Ensemble Variability and Uncertainty Interactions in Convective-Scale Forecasts

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Motivation

Convective-scale ensemble forecasts often exhibit underdispersion, partly due to **missing variability from uncertainty sources** that significantly affect forecast outcomes yet remain unaccounted for. This study systematically investigates the impact of **model uncertainty** on convection forecasts and examines **its interactions** with other uncertainty sources.

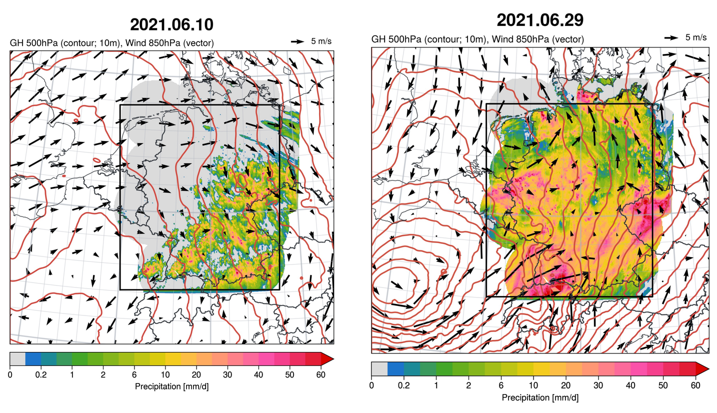
A. Convective forcing regime dependence

Convective adjustment timescale τ_c (Keil et al. 2014) to stratify convective regimes:

$$\tau_c = \frac{CAPE}{dCAPE/dt}$$

Removal time of CAPE by precipitation rates

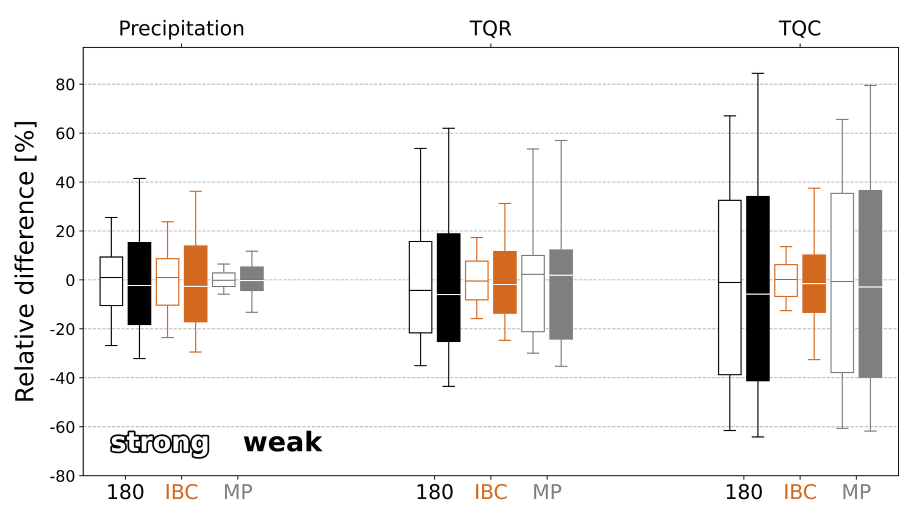
- small τ_c → **strong forcing**: instability immediately balanced
- large τ_c → **weak forcing**: absence of triggering



Different spatial structure of daily precipitation on 10 (left) and 29 (right) of June 2021.

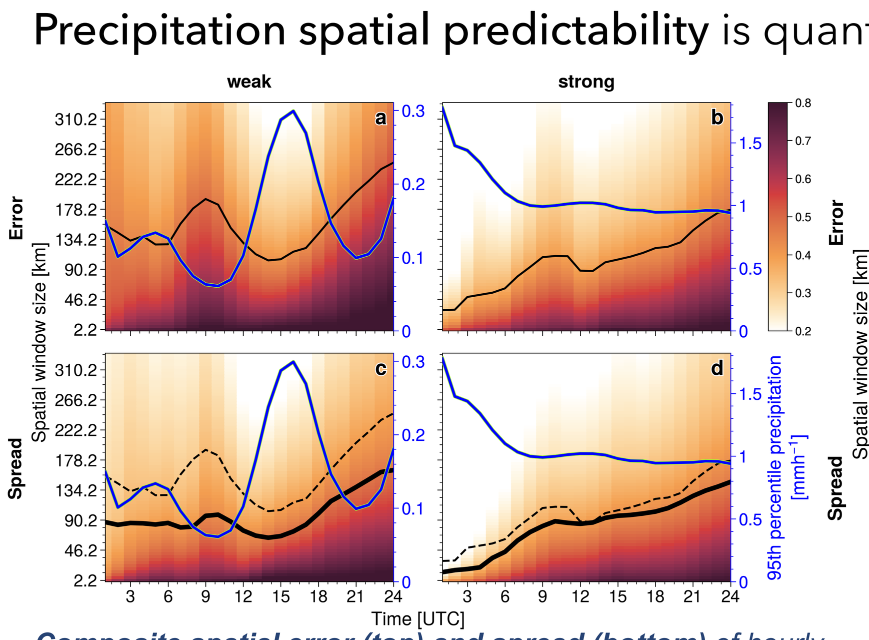
Relative variability is more sensitive in weak forcing (Matsunobu et al. 2022):

- Ensemble variability of moisture content relative to the ensemble mean is systematically larger during weak forcing.
- IBC is a primary source that varies precipitation amounts, while MPP is more dominant for TQR and TQC.

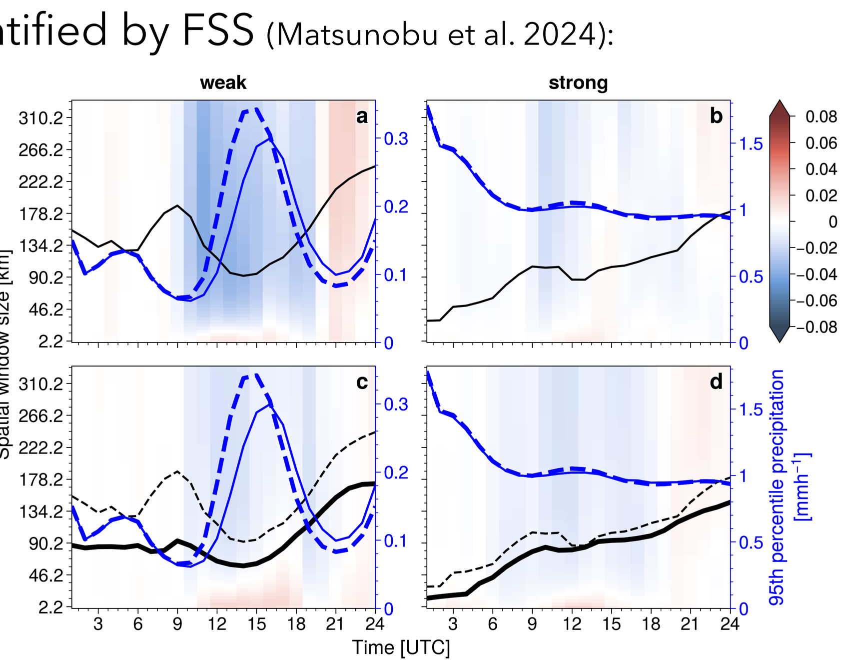


Relative variability given by different uncertainty sources for daily area-mean (left) precipitation, (middle) total column rainwater, and (right) total column cloud water.

Precipitation spatial predictability is quantified by FSS (Matsunobu et al. 2024):



Composite spatial error (top) and spread (bottom) of hourly precipitation across scales. Blue lines show precipitation diurnal cycles. Black lines show largest scales of agreements, showing better spread-error relationship when dashed and solid lines are close in c and d.



Change in spatial (top) error and (bottom) spread due to the activation of PSP. Dashed blue lines indicate the modulated diurnal cycle. Blue shading indicates reduction in error or spread.

- Persistent variability growth and good spread-error agreement in strong forcing
- Strong diurnal cycle and huge spread-error gap in weak forcing
- Clearer scale interactions and better spread-error relationship with the addition of PSP

Summary

Convective-scale predictability is characterized in terms of:

- **Flow-dependence** of predictability. The poorer spread-error relationship is exhibited during weak convective forcing regimes.
- **Strong association of model uncertainty impact with local convective activity.** A value of including model uncertainty scheme needs to be evaluated based on the gain beyond the convection displacement.
- **Necessary co-location of convection and dense observations.** Inhomogeneous observations propagate the impact inhomogeneously.

References

Keil, C., Heinlein, F., and Craig G. C. (2014) The convective adjustment time-scale as indicator of predictability of convective precipitation, *Quart. J. Roy. Meteor. Soc.,* 140(679), 480–490. doi: 10.1002/qj.2143.

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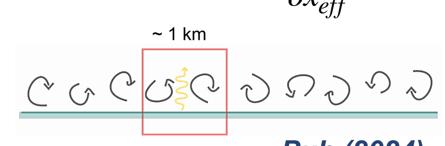
Sources of uncertainties

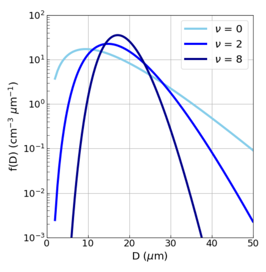
	IBC	PSP	MPP
Perturbation type	varying atmospheric states	stochastic perturbations	different parameters among ensemble members
Spatial and temporal scales	from km to synoptic scales, hourly update	10 km decorrelation, 10 min update	infinite (fixed in space and time)
Representing errors	imperfect state estimation	model errors due to sub-grid scale variability	model errors due to incomplete knowledge

DWD

$$\partial_t \Phi|_{PSP} = \alpha_{tuning} \eta_t \frac{l_{eddy}}{\delta x_{eff}} \sqrt{\overline{\Phi^2}}$$

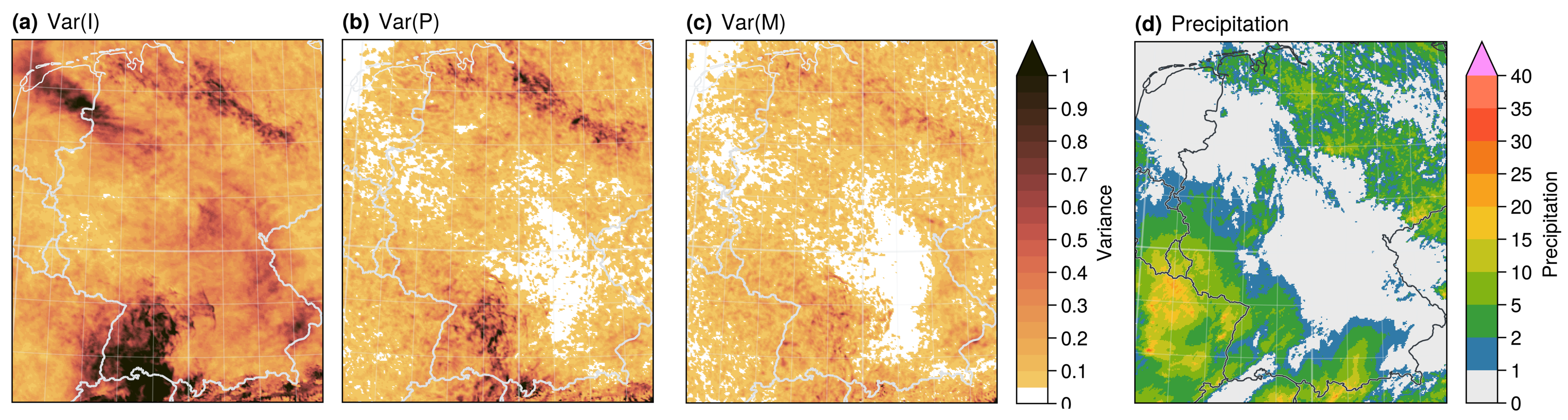


Puh (2024)



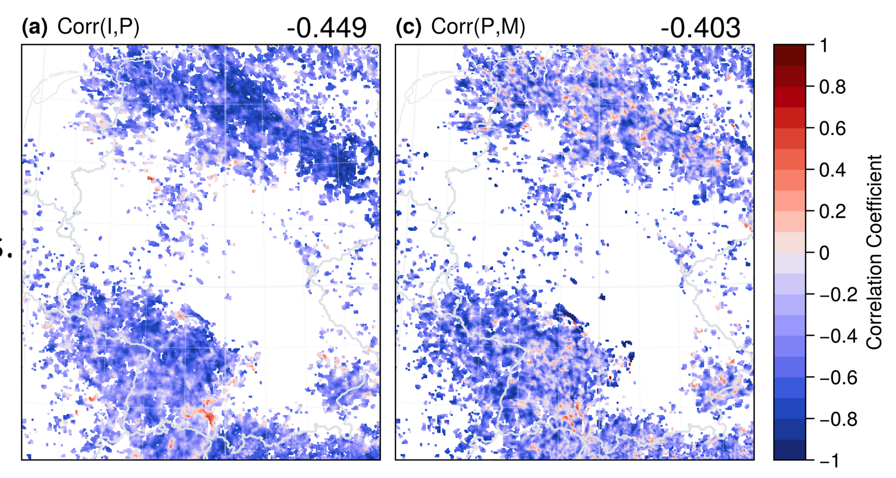
B. Uncertainty interactions in forecasts

A variance budget framework (Matsunobu et al. 2025) allows the quantification of variances from a single source and their interactions.



Temperature variance maps of the (a) IBC, (b) PSP and (c) MPP impact for weak forcing (1600 UTC on 15 August), and (d) precipitation accumulation from 00 UTC.

- The IBC variance is broadly distributed. PSP and MPP variance is concentrated in the part where local convection is active.
- Systematic negative correlations are found, reducing combined variance below the sum of individual variances,
- indicating redundancy among impacts.



Impact correlation coefficient maps for the impacts of (a) IBC and PSP, and (b) PSP and MPP.

- Strong negative correlations are found at small scales, caused by convective displacement.
- Net variance increase represents additional information beyond simple displacement.
- Scale-dependent analysis aids in understanding weather phenomena that benefit from the added schemes.

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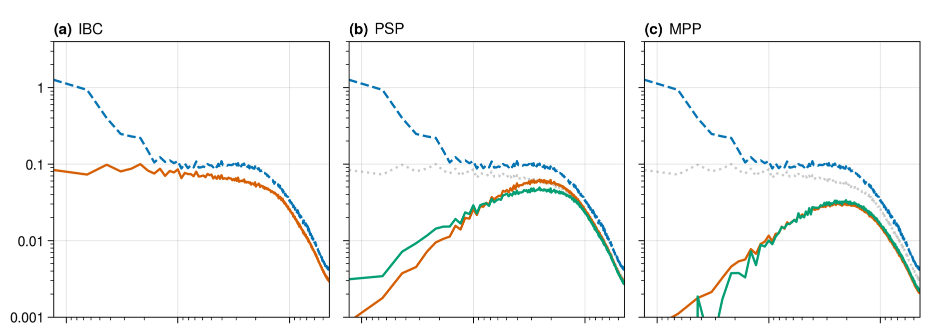
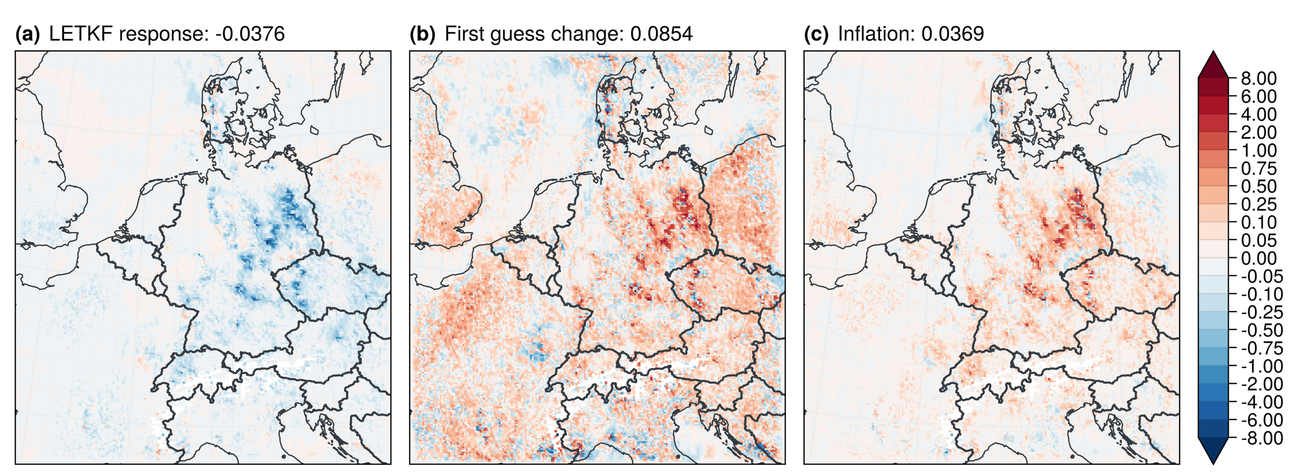


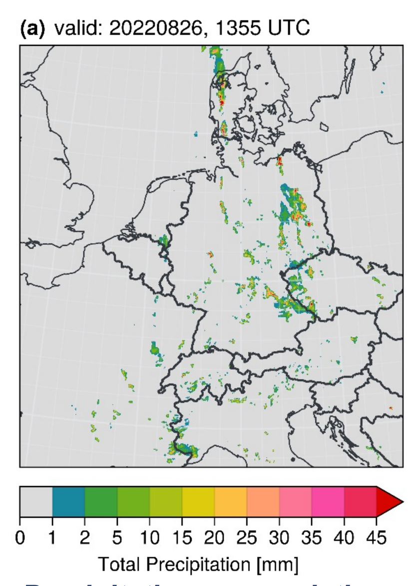
Spectra of (orange) variance terms, (green) interaction terms, and (blue) saturation level for T850 at 1400 UTC. Average over 8 days.

C. PSP impact in data assimilation using LETKF

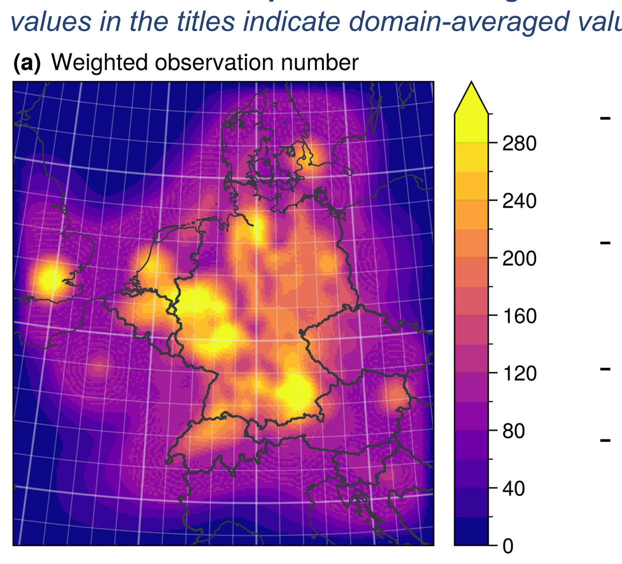
Increase in forecast variance does not translate directly into analysis variance.



Change in analysis variance of U840 at 1400 UTC due to (a) LETKF, (b) first-guess changes, and (c) inflation terms in response to including PSP. Red indicates an increase in analysis variance. The values in the titles indicate domain-averaged values.



Precipitation accumulation during the last DA interval.



Observation density at 840 hPa weighted based on distance between a grid and observations.

- PSP increases the first-guess variance over a wide region.
- LETKF responds by suppressing the increase, but in this case the effect is concentrated in East Germany.
- Inflation schemes counteract and reinflate.
- The regions where LETKF acts are observation-rich regions, showing that inhomogeneous observations affect how much the impact propagates to the analysis.

Manuscript in preparation

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