High-Resolution Coupled Eco-Hydrodynamic Modeling of the White Sea as an Arctic Shelf Testbed

The White Sea is one of the most thoroughly studied Arctic seas, possessing unique hydrological and biogeochemical characteristics (Filatov et al., 2005). It serves as a natural laboratory for understanding processes governing Arctic shelf ecosystem functioning under rapid climate change. Decreasing sea ice extent, rising water temperatures, increasing storm activity, and changing river runoff directly impact water circulation, primary production, and the carbon cycle – changes of critical importance for both global climate systems and regional environments. Using the Regional Ocean Modeling System (ROMS) (Shchepetkin & McWilliams, 2005) as the hydrodynamic core, we have developed a configuration of the White Sea with a horizontal resolution of 1 km and 22 terrain-following vertical layers. This model is coupled with the St. Petersburg Baltic Eutrophication Model (SPBEM) (Ryabchenko et al., 2016), adapted for Arctic conditions, to create a fully coupled eco-hydrodynamic model of the White Sea ecosystem.

The White Sea exhibits several features that make it an ideal testbed for Arctic shelf modeling: strong river runoff (Northern Dvina, Onega, Mezen) creating sharp salinity gradients and stratification similar to the North Sea and Baltic Sea conditions; high dissolved organic matter content (“yellow substance”) allowing studies of optical water properties and their impact on primary production; tidal dynamics (up to 10 m in Mezen Bay) enabling investigation of tide-ice-biogeochemistry interactions; and seasonal ice cover in winter-spring enabling analysis of under-ice production and marginal ice zone processes. Our preliminary simulations indicate that high spatial resolution is crucial for capturing the marginal ice zone dynamics and their influence on primary production in Arctic shelf seas. This finding is consistent with our previous results for the Barents and Kara Seas (Martyanov et al., 2018), where the moments of spring-summer peaks of primary production and marginal ice zone extent coincided completely with a correlation of 0.87.

Despite the relatively high resolution planned (1 km), it remains challenging to fully resolve the first baroclinic deformation Rossby radius in Arctic shelf seas. According to available estimates (Hallberg, 2013; Nurser & Bacon, 2014), the average baroclinic deformation radius in the White Sea is 2–4 km, but these values do not reflect spatial heterogeneity and seasonal variation. For example, in the shallow estuarine regions (Dvina Bay, Onega Bay), the deformation radius can be less than 1 km. Our planned 1 km resolution will make the model eddy-resolving in most areas of the White Sea, allowing adequate simulation of eddies with radii of 2 km and more (Smith et al., 2000). Moreover, according to Chelton et al. (2011), eddies may be 2–3 times larger than the Rossby radius, further increasing the model’s ability to correctly simulate eddy dynamics.

The choice of the White Sea for this research is also motivated by the existence of a unique long-term observational dataset, including: Electronic Atlas of the White Sea and its catchment (hydro-meteorology, hydrochemistry, biota); zooplankton time series since the 1950s; river runoff and nutrient load archives (R-ArcticNet, global databases); and a bio-optical atlas with satellite ocean color data calibrated by in-situ measurements. These data will be used for detailed verification of our high-resolution model. The planned work will yield, in addition to the refined coupled model of the White Sea, a quantitative explanation of how factors such as river runoff intensity, circulation, sea ice, water density stratification, turbidity, and atmospheric forcing influence White Sea primary production. Understanding these dependencies will enable predictions of future changes in the White Sea ecosystem functionality and help assess the impact of each factor.

This project benefits from a strong collaboration with the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI), which is a world leader in high-resolution Arctic climate modeling. We will use initial and boundary conditions from the global eddy-resolving AWI-CM3 model (Streffing et al., 2022; Sein et al., 2026). AWI-CM3 features an ocean resolution of 2–25 km (eddy-resolving) and an atmospheric resolution of ~15 km, making it an ideal forcing dataset for our White Sea configuration. The joint use of AWI-CM3 with our downscaled ROMS-SPBEM setup creates a unique two-way bridge between global and regional Arctic modeling. This collaboration directly supports German Arctic research priorities, including the MOSES program, and facilitates knowledge exchange between AWI and DKRZ user communities. Moreover, the high-resolution White Sea simulations will serve as a testbed for evaluating and improving the representation of shelf-sea processes (e.g., river plumes, under-ice production, coastal carbon fluxes) in the next generation of AWI Earth system models.

References

Chelton, D. B., Schlax, M. G., & Samelson, R. M. (2011). Global observations of nonlinear mesoscale eddies. Progress in Oceanography, 91(2), 167–216. https://doi.org/10.1016/j.pocean.2011.01.002

Filatov, N., Pozdnyakov, D., Johannessen, O. M., Pettersson, L. H., & Bobylev, L. P. (2005). White Sea: Its Marine Environment and Ecosystem Dynamics Influenced by Global Change. Springer-Praxis. https://doi.org/10.1007/3-540-27695-5

Hallberg, R. (2013). Using a resolution function to regulate parameterizations of oceanic mesoscale eddy effects. Ocean Modelling, 72, 92–103. https://doi.org/10.1016/j.ocemod.2013.08.007

Martyanov, S. D., Dvornikov, A. Yu., Ryabchenko, V. A., Sein, D. V., & Gordeeva, S. M. (2018). Investigation of the relationship between primary production and sea ice in the arctic seas: assessments based on a small-component model of marine ecosystem. Fundamentalnaya i Prikladnaya Gidrofizika, 11(2), 108–117. https://doi.org/10.7868/S2073667318020107

Nurser, A. J. G., & Bacon, S. (2014). The Rossby radius in the Arctic Ocean. Ocean Science, 10(6), 967–975. https://doi.org/10.5194/os-10-967-2014

Ryabchenko, V. A., Karlin, L. N., Isaev, A. V., Vankevich, R. E., Eremina, T. R., Molchanov, M. S., & Savchuk, O. P. (2016). Model estimates of the eutrophication of the Baltic Sea in the contemporary and future climate. Oceanology, 56(1), 36–45. https://doi.org/10.1134/S0001437016010161

Sein, D. V., Cabos, W., Vázquez, R., et al. (2026). Climate variability and change in the eddy resolving global model AWI-CM3: a regional view. Preprint. https://doi.org/10.13140/RG.2.2.23444.87680

Shchepetkin, A. F., & McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modelling, 9(4), 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002

Smith, R. D., Maltrud, M. E., Bryan, F. O., & Hecht, M. W. (2000). Numerical simulation of the North Atlantic Ocean at 1/10°. Journal of Physical Oceanography, 30(7), 1532–1561. https://doi.org/10.1175/1520-0485(2000)030<1532:NSOTNA>2.0.CO;2

Streffing, J., Sidorenko, D., Semmler, T., et al. (2022). AWI-CM3 coupled climate model: description and evaluation experiments for a prototype post-CMIP6 model. Geoscientific Model Development, 15, 6399–6427. https://doi.org/10.5194/gmd-15-6399-2022