Project: 704

Project title: Study of key oceanic processes with an eddy-resolving numerical simulation of the Arctic-Atlantic Ocean

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**Computational resources used during the project**

The computational resources made available in the DKRZ HLRE2 system enabled the integration of the project’s Atlantic-Arctic Oceans high-resolution model (at a resolution of 4 km) over the period 2002-2012. The integration was performed during the calendar years 2011, 2012 and 2013, having consumed a total of $1,570,007$ CPUh. The project generated **35 TB** of results, which were made available to users during the project. To that purpose DKRZ granted an additional disc space allocation throughout the years 2014 and 2015. The dataset is currently available to researchers through the Univ. Hamburg/Clisap/CEN “snow” system and in the future will be accessible in the HLRE3 (using Univ. Hamburg resources). A backup of the complete integration including the code, forcing and startup files is stored in the HPSS system, currently occupying **37 TB**.

**Scientific activities conducted during the project**

The high-resolution simulation spun off several analysis projects, some of which are still ongoing. The dataset is expected to continue raising interest and start new analysis projects, since it has an unprecedented high resolution over a vast oceanic region encompassing the whole Atlantic and Arctic Oceans. Brief overviews of the past and ongoing projects are given next.

**A. Variability of the dense water overflow east of Iceland** (N. Serra, R. Käse and D. Quadfasel, Univ. Hamburg)

Results from the 4-km resolution model corroborate the existence of the narrow overflow east of Iceland seen in the up-to-now only sparse in situ observations. Fig. 1a shows a snapshot of bottom temperature and velocity vectors. A continuous north-south flow transporting cold water to the south is seen along the small channel present to the east of the Icelandic slopes. The small overflow (amounting to 0.3 Sv on average) is mainly density driven but is barotropically modulated by wind stress variations, having a significant seasonal cycle with stronger overflow in summer (Fig. 1c). According to these realistic model results, the channel overflow contributes with about 10% of the total Iceland-Scotland Ridge overflow.

![Fig. 1](image)

**Fig. 1.** (a) Near-bottom temperature (°C - colours) and velocity (vectors) from the 4-km simulation in the Iceland-Faroe Ridge (see bottom topography in (b)). (c) East Iceland overflow volume transport, according to, respectively, the $\sigma_\theta=27.7$ kg m$^{-3}$ (black) and $\sigma_\theta=27.8$ kg m$^{-3}$ (red) light-dense water interface definition.
B. Dynamical properties of the St. Anna Trough Current (N. Serra, Univ. Hamburg, and I. Dmitrenko, Univ. Manitoba)

The halocline layer of the Arctic Ocean and its associated density gradient effectively suppresses the upward heat flux to the sea surface from the underlying warmer Atlantic Water inflow, which recently featured a temperature increase. Understanding the formation, spreading and modification of the halocline water is important to understand how the Arctic Ocean may respond to climate change. The halocline layer in the Eurasia Basin is influenced by advection from the Kara and Barents Seas. The on-slope halocline layer is believed to be more saline (than the off-slope) and comprised of Barents Sea branch water entering the Eurasia Basin in the northern Kara Sea through the St. Anna Trough. The dynamics of this St. Anna current and its time variability is being investigated with the 4-km resolution model output. Fig. 2b,c shows the dense and relatively strong outflow from the Kara Sea within the St. Anna Current (see box). The model shows enough resolution to resolve the small scales present in the vorticity field (Fig. 2d).

![Fig. 2](image)

**Fig. 2.** (a) Salinity, (b) potential density (kg m$^{-3}$), (c) current speed (m s$^{-1}$) and (d) normalized relative vorticity at 200m depth, illustrating some properties of the St. Anna Current (see red box).

C. Spatial and temporal scales of Sea Surface Salinity (SSS) variability (M. Sena-Martins, N. Serra and D. Stammer, Univ. Hamburg)

The ESA SMOS and the NASA AQUARIUS missions are collecting SSS measurements. The nominal spatial resolution of SMOS is 50 km but, in order to reduce salinity uncertainties to within 0.1, an averaging over 200 km (100 km) square regions and over 10 days (30 days) will be required. Due to the averaging, it is crucial to know the scales of temporal and spatial variability. In order to prepare the satellite data interpretation, work was developed to provide a detailed overview of the SSS variability in the Atlantic and Arctic using the 4-km model and the ARGO data. Fig. 3a presents the standard deviation of the non-seasonal part of the SSS signal and Fig 3b,c,d the derived temporal and spatial scales of variability, as simulated by the high-resolution model.

![Fig. 3](image)

**Fig. 3.** (a) Standard deviation of the non-seasonal part of sea surface salinity variability from the high-resolution simulation and associated (b) temporal (in days) and (c) zonal and (d) meridional spatial (in km) scales.
D. Sea Surface Height variability (S. Biri, N. Serra and D. Stammer, Univ. Hamburg)

We present frequency and wavenumber spectra of sea surface height (SSH) and surface geostrophic velocity computed for the Atlantic Ocean from a 19-year long altimeter data set and from output of ocean circulation model simulations with resolutions of 16 km, 8 km, and 4 km (Fig. 4). High-resolution is essential for reproducing the observed SSH spectral shape and, in some regions, the high-resolution model results agree well with altimetry results. However, discrepancies remain for small frequencies and wavenumbers over many regions, where altimeter results show excess of energy. The spectra of velocity derived from altimetric SSH are dominated by noise and aliasing. As for the SSH, model velocity spectra tend to approach the observed spectra with increasing resolution. Most differences in spectral magnitude are located in tropical regions, where the model presents much lower energy.

Fig. 4. Zonal average of frequency (left) and wavenumber (right) spectra for sea surface height (top) and surface geostrophic velocity (bottom) from the 4-km resolution simulation.

E. Error estimate of the dynamic ocean topography reconstruction in the Nordic Seas (F. Siegismund, Univ. Hamburg)

In the Nordic Seas, a dense data set of in-situ gravity measurements exists that allows a refinement of satellite gravity measurements from the GOCE satellite mission. After combination with a satellite Mean Sea Surface, the obtained geodetic Dynamic Ocean Topography (DOT) and the subsequent geostrophic surface circulation exhibits a considerably higher resolution than what could be computed applying a satellite-only geoid model. A detailed assessment of the geodetic DOT is, however, difficult since observations of time mean currents on a high resolution are limited to a few key sections. Here, the comparison to the 4-km resolution model (Fig. 5) helps to test and possibly improve the error estimate of the geodetic DOT and finally achieve a better understanding of the circulation and the underlying physics.
Fig. 5. 2002-2010 mean (left) and standard deviation (right) of the sea surface height in the Nordic Seas from the 4-km resolution model.

F. Particle retention in the east Greenland shelf (I. Nunez-Riboni and B. Cisewski, Von-Tuhnen Inst. Sea Fisheries)

Results from the 4-km resolution model are used to study the circulation in the Greenland shelf adjacent to the Kulusuk Bay (65°N, 35°W) and the particle retention mechanisms there. In the region, the onset of phytoplankton blooms is usually determined by the timing of the breakup of existing sea ice. The bloom develops rapidly because water from the melting sea ice establishes a shallow wind-mixed layer. The ice-edge bloom begins in March to April (Fig. 6 left). The chlorophyll concentration and sea surface height patterns from observations suggest a bifurcation of the East Greenland Current at 65°N, 35°W and the existence of quasi-permanent gyres in the area between the East Greenland Current and its parallel inshore flowing branch (Fig. 6 right). The gyres lead to upwelling of nutrients or sediments which are needed for the phytoplankton growth.

Fig. 6. (Left) Satellite-derived mean chlorophyll concentration for May 2009. (Right) Salinity at 250m and top-500m averaged velocity with the sea ice concentration superimposed from 15 April 2010 from the 4-km model.

G. Generation of Deep Western Boundary Current eddies in the South Atlantic (H. Paulsen and N. Serra, Univ. Hamburg)

The southward spreading of North Atlantic Deep Water in the Atlantic is mainly insured by the Deep Western Boundary Current (DWBC). It has been shown by Dengler et al. (2004, Nature, 432, 1018-1020) that the DWBC disrupts downstream of 8°S and from there on NADW is transported mainly within eddies (see Fig. 7). The details of the generation mechanism are still unclear as well as the main forcing factors for its variability. The main question addressed here was what are the main factors playing a role in the generation mechanism of the DWBC eddies at 8°S? In particular, the work clarified: 1) what is the role of bottom topography/coastal morphology in the instability process and 2) what is the role of wind stress forcing and upstream DWBC strength fluctuations in the variability of the eddy shedding at 8°S.
Fig. 7. Snapshot of current velocity magnitude (in m s\(^{-1}\)) at 2000m for 18 July 2006 from the 4-km model.


H. Tracer and velocity spectra inferred from output of a numerical model (S. Neske, N. Serra and D. Stammer, Univ. Hamburg)

Observing spatial scales of the full ocean eddy field is impossible given existing in situ and satellite measurements. Satellites still provide the best space-time coverage; however, they can only observe geostrophic currents on large scales. The 4-km model allows gaining insight into the relation between tracer and velocity spectra. Velocity and tracer wavenumber spectra were here examined in different spectral bands in the North Atlantic subtropical, Gulf Stream and equatorial regions and are analysed for their time mean and depth and temporal evolution. Results were put into the context of quasi-geostrophic and surface quasi-geostrophic theories. A relationship between tracer and velocity spectra for the whole ocean was sought (Fig. 8).

Fig. 8. (Left) Time-depth evolution of kinetic energy wavenumber power spectra (25-100km) slopes in the subtropical North Atlantic. (Right) Time mean slopes of velocity and tracer spectra.


I. Eddy Activity in the Confluence Zone Between the Labrador Current and the North Atlantic Current (C. Hinrichs and N. Serra, Univ. Hamburg)
The North Atlantic Current (NAC) flows northward along the North American continental slope until it turns east at the so-called “Northwest Corner” at 52°N. The flow there is highly variable (Fig. 9) and characterized by meanders and eddies. In the same region, the Deep Western Boundary Current (DWBC) flows southward at intermediate depths. At about 47°N both currents have to round the Flemish Cap and therefore the horizontal separation between them diminishes. In the present work, based on numerical model output from a 4-km resolution model, the ways the NAC and associated eddies might influence the DWBC transport were analysed. In particular, the coherence between the DWBC transport and the NAC position was investigated.

![Fig. 9. Standard deviation of velocities at the depths of the (left) NAC (75m) and (right) DWBC (1900m), from the 4-km resolution model.](image)


**J. SMOS derived sea ice thickness: Algorithm baseline, product specifications and initial verification** (X. Tian-Kunze, L. Kaleschke and N. Serra, Univ. Hamburg)

Brightness temperatures at 1.4 GHz (L-band) from the Soil Moisture and Ocean Salinity (SMOS) mission are used to retrieve sea ice thickness. Here we introduce an algorithm based on a model that includes a sea ice thermodynamic model and a three layer radiation model. The algorithm accounts, for the first time, for variations of ice temperature and salinity. During the iterative procedure, ice temperature and salinity are estimated from air temperature from a reanalysis and from the 4-km resolution ocean model weekly climatology of sea surface salinity (Fig. 10). The comparison with observational data shows a considerable improvement of results (compared to previous retrieval methods) when accounting for variations of ice temperature and ice salinity.

![Fig. 10. Mean (left) and standard deviation (right) of weekly sea surface salinity for the winter period from October to April, based on 8 years of daily model output from the 4-km model integration.](image)
K. Testing SMOS salinity retrievals against surface salinity observations and model results in the North Atlantic Ocean (J. Koehler, N. Serra and D. Stammer, Univ. Hamburg)

Sea surface salinity (SSS) measurements provided by SMOS are compared against quasi-simultaneous near-surface in situ salinity measurements obtained during August 2012 in the Northern North Atlantic. Although the SMOS SSS fields show a temperature-dependent negative bias of up to 2 psu, spatial salinity structures agree well between both data sets. Remaining differences are caused by land contamination in the SMOS retrievals. However, from analysing the 4-km resolution model, some differences could be attributed to ocean processes, such as a temporal variability of the position of frontal structures, e.g., around Greenland shelf (Fig. 11). The results show that even over cold waters SMOS SSS data show skill in observing variations of the surface ocean salinity field.

Fig. 11. (Left) Standard deviation of de-seasoned 4-km model salinity on time scales below 30 days. (Right) Temporal decorrelation scales from model salinity anomalies.

L. Surface and bottom circulation around the Azores Islands (B. Weiß, C. Hübscher and N. Serra, Univ. Hamburg)

This study focused on the impact of volcanism, erosion, tectonics, time-variant sediment support and climatic/oceanographic conditions on the submarine sedimentation processes in the south-eastern Terceira Rift, in particular around the São Miguel Island (Azores). Ocean currents are controlled and deviated by volcanic bathymetric highs or fault scarps, where they cause the deposition of drift bodies. High local accumulations of sediments caused by a channelized sediment flux, bottom currents or onshore volcanism are partly remobilized resulting in slumping/slide events and a volcanic ridge partly collapses due to tectonic stress and/or gravity spreading. The 4-km simulation was used to characterize the ocean circulation around the São Miguel Island. Surface currents in the south-eastern Terceira Rift show an overall NW-SE direction. Bottom currents flow around bathymetric highs in a clockwise manner (Fig. 12).
Fig. 12. Simulated surface (a) and bottom (b) currents in the south-eastern Terceira Rift based on the 4-km simulation.


M. Role of submesoscale instabilities in the lateral transport and mixing of freshwater (D. Mukiibi, N. Serra and G. Badin, Univ. Hamburg)

Large scale gradients of freshwater (Fig. 13 left) are primarily controlled by exchanges with the atmosphere, i.e. through the balance between evaporation and precipitation, and by freshwater input by riverine discharge near the coast, melting and freezing of ice in polar and sub-polar regions, and local upwelling/downwelling of water masses characterized by different salinity. While these gradients are further shaped by large scale ocean dynamics, such as advection by the general circulation), cross-frontal processes, such as mesoscale instabilities, assume a primary role both in determining the shape of freshwater gradients and in providing an integrated transfer of freshwater across the fronts. To approach the impact of mesoscale instabilities, studies of Lagrangian dispersion using the 4-km model output will be conducted. Such an analysis includes the computation of Finite Time Lyapunov Exponents (FTLEs), which can provide a mapping of the ocean stirring (Fig. 13 right). Detection of mixing barriers based on FTLEs can be important for the detections of barriers for the transfer of freshwater.

Fig. 13. (Left) Distribution of surface salinity on 1 August 2010 from the 4-km model. (Right) Finite Time Lyapunov Exponents at 5 m depth calculated for a region south of Iceland from the 4-km model results.
N. Variability of freshwater transports through the Canadian Arctic Archipelago (L. Zeigermann, N. Serra and D. Stammer, Univ. Hamburg)

Upstream from Davis Strait, the Canadian Arctic Archipelago (CAA) imposes a large constraint to the volume and freshwater exchange between the Arctic and the north Atlantic. Due to the small scale of the numerous islands and water passages separating the Beaufort Sea, in the Arctic Ocean, and the Baffin Bay, west of Greenland, resolving the flow through the CAA remains a challenge to ocean/climate modelling. The 10-years-long integration of the 4-km model was analyzed, aiming at assessing the realism of the simulation concerning the temporal variability of volume and liquid/solid freshwater transports through the CAA (Fig. 14). Simulated transports were compared with transports estimated from in situ measurements and the mechanisms responsible for the temporal variability were studied. In particular, the impact of sea level differences between the Arctic Ocean and the Baffin Bay on the variability was investigated.

Fig. 14. (Left) Time average (2002-2012) of salinity at 10m from the 4-km model. (Right) Corresponding time average of top-to-bottom freshwater content (relative to S=35, in m) with freshwater fluxes (arrows) superimposed (red arrows correspond to larger fluxes).