DASNordicSLR - Sea Level Projections for Northern Europe

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Sea level rise is an inevitable consequence and one of the most significant threats posed by climate change, increasing the risk of flooding in low-lying areas along the German coast. Based on the IPCC 6th Assessment Report (AR6) projections we aim to deliver improved projections of relative sea level change for Northern Europe's coastal regions. These projections are available as spatial data up to 2150. While most drivers of sea level change operate on a continental or global scale, vertical land motion is a regional factor – particularly relevant in northern Europe - resulting from glacial isostatic adjustment and local processes. By combining the IPCC projections of absolute sea level change with a new, high-resolution land elevation model for Fennoscandia, an optimized set of projections for relative sea-level change for the North Sea and Baltic Sea was developed. This dataset represents a contribution to the *DAS core service "climate and water"*, the operational climate service operated by four federal authorities under the umbrella of the German Federal Ministry of Transport.

Keywords: sea level change, climate change, German coast, vertical land motion, IPCC AR6 projections

Dataset details

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1. Introduction

As rising sea levels and increasing extreme water level events pose increasing risks to coastal areas, the need for enhanced protection along the coastlines will become more urgent in the coming decades to prevent damage to critical infrastructure and ensure public safety (Kiesel et al. 2023). Accurate projections of sea-level rise (SLR) are crucial for effective planning and risk management, particularly concerning coastal infrastructure and transportation networks (Arns et al. 2015). Regional sea-level changes are influenced by complex interactions between global sea-level rise and local land uplift or subsidence, which can vary significantly across different locations (Khan et al. 2015). Along the coasts of northern Europe this is particularly influenced by glacial isostatic adjustment (GIA), a slow uplift of the land surface following ice melt and subsidence in surrounding regions since the last ice age, but also local processes.

The probably most comprehensive set of projections of sea-level rise under different climate scenarios is provided by the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR6; (IPCC 2023)). However, the report itself states that '*there is low to medium confidence in the GIA and VLM projections employed in this Report. In many regions, higher-fidelity projections would require more detailed regional analysis'* (IPCC 2023).

We created an optimized, region-specific set of sea-level rise projections for the North Sea and Baltic Sea by combining two existing datasets: land uplift data from a semi-empirical model by the Nordic Commission of Geodesy (NKG) and the IPCC-AR6 projections of absolute sea-level rise. Such locally adjusted information is essential for safeguarding coastal infrastructure, ensuring the resilience of transportation routes, and enhancing the management of coastal defences like dikes (Hinkel et al. 2018; Marijnissen et al. 2020; Meier et al. 2022)

Similar adjustments to sea level projections have already been made for several other regions, such as the northern Mediterranean coasts (Vecchio et al. 2024), the Netherlands (Vermeersen et al. 2018) as well as Denmark (Su et al. 2021), which helped to improve the accuracy of local sea-level rise projections by better accounting for vertical land motion.

2. Data Description and development

2.1. Input data

2.1.1. IPCC AR6

The dataset "IPCC AR6 WGI Sea Level Projections" (Garner et al. 2022) provides sea level rise projections developed for IPCC-AR6. It includes detailed estimates of global and regional sea level changes under various greenhouse gas emission scenarios. The dataset (hereafter "IPCC") encompasses contributions from different sources, that is thermal expansion, melting of glaciers and ice sheets, changes in terrestrial water storage, and vertical land motion. An additional dataset similar but excluding only the vertical land motion is also provided (hereafter "IPCC novlm"). Projections span from the historical period up to the year 2100, with some extended simulations reaching beyond 2100 up to 2150. The dataset also includes associated uncertainties and is currently the most comprehensive database for researchers, policymakers, and planners to understand potential future sea level changes and to develop adaptive strategies for mitigating the impacts of sea level rise on coastal communities and ecosystems.

2.1.2. NKG2016_LU

We utilize vertical land motion rates derived from the official land uplift model NKG2016LU of the Nordic Commission of Geodesy (NKG), a semi-empirical model focusing on land uplift in the Fennoscandian region, as detailed by Vestøl et al. (2019). This model was developed within the Working Group of Geoid and Height Systems of the (NKG). It combines an empirical model with a geophysical model. The empirical model incorporates geodetic data like levelling and time series of Global Navigation Satellite System data (GNSS) whereas the geophysical model of Glacial Isostatic Adjustment (GIA) supplements data in regions with limited observations. Uncertainty in the model results from both, the observational data and the GIA model, are combined to provide a comprehensive estimate. The uplift data are referenced relative to the geoid ("NKG2016LU_lev") and give a constant rate of uplift for each grid cell.

2.2. Methods

Calculating Optimized Regional Sea Level Rise (RSLR) Projections

1. **Sea level change independent of land uplift**: In order to obtain a sea level change without the impact of land uplift we used the dataset provided by (Garner et al. 2022) which excludes only the "vertical land motion" data ($SLC_{IPCC,novlm}$).
2. **Interpolation of IPCC Data to NKG Grid**: To achieve compatibility of the IPCC data with the NKG model, we bilinearly interpolated the IPCC data (after preprocessing, see * below) onto the NKG grid. Interpolating the coarser field ($SLC_{IPCC,novlm}$) onto a finer grid (NKG) was chosen because its smooth, large-scale variations can be accurately represented at a finer resolution without introducing inconsistencies. This allows localized details and regional variations from the finer dataset to be incorporated in the final dataset while ensuring consistency with the global field.
3. **Addition of NKG VLM Median**: Using the NKG2016 model, which provides a constant rate of land uplift, we calculated cumulative land uplift values per grid cell and per decade. In this context, negative uplift represents sea level rise. Finally, we added the extrapolated data ($-LU_{NKG}$) to IPCC novlm sea level change values ($SLC_{IPCC,novlm}$). This calculation is represented by the following equation:

$$DASNordicSLR(q,t) = SLC_{IPCC,novlm}(q,t) + -LU_{NKG}(t),$$ where

q: Quantiles
t: Time (Decade)
$SLC_{IPCC,novlm,q}(t)$: Projected IPCC total sea level change excluding "vertical land motion" with all uncertainties
$LU_{NKG}(t)$: Cumulative vertical land uplift from the NKG2016 model up to time t

* ***Preprocessing Adjustment: Correction of Outlier Grid Cells***: We used the IPCC report to obtain the total sea level projections with uncertainties, which include the effects of vertical land movement ("vlm"). During the assessment of the fields we found a band of higher spread in isolated grid cells over Scandinavia through to the Iberian Peninsula in the "oceandynamics" contribution (see Figure A1 and Table in appendix). This higher spread is observable for all time steps and all scenarios. The location of the high spread varies within scenarios. All grid points that were higher in any scenario were therefore selected and corrected for all scenarios. As most of the impacted cells are over land this would most likely not be a major issue, but some grid cells in the Baltic Sea area are affected. After consultation with the authors of the dataset we decided to remove those outlier points (Table in appendix) and rather use neighbouring points by bilinearly interpolating over the area. This adjustment is done before steps 1 through 3

By following this method, we obtain an estimate of sea level rise that is optimized for the regional land uplift, thereby ensuring a more accurate representation of sea level changes specific to our study area. Furthermore, the enhanced resolution of the new data set is a consequence of this process.

2.3. Dataset description

The final datasets are provided via the BSH (Federal Maritime and Hydrographic Agency Germany).

The dataset includes:

1. decadal values for sea level projections from 2020 to 2150
2. for the SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.
3. covering the domain from 49° to 75° N and 0 to 50 ° E
4. with uncertainty information represented by 107 quantiles from 0% to 100%

A subset of the final dataset for ocean parts along the German Coasts is available and visualized in the web viewer of the DAS core service "climate and water" (https://das.bsh.de ; see also data access). Here the data is available in a NetCDF file and GeoTIFF file for each timestep (decade) and scenario (SSPs), all for the 17. (16.7th) and 83. (83,3th) percentile as well as the median.

3. Dataset Access

The full dataset associated with this study is publicly available and can be accessed through BSH at https://doi.bsh.de/10.60751/3x97-gp60

. The dataset is provided in NetCDF ensuring compatibility with common geospatial analysis tools.

Users can freely download the dataset under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided proper citation of the original source.

4. Comparison

In order to provide some first impression and to put our data into context, our DASNordicSLR-dataset is compared to the original IPCC sea level change.

First, we compare only the vertical land motion contribution from IPCC (see Figure a)) with the negative land uplift from NKG2016_LU (see Figure A1 Spread (difference between 83,3. quantile and 16,6. quantile) [m] of IPCC AR6 sea level rise projection from “oceandynamics” contribution. For year 2100 and scenario SSP2-4.5.Figure b)). IPCC features sharper contours over the North Sea/Atlantic whereas NKG has a smoother appearance. Over the Norwegian Sea the difference between these two datasets (see Figure c) is most obvious where NKG suggests a

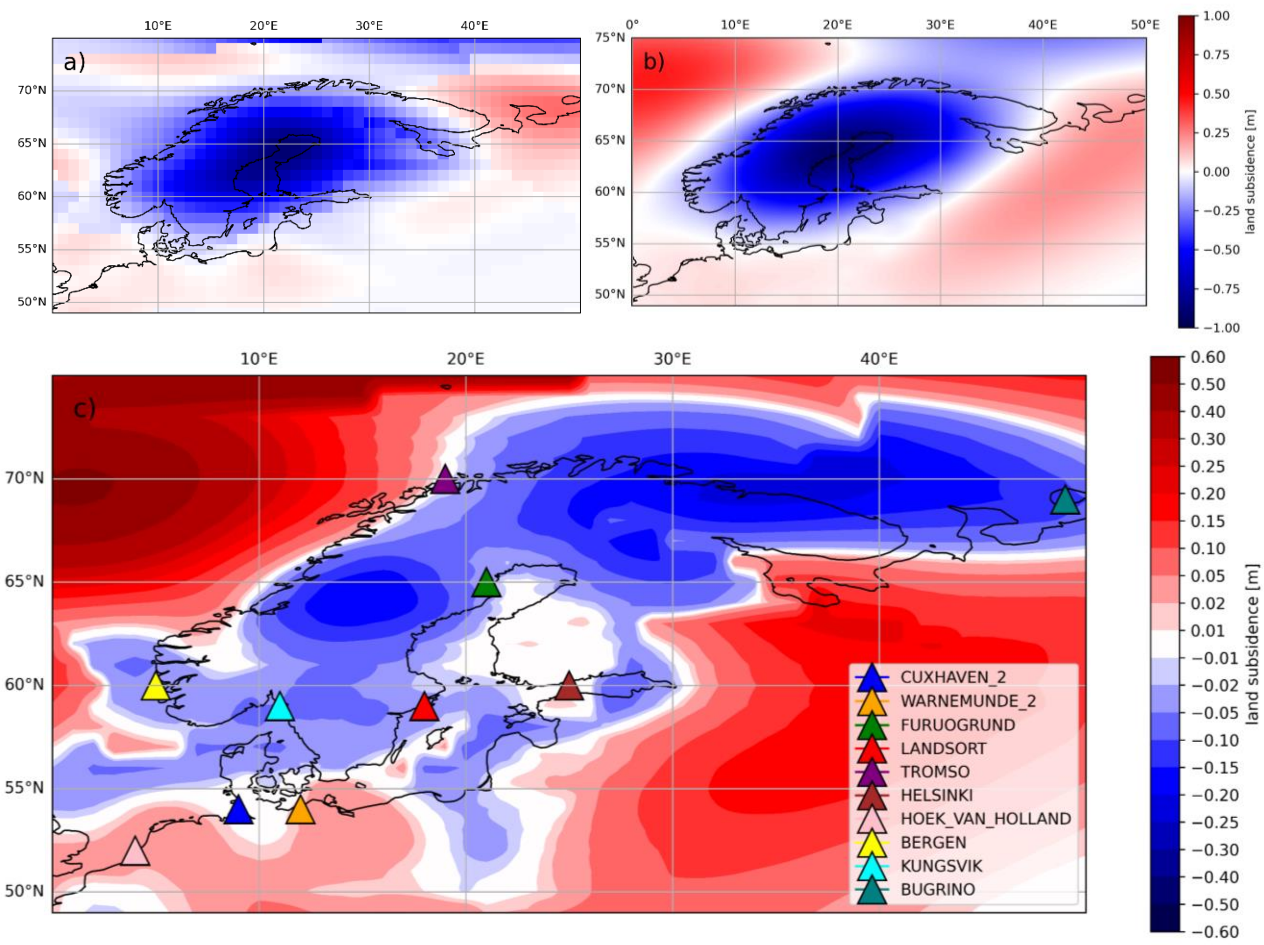

Figure 1 Land subsidence [m] relative to 1995 - 2014 until 2100 a) vertical land motion from IPCC ‘vlm’ contribution to sea level change (scenario SSP5-8.5, median), b) negative land uplift from NKG2016LU and c) Difference between both sources (NKG2016LU_lev - IPCC) including location of sample stations along the coast (nearest grid point close to station coordinates)

much lower uplift than IPCC. Furthermore, NKG calculates a higher land uplift over Scandinavia (up to 200 mm more than IPCC by 2100).

The resulting differences in a sea level rise by 2100 (median, SSP5-8.5 scenario) after implementing the new land uplift range from -200 mm to +500 mm over the whole area. When inspected along the coast for sample stations (see locations in Figure c) and values in Table 1) the differences range from -121 mm in Bugrino to +26 mm in Hoek van Holland. At the German coast the changes are slightly lower (-0.3 mm at Cuxhaven to +15mm in Warnemunde) due to the smaller influence of land uplift in this area. Figure 2 shows the timeseries of sea level change for three sample stations including their likely range.

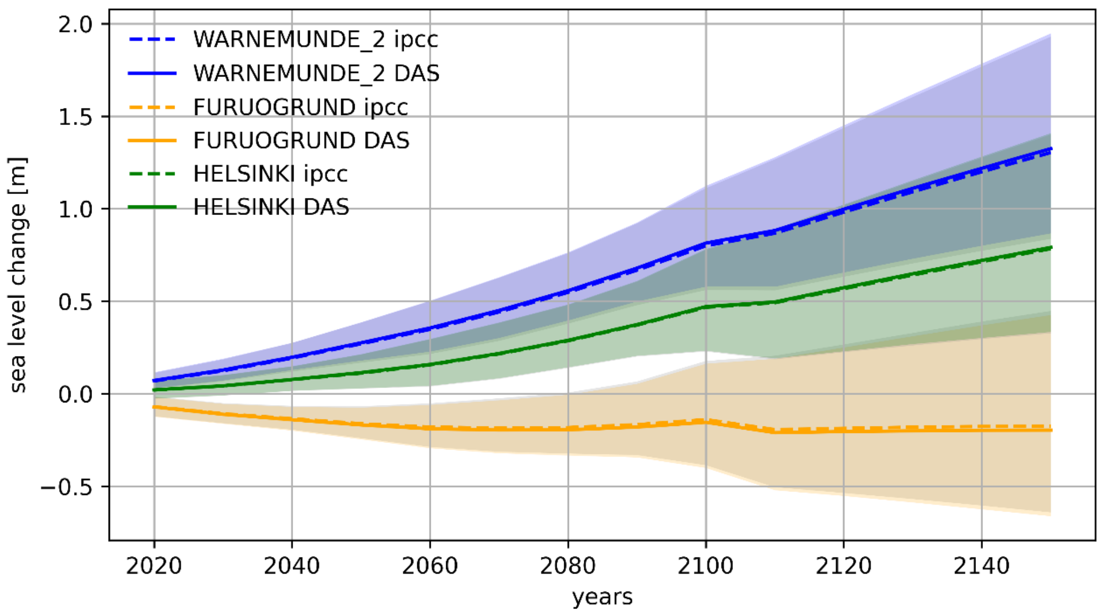

Figure 2 Timeseries of sea level change [m] relative to 1995 – 2014 from IPCC AR6 (dashed line/grey area) and DASNordicSLR (solid line/colored area) including respective likely ranges (16.7th – 83.3th percentile as shaded area) for the grid point nearest to stations WARNEMUNDE_2, FUROGRUND and HELSINKI in scenario SSP5-8.5

Table 1 Difference between DASNordicSLR and IPCC AR6 sea level change after implementation of NKG2016LU_lev uplift for 2100 relative to 1995 - 2014 (scenario SSP5-8.5, median) for sample station as shown in Figure c)

Station name	Absolute Diff [mm]	Relative Diff [%]
CUXHAVEN_2	-0.39	-0.0
WARNEMUNDE_2	14.52	1.8
FURUOGRUND	-14.28	10.2
LANDSORT	-28.42	-8.0
TROMSO	-2.57	-0.5
HELSINKI	4.23	0.8
HOEK_VAN_HOLLAND	26.20	3.2
BERGEN	-41.47	-6.2
KUNGSVIK	-50.54	-11.3
BUGRINO	-121.08	-11.2

5. Conclusions

This paper presents new sea level projections for northern Europe by optimizing the IPCC AR6 projections with a more suitable land uplift model (NKG2016LU). This approach results in a higher-resolution dataset, providing crucial information for effective planning and risk management.

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Conflicts of Interest

The authors declare no conflict of interest.

Appendix

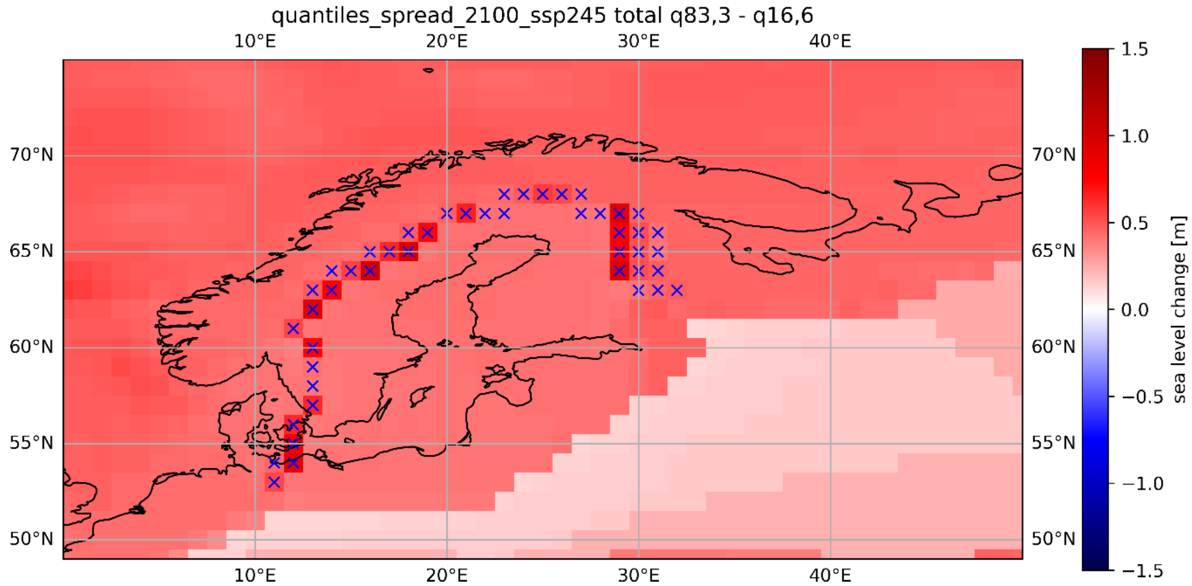

Figure A1 Spread (difference between 83,3. quantile and 16,6. quantile) [m] of IPCC AR6 sea level rise projection from "oceandynamics" contribution. For year 2100 and scenario SSP2-4.5. Blue crosses are omitted grid points (see also Table for coordinates).

Table A1 Omitted Grid points due to higher spread in oceandynamics contribution to IPCC AR6 sea level rise projections (Garner et al. 2022)

Coordinates (Latitude, Longitude)
(63°N, 32°E), (64°N, 31°E), (65°N, 31°E), (66°N, 31°E), (64°N, 30°E), (65°N, 30°E), (66°N, 30°E), (67°N, 30°E), (67°N, 29°E), (67°N, 28°E), (67°N, 27°E), (68°N, 27°E), (68°N, 26°E), (68°N, 25°E), (68°N, 24°E), (68°N, 23°E), (67°N, 22°E), (67°N, 21°E), (67°N, 20°E), (66°N, 19°E), (66°N, 18°E), (65°N, 17°E), (65°N, 16°E), (64°N, 15°E), (63°N, 13°E), (61°N, 12°E), (59°N, 13°E), (58°N, 13°E), (57°N, 13°E), (56°N, 12°E), (54°N, 11°E), (53°N, 11°E), (63°N, 31°E), (63°N, 30°E), (64°N, 14°E), (62°N, 13°E), (60°N, 13°E), (55°N, 12°E), (64°N, 29°E), (65°N, 29°E), (66°N, 29°E), (67°N, 23°E), (65°N, 18°E), (64°N, 16°E), (63°N, 14°E), (54°N, 12°E)

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