# Assimilation of satellite and tide gauge sea level measurements into forecasting numerical models and reanalysis products

## Summary

*The Baltic Sea is a semi-enclosed sea whose water levels are influenced by a mix of global and regional factors, making it an ideal natural laboratory for sea level studies. This PhD project aims to develop and test methods for assimilating satellite altimetry and tide gauge sea level data into state-of-the-art ocean models, with a focus on the Baltic Sea region. The overall goal is to improve the accuracy of sea level forecasts and reanalysis by optimally merging observational data with numerical simulations. The candidate will work in an exciting international research context that addresses both fundamental science (sea level variability and climate change impacts) and practical needs (better storm surge and sea level rise predictions). The position offers extensive collaboration opportunities – including potential internships at leading European marine forecasting centers – and a chance to contribute to the Copernicus Marine Service, the European operational ocean monitoring program. This is a fully-funded 4-year PhD where the student will benefit from a multidisciplinary environment, combining oceanography, data science, and AI, while engaging with top researchers across Europe.*

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| Research field: | Earth sciences |
| Supervisors: | Prof. Dr. Urmas Raudsepp<br>Priidik Lagemaa |
| Availability: | This position is available. |
| Offered by: | School of Science<br>Department of Marine Systems |
| Application deadline: | Applications are accepted between June 01, 2025 00:00 and June 30, 2025 23:59 (Europe/Zurich) |

## Description

*The research*

In the Baltic Sea, sea level variations are of great scientific and societal importance, ranging from short-term storm surges to long-term changes due to climate warming. Sea level change is a major concern under ongoing climate change, with rising oceans leading to increased flooding and extreme events globally. The Baltic Sea, being nearly tideless and semi-enclosed, experiences water level

fluctuations dominated by weather, hydrological inflows, and internal dynamics rather than tides. Accurate monitoring and forecasting of Baltic sea level is vital for coastal communities and infrastructure. However, achieving accuracy is challenging because the Baltic's sea level responds to a complex mix of processes and its narrow straits and coastline make coastal measurements and model predictions sometimes diverge.

This PhD project addresses these challenges by improving how observational data are merged with numerical models to produce the best possible representation of the Baltic Sea's sea level at any given time. Data assimilation – the process of combining observations with model output to obtain an optimal estimate of the ocean state – lies at the heart of this research. In operational forecasting, data assimilation takes the latest measurements and a short-range model forecast, and blends them to produce the best estimate of current conditions. This project will explore how to assimilate two key sources of sea level observations into Baltic Sea models: satellite altimetry (which provides wide-area sea level measurements from space) and coastal tide gauges (which provide continuous high-precision sea level records at specific locations). Each data source has strengths and limitations – satellite altimeters offer broad coverage but lower frequency (and historically had larger uncertainty near the coast), while tide gauges give reliable local sea level but at sparse points and relative to local vertical datums. A core question is how to effectively bring these datasets together in a model framework to capitalize on their synergy. Recent studies have shown that using both altimetry and tide-gauge data together can yield significantly better sea level analyses than either data source alone.

This PhD will build on such insights, aiming to develop assimilation techniques that harness the complementary nature of satellite and in situ sea level observations to improve model skill. Numerical modeling and assimilation techniques: The student will work with advanced general circulation models (e.g.

NEMO-based models or similar) configured for the Baltic Sea, which simulate the ocean's behavior under various forces (winds, pressure, inflows, etc.). The research involves implementing and testing different data assimilation methodologies within these models. We will investigate both traditional and novel assimilation schemes. Traditional techniques include variational methods (like 3DVAR/4DVAR, which adjust the model state by minimizing differences from observations over time windows) and

ensemble-based methods (like the Ensemble Kalman Filter or simpler Ensemble Optimal Interpolation, which use an ensemble of model states to estimate flow-dependent error statistics). Each approach comes with advantages and trade-offs: for instance, ensemble methods can capture the actual day-to-day uncertainty structure and have been shown to markedly improve forecast skill by leveraging

flow-dependent error covariances. In one study, an ensemble scheme reduced forecast errors by over 40% compared to a static 3DVAR method. Variational methods, on the other hand, are deterministic and can assimilate data smoothly in time, but may require more complex adjoint models and can be less adaptive to rapidly changing conditions.

The Baltic Sea's unique dynamics (e.g. narrow straits, occasional seiches, strong wind setup events) provide a testing ground for these methods. The PhD research will pose questions such as: which assimilation technique (or hybrid thereof) best handles Baltic Sea level features? How do we deal with biases in models or data – for example, the offset between model sea level "zero" and real-world vertical datum used by tide gauges? By systematically comparing assimilation approaches (e.g. testing a 3DVAR vs an Ensemble Kalman approach in identical conditions), the project seeks to elucidate the strengths and limitations of different techniques in the Baltic Sea context. Integration of AI methods: A cutting-edge component of the project is the application of AI and machine learning to augment the data assimilation workflow. AI is increasingly recognized as a powerful tool in Earth system science, capable of uncovering complex patterns and even accelerating parts of the modeling process.

In this PhD, we will explore how machine learning can enhance sea level data assimilation in two possible ways: (1) Bias correction and model error learning, and (2) Hybrid assimilation approaches. For bias correction, recent research in our department has demonstrated the use of deep learning to identify and quantify biases in a Baltic Sea model by comparing it with tide gauge and altimeter data. In fact, a multivariate deep neural network (inspired by WaveNet architecture) was able to learn the model's systematic errors and reduce sea level prediction error to about 4 cm (RMSE) when validated against satellite altimetry, achieving near-perfect correlation (0.98) with independent tide gauge measurements.

This novel approach effectively integrated model outputs with observations using AI, pointing to a new way to correct model forecasts and align them with absolute sea level reference frames. Building on such findings, the PhD student might train AI models (e.g. deep neural networks or other ML algorithms) on historical model-observation mismatches to predict and remove biases or to infer unobserved variables that improve assimilation. The second avenue is using AI as part of the assimilation cycle itself. For example, recent work in ocean forecasting has shown that convolutional neural networks (CNNs) can be trained to replicate the actions of a data assimilation update. In a Gulf of Mexico study, a CNN learned from an existing assimilation system's outputs to directly compute corrections to the model's sea surface height and temperature, effectively emulating the data assimilation step and speeding up the process. We will investigate whether a similar concept can be applied for the Baltic Sea: can an AI system learn from many assimilation cycles how to inject sea level observations into the model state, potentially providing a fast approximation to traditional assimilation algorithms? Such AI-assisted or hybrid methods could enhance assimilation by either expediting computations or by capturing nonlinear relationships that classical methods might miss. The outcome would not replace traditional data assimilation but rather complement it – for instance, an AI model could provide an initial guess or bias correction that makes the assimilation of altimetry and tide gauges more effective.

Research significance and context: Improving sea level forecasts and reanalysis in the Baltic has both regional and broader implications. Regionally, better short-term sea level forecasts (e.g. storm surge warnings) will directly benefit coastal hazard management in Baltic countries. On longer timescales, an improved Baltic Sea reanalysis (a historical reconstruction of the ocean state) contributes to understanding climate variability and trends, providing a baseline for detecting changes in mean sea level and extreme events. Importantly, this PhD project is aligned with and will contribute to the Copernicus Marine Service Baltic Sea forecasting activities, which currently provide operational analyses and forecasts for the Baltic Sea. The Copernicus Marine Environment Monitoring Service is Europe's flagship program for delivering

regular, systematic information on the marine state. By focusing on data assimilation of sea level – a parameter of high relevance to Copernicus – the research will feed into the next generation of Baltic Sea operational models. For example, if successful, the techniques developed could be adopted by national agencies or Copernicus partners to enhance their forecasting systems. The candidate will thus be working on a project with real-world impact, at the intersection of academic research and operational oceanography. The project's international collaborations (with partners in Europe such as marine research institutes and forecasting centers) will ensure that the developed methods are tested on real datasets and possibly integrated into pre-operational trials. The student will have opportunities to present findings in major conferences and to interact with the wider ocean modeling and satellite observation community. In summary, this PhD research addresses a pressing scientific and operational challenge – how to optimally merge multi-source sea level observations into numerical models – by combining rigorous oceanographic modeling with innovative data science (AI) techniques. The knowledge gained will advance our ability to monitor and predict sea level changes in the Baltic Sea, contributing to better climate resilience and marine services in the region and beyond.

**Research Questions:**

How can satellite and tide gauge sea level data be effectively assimilated into numerical forecasting models? – Exploring methods to integrate these observations, dealing with differences in data coverage, frequency, and reference levels, to improve model accuracy.

What are the comparative strengths and limitations of different data assimilation techniques in the Baltic Sea context? – Evaluating approaches (variational, ensemble, hybrid methods) for Baltic Sea level forecasting, and understanding which techniques perform best under various scenarios (e.g. storm surges, seasonal variations).

How can AI methods enhance traditional data assimilation workflows for sea level prediction? – Investigating the use of machine learning to complement or improve assimilation, such as by correcting model biases, accelerating the assimilation process, or uncovering nonlinear relationships in the sea level data that can refine forecasts.

*Responsibilities and (foreseen) tasks*

**Data analysis:** Collect, process, and analyze sea level observations, including satellite altimetry data (from missions like Sentinel-3, etc.) and long-term tide gauge records around the Baltic Sea. Ensure quality control and prepare these datasets for assimilation experiments.

**Learn and apply data assimilation methods:** Acquire a strong working knowledge of data assimilation techniques relevant to oceanography. Implement assimilation algorithms (e.g. optimal interpolation, Ensemble Kalman Filter, 3DVAR) within a Baltic Sea modeling framework, with guidance from supervisors and collaborators.

**Numerical modeling:** Use general circulation models for the Baltic Sea to run simulations and forecasting experiments. This includes setting up model scenarios for hindcasts (reanalysis) and forecasts, and modifying the model configuration as needed for assimilation runs.

**Develop AI-enhanced techniques:** Incorporate artificial intelligence or machine learning components into the workflow. For example, develop a prototype neural network to predict model bias corrections or to emulate the data assimilation update step, and test its impact on forecast skill.

**Collaborative research:** Work closely with European project partners and marine institutions. This may involve short research visits or remote collaboration with groups such as national oceanographic agencies or the Copernicus Marine Service team to exchange knowledge and co-develop tools.

**Dissemination:** Present research progress and results at international conferences and workshops. Contribute to writing scientific publications in peer-reviewed journals, showcasing findings on Baltic sea level data assimilation and the novel AI applications.

**Internships:** Participate in short- and mid-term internships at leading marine forecasting centers (e.g., national institutes or operational centers in Europe). During these internships, the candidate will gain hands-on experience with operational oceanography systems and ensure the research is aligned with practical needs.

**Reporting and academic duties:** Prepare progress reports and a doctoral thesis documenting the research. Engage with the Department of Marine Systems' academic community, including attending doctoral seminars, and possibly assisting in some teaching or mentoring of undergraduate projects related to the research topic.

*Applicants should fulfil the following requirements:*

**Educational Background:** A Master's degree (or equivalent) in a relevant field – e.g. oceanography, physics, applied mathematics, data science, or Earth system sciences. A solid foundational knowledge in dynamics of fluid or Earth systems is expected.

**Relevant Skills:** Background in one or more of the following areas is highly beneficial: **Earth system or ocean models** (experience with numerical modeling, CFD, or ocean circulation models), **big data analysis** (handling and analyzing large geophysical datasets), or **AI/machine learning for environmental data** (experience with Python/R, neural networks, etc. applied to scientific data).

**Programming and Tools:** Strong analytical and programming skills are required. Proficiency in programming languages or environments used in modeling (such as Python, MATLAB, or Fortran/C++ for model code) and data analysis is important. Familiarity with Linux-based HPC environments, version control (git), and data formats like NetCDF will be useful.

**Analytical Aptitude:** Ability to independently solve problems, statistically analyze results, and iterate on experimental setups. An interest in both the theoretical and practical aspects of data assimilation is key.

**Language:** Good command of written and spoken English is required, as it's the working language of the research group and collaborators.

**Soft Skills:** The ideal candidate is **team-oriented** and willing to collaborate and share knowledge, while also capable of independent research and self-motivation. Good communication skills are expected for interaction with the international team and for presenting work. A proactive attitude towards learning new methods (be it an algorithm or an AI technique) and integrating them into the project is highly appreciated.

*We offer:*

- **Four-year funded PhD position:** Full-time employment with a competitive stipend/study allowance, health insurance, and other benefits as per Tallinn University of Technology (TalTech) regulations. The position is funded as part of a research project, so the student can devote themselves entirely to research activities.
- **Top-tier research environment:** The student will join the Department of Marine Systems at TalTech, which has a strong track record in Baltic Sea research and operational oceanography. The group is involved in multiple international projects, providing access to a network of experts in ocean modeling and remote sensing.
- **Collaboration with leading European centers:** The project involves collaboration with some of Europe's top oceanographic institutions (including partners contributing to the Copernicus Marine Service). The PhD candidate will have opportunities to work with and learn from these experts, gaining exposure to the European marine research landscape.
- **International internships and visits:** We encourage the PhD student to undertake research visits or internships at renowned marine forecasting and research centers (for example, national marine institutes or Mercator Ocean International, etc.). These exchanges will provide practical training in an operational setting and foster networking with professionals in the field.
- **Conferences and training:** Funding is available for the PhD student to attend major international conferences (e.g. EGU, AGU, coastal engineering or oceanography conferences) to present their work. The student can also attend specialized training courses or summer schools (for instance, on data assimilation, ocean modeling, or machine learning in geosciences) to build their skill set.
- **Dynamic and supportive academic setting:** The student will be part of TalTech's graduate school, with access to courses and seminars to support their academic development. The Department offers a multidisciplinary atmosphere, and the student will collaborate with peers working on related topics (e.g. ocean modeling, marine climate studies, remote sensing). We provide modern computing facilities, including access to high-performance computing for model simulations.

*About the department*

The Department of Marine Systems at Tallinn University of Technology (TalTech) is a leading center for marine science and technology in the Baltic Sea region. As part of TalTech's School of Science, the department is dedicated to advancing knowledge and practical solutions related to the physical, chemical, and ecological dynamics of marine environments, with a particular emphasis on the Baltic Sea.

The department's mission is to conduct interdisciplinary research that supports sustainable marine management, enhances forecasting capabilities, and informs policy decisions at national and international levels. Its scientific work integrates field observations, remote sensing, numerical modeling, and data assimilation to study marine processes across multiple spatial and temporal scales.

**Key research domains include:**

Marine physics and hydrodynamics, particularly circulation, sea level variability, and mixing processes in the Baltic Sea;

Operational oceanography, including the development and application of high-resolution forecasting systems;

Marine biogeochemistry and ecosystem modeling;

Marine information systems and decision-support tools for environmental monitoring and management; Coastal zone dynamics and the impacts of climate change on marine systems.

The department operates modern infrastructure, including the research vessel SALME, FerryBox systems for real-time environmental measurements aboard commercial ships, and autonomous observation platforms such as buoys and gliders. These facilities support continuous in situ data collection and complement satellite-based Earth observation.

International collaboration is a core pillar of the department's activity. It actively participates in regional and European initiatives, including:

The Baltic Operational Oceanographic System (BOOS); EuroGOOS, the pan-European ocean observing system;

The Copernicus Marine Environment Monitoring Service (CMEMS);

The HELCOM framework for protecting the marine environment of the Baltic Sea; Multiple EU-funded research projects (e.g., Horizon 2020, Interreg, BONUS).

The department also contributes to academic training through its involvement in graduate and postgraduate education, including Master's and PhD programs in marine science and engineering. It offers students a research-intensive environment and access to international scientific networks.

Through its integrated approach to research, education, and operational development, the Department of Marine Systems plays a critical role in advancing scientific understanding of the Baltic Sea and supporting regional efforts toward sustainable and resilient marine governance.

*(Additional information)*

This PhD project is closely **aligned with the Copernicus Marine Service** activities for the Baltic Sea. This means the candidate may engage with Copernicus-related projects, data, and experts, ensuring that the research is oriented towards operational applications and impact. The university and department host a number of ongoing projects in marine science, providing a rich collaborative environment.

For more information about Tallinn University of Technology (TalTech) and the Department of Marine Systems, please visit the official TalTech website. The university is an equal opportunity employer and a vibrant international community located in Estonia's capital, Tallinn. We look forward to receiving applications from motivated candidates eager to contribute to advancing ocean forecasting and climate science in the Baltic Sea region.

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Urmas Raudsepp – Tenured Full Professor at the Department of Marine Systems, Tallinn University of Technology. (Prof. Raudsepp will co-supervise and provide expertise in physical oceanography and Baltic Sea dynamics.)

Prospective applicants are encouraged to reach out to the supervisors via email for any informal inquiries about the position or research topic.

To get more information or to apply online, visit https://taltech.glowbase.com/positions/960 or scan the the code on the left with your smartphone.