modellnest in Betrieb genommen werden: Zentrales Mittelmeer. Somit stehen gegenwärtig acht Modellnester zur Verfügung.

Dieser Betrieb von hochaufgelösten ozeanographischen Vorhersagemodellen für die außerheimischen Einsatzgebiete der Marine, so wie wir ihn von meteorologischen Vorhersagemodellen am DMRZ schon lange kennen (NWP, Numerical Weather Prediction), ist völlig neu und sollte schon alleine aus diesem Grund mit dieser Publikation bekannt gemacht werden. Als Folge der numerischen Modellvorhersagen ergibt sich ein Zugewinn für die ozeanographische Einsatzberatung der Flotte. Als Zielgruppe dieses Berichtes sind anvisiert: Derzeitige und zukünftige Modellbetreiber, Modellentwickler, Fachkollegen, Berater und schließlich alle, die interessiert sind und wissen wollen, wie eine numerische Ozeanvorhersage funktioniert und welcher Nutzen dadurch entsteht. Somit steht eine Dokumentation des Fachprojektes für den Geoinformationsdienst der Bundeswehr zur Verfügung.

Insgesamt stellt dieses Fachprojekt eine konsequente Fortführung/Erweiterung der ozeanographischen Modellfamilie dar (Strömung und Schichtung, Seegang bis Brandung): Nachdem der Verfasser das erste Ozeanmodell für die Marine im Oktober 2010 operationell nutzbar gemacht hat (für das NATO–Uboot Übungsgebiet östlich von Sizilien installiert und voll automatisiert, Paul 2012), konnte basierend auf diesen Erfahrungen das Fachprojekt mit weiteren Modellen realisiert werden, so wie es im Fachprojektblatt 3310-0050-5577, 2011, S.3 gefordert wurde.

Durch den bis jetzt erreichten Sachstand als „Basis" erschließen sich völlig neue Möglichkeiten, welche im Rahmen einer Weiterentwicklung realisiert und daher in diesem Bericht aufgezeigt werden (vgl. Kapitel 5).

Als Standard ist gegenwärtig für die Ozeanmodellnester eine Vorhersage über drei Tage (72 Stunden) vorgesehen, mit einer Schrittweite (S.8 Abb. 1a) der Vorhersagetermine von $\Delta t = 12$ Stunden[4]. Der Vorhersagezeitraum kann jeder Zeit erweitert und die Schrittweite (S.8 Abb. 1a) in der Ausgabedatei verkleinert werden. Somit gibt es als Modellausgabe einen „5D – Modellozean": (1) Länge-x, (2) Breite-y, (3) Tiefe/Höhe-z, (4) Zeit-t, für jeden ozeanographischen Parameter (5). Abbildung 1b) zeigt für einen ausgewählten Zeitschritt den 3D- Ozean für das Ionische See Modell für den Parameter Temperatur.

[1] Frei verfügbare Informationen aus dem Internet sind **nicht verlässlich**. Genau so schnell wie beliebige Modellvorhersagen auf ständig neu verbreiteten Webseiten angeboten werden, können diese auch wieder verschwinden. Überdies ist ein Zugriff auf externe Quellen wie z.B. MyOcean/Copernicus, über das Internet nicht möglich, da das Bundeswehrnetz über den PROXY – Server Strausberg aus IT- Sicherheitsgründen dieses nicht zulässt. Daher wurde das Fachprojekt im Deutschen Meteorologischen Rechenzentrum Anteil Bw realisiert. Offizielle, amtliche Ozeanmodellvorhersagen stellt das Bundesamt für Seeschifffahrt und Hydrographie (BSH) für den zivilen Bereich bereit, aber nur für Ost- und Nordsee bis zum NW- Schelf, um vorrangig verlässliche Informationen für die Deutschen Hoheitsgewässer zu erhalten. Für den militärischen Bereich, mit seinen weltweiten Einsatzgebieten, ist dies die Aufgabe des Geoinformationsdienstes der Bundeswehr (GeoInfoDBw). Diese Informationen sind mitunter sensibel/vertraulich, um eine Operation, Mensch und Material nicht zu gefährden.

[2] Das MarKdo wurde im Okt. 2012 neu aus dem Führungsstab der Marine, dem Flottenkommando und dem Marineamt aufgestellt.

[3] Eine wissenschaftliche Fachprojektfortsetzung (FP 3310-0050-5570) wurde anvisiert. Unabhängig davon konnten aber 2017 vermittels eines Rahmenvertrages der Bw (EuMetSys Projekt-Nr. 217401.70) mit der Firma Ernst Basler & Partner Deutschland umfangreiche technische Verbesserungen durchgeführt werden (Kapitel 5, Weiterentwicklung).

[4] Die selbst gewählte Schrittweite von 12h besagt einfach nur, dass alle 12 Stunden das berechnete Ergebnis in eine Ausgabedatei (history.nc) hineingeschrieben wird. Somit bleibt die Ausgabedatei für den RELOC-PC klein, da dort die Kapazitäten begrenzt sind. Das hat nichts mit der numerischen internen Rechenschrittweite zu tun! Siehe dazu Kapitel 4.4 Das ROMS-Modell/CFL- Kriterium.

1 The German Navy's Need, Aims of the Technical Project and Benefit for the Navy

1.1 Requirements of the German Navy as a User

The German Navy needs information about the oceanographic conditions in its theaters of operations for its entire spectrum of tasks. In the medium and long term, the contribution of oceanography to the planning, execution and evaluation of operations will become increasingly important.

In the past, the Bundeswehr Geoinformation Service (GeoInfoDBw) did not have an oceanographic prediction model in the routine service, capable of delivering reliable and secured advice on ocean currents and stratification and their impact on operations. It was therefore not possible to meet the requirement for oceanographic information regarding foreign operating areas.

With this capability gap now closed, the user's requirements can be satisfied. Some important goals have already been reached (Chapter 3), and some more are described in Chapter 7, "Further development".

1.2 The Technical Project's Aim

The "Regional Ocean Model" technical project's aim is to create and provide adequate and comprehensive oceanographic information regarding the German Navy's operating areas.

The idea behind the implementation of all eight ocean model nests (see Chapter 6 for descriptions) is

- *to ensure and enhance the Bundeswehr's ability to provide mission-related scenarios and employment area evaluations for planning purposes and, at short notice, for NRF support.*
- *to ensure and enhance the Bundeswehr's ability to meet its obligations to the NATO in terms of acting as lead nation in the IMETOC support concept and contributing to the NATO's "Rapid Environmental Assessment (REA)" and "Recognized Environmental Picture (REP)".*
- *to ensure and enhance the ability to quickly provide German Navy units and, if required, allies (NATO, EU) with oceanographic information regarding the operating areas and with mission-related advice for*

  - *SAR missions*

    Provide the "Search and Rescue Information System (SARIS)" with current predictions to minimize search times.

    The Federal Maritime and Hydrographic Agency (BSH) transfers a file with forecast data generated by the BSHcmod model to Glücksburg twice per day. There, the file is read by the SARIS programme and turned into SAR information (drift of a person in the water, SAR helicopter tracking, optimized usage of all assets: SAR helicopter, SAR vessels etc.)

    The bottom section of Figure 2 shows the relocatable ocean model nests required for the Navy's worldwide operations (incl. "Combat SAR (CSAR)"). These nests enable SARIS to be used worldwide.

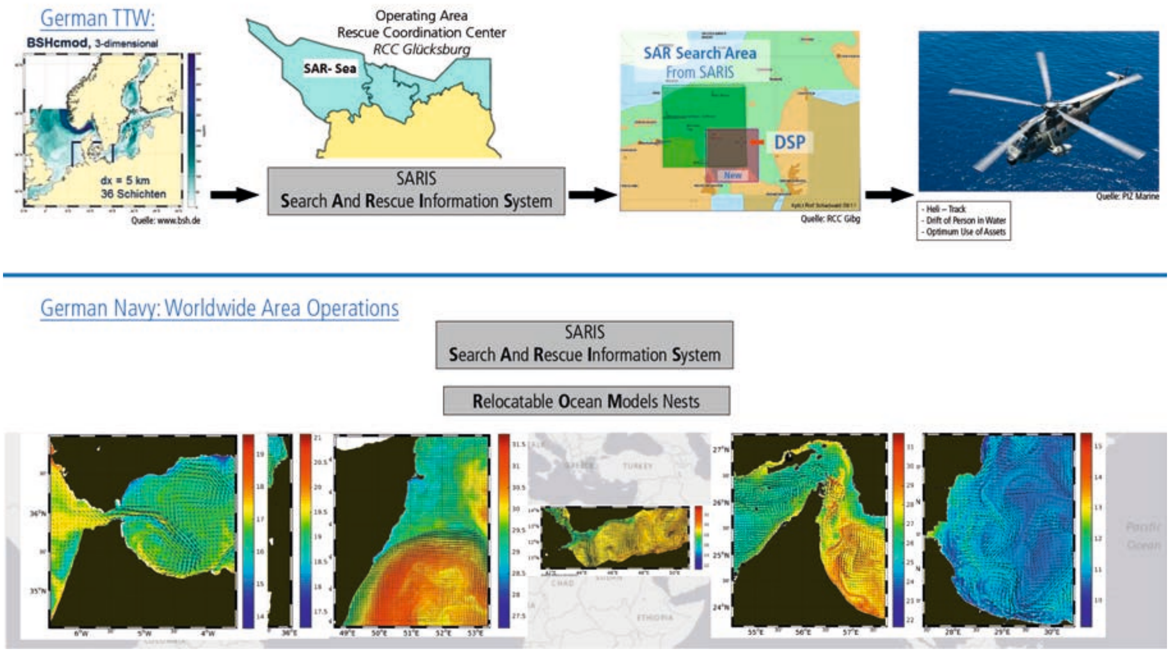

Figure 2: *Information flow for a SAR mission coordinated by the Rescue Coordination Centre (RCC) Glücksburg for SAR areas in German territorial waters. The relocatable ocean model nests enable SARIS to be used worldwide (bottom of Figure 2).*

- *AUV operations*

  Current predictions are required to support mission planning and execution, to minimize uncertainties caused by drifting and to determine the maximum operating time of an AUV in a current field. Stratification predictions are required to determine the range of underwater communication, in particular the distance in which the AUV can still be tracked, provided with new waypoints or queried for measured data

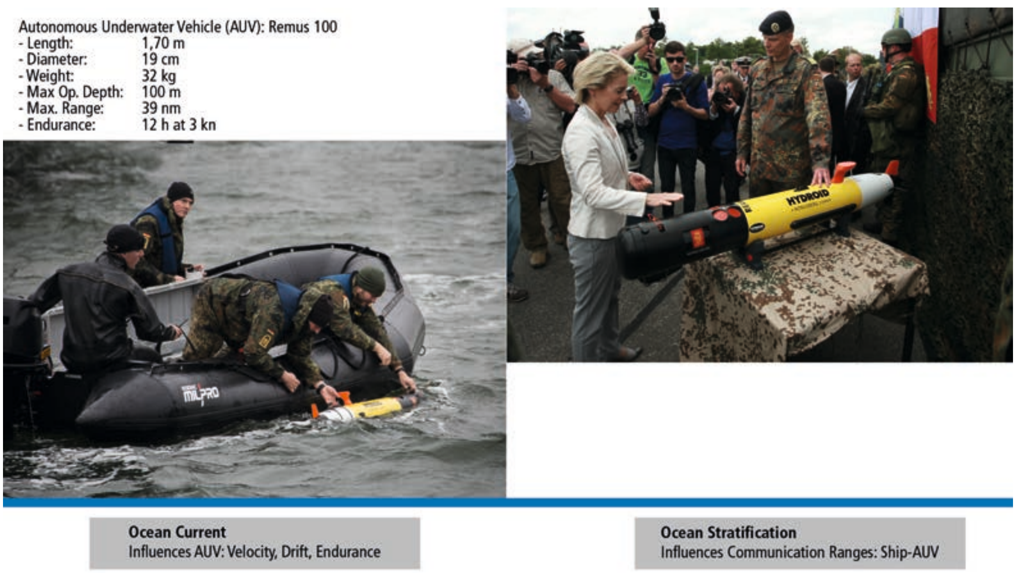

Figure 3: *The German Federal Minister of Defence (since 2013), Dr. Ursula von der Leyen, during a visit to Eckernförde Naval Base (16 June 2014). Commander Krüger, the Sea Batallion's Commander, explains the Autonomous Underwater Vehicle (AUV).*
The underwater drone is used in a joint exercise with the Dutch "Korps Mariniers" (1 November 2016). Predictions of ocean current and stratification can help to make an AUV mission a success: Current impacts the speed of an AUV (0-5 kn), the drift the AUV has to counter and hence the operating time/performance. Stratification impacts the range of underwater communication between the mother ship and an AUV or a cluster of AUVs.

- *Submarine- and Antisubmarine warfare (SW, ASW)*

  Prediction of the performance of various sonars/sensors using a hydroacoustic follow-up model. The oceanographic analyses and predictions can now be used to derive the acoustic conditions in 3D space underwater.

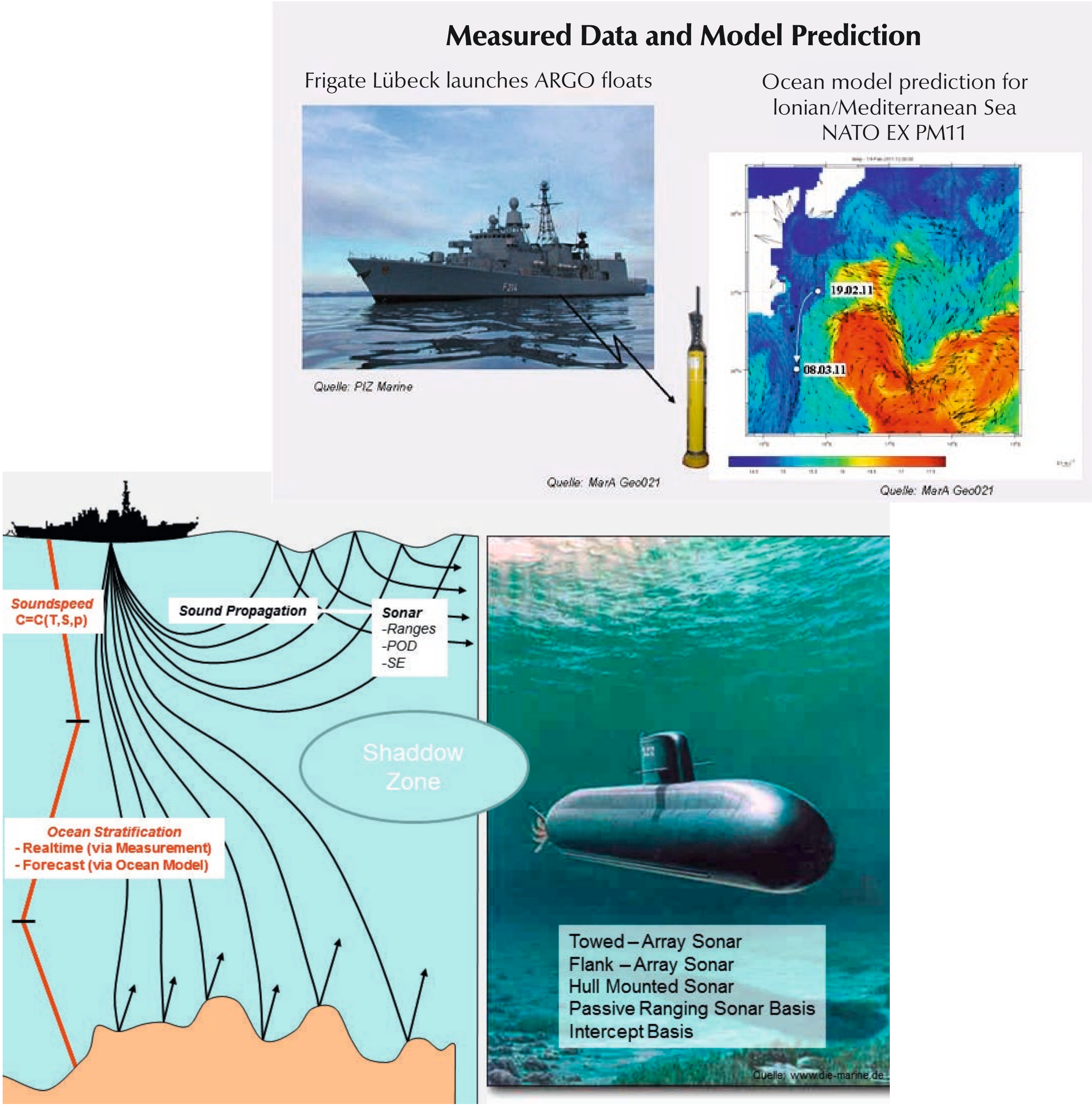

Figure 4: *Creation of sound velocity profiles by taking measurements with an ARGO float. The ocean prediction models can be used for 4D analyses and predictions of sound velocity fields (space and time). At the top right, Figure 4 shows an example of the Ionian Sea's surface temperature and current for a submarine exercise area. The sound velocity is calculated from temperature, salinity and pressure. At the bottom left, an example of a sound velocity profile is shown in red. This profile may be the prediction for a certain point in time. This prediction is then used to derive all the sonar parameters to be expected for this point in time: Sound ray paths (including a first information about the presence of sound ducts or shadow zones), probability of detection, signal excess etc. This also allows tactical considerations regarding the best point in time for antisubmarine warfare and the sonar performance to be expected from the various systems (bottom right of Figure 4).*

- *Mine countermeasures (MCM)*

  Prediction and analysis of minehunting conditions. The stratification predictions from the ocean model nests are included in the minehunting models "Minehunting Simulation Model (MSM)" (Figure 5a) or "Sonar Performance Indicator (SPI)". This way, sonar performance data can be obtained. For mission planning, the stratification data can also be imported into other tools, e.g. the operations research system MCMEXPERT.

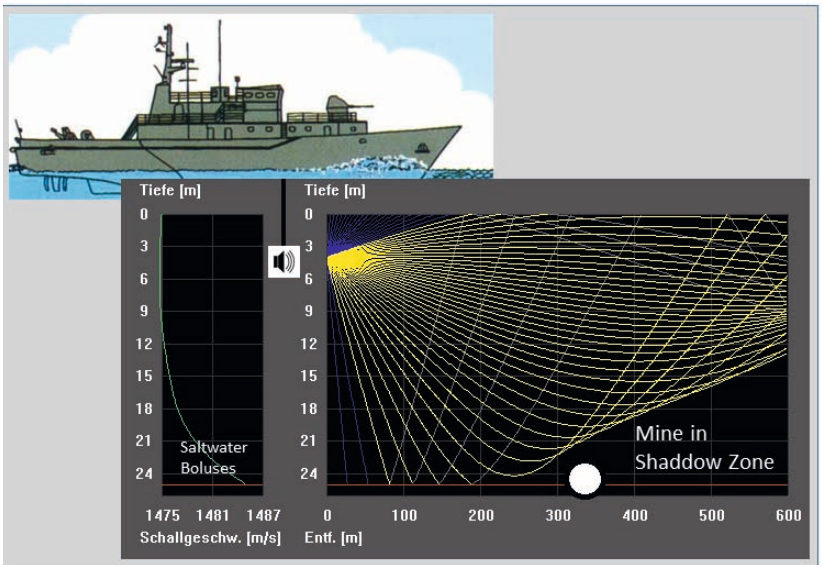

Abb. 5a

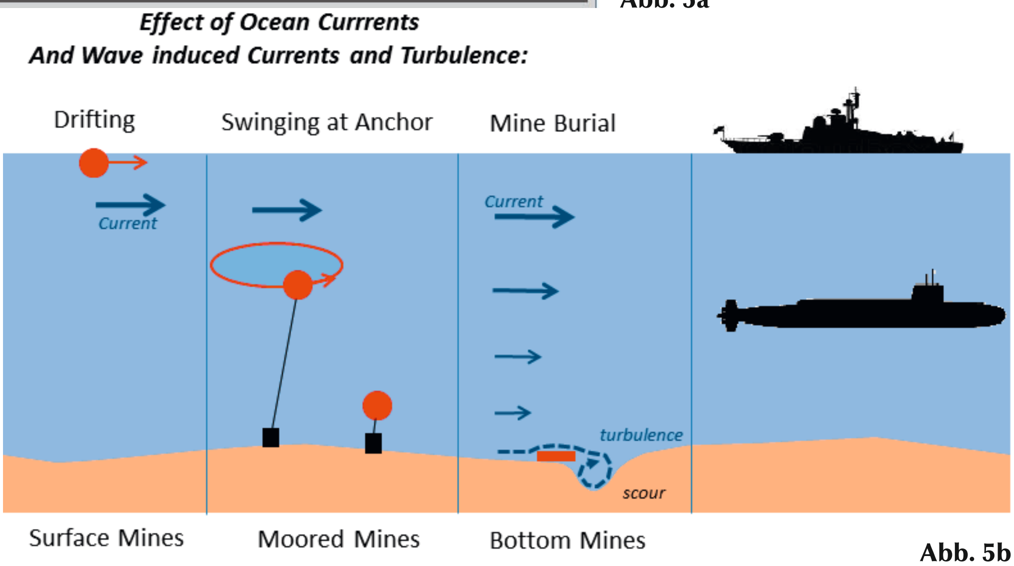

Abb. 5b

Figure 5: *Possible impact of a water column's stratification and current on mines and minehunting:*

Figure 5a: One layer or drops of highly saline water at the ocean floor (saltwater boluses) can "mask" a bottom mine (shadow zone) and make it "invisible".

Figure 5b: Surface mines can be carried away by ocean currents. Moored mines "circle" around their anchor. Bottom mines are prone to sanding up: Scourings on the lee side may cause the mine to sink into the ground so that it cannot be seen or detected later when the scour hole is back-filled with sediment.

- *Object drifting*

  Provide information as to where (partially) submerged objects (containers, uncontrolled AUVs) will drift.

- *Tactics*

  When considering tactics and submarine safety, areas of jet streams/jets, oceanic fronts and internal waves should be taken into account, as they are, for example, causing disturbances in signal propagation by varying the bandwidth of the oceanic transmitter channel ("sonar holes"). Submarines can also use such areas for efficient and silent movement and to save energy (battery power). AUVs or submarines can, at least to a certain extent, be carried along by the ocean current.

- *Marine mammals, active sonar employment, risk minimisation*

  Stratification predictions from ocean model nests can be used to identify areas in which e.g. convergences accumulate or focus the sound level emitted by a ship's sonar system, posing an increased risk to certain marine mammals. This must be considered when providing practical advice as a service. In practice, the ocean models are combined with hydroacoustic transmission loss models to create risk maps for advisory support.

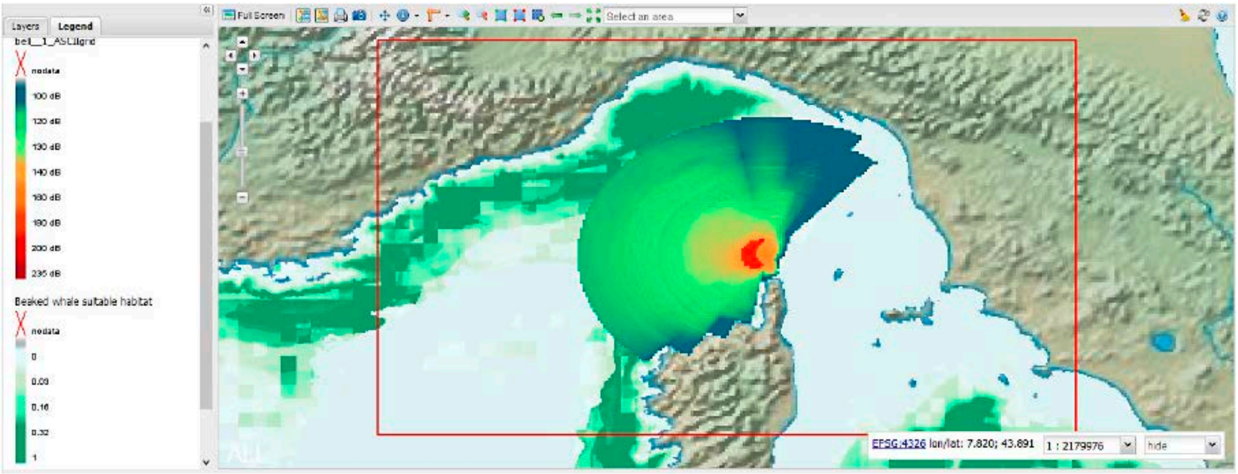

Figure 6: *Risk areas where the received sound level exceeds the threshold value of 140 dB re 1μPa, which might cause negative ecological effects. The area is shown in beige colour (A.B-Nagy et. al. (2012)). Areas with other threshold values which might be harmful to certain whale species can be mapped as well (area shown in red).*

- *Countering migrant smuggling and human trafficking*

  Current predictions from the ocean models are also used to provide METOC advice for the EU's EUNAVFOR MED Operation Sophia, in which the German Navy participates. Additional information can be found in the following leaflet: "Unsere Marine hilft Menschen in Not" (Our Navy helps people in need), (German Navy Headquarters, Press and Information Centre, www.marine.de). For the same purpose, other military users (Naval Intelligence Division, MilNW) and civilian agencies (Federal Police Department of Maritime Security, Federal Intelligence Service) are also provided with up-to-date ocean current predictions. In the context of Sea Battalion operations, there were also requests for information about littoral breaker height or longshore currents, as these may impact all kinds of littoral or surf zone activities (Paul, 2010).

Figure 7: *The German Navy's theatre of operations in the Mediterranean Sea (EUNAVFOR MED Operation Sophia) to counter migrant smuggling and human trafficking. (Source: Bundeswehr.de).*

These capabilities may also be of use for the operation and expansion of a multinational METOC support group (MN MSG).

The individual models are described in Chapter 6.

1.3 Provision of Results for Operational Use

The ocean model nests are set up for the theatres of operation of the German Navy. The results are delivered from the "place of production" to users aboard seagoing units or those at planning or operational headquarters via:

- Bundeswehr intranet
- FTP pickup points on a data server (e.g. to pick up data for the Norwegian Sea from the Multistatic Tactical Planning Aid (MSTPA))
- NATO METOC Data Hub (NMDH) at the Bundeswehr Geoinformation Centre in Euskirchen
- E-mail attachment

1.4 Association of the Technical Project with the Overall Objective of Coordinating the Research Activities of the Bundeswehr Geoinformation Centre

A system of objectives and key performance indicators was used to coordinate the technical project when it started. Within this system, the technical project was associated with the strategic objective "Expansion of individual geoinformation capabilities", the sub-objective "Further development of the family of oceanographic models for the Navy's worldwide operations" and the departmental objective "Expansion of circulation models to include worldwide operational applications".

In the course of the performance process "Ensuring Geoinformation Services" (LP GEO), the results from the technical project will now be operationalized and planned as a mediumterm project (including the maintenance of the associated software).

1.5 Approved Objectives of the Technical Project

The approved objectives of the technical project are the creation of six "regional ocean models" for the German Navy's operating areas and the setting up and development of a fully automated RELOC system (relocatable ocean modeling system):

- Creation of a bathymetric and numeric computational grid for the respective ocean model areas with allocation of the land-sea grid points and water depths, taking the stability criteria into account.
- Hence, for each model nest there is a grid.nc file which is read whenever the model is started.
- Provision of a meteorological forcing for the ocean model, customized for the respective ocean model grid (region and grid configuration).
- Embedding of RELOC into an ocean model with lower resolution in order to provide boundary values (MERCATOR boundary conditions).
- Data assimilation based on optimised interpolation.
- Smart functionalities for restart and reboot situations.

1.6 Benefit of the Technical Project for the German Navy

The project increases efficiency in some fields of maritime geoinformation support. Without it, however, this type of support wouldn't even be possible in certain other fields (e.g. exact SARIS predictions in foreign waters, predictions of stratification and sound fields and their effect on the sonar conditions for various platforms and sensors).

2 Formal Start of the Technical Project

At the beginning, comprehensive information about the planned technical project "Regional Ocean Model" was provided in the so-called "technical project publication". The information covered a wide range of topics and was verified by the Bundeswehr Geoinformation Office (now Bundeswehr Geoinformation Center). In a technical project conference, the project was introduced and substantiated by Naval Office representatives. Following a positive evaluation and an according prioritisation, the realization of the project was initiated.

The author of this text created and presented the technical project publication, which was approved on 31 January 2011 and signed by the "Deputy Commander Bundeswehr Geoin-formation Office (EDir Liebing) on 23 March 2011.

The technical project was then assigned to the Bundeswehr Geoinformation Office (now Bundeswehr Geoinformation Center) and financed with project funds from this departmental research institute and technically supported by the author, from the start of the project until it ended with the handover of the results in 2015.

Contractor for the project was the "NATO Centre for Maritime Research and Experimentation (CMRE)" with its expertise in worldwide operational ocean predictions for NATO operating areas, which at that time could not be provided by any German institution.

In the next processing step, all compulsory services specified in the abovementioned technical project publication, e.g. Number of model nests and their implementation at the Bundeswehr element of the DMRZ as well as the according notes of fee, were agreed upon in a contract between the originator (Bundeswehr Geoinformation Office) and the contractor (CMRE).

The contract "M/ AMG/ CA588" between the CMRE and the Bundeswehr Geoinformation Office (BGIO) was finally signed by General Brunner, Commander Bundeswehr Geoinformation Office, and Dr. Tielbürger, Director CMRE, on 22 June 2013.

Between 16 and 27 March 2015, the finished product – a computer containing all prediction models – was integrated into the DMRZ network, all input and output data streams were activated and the modelling system was put into operation.

3 Current Status, Achievements and Distinguishing Features

The most important result is that the RELOC project has been realized and has been working flawlessly since its installation at the DMRZ in March 2015, delivering ocean predictions for operational use to provide the fleet with real time advice on a daily basis.

The generated prediction products are automatically provided as data or graphics.

3.1 "Technical-Scientific" Status

The scientific status meets the requirements listed in the technical project publication and the contract with the CMRE: Development of the "model setup" for all six model areas, provision of the land-sea grid point bathymetries/topographies, organisation of a fully-automated data stream for the oceanographic parent model MERCATOR and the meteorological models (RLM and ICON EU) and of a script to control the entire modelling system. The underlying ROMS model is described in Chapter 4 and 5.

The project realisation and the following operational use revealed further options for technical-scientific development which are described later in this report (Chapter 7).

3.2 Status Regarding "Operational Use"

The overall system has been in continuous and stable operational use since March 2015.

However, it still requires support from oceanographic experts. Simple monitoring is not sufficient, as knowledge of the complex overall system is required in case it must be maintained: Occasionally, the input formats for the MERCATOR ocean model are changed or the high-resolution meteorological nests must be adjusted, e.g. if a new version of an RLM nest for a required region is available or new Python or NetCDF libraries have to be used. Knowledge of the overall system is required for porting the system to a new computer generation (at the DMRZ approx. every 3-5 years) or a new ROMS computer core (ROMS version) as well as for implementing technical-scientific innovations (see Chapter 7, "Further development").

3.3 Distinguishing Features

The following section describes the two main distinguishing features.

3.3.1 Fully Automated Operational Use with Smart Functionalities for "Restart and Reboot Situations"

If the program execution should stop, e.g. due to maintenance of the computer system, a computer crash or missing input files (meteorological and oceanographical fields), the overall system will restart automatically at the next opportunity using the fields currently being processed as restart file.

3.3.2 Optimal Provision of a High-Resolution Meteorological Forcing for the Ocean Models, Tailored to the Respective Region and Grid Configuration

The Bundeswehr Geoinformation Service runs own high-resolution meteorological regional models for its operating areas. These so-called RLM nests are based on the COSMO model and have a horizontal resolution of 7 km. The prediction period of the RLMs in use is 48-72 h. The RLM model nests can be configured individually by the numerical weather forecast model department of the Bundeswehr Geoinformation Center at the German Meteorological Service (MetBW in Offenbach). It is therefore possible to coordinate the meteorological and oceanographical models, e.g. in order to optimise the supply of data.

On 20 January 2015, the German Meteorological Service (DWD) introduced the global model ICON with a horizontal mesh of 13 km. By refining the mesh locally, it was possible to activate the so-called ICON EU nest for the Europe area on 21 Juli 2015. The particular dimensions (size and position) of this large nest were requested by the Bundeswehr. For this reason, part of the Bundeswehr element at the DMRZ is used for these calculations (Majew-ski et al, 2016, p.14). Comparisons by the DWD have shown that the ICON EU nest offers better predictions than the previously used COSMO EU nest. The ICON EU nest will therefore replace both, the DWD's COSMO EU nest and the respective RLM of the Bundeswehr for this region starting in 2016.

For regions or operating areas outside of the ICON EU area, the Bundeswehr still has to use the worldwide relocatable RLMs based on the COSMO model with a resolution of 7 km.

This means that from 2016 onwards, our ocean model nests from within the range of the ICON EU section also benefit from a considerably improved meteorological forcing. The affected ocean model nests are the Strait of Gibraltar, the Eastern Mediterranean Sea, and the Black Sea. Nevertheless, our ocean model nests outside of the ICON EU section can still be provided with worldwide RLMs with a resolution of 7 km. The affected ocean model nests are the Strait of Hormuz, the Gulf of Aden and the large sea area off Somalia.

4 Theoretical Background: From Physical Equations to Software Implementation Using the ROMS Model

The purpose of an ocean prediction model is to predict future trends of the ocean (prognosis/prediction) on the basis of its current status (analysis). The "analysis" provides information about the current status of quantities like e.g. ocean current or water temperature, while the "prognosis" indicates what these quantities will look like in the future, i.e. tomorrow or the day after. The selected ocean area is called "model area".

4.1 The System of Hydrodynamic Equations

The ocean's status can be fully described by seven physical state quantities, where "fully" means that the quantities

- u - easterly horizontal velocity
- v - northerly horizontal velocity
- w - vertical velocity
- p - pressure
- T - temperature
- S - salinity
- ρ - density

are known for any location at any time. There is an according system of seven linearly independent equations for the seven required quantities.

These seven equations are derived from the conservation laws of physics for angular momentum, mass and energy and from the equation of state of seawater.

Hence, there is a system of six nonlinear partial differential equations and one higher-order polynomial.

This system of equations is generally solvable, but it has not yet been solved analytically. It has therefore been discretized and solved numerically. The numerical solution is then carried out with a computer, in this case on the basis of the ROMS model (see Section 4.4).

The system of equations is also known as "primitive equations". It is the basis for almost any existing ocean model.

Detailed knowledge of the equations – in particular of their physical significance – is required for the understanding of the overall numerical system, especially if the RELOC overall system with its complex integration core ROMS is used. This is the case, for example, if control file settings must be changed to be able to call the respective physical programme modules, or if individual physical or numerical quantities or defined parameters must be redefined or updated. As ROMS itself is being further developed by a community, these further developments might periodically be implemented or replaced by new model versions. In case of computer regenerations, software might also have to be adapted, not least because of new compilers or modules. Let's now turn to the equations:

1) (3 differential equations, Equations (19), (20), (21)) The **"angular momentum conservation laws"** in hydrodynamics are described by the so-called "Navier-Stokes equations", named after Henri Navier and Gabriel Stokes. These equations for the space components x- (length), y- (width) and z- (depth) are used to describe the ocean current's "velocity vector variation with time".

   Important: The "Navier-Stokes equations" are the equations of motion for the instantaneous values of the current. The Reynolds equations are the equations of motion for the mean values of the current variables in a turbulent flow. These variables are used in the ROMS core.

   Preliminary note: The "Reynolds-averaged Navier-Stokes equations" (Reynolds equations) are derived from the "Navier-Stokes equations". This highlights the difference between both equations, which lies in the stress tensor, the so-called Reynolds stresses or the turbulent secondary stresses.

   The Navier-Stokes equation written in "vector notation" shows,

$$\rho \frac{D\vec{v}}{Dt} = \vec{g} + \vec{f} - \nabla p + \mu \Delta \vec{v} + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{1}$$

   that a change of the velocity vector is balanced by gravity, the Coriolis force, the pressure gradient and drag. The friction coefficient μ describes the viscosity of a liquid. Division (of all terms on both sides) by density ρ changes the dynamic viscosity μ into the kinematic viscosity ν, ν = μ/ρ. Approaches to ocean modelling (see the community webpage www.myroms.org and the detailed ROMS tutorial (Hedström, 2016) or ROMS-based modelling systems like RELOC, CORSAR (Onken, 2015a, 2015b) or ROPS (Onken, 2017)) use two additional terms which (due to simplification) can usually not be found in hydrodynamics textbooks, but which are also part of Equation (1) in order to model the natural conditions as closely as possible:

- $\vec{\mathcal{F}}$, "forcing term" for external forces, e.g. tidal forces, wind forces, or the so-called "buoyancy forces" (long/short wave radiation, latent/sensible heat, evaporation, precipitation, river water inflow, all affecting ocean temperature and salinity and, hence, density and buoyancy).
- $\vec{\mathcal{D}}$, "diffusive term".

In Equation (1),

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + (\vec{v} \cdot \nabla) \tag{2}$$

is the Lagrange operator. In "multi-index notation", Equation (1) then is

$$\frac{\partial \vec{v_i}}{\partial t} + \vec{v_j}\,\frac{\partial \vec{v_i}}{\partial x_j} = \vec{g_i} + \vec{f_i} - \frac{1}{\rho}\,\frac{\partial p}{\partial x_i} + \nu\,\frac{\partial^2 \vec{v_i}}{\partial x_j^2} + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{3}$$

with i,j=1,2,3, $\vec{v_{i,j}} = (u, v, w)$, $x_{i,j} = (x, y, z)$, $\vec{f_i} = (f_x, -f_y, f_z)$

Equation (3) in "component notation" directly gives:

j=1,2,3

$$i = 1 \quad \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = g_x + f_x - \frac{1}{\rho}\,\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + \mathcal{F}_u + \mathcal{D}_u \tag{4}$$

$$i = 2 \quad \frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = g_y - f_y - \frac{1}{\rho}\,\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + \mathcal{F}_v + \mathcal{D}_v \tag{5}$$

$$i = 3 \quad \frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = g_z + f_z - \frac{1}{\rho}\,\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + \mathcal{F}_w + \mathcal{D}_w \tag{6}$$

Approximations: First, the horizontal components of the gravitational acceleration $g_x = g_y = 0$ and the vertical component of the Coriolis force $f_z = 0$ are dropped. Then, the hydrostatic approximation $\frac{Dw}{Dt} = 0$ (left side, cf. (2)) is applied to the vertical momentum Equation (6) and the friction (in the vertical component $\nu(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}) = 0$ is neglected. Likewise $\mathcal{F}_w = 0$, $\mathcal{D}_w = 0$.

Remaining from Equations (4), (5) and (6) then is

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = f_x - \frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + \mathcal{F}_u + \mathcal{D}_u \tag{7}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -f_y - \frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + \mathcal{F}_v + \mathcal{D}_v \tag{8}$$

$$0 = g_z - \frac{1}{\rho}\frac{\partial p}{\partial z} \tag{9}$$

Let's now turn to the Reynolds formulation: In this approach, the velocity field consists of a mean value und fluctuations around the mean value: $\vec{v} = \bar{v} + v'$, $p = \bar{p} + p'$. The mean value across all fluctuations shall be zero: $\overline{v'} = 0$, $\overline{p'} = 0$. Substituting this formulation directly into Equation (3) (simplest/shortest method), we get:

$$\frac{\partial \bar{v}_i}{\partial t} + \frac{\partial v_i'}{\partial t} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j} + v_j'\frac{\partial \bar{v}_i}{\partial x_j} + \bar{v}_j\frac{\partial v_i'}{\partial x_j} + v_j'\frac{\partial v_i'}{\partial x_j} =$$

$$g_i + f_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial p'}{\partial x_i} + \nu\frac{\partial^2 \bar{v}_i}{\partial x_j^2} + \nu\frac{\partial^2 v_i'}{\partial x_j^2} + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{10}$$

Now both sides are averaged over time:

$$\overline{\frac{\partial \bar{v}_i}{\partial t} + \underbrace{\frac{\partial v_i'}{\partial t}}_{=0} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j} + \underbrace{v_j'\frac{\partial \bar{v}_i}{\partial x_j}}_{=0} + \underbrace{\bar{v}_j\frac{\partial v_i'}{\partial x_j}}_{=0} + v_j'\frac{\partial v_i'}{\partial x_j}} =$$

$$\overline{g_i + f_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \underbrace{\frac{1}{\rho}\frac{\partial p'}{\partial x_i}}_{=0} + \nu\frac{\partial^2 \bar{v}_i}{\partial x_j^2} + \underbrace{\nu\frac{\partial^2 v_i'}{\partial x_j^2}}_{=0} + \vec{\mathcal{F}} + \vec{\mathcal{D}}} \tag{11}$$

For the remaining terms

$$\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j} + \underbrace{\overline{v_j'\frac{\partial v_i'}{\partial x_j}}}_{=a} = g_i + f_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \bar{v}_i}{\partial x_j^2} + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{12}$$

a) is moved to the right-hand side and rewritten (continuity equation and reverse product rule), which gives the Reynolds equation:

$$\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j} = g_i + f_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \underbrace{\nu\frac{\partial^2 \bar{v}_i}{\partial x_j^2}}_{=b} \underbrace{- \frac{\partial}{\partial x_j}\overline{\left(v_j'v_i'\right)}}_{\text{a\_Reynolds}} + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{13}$$

Formally, the Reynolds equation differs from the Navier-Stokes equation in only one additional term, the Reynolds stresses, which have been marked "a_Reynolds" in Equation (13) and which are often also referred to as "turbulent secondary stresses". Collecting the terms "a_Reynolds" and "b" in Equation (13) by putting $\frac{\partial}{\partial x_j}$ outside the brackets,

$$\frac{\partial \bar{v}_i}{\partial t} + \bar{v}_j\frac{\partial \bar{v}_i}{\partial x_j} = g_i + f_i - \frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\overline{\left(v_j'v_i'\right)} - \nu\frac{\partial \bar{v}_i}{\partial x_j}\right) + \vec{\mathcal{F}} + \vec{\mathcal{D}} \tag{14}$$

gives the established Reynolds equations as components (Hedström, 2016, Equations (1) – (3), or Onken, 2015b, Equations (1) – (3)):

$$\frac{\partial u}{\partial t} + \underbrace{\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right)}_{=\vec{v}\cdot\nabla u} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} - \frac{\partial}{\partial z}\left(\overline{u'w'} - \nu\frac{\partial u}{\partial z}\right) + \mathcal{F}_u + \mathcal{D}_u \tag{15}$$

$$\frac{\partial v}{\partial t} + \underbrace{\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right)}_{=\vec{v}\cdot\nabla v} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} - \frac{\partial}{\partial z}\left(\overline{v'w'} - \nu\frac{\partial v}{\partial z}\right) + \mathcal{F}_v + \mathcal{D}_v \quad (16)$$

$$\rho g = \frac{\partial p}{\partial z} \quad (17)$$

Next, the Reynold stresses are parameterised:

$$\overline{u'w'} = -K_M\frac{\partial u}{\partial z} \text{ and } \overline{v'w'} = -K_M\frac{\partial v}{\partial z} \quad (18)$$

$$\frac{\partial u}{\partial t} + \vec{v}\cdot\nabla u - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(-K_M\frac{\partial u}{\partial z} - \nu\frac{\partial u}{\partial z}\right) + \mathcal{F}_u + \mathcal{D}_u \quad (19)$$

$$\frac{\partial v}{\partial t} + \vec{v}\cdot\nabla v + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(-K_M\frac{\partial v}{\partial z} - \nu\frac{\partial v}{\partial z}\right) + \mathcal{F}_v + \mathcal{D}_v \quad (20)$$

$$\rho g = \frac{\partial p}{\partial z} \quad (21)$$

2) (1 differential equation, Equation (25)) The **"continuity equation"** says that the "ocean water mass" is conserved ("water mass conservation"). It relates current velocity with current cross section: If the current cross section decreases (while the volume of water moved remains unchanged), the current velocity must increase. The streamlines get narrower and an "ocean jet stream" may occur.

Lagrange's mass conserva-tion: $\frac{D\rho}{Dt} + \nabla\cdot(\rho\,\vec{v}) = 0$ (22)

Euler's mass conservation: $\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\,\vec{v}) = 0$ (23)

Approximations: The Boussinesq approximation is applied, i.e. small-scale differences and variations in density are neglected, $\frac{D\rho}{Dt}=0$, $\frac{\partial\rho}{\partial t}=0$. If the density ρ is independent (or only slightly dependent) from the location/position, it can be put in front of the divergence operator $\rho\nabla\cdot\vec{v}$ and the mass conservation is reduced to the volume conservation in the incompressible fluid:

$$\nabla\cdot\vec{v} = 0 \quad (24)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (25)$$

3) (2 differential equations, Equation (26), for C = T und C = S respectively) The **"conservation of a quantity C"** is described by a "advection-diffusion equation". If we put quantity C = S (salt), this means that salt cannot simply disappear in ocean water. "In a closed system", salt can change location by advection (ocean current), or move on small space scales (millimeter-scale or smaller, down to the size of molecules, atoms or charge carriers) due to thermal energy, but never disappear completely. The equation therefore describes the mass conservation of salt in the ocean (**"salt mass conservation"**).

If we put scalar C = T (temperature), the equation leads to the "conservation of thermal energy". This form of **"energy conservation"** corresponds to the "first law of thermodynamics" which describes the energy exchange between a system and its environment. Only in a closed system, the total energy is constant, and its change is zero. Energy in the form of heat or work can be transformed, but neither created nor destroyed.

$$\frac{\partial C}{\partial t} + \vec{v} \cdot \nabla C = -\frac{\partial}{\partial z}\left(-K_C \frac{\partial C}{\partial z} - \nu_\theta \frac{\partial C}{\partial z}\right) + \mathcal{F}_C + \mathcal{D}_C \tag{26}$$

The turbulent tracer fluxes herein are again parameterised (cf. Equation (18)):

$$\overline{C'w'} = -K_C \frac{\partial C}{\partial z} \tag{27}$$

4) (1 polynomial, Equation (28)) The **"equation of state"** for seawater uses a function – a polynomial – to describe the correlation between temperature, salinity, pressure and the resulting density. Density is a nonlinear function of temperature (T), salinity (S) and pressure (p).

$$\rho = \rho\,(T, S, p) \tag{28}$$

Table 1: List of variables used

C (x,y,z,t)	scalar quantity, e.g. temperature, salinity, nutrients etc.
$\mathcal{D}_u$, $\mathcal{D}_v$, $\mathcal{D}_C$	diffusive terms
$\mathcal{F}_u$, $\mathcal{F}_v$, $\mathcal{F}_C$	forcing terms
f (x,y)	Coriolis parameter
g	gravitational acceleration
h (x,y)	water depth between ocean floor and mean sea level
ν, ν_θ	molecular viscosity
K_M, K_C	vertical eddy viscosity and diffusivity
p	total pressure
Q_C	surface concentration flux of temperature or salinity
t	time
T (x,y,z,t)	potential temperature
S (x,y,z,t)	salinity
τ_b^x, τ_b^y	(x,y) components of the bottom stress vector $\vec{\tau_b}$
τ_s^x, τ_s^y	(x,y) components of the bottom stress vector $\vec{\tau_s}$
u,v,w	(x,y) components of the wind stress vector $\vec{v}$
x,y	horizontal coordinates
z	vertical coordinate
c_p	specific heat of seawater
ζ (x,y,t)	surface elevation

4.2 Initial Conditions

A set of nonlinear partial differential equations usually poses an "inital value problem"and a "boundary value problem". This section covers the *initial value problem*. The differential equations can be solved numerically except for a random "integration constant". This is also a well-known problem when solving differential equations analytically. This integration constant represents the initial state from which to start the integration for each individual calculation step. At this starting time, the seven state quantities must be known for all grid points.

The analysis of the operational “MERCATOR global” model is used to initialise the grid points. The “parent model” has a resolution of 1/12° (= 5′ = 5 nm = 9.26 km) and a prediction period of 7 days.

Using higher-resolution basin-scale models for various regions as an alternative was also discussed and temporarily tried. For example, the Mediterranean Forecasting System (MFS) of the INGV at the University of Bologna (ITA) could be used for the Mediterranean Sea. It has a resolution of 1/16° (= 3.75′ = 3.75nm = 6.945 km). So the MFS model’s resolution is only 1.25 nm higher, while the MERCATOR global model with its slightly lower resolution has the advantage that the individual RELOC nests can be moved freely to the varying global operating areas[5].

The use of too many different model sources to define the initial conditions for the RELOC nests is unintended (“potpourri of different models”) because the resulting large number of different data streams with its accordingly high susceptibility to failure is inacceptable for a fully automated “operational model use”. This is also the reason why large institutions like the British Weather Service, for which oceanography also is an important field (UKMO), use their global ocean model (FOAM) as the basis for their regional ocean nests for crisis regions. The model core of the British global model FOAM, like the core of the French global model MERCATOR, is based on the community model NEMO (Nucleus for European Modeling of the Ocean), which is constantly being further developed by the community.

The European Commission has delegated the French non-profit company Mercator Ocean to provide a service known as “Copernicus Marine Environment Monitoring Service” (CMEMS).

This service (CMEMS) is a European maritime provider and will in the future be funded by ownership shares to various nations. Again: From the diverse pool of models, the MERCATOR model has been selected for use due to the reasons mentioned above.

The CMEMS server is accessed on a daily basis by means of a Python script. For the individual model nests, an appropriate section is extracted from the global model and copied to the DMRZ. The data is then preprocessed further, i.e. the MERCATOR data is adapted to the RELOC nests, because these nests use different (vertical and horizontal) grid point fields and projections. This includes coordinate transformations, vector conversions and interpolation for the individual model nests.

Initialisation with climate data is not used, as this data often deviates considerably from the current climate conditions. This is due to the fact that the 30-year averaging erases or blurs mesoscale structures (e.g. eddies, meanders, transients). Initialisation using real measurements, i.e. in situ data, e.g. ARGO data, is the ideal solution for global scales/models. However, adequate (area-wide) data is not always available for small nests. Own area-wide simultaneous in situ measurements with several research vessels, e.g. to provide data for regional models, are very complex and have therefore only been carried out for certain temporary projects like MILOC or REA surveys (Paul, 2015, p.27ff).

4.3 Boundary Conditions

The following section covers the boundary value problem of the system of differential equations, i.e. the solution must be prescribed or satisfied at the boundaries. The “model box” has a surface, a boundary surface towards the ocean floor, and usually four lateral boundaries/surfaces (north, south, west and east), depending on the geographic location of the model box and the resulting distribution of the land-sea grid points.

4.3.1 Surface Boundary Conditions

The condition, i.e. the solution of the model ocean at the surface, largely depends on the exchange with the atmosphere above. For operational use, the individual ocean model nests are therefore linked in real-time to the “overlying” high-resolution meteorological model nests[6], the RLMs of the MetBW group at the DWD in Offenbach (Majewski et al, 2016). In areas for which the DWD’s ICON EU nest is available, this nest will be

[5] Furthermore, the MERCATOR model is more suitable for the Mediterranean region than the MFS Modell initially used for testing purposes (personal note by Dr. Onken, CMRE/HZG), as it offers a better reproduction of water masses. MFS is too cold in the thermocline.

[6] For comparison purposes, here are the resolutions of some established meteorological models/model nests:
- ICON global (DWD): horizontal 13 km
- ICON EU (DWD): horizontal 7 km, used for the following ocean nests: Strait of Gibraltar, Eastern Mediterranean Sea, Western Black Sea
- RLMs (BW): 7 km, used for the following ocean nests: Gulf of Aden, Strait of Hormuz, Somalia
- GFS global (NOAA/NCEP): horizontal 28 km. Available for free on the Internet and therefore often used by sailors, despite its low resolution. The associated software “zyGrib” can then be used to select and download via modem a tailored and compressed data section in the Grib format GFS and then plot meteorological maps on board (“box around own boat”). Due to the resolution, this data is not used as forcing field.

used. The link is currently established as a one-way link[7], i.e. the current status of the atmosphere (analysis) and the state quantities predicted with regard to time and space (predictions) are transferred to the ocean model in exactly fitting "one-hour steps" (current sampling interval). The ocean model then responds to this meteorological forcing. Seven meteorological quantities with hourly values are retrieved from the DWD's database, prepared (adjustment of the various grids and projections, calculation of derived quantities, e.g. the wind stress from the wind vector) and provided as input file *(roms_met_frc_datum.nc)* for the upcoming ROMS calculation run:

1) **Surface wind** *(wind_u_v_10m_date.nc)*. Ocean surface currents are mainly determined or modified by wind friction[8] (Ekman transport), which also changes the pressure field.
2) **Precipitation** *(total_accumulated_precipitation_date.nc)*. Salinity is changed by precipitation and evaporation. Ocean density depends on temperature, salinity and pressure.
3) **Shortwave radiation** *(short_wave_radiation_date.nc)*. Affects the temperature and, hence, the heat content in near-surface layers. This is the main cause of diurnal variations in the ocean surface temperature.
4) **Cloud cover** *(total_cloud_cover_date.nc)*. During periods of heavy cloud cover, less of the sun's radiant energy reaches the ocean surface to increase the temperature (item 3), so the cloud cover must be known. Constant longwave terrestrial radiation can be concealed or permitted by cloud cover: "radiation weather".
5) **Atmospheric pressure** *(pressure_msl_date.nc)*. Changes in the atmospheric pressure over wide areas also affect the amount of surface elevation and must be considered in the calculation of the evaporation.
6) **Relative humidity** *(relative_humidity _date.nc)*. Indicates the current percentage of the maximum possible water vapour content of the air. The relative humidity and the current temperature can be used to calculate the dew point temperature, and vice versa. Below the dew point temperature, the water vapour contained in the air can (at constant pressure) condense as dew (or fog) which may result in a humidity input in the ocean (latent heat). The opposite effect, evaporation, is also important for the heat and water balance.
7) **Air temperature** *(air_temp_2m_date.nc)*. The air temperature is an important quantity for the heat exchange between the ocean and the atmosphere (sensible heat) and for the calculation of latent heat.

These seven quantities are essential for the <u>exchange between the ocean and the atmosphere</u>. They interact or depend on each other, which can be seen in the example of heat and radiation fluxes:

– When looking at the *<u>heat fluxes</u>* in direct conduction (e.g. from warm to cold in two bodies of different temperature) or thermal convection (e.g. Gulf Stream), the effects of a heat exchange can be measured directly in the form of "sensible heat" (item 7, "Air temperature"). In the case of evaporation or precipitation (items 2 and 6) of water vapour, the "hidden/latent energy" associated with the process (phase transition) is released or absorbed, which in turn may lead to an increase or decrease of the air temperature.
– In addition to the (sensible and latent) heat fluxes, *<u>radiation fluxes</u>* (thermal radiation, i.e. electromagnetic radiation, e.g. in the infrared spectrum) are also important: Shortwave radiation is described in item 3. Longwave terrestrial radiation, again, is dependent on the temperature (globally averaged in accordance with the Stefan-Boltzmann law), but also on cloud cover, which can reduce terrestrial radiation. Items 3 and 4 refer to a consideration of the "radiation balance".

---

[7] A "two-way link", in which the ocean's response to the meteorological forcing is returned to the atmospheric model, is a current topic of research. With such a link, an increase in the heat content of the ocean could, for example, affect the state quantities of the atmosphere, as known from the formation of hurricanes, El Nino etc.

[8] There are also strong currents without wind, e.g. tidal currents. These are, however, modified under (strong) wind conditions: "storm surges".

At the ocean surface z = ζ(x,y,t), the vertical momentum transport is described by the wind stress ($\overrightarrow{\tau_s}$), and the angular momentum equations (19) and (20) are replaced by

$$K_M \frac{\partial u}{\partial z} = \tau_s^x (x, y, t) \quad (29)$$

$$K_M \frac{\partial v}{\partial z} = \tau_s^y (x, y, t) \quad (30)$$

The associated routine calculates the wind stress from the wind (bulk flux routine).
At the ocean surface, the continuity equation (25) is converted to

$$w = \frac{\partial \zeta}{\partial t} \quad (31),$$

i.e. the vertical velocity w equals the vertical movement of the ocean surface ζ(x,y,t).

The conservation equation of a scalar quantity C (26) is converted to an equation of the surface concentration fluxes, e.g. for temperature and salinity.

$$K_C \frac{\partial C}{\partial z} = \frac{Q_C}{\rho_0 \, c_p} \quad (32)$$

4.3.2 Ocean Floor Boundary Conditions

The bottom boundary condition is the ocean floor: z = -h (x, y). In ROMS, the horizontal velocity can be specified by a linear, squared or logarithmic soil stress term $\overrightarrow{\tau_b}$. The velocities are parallel to the ocean floor. Due to friction, they drop to zero directly at the ocean floorl: u ≡ v ≡ 0

$$K_M \frac{\partial u}{\partial z} = \tau_b^x (x, y, t) \quad (33)$$

$$K_M \frac{\partial v}{\partial z} = \tau_b^y (x, y, t) \quad (34)$$

The same is true for the vertical velocity: No exchange takes place through the ocean floor: w ≡ 0

$$w = \vec{v} \cdot \nabla h \quad (35)$$

The vertical concentration fluxes are also set to zero at the ocean floor

$$K_C \frac{\partial C}{\partial z} = 0 \quad (36)$$

(cf. www.myroms.org, Hedström, 2016, Onken 2015a and 2015b).

4.3.3 Lateral Boundary Conditions

The high-resolution ocean models have different boundaries. Depending on the geographic location, the distribution of the land-sea grid points is also different.

- Where lateral boundaries are formed by a coast, they are referred to as closed boundaries and an exchange of physical quantities does not occur.
- If the lateral boundaries run through the open sea/ocean, they are referred to as open boundaries. In this case, an exchange with the environment must take place via the parent model, because not all of the oceanographic processes in this small high-resolution model area originate from or evolve in the area itself. Instead, currents or waves can be introduced into this model area via the open boundaries and then propagate or interact further. Therefore, a method known as "nesting" is used. In this method, the current state quantities are taken over at the open boundaries from the global model MERCATOR. In a first step, a Python script is used to cut out and transfer data from the global model. This data also covers the model nest. However, as already described in Section 2.2, "Initial conditions", the RELOC model nest differs from the MERCATOR parent model:

- The RELOC nests are based on the ROMS model, which is a *"sigma-coordinate model"*, where the vertical coordinates follow the respective ocean floor topography. The MERCATOR model is based on the NEMO model, which is a "z-coordinate model" using fixed vertical support points. Hence, a vertical interpolation to the ROMS depths to be calculated must be performed.
- Horizontally, interpolation to the higher-resolution RELOC grid is required.
- RELOC and MERCATOR use different land masks and bathymetries, which have to be developed during model setup and then adapted to the higher-resolution RELOC model grid *(grid.nc)*.
- Variable names must be adapted, time data must be aligned with a unified reference date and the boundary values must be retrieved from the three-dimensional fields.

The MERCATOR output therefore has to be processed in various preparation steps (routine LARGE-2ROMS.m) resulting in one single input file for the respective RELOC nest *(boundary.nc)*. This file provides the boundary values for each time step at each boundary grid point and is read in prior to each RELOC model run.

Recap: Prior to each model run, four ROMS files are read from the input directory (ROMS-input):

- *boundary.nc* contains the lateral boundary values. A new version of the file is generated from the oceanographic parent model on a daily basis.
- *forcing.nc* contains the surface boundary values from the meteorological model. A new version of the file is generated on a daily basis.
- *grid.nc* contains the numerical grid, the land-sea grid point distribution, i.e. the topography and bathymetry which have been processed in such a way as to ensure stable operation of the model. Too steep slopes, small islands, extreme shallow water zones with numerous vertical layers etc. can have a negative impact on model stability. It is therefore not possible to use just "any" bathymetry when stable operation of the model is to be achieved. Once this file has been created successfully in terms of model stability, it remains unchanged for this model nest.
- *restart.nc* contains the model results from the most recent model run.

4.4 The ROMS Model

Sections 4.1 to 4.3 described the "primitive equations" with the initial and boundary conditions. If these equations are approximated with an appropriate procedure (finite difference method, grid point method), forward integration can be used to calculate the future state $t = t_0 + \Delta t$ if the ocean's state at time $t_0 = t_0$ (u, v, w, T, S, …) is known.

This is exactly what the ROMS model is doing. The various ocean models (e.g. ROMS, NEMO[9] use different methods of discretisation:

a) Numerical scheme

b) Horizontal grid

c) Vertical grid

d) Time discretisation and CFL criterion

a) Numerical scheme

ROMS uses a second-order "centered difference scheme" (central grid point *i* calculated using grid point *i-1* and grid point *i+1*) (Taylor series expansion up to square terms).

[9] Information on whether to select ROMS or NEMO as a basis for this technical project can be found in Section 3.

b) Horizontal grid

The "Arakawa C-grid" is used. Figure 8 shows that it is a "staggered" grid. The free surface (ζ), density (ρ), temperature (T) and salinity (S) is calculated at the centre of the grid cells (rho-points), while the velocity components (u, v) are calculated at their (east, west) and (north, south) boundaries (u-points, v-points). The Xs in Figure 8 are called "psi points". They are required for internal calculations, e.g. to initialise and process the land-sea grid point field.

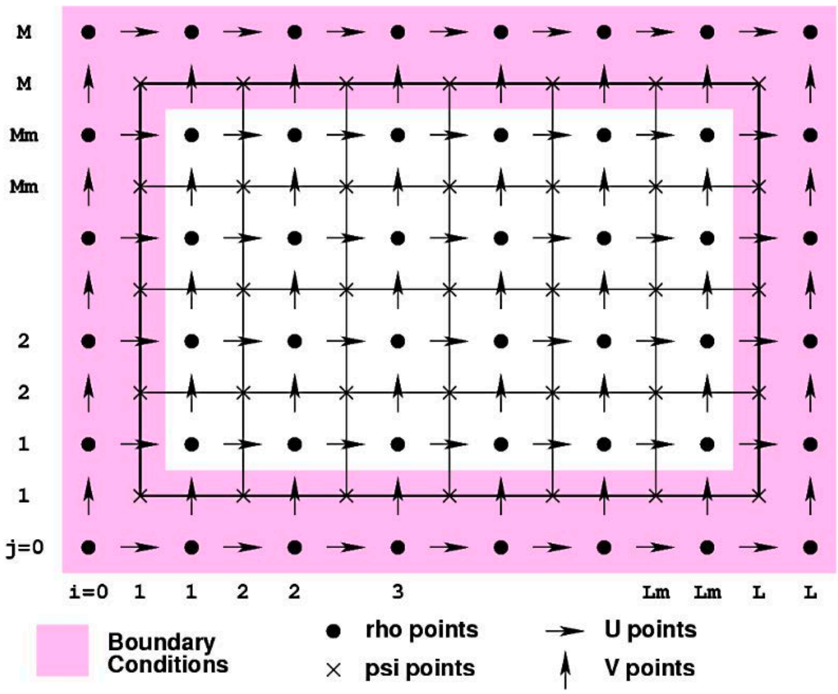

Figure 8: *The horizontal ROMS calculation grid (Arakawa-C). The model area is shown in white, the red area is the boundary condition taken from the parent model. The variables are explained in the text (source: www.myroms.org).*

c) Vertical grid

The vertical discretisation is also performed using second-order centered differences on a staggered grid. "Terrain-following coordinates" in parallel with the ocean floor topography are used as vertical coordinates. Figure 9 shows that the number of vertical coordinates j = 0, …, N from the ocean floor h (i, j) to the ocean surface ζ (i, j) is one greater than the number of the intermediate layers Hz (1, …, N)[10]. Each grid cell can have different layer thicknesses (Hz) and volumes.

The state variables u, v, ρ, T, S are calculated at the centre of each grid cell, while the vertical velocities are calculated at the surface and floor of each grid cell. This shows: Near the coast, the layers get extremely shallow so that even at Hz/2 the surface is almost reached, with only a few centimetres missing. In the open ocean, the uppermost grid point for (u, v, ρ, T, S) also doesn't reach the ocean surface (only for the vertical velocity w), but only Hz/2, which, however, can be a couple of metres here.

If required, the oceanographic parameters at the ocean surface (z = 0 metres) can be gained by interpolating between the sigma grid point Hz/2 closest to the surface and the surface itself (z = 0 metres)

[10] Usually the terms "Layers" (Hz (1, …,N)) and "Levels" (vertical coordinates j = 0, … , N) are used, showing that there are N layers and N+1 levels. ROMS takes this into account by using different starting points for the run index.

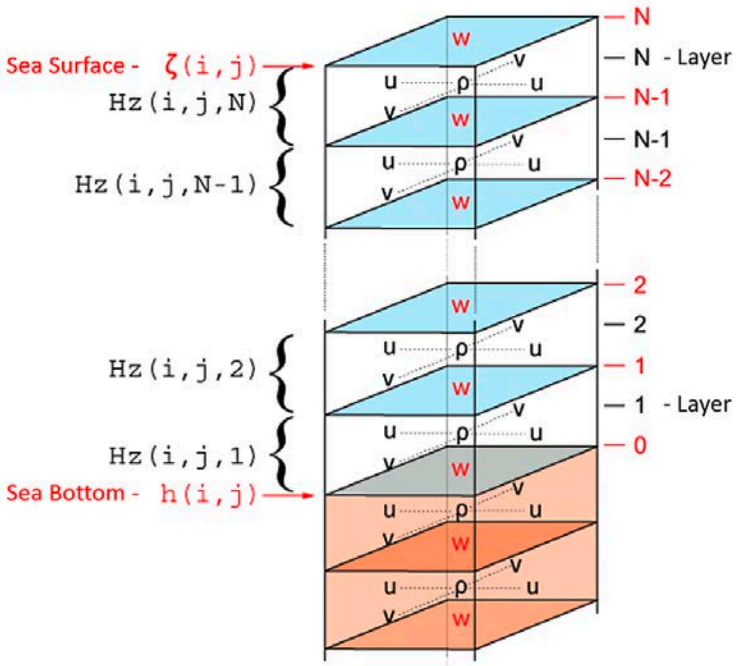

Figure 9: *The vertical ROMS calculation grid. The oceanic area is shown in blue (see text for description).*

d) Time discretisation and CFL criterion

Making predictions requires forward integration. Various numerical schemes are available (Euler, Leapfrog, AB3, etc.), and the various ROMS versions use different forward integration algorithms. An overview can be found on the ROMS community website (www.myroms.org).

This section provides only the information required for the understanding of the operational use of the model nests (e.g. in case of necessary changes to the control file).

Each model nest has an *"ocean.in"* control file. This file can easily be adjusted, e.g. to change the interval (parameter: NHIS) in which the prediction results are written to an output file, e.g. every 12 hours to limit the size of the output files or every 30 minutes to get detailed ocean current information including the tides (e.g. Siedler and Paul, 1991) or to create ocean current videos.

The calculation time steps, however, cannot be chosen freely! They have to be determined in accordance with the Courant-Friedrichs-Lewy stability criterion (CFL criterion). The following considerations are made:

The required computing time is proportional to the number of model grid points used in (x, y, z) and the number of required calculation time steps t. In order to represent nature as realistically as possible, the highest possible model grid point resolution is desired[11], which leads to an increasing number of model grid points[12]. The aim is therefore to keep the number of calculation time steps t small, which means using the largest possible calculation interval Δt_{max}.

It is this Δt_{max}that is predefined by the CFL criterion (Equation (38)). This is based on the idea that for a predefined model grid point resolution Δx, Δy und Δz the sampling time interval Δt may not be greater than a Δt_{max}, to be determined, to make sure that signals propagating in the ocean (currents and waves) will be resolved and won't fall through the calculation grid.

[11] Hence, the "nesting" method is used, because arbitrarily high resolutions cannot be used for calculations on a global scale.

[12] If only half of the horizontal grid point distance were used in a numerical model, the computer calculation would take eight times longer (Roeckner, 2003).

The maximum velocity of the numerical integration must therefore be higher than that of the fastest propagating signals in the ocean:

$$\frac{\Delta x}{\Delta t_{max}} > \vec{v}_{max} \tag{37}$$

A scaling factor, the CFL number, can be introduced, where cfl < 1 is required to facilitate a stable numerical integration [13] converging towards a solution and to prevent numerical values from growing endlessly and causing the model to "burst":

$$\frac{\Delta x}{\Delta t_{max}} \cdot cfl > \vec{v}_{max} \quad , with\ cfl = [0,1] \tag{38}$$

For cfl = 0.5, the "sampling theorem" can be recognized, which says,

$$\Delta t_{max} < 0{,}5 \cdot \frac{\Delta x}{\vec{v}_{max}} \tag{39}$$

that the maximum interval Δt_{max} must be selected in such a way that during one time step t, the signal $\vec{v}_{max}$ may not propagate through more than one half of a grid cell 0.5 ·Δx.

In its control file *(ocean.in)*, the ROMS model uses two different time steps:

1) DT, the *"baroclinic time step"*
2) DTFAST, the *"barotropic time step"*

Re. 1: DT is used to resolve the signal of the fastest baroclinic current or wave. This current or wave may not propagate through more than one half of a grid cell during one time step (Equation (39)). If, as a "first guess", $\vec{v}_{max}$ ~ 2 m/s und Δx ~ 1500 m (e.g. for the Gibraltar model) is chosen, we get

$\Delta t_{max(horizontal,\ baroklin)}$ ~ 375 sec.

Re. 2: DTFAST is used to resolve fast barotropic gravity waves, i.e. long waves like, for example, tsunamis. If, as a "first guess", a water deph of H = 4000 m is chosen, we get a phase velocity for these waves of

$$\vec{v}_{max} = \sqrt{g\,H}\ \left[\frac{m}{s}\right] \sim \sqrt{40.000}\ \frac{m}{s} \sim 200\ m/s$$

and with Δx ~ 1500m we get $\Delta t_{max(horizontal,\ barotrop)}$ ~ 3,75 sec.

The ROMS model interrelates both time steps (DT, DTFAST) by predefining in the control file the number of barotropic time steps the slow baroclinic time step can be split up into: NDTFAST = DT/DTFAST.

$$NDTFAST = \frac{\Delta t_{max(horizontal,\ baroklin)}}{\Delta t_{max(horizontal,\ barotrop)}} \sim \frac{375\ sec}{3{,}75\ sec} = 100$$

Hence, as a "first guess", the results for the largest possible time steps with respect to the horizontal CFL criteria are known: DT = 375 sec and NDTFAST = 100.

However, the vertical CFL criterion must still be considered:

"The current's vertical velocity may also not propagate through more than one half of the vertical layer thickness."

If the number of layers is large (N = 40 or larger), these layers become very thin in shallow water zones. The time steps become accordingly shorter, depending on the number of layers, the bathymetry (depending on the occurrence of extreme shallow water zones) and the maximum occurring vertical velocities (e.g. strong upwelling area or not). Starting with the "first guess" described above, Δt_{max} is then determined iteratively. Hence, the largest possible time steps differ for the various regional model nests. For the currently operational eight model nests, they range from DT = 108 sec and DT = 432 sec with NDTFAST = 30 to 40.

[13] This is true for an „explicit Euler scheme". Other discretisation schemes might result in other stability conditions.

5 Progression from ROMS Computer Core to RELOC System, Project Performance

5.1 Preliminary Remarks: Selecting the ROMS Ocean Model as the Basis

When selecting an appropriate ocean model as the basis for this technical project, the only suitable options available were the ROMS and NEMO models. NEMO has become well established for global modelling and basin-scale models. But NEMO is also used for "regional models": For example, regional NEMO models are nested in the global NEMO model at the UKMO. ROMS, on the other hand, has become established worldwide as a regional model. In addition, there is a large developer and user community (www.myroms.org). The ROMS model also offers some considerably large expansion stages (Section 3.2). ROMS was preferred for operational use in the NATO (NURC/CMRE) and the US NAVY (as TOMS model version: Tactical Ocean Modeling System). Therefore, the ROMS model was selected in the initialisation phase of the technical project in 2011.

5.2 From ROMS Computer Core to RELOC System – Project Performance

The ROMS package is available for free on the Internet[14]. Various modules can be loaded into ROMS as expansions: a tidal model, a sediment dispersion model, a sea-ice model or a bio-geochemical model. ROMS is provided with modules for data assimilation using different variation methods and with software for ensemble prediction. It can be linked to the sea state model SWAN, and there are other large pre and post processing software packages available.

Project performance:

In 2011, the author of the technical project has written up detailed specifications for the overall RELOC system to ensure its compliance with both the requirements of the German Navy and the requirements for operational use.

It is not sufficient to provide highly complex mathematical ROMS software routines as source texts. Moreover, model nests reflecting the special environmental conditions in each operating area must be set up and then configured to run fully automated. The resulting "system" must be programmed for robust and reliable operation.

The list below shows some example specifications:

- Prediction models for the known operating and exercise areas of the German Navy shall be created.
- ROMS shall be used as integration core.
- The models shall be high-resolution models.
- Models shall be nested to achieve high resolution.
- Real-time MERCATOR model data shall be used to initialise the model and provide boundary values, as an initialisation with climatological fields will definitely deliver wrong results.
- Data from the MetBw at the DWD or the DWD itself shall be used to provide boundary values.
- Land-sea grid point fields shall be created for each model nest.
- The entire model operation shall be automated by means of scripts. This also applies to all of the data streams from France (MERCATOR) or Offenbach (MetBW/DWD).

---

[14] The ROMS package is "open source" distributed under the GNU/MIT/X license: „Copyright © 2002-2014 The ROMS/TOMS Group ". See http://www.opensource.org/licenses/mit-license.php
„Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the „Software"), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:
The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.
THE SOFTWARE IS PROVIDED „AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PAR-TICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE."

- Operational use shall be fail-safe. A smart restart and reboot method has been implemented to this end.
- Prediction results shall be archived for 7 days to allow for follow-ups.
- The overall RELOC system shall be run at the DMRZ

The "RELOC system" was developed in close cooperation between the technical project management and the project scientist in accordance with the specifications. The overall system was developed by the project scientist Dr. Onken at the NATO CMRE in La Spezia (now HZG, Helmholtz Zentrum Geesthacht).

5.3 Currently Used Computer Platform and Environment at the DMRZ

A standard "personal computer Intel i5 with 4 cores" ("RELOC computer") integrated into the DMRZ network at the DWD has been used as computer platform since 2015. Using the DWD network, it was possible to establish a connection with external computers, which was necessary to provide the external data (MERCATOR model data/FRA) required for routine operation (see footnote 1).

The "RELOC computer" has only few processor cores, so all of the model nests had to be computed in succession. During the further development of the software (Section 7.1), the models were in part ported to the DMRZ computers for testing purposes. On these computers, the models are operated in parallel. However, routine operation will continue on the RELOC computer (parallel operation) until the end of the test phase. The following section describes the serial run of the programme on the RELOC computer. Section 7.1 then describes the further development on the DMRZ computers.

5.4 The Time Sequence on the RELOC Computer in "Operational Use"

The model runs start with *"Aden"* at 05:30 UTC and are completed with *"BlackSea"* at 18:30 UTC. All models perform a hindcast of three days (see Section 7.2.1, data assimilation). The following models perform a forecast of two days: Aden, Somalia, Hormus. The models Gibraltar, EastMed, BlackSea perform a forecast of three days. Pre-processing includes data transfer (download) of the oceanographic and meteorological input data and their full preparation. The integration time includes the forward integration of the hindcast and forecast using ROMS. Preprocessing includes the interpolation to a regular vertical grid, the summarisation of the output files ("merge and grid"), the entire graphics production and the data transfer from the RELOC computer in Euskirchen to the Navy GeoInfo computer in Rostock. Details are shown in the following list (excerpt from the log files):

I)	Aden		
	05:30Z Start	Preprocessing: 33′	Overall runtime: 2h 16′
	06:03Z Integration day 1: Start	Integration time: 54′	
	06:57Z Integration day 5: End		
	07:46Z Job finalized	Post-processing: 43′	
II)	Somalia		
	07:45Z Start	Preprocessing: 31′	Overall runtime: 4h 2′
	08:16Z Integration day 1: Start	Integration time: 2h 17′	
	10:33Z Integration day 5: End		
	11:47Z Job finalized	Post-processing: 1h 14′	
III)	Hormus		
	11:00Z Start	Pre-processing: 23′	Overall runtime: 1h 54′
	11:23Z Integration day 1: Start	Integration time: 53′	
	12:16Z Integration day 5: End		
	12:54Z Job finalized	Post-processing: 38′	

IV)	Gibraltar		
	12:45Z Start	Pre-processing: 15'	Overall runtime: 1h 30'
	13:00Z Integration day 1: Start	Integration time: 49'	
	13:49Z Integration day 6: End		
	14:15 Job finalized	Post-processing: 26'	
V)	EastMed		
	14:20Z Start	Pre-processing: 19'	Overall runtime: 2h 41'
	14:39Z Integration day 1: Start	Integration time: 1h 36'	
	16:15Z Integration day 6: End		
	17:01Z Job finalized	Post-processing: 46'	
VI)	BlackSea		
	17:15Z Start	Pre-processing: 14'	Overall runtime: 1h 13'
	17:29Z Integration day 1: Start	Integration time: 29'	
	17:58Z Integration day 6: End		
	18:28 Job finalized	Post-processing: 30'	

This shows that the overall production run takes 13 hours, and that the end results are not available until 18:28 UTC. With the further development (Section 7.1), the overall production run has been reduced to a maximum of two hours.

6 Examples for the Eight Ocean Prediction Models Currently in Operational Use and their Military Relevance

In accordance with the chronological development of the models, the Ionian Sea model, which served as the "prototype" for the technical project, is described first, followed by the six RELOC models. The last example shows the operation model Libya/SOFIA, a result of the further development which has been in operational use since 2017.

For each model, a table with a summary of the facts is provided.

6.1 Ionian Sea

This ocean model has been in operational use by the German Navy since October 2010. It runs on a server in Rostock[15] (Paul, 2012) and was used for demonstration purposes in the development of all follow-up models. As part of the further development (Section 7.1), this model will be rewritten in advanced Python code for pre- and post-processing and job management purposes in 2019, after which it can also be run in parallel with all the other ocean models at the DMRZ. In order to standardise and improve the operational service, the provided initial and boundary values will also be changed from MFS to MERCATOR.

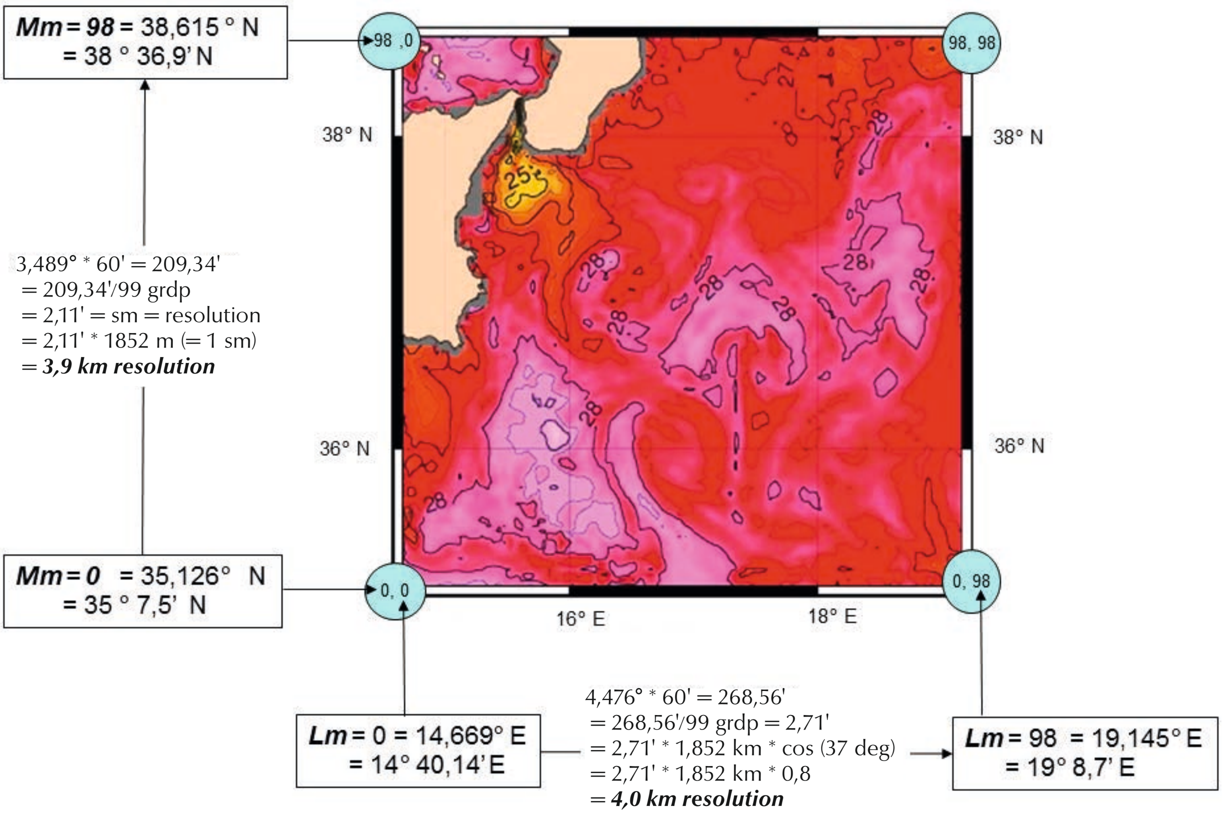

Figure 10: *The "Ionian Sea" area east of Sicily and the ocean surface temperature. This figure shows the number and distribution of the grid points in length and width as well as the resulting model resolution (cf. Figure 8). The array Lm x Mm can easily be recognized.*

Short name: IonSea Military relevance: NATO submarine exercise area ("Proud Manta", "Noble Manta", etc.)	
Horizontal resolution: 3.9 km	Number of vertical layers N = 40
Lm = 98 Mm = 98	NTIMES = 864 DT = 300 sec NDTFAST = 30

[15] The model has been running on a server at the GeoInfoW MarA Rostock, later MarKdo Rostock, since 2010. A RELOC computer was not used until 2015.

6.2 Strait of Gibraltar

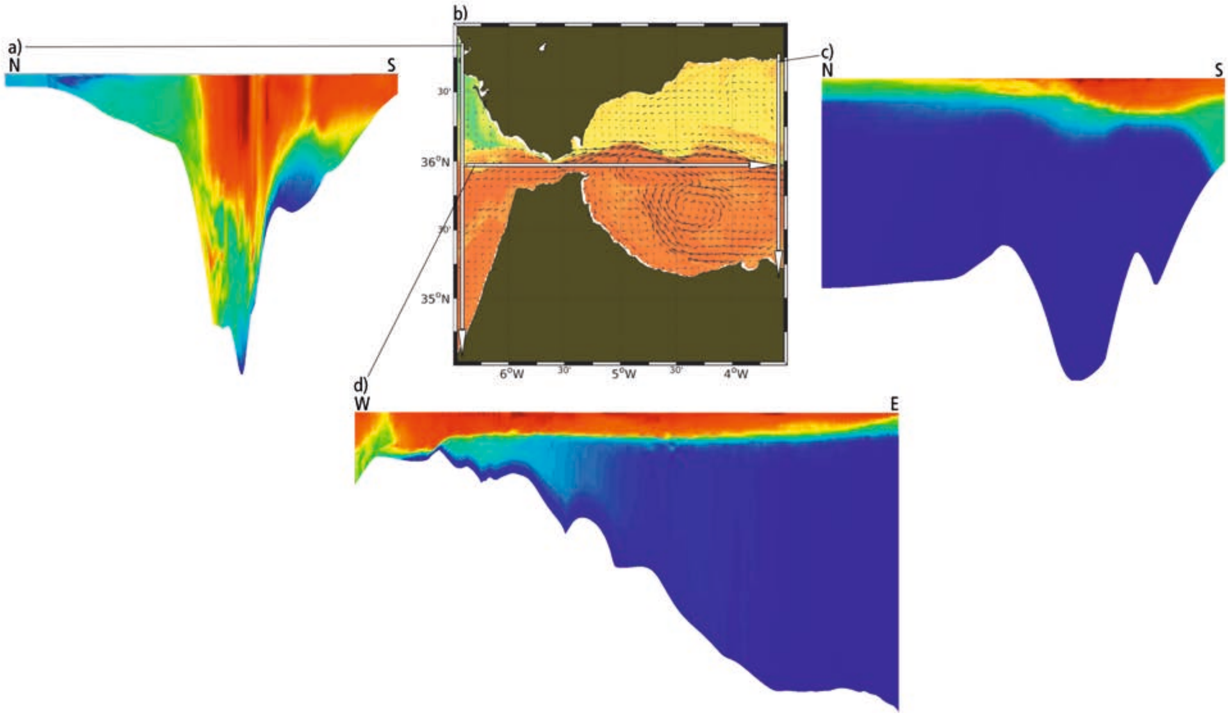

Figure 11: *The "Strait of Gibraltar" model area and three vertical sections. The first vertical section (a) runs from north to south along the western boundary, which is marked with (b) in the horizontal representation. The second section (d) runs from west to east across the strait, and the third section (c) runs from north to south along the eastern boundary. It is plain to see how shallow the entry to the strait is (max. 300 m) and how rapidly the ocean floor descends towards the Alboran Sea down to more than 1400 m. The Alboran Gyre can easily be recognised, although it only encompasses the southern part of the Alboran Sea due to the position of the influx. The central section (d) shows a distinct boundary between the warm water flowing in from the Atlantic Ocean near the surface (red) and the outflowing cold water below (blue). In the vertical section, interruptions of the two-layer regime appear near the flat anticline at the entry to the strait (d). These interruptions may be attributed to eddies, hydraulic jumps and resulting internal waves.*

Short name: Gibraltar Military relevance: OAE, OSG (Operation Active Endeavor, NATO Operation Sea Guardian)	
Horizontal resolution: 1.84 km	Number of vertical layers N = 32
Lm = 179 Mm = 183	NTIMES = 800 DT = 108 sec NDTFAST = 40

6.3 Eastern Mediterranean Sea

The sea area, the surface temperature and currents are shown in Figure 1a.

Short name: EastMed Military relevance: UNIFIL	
Horizontal resolution: 1.78 km	Number of vertical layers N = 32
Lm = 191 Mm = 294	NTIMES = 800 DT = 108 sec NDTFAST = 40

6.4 Western Black Sea

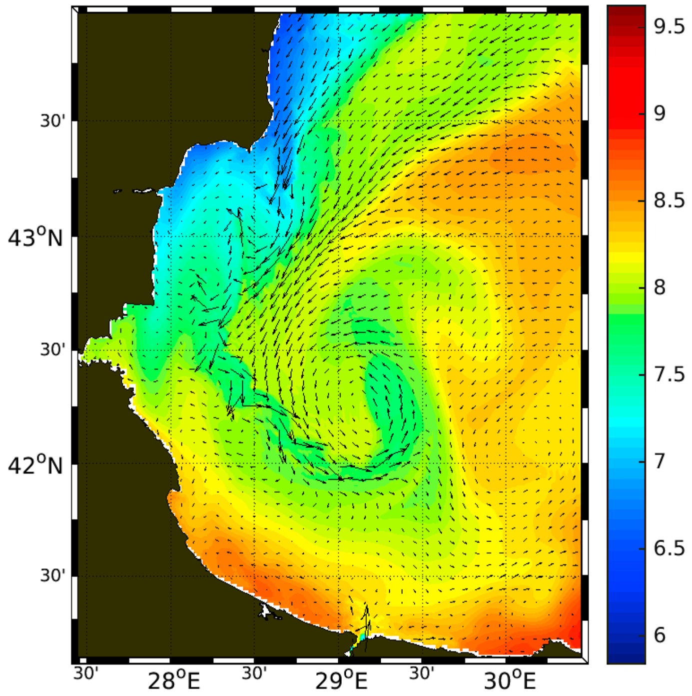

Figure 12: *Shown as an example is the "Western Black Sea" area, the ocean surface temperature and the ocean currents.*

Short name: BlackSea Military relevance: NATO forces	
Horizontal resolution: 2.03 km	Number of vertical layers N = 32
Lm = 168 Mm = 213	NTIMES = 400 DT = 216 sec NDTFAST = 40

6.5 Gulf of Aden

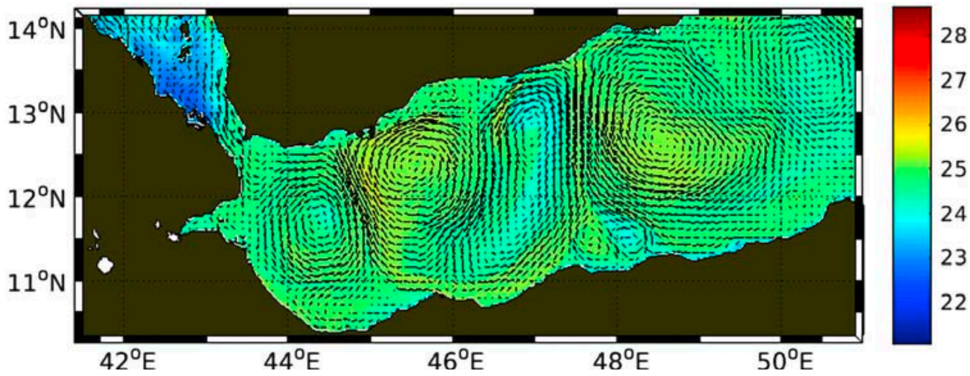

Figure 13: *Example for the surface temperature and ocean currents of the "Gulf of Aden" sea area. The central double eddies in this region have been observed repeatedly and are also described in literature/ briefing dockets.*

Short name: Aden Military relevance: ATALANTA/Ocean Shield	
Horizontal resolution: 2.56 km	Number of vertical layers N = 32
Lm = 414 Mm = 176	NTIMES = 400 DT = 216 sec NDTFAST = 40

6.6 East Coast of Somalia

The North Monsoon (similar to the Northeast Trades) occurs off the coast of Somalia between December and March. It is linked to a strong littoral southbound current, the Somali Current. Figure 14 shows a strong southbound current parallel to the coast.

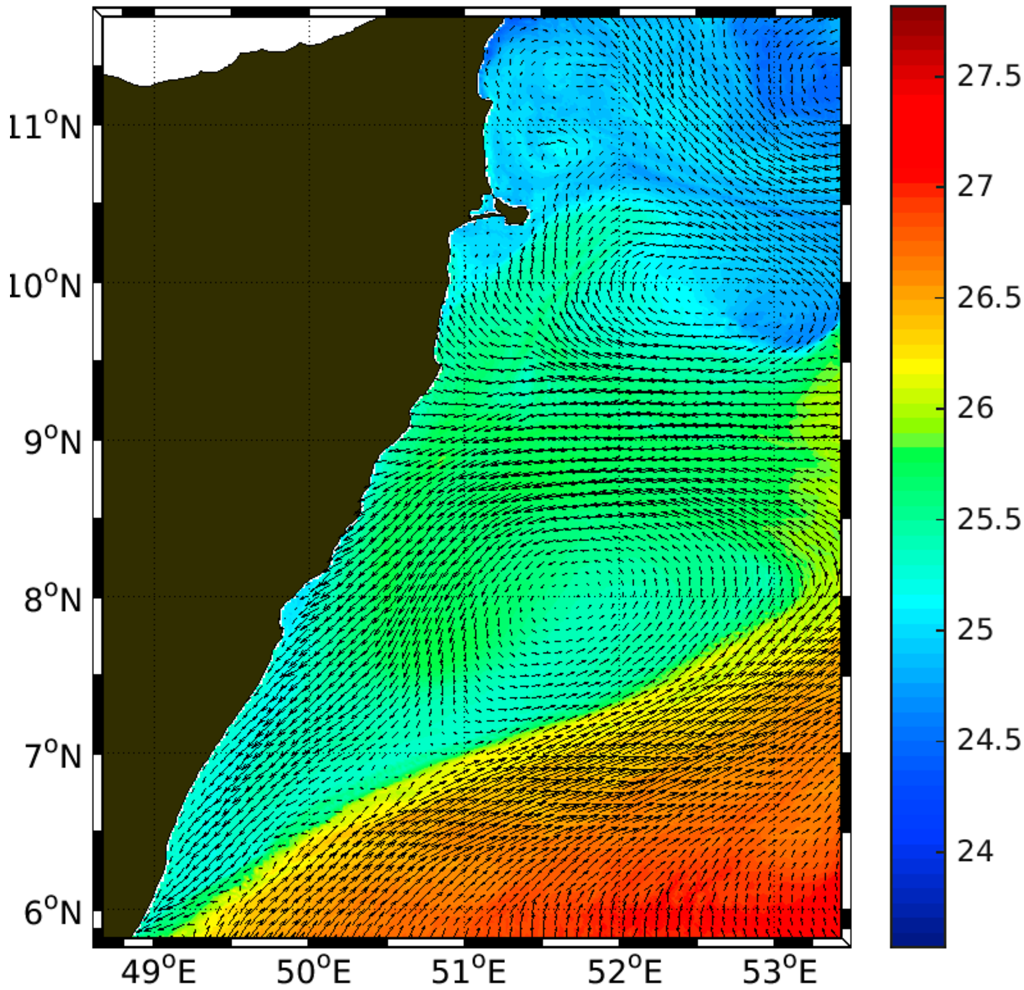

Figure 14: *The large sea area off Somalia, dominated by seasonal monsoon winds and currents. A strong southbound current can be observed off the coast.*

Short name: Somalia Military relevance: ATALANTA/Ocean Shield	
Horizontal resolution: 2.02 km	Number of vertical layers N = 32
Lm = 268 Mm = 331	NTIMES = 800 DT = 108 sec NDTFAST = 40

6.7 Strait of Hormuz

The model shows eddies, meanders and current branches. Warm water at a temperature of more than 30°C frequently accumulates off the coast of Oman, which can be seen in satellite images. Warm water from the Arabian Sea often spreads from the Gulf of Oman to the most northern point of the strait (30 nm wide at the narrowest point) where the Gulf of Oman transitions into the Persian Gulf.

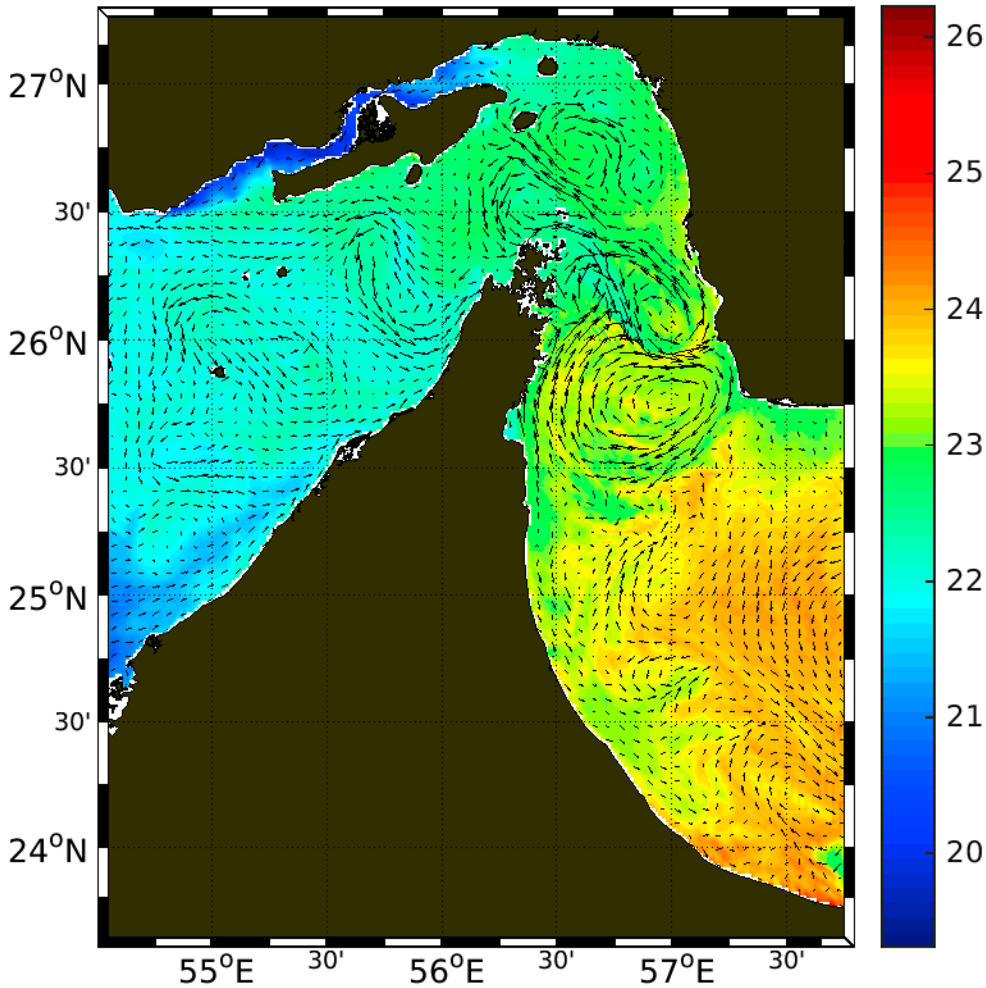

Figure 15: *The "Strait of Hormuz" sea/model area. Eddies, meanders and current branches can easily be recognised, as well as the warm water inflow from the open sea, the Gulf of Oman.*

Short name: Hormus Military relevance: Ocean Shield	
Horizontal resolution: 1.66 km	Number of vertical layers N = 32
Lm = 219 Mm = 271	NTIMES = 400 DT = 216sec NDTFAST = 40

6.8 Central Mediterranean Sea

The Libya model was created to provide advice for operations in the context of the refugee problem. Operational use of the model could not commence until the technical improvements were implemented in 2017 (Section 7.1).

Figure 16 shows the model area, the surface temperatures and ocean currents. Particularly interesting is the fact that the (virtually) permanent eddy "Iera Petra", which is known in literature, is also captured (Mkhinini N. et al., 2014). This is sometimes also used as a "quality attribute for models" (Kantha L., (2000), S.618). The eddy is named after Europe's southernmost city ("Iera Petra") and is located south of the Isle of Crete.

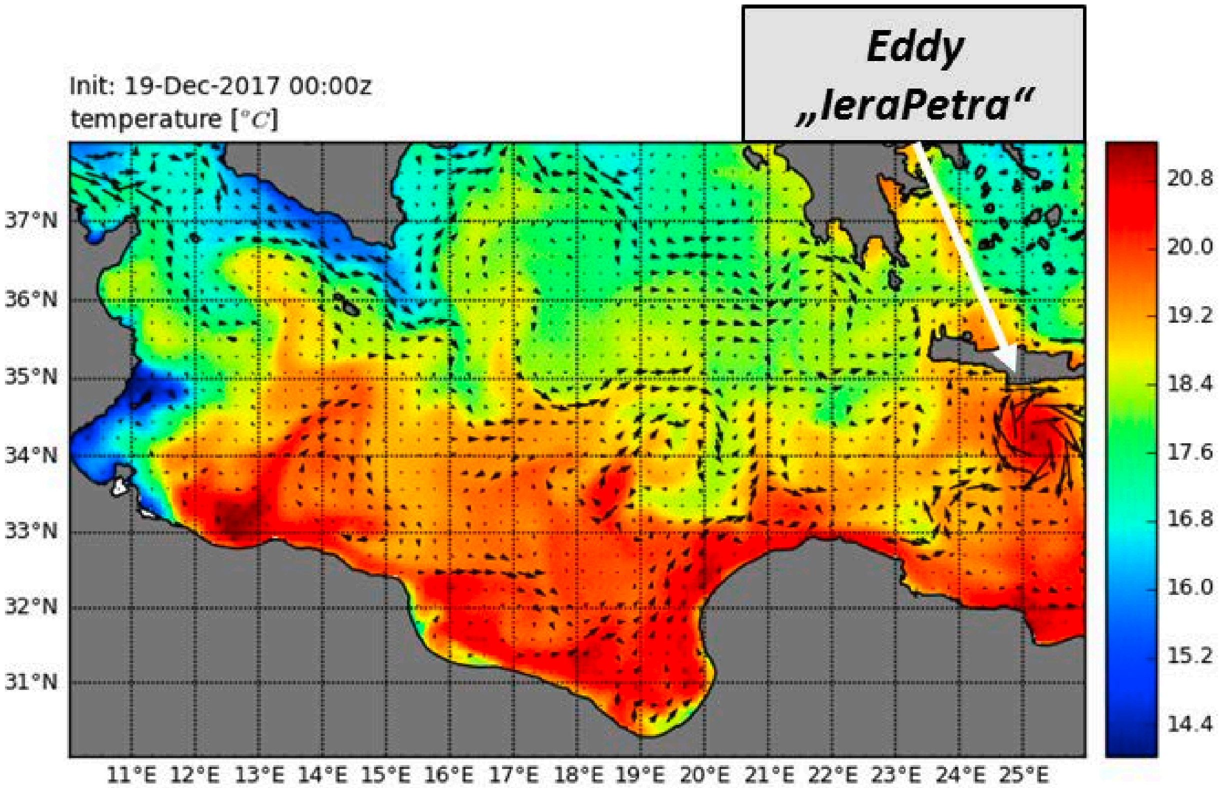

Figure 16: *The "SOFIA" operating area. The ocean currents and surface temperatures are shown as examples. This is an "eddy-resolving" model, which is reflected in the (virtually) permanent eddy "Iera Petra".*

Short name: Libyn Military relevance: Operation SOPHIA	
Horizontal resolution: 4.8 km	Number of vertical layers N = 32
Lm = 414 Mm = 220	NTIMES = 200 DT = 432 sec NDTFAST = 40

7 Further Developments

The following section discusses two areas of further development: Technical advancements of, for example, the computer architecture (PC or HPC) or the software running on those computers etc. and scientific advancements by implementation of new scientific findings.

7.1 Technical Advancements

– *Relocatable Ocean Circulation Model (ROCM)*

The programme control for the eight model nests and the entire pre- and post-processing were reprogrammed from MATLAB to Python. During this process, the majority of the Python code has been optimised and parallelised. This was a pre-requisite for porting the models to the DMRZ computers[16] and running them in parallel. The new versions of the models, which are now also running on the DMRZ computers, shall be designated as ROCM in the following to be able to differentiate between the two versions (PC version in MATLAB vs. HPC version in Python).

– *Product server*

The eight models mentioned above have been installed on the Bundeswehr's so-called "lcb" product server. This product server is a Linux cluster with currently 384 cores which the Bundeswehr has procured for special tasks in addition to the 20% share of the DMRZ mainframe computer. Unlike when running the models on a RELOC PC, it is now necessary to define the number of cores to be used. This number depends on the size of the operating area: One MPI task is created for each degree, resulting in 6 MPI tasks for an area of 3 x 2 degrees (see Table 2). The calculated number is written into the model control file *(ocean_service.ksh)*. The total number is limited to a maximum of 128 to avoid resource problems.

Figure 17: *The product server of the Bundeswehr element of the DMRZ in Euskirchen, on which all of the ocean model nests are currently run.*

[16] This does not apply to the computer core ROMS (!), as this has already been programmed in modern F90/F95.

Table 2: Overview of the total run time of the individual models with the corresponding number of cores currently used[17].

Model	Computing time	Cores
Aden	1h 25′	55
Somalia	1h 35′	42
Hormus	1h 9′	20
Gibraltar	46′	16
EastMed	1h 27′	20
BlackSea	1h	16
Libyn	2h	128

– *High Performance Computer, mainframe (HPC)*
  The port to the DMRZ routine computer (HPC CRAY-XC40)[18] is scheduled to take place after the completion of the test phase on the product server (Figure 17). A further decrease of the overall model run times can currently be expected more in the field of model integration than in the pre- and post-processing times. In case advanced scientific methods like ensemble predictions and data assimilation (Section 7.2) shall be introduced, usage of an HPC is obligatory.

Figure 18: *Mainframe computer of the DMRZ (CRAY-XC40) in Offenbach. The computer is operated by the DWD; the Bundeswehr's share of the computing capacity is 20 % (source: DWD).*

[17] The Ionian Sea model will be ported in the near term because the way the boundary values are provided must also be changed (from MFS to MERCATOR).

[18] The DMRZ is provided with two mainframe computers (CRAY-XC40), one for routine operation (west building) and one for research (east building).

7.2 Scientific Advancements

Improved quality of advisory services and instant provision of high resolution infor-mation/predictions for new sea/operating areas supported by *“simple, quick and worldwide relocatability of the ocean nests”* is definitely worth striving for! This requires the creation of a worldwide numerical grid with a regional resolution (minimum 1 km – 4 km) containing a “land-sea grid point distribution” of the bathymetry and topography and which can be used as the basis for numerically stable calculation (see Section 4.4, part d, CFL criterion). This frequently requested advancement has the potential to become a scientific project of its own. Prof. Allan Robinson[19] of Harvard University had already prepared the project “Dynamical Modelling Along the Fleet” (personal note by Dr. Onken), which was unfortunately never carried out or published.

7.2.1 Data Assimilation

The CMRE and Joint Research Partner (JRP) conducted various data assimilation (DA) experiments in which the measured data collected by the research vessels “RV Alliance” and “FS Planet” was assimilated into ROMS ocean models in real time, using different assimilation methods (Onken et al., 2014):

- ROMS EnKF, Ensemble Kalman Filter
- ROMS 4Dvar, four-dimensional variation scheme (JRP, WTD71)
- ROMS EnOI, Ensemble Optimal Interpolation

These methods were tested at the NATO CRME. As they are very sophisticated, their use is at the moment reserved for scientific studies due to the following reasons:

- Using, for example, the 4Dvar method, the computing time for a model run is 10 to 100 times higher (60 hours of CPU time on an 8-core Intel workstation for the above experiment, Onken et al, 2014, p. 55). Such an extensive computing time is insignificant for the scientific analysis of the above data material in the hindcast. Handling the massive computing effort of a real time prediction for operational use, however, would require the use of a mainframe computer.
- A suitable supply of data must be ensured at all times. A sufficient number of measured values and their proper areal distribution must be provided for each model run.

Hence, the following approach is currently preferred:

- First, the exact prediction quality for the eight models currently in operation must be determined. This will show whether improvement of the prediction quality by means of sophisticated data assimilation is required at all or if the current prediction quality is sufficient for operational purposes. It must be considered that measured data is already assimilated into the MERCATOR parent model and that this information is handed over during initialisation using the “nesting” method. The model nest then runs with a relatively short look-ahead time (3 days) for which it is consistently provided with up-to-date boundary values from the parent model.
- Model validation shall be carried out using all available data sources (satellite data, measured data collected by vessels, ARGO floats etc.) It must be considered that, due to their high resolution (sometimes less than 2 km), regional model nests only cover a comparatively small area, for which adequate data for a model-data comparison must be available so that a reliable statistical prediction can be made.

[19] Allan Robinson (17 October, 1932 – 25 September, 2009) was a Professor at Harvard University in Cambridge (Massachusetts, USA). He has carried out joint projects with the NATO Underwater Research Centre in La Spezia (SACLATCEN/NURC, now CMRE), e.g. in the field of ocean modelling (Harvard Ocean Prediction System, HOPS).

- If the prediction quality of the ocean nests is to be further improved and an adequate amount of data for a sufficiently large area is available, a relatively straightforward, quick and well-established data assimilation method, like e.g. the optimised interpolation (OI), can be used. A simple method for the creation of grids can also be found, for example, in Paul (1994). Current status: The OI method is already implemented in the system and the models are able to calculate the required 3-day hindcast. All that is left to do is to create a data pool for routine operation, which will also be made freely available by CMES.

7.2.2 Introduction of a Nudging Algorithm

In operational use, the ocean models run fully automatically. A nudging algorithm is to be installed between the model nest and the parent model to prevent the model solutions from drifting off too far from the parent model. Current status: The algorithm is ready to be implemented as part of the next software update.

7.2.3 Follow-up Models

All oceanographic parameters are now available as analyses and predictions for various operating areas (5D information, e.g. sound velocity fields c (x, y, z, t)). For the first time, these parameters can be used as the forcing for a hydro-acoustic follow-up model which is range-dependent in terms of time and space to determine sonar conditions. It represents nature more realistically than a rangeindependent method, because the impact of fronts, eddies, meanders etc. on the sonar conditions can be taken into account when calculating the sound propagation in the ocean. The dimensions of these factors also vary over time. Findings from the models are also being used in the multistatic sonar field.

Information about other follow-up models (drift etc.) and their benefit for the Navy can be found in Section 1.2.

8 Outlook

The increasing number of Navy operations in foreign waters worldwide requires knowledge of the maritime environment. Oceanography-based advice will be crucial for many tasks, e.g. planning operations abroad, making the best-possible use of sensors, including tactical aspects, or avoiding danger to personnel and equipment.

Oceanographic features and characteristics may change rapidly over time. It is therefore necessary now and in the future to anticipate these changes with numerical prediction models and take the possible impact on military operations into account.

List of References

Fachprojektblatt 3310-0050-5577 (2011) *Regionales Ozeanmodell*. Projektmanagementhandbuch, AGeoBw.

Hedström K. (2016) *Technical Manual for a Coupled Sea-Ice/ Ocean Circulation Model (Version4)*. Arctic Regional Supercomputing Center University of Alaska Fairbanks, US Department of the Interior, Bureau of Ocean Energy Management, Alaska OCS Region, Anchorage Alaska, Cooperative Agreement No. M14AC00014, OCS Study BOEM 2016-037.

Mkhinini N., Coimbra, A. L. S., Stegner, A., Arsouze, T., Taupier-Letage, I., Béranger, K (2014) *Long-lived mesoscale eddies in the eastern Mediterranean Sea: Analysis of 20 years of AVISO geostrophic velocities*. J. Geophys. Res., Oceans 119.

Kantha L. (2000) *Numerical Models of Oceans and Oceanic Processes. AP International Geophysics Series*, Volume 66.

Majewski D., Reinhard T., Thiel D. (2016) *Numerische Wettervorhersage*. GeoInfoForum, Mitteilungen des Geoinformationsdienstes der Bundeswehr, 1/2016.

Marinekommando (2015) *Unsere Marine hilft Menschen in Not*. Marinekommando Presse- und Informationszentrum, 5.8.2015, (www.marine.de).

Nagy A. B. et.al. (2012) *Integrated Decision Aid (IDA)*, User Manual. Draft CMRE Technical Report.

Onken R., Ampolo-Rella M., Baldasserini G., Borrione I., Cecchi D., Coelho E., Falchetti S., Fiekas H.-V., Funk A., Jiang Y.-M., Knoll M., Lewis C., Mourre B., Nielsen P., Russo A., Stoner R. (2014) *REP14-MED Cruise Report*. NATO Science and Technology Organization Centre for Maritime Research and Experimentation (STO-CMRE). CMRECR201406REP14MED.

Onken R. (2015a) RELOC. *Eine detaillierte Systembeschreibung*. Unveröffentlichtes Manuskript, CMRE-Februar 2015.

Onken R. (2015b) CORSAR- *A Rapidly Relocatable Ocean Forecasting System*. CMRE-MR-2015-011. November 2015.

Onken R. (2017) *Forecast skill score assessment of a relocatable ocean prediction system, using a simplified objective analysis method*. Ocean Science, EGU, 13.

Paul U. (1994) *Objektive Analyse ozeanographischer Daten mit orthogonalen Polynomflächen*. Deutsche Hydrographische Zeitschrift, Vol 46, No. 1, 29 -60.

Paul U. (2010) *Vorhersage von Wellen und Strömung in der Brandungszone als taktische Entscheidungshilfe*. GeoInfoForum, Mitteilungen des Geoinformationsdienstes der Bundeswehr, 1/2012.

Paul U. (2012) *Erstmals ARGO- Drifter von Deutscher Marine ausgelegt – FGS Lübeck in der Ionischen See*. GeoInfoForum, Mitteilungen des Geoinformationsdienstes der Bundeswehr, 1/2012.

Paul U. (2012) *Das Regionale Ozeanmodell bei MarA Geo für die Ionische See/Mittelmeer im operationellen Betrieb*. GeoInfoForum, Mitteilungen des Geoinformationsdienstes der Bundeswehr, 1/2012.

Paul U. (2015) *Mehrzweckboot „FGS Kronsort" im Einsatz: Ozeanographische Messfahrt in der Straße von Gibraltar, im Nordostatlantik und bei den Britischen Kanalinseln*. Schriftenreihe Geoinformationsdienst der Bundeswehr, Heft 1, 2015, ISSN 1865-6978.

Paul U. (2018) *Regionale Ozeanvorhersagemodelle im operationellen Betrieb für die Marine*. Schriftenreihe Geoinformationsdienst der Bundeswehr, Heft 1, 2018, ISSN 1865-6978.

Roeckner E. (2003) *Allgemeine Zirkulationsmodelle*, Atmosphäre. Promet, Jahrg. 29, Nr. 1–4, 2003.

Siedler G., Paul U. (1991) *Barotropic and Baroclinic Tidal Currents in the Eastern Basins of the North Atlantic*. Journal of Geophysical Research, Vol. 96, 22259 - 22271.

Strode C. (2010) *Transitioning the Multistatic Tactical Planning Aid (MSTPA) towards decision support software*. NURC-FR-2010-013.

List of Abbreviations

AGeoBw	Amt für GeoInformationswesen der Bundeswehr (Bundeswehr Geoinformation Office). Now ZGeoBw.
ARGO	The ARGO programme is a joint project of more than 30 nations worldwide. Approx. 3900 so-called ARGO floats provide real time ocean ranging. These diving and surfacing robots measure temperature, salinity, oxygen and other parameters from the surface down to a depth of approx. 2000 metres. The ARGO programme is part of the GOOS global ocean observing system and is named after the Greek mythical ship Argo.
ASW	Anti submarine warfare (e.g. frigate vs. submarine).
ATALANTA	EU NAVFOR Somalia - Operation ATALANTA. EU naval forces formed to protect humanitarian aid for Somalia and the freedom of shipping and to counter piracy off the coast of Somalia, the Horn of Africa and in the Gulf of Aden. The operation is named after the virgin huntress Atalanta in Greek mythology.
AUV	Autonomous underwater vehicle.
BND	Bundesnachrichtendienst (Federal Intelligence Service)
CFL criterion	Courant-Friedrichs-Lewy stability criterion.
COSMO	Consortium for small-scale modelling. Weather prediction model used as the basis for RLM model nests.
COSMO - EU	COSMO - Europe segment.
CMEMS	Copernicus Marine Environment Monitoring Service. European maritime service provider.
CMRE	Center for Maritime Research and Experimentation (previously NURC, SACLANT CEN, NATO Undersea Research Centre in La Spezia, ITA).
CSAR	Combat SAR. Conduct of SAR missions in combat areas.
DMRZ	German meteorological data processing centre. Jointly operated by DWD and the Bundeswehr.
DWD	Deutscher Wetterdienst (German Meteorological Service).
EUNAVFOR MED	EU operation SOPHIA to counter migrant smuggling and for crisis management in the Mediterranean Sea.
FOAM	Forecasting Ocean Assimilation Model. A British ocean model.
FTP	File Transfer Protocol. Method for the transmission of data between computers.
GeoInfoDBw	Geoinformationsdienst der Bundeswehr (Bundeswehr Geoinformation Service).
GOOS	Global Ocean Observing System.
HPC	High Performance Computer. DWD mainframe computer, currently two CRAY XC40 systems with a Linux pre-cluster.
HZG	Helmholz-Zentrum Geesthacht. Zentrum für Material- und Küstenforschung GmbH (Centre for Materials and Coastal Research). Member of the Helmholtz Association of German Research Centres (the largest scientific organization in Germany).
ICON	ICOsahedral Nonhydrostatic. The DWD's global nonhydrostatic weather prediction model using an icosahedral grid.
ICON – EU	ICON - Europe segment.

IMETOC	NATO cooperation for METOC support of exercises and operations.
INGV	Instituo nationale di geofisica e vulcanologia (Italian). Italian government-owned research facility located in Rome, with various branches and observatories.
MarA	Marineamt (German Naval Office).
MarKdo	Marinekommando (German Navy Headquarters).
MCM	Mine countermeasures.
MERCATOR	Name of the ocean model operated by the French non-profit organisation Mercator Ocean.
MetBw	ZGeoBw branch at the DWD.
MFS	Mediterranean forecasting system.
MilNW	Militärisches Nachrichtenwesen (military intelligence).
METOC	Meteorology and Oceanography.
MN MSG	Multinational METOC Support Group.
MSTPA	Multistatic Tactical Planning Aid.
NATO	North Atlantic Treaty Organization.
NEMO	Nucleus for European Modeling of the Ocean. EU community ocean model.
NetCDF	Network Common Data Format. Format widely used in geosciences for saving/exchanging data.
NMDH	NATO METOC Data Hub. Computer with software for the distribution of METOC data to support NATO operations.
NURC	NATO Undersea Research Center (now CMRE).
NWP	Numerical weather prediction.
OAE	Operation Active Endeavor. NATO solidarity and counter-terrorist operation in the Mediterranean Region.
Ocean Shield	Operation Ocean Shield is a NATO navy operation to counter piracy in the Gulf of Aden.
OSG	Operation Sea Guardian. OAE has been superseded by OSG.
REA	Rapid Environmental Assessment. NATO concept for rapid environmental assessment. Assessment of environmental conditions and evaluation of impacts on NATO operations.
RLM	Relocatable Local Model. High-resolution meteorological model nest.
ROMS	Regional Ocean Modeling System. Ocean model of Rutgers University, USA. Currently the largest community with highly active users (ROMS forum): www.myroms.org.
RELOC	Relocatable Ocean Modeling System. Ocean prediction system with MATLAB-based pre- and post-processing.
ROCM	Relocatable Ocean Circulation Model. Ocean prediction system with PYTHON-based pre- and post-processing. Further development of RELOC, run-time optimised.
SACLANT CEN	Supreme Allied Commander Atlantic (SACLANT) Anti Submarine Research Center (now CMRE).

SAR	Search and Rescue. Emergency rescue services operating internationally on behalf of the government. All countries are obliged to establish Rescue Coordination Centers (RCCs) for coordination purposes. The German Maritime Rescue Coordination Center (MRCC) is located in Glücksburg.
SARIS	Search and Rescue Information System. Software/computer programme to optimise the conduct of SAR missions.
SW	Submarine warfare (e.g. submarine vs. submarine).
MCM	Mine countermeasures.
MCMEXPERT	NATO MCM EXclusive Planning Evaluation Risk Tool. NATO software/model for mine countermeasures.
MSM	Minehunting simulation model. Similar to SPI, sonar performance indicator for minehunting sonar systems.
SPI	Sonar performance indicator for minehunting sonar systems.
TOMS	Tactical Ocean Modeling System. ROMS version for the US Navy.
UKMO	United Kingdom Met Office. British Weather Service, headquarters located in Exceter, UK.
UNIFIL	United Nations Interim Force in Lebanon. Naval force under the command of the United Nations off the coast of Lebanon. Mission to promote peace between Israel and Lebanon, to control sea routes and to train the Lebanese navy.
ZGeoBw	Zentrum für Geoinformationswesen der Bundeswehr (Bundeswehr Geoinformation Centre).

Notizen

Bisherige Veröffentlichungen in der Schriftenreihe des GeoInfoDBw

Mit der Fusion des Militärgeographischen Dienstes der Bundeswehr und des Geophysikalischen Beratungsdienstes der Bundeswehr werden die Fachpublikationen der beiden Dienste in der Schriftenreihe des GeoInfoDBw zusammengefasst. Damit beginnt eine neue Aufzählung der bisherigen Veröffentlichungen.

Heft 1, 2003 Regierungsdirektor Dr.-Ing. Fischer
Geophysikalisch bedingte Leistungsgrenzen der Hubschrauber CH-53G und CH-53GS

Heft 1, 2004 Oberst a.D. Dipl.-Ing. Oskar Albrecht
Beiträge zum militärischen Vermessungs- und Kartenwesen und zur Militärgeographie in Preußen (1803-1921)

Heft 2, 2004 Oberst a.D. Dipl.-Ing. Hafeneder
Überblick über das Militärische Geowesen Deutschlands im 19. und 20. Jahrhundert

Heft 1a, 2008 Oberst a.D. Dipl.-Ing. Rudolf Hafeneder
Deutsche Kolonialkartographie 1884–1919 (TEXT-BAND)

Heft 1b, 2008 Oberst a.D. Dipl.-Ing. Rudolf Hafeneder
Deutsche Kolonialkartographie 1884–1919 (ANLAGEN-BAND)

Heft 1, 2009 Regierungsdirektor Dipl.-Met. Wolfgang Meyer und weitere Autoren
Geschichte des Geophysikalischen Beratungsdienstes der Bundeswehr – 1956 bis 2003 –

Heft 2, 2009 Georg Mischuk
Piraterie in Südostasien

Heft 3, 2009 Hartmut Behrend, Dr. Wolfhart Dürrschmidt, Christian D. Falkowski, Dr. Monika Lanik, Dr. Judith Miggelbrink, Dennis Tänzler, Prof. Dr. Heinz Theisen, Frank Wehinger
Jahresheft Geopolitik 2008 (Inhalt: • Migration in die erweiterte EU • Klimawandel)

Heft 4, 2009 GeoDir Dr. Willig
Die Odyssee des Wehrgeologenarchivs als Teil der Heringen Collection

Heft 5, 2009 Oberst a.D. Dipl.-Ing. Theo Müller und Dirk Hubrich
Überblick über das Karten- und Vermessungswesen des deutschen Heeres von 1919 bis 1945

Oberst a.D. Dipl.-Ing. Theo Müller
Die Divisionskartenstellen des deutschen Heeres von 1939 bis 1945

Heft 1, 2010 T. Albrecht und D. Gärtner
Besonderheiten der Seewetterberatung (Teil 1)

T. Albrecht und I. Hinrichs
Der Einfluss des küstennahen Auftriebsphänomens auf die Konzentrationen von Dimethylsulfid an der Meeresoberfläche (Teil 2)

T. Albrecht und R. Wolke
Messung und Modellierung von CH2O-Variationen in der marinen Atmosphäre (Teil 3)

T. Albrecht
Meteorologische Verhältnisse im Atlantik und Nordpazifik im Sommer 2004 (Teil 4)

Heft 2, 2010 Steffen Bauer, M.A., PD Dr. Stefan Bayer, Col John Fitzgerald, Prof. Hermann Kreutzmann, Dr. Hans-Jochen Luhmann, Prof. Christian-D. Schönwiese
Jahresheft Geopolitik 2009 (Inhalt: • Geopolitische Herausforderungen des 21. Jahrhunderts • Klimawandel und Energiesicherheit)

Heft 3, 2010 Andreas Dachs
Rechenzeitoptimierung, Robustifizierung und Tuning eines Kalmanfilters zur Datenfusion für Navigationsanwendungen

Heft 4, 2010 Dr. Torsten Albrecht
Atmosphäre und Ozean im Nördlichen Polargebiet

Heft 1, 2011 Rolf Clement, Leonhardt Van Efferink, Melanie Hanif, Michel-André Horelt, Ralf Lasinski, Annegret Mähler, Peter Cornelius Mayer-Tasch, Georg Mischuk & Johannes Hamhaber, Martin Müller, Heinz Nissel, Rainer Rothfuß, Wolfgang Schreiber, Ricarda Steinbach
Jahresheft Geopolitik 2010 (Inhalt: • Teil A: Geopolitik und Politische Geographie - Konzepte, Methoden, Potenziale • Teil B: Afrika - Geopolitische Herausforderungen und Zukunftsperspektiven)

Heft 1, 2012 Christian Marius Stahmer, Hans-Günter Mylius, Arno Langanke
Jahresheft Geopolitik 2011 (Inhalt: • Ziviler Aufbau unter Konfliktbedingungen – Die Arbeit der GIZ in Afghanistan • Umweltgeologie hilft die Lebensbedingungen der Menschen zu verbessern – Fallbeispiel Malawi • Rolle und Aufgabenwahrnehmung durch die internationale Polizei im Rahmen multinationaler Einsätze der Vereinten Nationen)

Heft 1, 2013 Wolfgang Schreiber, Kinan Jaeger, Reza Hajatpour, Daniel Lambach, Leonhardt van Efferink, Inken Wiese, Werner Ruf
Jahresheft Geopolitik 2012 (Inhalt: • Tunesien – Hintergründe und Perspektiven der Jasmin-Revolution • Der Syrien-Konflikt – Risiken und Chancen • Islamische Republik Iran und die Grüne Bewegung • Fragile Staatlichkeit – ein brauchbares Konzept zur Erklärung der Umbrüche in Nordafrika und Nahost? • Länderrisiken, Rating Agenturen und der Arabische Frühling • Deutsche Nahost- und Nordafrikapolitik:… • Möglichkeiten und Grenzen der Demokratieförderung in der arabischen Welt)

Bisherige Veröffentlichungen in der Schriftenreihe des GeoInfoDBw