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BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE

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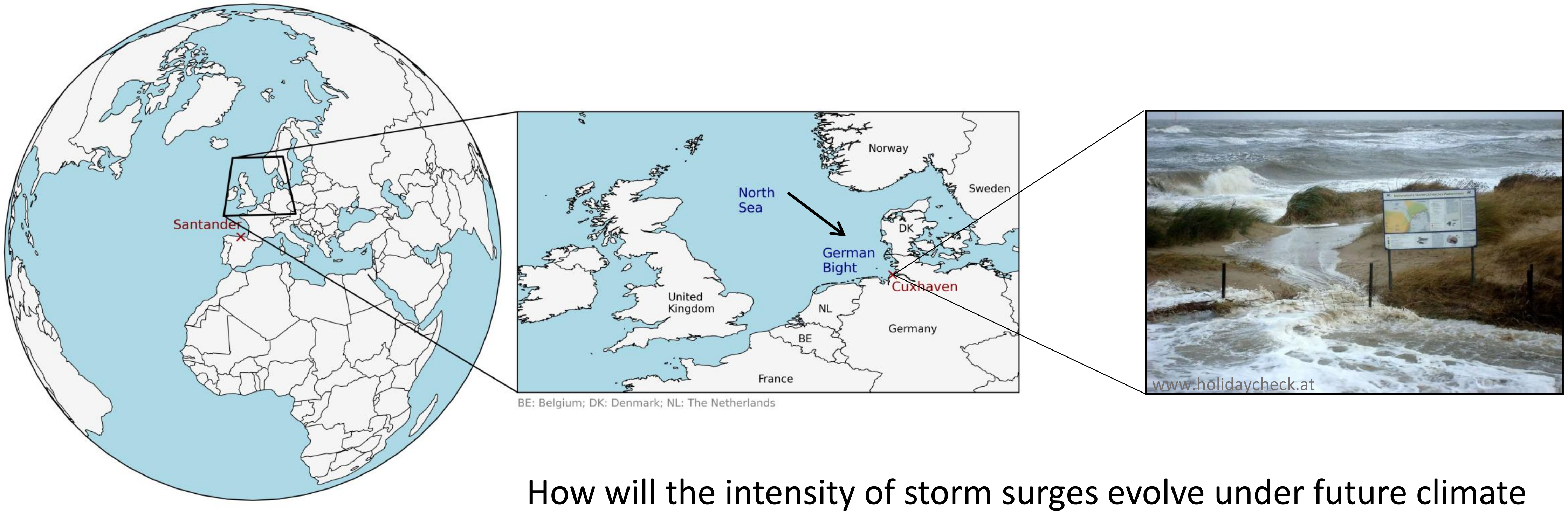
4th International Workshop on Waves, Storm Surges, and Coastal Hazards 23.09.2025

# Efficient statistical modeling of storm surges in the German Bight: historical evolution and future changes

**Laura Schaffer**, Johanna Baehr, Tim Kruschke

# Why we need simpler tools to predict storm surges




BE: Belgium; DK: Denmark; NL: The Netherlands

How will the intensity of storm surges evolve under future climate conditions?

# From concept to code: Building the model

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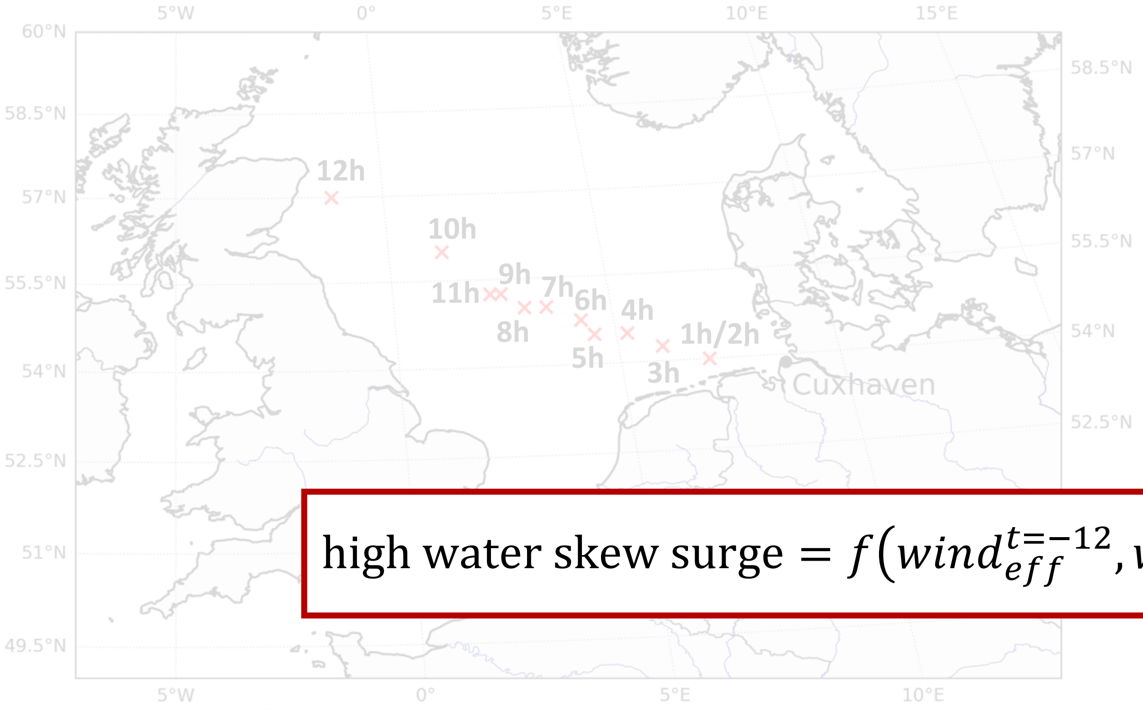
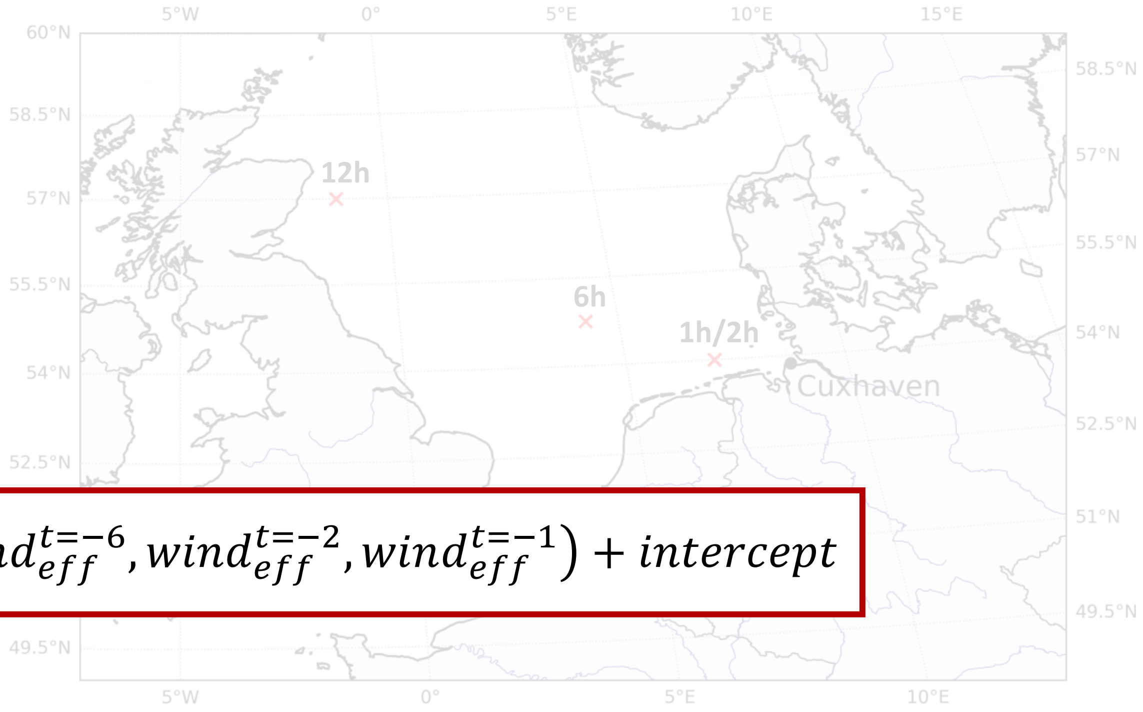
| Multiple linear regression | |
|---|---|
| **Input** | **Outcome** |
| | |

# Where and when: Important predictors in space and time




Schaffer et al. (2025a)




$$\text{high water skew surge} = f\left(wind_{eff}^{t=-12}, wind_{eff}^{t=-6}, wind_{eff}^{t=-2}, wind_{eff}^{t=-1}\right) + intercept$$

Predictor locations move from **north-west** to **south-east**
→ In line with meteorological expectation

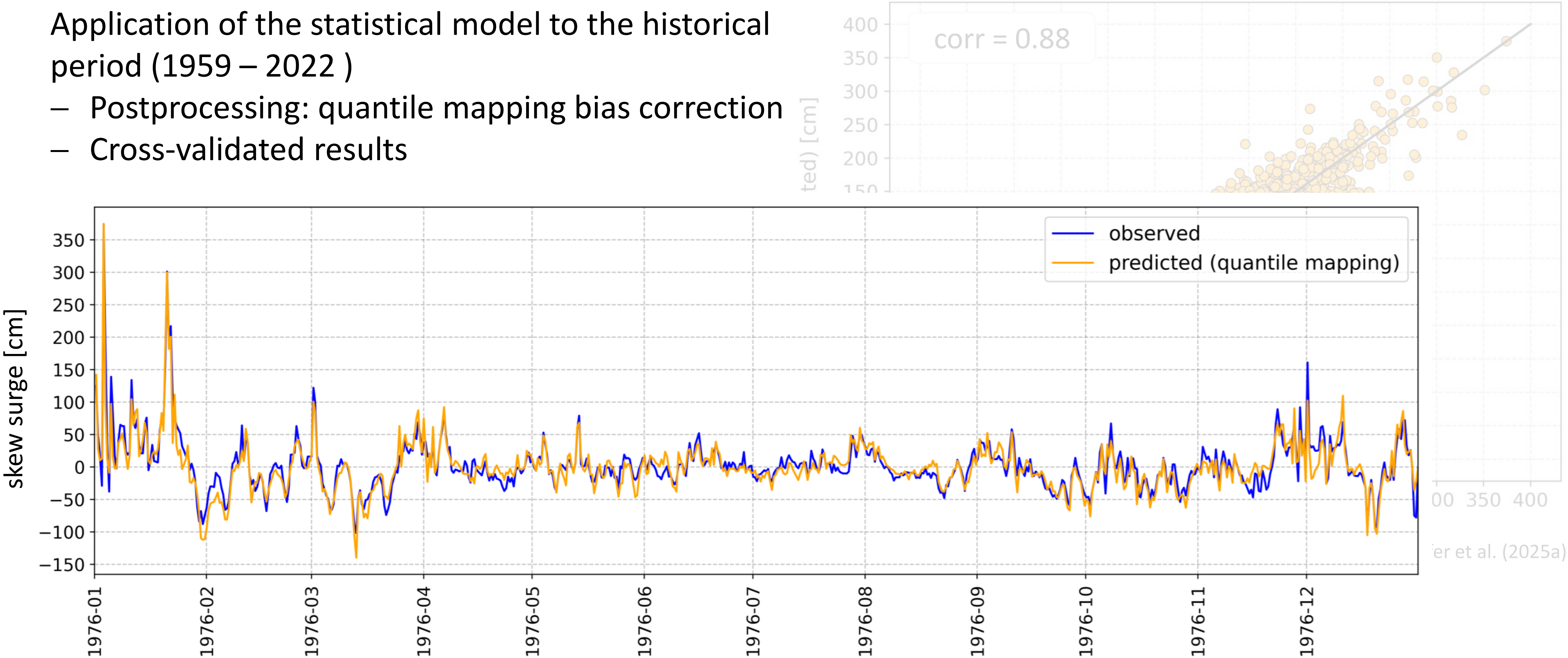
**Elastic net regression**

- Predictor selection
- Coefficient shrinkage

# Looking back to look forward: Validating with the past

Application of the statistical model to the historical period (1959 – 2022 )

- Postprocessing: quantile mapping bias correction
- Cross-validated results




Schaffer et al. (2025a)

# Looking ahead: Wind surges in a changing climate

Multi-model ensemble of CMIP6 global climate simulations

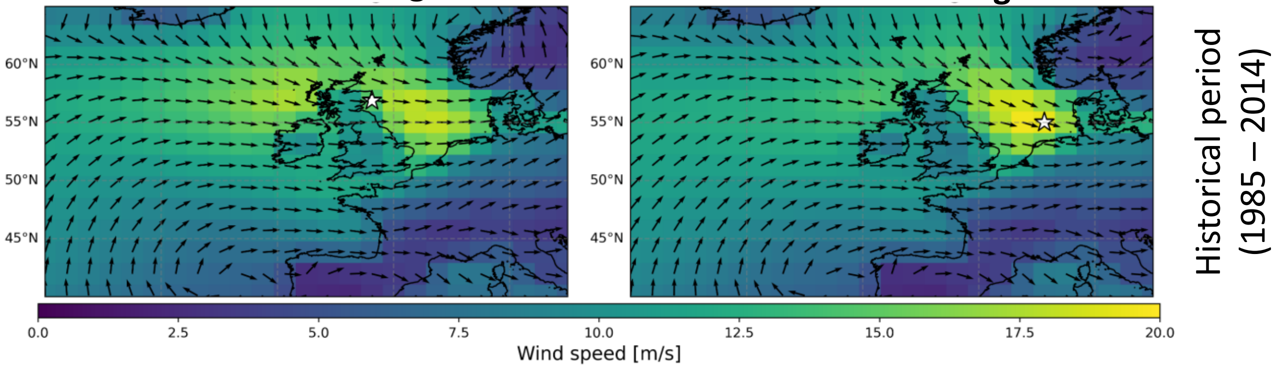
– 25 ensemble members from 9 climate models (SSP2-4.5, SSP3-7.0, SSP5-8.5)

Frequency of positive wind surges and potential storm surge situations

- Significantly **increase** during **winter** (up to **10%**)

# Looking ahead: Storm surge events in a changing climate

**12 hours before wind surge ≥ 150cm** **3 hours before wind surge ≥ 150cm**




☆ Grid cells used as input for the statistical storm surge model

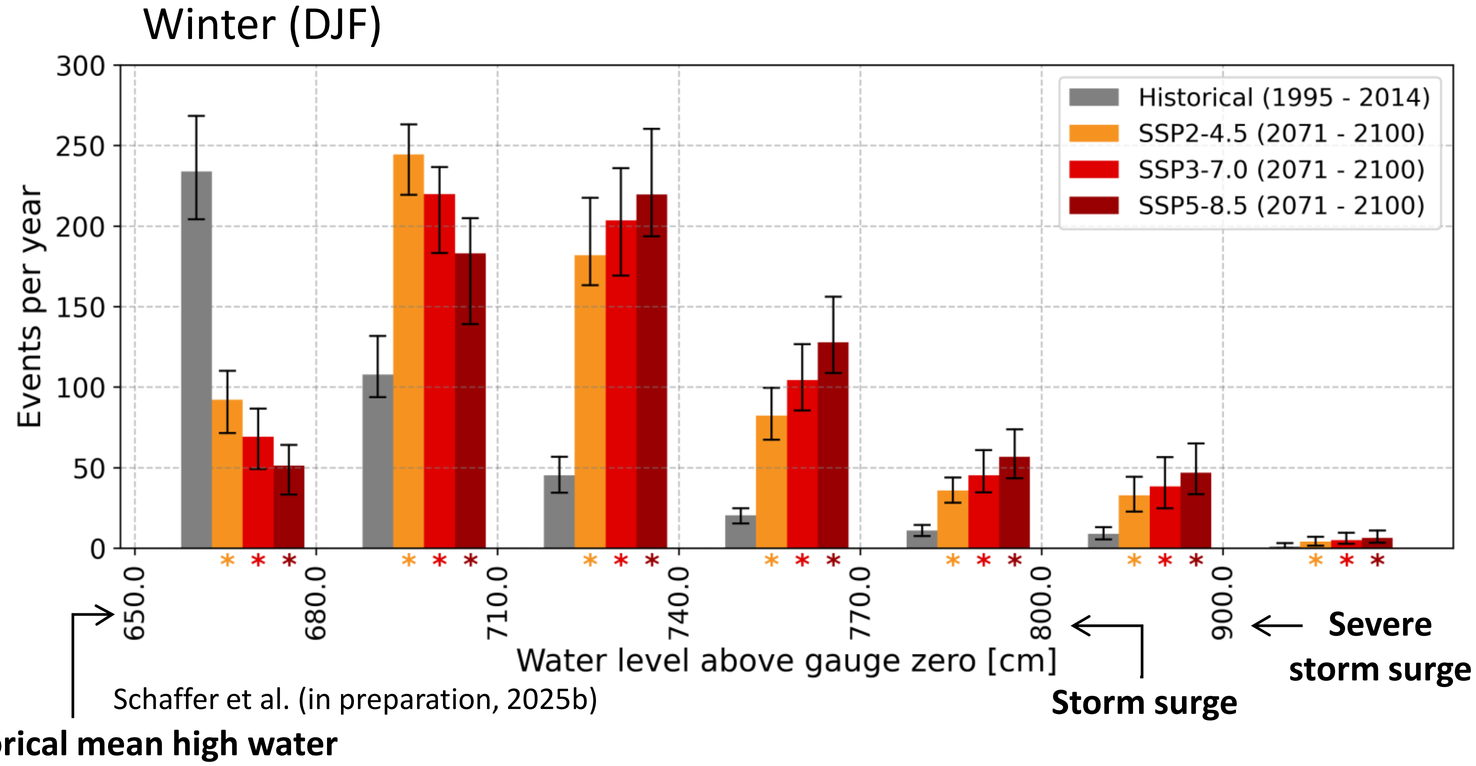
| **Hours before storm surge event** | **Historical period (1985 – 2014)** |
|---|---|
| 12 | • Westerly winds<br>• High wind speeds |
| 3 | • Northwesterly winds<br>• Intensification of wind speeds |

12 hours before storm surge event ☆
- **Increase** in frequency of **westerly winds**
- Significant **decrease** in **wind speed**

Schaffer et al. (in preparation, 2025b)

# Looking ahead: Water levels in a changing climate

*Water Level = Historical Mean High Water + Projected Wind Surges + Projected Sea Level Rise*




Schaffer et al. (in preparation, 2025b)

Exceedance of storm surge threshold (800cm)

| | Events / year |
|---|---|
| Historical period | 9 |
| SSP2-4.5 | 33 |
| SSP3-7.0 | 38 |
| SSP5-8.5 | 47 |

**3-fold** to **5-fold increase**

! Assuming high tide at every time step (3-hour resolution) !

Combined effect of projected wind surges and sea level rise

- Clear increase in the frequency of high water levels compared to the historical period

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## Aim of the study

Development of a **simple storm surge model** for German Bight that can be **applied to climate model projections**

## Statistical model approach

- Statistical storm surge model comprises **only five terms**
  - Elastic net regression combined with quantile mapping
- **High predictive accuracy** (corr = 0.88), rivaling more complex models

**Schaffer et al.**: Development of a wind-based storm surge model for the German Bight, Nat. Hazards Earth Syst. Sci., 2025a

## Application result

- **Future**: multi-model ensemble of CMIP6 global climate simulations
  - **Increase in frequency** of potential storm surge situations by **up to 10%** (**DJF**)
    - ➢ Driven by **more frequent westerly** and **northwesterly winds** combined with **stronger wind speeds** over the southern North Sea
  - **Combination** of **projected wind surges and sea level rise**
    - ➢ **moderate** and **severe present-day storm surge thresholds** are **exceeded 3 to 5 times more often** than in the historical period

**Schaffer et al.**: Future Storm Surge Risk in the German Bight, GRL, [in preparation], 2025b

# DASNordicSLR – Sea Level Projections for Northern Europe

## Supplementary material

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# DASNordicSLR – Sea Level Projections for Northern Europe

- Sea level rise projections for Cuxhaven (2070 – 2100) under SSP2-4.5, SSP3-7.0 and SSP5-8.5
- Dataset **combines IPCC projections** of **total sea level change** with a **high-resolution land elevation model for Fennoscandia**

## Sea Level Projections (Data)

Jensen, C. (2025) *DASNordicSLR. Sea Level Projections for Northern Europe (2020-2150). Based on IPCC AR6 SSP Sceanrios and NKG Land Uplift Data.* Federal Maritime and Hydrographic Agency of Germany (BSH). [Data set] DOI: https://doi.bsh.de/10.60751/3x97-gp60

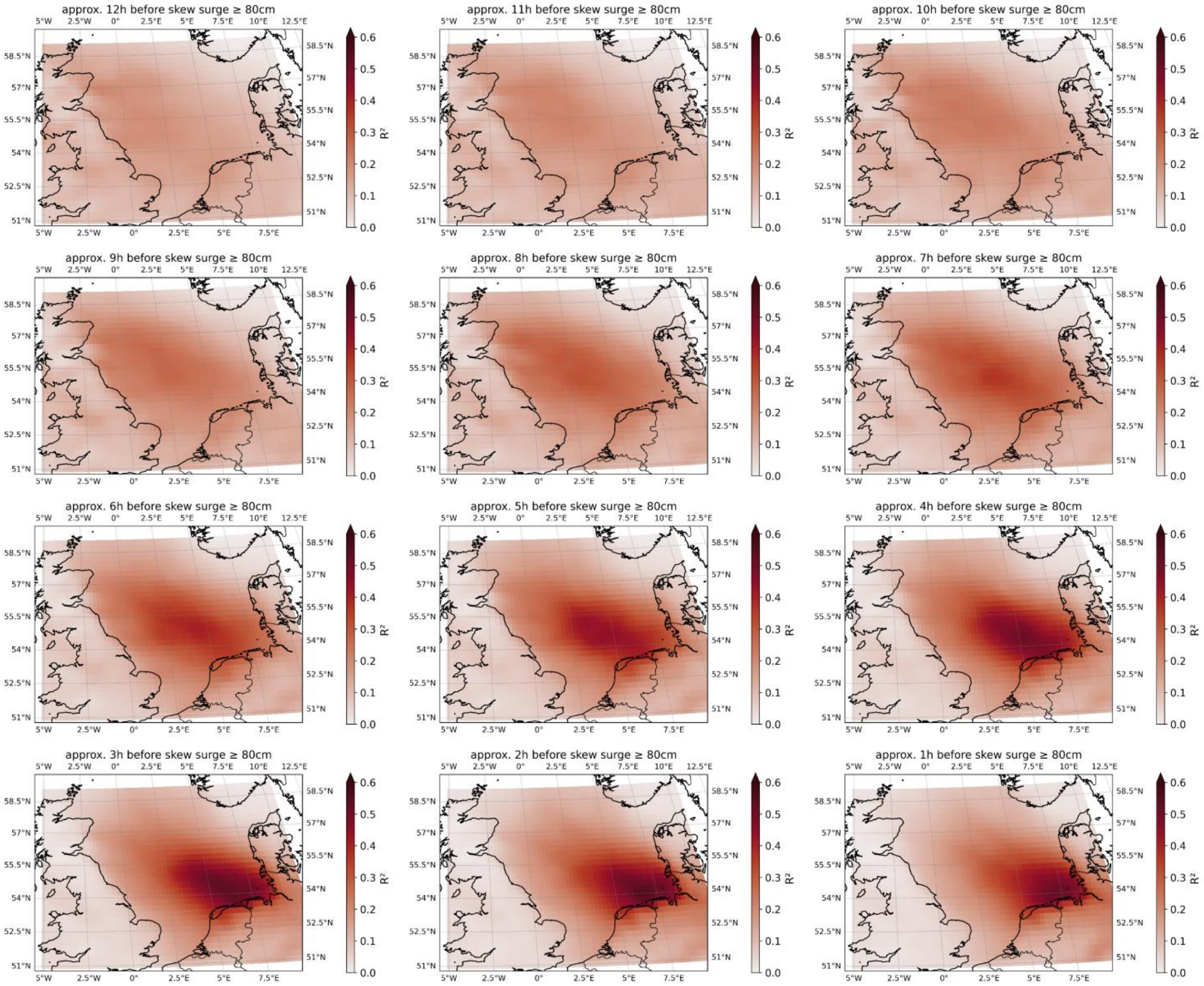
## Sea Level Projections for Northern Europe (Preprint)

Jensen, C., Janssen F., and Kruschke, T.  (2025) *DASNordicSLR – Sea Level Projections for Northern* EarthArXiv . Retrieved from: https://doi.org/10.31223/X5TJ24 (Preprint) DOI: 10.31223/X5TJ24

# Development of a wind-based storm surge model for the German Bight

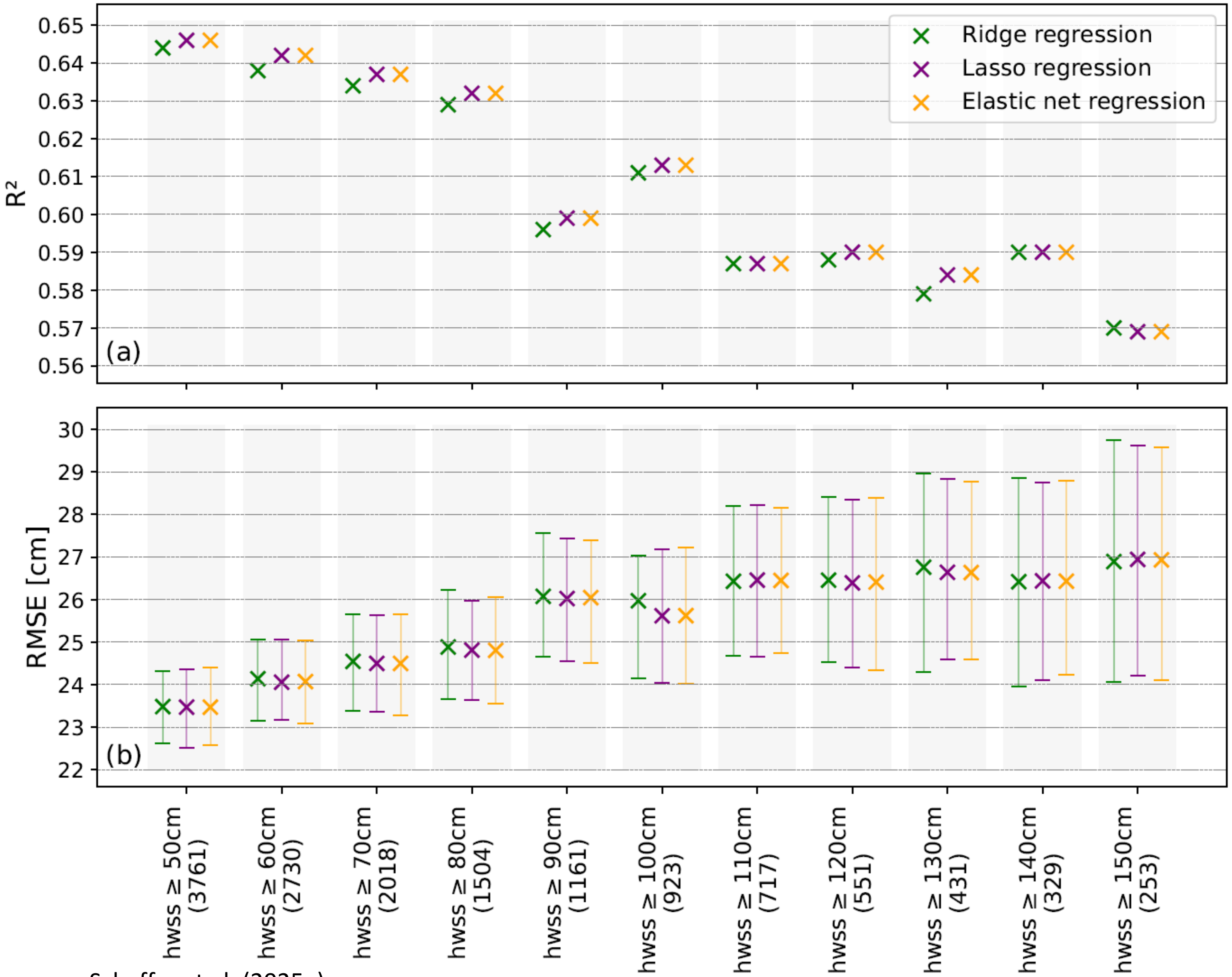
## Supplementary plots

# Quadratic regression



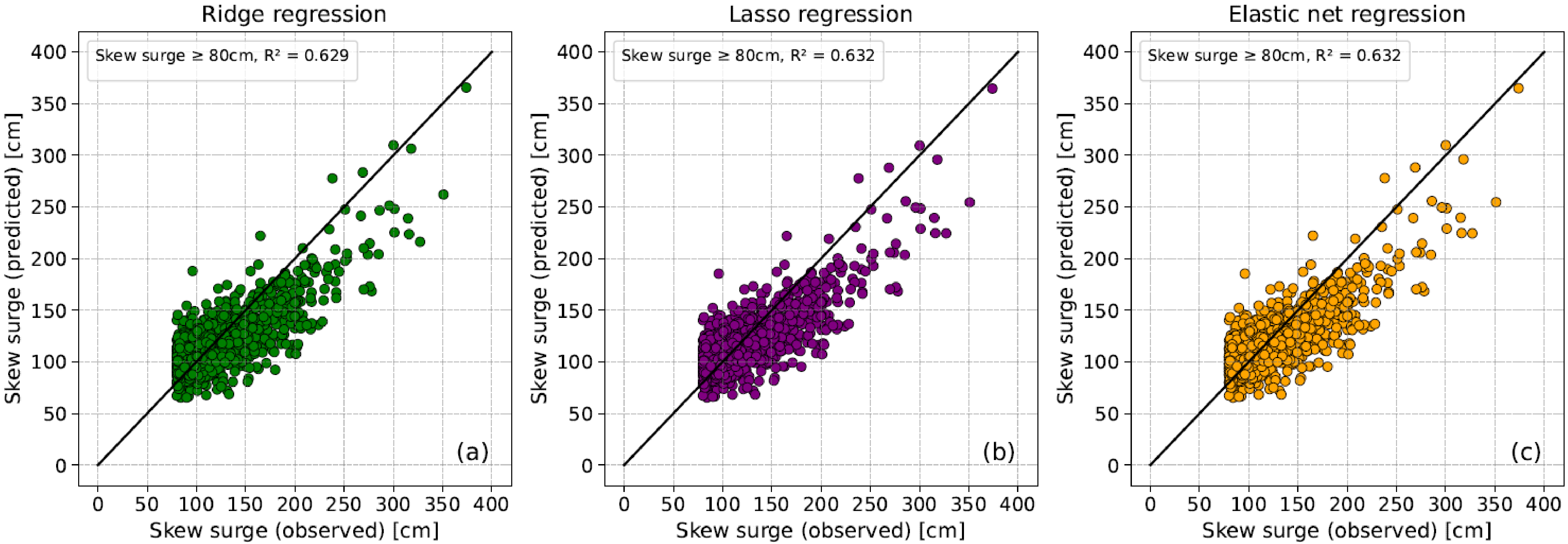

Schaffer et al. (2025a)

# Regularization methods and training threshold



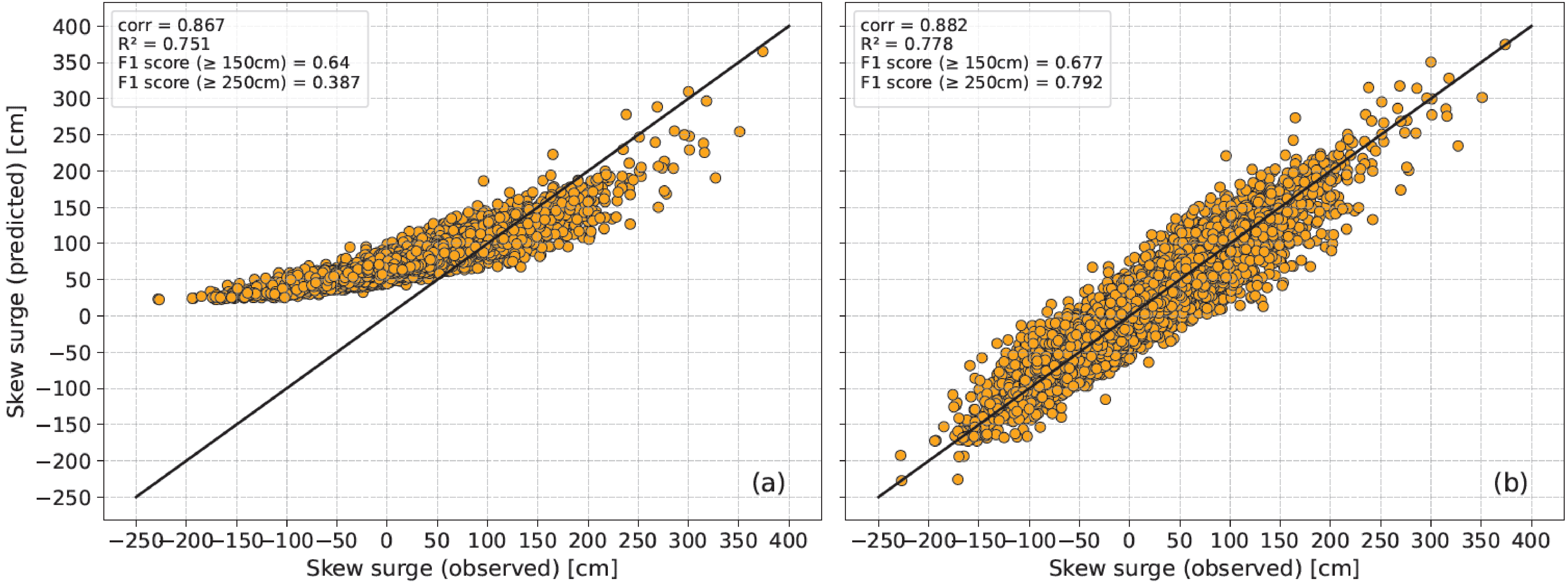

Schaffer et al. (2025a)

# Regularization methods



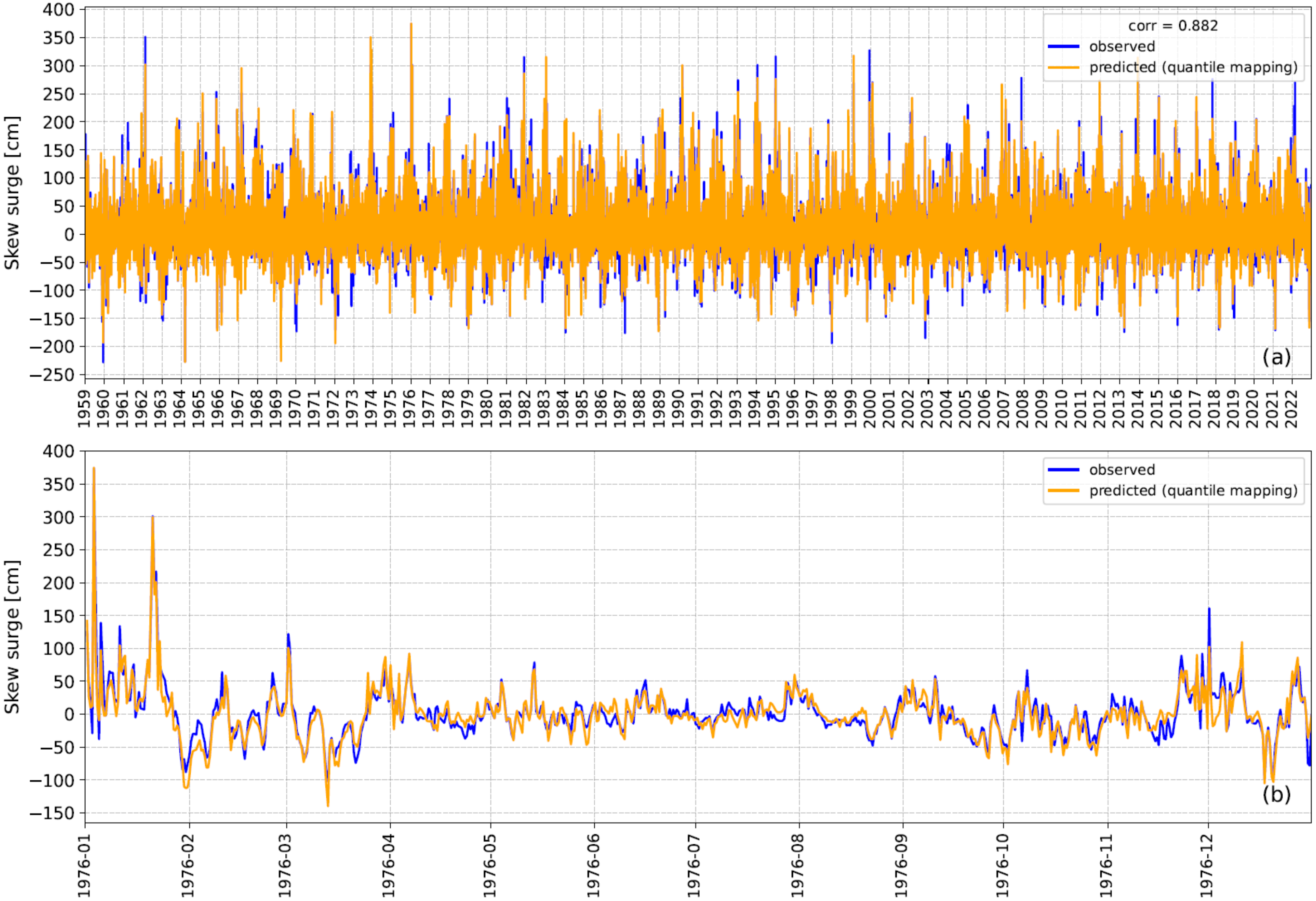

Schaffer et al. (2025a)

# Application to the historical period and validation




Schaffer et al. (2025a)

# Application to the historical period and validation




Schaffer et al. (2025a)

# Future Storm Surge Risk in the German Bight

## Supplementary plots

# CMIP6 Multi-Model Ensemble

| | Number of Ensemble Members | | | | |
|---|---|---|---|---|---|
| Model | Historical | SSP2-4.5 | SSP3-7.0 | SSP5-8.5 | Reference |
| AWI-CM-1-1-MR | 1 | 1 | 1 | 1 | Semmler et al. (2018) |
| BCC-CSM2-MR | 1 | 1 | 1 | 1 | Wu et al. (2019) |
| CMCC-CM2-SR5 | 1 | 1 | 1 | 1 | Cherchi et al. (2019) |
| CNRM-CM6-1-HR | 1 | 1 | 1 | 1 | Voldoire et al. (2019) |
| EC-Earth3 | 1 | 1 | 1 | 1 | Döscher et al. (2022) |
| IPSL-CM6A-LR | 6 | 6 | 6 | 6 | Boucher et al. (2020) |
| MIROC6 | 3 | 3 | 3 | 3 | Tatebe et al. (2019) |
| MPI-ESM1-2-LR | 10 | 10 | 10 | 10 | Mauritsen et al. (2019) |
| MRI-ESM2-0 | 1 | 1 | 1 | 1 | Yukimoto et al. (2019) |

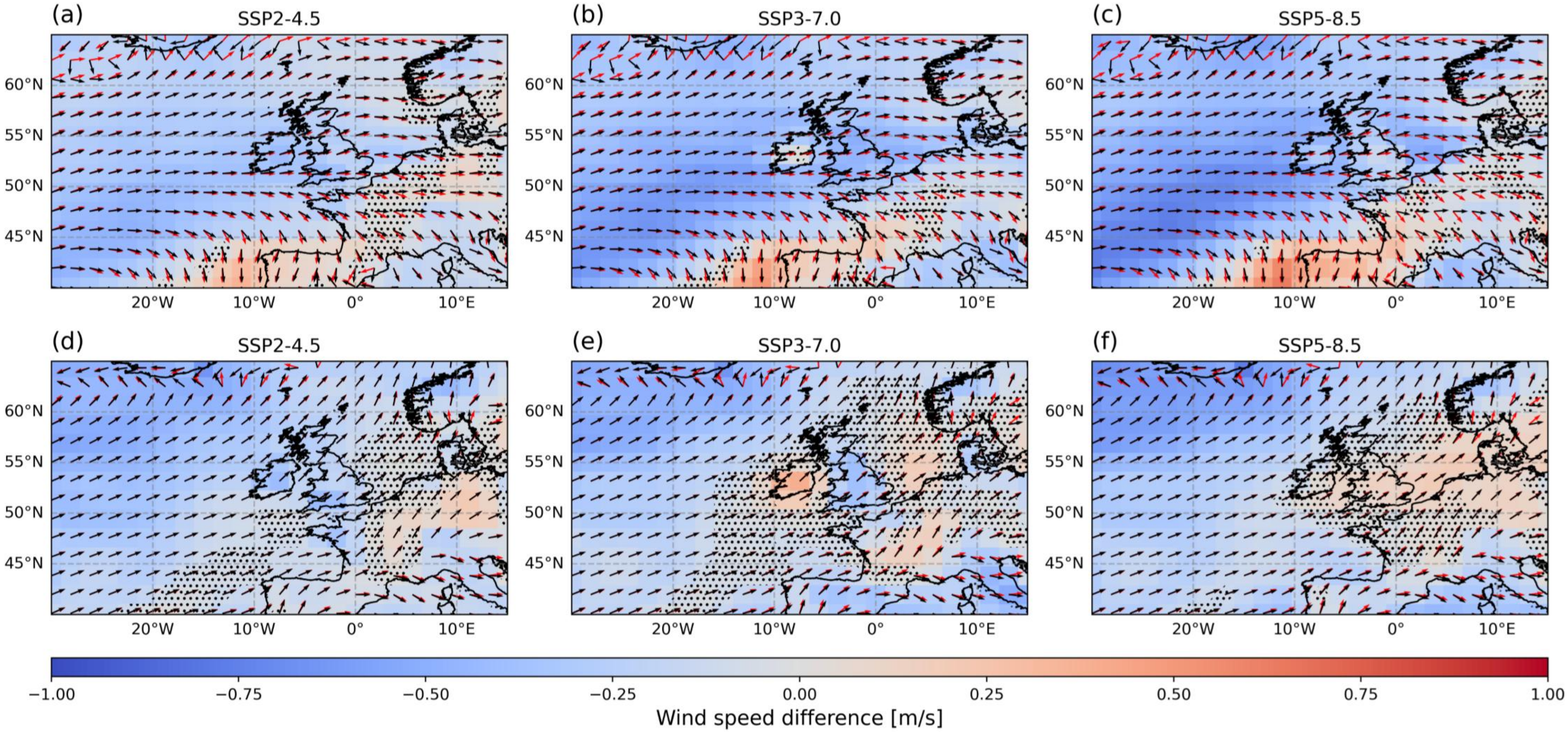
Schaffer et al. (in preparation, 2025b)

# Number of events (≥ 150cm) contributing to the composite analysis

| Model | Ensemble size | Number of Wind Surge Events (≥ 150 cm) Historical (1985-2014) | SSP5-8.5 (2071-2100) |
|---|---|---|---|
| AWI-CM-1-1-MR | 1 | 595 | 697 |
| BCC-CSM2-MR | 1 | 366 | 615 |
| CMCC-CM2-SR5 | 1 | 420 | 499 |
| CNRM-CM6-1-HR | 1 | 424 | 484 |
| EC-Earth3 | 1 | 440 | 370 |
| IPSL-CM6A-LR | 6 | 2874 | 3533 |
| MIROC6 | 3 | 1212 | 1124 |
| MPI-ESM1-2-LR | 10 | 4921 | 5279 |
| MRI-ESM2-0 | 1 | 589 | 406 |

Schaffer et al. (in preparation, 2025b)

# Looking ahead: Changes in mean wind speed




**Summer (JJA)**

**Winter (DJF)**

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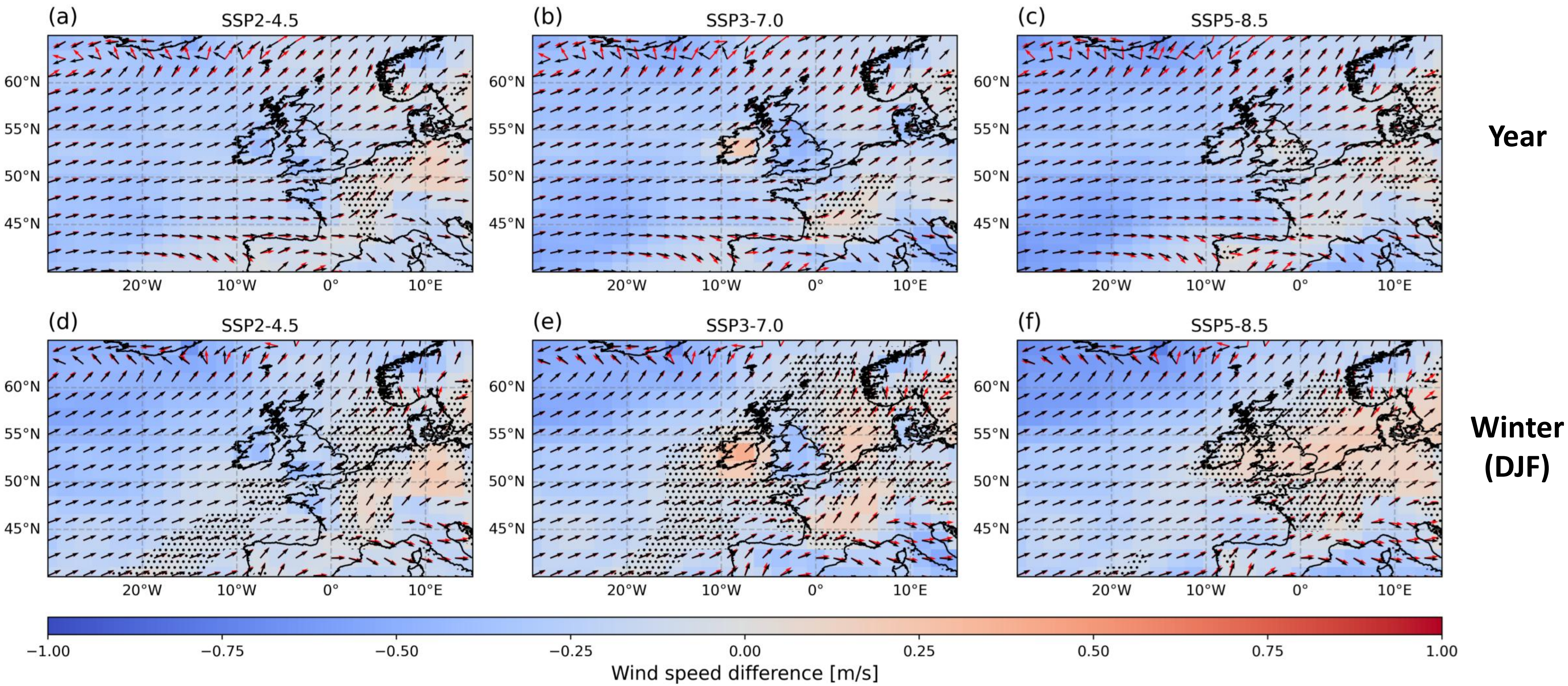
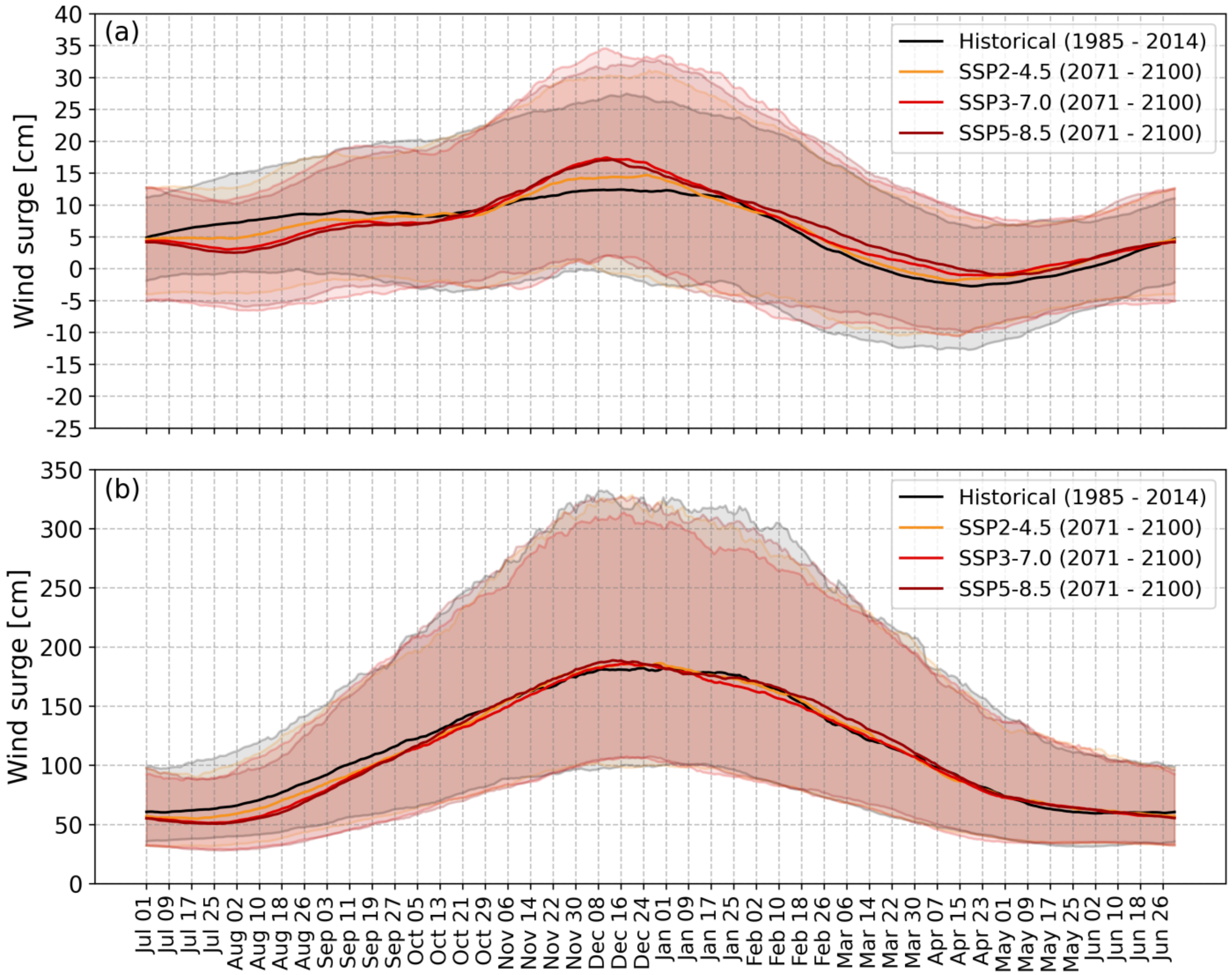
# Looking ahead: Changes in mean wind speed




Schaffer et al. (in preparation, 2025b)

# Looking ahead: Changes in seasonality



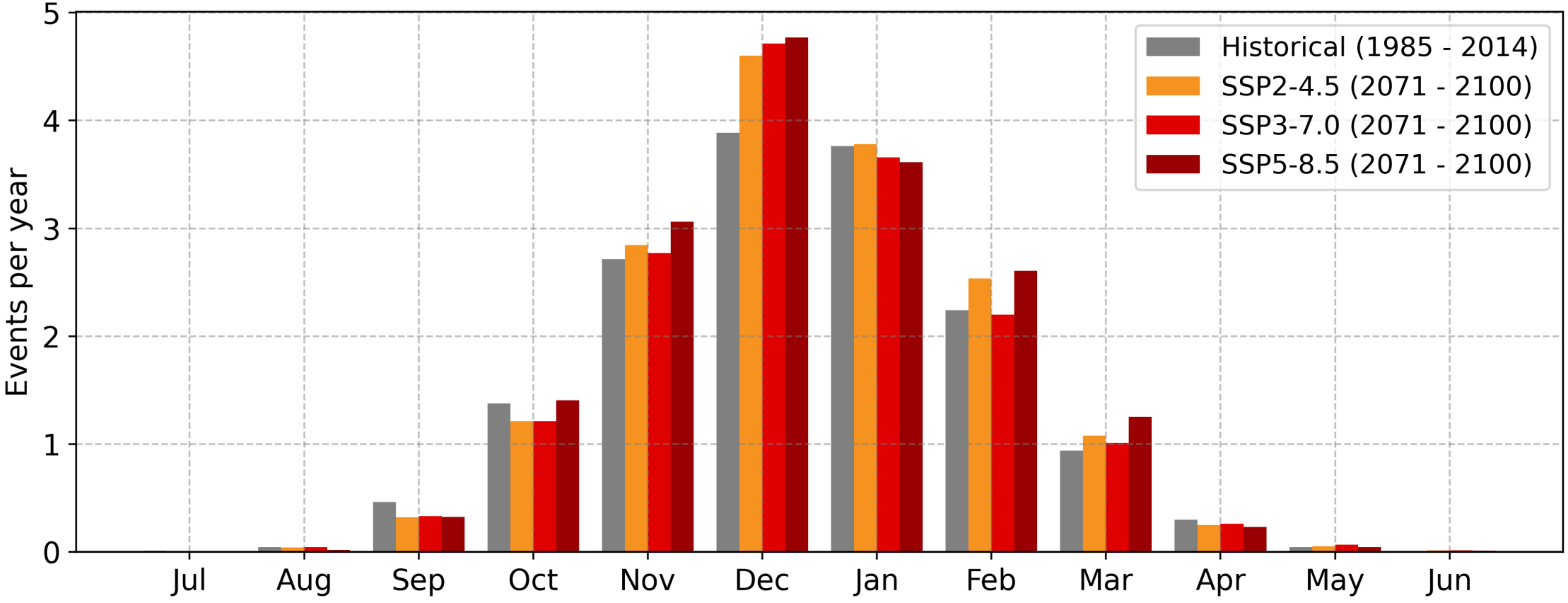

**31-day running mean wind surge**

**31-day running 99.45th percentile wind surge**

Schaffer et al. (in preparation, 2025b)

# Looking ahead: Changes in seasonality

Number of events (≥ 150cm) for each month of the year




Schaffer et al. (in preparation, 2025b)