Ensemble projections of storm-surge changes along European coasts using statistical downscaling

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Waves, storm surges and coastal hazards workshop

23/09/2025

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This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101003598

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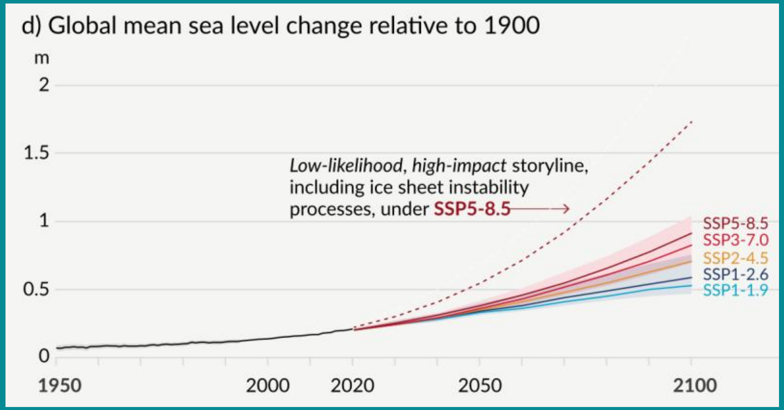
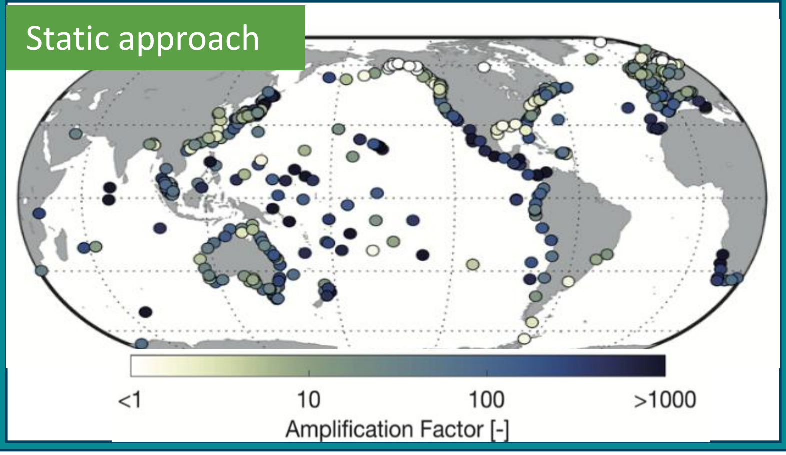
Context and Motivation

Today…

Future……



IPCC AR6 (SSP5-8.5 2050) 100year event



- Increase confidence on projected local ESLs➔ Need to account for **future storm surge** (SS) changes
- SS projections are **sparse**, typically based of relatively **costly dynamical downscaling** (DD) ➔ Limited ensemble sizes , <5 GCMs for EU, exceptionally higher (8, Vousdoukas et al. 2018), **strong inter-model spread**

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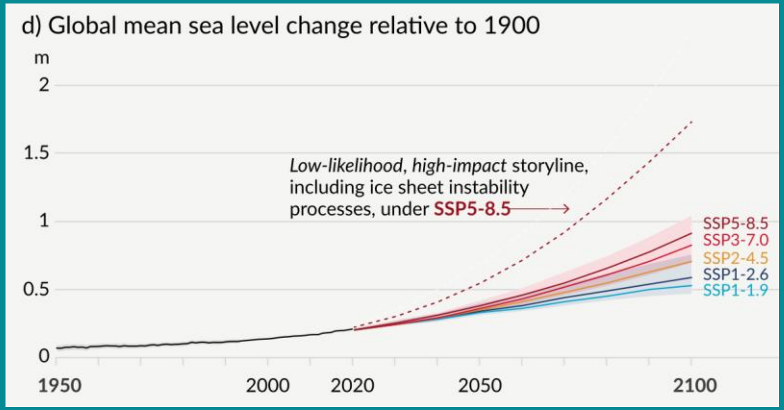

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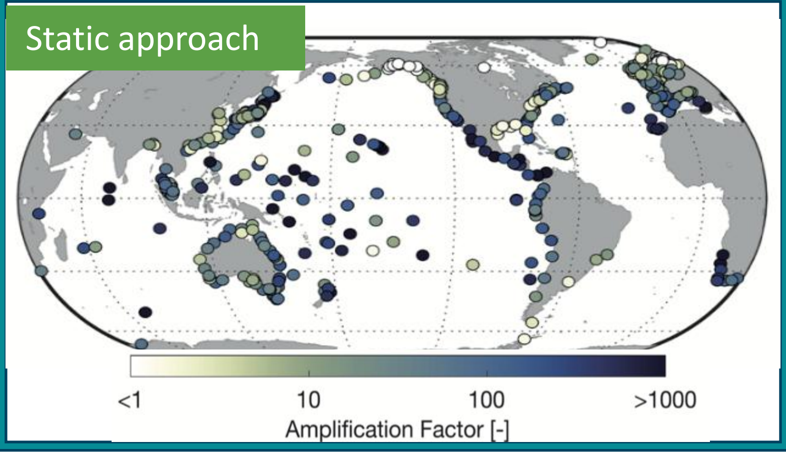

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- **Statistical downscaling** methods skillful for SS reconstructions, but poorly explored so far **for projections** (incl. for EU)
- They depend on extensive **data availability** for training ➔ train on DD outputs (**hybrid downscaling**)

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Research questions

- Can cost-effective statistical downscaling models emulate projected extreme storm surge (ESS) changes from dynamically downscaled projections (*hybrid* downscaling approach) at pan-European scale?

- What is the magnitude and uncertainty of projected ESS changes based on extended CMIP6 ensembles? (x17 GCMs)

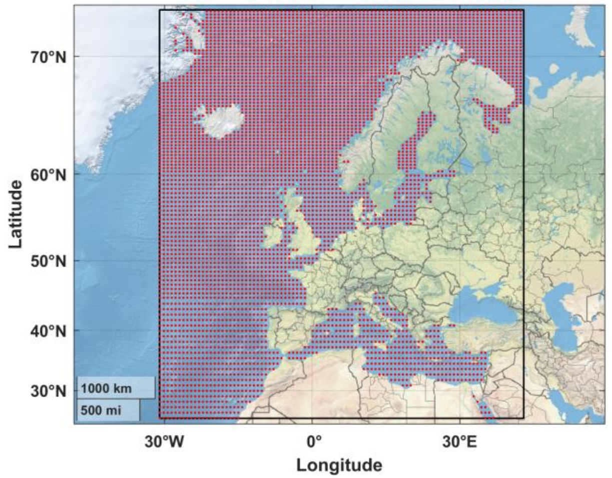
Irazoqui et al. 2025, submitted to NHESS

Dynamical downscaling model (DDM)

- ROMS barotropic storm-surge model for Europe
- Resolution: 5-11km, hourly outputs
- Forced by PSL, U10,V10
- Bathymetry: ETOPO1 at 1-arc minute resolution
- IBC at boundaries
- ~7000 cps ➔600 subset for this study

Hindcast (contemporary SS conditions):

- ERA5 forcing
- 1997-2021 (25yr)



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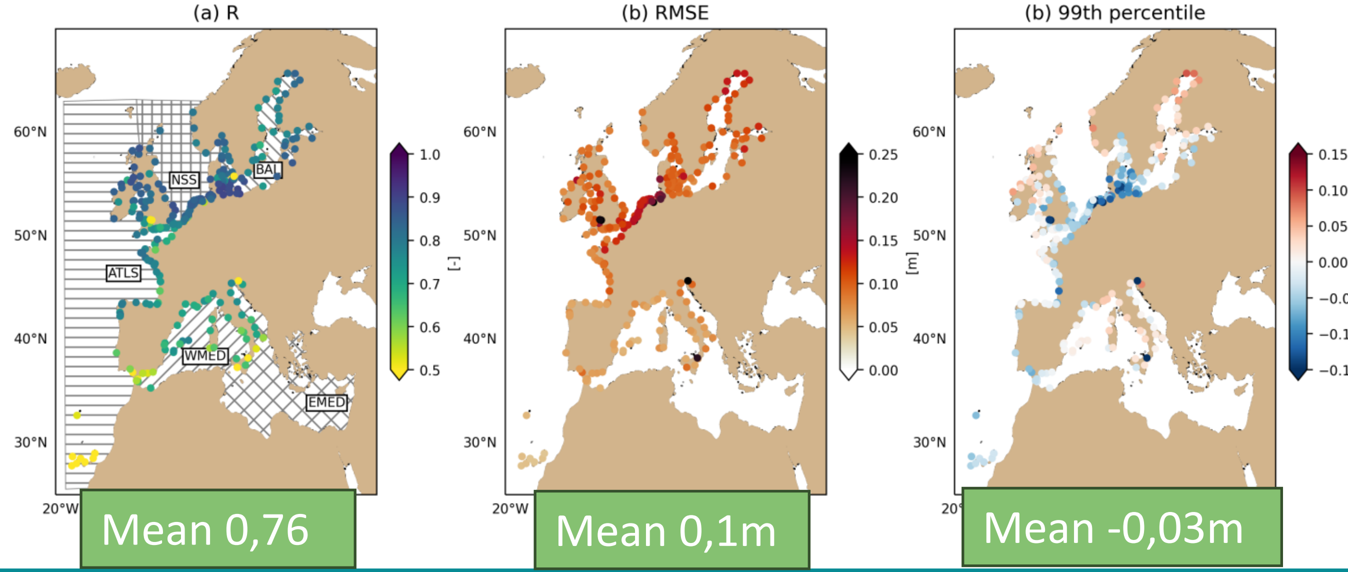
Validation against GESLA3 observations (NTR) with >4 years data



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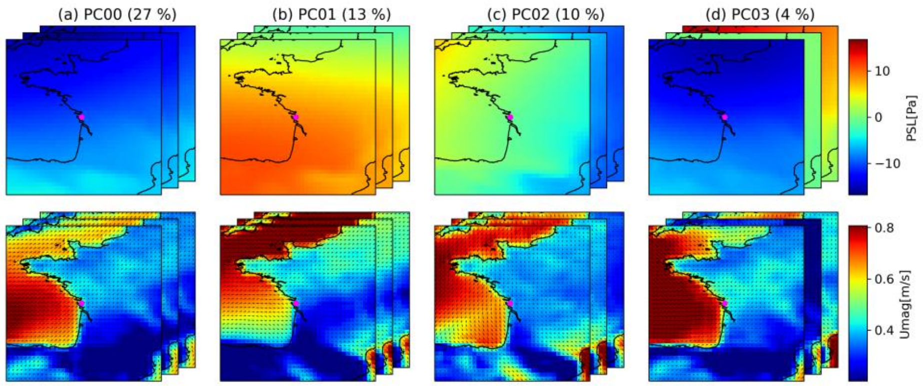
Statistical downscaling model (SDM)

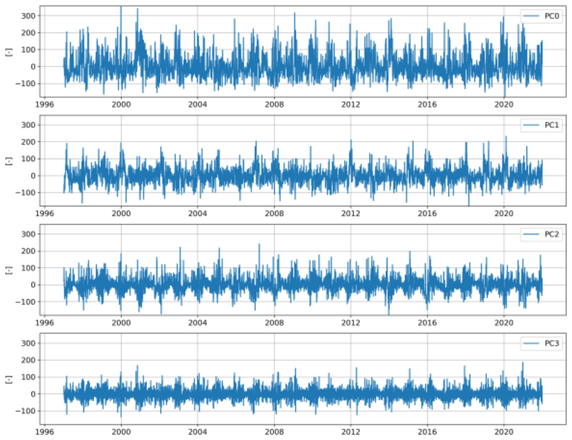
- Multi-linear regression (MLR) between atmospheric predictors (PSL,U10,V10) and *simulated* storm surges (predictand)
- Trained on contemporary SS conditions: DDM hindcast using ERA5
- Degradation of ERA5 fields to 1 degree to match CMIP6 typical resolutions
- Dimensionality reduction of predictors via PCA within RoI around target CP

EOFs (ERA5)



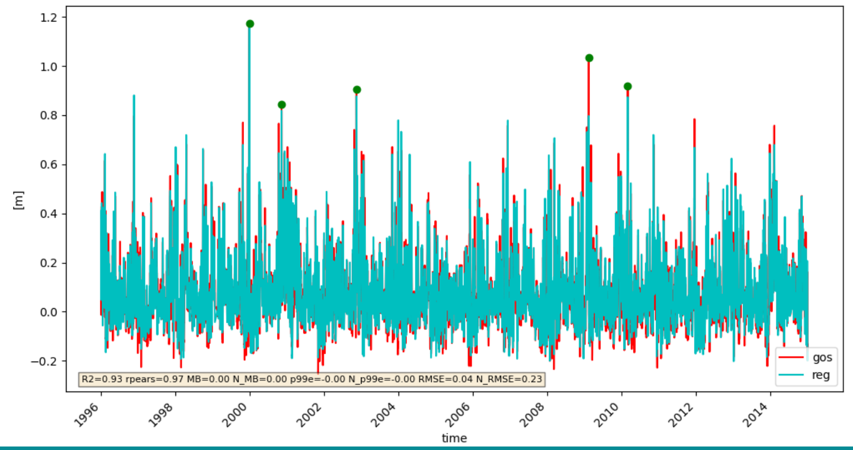
Example for La Rochelle, FR

PCs

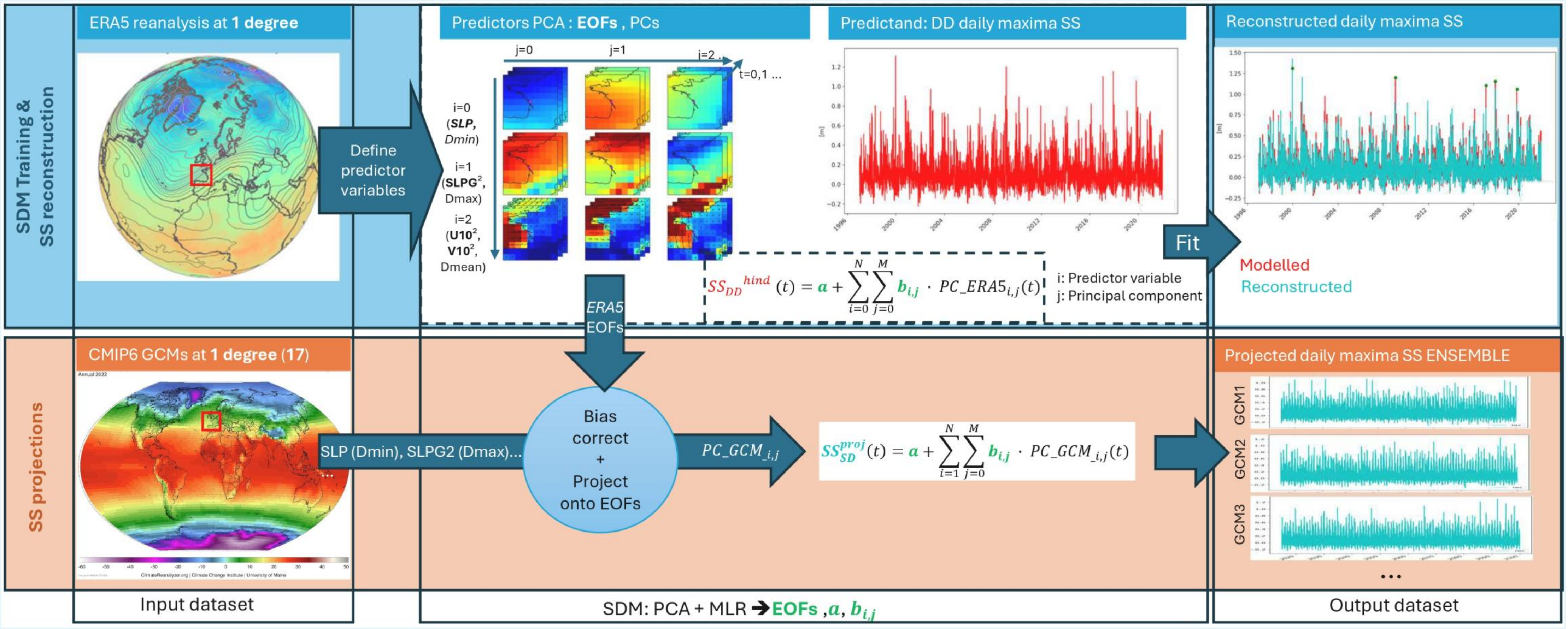


Daily max SS reconstruction

Modelled *Reconstructed*



Wokflow for statistical storm surge projections



Calibrated SDM configuration

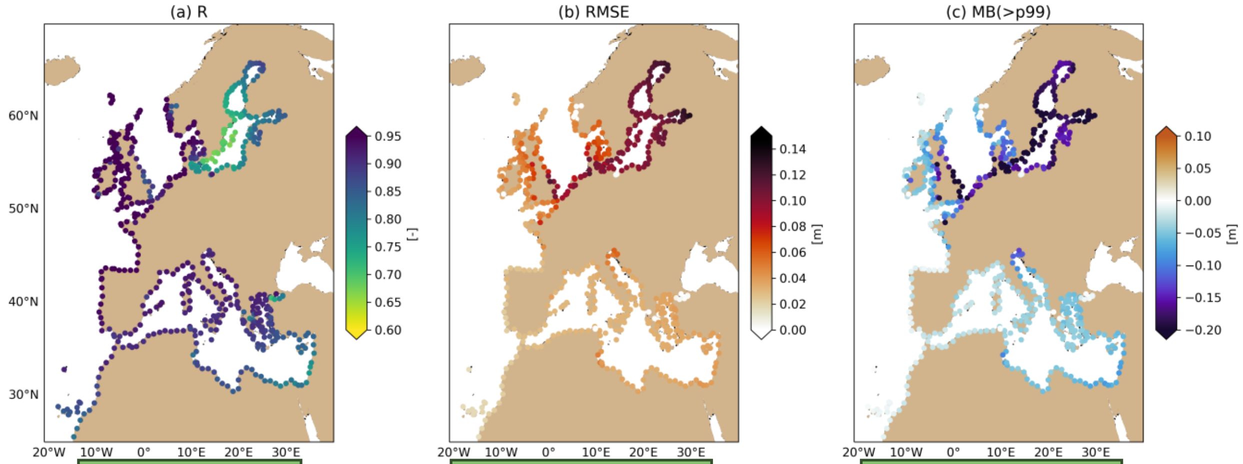
- Calibration (K-fold): set of predictors, region size, time-lags

Predictor variables	Bounding-box size (degrees)	Time-lag (days)
SLP–$D_{\min}$ (T1)	3 × 3 (D3)	0 (L0)
SLP–$D_{\min}$; SLPG–$D_{\max}$ (T2)	6 × 6 (D6)	1 (L1)
SLP–$D_{\min}$; SLPG–$D_{\max}$; U10–D_{mean}, V10–D_{mean} (T3)	9 × 9 (D9)	2 (L2)
SLP–$D_{\min}$; SLPG–$D_{\max}$; U10–$D_{\max}$, V10–$D_{\max}$ (T4)	12 × 12 (D12)	
SLP–$D_{\min}$; SLPG–$D_{\max}$; $U10^2$–D_{mean}, $V10^2$–D_{mean} (T5)		
SLP–$D_{\min}$; SLPG–$D_{\max}$; $U10^2$–$D_{\max}$, $V10^2$–$D_{\max}$ (T6)		
SLP–$D_{\min}$; SLPG–$D_{\max}$; $U10^2$–5h-mean, $V10^2$–5h-mean (T7)		

- Best configuration:
  - PSL (Dmin), $PSLG^2$ (Dmax), $U10^2$ and $V10^2$(Dmean)
  - 9x9 degree RoI
  - 2-day lag

Calibrated SDM configuration

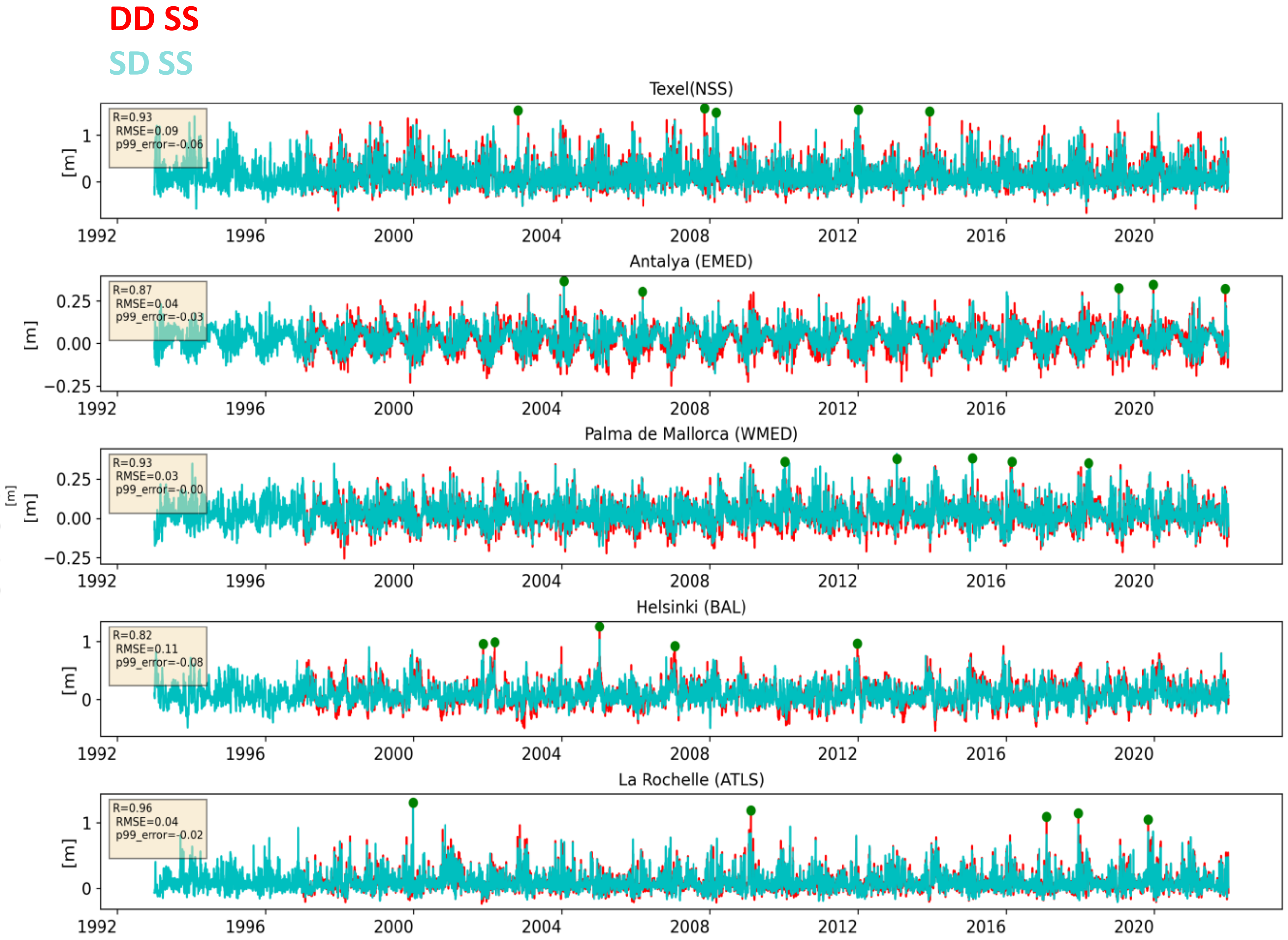
- Worst for Baltic, eastern Mediterranean
- Tendency to underpredict extremes



Mean 0,89

Mean 0,06m

Mean 0,08m

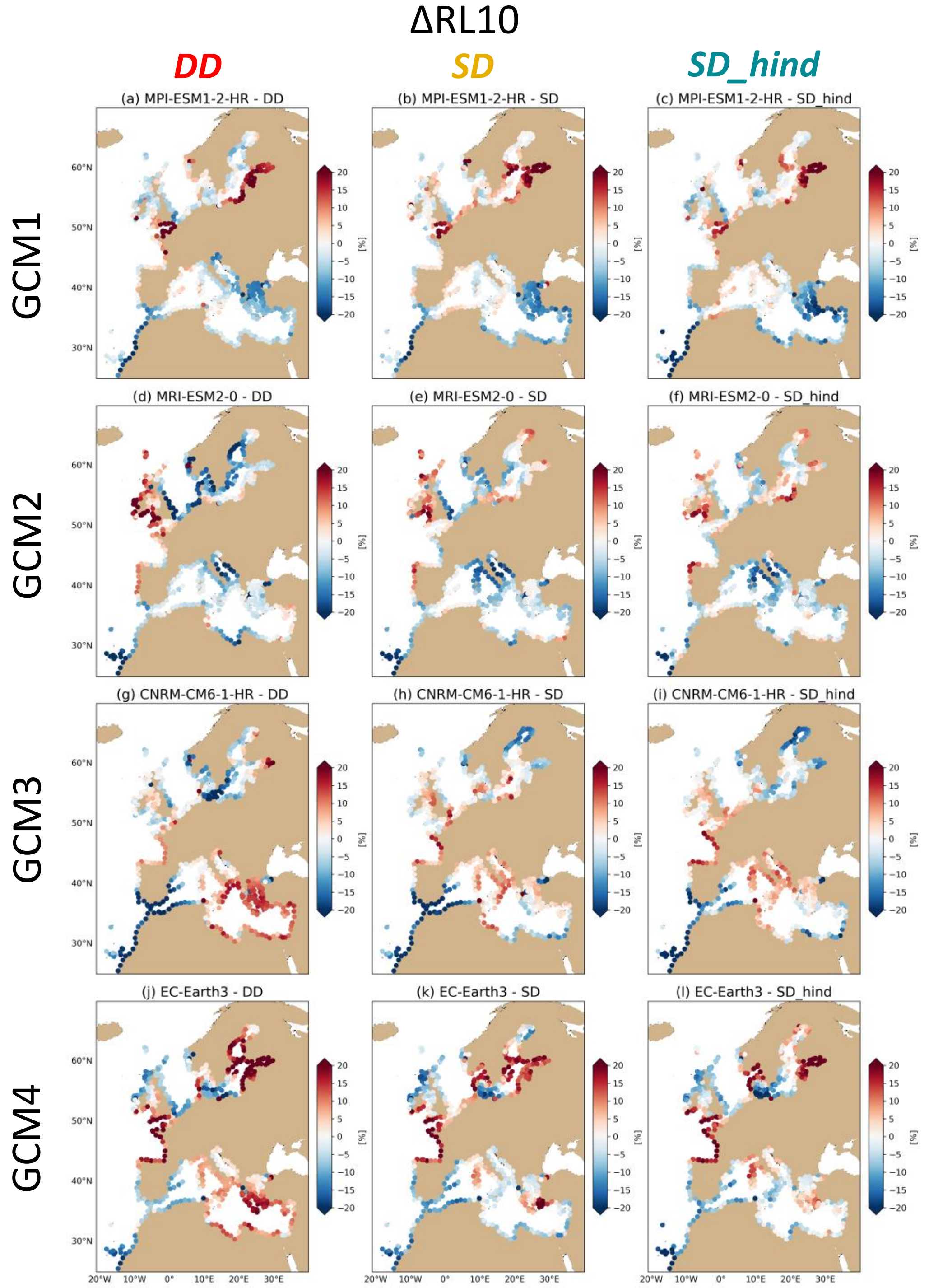


SDM validation for climate projections: CC signal

Can the hindcast-trained SDM reproduce the CC signal in dynamical simulations?

➔Comparison to DD projections for 4GCMs, SSP5-8.5

- CC signal: RL10 changes [1985-2014] vs [2070-2099]
- Stationary-on-slice EVA (POT+GPD)
- 3 estimates:
  - ***DD*** : DDM projections
  - ***SD*** : SDM projections trained on GCM-forced historical simulation
  - ***SD_hind***: SDM projections trained on ERA5-forced hindcast



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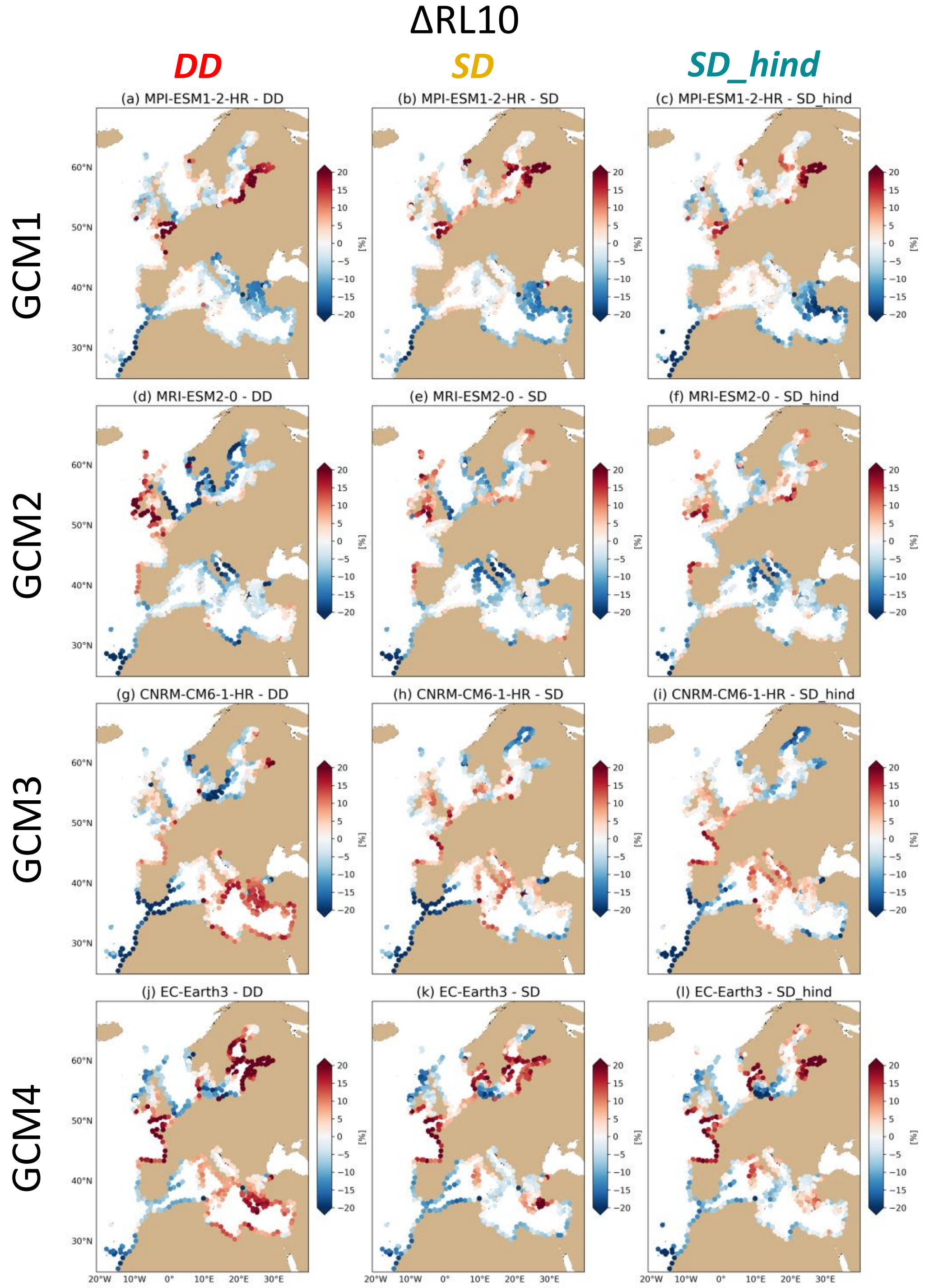
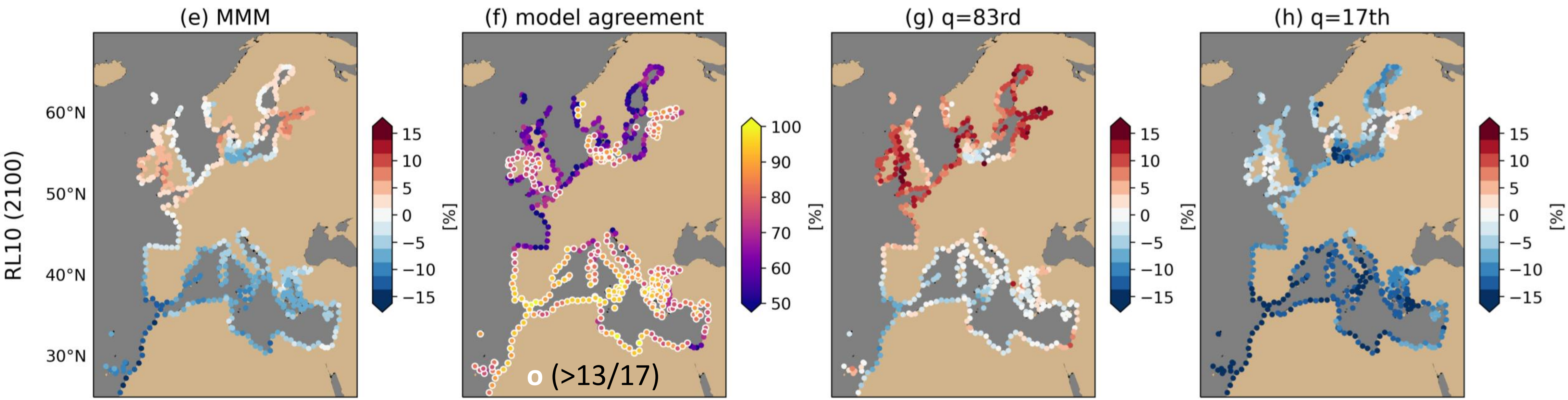
- SD tend to slightly underestimate DD ΔRL10
- Spatial features and GCM-specific responses well reproduced by SDM
- Exceptions: BAL, EMED
- SD and SD_hind very similar➔ **extrapolability of hindcast-trained SDM to climate forcings**



Statistical storm surge projections (x17 GCMs)

Relative ΔRL10 by 2100, SSP5-8.5, EVA on 30-yr slices



- Mediterranean Sea (–7%) Moroccan Atlantic coast (–10%) Danish Straits (–6%)
- +6% for the Celtic and Irish Seas, western Denmark, and the Gulf of Finland
- Large inter-model spread!
- Low confidence in southern North Sea and northern Baltic Sea

Conclusions and perspectives

Conclusions

- The SDM showed satisfactory skill in emulating dynamically downscaled ESS change projections at a fraction of the cost
- Based on extended CMIP6 ensemble sizes (x17), statistical projections reveal regions of robust changes across Europe, but inter-model spread remains large (caution for small ensembles!)

Future works:

- Significance of projected ESSs changes relative to internal variability
    - SD pre-industrial control simulations (high-frequency forcing?)
    - Non-stationary EVA with covariates for climate indexes

    ➔isolate forced trends, reduce inter-model spread?
- GCM weighting
    - Representativity of circulation patterns (e.g., weather types approach Perez et al. 2014, or variance explained)
    - historical ESS performance (regional/per CP)
- Evaluating drivers of projected ESS changes (e.g., atmospheric predictor/principal component)

Thank you

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Géosciences pour une Terre durable brgm

Aristotle University of Thessaloniki

UEA University of East Anglia

Mercator Ocean International

Sayers and Partners

IH cantabria Instituto de Hidráulica Ambiental

Guerilla Creative Think · Create · Do

Deltares Enabling Delta Life

CAU

VU Vrije Universiteit Amsterdam

cnrs

federlogistica

ICLEI Local Governments for Sustainability

ENEA

vizzuality.

Global Climate Forum

LGi sustainable innovation

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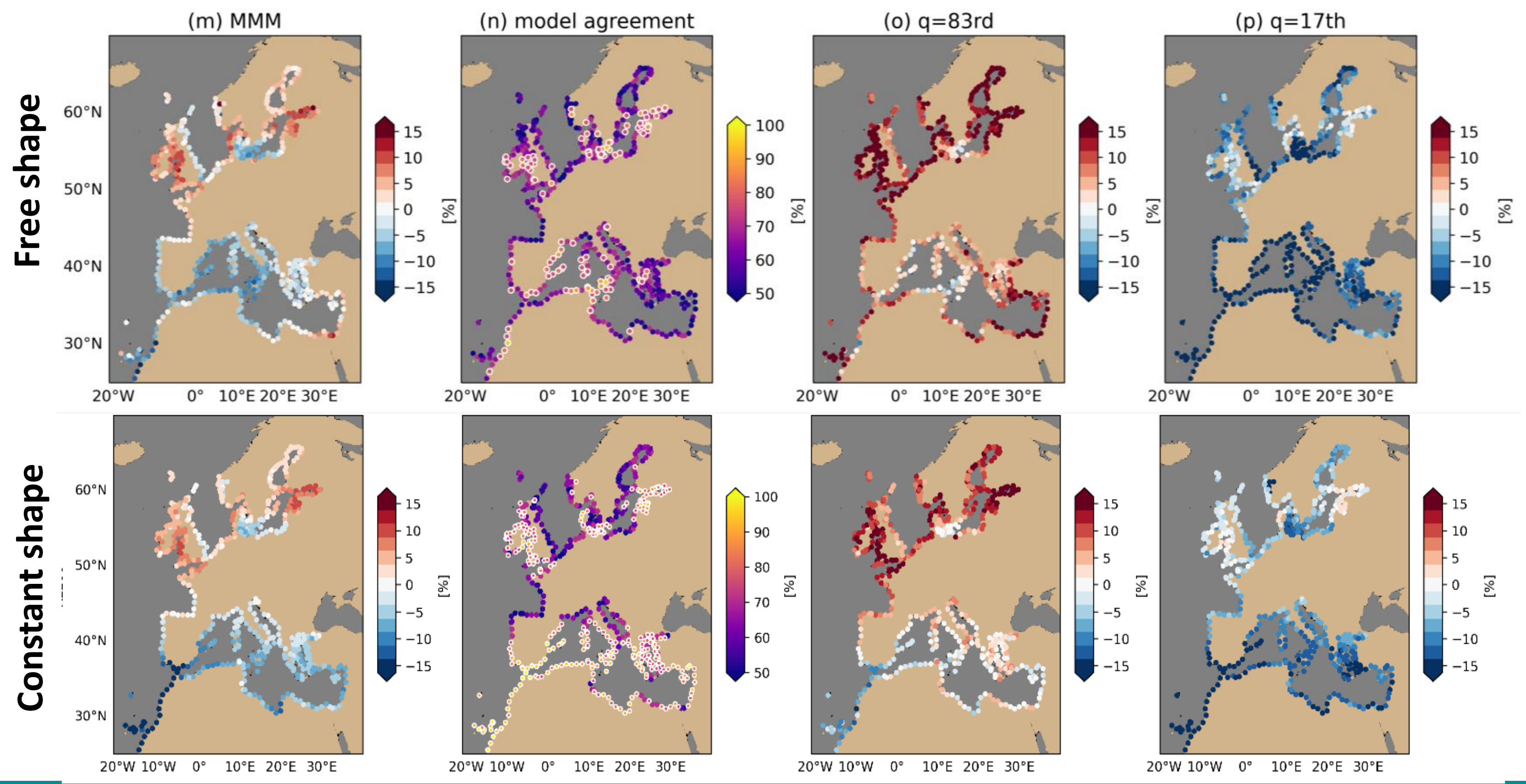
Statistical storm surge projections (x17 GCMs)

- RL100: larger inter-model spread, lower robustness in sign of CC
- Impact of EVA shape parameter constant vs free
- No standardized practice in projections…?

Relative ΔRL100, SSP5-8.5 by 2100 , EVA on 30-yr slices



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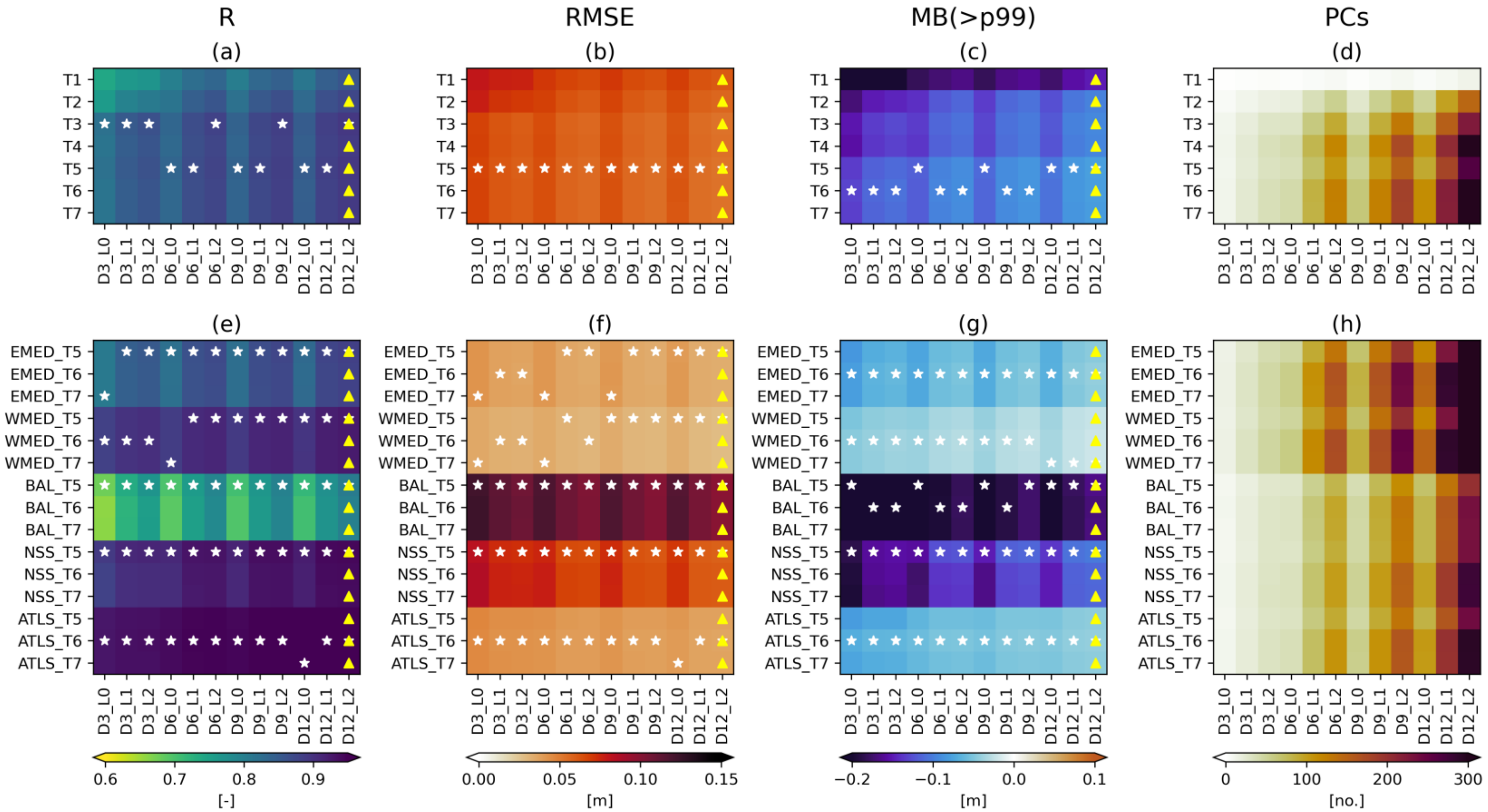
SDM calibration



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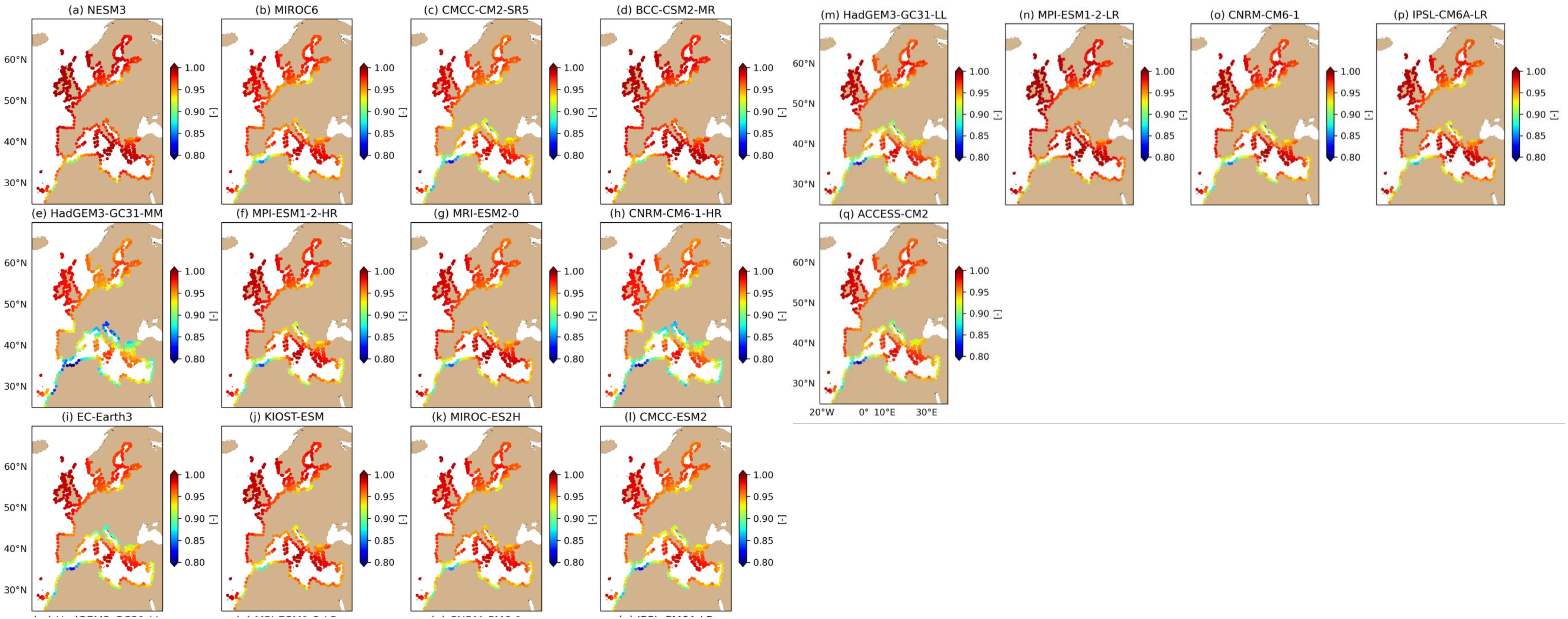
Variance retained in GCMs (historical)



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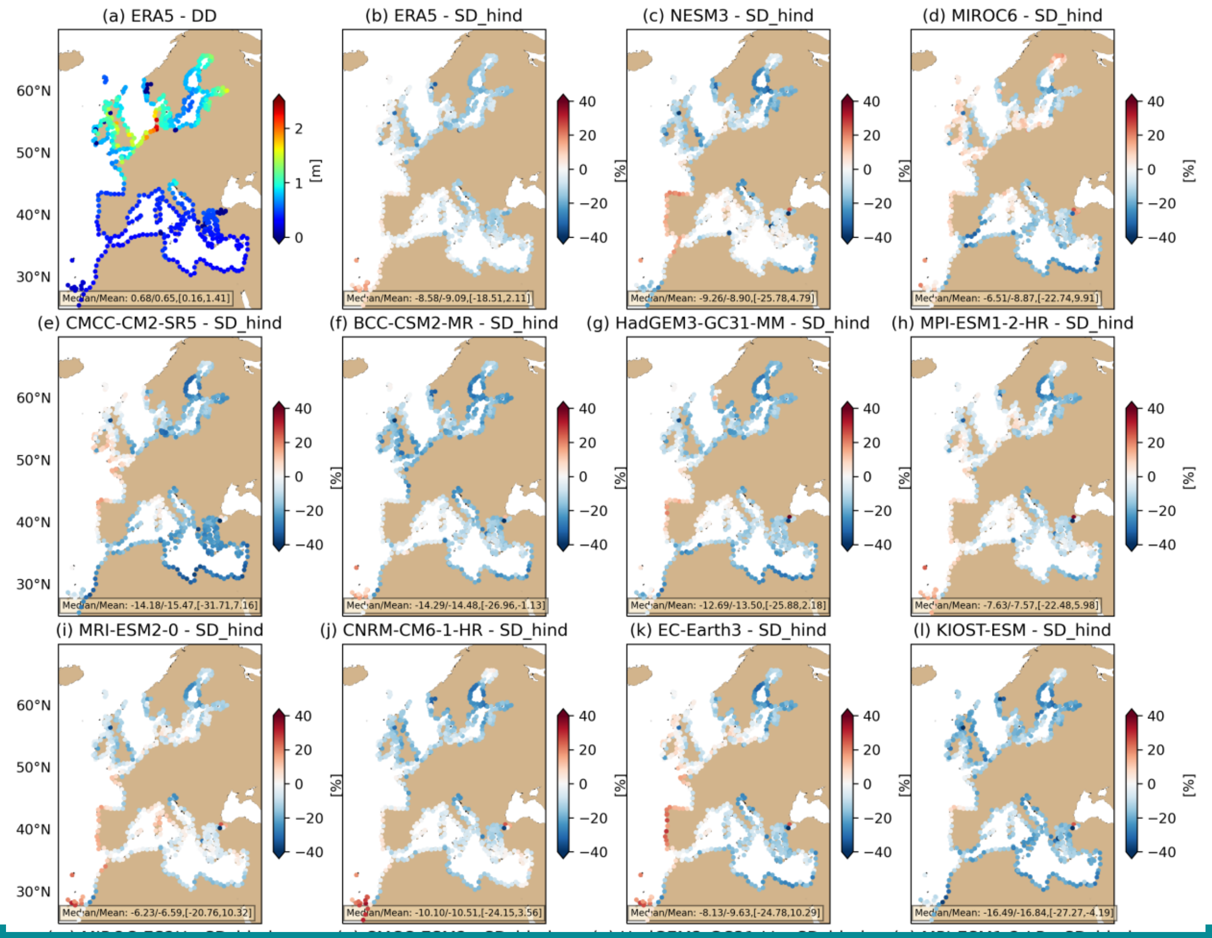
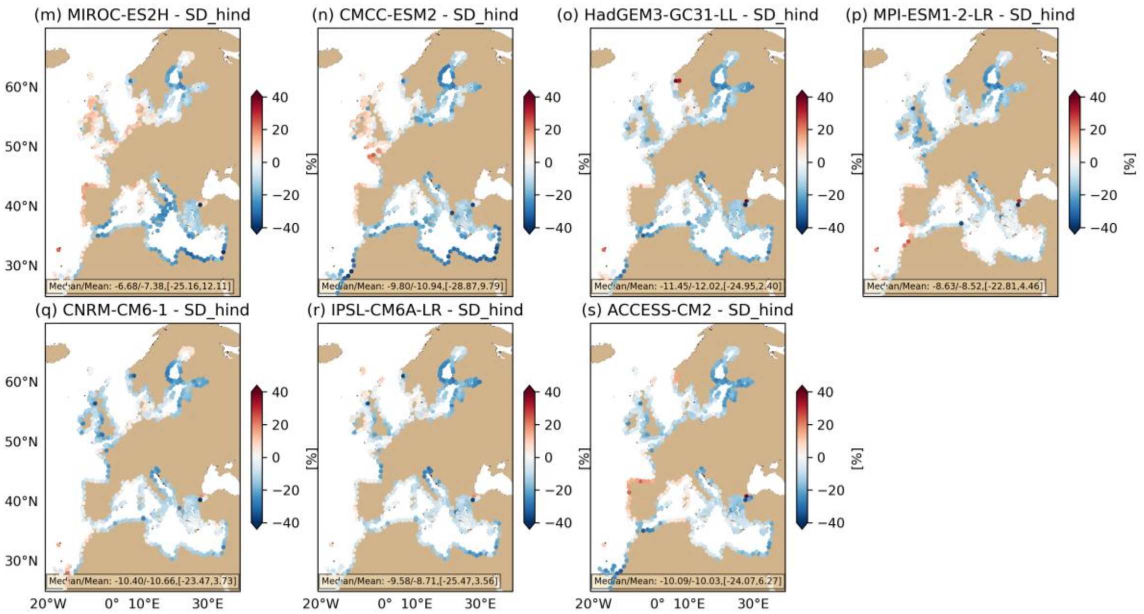
Historical RL10 error in GCMs





RL10 projections each GCM - 2100