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Presentation for the EGU 2026

Evaluating multiscale performance of the TETIS distributed hydrological model using satellite and in situ observations in the Tugela basin

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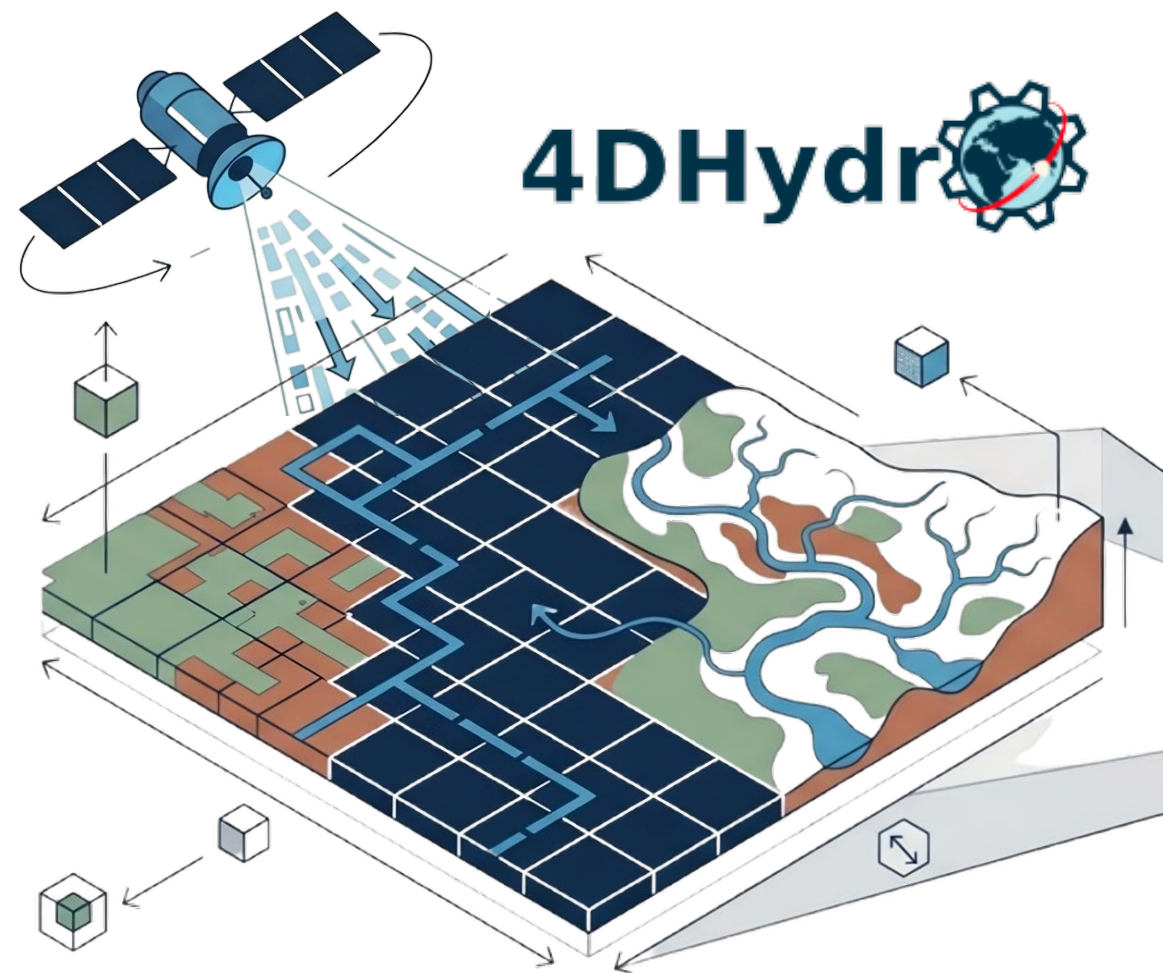


Introduction

- Rapid growth of satellite-based hydrological observations
- Increasing use of hyper-resolution hydrological modelling
- Improvements in the use of Earth Observation (EO) data for model calibration
- Hydrological processes and model performance are **scale-dependent**

Research Objective

Quantify the sensitivity of distributed hydrological simulations to spatial resolution by performing a multiscale evaluation of evapotranspiration (ET), surface soil moisture (SSM), and discharge (D) using satellite and in situ observations.



Tetis V9.1 Ecohydrological model

- Spatially distributed conceptual model
- Regular grid cells and finite-difference schemes
- Seven interconnected tanks represent the various processes occurring within the soil and subsoil.



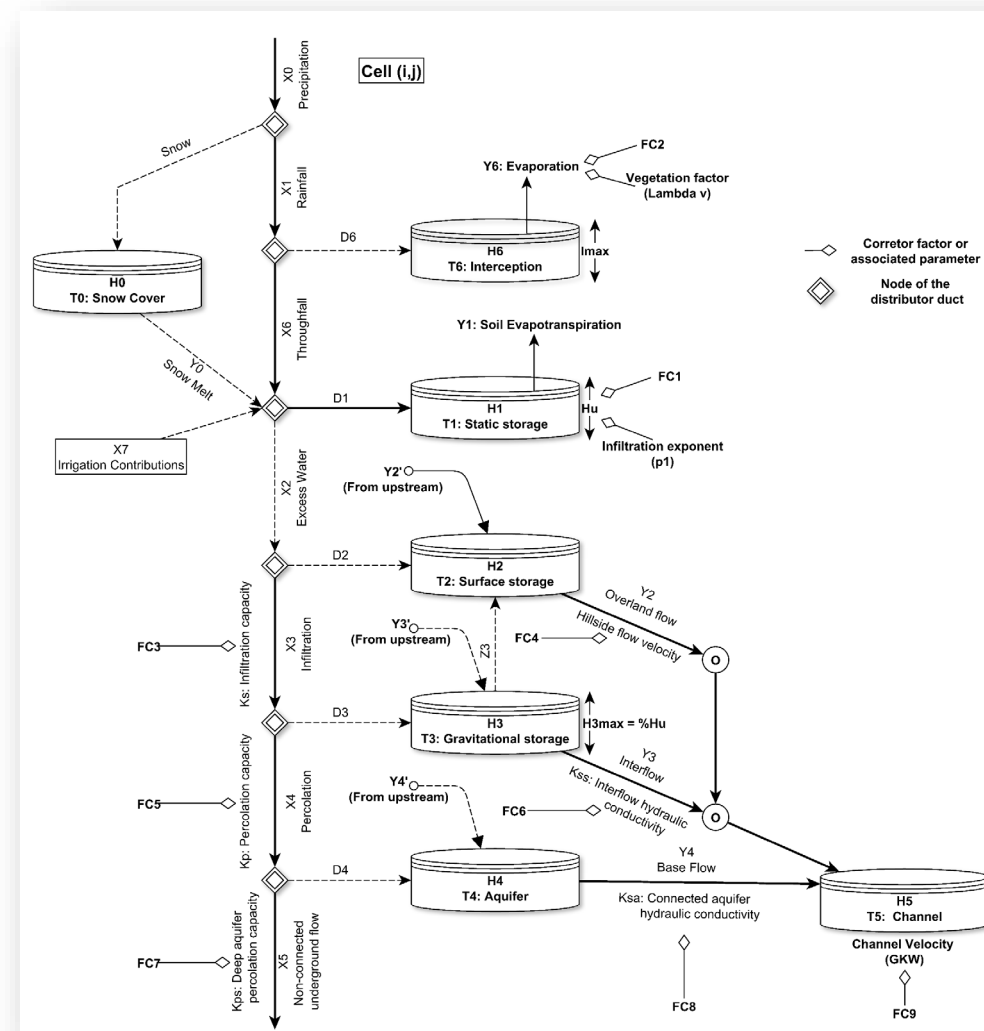
➤ D = Discharge



➤ ET = Evapotranspiration



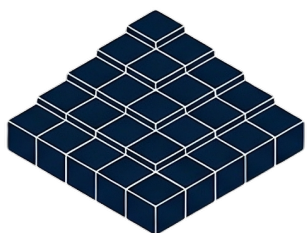
➤ SSM = Surface Soil Moisture



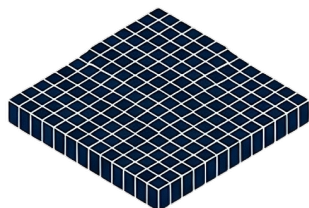
Study area

➤ Tugela River Basin (South Africa) – 28,000 km²

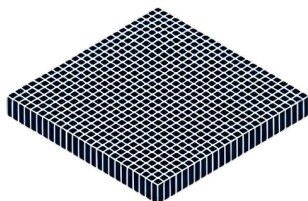
➤ Simulations spatial scales



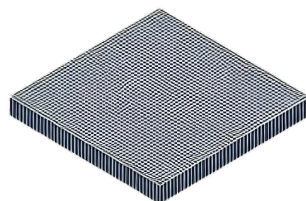
5km



1km



500m

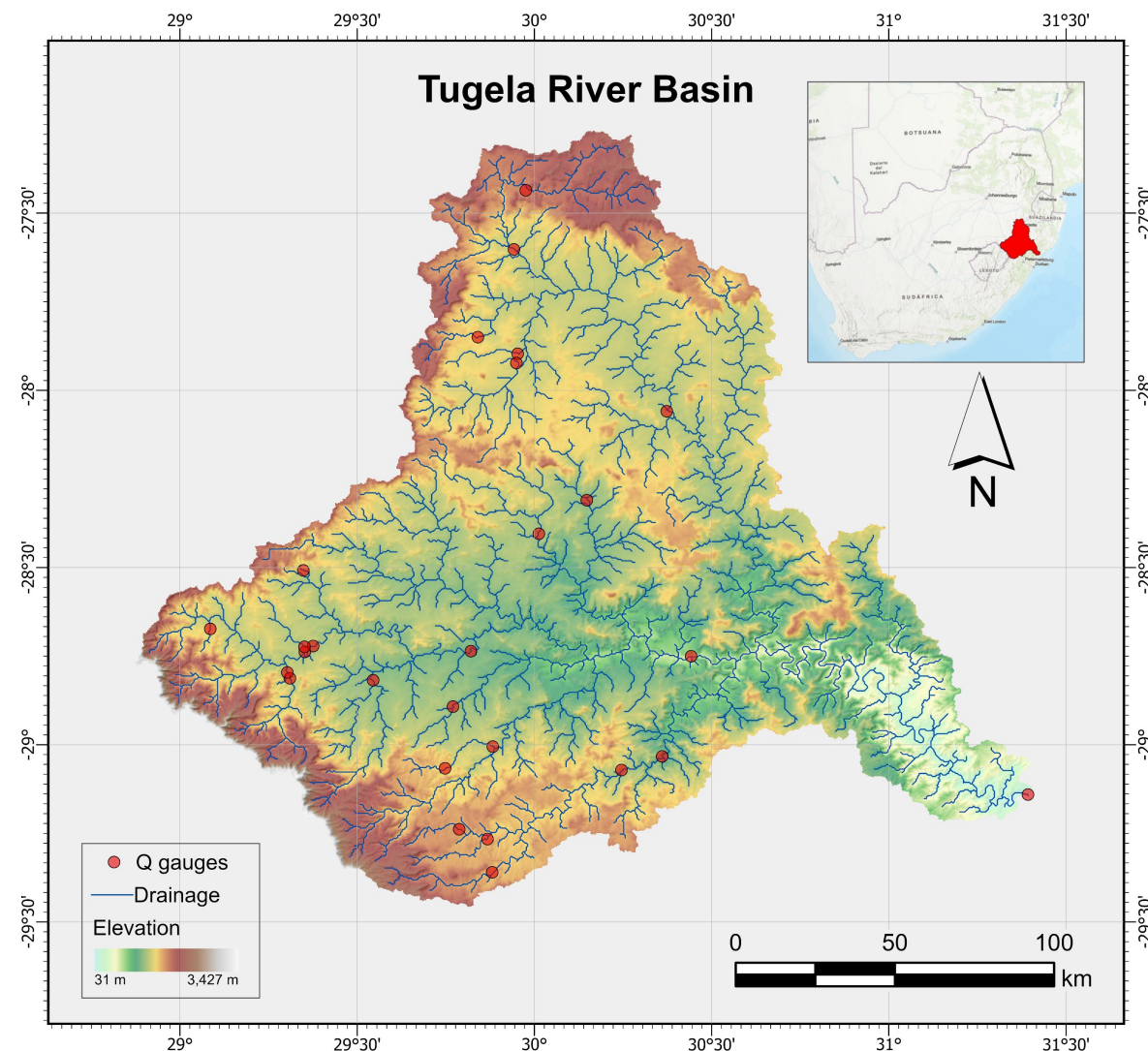


250m

➤ 27 In situ Discharge gauges

➤ Daily temporal resolution

➤ EO: P – CHIRPS & ERA5-IMERG-SM2A
ET – MODIS Terra
SSM – NSIDC SMAP



Experiment configurations

BASELINE EXPERIMENTS

exp10 Default parameters

exp21 Exp20 parameters

exp30 Default parameters

MONO-OBJECTIVE CALIBRATION

exp20 Q at 5km

exp31 SSM at 1km

exp32 ET at 1km

exp40 Q at 1km

MULTI-OBJECTIVE CALIBRATION

exp34 SSM+ET at 1km

exp41 SSM+Q at 1km

exp42 ET+Q at 1km

exp44 SSM+ET+Q at 1km

➤ Forcings and total period

CHIRPS

1988 - 2022

ERA5-IMERG-SM2A

2007 - 2022

➤ Objective functions



KGE

(Kling-Gupta Efficiency)



SPAEF

(Spatial Efficiency Metric)

* Calibration period for 5km (2005-2011)

** Calibration period for 1km (2019-2021)

Evaluation Framework

Discharge performance Hydrological response

KGE Discharge (Q)

- ✓ Correlation
- ✓ Variability ratio
- ✓ Bias

Evaluate temporal
hydrological performance

Spatial agreement Spatial patterns

SPAEF Et and SSM

- ✓ Spatial pattern similarity

Error Et and SSM

- ✓ Median analysis
- ✓ Absolute and relative error

Assess spatial agreement
with EO products.

Spatial scaling analysis

Multiscale Spatial structure changes

CDF analysis Et and SSM

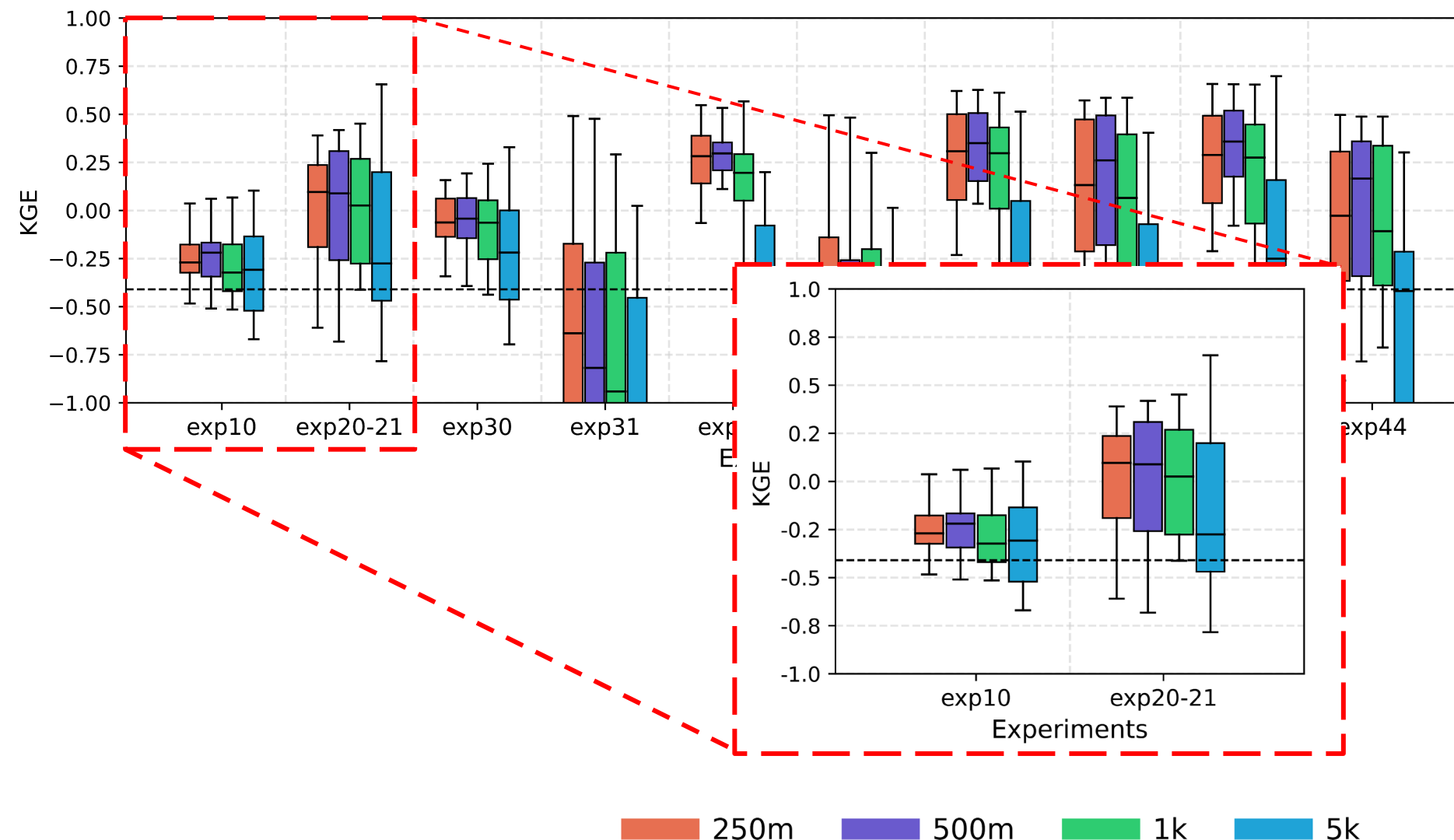
- ✓ Kolmogorov-Smirnov distance
- ✓ Scale breakpoint detection

Spatial Variogram Et and SSM

- ✓ Log-log scaling exponent (α)
- ✓ Spectral exponent
- ✓ Hurst exponent (H)
- ✓ Fractal dimension (D)
- ✓ Two-factor ANOVA test

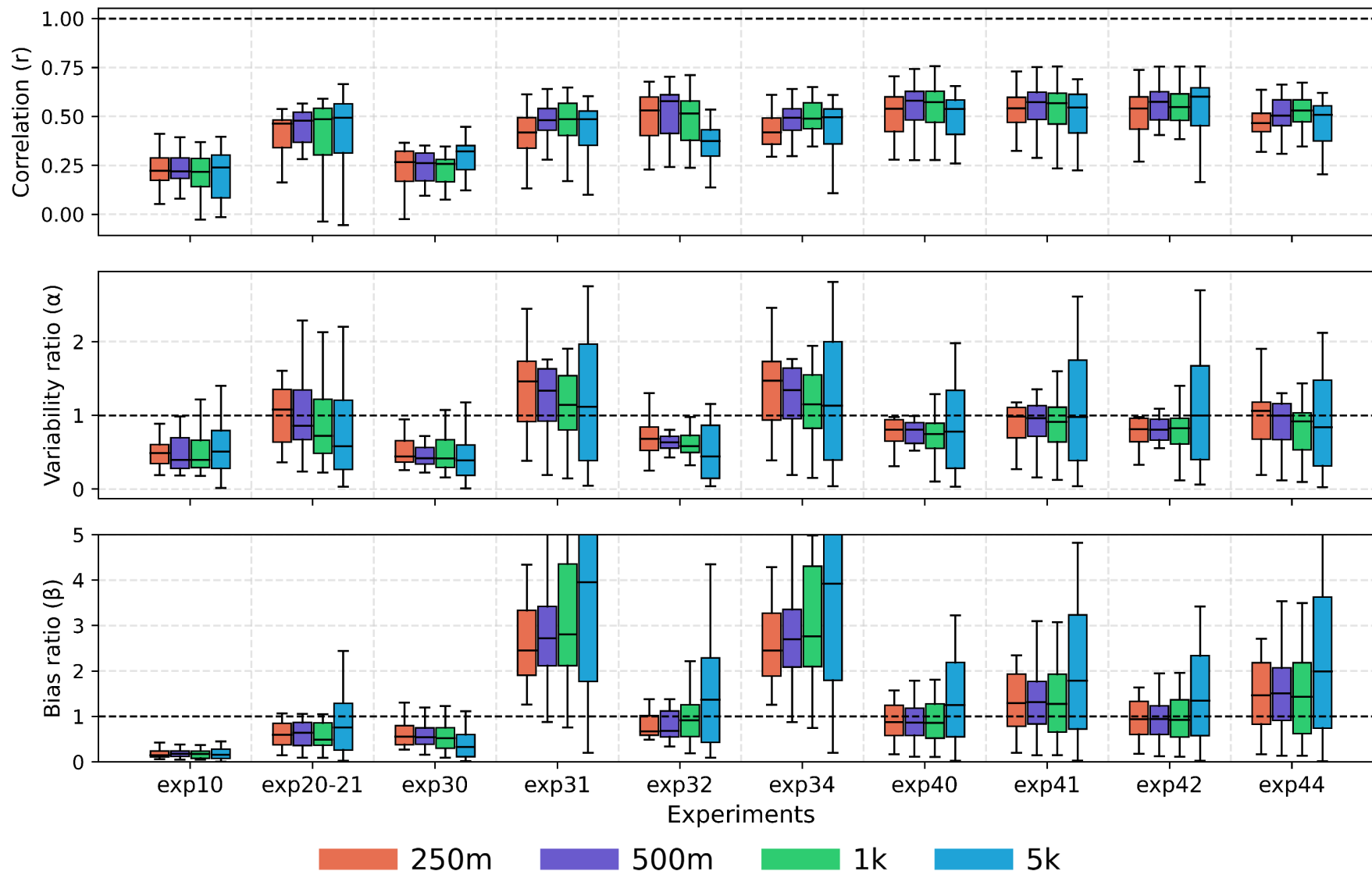
Characterize spatial structure and
scaling behavior

Results discharge (Q)



- KGE decreases with coarser resolution
- Coarse calibration still provide acceptable validations

Results discharge (Q)



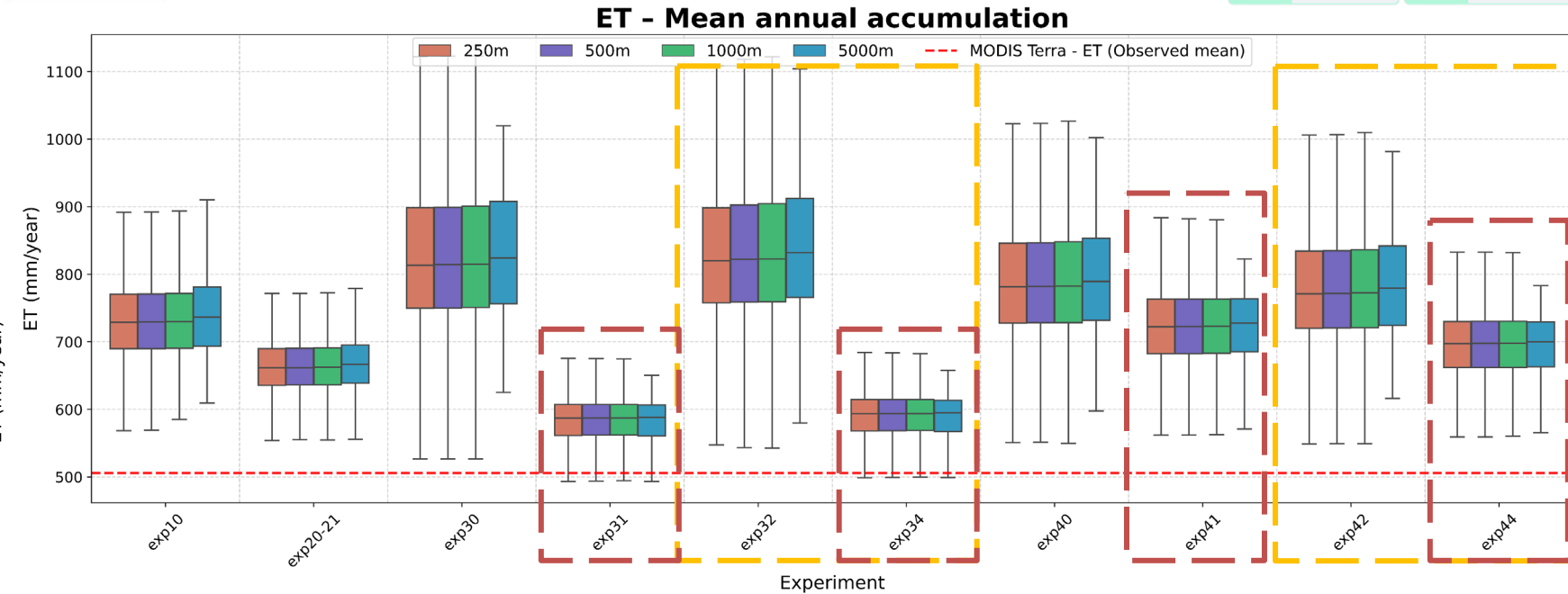
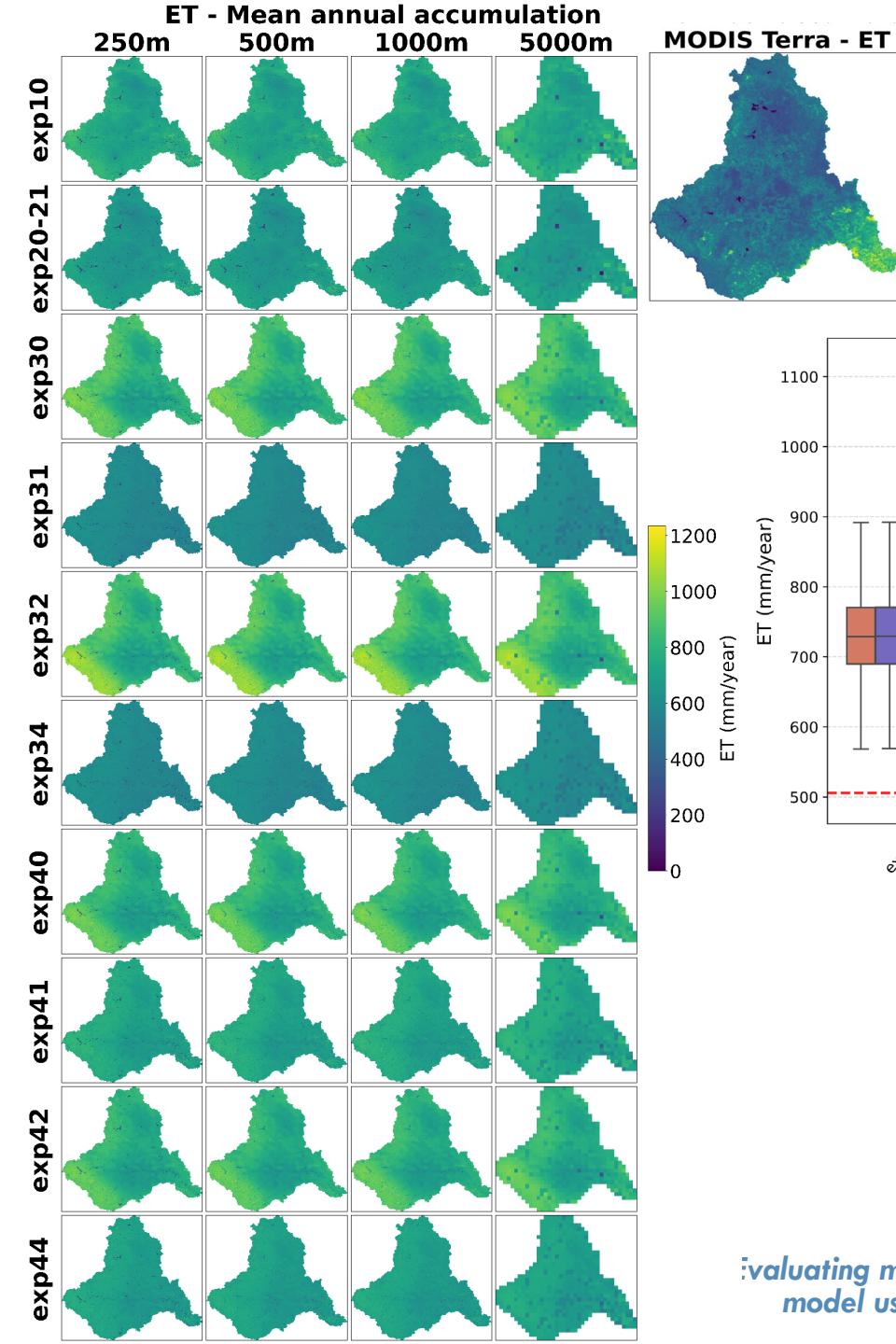
➤ Correlation improves after calibrated

➤ Variability ratio often overestimated at fine scales

➤ Bias ratio increases and dispersion grows at coarse scales



Results Evapotranspiration (ET)



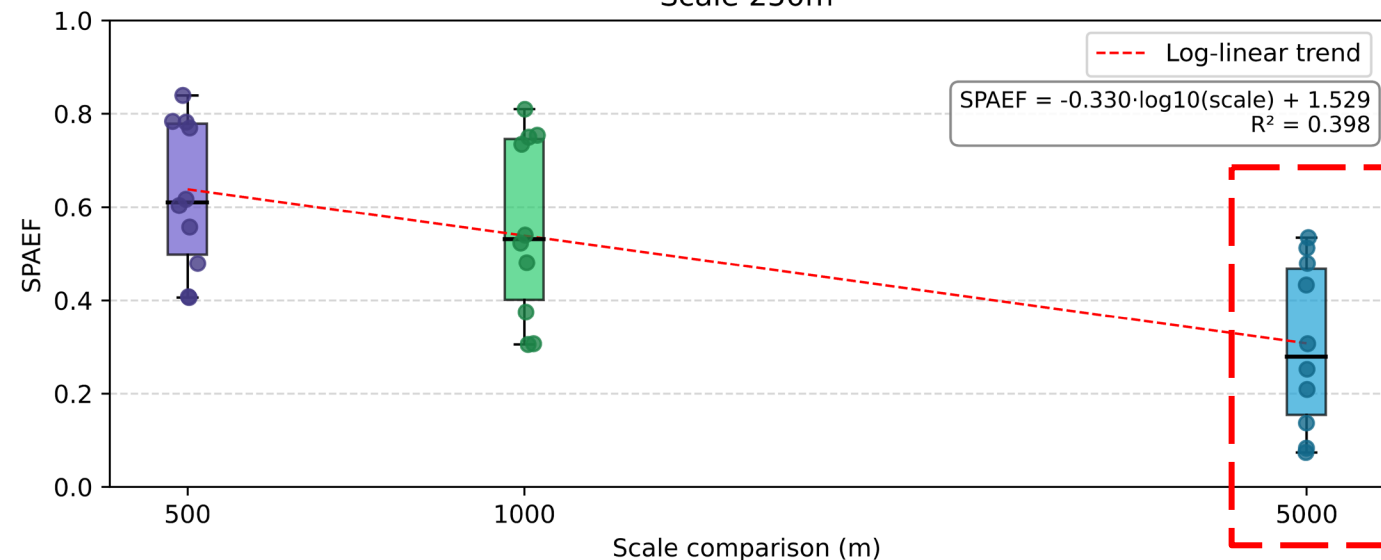
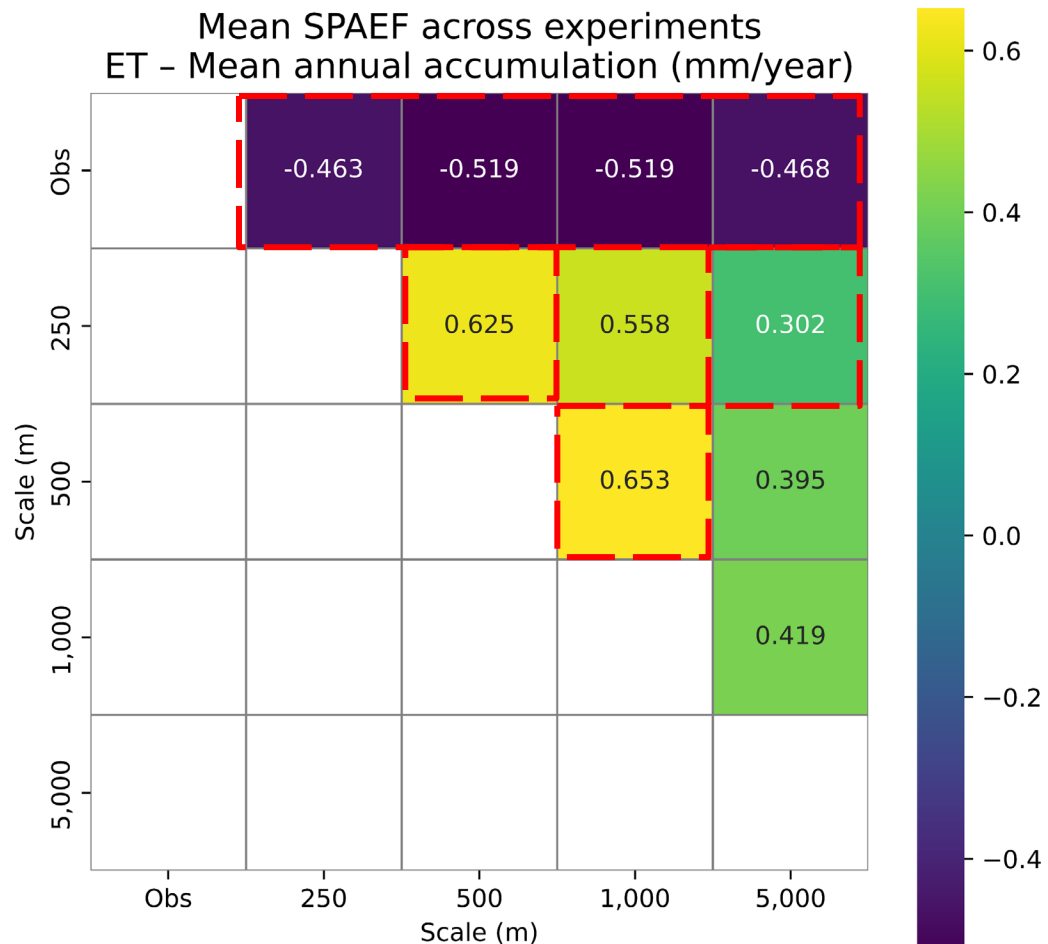
- Simulated ET tends to exceed MODIS estimates
- Coarser grids increase ET
- ET calibration has limited impact
- SSM calibration improves ET agreement

Results Evapotranspiration (ET)

SPAEF distribution across scale comparisons

ET | Mean annual accumulation (mm/year)

Scale 250m

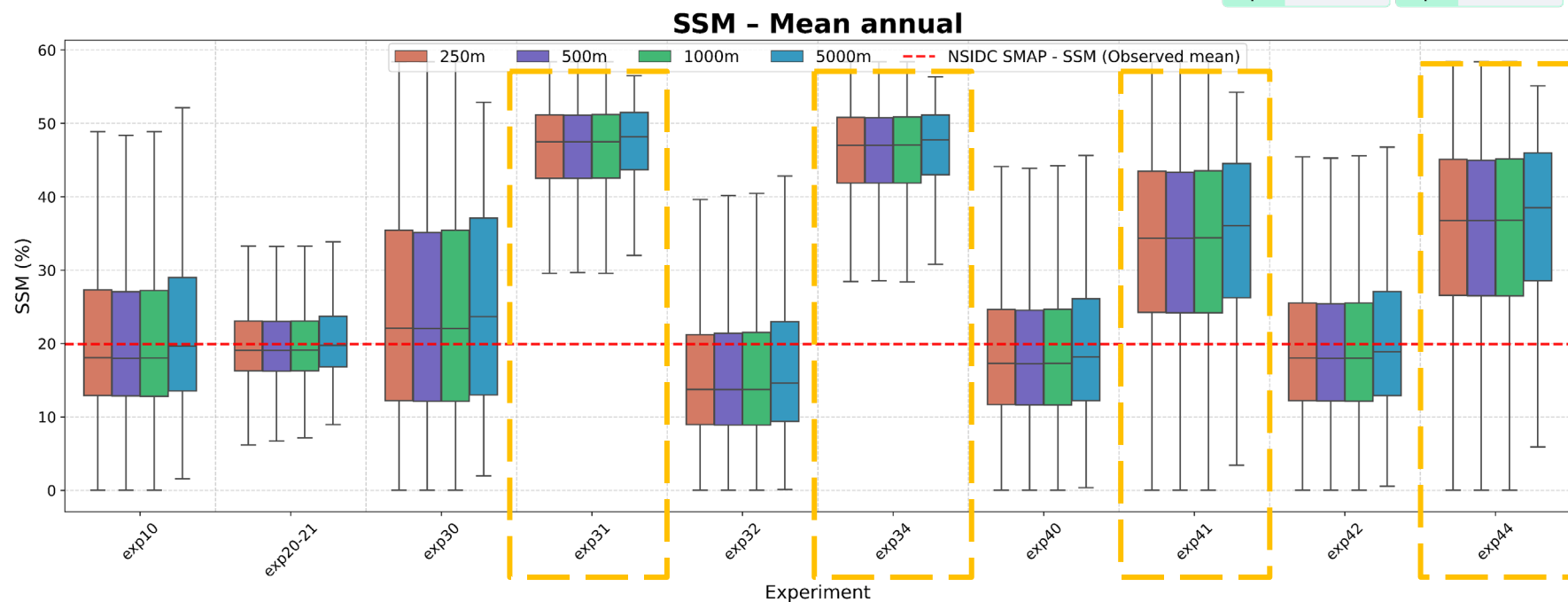
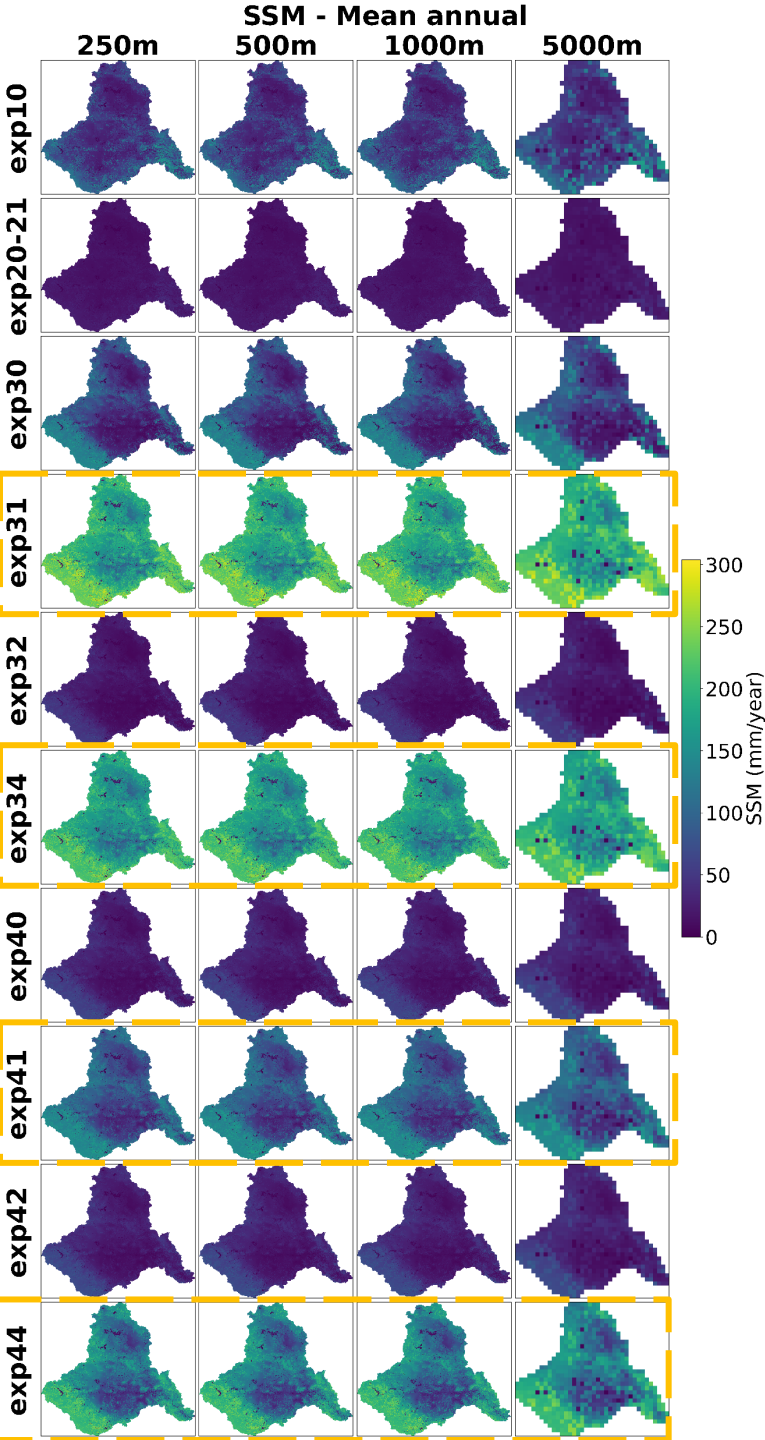


- SPAEF < 0 → strong mismatch with MODIS
- High consistency between neighboring scales
- SPAEF decreases with scale difference
- Strongest degradation: 250 m vs 5 km



Results Surface Soil Moisture (SSM)

exp10	Default parameters	exp30	Default parameters	exp40	Q at 1km
exp20	Q at 5km	exp31	SSM at 1km	exp41	SSM+Q at 1km
exp21	Exp20 parameters	exp32	ET at 1km	exp42	ET+Q at 1km
		exp34	SSM+ET at 1km	exp44	SSM+ET+Q at 1km

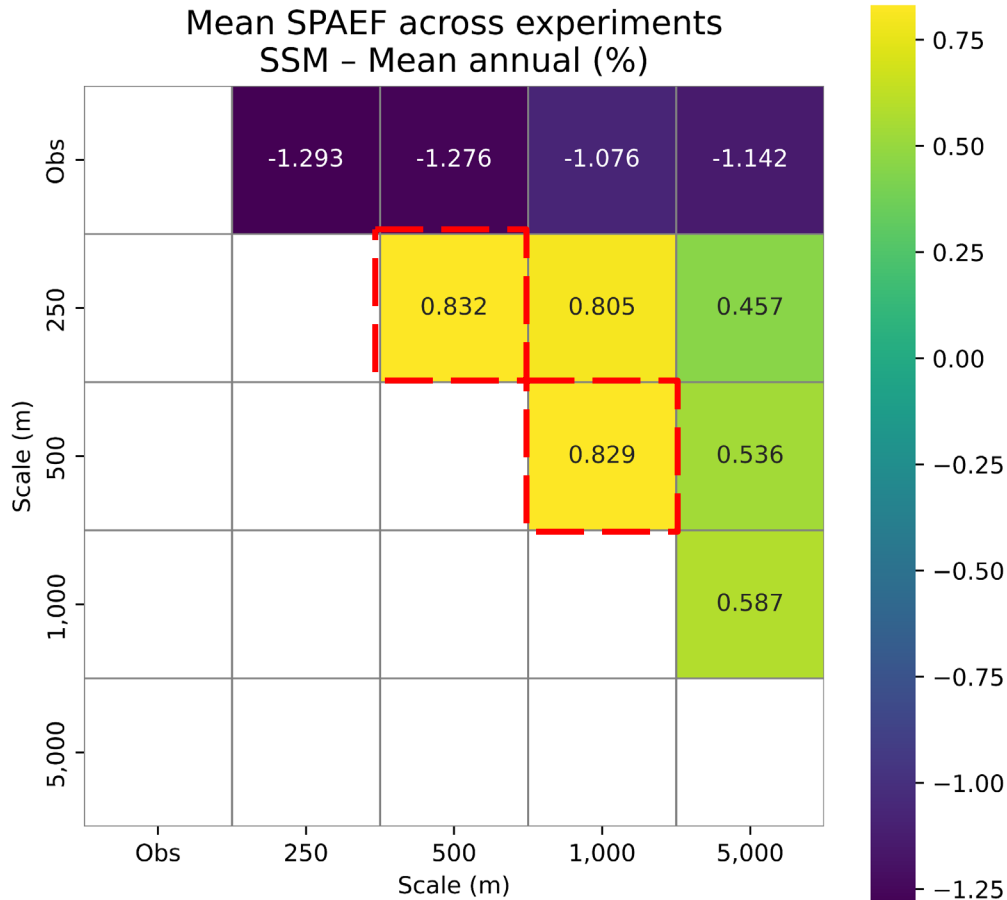


- Coarser resolution increases SSM
- SSM calibration leads to higher SM states
- Strong sensitivity to calibration

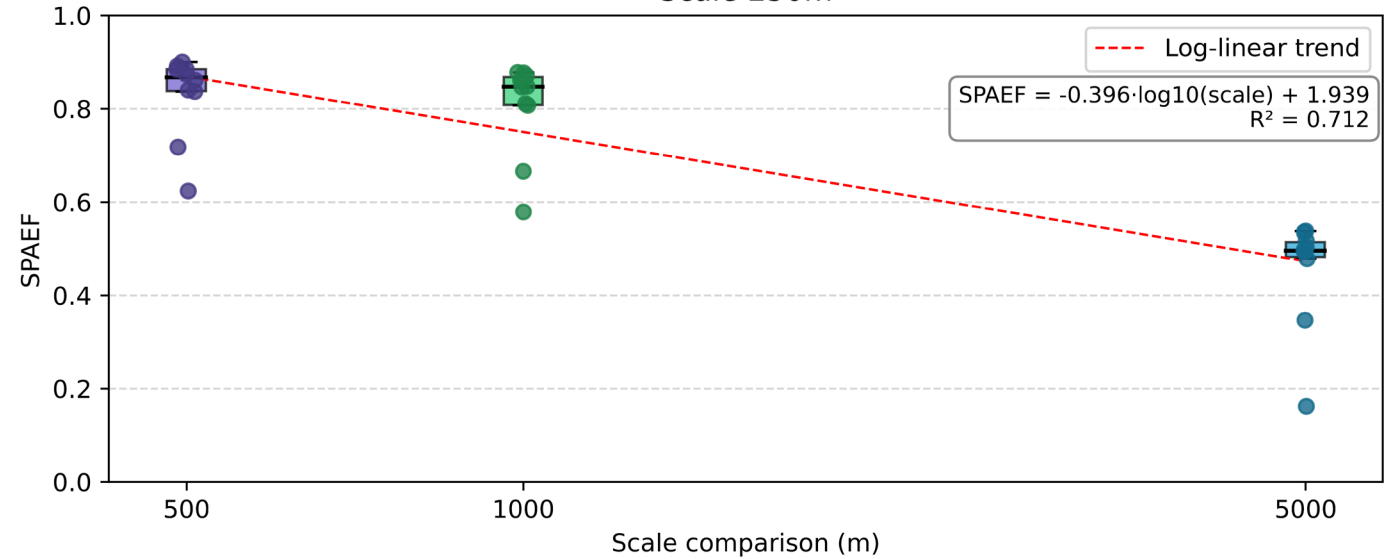
Results Surface Soil Moisture (SSM)



Mean SPAEF across experiments
SSM - Mean annual (%)

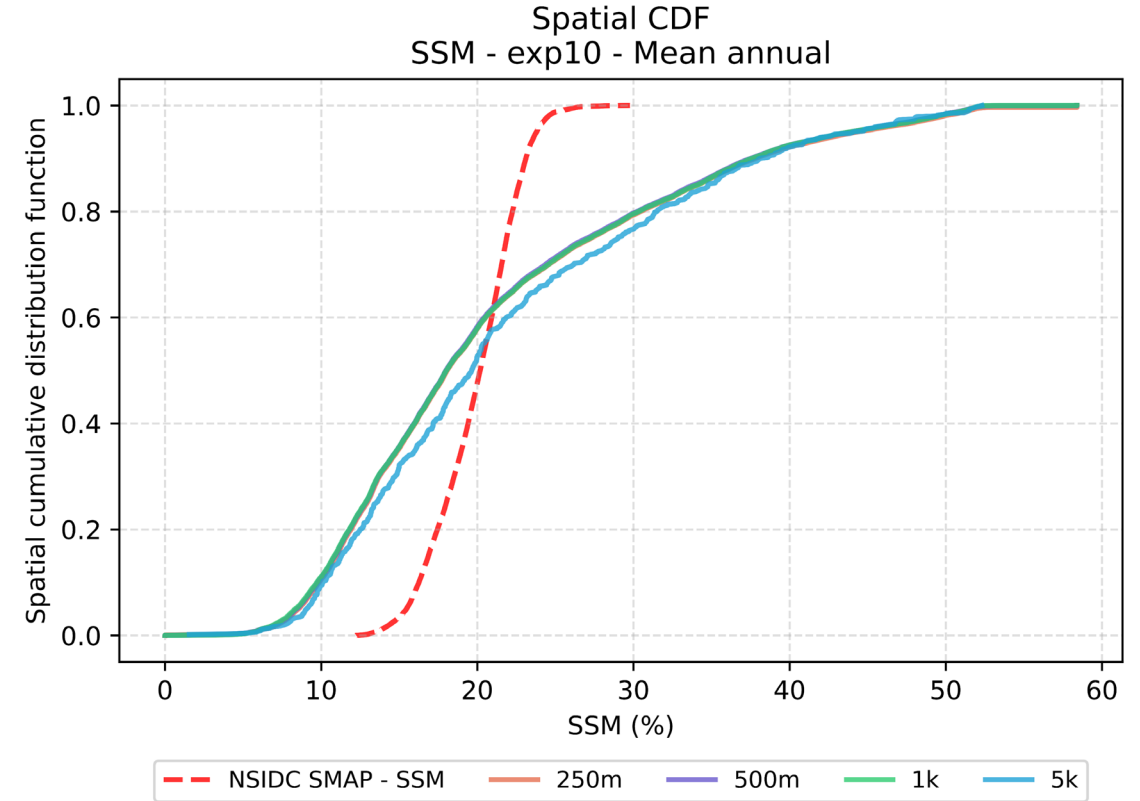
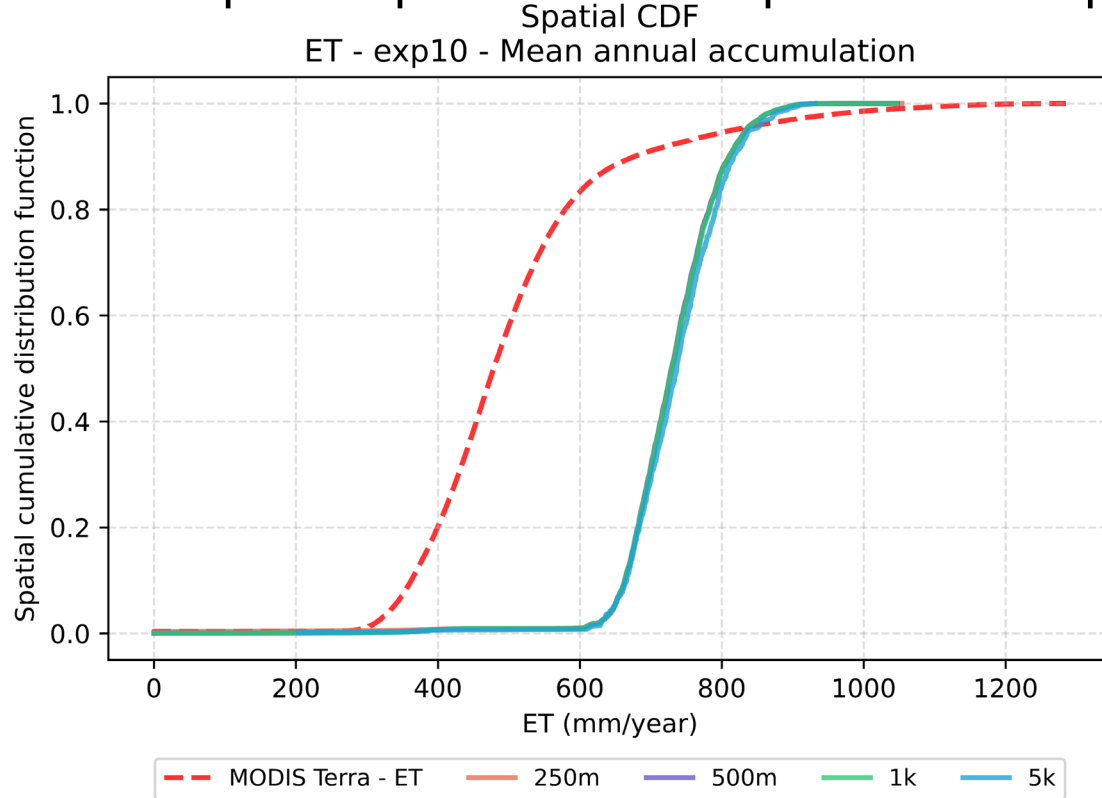


SPAEF distribution across scale comparisons
SSM | Mean annual (%)
Scale 250m



- Similar behavior to ET
- SPAEF decreases with scale difference
- High agreement between neighboring scales
- Strongest degradation: 250 m vs 5 km

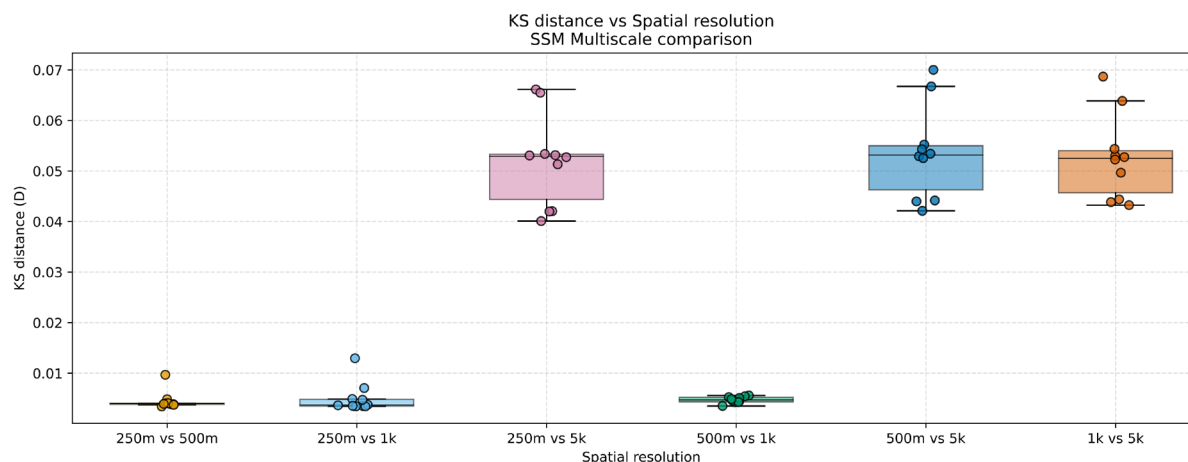
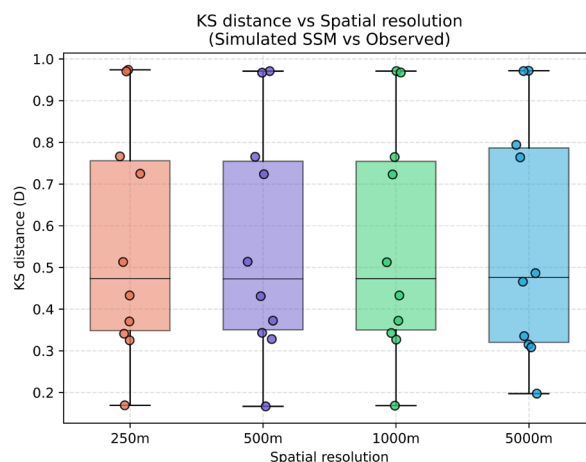
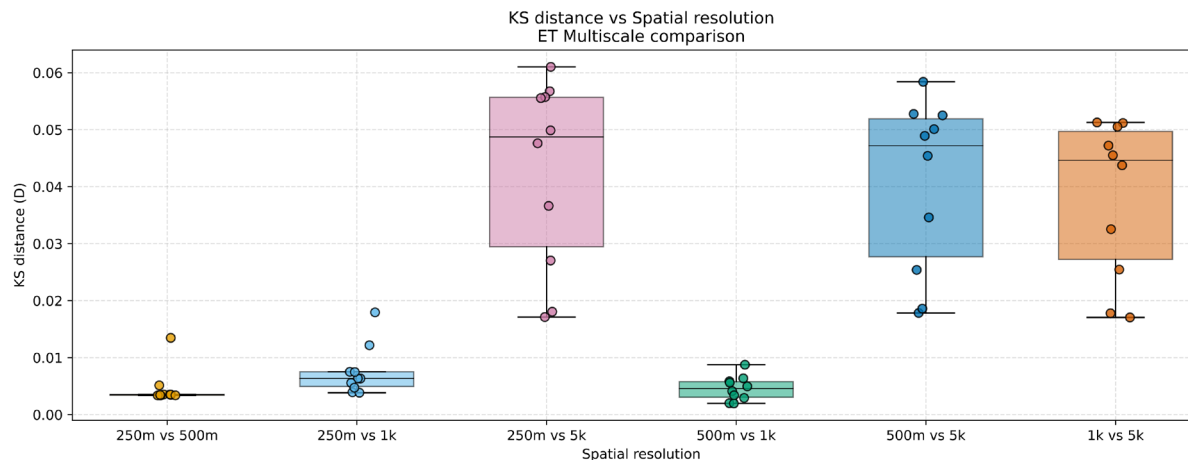
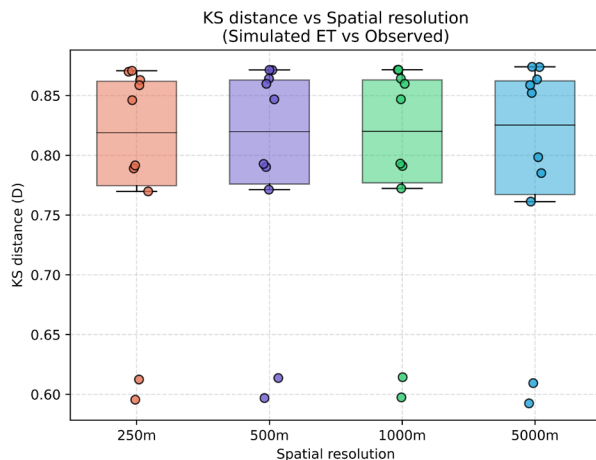
□ Example of spatial CDF comparison for exp10



- Simulated spatial distributions differ from EO (ET and SSM)
- Distributions consistent across resolutions



□ Kolmogorov–Smirnov distance

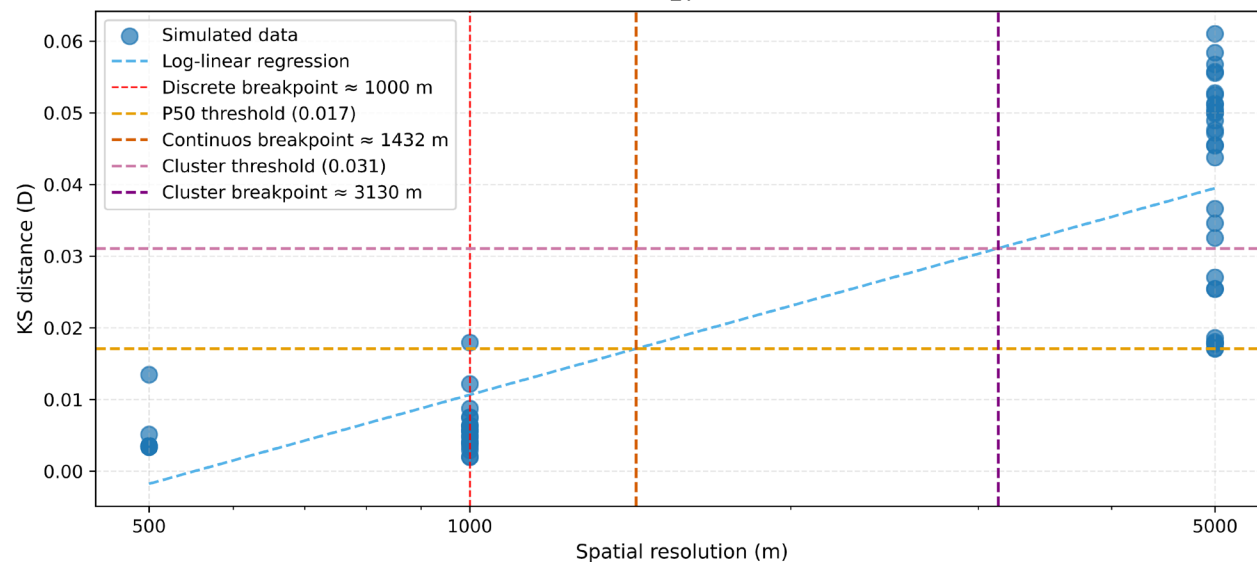


- KS confirms strong model–EO differences
- Small differences between neighbouring scales
- Large differences for coarse vs fine
- **Model–EO mismatch dominates**

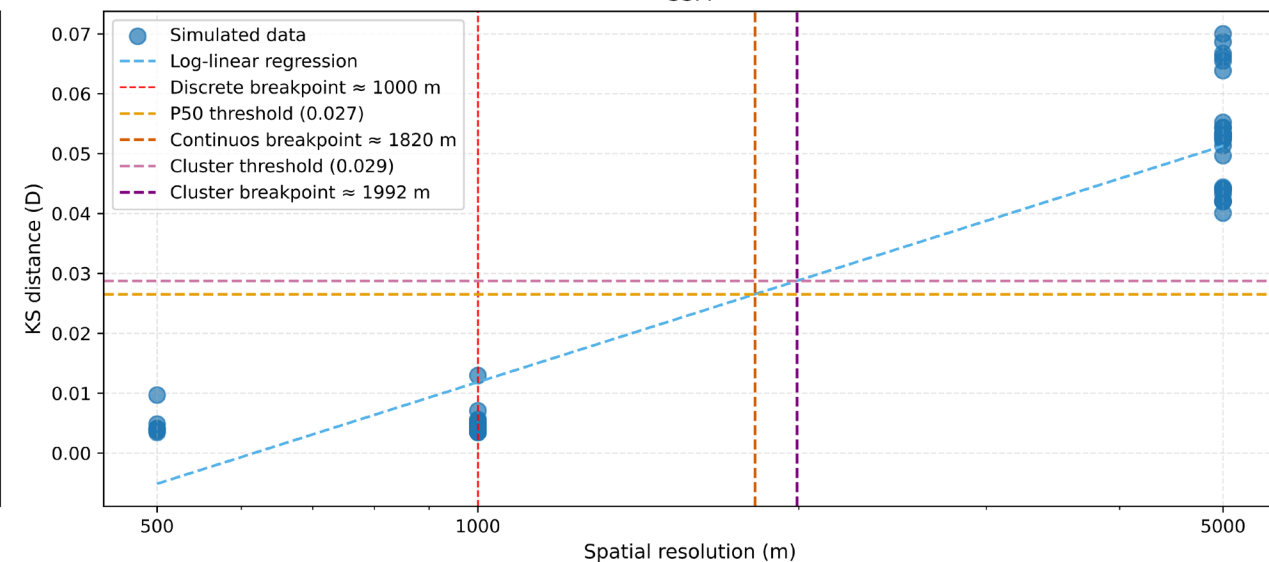


Scale breakpoints

Detection of scale breakpoints
ET

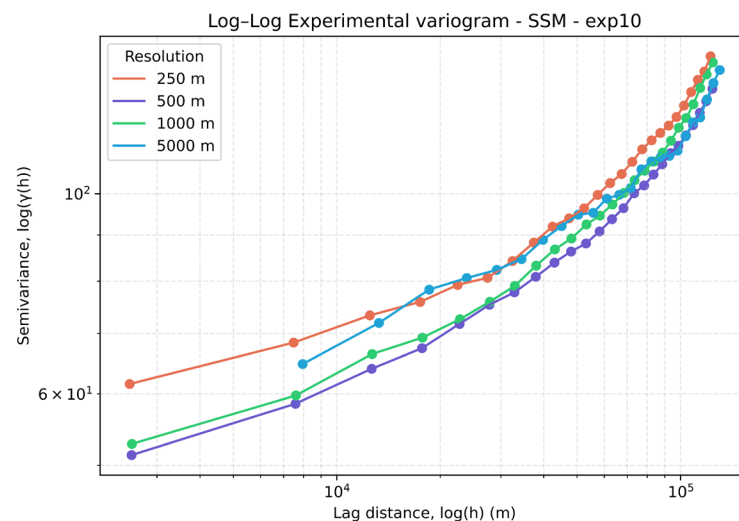
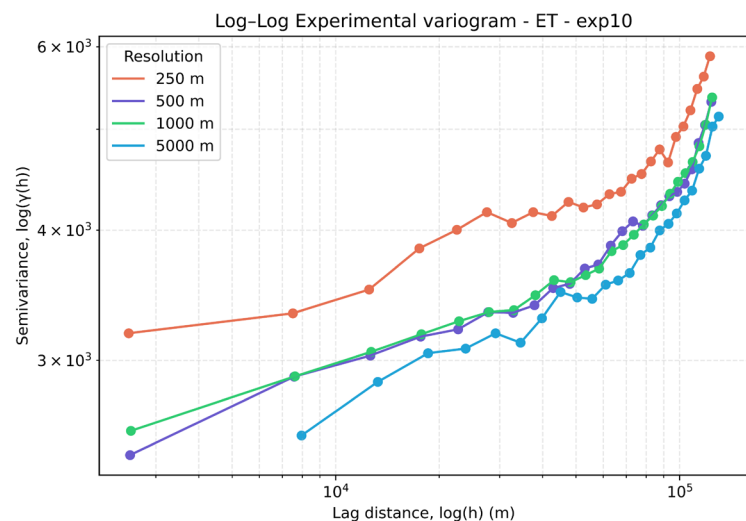


Detection of scale breakpoints
SSM



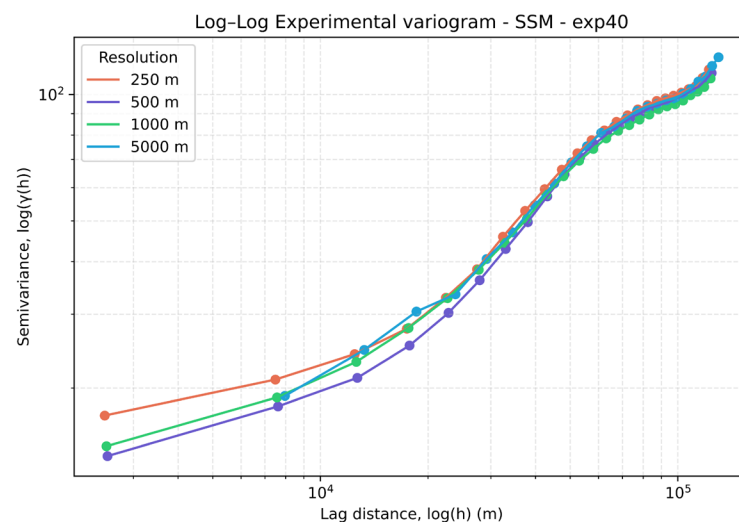
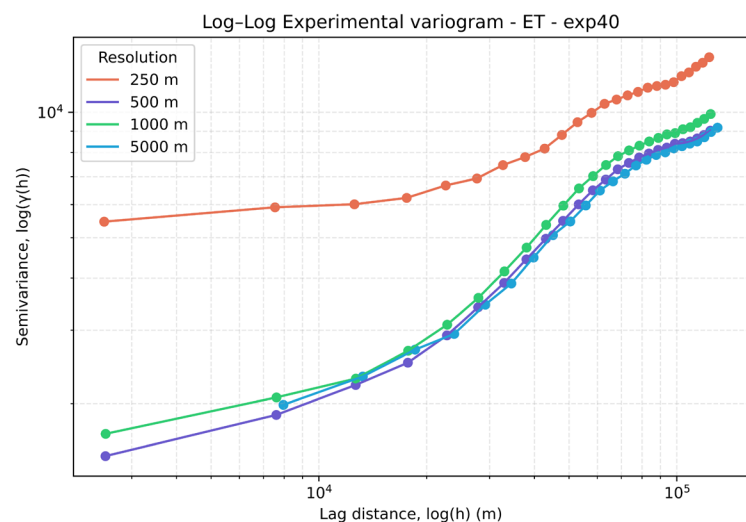
- Two regimes identified:
 - ✓ ≤ 1 km $\rightarrow$ Small structural differences
 - ✓ ≥ 5 km $\rightarrow$ High distortion
- Transition range: 1–3 km

Results Spatial Variogram



$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

- Clear spatial dependence (ET & SSM)
- Fine scales → Stronger short-range variability
- Coarse scales → smoothing spatial structure



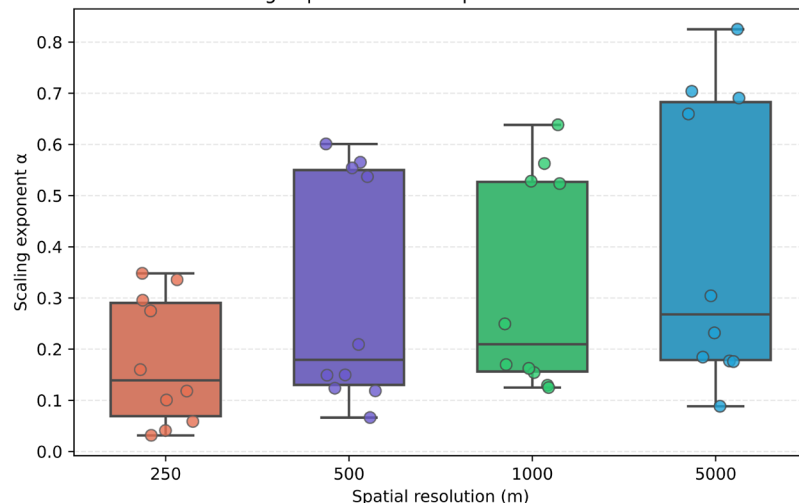
Results Spatial Variogram

Scaling exponent

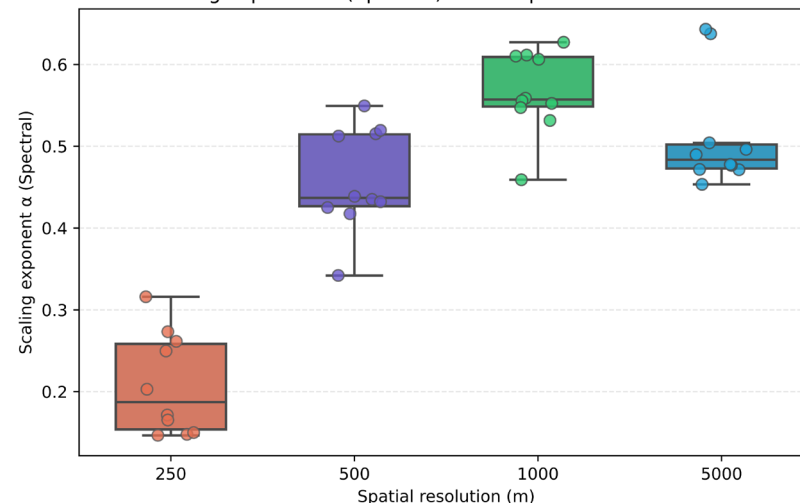
$$\gamma(h) \propto h^{\alpha}$$

- α increases with scale $\rightarrow$ smoother fields
- Resolution controls scaling behavior
- Calibration modulates magnitude
- **Power-law behavior observed**

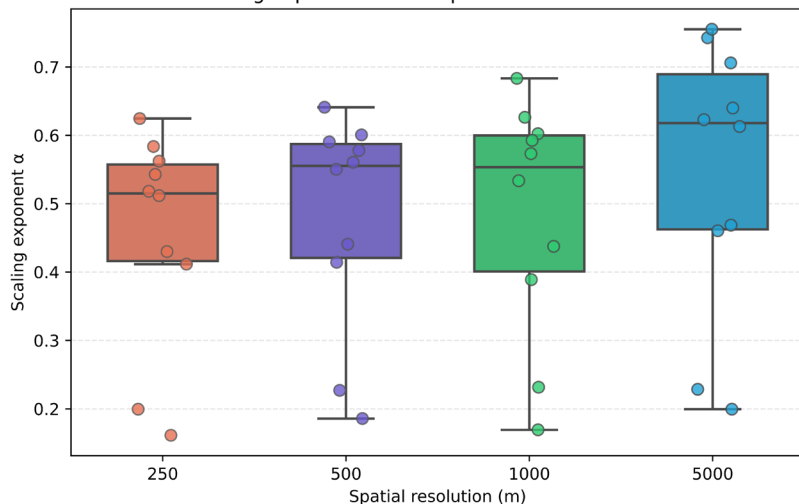
Scaling exponent across spatial resolutions - ET



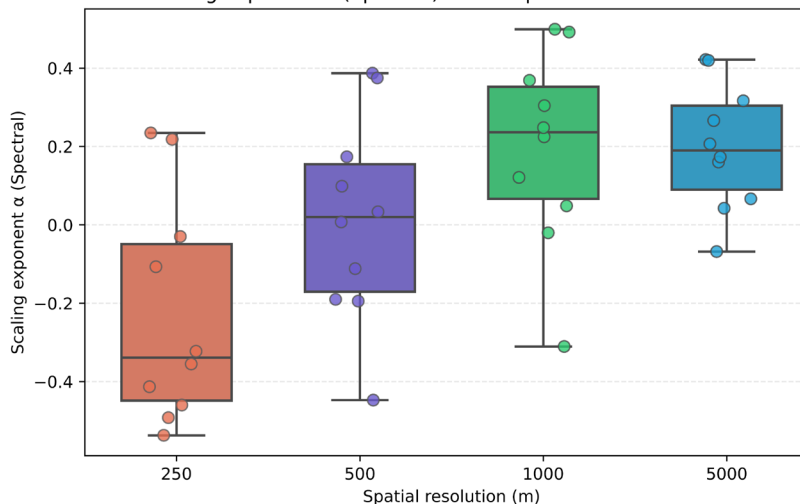
Scaling exponent α (Spectral) across spatial resolutions - ET



Scaling exponent across spatial resolutions - SSM



Scaling exponent α (Spectral) across spatial resolutions - SSM

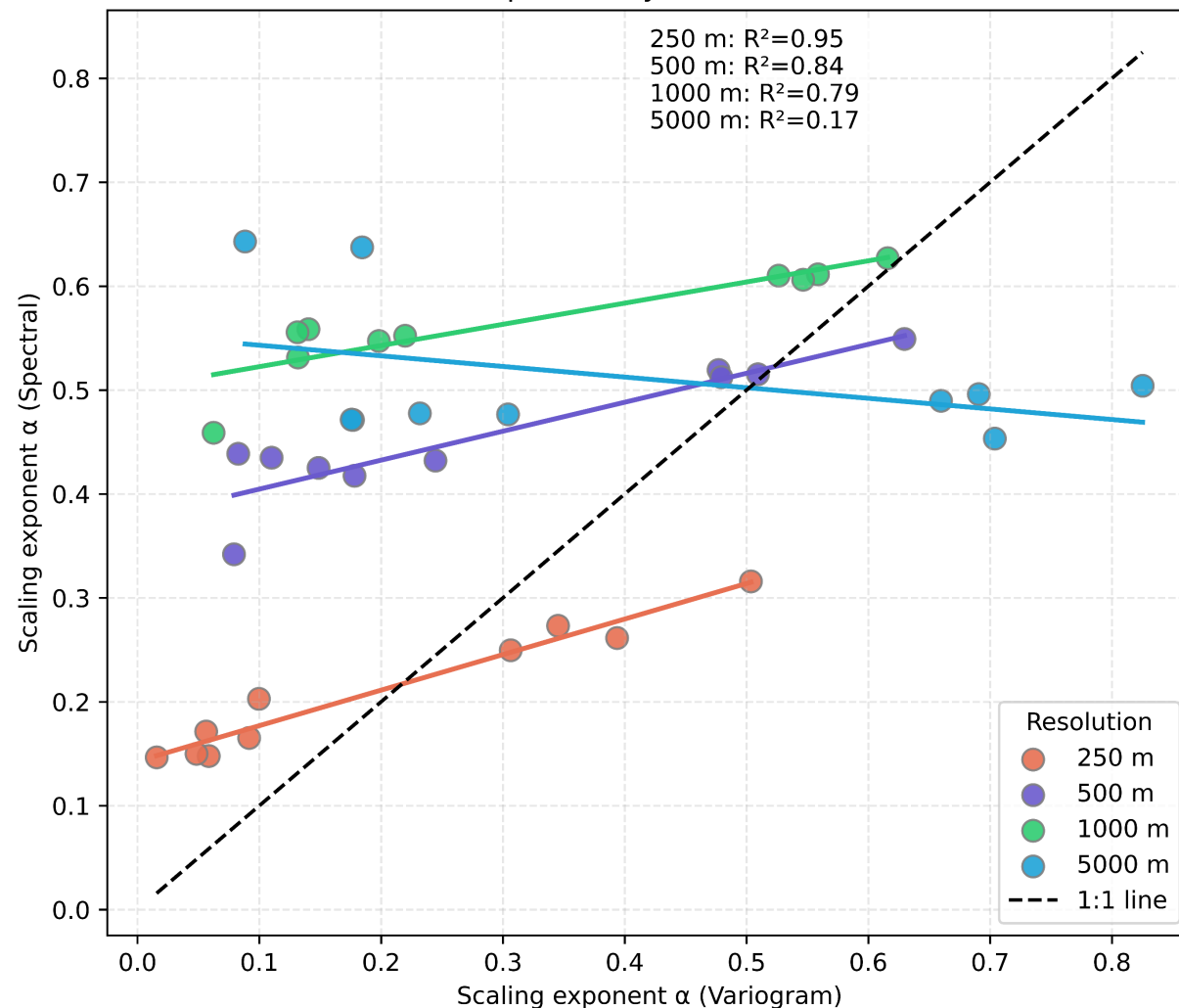


Results Spatial Variogram



□ Scaling exponent comparison

α comparison by resolution – ET



- Strong agreement at fine scales
- Weak agreement at coarse scales
- Aggregation alters scaling behavior
- **Fine scales preserve the multiscale structure**

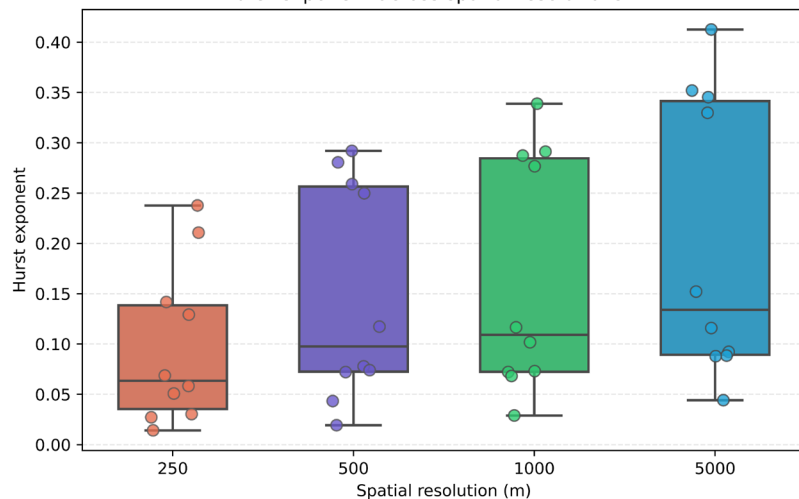
Results Spatial Variogram



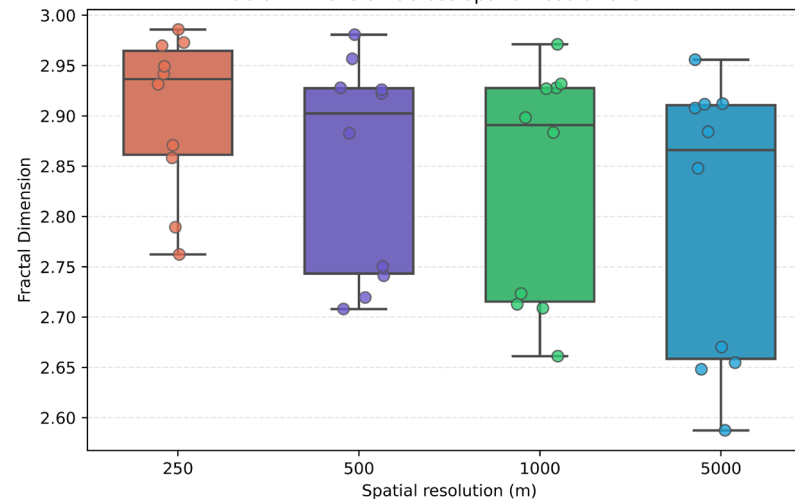
$$H = \frac{\alpha}{2}$$

$$D = 3 - H$$

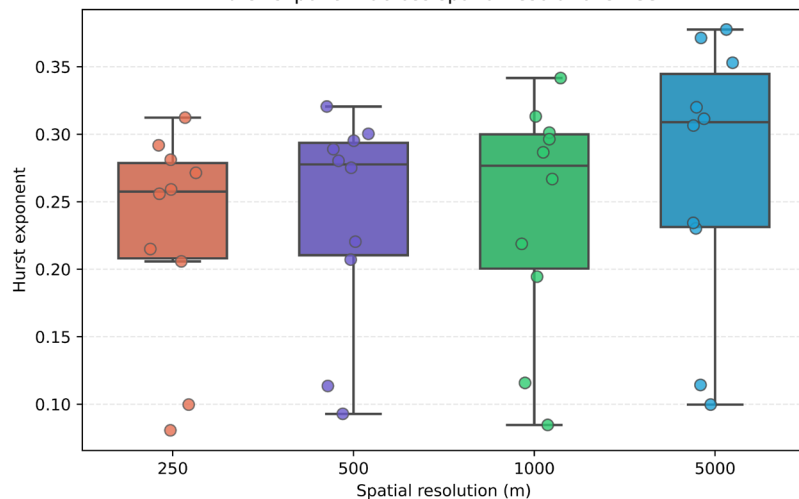
Hurst exponent across spatial resolutions - ET



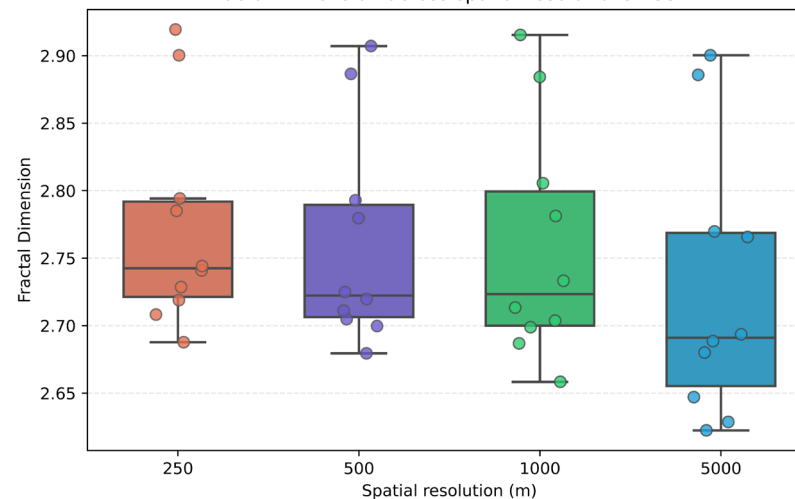
Fractal Dimension across spatial resolutions - ET



Hurst exponent across spatial resolutions - SSM



Fractal Dimension across spatial resolutions - SSM



- H (Hurst exponent) ↑ with scale
→ smoother fields
- D (fractal dimension) ↓ with
scale → reduced complexity
- **Consistent for ET and SSM**

Results Spatial Variogram

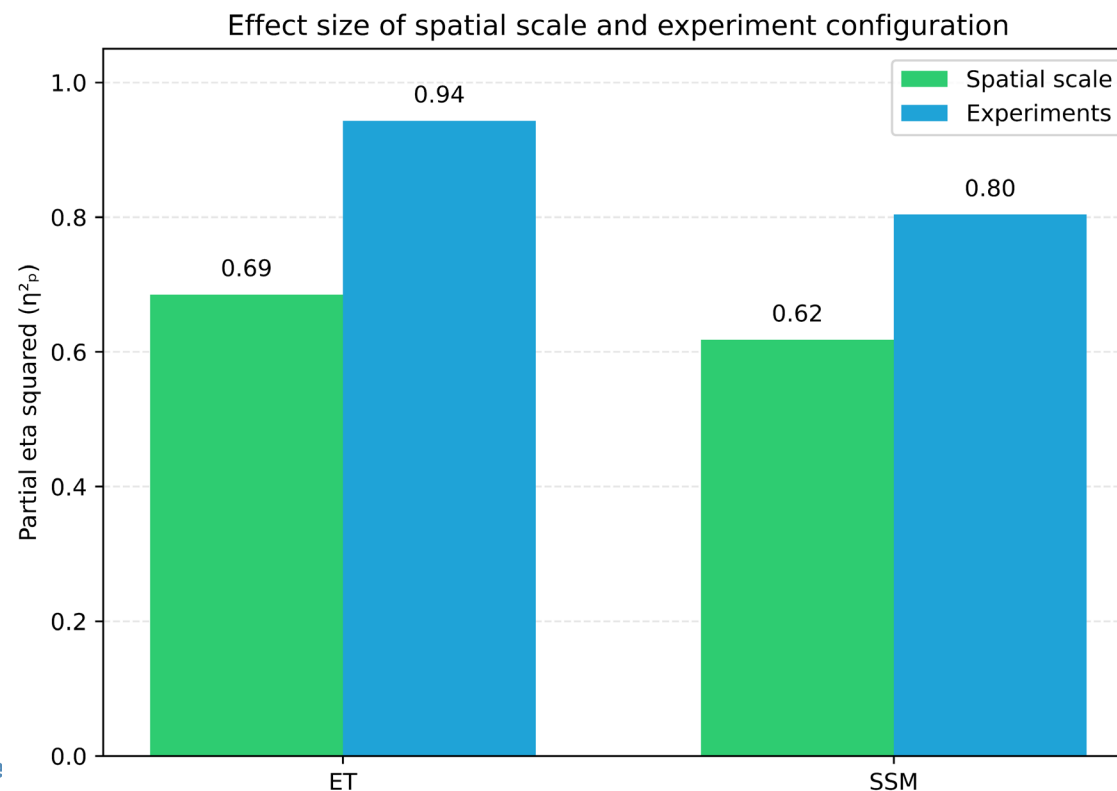


❑ ANOVA test

- Factors: spatial scale and experiment configuration

Variable	ET			SSM		
	SS	F	p-value	SS	F	p-value
Spatial scale	0.229	19.59	5.99e-07	0.042	14.92	6.35E-06
Experiment configuration	1.748	49.80	1.68e-14	0.106	122.92	1.5E-19

- Effect size estimated using partial η_p^2
 - ✓ **Experiment configuration exerts a stronger control on spatial structure behavior than spatial resolution**



Conclusions

Discharge performance

Performance decreases with coarser resolution, although coarse-scale calibration can still provide acceptable performance at finer scales

Spatial patterns (ET & SSM)

SPAEF indicates stronger agreement between neighboring scales, while coarser grids show higher values and larger variability

Distributional behavior (CDF analysis)

Simulated spatial distributions differ substantially from EO products, highlighting the need for improved calibration strategies

Conclusions

Spatial scaling behaviour

Variogram analysis shows progressive smoothing of spatial structures with increasing scale (α , H and D)

Simulations remain internally consistent across spatial resolutions, with small statistical differences between neighboring scales

Drivers of spatial scaling

ANOVA indicates that ~60% of the variability in scaling behavior is explained by spatial resolution, while calibration strategy also plays an important role

IMPLICATION

Multiscale hydrological modelling in large basins may operate efficiently at intermediate resolutions (~1–3 km) without major loss of spatial statistical structure



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Thanks for your attention

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