Project Report

Project:	1102
Project title:	SFB-Transregio (TRR181)
Principal investigator:	Giulia Castellani, Evridiki Chrysagi, Nils Brüggemann
Report period:	2025-11-01 to 2026-10-31

This report discusses results from two former DKRZ projects (bm1102 and bm1239) that we are merging for the upcoming compute time allocation period. Both projects supported research of the DFG Transregio project TRR181. During the last allocation phase, the reviewers asked us to merge both projects, which is what we are doing now with our new proposal.

The TRR181 dedicates large parts of its research to improving the two German climate models ICON and IFS-FESOM. Both DKRZ projects performed essential simulations for key subprojects of the TRR181. In particular, these DKRZ projects supported the ICON-SMT configurations, which are among the highest-resolution ICON ocean configurations. Furthermore, the two DKRZ projects performed essential simulations for the TRR181 synthesis project, where novel parameterizations are implemented into both model systems and where the energetics of these models are investigated.

In the following, we list key results that used considerable compute resources of our project. While the TRR181 has already been running for more than ten years, the previous allocation period fell into the first part of the third and last phase of the TRR181. Therefore, many projects were finalized and new ones needed to be developed. As a consequence, we could not use up all the resources that were granted to us in the previous allocation phase.

T2: In this project, we are investigating the interactions between submesoscale motions and Langmuir turbulence. During the previous allocation period, we set up and ran paired simulations with the ICON-SMT-WAVE configuration in order to quantify the effect of Langmuir turbulence on upper-ocean mixing in a submesoscale-permitting setting. We started by configuring the Axell (2002) Langmuir parameterisation in icon-mpim 2025-10 and establishing atmospheric forcing from hourly ERA5 fields delivered through a YAC-coupled data provider. Two experiments were then run from a common August 2019 restart file: one with the Langmuir scheme active and an otherwise identical control with it switched off. We chose this period for our study because restart files from previous ICON-SMT simulations of the South Atlantic were only available for this period. We deactivated the tidal module for both runs.

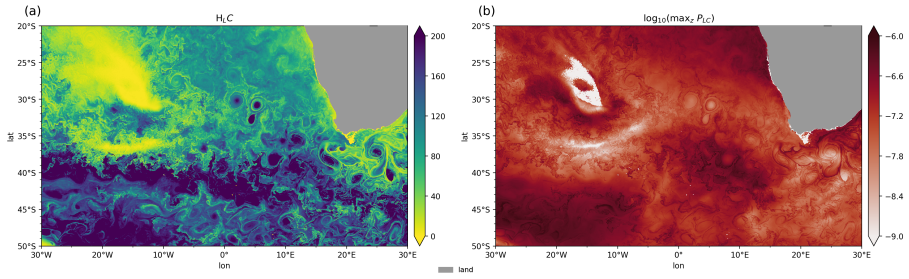


Figure 1: Snapshot of the Langmuir cell depth (a) and the depth-integrated TKE due to Langmuir turbulence (b), for the study domain.

During the initial analysis a configuration error was identified in which surface salinity was relaxed toward zero, due to an active relaxation term without a corresponding reference file. Correcting this changed the area-averaged mixed-layer depth over the study region from approximately 18 m to 116 m, bringing it into agreement with the climatological value of 110 m (Montegut, 2023). The affected period was then rerun. Analysis of the corrected simulations

showed that the Langmuir scheme is active across the study region, with Langmuir cell depths ranging from 100 to 200 m south of the Cape Basin and inside the weakly stratified Agulhas Rings. The depth-integrated turbulent kinetic energy (TKE) production peaks where the Langmuir cells are deeper (Fig. 1). An area-averaged time series of mixed-layer depth also showed a gradual increase compared to the control experiment, as expected when activating the Langmuir turbulence parameterisation (Fig. 2).

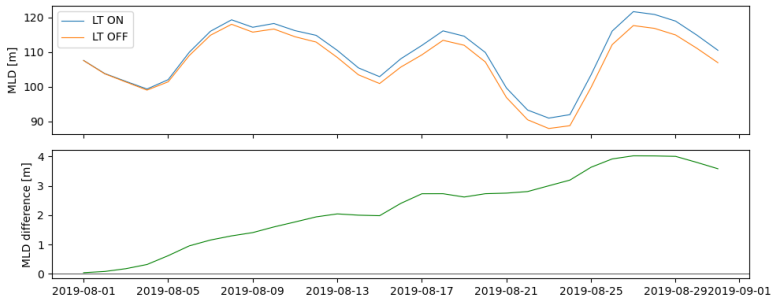


Figure 2: Area-averaged time series of mixed-layer depth and their difference.

For this part of the project, simulations are still ongoing and we are about to start moving some data to the archive as soon as we have finalized the analysis and can be sure that these simulations will be used for publications. Once our anticipated publications are finished, we will transfer key data to the long-term archive and make disk space available.

L4: This project used ICON SMT-WAVE and ICON R2B9 configurations to conduct ocean simulations covering periods of up to one year. The simulations were performed using resources provided by DKRZ, granted by its Scientific Steering Committee (WLA) under project ID bm1102. Results of this project have been submitted to the *Journal of Physical Oceanography*[1] and this DKRZ project is properly acknowledged.

The continuous oceanic energy spectrum is shaped by a range of physical processes, but the mechanisms that redistribute energy across spatial and temporal scales are not yet fully understood. In this study, we use a submesoscale-resolving ICON simulation of the eastern South Atlantic to investigate the roles of tides, mesoscale eddies, high-frequency winds, and nonlinear wave interactions. With this high-resolution model, we reproduce observed energy levels across a broad range of spatial and temporal scales and extend predictions beyond the observational noise floor. Furthermore, sensitivity experiments allow us to isolate the contribution of individual processes. We find that tides and high resolution are essential for reproducing realistic energy levels within the internal wave band, while wave-wave interactions help maintain the continuous spectrum between tidal and inertial peaks and their subharmonics. Mesoscale eddies also contribute to the redistribution of energy across scales and may become the dominant mechanism in regions with weaker winds. These findings provide new insight into the processes that shape high-frequency ocean energetics and the continuous oceanic energy spectrum.

The overview in Fig. 3 depicts the focus region of the SMT configuration, which aligns with the SONETT[2] study region. We combine the model simulations with an extensive high-frequency observational dataset from dedicated SONETT field campaigns designed to capture local ocean dynamics and high-frequency variability. Figure 4 assesses the observed and simulated variability

[1] **Drivers of High-Frequency Ocean Energetics** by Moritz Epke[1,2], Christian Mertens[3], Peter Korn[1], and Nils Brüggemann[1,4]. ([1] Max Planck Institute for Meteorology, Hamburg, Germany; [2] Institute of Oceanography, University of Hamburg, Hamburg, Germany; [3] Institute of Environmental Physics, University of Bremen, Bremen, Germany; [4] Leibniz Centre for Tropical Marine Research, Bremen, Germany.)

[2] SONETT stands for "Synoptic Observations – a Nested Approach to Study Energy Transfer and Turbulence in the Ocean in the Eastern South Atlantic/Walvis Ridge".

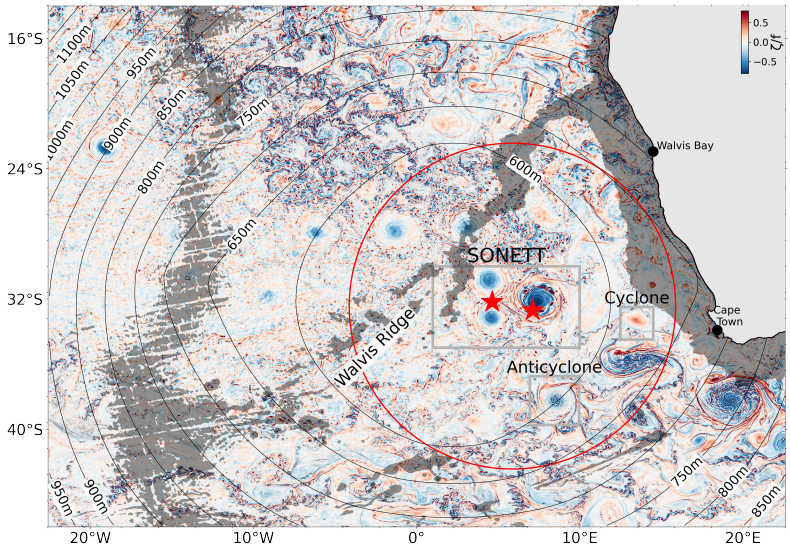


Figure 3: Snapshot of relative vorticity over planetary vorticity in the Southeast Atlantic. The study area of the SONETT cruises is marked by a rectangle. Mooring locations are indicated with red stars, while PIES instruments are positioned near the eastern star. The red circle highlights the region included in the spectral evaluation. Grey lines represent constant horizontal resolution in the ICON-SMT configuration.

through spectra of sea surface height, bottom pressure, and kinetic energy.

The major part of the data is now stored in the DKRZ archive system. Parts of the data are currently still on disk since further analysis is performed and a paper was recently submitted. Once the paper is published and there are no further requirements for the data, we will remove the simulation from WORK but keep it in the archive for a bit longer. Parts of the data will be also archived in the long-term archive system.

Report from bm1239 for project S: In the TRR181 synthesis sub-project, we ran several FESOM and ICON model simulations with different resolutions and parameterizations and compared their results. We focused our analysis on the impacts on mixed layer depth (MLD) and sea ice concentration. The oceanic mixed layer plays a central role in climate dynamics in polar regions by mediating the exchange of heat and momentum between the atmosphere and the sea ice. Variability in MLD is closely linked to sea ice extent and has played a significant role in shaping the record-low sea ice minima observed in recent years. The ability of ocean models to simulate the MLD depends critically on how these processes are represented, either explicitly resolved or parameterized.

We use a new set-up of FESOM2.6 which is coupled to ICEPACK and forced by ERA5 reanalysis. In FESOM2-Icepack, the fundamental sea ice thermodynamic module (FESIM) is replaced by the advanced Icepack module (`https://github.com/cice-consortium/ICEPACK`). The first simulations using the standard parameters employed in Icepack produced disappointing results, particularly in the Arctic in summer, where the extent of the summer sea ice was significantly underestimated. Although Icepack is much more advanced than FESIM, tuning it turned out to be much more complicated than tuning FESIM. Approximately 100 sensitivity experiments have been performed with FESOM2-Icepack (each spanning 25 years). Finally, adapting the parameterisation of the mushy physics, the snow conductivity, and the parameterisation of the dependence of the snow grain size on the snow surface temperature (important for the scattering module for solar insolation) dramatically improved the performance of FESOM2-Icepack, as can be seen by comparing Fig. 5b and e to the observations (Fig. 5a).

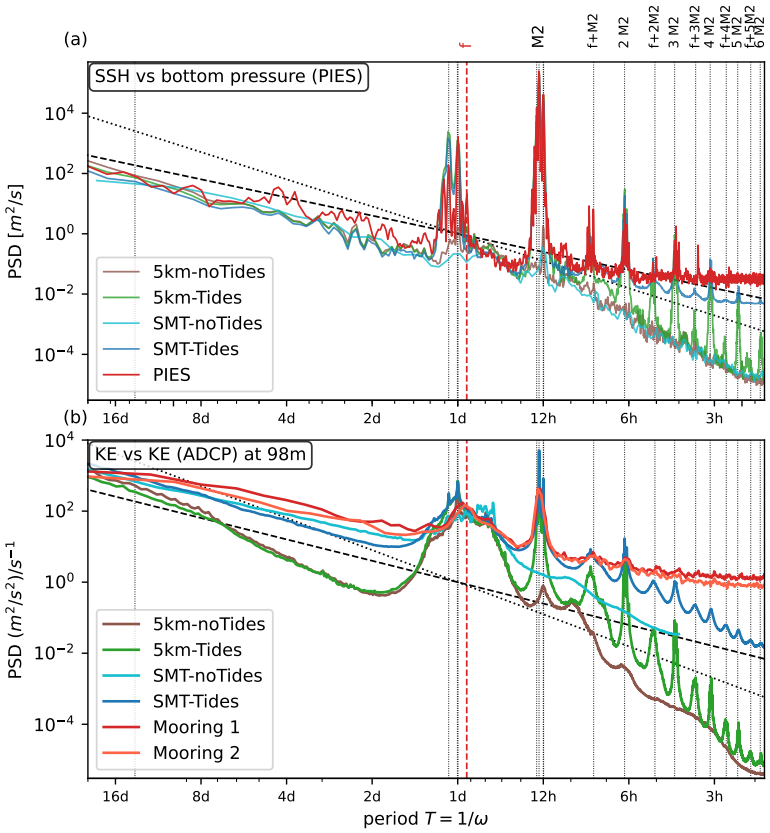


Figure 4: The SSH frequency spectra compared to PIES (a) and the frequency spectra of the horizontal KE at 98 m depth compared to moored ADCPs (b). Note that the model configurations considered here cover a time span of roughly a year with hourly output, except for the SMT-noTides simulation in (b), which covers July to October 2019 with 2-hourly output. The Coriolis frequency is shown as a red dashed line, tidal constituents and subharmonics as grey dotted lines, and spectral slopes of ω^{-2} (dashed) and ω^{-3} (dotted) are indicated as well.

For the comparison in the synthesis sub-project, we use two resolutions: a low-resolution one (CORE2), where eddies are parameterized with the GM and Redi schemes (Redi, 1982; Gent and McWilliams, 1990), and a high, eddy-resolving one (DARS2). The main vertical mixing schemes that we considered are: **TKE**, which solves a prognostic equation for turbulent kinetic energy (TKE) and uses it to compute a vertical eddy viscosity/diffusivity profile; **KPP**, which prescribes a shape (profile) for vertical diffusivity within the mixed layer, tapering smoothly into the thermocline; and **PP**, a Richardson-number-dependent vertical turbulent diffusion and viscosity.

Task i: As baseline runs, FESOM2-Icepack was run at CORE2 and DARS2 resolution using the TKE scheme. Figure 6 shows the annual cycle of MLD in the Labrador Sea from these runs and a difference map of the Arctic Ocean between the two resolutions. ICON baseline runs are planned for the remaining project months.

Task ii: To test further parameterizations, runs with KPP and PP were added, as well as a third, intermediate resolution (DART2). A comparison between TKE and KPP is included in Figure 6.

Task iii: Data analysis and comparison were done using pyfesom and ESMValTool; Figures 6 and 7 include diagnostics produced with ESMValTool.

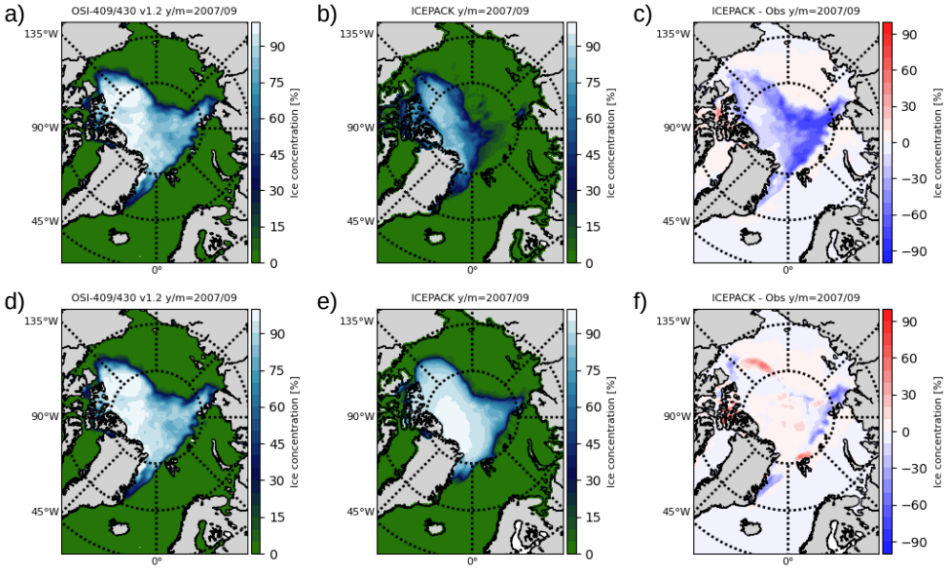


Figure 5: Observed (a and d, which are identical), simulated (b and e) and misfit (c and f, model – observation) sea ice concentrations (in %) for September 2007 obtained with FESOM2-Icepack for the Arctic.

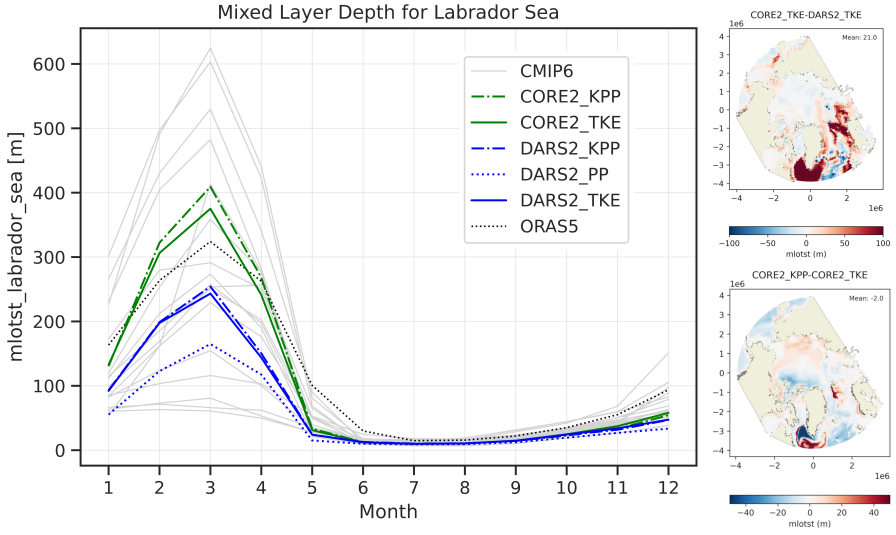


Figure 6: Differences in winter MLD annual cycle between the resolutions and parameterizations for vertical mixing compared to CMIP6 simulations and ORAS5 reanalysis data in the Labrador Sea, 2000-2003. The maps show the differences in MLD between both resolutions (top) and the TKE and KPP vertical mixing scheme for the lower resolution (bottom).

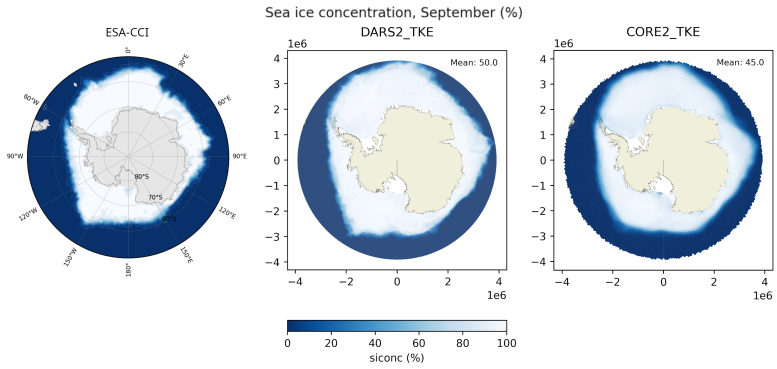


Figure 7: Sea ice concentration in the Southern Hemisphere in September 2000: ESA-CCI observations and FESOM2.6 at CORE2 and DARS2 resolution.

The results show that the simulated winter MLD is deeper at low resolution, which is also linked to lower sea ice concentrations. Regarding the vertical mixing schemes, KPP results in a deeper MLD compared to TKE. Both resolutions are sensitive to the parameterization used; however, the effects of the different parameterizations are larger at low resolution than at high resolution. Furthermore, the differences between TKE and KPP are smaller than those caused by the change in resolution, and the spatial pattern differs more between resolutions. A larger difference in MLD results from using the PP vertical mixing scheme, which also shows the largest difference from the ORAS5 reanalysis.

The data is still on disk of the bm1239 account since further analysis is required. In the next weeks, we will request to transfer the data that is still needed to the bm1102 account and from there, we will begin the archiving process. Once our planed publications are accepted, we will add key simulation and analysis data to the long-term archive and free the disk space.