Implementation of the machine learning to estimate changes and uncertainty of storm surge extremes from the large scenario ensembles.

Lidia Gaslikova[1], Daniel Krieger[2], Ralf Weisse[1]

[1]Helmholtz-Zentrum Hereon, Geesthacht, Germany
[2]Max-Planck-Institute for Meteorology, Hamburg, Germany

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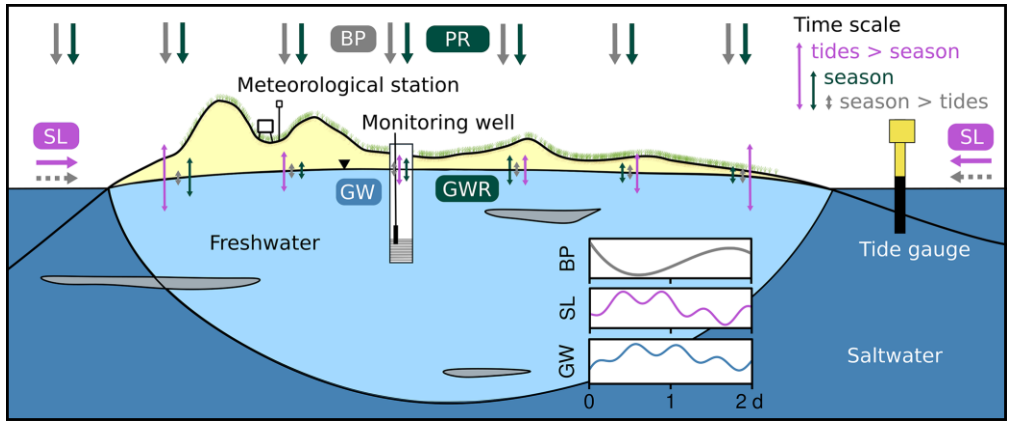
Background and objectives

- manifestation of climate change on local systems is of particular interest
- for many application need for **highly resolved** storm surge / storm tide data over **decade/century** periods

Helge Bormann

How compounding storm tide (series) and heavy precipitation events can affect the hinterland drainage system?



from Haehnel et al. (2024) Hydro. Earth Sys. Sci.

How changing mean and extreme water levels influence development of freshwater lenses on barrier islands?

How compound sea level extremes and high river discharge may change coastal protection standards?

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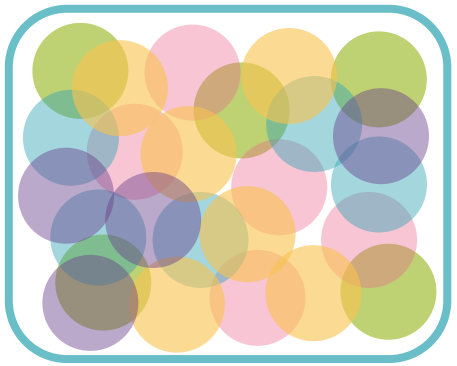
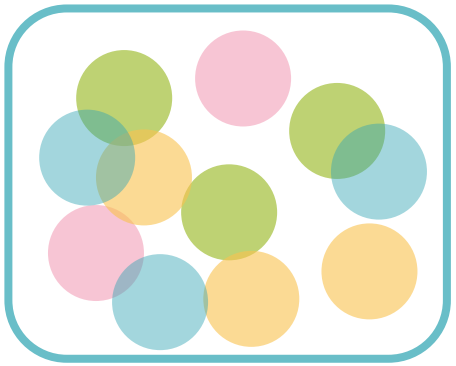
Background and objectives

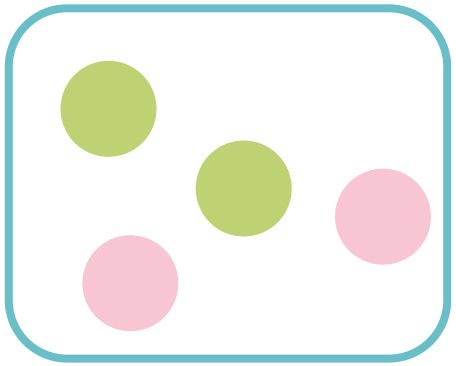
GCM realizations
CMIP3 (SRES),
CMIP5 (RCP),
CMIP6 (SSP)



realizations selected for **RCM downscaling**



realizations selected for **local applications** (e.g. hydrodynamic, hydrological models)



Actual questions:

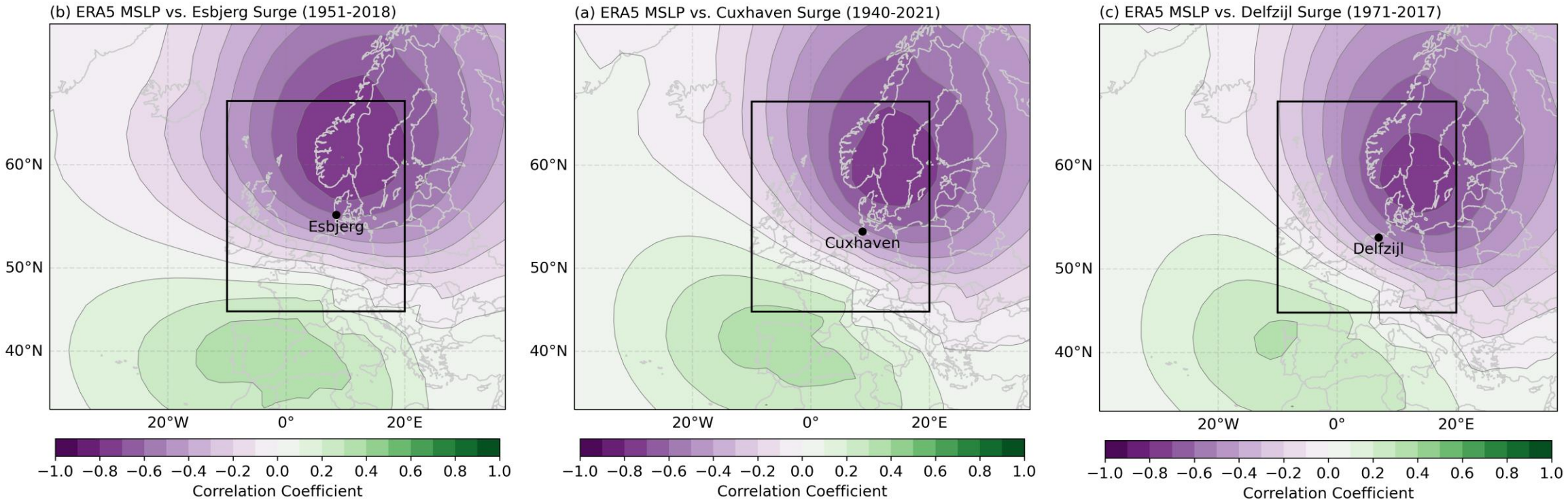
- are the selected realizations representative for a particular scenario in terms of surge extremes
- what are the uncertainties related to extreme events for selected pathway
- which ensemble members(s) (scenarios, models, realizations) should be considered for further downscaling and more in-depth analysis

Method:

- fast
- requires small number of parameters and is suitable for coarse GCM data
- converts these parameters to surge heights retaining inter-annual variability of extremes

Potential input parameters

correlation between hourly MSLP anomalies from ERA5 and 12-hour running mean surge heights from tide gauges



from Krieger et al (2025) GRL

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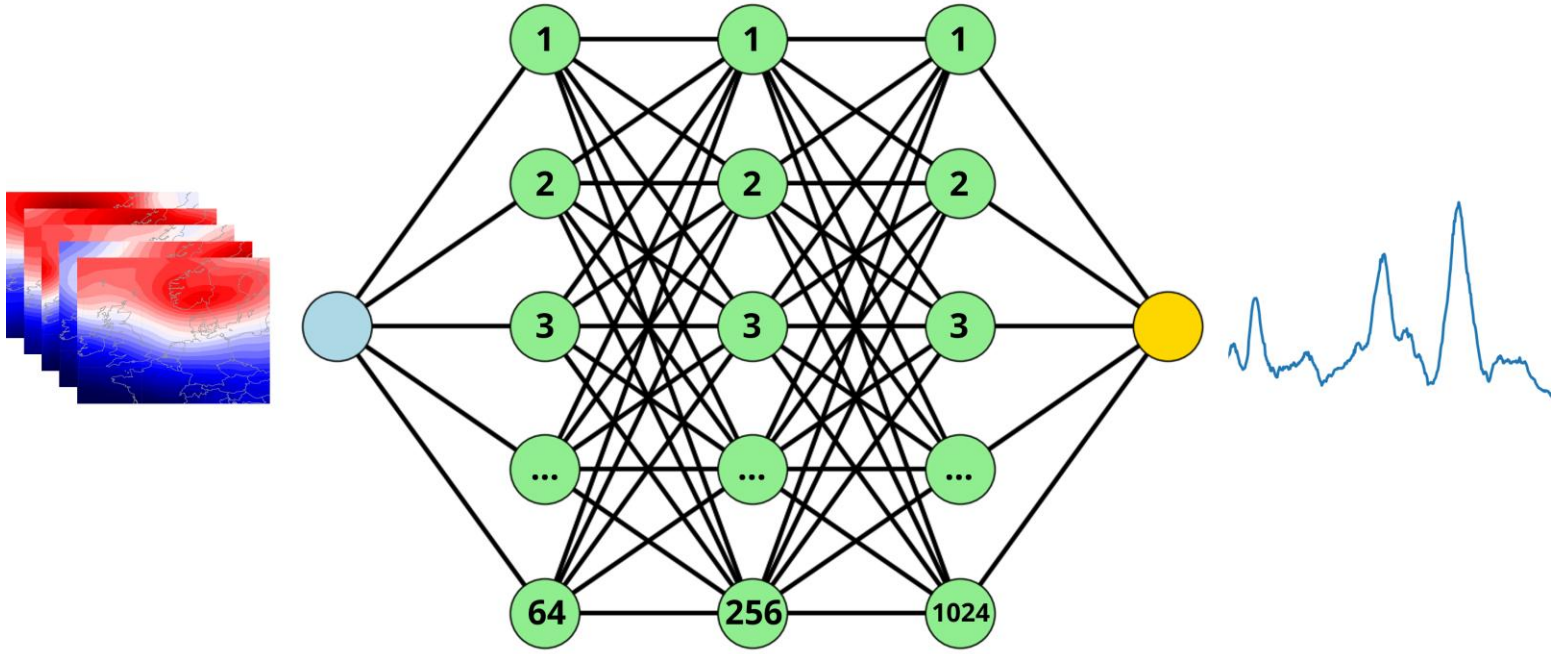
Artificial Neural Network



Input Layer
MSLP anomalies

Hidden Layers

Output Layer
Surge heights

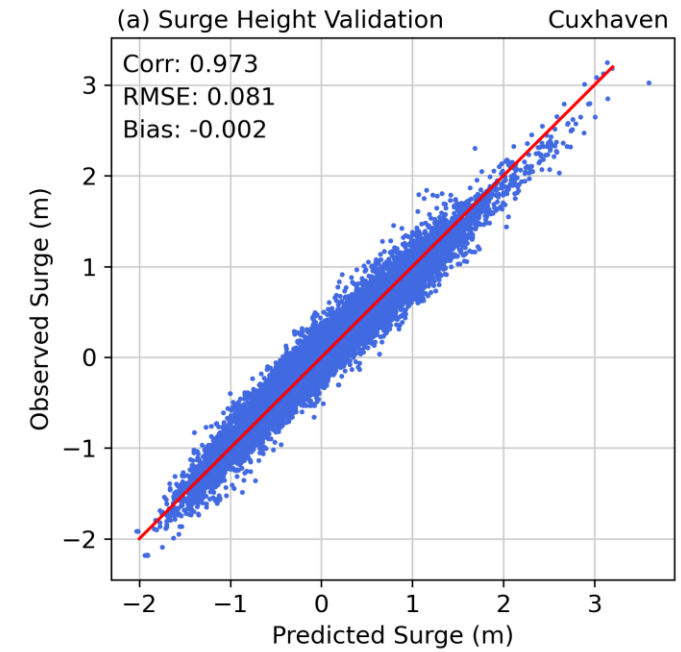
ERA5 standardized MSLP anomalies upscaled to 1.86° spatial resolution compatible with GCM output

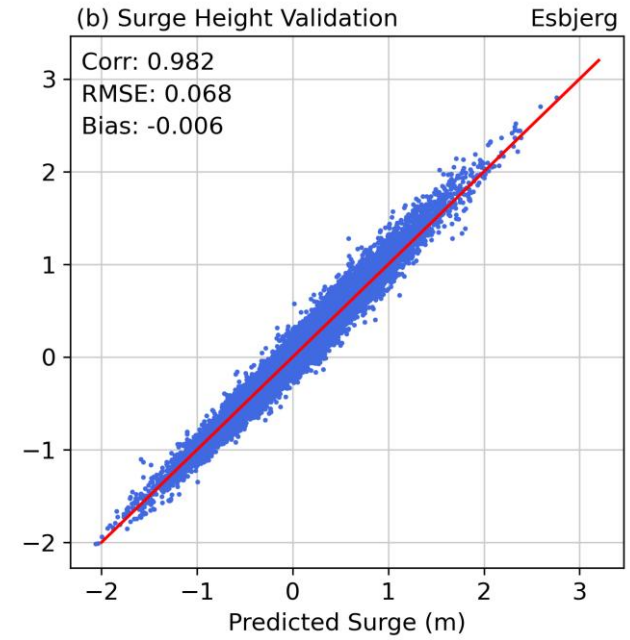
Cuxhaven	1940-2021
Esbjerg	1950-2019
Delfzijl	1971-2017

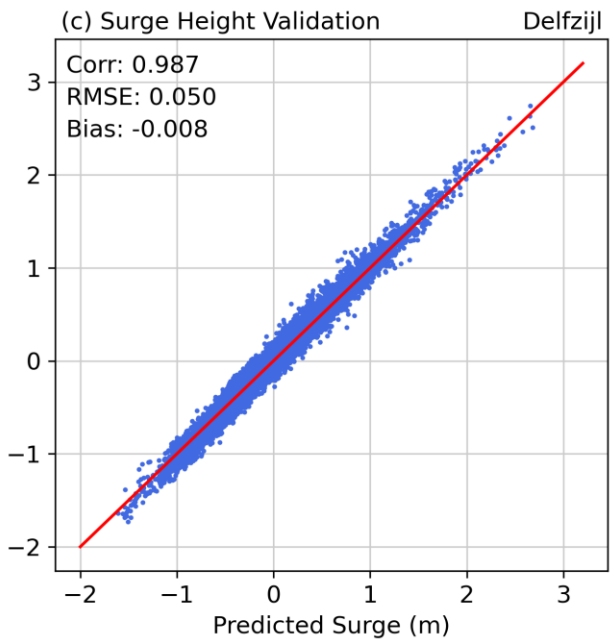
12-hour running mean of non-tidal residuals estimated from the tide gauge

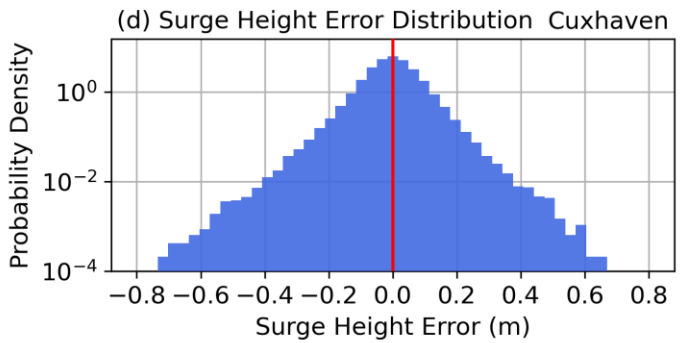
Krieger et al (2025) GRL

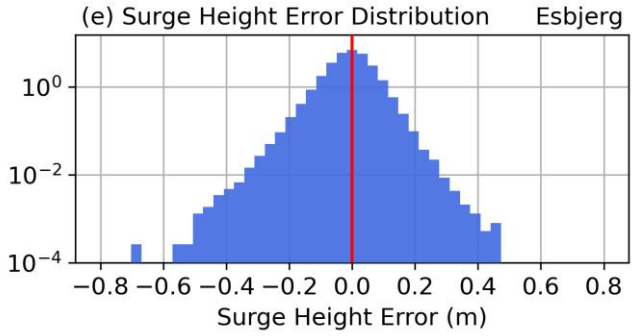
ANN model results vs. observations

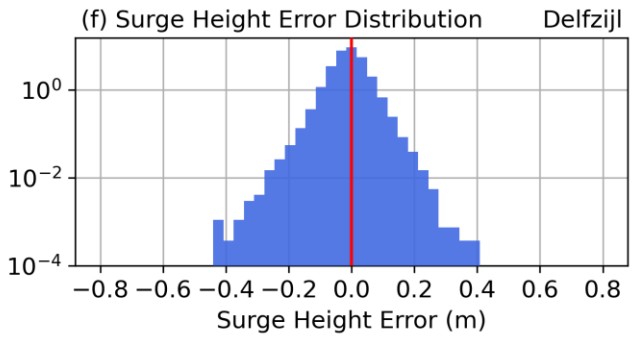












Krieger et al (2025) GRL

CMIP6 ensemble

MPI-GE – Max Planck Institute Grand Ensemble

MPI-ESM1-2-LR model

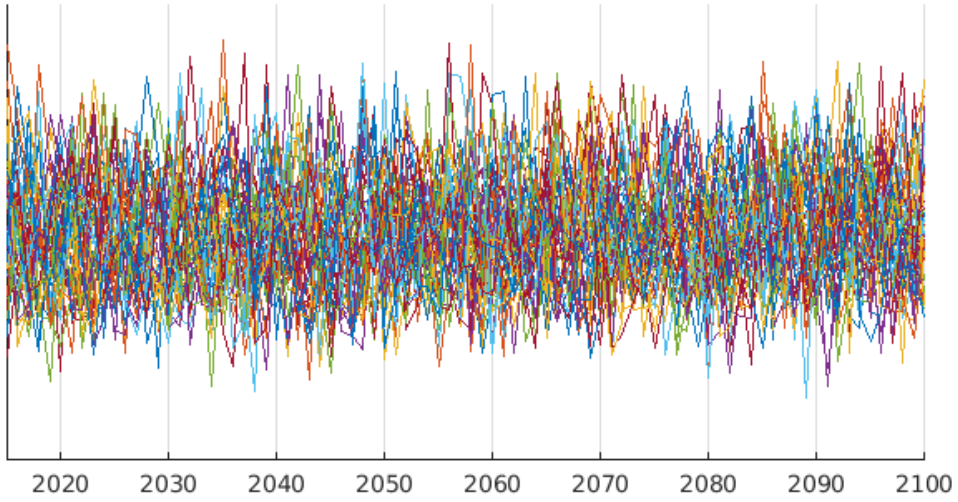
50 members started with different initial conditions

historical conditions → 1850-2014

SSP1-1.9
SSP1-2.6
SSP2-4.5
SSP3-7.0
SSP5-8.5
→ 2015-2100

3h MSLP → ANN → 12-h surge timeseries

annual 99%-tile of 12h-averaged surge



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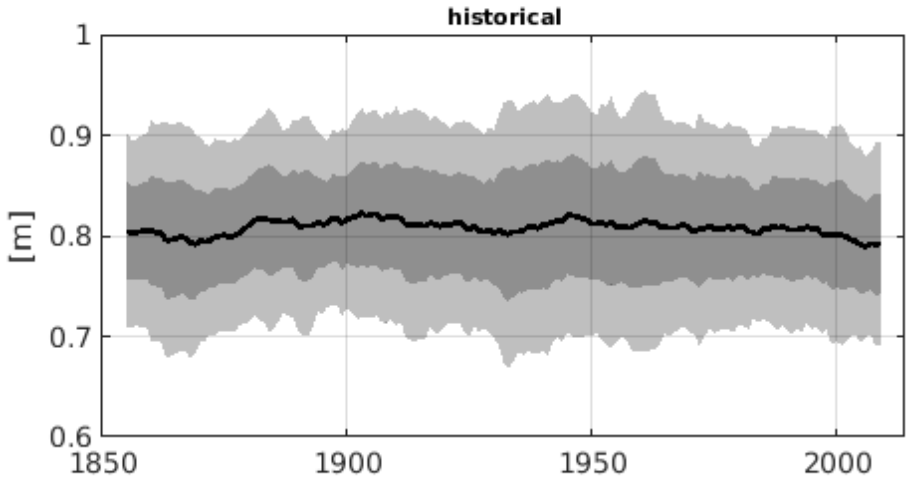
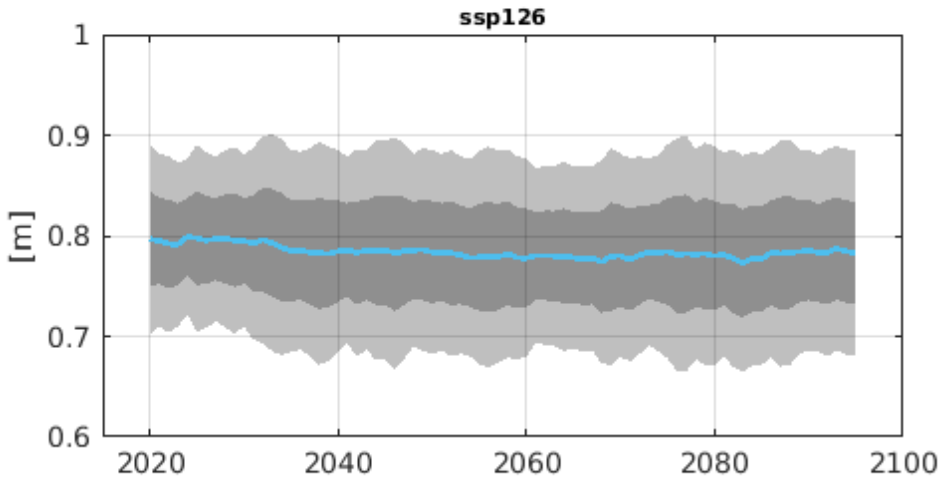
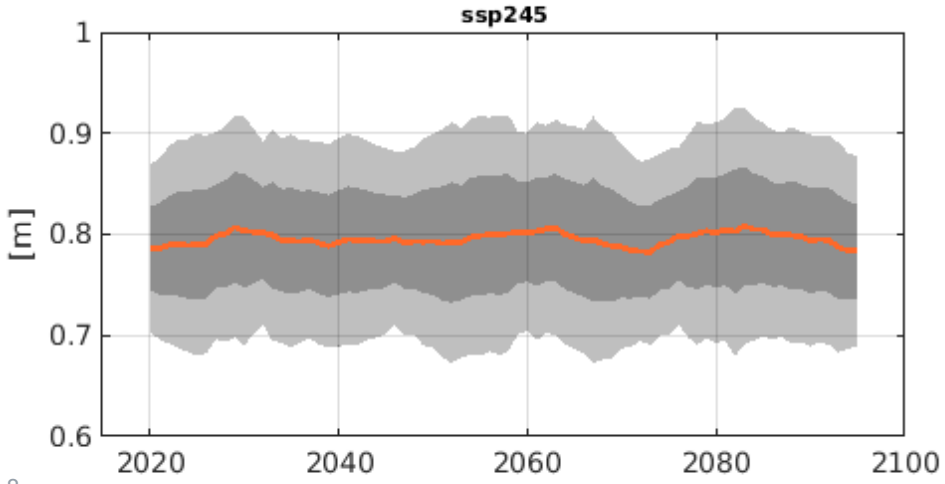
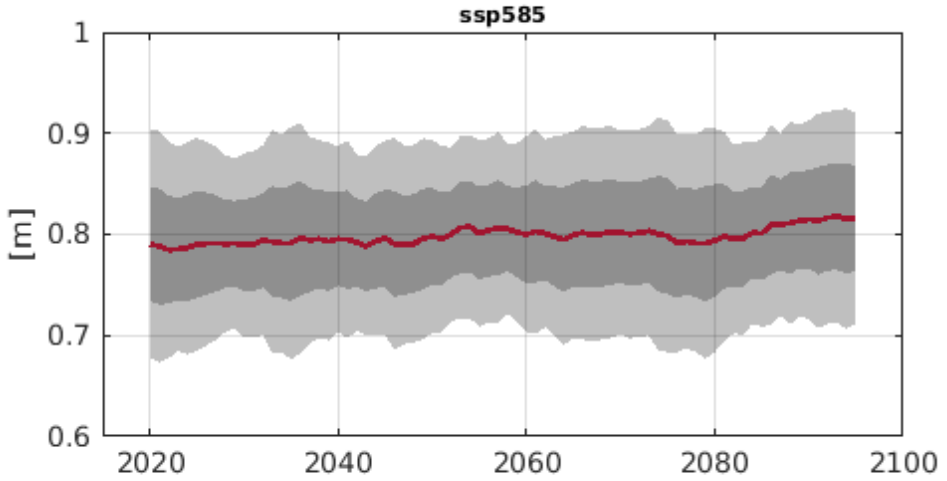
CMIP6 MPI-GE

ensemble mean, +/-1σ, +/-2σ of 10-year average annual 99%-tile of surge for Cuxhaven









decreased ensemble mean for lower emission scenarios

smaller spread and a slight increase towards 2100 for SSP5-8.5

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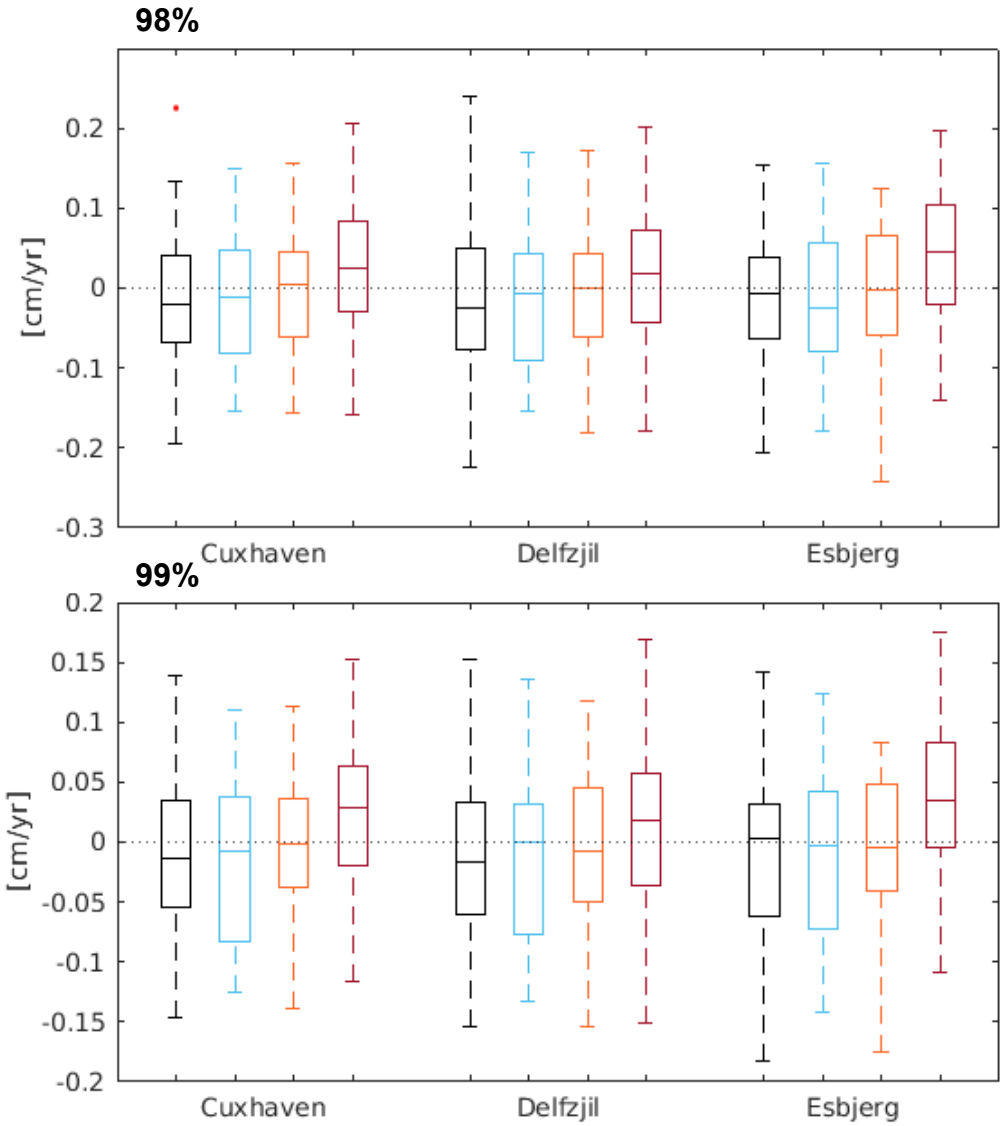
Surge trends from CMIP6 MPI-GE

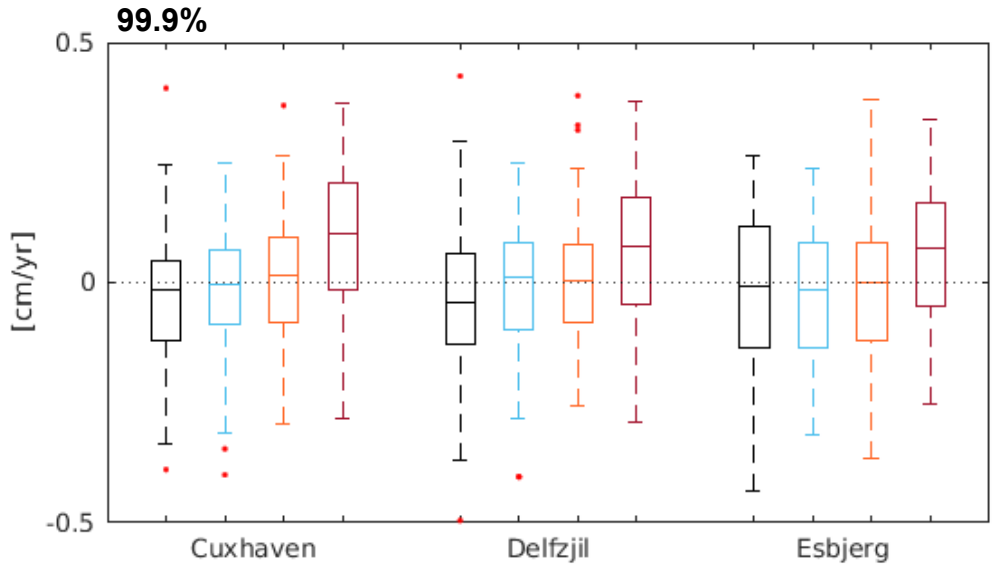


"Historical": tendency to slightly negative trend

SSP126 and SSP245: smallest spread and signal centered around 0

For Cuxhaven median of trends increases for each SSP

For SSP585 all median trends are positive, most pronounced signal for Esbjerg



historical
SSP1-2.6
SSP2-4.5
SSP5-8.5

trends for 10-year moving average of annual percentiles for MPI 50-member ensemble over [1929-2005] for historical, [2015-2091] for SSPs

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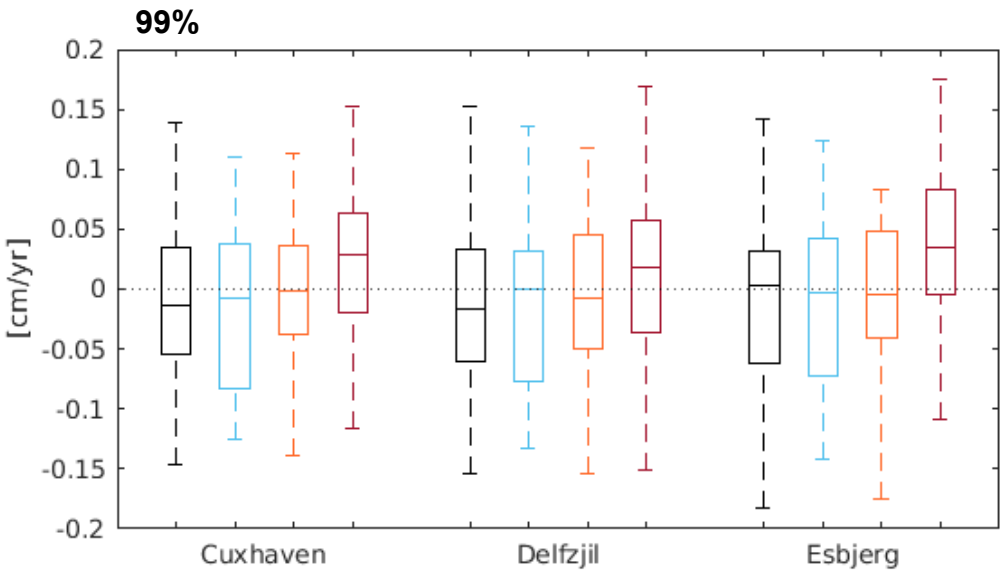
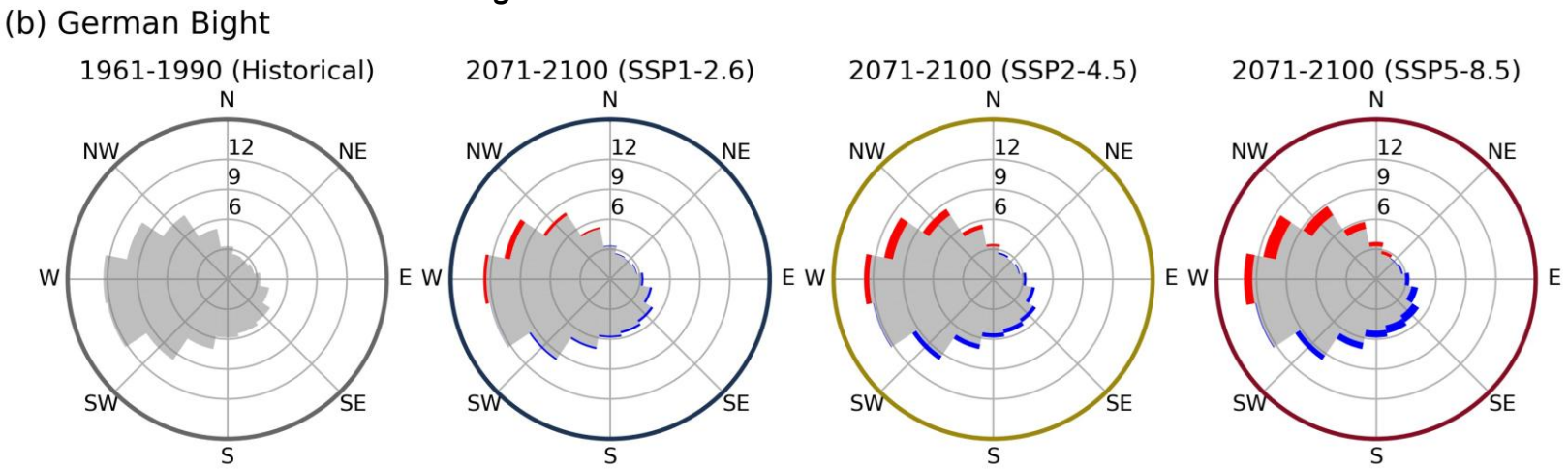
Surge trends from CMIP6 MPI-GE



Increased frequency of westerly to northwesterly wind directions for future projections from SSP2-4.5 and SSP5-8.5.

Increase in surge upper percentiles for the eastern German Bight.

changes in wind direction distribution from MPI-GE



from Krieger et al, In review. EGUsphere

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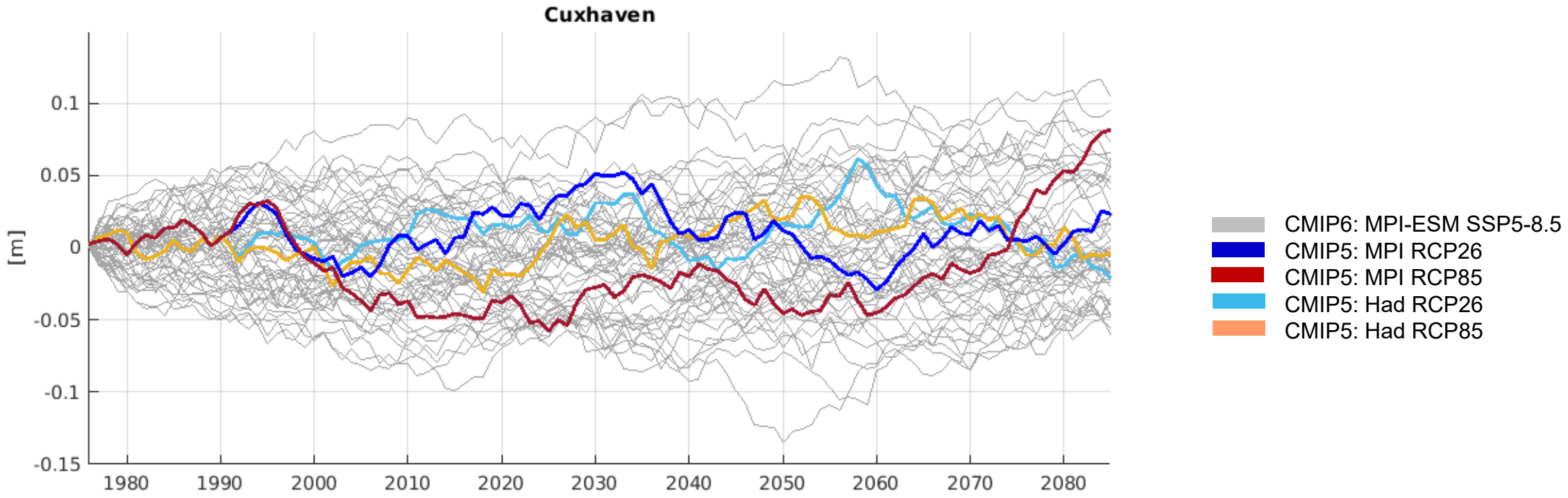
CMIP6 MPI-GE and CMIP5

4 realizations from CMIP5 ensemble - MPI-ESM and Had-GEM global models, hist: 1950-2005, RCPs: 2006-2100



anomaly of 30-year average of 99%-tiles of surge heights relative to 1961-1990

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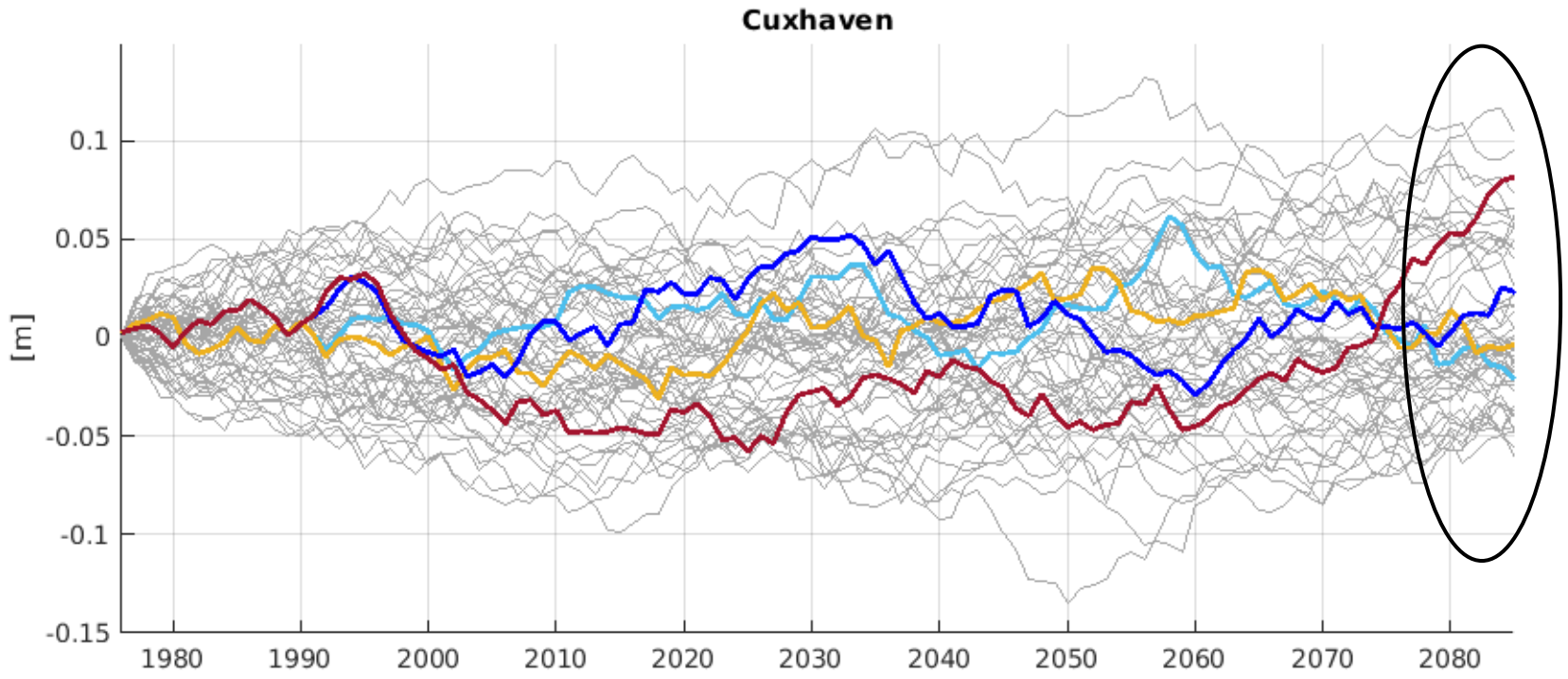
CMIP6 MPI-GE and CMIP5

4 realizations from CMIP5 ensemble - MPI-ESM and Had-GEM global models, hist: 1950-2005, RCPs: 2006-2100



anomaly of 30-year average of 99%-tiles of surge heights relative to 1961-1990

For surge high percentiles differences at the end of the century (2071-2100) with respect to reference period (1961-1990) are within the ensemble range

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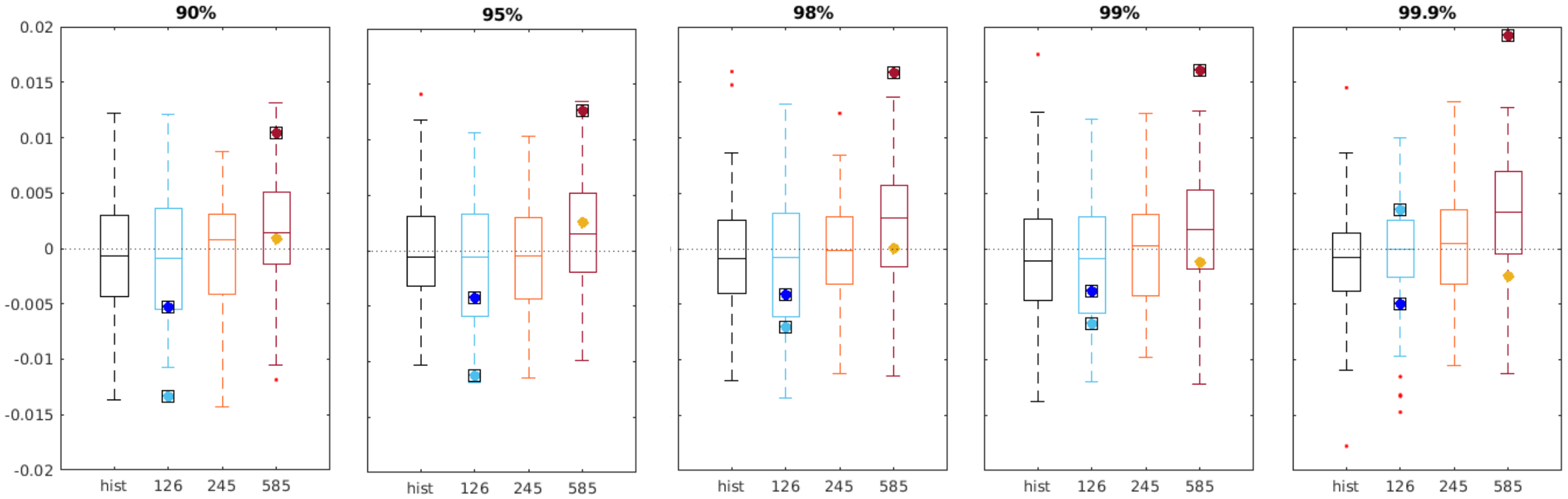
Surge trends from CMIP5 and CMIP6 projections

trends for 10-year average of 99%-tiles of surge heights standardized to 1961-1990 from CMIP6 ensemble (boxes) and CMIP5 (circles) for 77-year periods at the end of each scenario for Cuxhaven



MPI RCP85 shows large positive trend and is an outlier based on CMIP6 ensemble

Had RCP2.6 is an outlier with the negative trend

- CMIP5: MPI RCP26
- CMIP5: MPI RCP85
- CMIP5: Had RCP26
- CMIP5: Had RCP85
- significant

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Summary

Artificial Neural Network was trained for standardized MSLP fields and storm surge timeseries from three tide gauges.

Reconstructed data reproduce well the observed surges in mean and extremes.

CMIP6 single-model ensemble used for assessment of internal variability (MPI-GE).

This method can facilitate selection of appropriate climate change projections for further downscaling or evaluation of currently used projections for their representability.

Krieger D., et al. “Machine learning-driven skillful decadal predictions of the German Bight storm surge climate”, 2025, GRL

Krieger D., et al. “CMIP6 Multi-model Assessment of Northeast Atlantic and German Bight Storm Activity”, in review, EGUsphere

Thank you for your attention

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