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CLUSTER OF EXCELLENCE
CLIMATE, CLIMATIC CHANGE, AND SOCIETY (CLICCS)

Project: bm1173

Project title: Climate, Climatic Change and Society

Principal investigator: Detlef Stammer

Allocation period: 01.01.2022 – 31.12.2022

Report on usage of the DKRZ Resources for the first 9 months

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Preface

The report summarizes the individual reports of projects of the Cluster of Excellence CLICCS (Climate, Climatic Change and Society). The reporting will cover the time period from 01. January 2021 to 31. December 2022. The numbers for used computation time and storage resources are taken end of September, unless stated otherwise. The individual DKRZ project numbers are bm1183, bg1184, bg1186, mh1212, bu1213, bu1214, and bm1219. Please note that the current report covers only 9 months.

Low resource consumption in 2022

This was mainly due to the delayed transition from Mistral to Levante. The various projects therefore ran more simulations than planned on Mistral instead of Levante.

On the other hand, some projects as part of the "Early Access" team had received very early access on Levante to run the rest of the planned simulations there. For this purpose, resources were drawn from the Early Access project, since the projects could not yet be used on Levante at that time. Additionally, for example project bu1213 encountered a lot of model integration obstacles because of numerical instabilities as well as Levante issues. Nevertheless, DKRZ and Atos have been working very hard to help us out with the various issues, and we would surely like to continue our pursuit of these cutting-edge climate model simulations.

Report project bm1219

Project title: CLICCS A1 - Carbon Dynamics in the Arctic
Project lead: Victor Brovkin
CLICCS project chairs: Victor Brovkin, Lars Kutzbach, Dirk Notz
Reporting Period: 01.01.-06.10.2022

	Allocated for 2022	Consumed (06.10.2022)	Projection of consumption to end of 2022
Computing time (Levante & Mistral) [node h]	24,507	12,944 (12,944 expired)	13,707
Levante storage (TB)	13	14	13
Archive project (TB)	19	0	14
Archive long term (TB)	19	0	14
Mistral Lustre work (GB)	18000	15011	15011
Swift Object Storage (GB)	10240	0	10240

Experiments performed successfully at project account bm1219

After successful simulations in 2021, 2022 was spend mainly on writing manuscripts and model development. However, the model did not reach a state at which simulations could be run, partly due to the transition from Mistral to Levante. We expect to be able to use up the node hours granted for Levante until the end of the year.

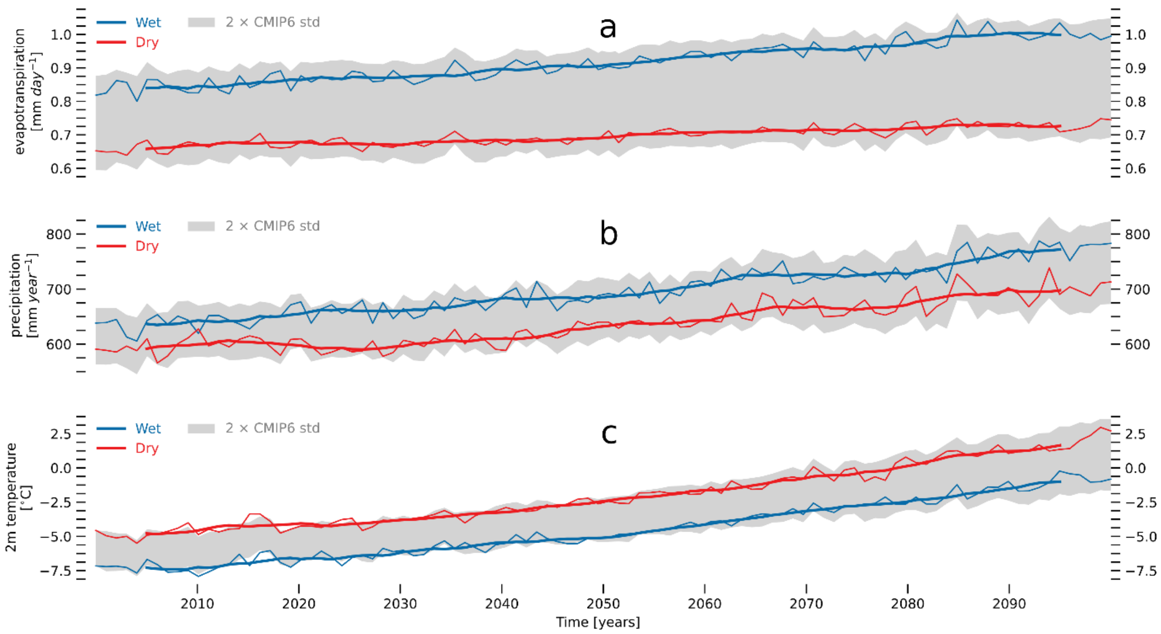

Figure 1: a) Simulated evapotranspiration rates averaged across the northern permafrost regions. Red lines refer to the MPI-ESM setup with a low soil water retention and availability (Dry), while blue lines refer to a high water retention and availability (Wet). The width of the shaded (grey) area indicates 2 x the CMIP6 ensemble standard deviation—note that it does not indicate the absolute value of the CMIP6 ensemble as the area is centered on the mean of the Wet and the Dry simulations. b) Same as a but showing average precipitation rates. c) Same as a but showing simulated 2m-temperature. From de Vrese et al. (2022a).

Scientific results of project bm1219

Current generation Earth system models (ESMs) show large differences in the simulated climate of the high northern latitudes (Davy and Outten, 2020). At the same time, their land surface components exhibit a wide range of responses when forced with similar prescribed atmospheric conditions (Andresen et al., 2020). However, it is not clear whether the variations in the simulated climate of different ESMs originate in the differences in the representation of soil processes in the terrestrial Arctic, or whether the differences stem from differences in the atmospheric model component, differences in the latitudinal heat and moisture transport or other differences in simulated large scale climate patterns and remote effects.

By comparing simulations with the Wet and the Dry setups we found that, differences in the representation of the soil hydrology in the northern permafrost regions lead to variations in the simulated climate in the Arctic that are comparable to the spread in the CMIP6 ensemble (see Figure 1). This is a strong indication that the terrestrial soil hydrology could indeed be responsible for the large spread in the simulated high latitude climate. Furthermore, it is often assumed that future methane emissions in the high latitude will be higher if the soils stay relatively moist after the near-surface permafrost disappeared (Lawrence et al., 2015). Here, it was found that the Dry setup actually produces methane emissions that are very similar to those of the Wet setup, because the effects of a smaller fraction of inundated soils (where organic matter is decomposed to CH_4 rather than CO_2) are compensated by a higher vegetation productivity, resulting from the higher near-surface temperatures.

Publications in 2022 that use data of project bm1219

The manuscripts "Representation of soil hydrology in permafrost regions may explain large part of inter-model spread in simulated Arctic and subarctic climate" and "Higher Arctic CH4 emissions under dry than under wet conditions“ were submitted and are currently being reviewed by The Cryosphere (de Vrese et al., 2022a) and Nature Climate Change (de Vrese et al., 2022b), respectively. These manuscripts rely heavily on simulations done in the project bm1219 in 2021.

Data Management of project bm1219

The primary data produced for the two above publications will be made available via the German Climate Computing Center long-term archive for documentation data, upon successful publication. Other data produced in bm1219 is not intendent for sharing as it was produced for the sake of model development.

References

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Davy, R. and S. Outten, 2020: The Arctic surface climate in CMIP6: status and developments since CMIP5. J Clim, 33(18), 8047-8068.

Lawrence, D.M., C.D. Koven, S.C. Swenson, W.J. Riley, and A. Slater, 2015: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO2 and CH4 emissions. Environ Res Lett, 10(9), 094011.

Report project bm1183

Project title: CLICCS A2 - Clouds and Tropical Circulation
Project lead: Ann Kristin Naumann, Theresa Lang (UHH)
CLICCS project chairs: Stefan Bühler, Bjorn Stevens
Reporting Period: 01.01.2022 - 29.09.2022

	Allocated for 2022	Consumed (29.09.2021)	Projection of consumption to end of 2022
Mistral computing time [node h]	22,400 (first two quarters of 2022)	13,084 (58%)	13,084
Mistral storage /work [GiB]	100,000	95,137 (95%)	95,137
Levante computing time [node h]	13,005	0 (0%)	0
Levante Temporary storage /work [TiB]	139	135 (98%)	0
Storage /arch [GB]	407	82 (20%)	272
Long term storage /doku (GB)	0	0	0

Experiments performed successfully at project account bm1183

For 2022, DKRZ provided us with resources to perform an ensemble of ICON experiments in R2B09 (i.e., ~5 km grid spacing) to investigate the sensitivity of tropical relative humidity to changes in model resolution and parameterizations in a global storm-resolving model (GSRM). Originally, we had planned to perform five experiments on Levante; one control experiment, three experiments with changes in the parameterizations of microphysics and turbulence, as well as one experiment with an increased number of vertical levels (see A2 proposal for 2022).

Due to several changes in our original plan, we ended up mainly using the storage provided through project bm1183 on Levante for model output, while the simulations were partly performed using the computing time from bm1183 on Mistral, and partly using computing time from other projects on Levante. First, we did not perform the control experiment and the experiment with increased vertical resolution ourselves, but instead made use of two experiments that were performed as part of the AVR experiments by Hauke Schmidt at the MPI-M in August 2021. Additionally, we made use of a third experiment with decreased vertical resolution available from the AVR project, which we had not planned originally. Second, we performed the two microphysics sensitivity experiments on Mistral, using bm1183 resources for 2021 and 2022. Third, since the commissioning of Levante was delayed in early 2022, we got the opportunity to perform simulations as part of the "Early Access" team, using resources from project mh0287. We performed one experiment with an exchanged turbulence scheme, as well as three further experiments that were not planned originally: one second control simulation with perturbed initial conditions to obtain an estimate of internal variability in tropical humidity, one with increased horizontal resolution (R2B10, i.e. ~2.5 km grid spacing) and one for a different season.

Scientific results of project bm1183

The aim of our study is to better understand sources of uncertainties in modelling processes that drive the distribution of tropical free-tropospheric relative humidity (RH). Therefore, we examined how much and through which physical mechanisms the relative humidity in a GSRM is affected by changes in model resolution and paramtererizations. The physical mechanisms are examined using a trajectory-based assessment of the last-saturation paradigm (Sherwood, 1996; Sherwood et al., 2010).

The rather strong perturbations we apply to the model result in RH changes ranging from 0.5% to 8% in the mid troposphere (Figure 2a,b). The generated RH spread is similar to that in DYAMOND (Stevens et al., 2019), a multi-model ensemble of GSRMs (Figure 2c). An earlier study had shown based on the DYAMOND ensemble that the RH spread across GSRMs is reduced compared to classical GCMs with convective parameterizations (Lang et al., 2021). Our experiments support this finding by showing that even strong perturbations in GSRMs cannot reproduce the spread across models with convective parameterizations. Moreover, our experiments show that tropical RH is rather robust to changes in model resolution within the general scale of GSRM resolutions. The three experiments with different vertical resolutions (800 m, 400 m and 200 m in the free troposphere; $2\Delta z$, $Control$ and $\Delta z/2$ in Figure 2) show that RH changes are modest as soon as a certain threshold vertical resolution is exceeded. The experiments with 5 km and 2.5 km horizontal grid spacing produce a very similar RH distribution ($Control$ and $\Delta x/2$ in Figure 2). While these results suggests that differences in model resolution do not contribute significantly to the current RH spread across GSRMs, it does not exclude the possibility that increasing the resolution to much finer scales (on the order of 200 m) could make a significant difference, which needs to be tested in future experiments. In our experiments, RH changes more strongly in response to exchanging the microphysics and turbulence schemes ($2v_{ice}$, $2-mom$ and TTE in Figure 2), indicating that the model physics are the major source of RH spread across GSRMs.

The mid-tropospheric RH changes in our experiments, including the strong moistening in the experiment with the exchanged turbulence scheme, are largely captured by the last-saturation model. This means that most RH changes are explained by changes in source temperature, i.e. the temperature at which air parcels typically experience last condensation, whereas changes in the moistening or drying by parameterized processes after last condensation play a minor role. This is even true when the parameterized moisture sources are modified directly, like in our microphysics and turbulence experiments.

In our experiments the most substantial RH change was found in response to changing the turbulence parameterization from a Smagorinsky-type scheme to a total turbulent energy (TTE) scheme (TTE in Figure 2). The resulting increase in RH was largest in the mid troposphere of moist regions. The reason appears to be that the TTE scheme produces a strong turbulent moistening of the mid troposphere in the inner, moist tropics. This moistening favours condensation, which is why from a last-saturation perspective the share of young air parcels with warm source temperatures increases in the TTE experiment. Thus, the RH of the moist tropical regions is disproportionally sensitive to vertical mixing processes that structure the humidity through their effect on the last-saturation temperatures, i.e. by increasing mid-level cloudiness, rather than their effect on the evolution of humidity since its last saturation.

While the behavior of the TTE scheme is certainly unexpected and indicates that the scheme has either not been sufficiently adapted to (or is not at all eligible at) storm-resolving resolutions, the fact that even this extreme perturbation does not change RH beyond the differences in the DYAMOND ensemble is very promising. Due to their early development stage, many of the DYAMOND models in fact used turbulence parameterizations that were not specifically adjusted to storm-resolving resolution. This nourishes hopes that tropical relative humidity will become even more consistent across future model versions with better adapted schemes.

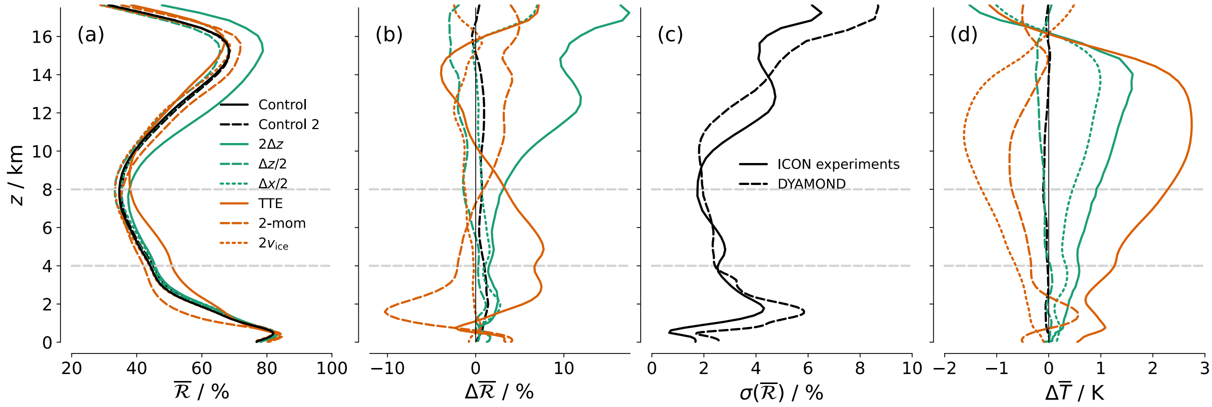

Figure 2 Changes in tropical mean relative humidity ($\mathcal{R}$) and temperature (T) resulting from changes in model resolution and parameterizations in the sensitivity experiments. (a) Vertical profiles of $\mathcal{R}$ in control and sensitivity experiments, (b) change in $\mathcal{R}$ compared to the control experiment and (c) standard deviation of $\mathcal{R}$ across ICON experiments (solid) and the DYAMOND multi-model ensemble (dashed). (d) Change in temperature T compared to the control experiment.

Publications in 2022 that use data of project bm1183

The results described above have been submitted for publication in the *Journal of Advances in Modeling Earth Systems (JAMES)*. Furthermore, the work has been presented at the EGU General Assembly in Vienna (23-27 May 2022) and at the 3rd Pan-GASS Meeting on Understanding and Modeling Atmospheric Processes in Monterey, California (25-29 July 2022).

Data Management

Currently the model output from all experiments is stored under project bm1183 on Levante. Only the output from the R2B09 experiment is stored under a different project. As soon as the analysis of the data is completed (latest by the end of this year), the model output from all eight experiments will be moved to /arch (190 TiB in total).

There is an ongoing collaboration with the scientific data visualization group which is part of the HPC group in CLICCS. The group uses one of this project's simulations for a visual analysis of humidity transport. Output from one of our simulations is currently also used in another project in the Radiation and Remote Sensing group at the Meteorological Institute at UHH. The aim is to study Karman vortex streets forming in the wake of islands.

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Sherwood, S., Roca, R., Meckwerth, T., & Andronova, N. (2010). Tropospheric water vapor, convection and climate. *Reviews of Geophysics*, 48 , RG2001.

Stevens, B., Satoh, M., Auger, L. et al. (2019). DYAMOND: the DYnamics of the atmospheric general circulation modeled on non-hydrostatic domains. Progress in Earth and Planetary Science, 6 (61).

Report project mh1212

Project title: CLICCS A4 – African and Asian Monsoon Margins CLICCS
Project lead: Katharina D. Six (MPI-M), Shabeh ul Hasson(UHH)
CLICCS project chairs: Jürgen Böhner (UHH), Martin Claussen (MPI-M/UHH), Gerhard Schmiedl (UHH)
Reporting Period: 01.01.-31.12.2022

	Allocated for 2022	Consumed (10.10.22)	Projection of consumption to end of 2022
Computing time [node h]	70,954	55,483	70,954
Temporary storage / work [GB]	33,000	33,000	33,000
Storage / arch [GB]	201,000	14,180	40,000
Long term storage / doku [GB]	32,000	0	0

The project aims at understanding the sensitivity and the variability of the tropical precipitation over the African and Asian monsoon margins, which the livelihood and well-being of a large part of the human population depend on. We will be able to assess the realism of state-of-the-art climate models in simulating monsoon dynamics and their changes, including the influence of internal climate variability. The comparison of simulations, paleo-reconstructions, and instrumental observations allows us to interpret data, to evaluate models, and to reduce uncertainty in projections. We focus on rapid climate changes such as the 8.2k-event and the termination of the African Humid Period some 5000 years ago, as well as the recent global warming with an outlook on possible future climate changes.

Of the four work packages (WP) within CLICCS A4 only WP 1) Marine sediment archives and ocean modelling and WP 2) Environmental process modelling applied for DKRZ resources. At the current stage, we report for each individual WP.

Experiments performed successfully at project account mh1212

WP1 Marine sediment archives and ocean modelling

In this reporting period, we finalized the development of a regional ocean biogeochemical model system for the Mediterranean Sea that is capable to simulated the entire deglaciation (21,000 years) with the forcing taken from paleo-simulations with the MPI-ESM (Kapsch et al 2022)

We have now an evaluated framework available to perform consistent transient model simulations including automatic bathymetry adjustment and transient river nutrient supply. However, we had to deal with some delay in our work program by the shift of the computer platform from Mistral to Levante. This required an optimization of the allocated resources to achieve a similar good model performance as on Mistral. The current model set-up has a performance of 130yr / 24h on 8 nodes.

We performed two sets of experiments. The first one focuses on the starting conditions for the deglaciation.

- To estimate the sensitivity and variability of the biogeochemical state we performed simulations with different vertical mixing based on two different atmospheric forcing sets. Each of the four runs covers in total 2000 simulation years with a transient forcing from

22000-20000 years BP. A selection of these runs serves as starting conditions for the transient simulations.

- For all LGM runs we performed corresponding present-day simulations (4x 2000 years) covering the period 1750-1950.
- One additional sensitivity LGM run (2000yrs) with artificial modification of the strait bathymetry to analyse the impact of sea level on the water exchange between the North Atlantic and the Mediterranean Sea

The second set comprises transient simulations from the LGM to the mid Holocene:

- A first transient simulation based on one atmospheric forcing (22000-6000 yrs BP) is finalized.
- Two simulations with lower vertical mixing and atmospheric forcing from two different ice sheet reconstructions are currently running (they already reached simulation year 15,000 yrs BP and 19,000 yrs BP).
- One simulation with lower vertical mixing and the atmospheric forcing from a fully couple ESM with interactive ice sheets is in the spin-up phase.

WP2: Environmental process modelling

It is to mention that the WP2 computational resources are shared between the accounts uc0977 and mh1212. The simulations are performed in three groups:

1. First few sensitivity experiments were conducted at convection permitting scale over the whole Tibetan Plateau to see how the regional model performs in simulating the select extreme events, which include:
   a. Mesoscale Convective System (MCS) event during 14-24 July 2008
   b. A month-long simulation for the Monsoon season during July 27 and September 01, 2014
   c. A heavy snowfall event during 4-9 October 2018

   These experiments are a single member contribution to the multi-model and multi-physics ensemble-based study by several groups under the 'Convection-Permitting Tibetan Plateau' CORDEX Flagship Pilot Study. The primary goal of these experiments is to better understand the performance of state-of-the-art, non-hydrostatic regional modelling systems in simulating precipitation and T2M during different weather situations over the TP region and to find suitable model settings that can be used for climate-length runs in the future.

2. To better understand the seasonality of model biases and the potential for bias accumulations over time, additional year-long simulation for the water year 2020 (Oct 2019 - Sep 2020) has been completed and being analyzed. Year 2020 was selected due to the availability of high-quality observational datasets over the TP from the TPE project. The year-long simulations will be the basis for decadal runs of historical and future climate periods that will be performed by CPTP modelers in the next three years.

3. A kilometre scale dynamical downscaling was performed over the NAMAL watershed region to produce and understand retrospective high resolution hydroclimatology of the ungauged NAMAL watershed at the monsoon margin regions within the Indus basin. The simulations were performed using the WRF model and ERA5 has been downscaled in yearly simulations for the period October 1994 to September 2019.
4. Additionally, downscaling CMIP6 models over the Indus basin is in progress as the boundary conditions are being prepared.

Scientific results of project mh1212

WP1: Marine sediment archives and ocean modelling

The overall goal of this project is to understand the mechanisms of organic-rich sediment layer formation under anoxic or low oxygen concentrations in the eastern Mediterranean Sea (MedSea) during the deglaciation. Prerequisites for the development of these Sapropel layers are pronounced temporal changes in physical and biogeochemical conditions of the MedSea.

To simulate the entire deglaciation, we need to know the initial conditions of the physical and biogeochemical ocean state at the LGM. Thus, we run a set of experiments over the LGM period (22,000-20,000 years BP) and analyse driving forces of the changes in circulation and the corresponding biogeochemical realm. Here we present results only from one simulation, which is also the basis for the first deglaciation simulation.

We find, that the zonal overturning circulation at the LGM is shallower and is less strong compared to present day. Overall colder surface temperatures lead to lower evaporation and a reduced compensatory surface inflow from the North Atlantic (from 1.3Sv for PI to 0.72 Sv). Moreover, the shallower sill depth at the Strait of Gibraltar (214m instead of 296m) limits the outflow of saline intermediate water which results in a stronger vertical density gradient in the entire MedSea. As a consequence, annual mixed layer depths are shallower, especially in the Eastern MedSea and deep-water formation areas in the Gulf of Lions and the Adriatic Sea are missing.

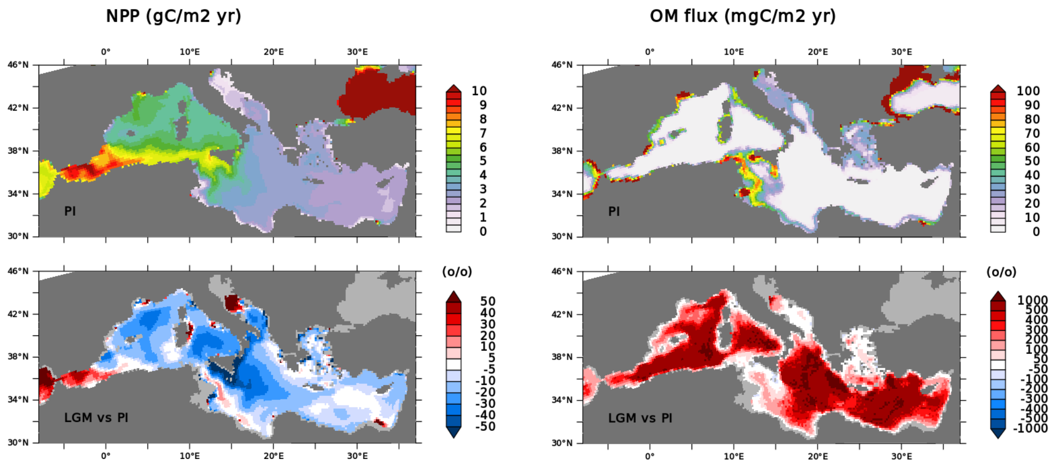

Figure 3 Net primary production (NPP, gC/m^2 yr) for present day (PI) and relative change in NPP between LGM and PI (%) (left column) ; organic matter (OM, mgC/m^2 yr) flux to the sediment for present day (PI) and relative change in OM flux between LGM and PI (%) (right column)

The resulting biogeochemical state at the LGM is very different compared to today's ocean. Colder temperatures and shallower mixed layer depths induce lower net primary production (by ~10 %) compared to present day (Figure 3, left). In contrast, the organic matter flux to the sediment is enhanced (+12%) because the remineralization rate of organic matter is also a function of temperature (Figure 3, right). Thus, colder temperatures increase the remineralization length scale and gravitational sinking transports more organic matter to greater depth. This, in combination with less effective export of intermediate water masses in the Strait of Gibraltar, leads to an accumulation of nutrients in the MedSea (Figure 4). The simulated LGM surface ocean is as nutrient depleted as present day, but we find higher nutrient concentrations closer to the surface in a well stratified water column. The impact of this high nutrient depot at greater depth on the Sapropel formation at the end of the stagnation (around 6kyr) needs to be investigated.

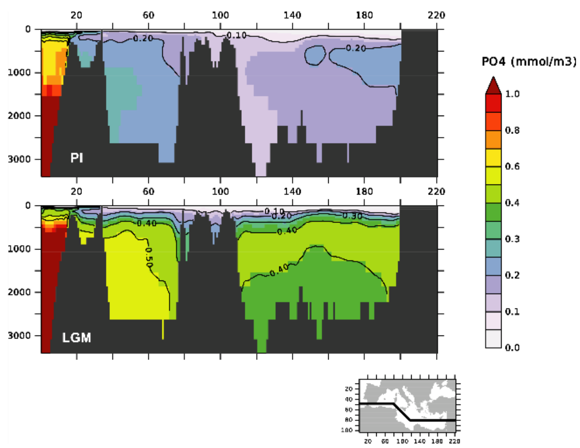

Figure 4: Mean phosphate concentrations (mmol/m^3) along a west – east transect for present day (PI) and LGM. Small map shows position of transect.

Our results on the LGM state are in line with previous studies on the LGM circulation (Myers etal 1998, Mikolajewicz, 2011). As Myers et al (1998) we find a shallowing of the pycnocline in the eastern MedSea being well inside of the present-day euphotic zone. Myers et al. (1998) inferred that there must have been increased biological production which then led to the observed higher deposition of organic matter. In our simulation, we find that we can achieve enhanced organic matter deposition even with lower biological production, primarily due to the temperature dependency of the remineralization length scale.

The first deglaciation simulation shows the expected tendencies in temperature und salinity with an increased stratification of the water column in the eastern basin. Stagnation of the deep-water leads to reduced ventilation and a decrease of the oxygen concentrations below 2500 m well before Sapropel formation as postulated by Grimm et al (2015). However, constant water mass ages between 14-10 kyr indicate a too early breakdown of the deep stagnation and reventilation of the deep water at high times of Sapropel formation (10-6 kyr). These findings initiated new model simulations with a reduced vertical mixing. Preliminary results show a clear trend towards lower oxygen concentration at depth due to stronger stratification and reduced ventilation.

WP2: Environmental process modelling

1. For the planned sensitivity runs under WP2.2, we performed simulations of three selected extreme events over the whole Tibetan Plateau using the Weather Research and Forecasting Model driven by the ERA5 reanalysis at 4km resolution with explicitly resolved convection (3). These experiments include: 1) Mesoscale Convective System (MCS) event during 14-24 July 2008 (Figure 5, left), 2) a month-long simulation for the Monsoon season during July 27 and September 01, 2014 (3, middle), and 3) A heavy snowfall event during 4-9 October 2018 (Figure 5, right). Initial assessment suggests that the experiments can imitate the extreme events well. The following points summarize main findings of the sensitivity runs performed under first group of simulations:

    - The performance of participating modelling systems is comparable but varies from case to case and among metrics.
    - The WRF multi-physics ensemble typically encompasses the spread of the other modelling systems particularly for simulating precipitation, like previously published results over Europe (Katragkou et al., 2015).
    - Differences in observational datasets are the dominant source of uncertainty in the model evaluation and are typically larger than model formulation, and model physics uncertainties. Model biases and observational uncertainties are particularly large for

the Snow case, which might be partly related to precipitation under catch issues (Prein and Gobiet, 2017).

- WRF PBL scheme uncertainties have similar magnitudes for all cases and are comparable to uncertainties stemming from the microphysics.

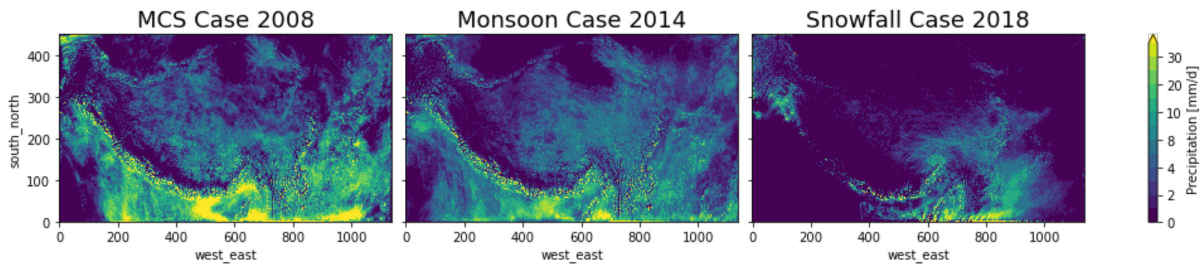

Figure 5: WRF-ERA5 downscaled mean precipitation (mm/day) at 4km resolution using explicitly resolved convection over the whole Tibetan Plateau for three extreme events.

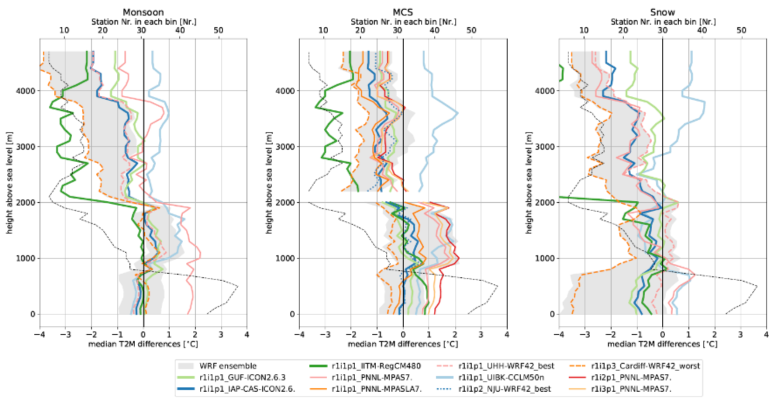

Figure 6: Differences in T2M between model simulations and hourly HadISD station observations dependent on the height above sea level. Differences are calculated in bins with 100m size, and we use a 250m window around each bin to reduce noise. The WRF ensemble spread is shown in grey contours and only the WRF simulations with the lowest and largest absolute difference to the station data are shown. The number of stations in each bin is shown as a dotted black line on the secondary x-axis.

2. A yearlong convection permitting simulation performed over the Tibetan Plateau is being post processed and will be analysed in near future
3. A 25-year 1-kilometre scale hydroclimatology of the NAMAL watershed is being postprocessed and will be analysed in near future (Figure 7)

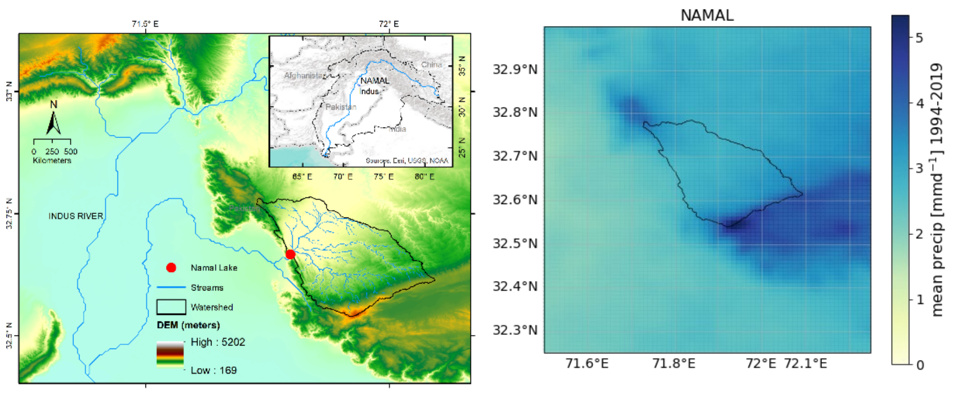

Figure 7: On left NAMAL watershed study map, on right 25-year (1994-2019) climatology of mean daily precipitation

Publications in 2022 that use data of project mh1212

WP1: The work has been presented at the EGU 2022 in Vienna and at the MedCLIVAR conference in Marrakesh, Morocco. Publication of the first results on the biogeochemical conditions at the Last Glacial Maximum is in preparation.

WP2: The following publication of the sensitivity experiment design and their initial scientific results is under review.

Prein AF, Ban N, Ou T, Tang J, Sakaguchi K, Collier E, Jayanarayanan S, Li L, Sobolowski S, Chen X, Zhou X, Lai H, Sugimoto S, Zou L, **Hasson Su**, Ekstrom M, Pothapakula PK, Stuart R, Steen-Larsen HC, Leung R, Belusic D, Kukulies J, Curio J, Chen D.: Towards Ensemble-Based Kilometer-Scale Climate Simulations over the Third Pole Region, 2022 DOI: 10.21203/rs.3.rs-1570621/v1 *(preprint under review)*

Data Management of project mh1212

WP1: Output of all simulations is stored on /arch. We have not yet used the applied space on /docu.

WP2: The WP2 project collaborates on the Convection-permitting Tibetan Plateau (CPTP) CORDEX Flagship study project. Experiments conducted so far are already shared with the project partners/collaborators and are placed on a Project's shared space other than /arch and /docu. The storages of /arc and /docu will be utilized in due course of time.

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Report project bg1184

Project title: CLICCS A5 - The Land-Ocean Transition Zone

Project lead: Moritz Mathis

CLICCS project chairs: J. Hartmann (UHH), P. Korn (MPI-M), C. Schrum (Hereon)

Reporting Period: 01.01. - 31.12.2022

	Allocated for 2022	Consumed (30.09.2022)	Projection of consumption to end of 2022
Computing time [node h]	112,710	84,011	112,710
Temporary storage / work [GB]	56,000	56,000	56,000
Storage / arch [GB]	35,000	33,000	35,000
Long term storage / doku [GB]	5,000	0	0

Experiments performed successfully at project account bg1184

During reporting period 2022, our experiments were mainly related to i) production runs of the regional marine ecosystem model SCHISM-ECOSMO and the global ocean-biogeochemistry model ICON-Coast, and ii) test simulations for the development of a new model system which for the first time couples the global ocean model ICON-O with the ecosystem component ECOSMO.

One of the central goals of the project A5 is the development of ICON-Coast, the first global ocean-biogeochemistry model with a seamless integration of coastal carbon dynamics. The technical development of the original model version could be accomplished in 2021 and we successfully published our conceptual approach in 2022 (Mathis et al., 2022). Another focus during 2022 therefore was laid on the first scientific application of ICON-Coast. To this end we have conducted hindcast simulations over the 20th century (including spinup runs of 400 yr in total) that account for potential anthropogenic impacts on coastal carbon dynamics, such as increasing atmospheric greenhouse gas concentrations and matter fluxes from land to the ocean. The scientific results obtained from these simulations are presented in the next section.

In addition, we have performed new multidecadal test simulations with ICON-Coast to assess the response of the model when increasing the resolution of the numerical grid. This is important as it is not obvious whether a transition in resolution causes a significant disturbance of the simulated physical and biogeochemical states, thus requiring grid-dependent spinup procedures. We found that an increase in the resolution by a factor of 2 (resulting in highest resolution of 10 km in the coastal ocean) is not critical in this respect, which means that we can pursue a coarser grid resolution (20 km) for efficient spinup simulations before switching to a higher resolution (10 km) for production runs.

The high-resolution configuration of SCHISM-ECOSMO was developed further for use in a wide range of research on the shelf carbon cycle. Extensive tuning simulations were performed to improve the representation of shelf-specific processes related to the marine carbonate system on the Northwest European Shelf. The improved SCHISM-ECOSMO model was then used to run a 10 year spinup simulation, a hindcast simulation over the period 2010-2015 and a sensitivity experiment over the same period excluding tidal forcing to investigate the impact of vertical mixing generated by internal tides on net carbon sequestration, transport and storage on the Northwest European Shelf. The high resolution of this model is essential to resolve the propagation of internal tides as well as their interaction with local bathymetric features (Guihou et al., 2018).

The ICON-ECOSMO coupling, using the FABM interface, obtained first satisfactory results after the concentration of dissolved iron was included in the model. With an approximation to iron dynamics in the world ocean, the initially strongly overestimated primary production could be corrected to much more realistic values by implementing iron limitation to ECOSMO´s formalism of marine primary production. In another step forward, we utilized our experience with ICON-Coast and successfully mastered the transition from a regular, coarsely resolved, to an irregular numerical grid with 14 km coastal resolution (Figure 8).

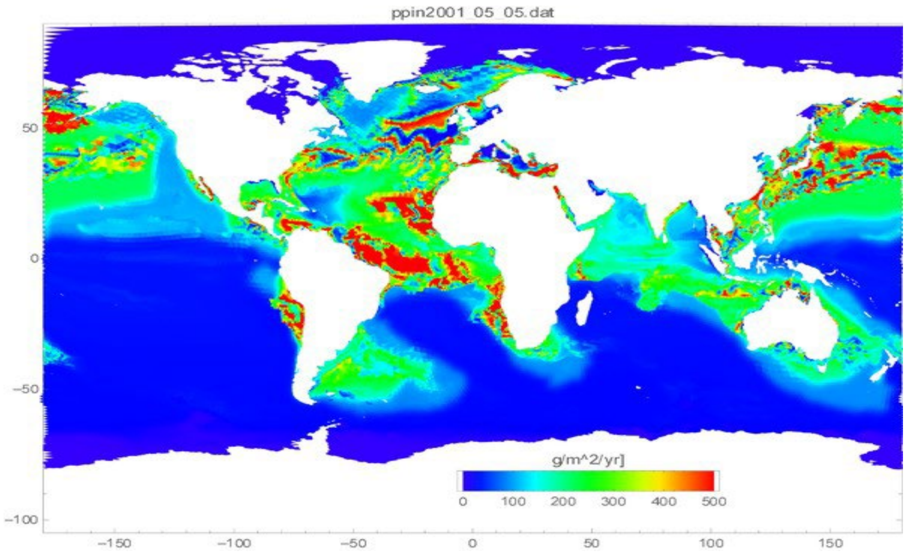

Figure 8: Weekly mean of vertically integrated primary production for begin of May, simulated by the ICON-ECOSMO model. The resolution of the used grid varies between 160 km (ocean interior) and 14 km (coastal regions).

Scientific results of project bg1184

Based on our first hindcast simulations with ICON-Coast, we derived an explanation for the disproportionally increasing CO2 uptake efficiency of the coastal ocean, evidenced from pCO2 observations during the last decades (Laruelle et al., 2018). We found that increasing biological productivity due to stronger upwelling as well as anthropogenic riverine nutrient inputs lead to higher C fixation in the coastal ocean and enhanced export to the open ocean and sediments. These changes in the coastal C budget effectively slowed down the pCO2 rise in the ocean relative to the atmosphere (Figure 9), thus driving the coastal ocean into a stronger CO2 sink. The increasing upwelling, caused by changes in the global large-scale wind fields, contributed to an increase in the coastal CO2 uptake efficiency by 30%, far compensating impacts of the warming-induced shoaling and strengthening of ocean stratification. Riverine nutrient loads contributed another 20%, adding up to a total increase in coastal CO2 uptake efficiency by 50% during the 20th century.

The results of the experiments with the high-resolution SCHISM-ECOSMO are used to investigate the relevance of tidal processes for the biological drawdown of atmospheric CO2. In a current paper draft (Kossack et al., in prep.) we demonstrate the ability of the multi-scale SCHISM-ECOSMO system to simulate the entire Northwest European Shelf region with an adaptive horizontal resolution that enables to resolve local small-scale processes like internal tides. The paper presents for the first time a shelf-scale quantitative assessment of the contribution of internal tides to biological primary production and analyses regional differences in the ecosystem impact of internal tides. We found that in stratified areas, tide-induced mixing enhances the vertical nutrient supply for phytoplankton growth above the thermocline, thus strengthening the biological productivity on the shelf by 22%. Moreover, in shelf areas with increasing distance to the shelf break, effects of internal tides become dominated by locally excited internal waves due to the influence of fine-scale bathymetric features on the circulation, rather than the traditional view by internal waves propagated from the shelf break.

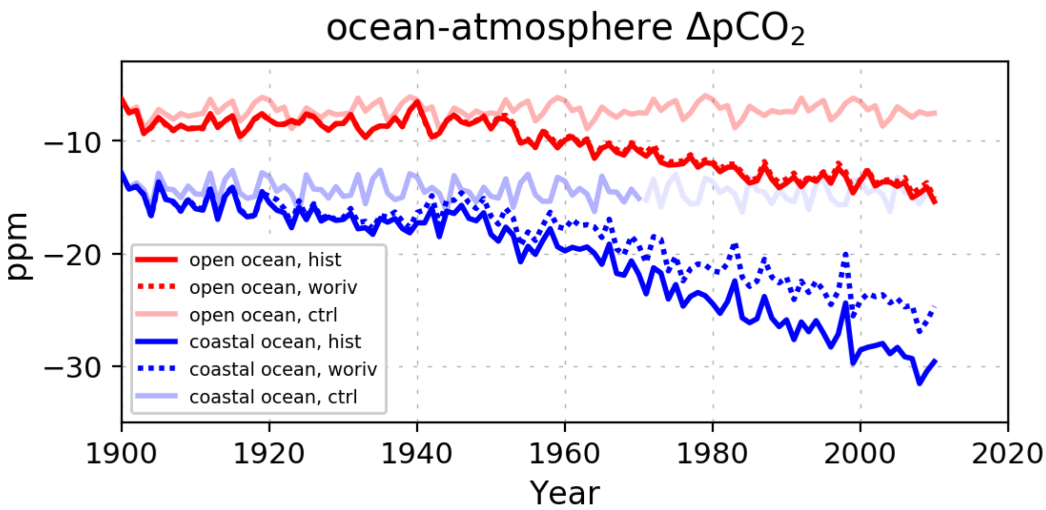

Figure 9: Evolution of the difference in CO2 partial pressure (pCO2) between the ocean and atmosphere during the period 1900-2010, simulated with ICON-Coast. Blue lines represent the coastal ocean, defined by the 500 m isobaths. Red lines represent the open ocean, excluding coastal areas. Ctrl: control run with continuous looped forcing of 1900-1919. Hist: historical run with reanalysis atmospheric forcing, increasing atmospheric CO2 concentrations, and increasing nutrient input from rivers and atmospheric deposition. Woriv: experiment like hist but without increasing nutrient input.

Publications in 2022 that use data of project bg1184

Mathis, M., K. Logemann, J. Maerz, F. Lacroix, S. Hagemann, F. Chegini, L. Ramme, T. Ilyina, P. Korn, C. Schrum (2022). Seamless integration of the coastal ocean in global marine carbon cycle modeling. Journal of Advances in Modeling Earth Systems, 14, e2021MS002789. https://doi.org/10.1029/2021MS002789

Data Management of project bg1184

The data produced during the project so far are primarily related to model development and the first hindcast simulations of ICON-Coast and SCHISM-ECOSMO are not yet fully evaluated to be shared with the community for further analysis. The hindcast simulations though are planned to be published in 2023 and will then be transferred to LTA Doku. Moreover, many of our test simulations will be moved from currently /work to the DKRZ archive, as they provide valuable information for ongoing and further development but we can dispense quick and direct access.

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Mathis, M., K. Logemann, J. Maerz, F. Lacroix, S. Hagemann, F. Chegini, L. Ramme, T. Ilyina, P. Korn, C. Schrum (2022). Seamless integration of the coastal ocean in global marine carbon cycle modeling. Journal of Advances in Modeling Earth Systems, 14, e2021MS002789. https://doi.org/10.1029/2021MS002789

Report project bu1213

Project title: CLICCS A6 - Earth System Variability and Predictability in a Changing Climate
Project lead: Johanna Baehr (UHH), Dian Putrasahan (MPI-M)
CLICCS project chairs: J. Baehr (UHH), T. Ilyina (MPI-M), J.-S. von Storch (MPI-M), E. Zorita (HZG)
Reporting Period: 01.01.-09.10.2022

	Allocated for 2022	Consumed (Sept.2022)	Projection of consumption to end of 2022
Computing time [node h]	711859	275,405	441,000
Temorary storage / work [TiB]	1235	474	1,000
Storage / arch [TiB]	4481	23	700
Long term storage / doku [TiB]	62	0	62

Because the scope of CLICCS A6 covers a wide range, there are six work packages that work collaboratively to achieve the goals of A6. For 2023, only three work packages applied for computational resources, and thus their reports are summarized based on their work packages:

WP1: Scale interactions and their impact on variability in a transient climate

WP2: Decadal ensemble simulations within a coupled wave-ocean-atmosphere-compartment

WP3: Variability of biogeochemistry in a mesoscale-resolving ICON ocean

1.1 Experiments performed successfully at project account bu1213

WP 1:

The coupled R2B8/R2B8 ICON-ESM have successfully been ported to Levante, and preliminary runs have produced quite some data for analysis. The success of migrating ICON-ESM and to have multi-decadal 10km coupled ICON-ESM simulations can be attributed to the collective effort and aid provided from DKRZ and CIMD from MPIM, as well as DKRZ computational resources billable to bu1213, mh0287 (MPIM shareholder account; GEMS) and bm1235 (NextGEMS). We are also continuously working with DKRZ and CIMD to improve the throughput of ICON-ESM and ICON-O, so that we can meet our next goals of centuries-long coupled R2B8/R2B8 ICON-ESM simulations. This year, after much hurdles for porting, debugging and tuning, we were able to produce *two 30-year simulations with coupled R2B8/R2B8 ICON-ESM*, which is the first in the scientific community in terms of length of simulation at a decently high-resolution for a coupled system! Both simulations use the new z*-vertical coordinate system for the ocean, which allowed us to have thin surface layers (~2m) in one experiment and thick surface layers (~11m) in the other experiment. This allows us to study the effects of ocean surface layer thickness on air-sea interactions and climate modes/variability.

The ability to obtain the mutli-decadal runs also arose from obtaining a higher throughput. On 400 nodes, we were able to get about 1 SYPD for the coupled R2B8/R2B8 ICON-ESM, which translates to 9600 node hours per simulation year for ICON-ESM. This is a decent improvement from last year's estimate of ~12,000 node hours per simulated year on Levante when we assumed 1:4 computation time for Levante:Mistral. At the peak, we were able to reach 1.5 SYPD, but encountered many UCX errors and numerical instabilities along the way that brought the throughput down. There's still much room for improvement if we are to run centennial simulations with coupled R2B8 ICON-ESM. Output variables and restart files were trimmed to on average ~10TiB per simulation year, with the latest down to ~6 TiB per simulation year.

WP 2:

The Coupled cOAstal model SysTem (GCOAST) setup used for the present application consists of the three Earth system compartments ocean, waves and atmosphere covered by the models GCOAST-NEMO for the ocean, GCOAST-WAM for the waves and GCOAST-CCLM for the atmosphere at regional scales (North Sea and the Baltic Sea, 2 nm) and downscaled for the German Bight (400 m).

Ensemble simulations were performed over a 2-3 year period (2016-2018) with changing coupling combinations of the GCOAST compartments: atmosphere, ocean, and wave. A publication of the results documenting the performance of the fully coupled system is currently in preparation and will be submitted shortly. In addition to this work, simulations with the same configurations were performed to investigate the effects of (large-scale) anthropogenic changes such as artificial islands or large-scale diking.

Several five-year simulations (2010-2014) were performed with the coupled GCOAST-NEMO-WAM setup. These runs used forcing data derived from global projection runs of the MPI-ESM Earth system model of the Max Planck Institute for Meteorology in Hamburg, Germany. The simulations were analyzed to prepare the GCOAST framework for longer simulations using these forcing data.

The downscaled high-resolution GCOAST-NEMO setup for the German Bight was updated to the latest NEMO source code (version 4.2). Subsequently, several one-year (2018) validation runs were performed with and without wave coupling.

During the reporting period, the GCOAST setup with all its components had to be migrated and adapted to the LEVANTE cluster. Unfortunately, due to technical reasons (changed MPI library and memory structure on LEVANTE), continuous production could not be maintained during the migration and was stopped from mid-May until the end of August 2022. The experiments described above were performed exclusively on MISTRAL. Longer simulations were not feasible because consistency of results could not be guaranteed when switching between the two clusters.

WP3:

We performed experiments that represent important technical improvements towards the high-resolution fully coupled system with ICON.

- **10km z-levels HAMOCC**: This is the highest-resolution simulation of the global ocean biogeochemistry ever performed. The results contributed to the milestone publication of Hohenegger et al. (2022, submitted).
- **10km z-levels concurrent HAMOCC**: After a bug fix in YAXT (by DKRZ), we are now able to run HAMOCC concurrently in the 10km setup, enabling a higher throughput.
- **40km z* ERA5-forced AMOC spin-up**: The transition to the dynamically-changing z* vertical coordinates (as opposed to fixed z-levels) is a necessary technical step at high-resolution

simulations. Also, in order to more realistically represent the ocean physics, and thereby biogeochemistry, we switched to a more recent climatology from ERA5 reanalysis (as opposed to the outdated OMIP forcing) to spin-up the ocean physics with ICON in with z*. About 3675 years of simulation were necessary to bring the AMOC to a steady state. For this long experiment, we used the r2b6 (40 km) setup. This experiment allows HAMOCC to be initialized (and tuned) with a steady-state ocean physics and to better understand ICON sensitivity to changing the forcing.

- **40km z-levels HAMOCC tuning:** It takes a substantial computational power to do a model spin-up for the biogeochemical model HAMOCC. Thus as a viable approach to achieve high resolution, it is expected to have a good tuning in a coarser grid and then interpolate the data to a higher spatial resolution grid. This tuning was done using the ERA5 forcing. It took 220 model years to reach a good equilibrium.

- **40km z-levels HAMOCC transient CO_2:** As a continuation of the experiment above, a transient CO_2 simulating historical emissions was started. The model was run with ERA5, z-levels, ocean only with HAMOCC. The total period contemplated was from 1850 to 2021.

- **Phytoplankton feedback:** Sunlight absorption by ocean biology changes the vertical profile of temperature and, thereby, the ocean physics. Although this process was already included in ICON (as legacy from MPI-ESM), the implementation had never been tested and contained problems. Several experiments were performed to have the phytoplankton feedback working in ICON at 40km with z-levels and z* vertical coordinates.

- **Arctic Coastal Erosion in MPI-ESM-LR:** Simulations partly used bu1213 resources for analysis. In total, a small ensemble of 6 simulations, differing at organic matter characterization, were performed following the CMIP6 protocol comprehending the historical period (1850-2014) and three future scenarios (2015-2100): SSP1-2.6, SSP2-4.5 and SSP5-8.5. This work builds up on the results published by Nielsen et al. (2022), in which organic matter fluxes from coastal erosion are estimated. Here, we provide the estimated fluxes to HAMOCC to investigate the impacts of coastal erosion on the Arctic biogeochemistry, in specific CO2 uptake from the atmosphere.

1.2 Scientific results of project bu1213

WP 1:

In addition to the hurdles posed for porting climate models, climate stability of a coupled system is a gigantic challenge. We use a coupled R2B8/R2B8 (10km) ICON-Sapphire configuration, which means that convection and gravity wave parameterisation in the atmosphere is turned off, and the ocean is rich with mesoscale eddies such that GM/Redi parameterisation is also turned off. As we try to make improvements to various physics schemes, in this case the atmospheric turbulence scheme, the coupled climate system, represented here by the coupled R2B8/R2B8 ICON-ESM simulation, was cooling substantially. We saw a cooling in global mean surface temperature (GMST) of about 1degC per year even though the top of atmosphere (TOA) imbalance was about 0W/m2. This points to an energy leak while the continuous cooling of global mean surface temperature meant that the climate is not stable. It seems that the big symptom for the cooling is likely due to too much cloud production that reflects shortwave radiation. It worsens in lower resolution as there isn’t enough turbulence (vertical velocity) to mix the boundary layer, so moisture stays in the lower levels and produces quite some cloud. Much of the issue points to turbulence in the atmospheric boundary layer, so perhaps the old TTE scheme can provide a different profile to the turbulence and help the cloud distribution and associated radiative quantities.

We tried with the TTE scheme and were pleasantly surprised with the stable GMST, albeit a TOA imbalance of about 5W/m2. While we have a somewhat stable climate, it is quite likely resulting from compensating errors that involve the energy leak of the dynamical core (AES department in MPIM is working to fix this issue). Figure 10, WP1.1 shows a cooling climate with Smagorinsky scheme (blue line) but a warm and stable climate with TTE scheme (green line). The warmer climate from using the TTE scheme (ngc2013) relative to using the Smagorinsky scheme (ngc2012) is namely attributed to much less cloud cover, although it should be noted that ngc2013 now has too little cloud.

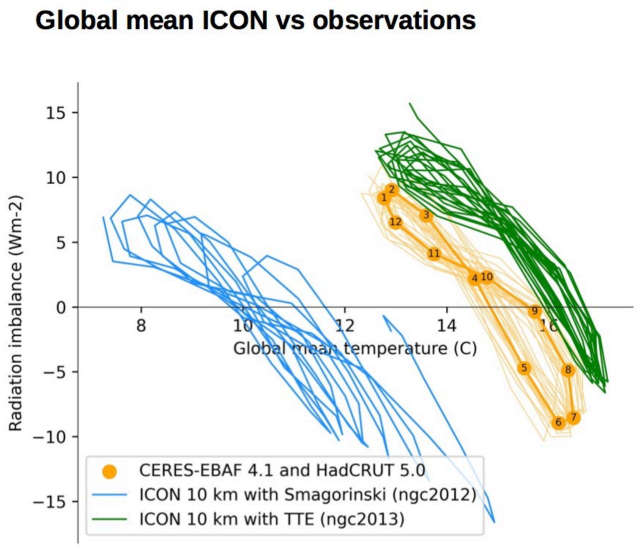

Figure 10: WP1.1: Seasonal cycle of top of atmosphere (TOA) radiation imbalance against global mean surface temperature to indicate climate state of the coupled system. Yellow line is based on observations while blue and green lines are based on coupled R2B8/R2B8 ICON-ESM simulations, the only difference between them is the atmospheric turbulence scheme employed. Blue line uses the Smagorinsky scheme, while the green line uses the TTE scheme.

Having a stable climate indicates we can perhaps use this configuration for climate studies that need long-term simulations. Along those lines, we have now performed a twin experiment using the coupled R2B8/R2B8 ICON-ESM with only differences in surface ocean layer thickness, and each has a 30-year integration period. These outputs are just produced and analyses are currently in progress.

WP 2:

Coupling of atmospheric and ocean models is already widely used to improve predictions for the two components of the earth system. Because waves occur directly at the interface between the atmosphere and ocean, they can be critical in describing the exchange of energy, heat, mass, and momentum between them. Nevertheless, wave models are still rarely included in earth system modeling studies. The effects of including the wave component in an Earth system model that already consists of an atmospheric and oceanic component, e.g., on wind speed during storms, are already well documented. The experiments conducted in WP2 aim to investigate the influences of wave coupling under more general conditions and on longer time scales, in the future also within climate-relevant time periods. Images in Figure 11,WP2.1 illustrate some of the results documenting the effect of having a model setup coupling all three components. Figure 11, WP2.1a shows a snapshots (28/05/2017) of differences in simulated sea surface temperature (SST) between a full coupled model run (atmosphere, ocean, and wave; AOW) and a model run coupling only atmosphere and ocean (AO). Figure 11, WP2.1b shows the according time series of absolute temperatures averaged over the North Sea area in blue (AOW) and in orange (AO). In addition, the time series for a model run coupling only atmosphere and waves (AW) is given in red.

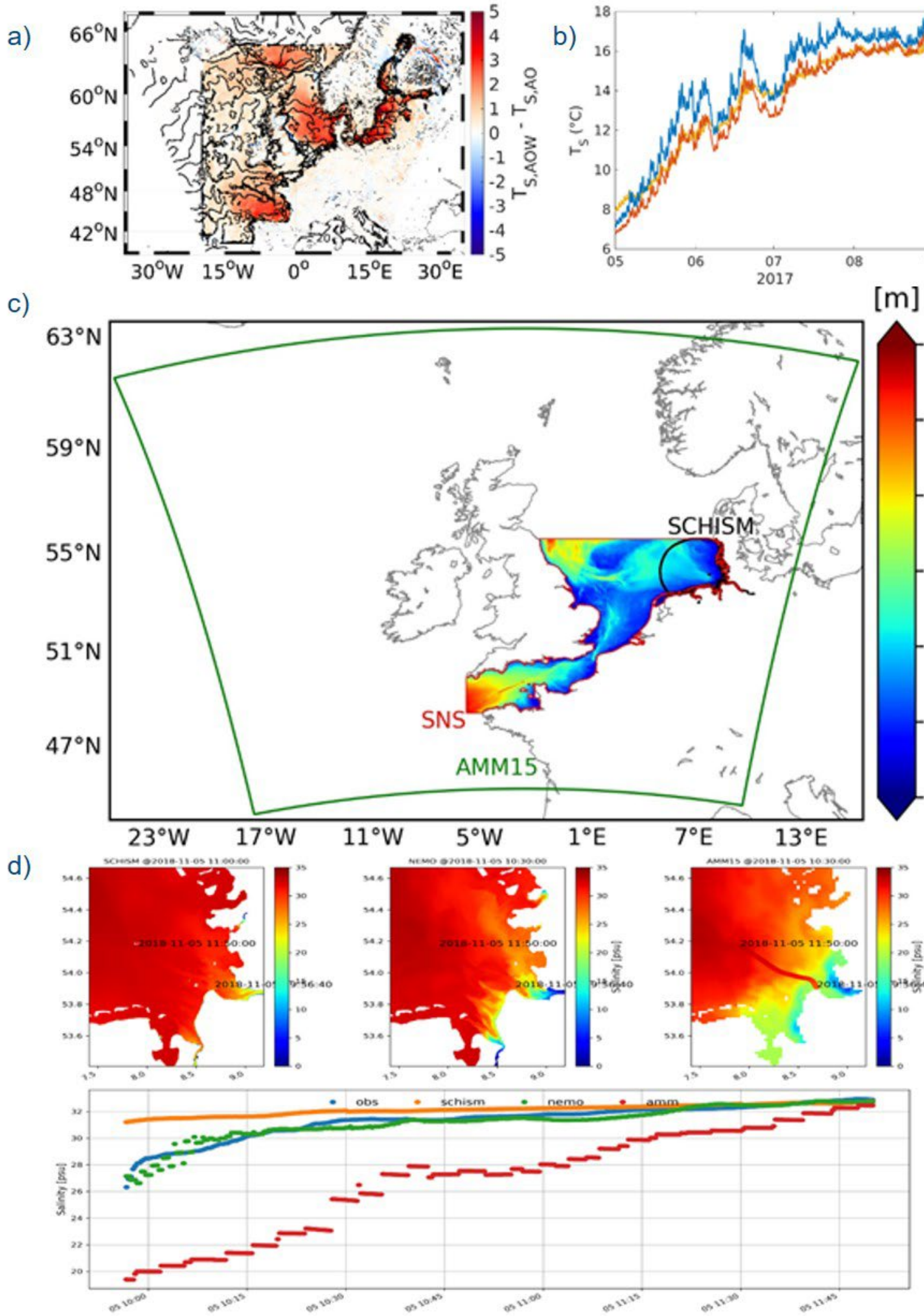

Figure 11 WP.2.1: (a) Snapshots (28/05/2017) of differences in simulated sea surface temperature between a full coupled GCOAST model run (atmosphere, ocean, and wave) and a model run coupling only atmosphere and ocean. (b) Time series of absolute surface temperature of model run with changing coupling combination: atmosphere, ocean, and wave (blue); atmosphere and ocean (orange); atmosphere and wave (red). (c) Model area of GCOAST (400m resolution), CMEMS' AMM15 (1.5km resoluton; https://doi.org/10.48670/moi-00054) and Hereon's unstructured SCHISM model setup (1.5km-50m resolution). (d) Shows a comparison of ship-based measurements in November 2018 derived from the Ferry Box with the snapshots (top row) and simulated sea surface salinity along the track (bottom panel) derived from the three models.

Compared to other model simulations, the high-resolution GCOAST model (400m resolution) performs very well in simulating frontal structures in the German Bight. We compared the model with the results of CMEMS' AMM15 (1.5km resolution; https://doi.org/10.48670/moi-00054) and Hereon's unstructured SCHISM model setup (1.5km-50m resolution) for the region. The model domains of the three model approaches are shown in Figure 11, WP2.1c. Figure 11, WP2.1d shows a comparison ovn ship-based measurements in November 2018 derived from the Ferry Box with the snapshots (top row) and simulated sea surface salinity along the track (bottom panel) derived from the three models. An high prediction skill for the frontal structures is in valuable for ecosystem models and the anticipated simulations with the GCOAST setup will be prove useful as forcing and boundary data for the planned ecosystem simulation experiments in CLICCS C3.

Experiments reconstructing the multiannual (1993-2020) variability of the Baltic Sea coastal sea level with a Kalman filter approach, were conducted and published in CMEMS' Ocean State Report Issue 6 (https://doi.org/10.1080/1755876X.2022.2095169). Observations at tide gauges and the leading EOF modes of SSH simulated by the SMHI (CMEMS) were used for reconstruction and validation in the publication. Further work were performed to extend the usage of Altimeter data within the study and planned to be submitted in a second publication soon.

WP3:

HAMOCC-ICON-O 10km setup

To assess HAMOCC in a mesoscale-resolving ICON ocean setup, as a first step, we ran a 10km (R2B8) HAMOCC-ICON-O setup for 4 years and evaluated the simulations against satellite observations. The model captures the observed spatial pattern of the yearly mean chlorophyll-a concentration (not shown). The concentrations are overestimated, but given the simplified representation of biology in HAMOCC with the use of a bulk phytoplankton and the large uncertainties in the observations (35%), this first comparison looks generally promising. Moreover, zooming into the North Atlantic region, indeed reveals that the 10km model can capture the effect of mesoscale ocean eddies on ocean productivity, as expected from observations (Figure 12, WP3.1a & b).

The model can also reproduce the seasonal cycle in chlorophyll-a concentration for the two hemispheres (not shown). In the Northern Hemisphere, the simulated seasonal cycle is in reasonable agreement with observations. It captures the spring bloom, but not the autumn one. In the Southern Hemisphere, the austral summer bloom is reproduced but with a much too strong amplitude, likely due to a lack of production in ice covered regions in the model, leading to a large abundance of nutrients when the ice melts.

When comparing the 40 km with the 10 km it was possible to observe strong mesoscale activity difference between the models. Comparing the sea surface height (SSH) variability, a proxy for mesoscale activity, between both resolutions (not shown) shows that the 10km model has more variability than the 40 km as it was expected, especially in dynamic rich areas such as western boundary currents (e.g. Gulf Stream and Kuroshio Current). Following this scenario a correlation was made between the SSH and phosphate (PO_4) , one of the major nutrients in the ocean, on the 10 km resolution (Figure 12, WP3.1c). Strong regions of high correlation were observed along the regions of strong SSH variability , possibly showing preliminary evidence of the effect of mesoscale eddies on biogeochemical tracers.

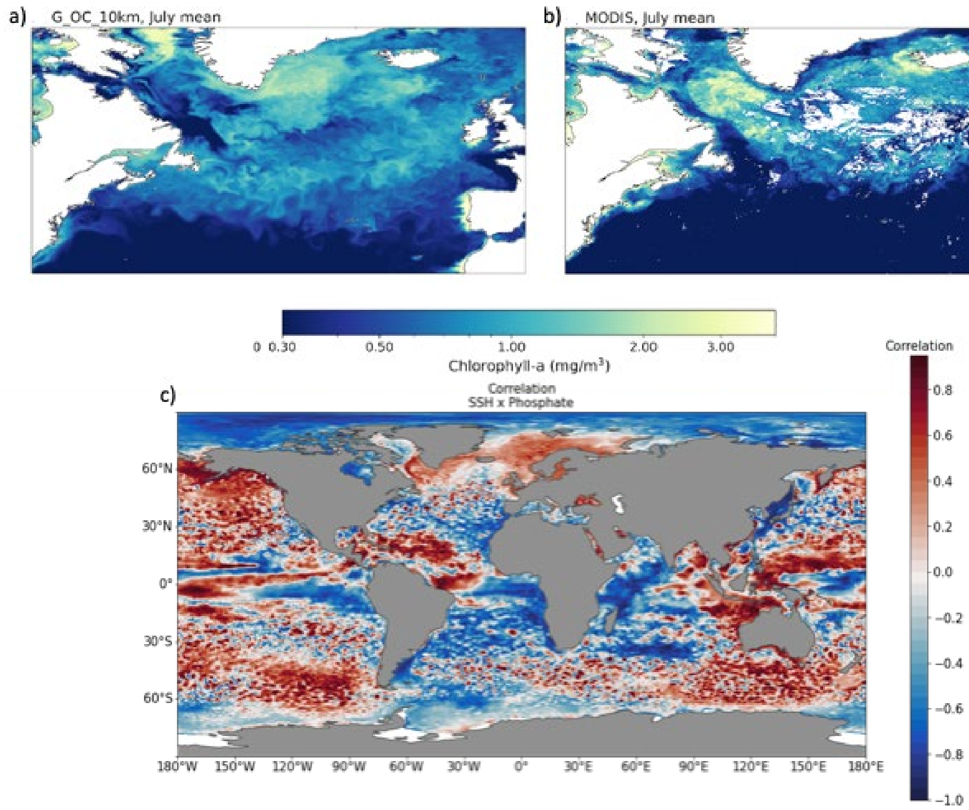

Figure 12: WP3.1. a) Chlorophyll-a from zoom into the North Atlantic for July 2016 in model; b) same as (a) except for observations; c) correlation between SSH and phosphate on the 10 km resolution (R2B8)

Arctic Ocean's CO_2 uptake response to permafrost organic carbon loss

The Arctic coast consists of permafrost – perennially frozen soil – rich in ground ice and organic carbon (OC). The erosion of the coastal permafrost is projected to increase by a factor of 2 to 3 by the end of this century (Nielsen et al. 2022). However, the effect of coastal erosion on the Arctic Ocean's carbon cycle is still uncertain. The eroded organic matter may degrade producing CO_2, boost primary production consuming CO_2, or become buried in the sediment. As coastal erosion increases, where will the eroded carbon go? How will the Arctic Ocean's CO_2 uptake change in response to coastal permafrost erosion in the future? Here, we perform enhanced simulations with MPI-ESM, considering the OC flux from the eroding coastal permafrost, and its ocean biogeochemical effects, covering the historical period (1850-2014) and a wide range of CMIP6 emission scenarios (2015-2100).

We find that coastal permafrost erosion decreases the Arctic Ocean's CO_2 uptake by 9-22% in the Inner Arctic region (excluding regions of strong Atlantic influence) or by about 3-5% considering the entire Arctic circle (not shown). The percentage decrease is robust across all sensitivity simulations, and all relatively constant in all periods and scenarios. Moreover, with the addition of coastal permafrost erosion fluxes, the Siberian shelf seas switch from net sink to source regions of CO_2 in all simulations and in all time periods, although the signal is strongest in SSP5-8.5. This switch in sign is in accordance with observations (Anderson et al. 2009; Pipko et al. 2011), which suggest a weak uptake to net outgassing role of the Laptev and East Siberian seas.

Arctic coastal erosion promotes a relatively constant increase in surface pCO_2 as a result of the combined effects of surface alkalinity and dissolved organic carbon (DIC). On the one hand, OM remineralization decreases surface alkalinity, increasing surface pCO_2. On the other hand, the increase in DIC by direct input and due to OM remineralization increases surface pCO_2. In the historical period, alkalinity and DIC contribute similarly to the pCO2 increase (Figure 13, WP3.2). With time, primary production decreases DIC to the point that DIC contributes negatively to the total *Δ*pCO2 in the future. Meanwhile, the effect of decreasing alkalinity becomes stronger, compensating for the negative DIC anomaly. The net decrease in CO2 uptake is only allowed by the stronger effect of alkalinity than that of DIC, maintaining a steady pCO2 increase in the future.

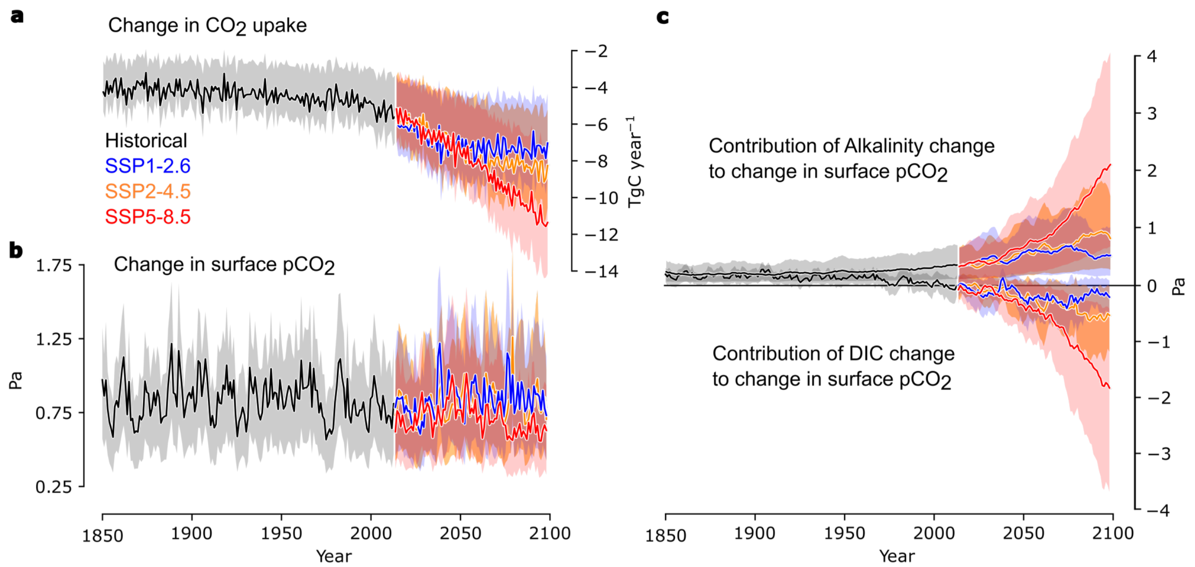

Figure 13 WP3.2: Yearly changes in CO_2 uptake (a) and surface pCO_2 (b) due to Arctic coastal permafrost erosion, and the contributions of changes in surface alkalinity and DIC to the total change in surface pCO_2 (c). All plots show only the difference between simulations with and without erosion. Lines are the mean across the 6 sensitivity simulations with different organic matter characteristics, while the shading represents the total range.

1.3 Publications in 2022 that use data of project bu1213

WP1:

- Publication on the effect of resolved vs parameterized deep convection on Hadley Cell is currently in preparation (von Storch et al.)
- Publication on the multi-decadal coupled R2B8/R2B8 ICON-ESM with different surface ocean layer thickness is in preparation (Putrasahan et al.)
- Publication on the coupled variability and air-sea interactions based on 2-years of coupled R2B9/R2B9 ICON-ESM is in preparation (Putrasahan et al.)
- Contributions of coupled variability analysis in Sapphire overview paper Hohenegger et al. (2022, submitted to GMD)

Hohenegger, C., Korn, P., Linardakis, L. et al. (2022): ICON-Sapphire: simulating the components of the Earth System and their interactions at kilometer and subkilometer scales, *Geosci. Model Dev. Discuss.* [preprint], https://doi.org/10.5194/gmd-2022-171, in review.

WP2:

- Two publications with results obtained from ensemble experiments based on lateral forcing and coupling are under preparation (A6 PhD Student Thoa Ngyen as a leading author) and soon will be submitted to the journals NHESS (Copernicus) and Regional Studies in Marine Science (Elsevier)
- Experiments reconstructing the multiannual (1993-2020) variability of the Baltic Sea coastal sea level with a Kalman filter approach, were conducted and published online in CMEMS'

Ocean State Report Issue 6 (https://doi.org/10.1080/1755876X.2022.2095169). Observations at tide gauges and the leading EOF modes of SSH simulated by the SMHI (CMEMS) were used for reconstruction and validation in the publication. Further work were performed to extend the usage of Altimeter data within the study and planned to be submitted in a second publication soon.
- A study analysing the effects of fully coupling the atmosphere, waves and ocean compared to two way coupled simulations of either atmosphere and waves or atmosphere and ocean in GCOAST35 model simulations will be published soon.

WP3:

- The 4-year 10-kilometer ICON simulation contributed to the paper of Hohenegger et al. (2022, submitted to GMD). This represents a significant step forward towards the fully-coupled system with ICON in high resolution.
- The work of Nielsen et al. (2022) combines research from A1 and A6 and partly used resources from the two projects for analysis. The current work on the Arctic Ocean's CO2 uptake response builds up on this work. We use the organic carbon flux estimates from Nielsen et al. (2022) and prescribe them to MPI-ESM simulations in the historical period and three CMIP6 scenarios.

Hohenegger, C., Korn, P., Linardakis, L. et al. (2022): ICON-Sapphire: simulating the components of the Earth System and their interactions at kilometer and subkilometer scales, *Geosci. Model Dev. Discuss.* [preprint], https://doi.org/10.5194/gmd-2022-171, in review.

Nielsen, D. M., Pieper, P., Barkhordarian, A., Overduin, P., Ilyina, T., Brovkin, V., Baehr, J. & Dobrynin, M. (2022). Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. *Nature Climate Change*, **12**(3), 263-270. https://doi.org/10.1038/s41558-022-01281-0

1.4 Data Management of project bu1213

WP1

Data generated for the study of the role of vertical resolution and ocean eddies are 30-years coupled R2B8/R2B8 ICON-ESM experiments with mainly daily and monthly ocean and atmosphere outputs, and some higher temporal outputs that follow DyamondWinter style. While these simulations are complete, they require storage space for analysis, and are thus italicised in the table. This study is conducted in conjunction with MPI-M Ruby-Thin project and NextGEMS. Data from these experiments is used within CLICCS as well as outside of CLICCS in projects like NextGEMS, and by other MPI-M/UHH users.

Data generated for the study of the effects of resolved convection are 1-year R2B9 and 10-years R2B6 experiments with mainly daily outputs and some hourly outputs for 2D variables and a few 3D variables. These simulations are complete but occupy storage space for analysis, hence they are italicised in the table. This study was conducted in conjunction with MPI-M Dyamond-Circulation project, and hence data is also used by MPI-M scientists.

Storage space in work

For the 150-year transient simulation using coupled R2B8/R2B8 ICON-ESM and it requires storage of 6TiB per simulation year, resulting in 900 TiB for the simulation alone on Levante storage. However, we will store this on EERIE account to consolidate all the outputs. ICON-A (R2B6/R2B9) simulations are complete, but storage space for them is still required as ongoing analyses are in progress. We therefore request **62 TiB** of storage space on 'Levante storage' for these simulations (two R2B6 simulations and one R2B9 simulation). The other R2B9 simulation is stored on mh0256. Similarly, ICON-ESM (R2B8/R2B8) simulations completed over this year need storage space on Levante for studying/analyzing the impact of ocean layer thickness on climate modes. We request to store one 30-year simulation of data that amounts to **285TiB**. And the other 30-year simulation is stored on bm1235.

In summary, for A6-WP1, we ask a total of **347 TiB** for work storage space the upcoming year.

Storage space in Archive project

We intend to archive raw outputs from the production runs so that data is available for usage to project partners and for extended analysis. We will archive one of the completed 30-year ICON-ESM simulations. We would also like to archive all the ICON-A experiments under CLICCS for easier data management, rather than distributing the archiving to separate projects. Therefore we request ***272 TiB*** for storage on the tape archive.

Storage space in Archive long term

Because of how expensive these runs are and how useful they would be for future studies, we would like to ensure long-term storage and accessibility of these runs. Also, this is in consideration to ensure compliance of data availability for journal publication. We intend to store on Doku ***272 TiB*** in 2023 for ICON-A simulations and one 30-year ICON-ESM simulation, and much more in 2024 for centuries-long ICON-ESM simulations.

Data volume for simulations under CLICCS (*italics for completed simulations*):

Experiment	Raw output generated per integration year	Total storage requirements		
		Lustre Work [TiB] for 2022	Archive project [TiB] for 2022	Archive long term [TiB] for 2022
ICON-A (R2B6) 10-year perpetual January (PI-control)	*0.34 TiB/year*	*3.4*	*3*	*3*
ICON-A (R2B9) 1-year perpetual January (PI-control)	*55 TiB/year*	*0 (stored on mh0256)*	*28*	*28*
ICON-A (R2B6) 10-year perpetual January (4K warmer world)	*0.34 TiB/year*	*3.4*	*3*	*3*
ICON-A (R2B9) 1-year perpetual January (4K warmer world)	*55 TiB/year*	*55*	*28*	*28*
ICON-ESM (R2B8/R2B8) 30-years control (thick surface ocean)	9.5 TiB/year	285	210	210
TOTAL for WP1 (in 2023)		**347 TiB**	**272 TiB**	**272 TiB**

This project requires an enormous amount of computational resources as well as data storage. Therefore, we are applying for resources from CLICCS, MPI-shareholder and EERIE, not as duplication but rather to complement one another. Resources applied from MPI under project Sapphire/Ruby are for model tuning, while resources applied from EU project EERIE would be for the fixed-1950 control ICON-ESM run. Resources applied for CLICCS are more for the climate change ICON-ESM runs.

WP2

Due to the ongoing analysis and publication work, most simulation data is stored on "work/". 200 TB are used here. The three-year ensemble simulations with the fully and partially coupled GCOAST35 model setup are stored in "archive/" and use 100 TB of data. Since the archiving procedure is automatically easier to handle with the new slk software, we plan to implement on-the-fly archiving for future model simulations, which will reduce the use of "work/".

WP3

The data generated in most experiments will be kept at the “/work” directory in project bu1023, adding up to 206 TB. The final year of data generated in the 4-year experiment of ICON-O with HAMOCC at R2B8 (10 km), which contributed to the SOP paper (Hohenegger et al.), is stored in the long term archive, amounting to 6.3 TB. The table below describes the data storage details per experiment in the reporting year 2022 for WP3:

Experiment	**Raw output generated per integration year**	**Total storage requirements**		
		Work [TB] for 2022	**HPSS Arch [TB] for 2022**	**HPSS Doku [TB] for 2022**
Phytoplankton feedback R2B6	0,2 TB	120 TB	0	0
10km (R2B8) z-levels HAMOCC (SOP)	6.3 TB	24 TB	6.3 TB	0
HAMOCC spinup in R2B6	0.13 TB	38 TB	0	0
AMOC spinup	0.01 TB	18 TB	0	0
HAMOCC transient runs in R2B6	0.03 TB	6 TB	0	0

1.5 References

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Li, D., J. Staneva, J.-R. Bidlot, S. Grayek, Y. Zhu, and B. Yin, 2021: Improving regional model skills during typhoon events: A case study for super Typhoon Lingling over the northwest Pacific Ocean. Frontiers in Marine Science.

Putrasahan, D.A., O. Gutjahr, H. Haak, J.H. Jungclaus, K. Lohmann, M.J. Roberts, and J.S. von Storch, 2021: Effect of Resolving Ocean Eddies on the Transient Response of Global Mean Surface Temperature to Abrupt 4xCO2 Forcing. Geophys Res Lett, 48(8), e2020GL092049.

Putrasahan, D.A. and J.S. von Storch, 2021: Piecewise Evolutionary Spectra: A Practical Approach to Understanding Projected Changes in Spectral Relationships Between Circulation Modes and Regional Climate Under Global Warming. Geophys Res Lett, 48(14), e2021GL093898.

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Hohenegger, C., Korn, P., Linardakis, L. et al. (2022): ICON-Sapphire: simulating the components of the Earth System and their interactions at kilometer and subkilometer scales, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2022-171, in review.

Nielsen, D. M., Pieper, P., Barkhordarian, A., Overduin, P., Ilyina, T., Brovkin, V., Baehr, J. & Dobrynin, M. (2022). Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change, 12(3), 263-270. https://doi.org/10.1038/s41558-022-01281-0

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Paulsen, H., Ilyina, T., Jungclaus, J. H., Six, K. D., & Stemmler, I. (2018). Light absorption by marine cyanobacteria affects tropical climate mean state and variability. Earth System Dynamics, 9(4), 1283-1300.

Report project bu1214

Project title: CLICCS C1 - Sustainable Adaptation Scenarios for Urban Areas – Water from 4 Sides
Project lead: Franziska S. Hanf
CLICCS project chairs: Jörg Knieling (HCU), Jana Sillmann (UHH, since 2022), Bernd Leitl (UHH), Jürgen Oßenbrügge (UHH)
Reporting Period: 01.01.-01.10.2022

	Allocated for 2022	Consumed (01.10.2022)	Projection of consumption to end of 2022
Computing time [node h]	2728	Used: 308 Expired: 1710	2728
Temorary storage / work [TiB]	13	9	13
Storage / arch [TiB]	23	0	
Long term storage / doku [GB]	5	0	

6.1 Experiments performed successfully at project account bu1214

For the purpose of this project, we firstly implemented the model setup COSMO-DCEP-MUSCAT on Mistral, last year. The MUSCAT model was provided by its developers from the Leibniz Institute for Tropospheric Research (TROPOS). The model system consists of the meteorological model COSMO, the chemistry transport model MUSCAT and the urban parametrization DCEP.

This year, we transitioned the model-system to Levante, which took a long time and was not easy. This is also due the problem that the reliability of Levante has greatly diminished. Neither the archiving nor the queuing system were reliable. This has caused significant delays in the transition to "production runs".
In addition, the selection of a new model domain caused some delay, as the preparation of new input data took much longer than expected.
For the scientific work, different convective meteorological situations had to be selected, which took more time than expected. First simulations with ERA5 as model input had difficulties, as smaller convective rain systems were not resolved due to the coarse resolution of the input data. Therefore, we started working with additional input data, the dataset PAMORE provided by the German weather service. However, there were some difficulties with the data format on Levante. After some time searching for the problem, we found, that the right decoding on Levante for the data format was missing. Facing all those hurdles, which were not predictable before, it was not possible to start with planned production runs yet.

6.2 Scientific results of project bu1214

Using the model setup COSMO-DCEP-MUSCAT we aim to investigate the interactions between atmospheric aerosol particles, emitted in the urban environment, and the formation of clouds and precipitation in the vicinity of large urban agglomerations. In order to simulate a direct aerosol-cloud-precipitation coupling the 2-moment microphysics scheme from COSMO was extended to allow cloud condensation nuclei to be calculated directly from aerosols simulated with MUSCAT.
With all problems mentioned in chapter 6.1 we were not able to start with the production runs.

However first runs with and without the extended microphysics where performed. The model runs were initialized with ERA5 data.

As a weather situation for the comparison runs, we choose a convergence line running diagonally across Germany, which occurred on May 30, 2018. In the area close to the convergence zone, an additional uplift drive developed, which was responsible for the heavy showers and thunderstorms that occurred in central-eastern Germany in the afternoon.

Preliminary results show, that comparing the simulated precipitation with standard and extended microphysics, the runs considering the MUSCAT aerosol distribution lead to more precipitation outcome (Figure 13).

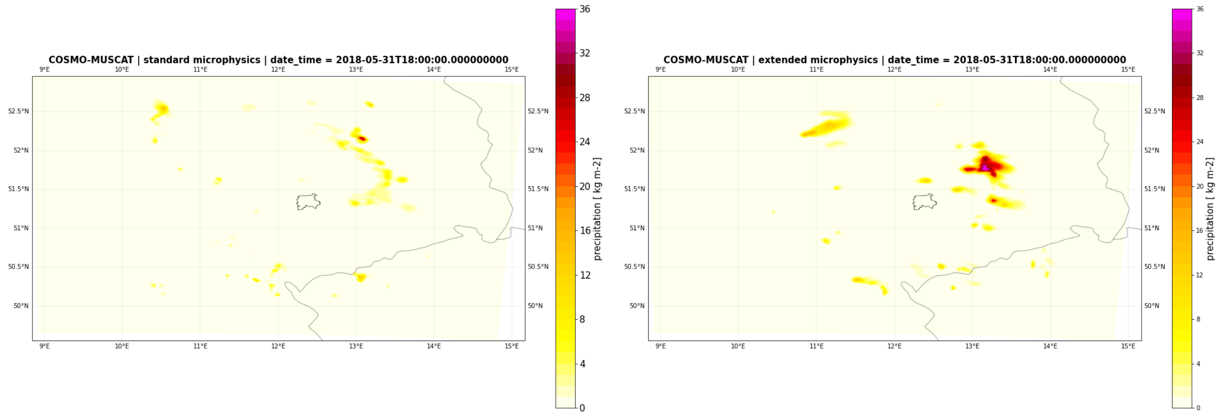

Figure 13: Simulated precipitation in [kg m^{-2}] for model domain central/east Germany with resolution of 2.2km. On the left, the precipitation field simulated with the standard microphysics, on the right with the extended microphysics.

The cloud mixing ratio (Figure 14) indicates, that clouds simulated with the extended version reach higher vertical levels. Moreover, comparing the rain mixing ratios indicates, that cloud water is converted into rain water more efficiently leading to more precipitation outcome. Further analysis of the runs with and without the extended microphysics is currently underway.

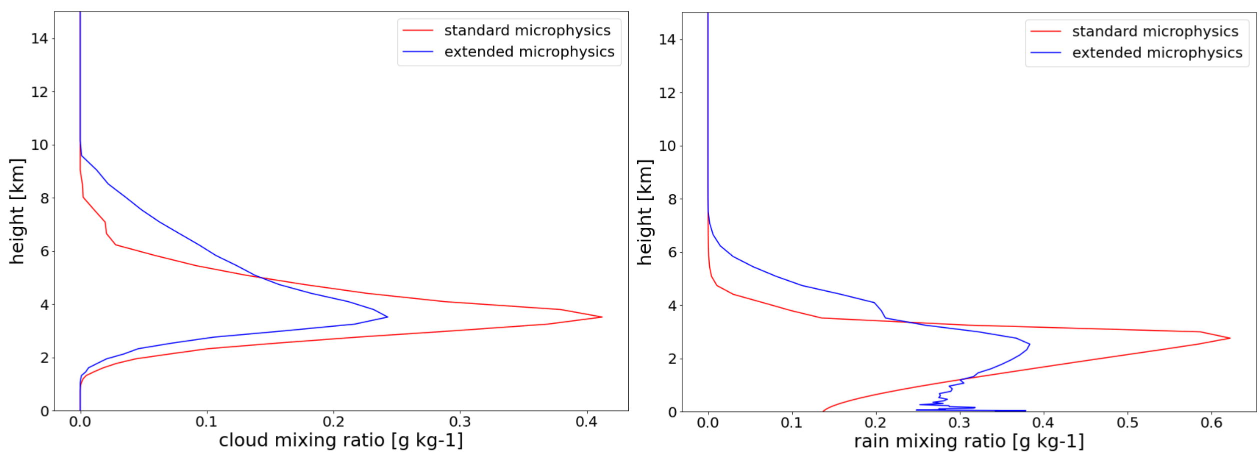

Figure 14: On the left vertical cloud mixing ratio profile and on the right vertical rain mixing ratio profile, summarized over the central Germany model domain. The red lines show the mixing ratios for the simulations with standard microphysics and the blue lines for the extended microphysics.

Nevertheless, this could be consistent with the theory Rosenfeld (2000, 2008), that higher number of aerosols lead to more, but smaller cloud droplets. Smaller cloud droplets are less efficient in collision and coalescence processes resulting in reduced activation as rain droplets in the early stage of the convective cloud. However, once the more and smaller cloud droplets reach freezing point, high amounts of latent heat are released as the droplets freeze. Consequently, rimming and updraft formation are enhanced, leading to stronger and higher reaching convective systems and thereby resulting in heavier precipitation.

6.3 Publications in 2022 that use data of project bu1214

-Poster/Abstract at the EMS conference 2022:
Bär, F., Petrik, R., Heinold, B., and Quante, M.: Model study on the influence of aerosol-cloud interaction processes on precipitation in urban areas, EMS Annual Meeting 2022, Bonn, Germany, 5–9 Sep 2022, EMS2022-506, https://doi.org/10.5194/ems2022-506, 2022.

6.4 Data Management of project bu1214

Currently 9 TiB storage on work are used. This includes the model setup, the input data and first finished model-runs.

6.5 References

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D. Rosenfeld, U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae. Flood or drought: How do aerosols affect precipitation? science, 321(5894):1309-1313, 2008.

Report project bg1186

Project title: CLICCS C3 - Sustainable Adaptation Scenarios for Coastal Systems
Project lead: Johannes Pein
CLICCS project chairs: K. Dähnke (UHH/HZG), P. Fröhle (TUHH), C. Möllmann (UHH), B. Ratter (UHH/HZG)
Reporting Period: 01.01. -02.09.2022

	Allocated for 2021	Consumed (01.09.2022)	Projection of consumption to end of 2021
Computing time (node h)	349,569	174,784 (Mistral) 50,700 (Levante)	275,000
Temporary storage / work (TiB)	117	449.28	117
Storage / arch (TiB)	166	17.2	166
Long term storage / doku (GB)	-	-	-

1.1 Experiments performed successfully at project account bg1186

1.1.1 NEMO-ECOSMO

The GCOAST-NEMO+ECOSMO configuration for the North-Western shelf has been run for a multi-year period. This long-term simulation was used to produce maps of estimated average quantities of the coupled physical-biogeochemical dynamics. Although the simulation revealed good performance in reproducing nutrient concentrations and primary production most of the model domain, certain areas like the Baltic Sea remain challenging to parametrise. The issues relate also to the coupling between NEMO and ECOSMO and further development is necessary.

7.1.2 SCHISM-ECOSMO

During the reporting period, the new framework for downscaling of regionalized global climate scenarios to the German Bight and Elbe Estuary went into production. The set-up of southern North Sea with Elbe Estuary represented by a high-resolution mesh (Pein et al., 2021) was coupled to combined climate model information represented by probabilistic estimates of global mean sea level rise from the UKCP18 project (Palmer et al., 2018, 2020) and regional climate model simulations from the A9Extreme project (Lang and Mikolajewicz, 2019, Mayer et al., 2022). The model was calibrated to match the observed tidal range at the mouth of Elbe Estuary during the last year of the historic period covered by the MPIOM-REMO regional climate simulations (2005). Then the model framework was integrated for the future period 2090-2099. For an optimal result of the downscaling exercise, the SCHISM set-up was used in two configurations. The 2D configuration covering a greater area in the English Channel and the central North Sea was driven by mean sea level, hourly sea level and wind. Then the results of the 2D simulation, namely hourly sea level and barotropic currents, were used to drive the 3D model configuration, whereas the forcing was complemented by monthly baroclinic currents, salinity and temperature from the MPIOM simulation (see workflow Figure 22). This downscaling concept provides a tight coupling of the child model to the climate simulations even on tidal time scales. To directly drive a 3D model with hourly sea level data is not feasible, which is why previous modelling studies used tidal data from tidal atlas like FES2014 for the tidal forcing (Hermans et al., 2020).

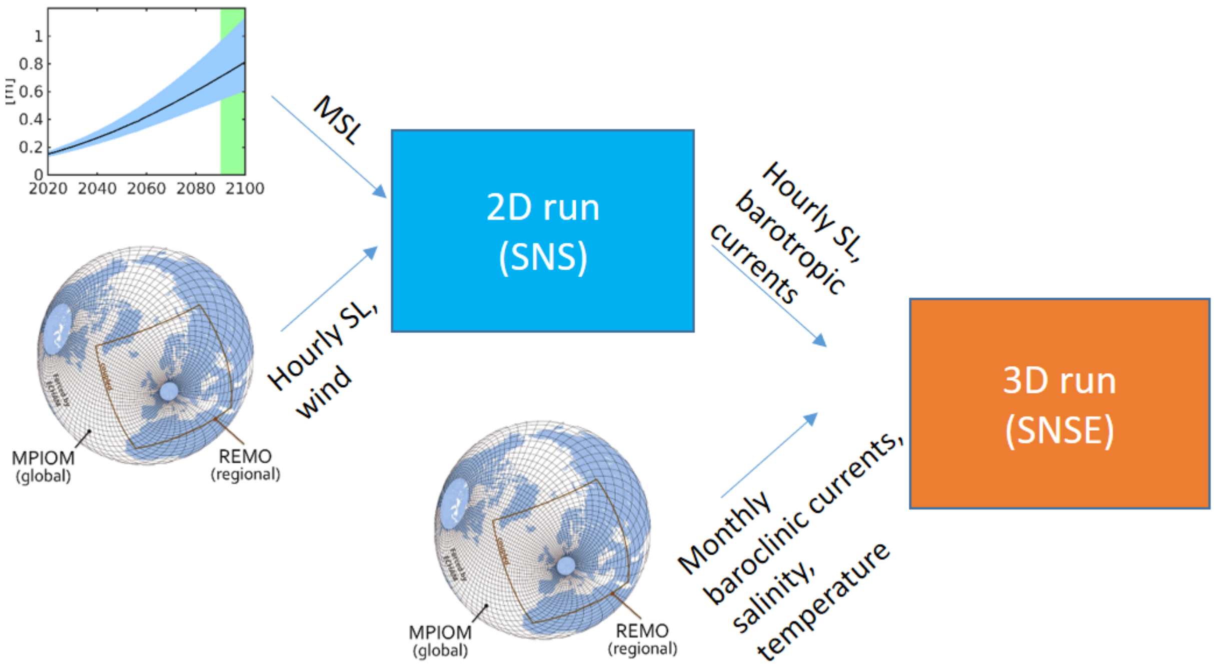

Figure 15: Workflow for the downscaling of climate projections to the Elbe Estuary.

1.1.3 SCHISM (German-Bight)

The SCHISM- German Bight model was setup migrating from Mistral to the new Levante system, as well as performing tests switching to the most recent source-code version introducing new i/o.
For ongoing and planned scientific activities, the SCHISM- German Bight model was setup coupling hydro- wave and sediment dynamics, incorporating the effects of coastal seagrass vegetation on the coupled physics to study the role of coastal sea grasses for risk reduction. Therefore, different experiments were configured running the model for the time period 2017 and 2018 with different Seagrass extents, such as no seagrass, seagrass coverage corresponding to present-day extend and different restoration scenarios of covering the entire Wadden Sea areas, respectively covering only the low and high energy regimes.

1.2 Scientific results of project bg1186

The different computational activities this project aim at highly resolved climate projections of hydrodynamics and biogeochemical dynamics. The latter are closely related to wind waves, sediment and morpho-dynamics. The coupled hydrodynamics and biogeochemistry are tackled by a structured approach, represented by the NEMO-ECOSMO framework, and by unstructured approach, represented by the SCHISM-ECOSMO framework. The former covers a larger spatial region (i.e. the North-Western shelf of the Atlantic Ocean) and shall provide boundary conditions for the estuarine unstructured modelling in the future.

1.2.1 NEMO-ECOSMO

The full implementation of ECOSMO in the GCOAST (Geesthacht Coupled cOAstal model SysTem) will enable to investigate the response of the North-Baltic Sea regional climate system and the German coast to the natural and anthropogenic changes in respect to coupled wave-ocean processes and changing hydrological forcing.

1.2.2 SCHISM-ECOSMO

Setting-up the downscaling framework (Figure 16), an important step has been taken to realize a consistent cross-scale coupling that yields the tidal information from the regional climate ensemble simulations. By this means, the relationship between tidal variability and other crucial physical scales like seasonal variability, decadal/internal variability from the MPIOM-REMO forcing is con20!served.

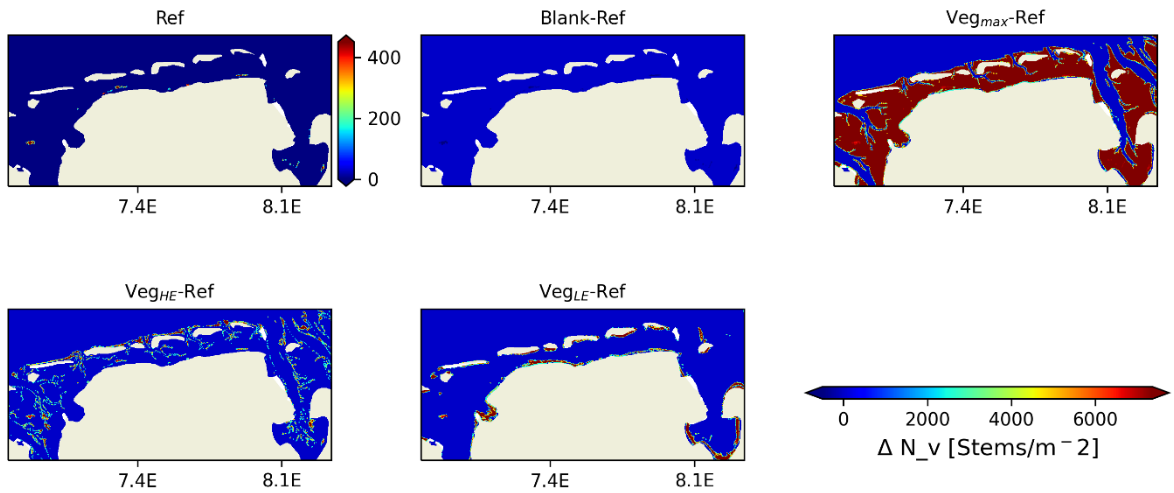

Figure 16: Seagrass restoration scenarios in the EFWS. Left: Present day sea grass density, followed by diffrences towards scenarios, no Seagrass (blank), full intertidal restoration (Veg_{max}), deep area restoration (Veg_{HE}) and shallow area restoration (Veg_{LE}).

To represent the ensemble spread from the 30 MPIOM-REMO runs, a subset of three runs was chosen that fits best to the 5th, 50th and 95th percentiles of monthly mean water levels during the 2090-2099 period. These three members were combined with the median of projected mean sea level rise from Palmer et al. (2018) to drive three realizations of southern North Sea and Elbe Estuary hydrodynamics with SCHISM. The small ensemble served to compute a mean trajectory and the ensemble spread representing internal climate variability of various estuarine parameters like mean water level, tidal range and surge levels (see projected mean state and trends for the southern North Sea Figure 17). For a comparison of the spread/uncertainty related to internal variability to the one relating to the spread of the global sea level rise projection, the median MPIOM run was also combined with low-end and high-end trajectories of projected mean sea level rise. As expected, the uncertainty of mean sea level rise dominated the spread of estuarine water levels. However, internal variability led to a comparable bandwidth of the estuarine response, for example regarding monthly extreme water levels in the upper estuary including the Hamburg port area. This work demonstrated the advantage of calculating even a small number of possible trajectories and gave a consistend projection of the uncertainty of estuarine dynamics at the end of the century. To the best of our knowledge these is the first assessment of climate uncertainty for an estuary in a consistent scenario downscaling framework.

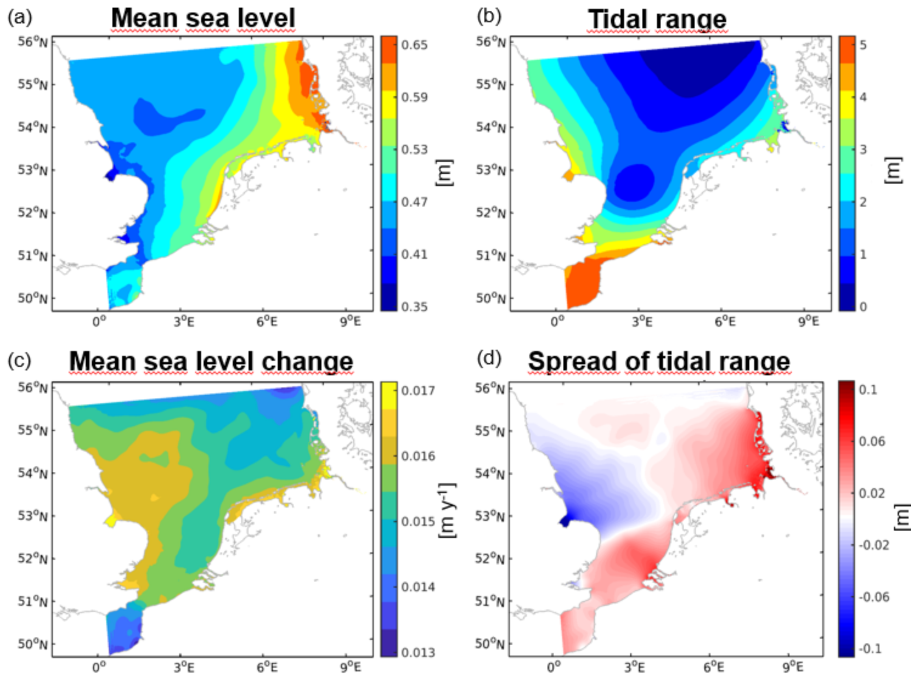

Figure 17: Simulated ensemble-averaged (a) mean sea level, (b) mean tidal range, (c) annual change of mean sea level and (d) spread of tidal range due to spread of mean sea level rise during the simulation period 2090-2099.

1.2.3 SCHISM-German-Bight

The results of the ongoing SCHISM German Bight Seagrass experiments described in 7.1.3 indicate the presence of seagrass to have a strong local dissipative effect on current velocities and there for bottom shear stresses, locally by more than 30% with respect to the monthly 95 percentiles. Which in turn reduces sediment mobilization tendencies, the upper potential effects illustrated in Figure 18 for instantaneous conditions during maximum flood and ebb (comparing the orange line for the case with no sea grass and the blue line representing present day sea grass conditions). The attenuation increases for a denser population and larger spatial extends (other colors). The reduced sediment mobilization overall favors the accumulation of sediments and contributing to the stabilization of the Wadden Sea (Figure 19). This shows that seagrass is capable to help protecting from coastal erosion. The analyses on the impacts of seagrass on the sea level show a minor effect and thus a limited potential to protect from coastal flooding, where the major potential can be seen in wave attenuation.

The role of heat wave events in the occurrence and persistence of thermal stratification was analysed by simulating the water temperature of the North Sea from 2011 to 2018 using a fully coupled hydrodynamic and wave model within the framework of the Geesthacht Coupled cOAstal model SysTem (GCOAST). Different from the northern North Sea, where the water column is stratified in the warm season each year, the southern North Sea is seasonally stratified in years when a heat wave occurs. Heat wave events play role in the form of two aspects, i.e. a rapid rise in sea surface temperature at the early stage of the heat wave period and a higher water temperature during summer than the multiyear mean. Another factor that enhances the thermal stratification in summer is the memory of the water column to cold spells earlier in the year. Water depth appeared to be the factor that controlled the sensitivity of the stratification to summer heat wave events. In a broader context, this research is expected to have fundamental significance for further investigating the secondary effects of heat wave events, such as in ecosystems, fisheries, and sediment dynamics.

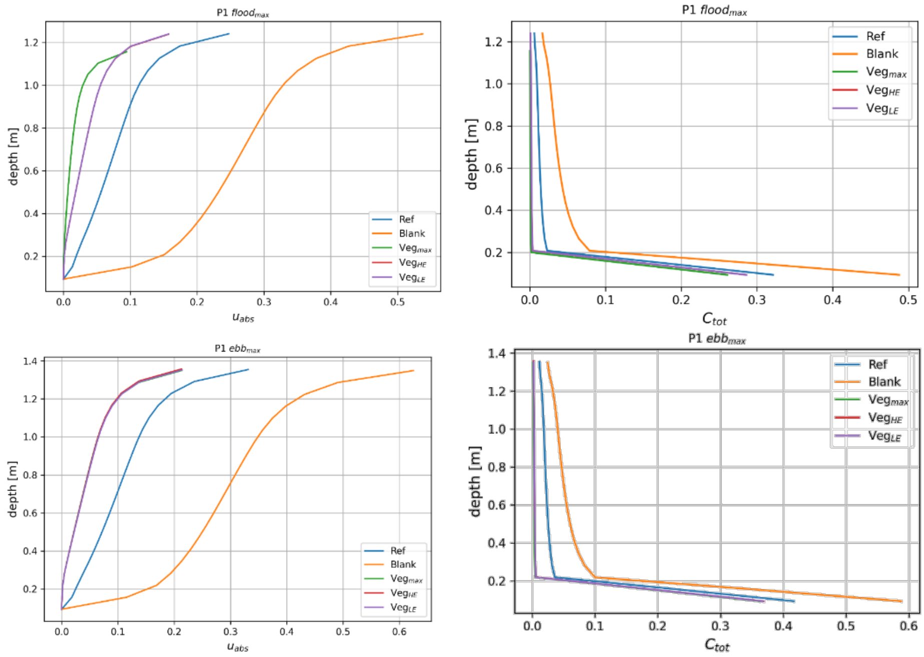

Figure 18 Vertical profiles of instantaneous current velocities (left) and spm concentration (right) during maximum flood (top) and maximum ebb (bottom) at a seagrass meadow SE of Borkum Island in the east Frisian Wadden Sea,

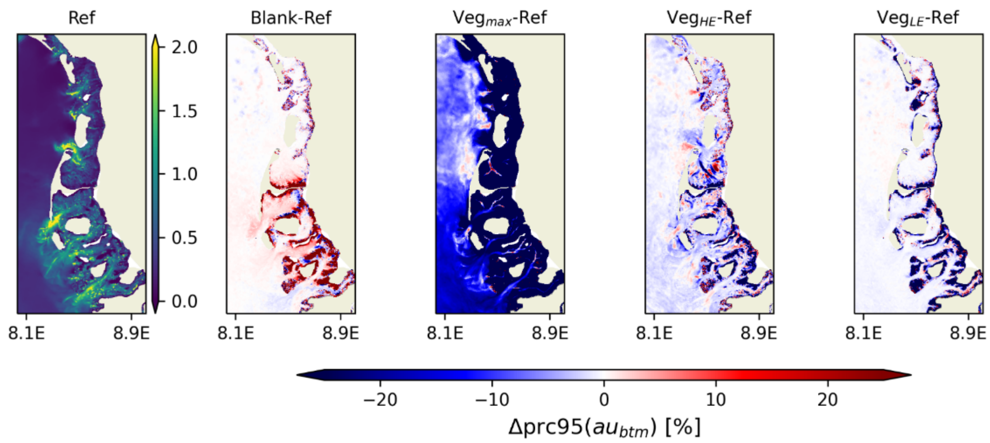

Figure 19 Relative change in bottom shear stress 95 percentiles in the North Frisian Wadden Sea during October 2010. Showing to the left the shear stress quantiles with present day seagrass extent and in the panels to the right the relative difference [%] for the case with no Sea Grass, Full intertidal restoration, restoration focussing on the deepest areas, and restoration for the shallowest areas only.

1.3 Publications in 2022 that use data of project bg1186

Published:

Chen, W., Staneva, J., Grayek, S., Schulz-Stellenfleth, J., and Greinert, J.: The role of heat wave events in the occurrence and persistence of thermal stratification in the southern North Sea, Nat. Hazards Earth Syst. Sci., 22, 1683–1698, https://doi.org/10.5194/nhess-22-1683-2022, 2022.

In preparation:

Jacob B, Staneva J e al. 2022: Evaluation of seagrass plantation scenarios as nature based solution for coastal protection in the German Bight.

Pein J, Staneva J, Mayer B, Palmer M, Schrum C, 2022: Response of a deepened meso-tidal estuary to mean sea level rise and internal variability.

1.4 References

Andresen, C.G., D.M. Lawrence, C.J. Wilson, A.D. McGuire, C. Koven, K. Schaefer, . . . I. Gouttevin, 2020: Soil moisture and hydrology projections of the permafrost region–a model intercomparison. The Cryosphere, 14(2), 445-459.

Davy, R. and S. Outten, 2020: The Arctic surface climate in CMIP6: status and developments since CMIP5. J Clim, 33(18), 8047-8068.

Grimm, R., E. Maier-Reimer, U. Mikolajewicz, G. Schmiedl, K. Müller-Navarra, F. Adloff, . . . K.-C. Emeis, 2015: Late glacial initiation of Holocene eastern Mediterranean sapropel formation. Nat Comm, 6, 7099.

Hermans, T. H., Tinker, J., Palmer, M. D., Katsman, C. A., Vermeersen, B. L., & Slangen, A. (2020). Improving sea-level projections on the Northwestern European shelf using dynamical downscaling. Climate Dynamics, 54(3), 1987-2011.

Lawrence, D.M., C.D. Koven, S.C. Swenson, W.J. Riley, and A. Slater, 2015: Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO2 and CH4 emissions. Environ Res Lett, 10(9), 094011.

Logemann, K., L. Linardakis, P. Korn, and C. Schrum, 2021: Global tide simulations with ICON-O: testing the model performance on highly irregular meshes. Ocean Dyn, 71(1), 43-57.

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