Institute of Geophysics and Meteorology
UNIVERSITY OF COLOGNE

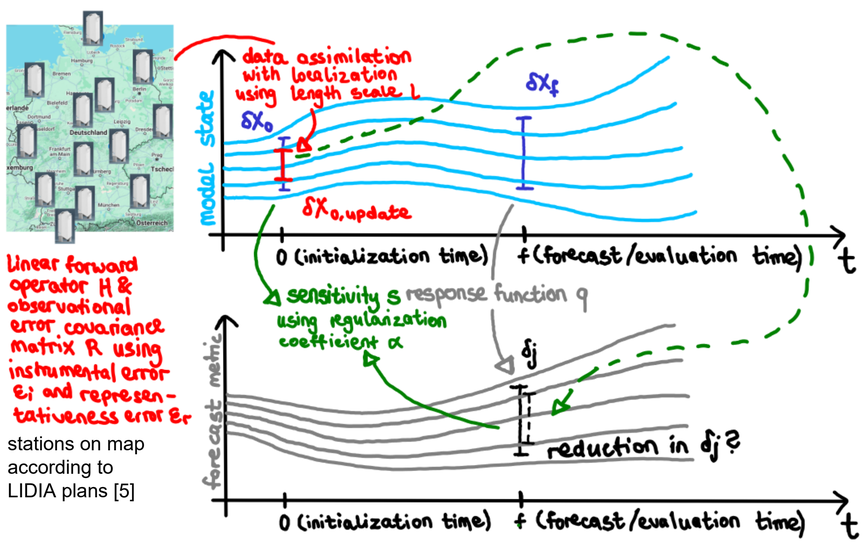
Contact: Nina Raabe,
nina.raabe@uni-koeln.de

Ensemble sensitivity analysis case study: observational impact of ground-based water vapor profiling networks and methodological questions

Nina Raabe[1], Philipp Griewank[2], Martin Weissmann[2], Takumi Matsunobu[3], Maria Toporov[1], and Ulrich Löhnert[1]
1: University of Cologne, 2: University of Vienna, 3: University of Reading

ESA – ensemble sensitivity analysis method

… in the so-called global explicit specification [1], [2], [3], [4]



$\delta \boldsymbol{X}_{0/\mathrm{f}}$ – ensemble data spr. initialization/evaluation time

q – response function with $q(\delta \boldsymbol{X}_{\mathrm{f}}) = \delta \boldsymbol{j}$ forecast metric spr.

$\boldsymbol{s}$ – sensitivity

$\boldsymbol{H}$ – linear forward operator

$\boldsymbol{R}$ – observ. error covariance matrix

$\delta \boldsymbol{X}_{0,\,\mathrm{update}}$ – upd. ensemble data spr. initialization time

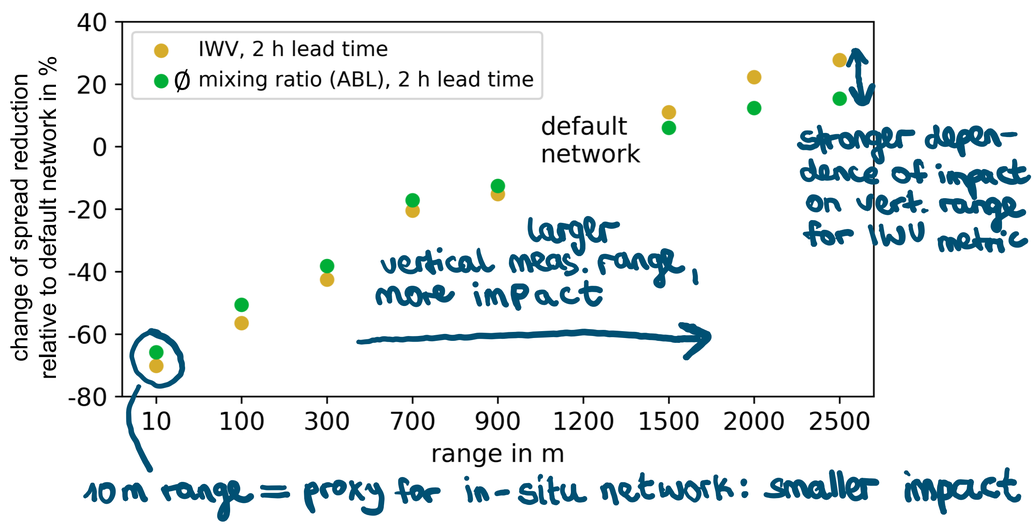
visualization of global explicit ensemble sensitivity analysis based on [1], [2], [3], [4] using graphics from [6]

requirements: pre-comp. ensemble ($\delta \boldsymbol{X}_0$, $\delta \boldsymbol{X}_f$), assumptions on observations ($\boldsymbol{H}, \boldsymbol{R}$)

steps: 1. define response function q, apply at forecast time → forecast metric spr. $\delta \boldsymbol{j}$
2. assume sensitivity $\boldsymbol{s}$ of $\delta \boldsymbol{j}$ to $\delta \boldsymbol{X}_0$ ($\delta \boldsymbol{j} \approx \boldsymbol{s}^T\, \delta \boldsymbol{X}_0$), calculate it (regulariz. [7])
3. update $\delta \boldsymbol{X}_0$ to $\delta \boldsymbol{X}_{0,\,\mathrm{update}}$ by assimilating [8] hypothetic. network (localiz. [9])
4. project the change in $\delta \boldsymbol{X}_0$ onto the change in $\delta \boldsymbol{j}$ using $\boldsymbol{s}$ to quantify impact

First ESA observational impact results

set-up: - 180 member-ensemble [10] based on convection-perm. ICON-D2 [11]
- two summer afternoon cases (2020-08-17/18, assimilation at 13 UTC)
- ground-based water vapor profiling network with 13 WV-DIALs as planned by German Meteorological Service (vert. range 1200 m) [5], [12]
- metrics: ∅ IWV/ ABL humidity over 200 km boxes, lead times up to 3 h



open issue: first results qualitatively checked (train-validate split for test cases' sensitivities consistent) but method doesn't seem to generalize well in this set-up to other metrics → see below for details and plans

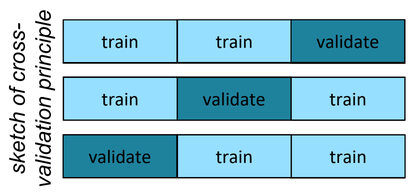
How to design future observational networks for physical and data-driven convection-permitting weather prediction?

motivation: improve (high impact) weather forecasts of current and future models by effectively adding observations

Plans addressing methodological questions regarding the ESA

further characterization of issue: sampling noise in 180 member-ensemble and overfitting to it suspected – especially harmful for metrics with weak signals

suggestion: use adaptive regularization strength determined from method such as (generaliz.) cross-validation [13]



for example, to investigate time-dependence

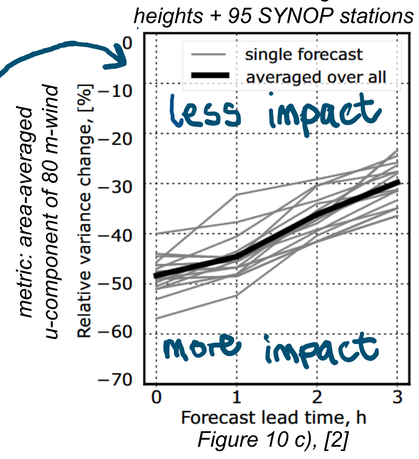
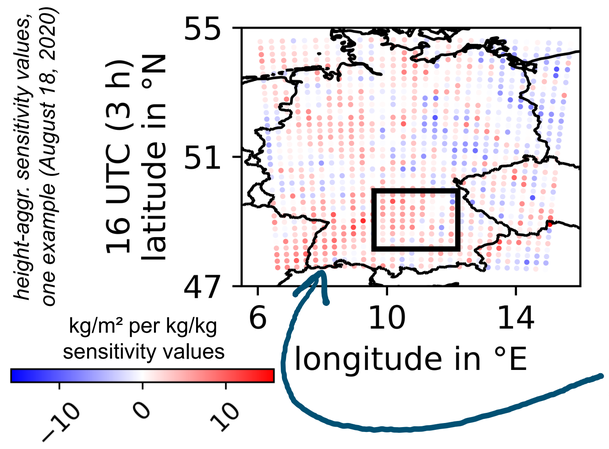


Figure 10 c), [2]

goals: 1. stabilize method in current set-up
2. test general applicability when using adaptive regularization → use in study for future network design guidance?

Outlook – using sensitivity fields to guide design of future observational networks

concept: sensitivities forecast metric j to state variables $(x_0)_i$ at initialization time and different grid points



$\frac{\partial j}{\partial (x_0)_i}$ here: ∅ IWV in box after 3 h
here: water vapor mixing ratio

moisture advection from south-west

application: use these sensitivity fields to determine where to install which new measurements [3], [4], e.g.

References

[1] P. J. Griewank, M. Weissmann, T. Necker, T. Nomokonova, and U. Löhnert. Ensemble-based estimates of the impact of potential observations. Quarterly Journal of the Royal Meteorological Society, 149(754):1546–1571, 2023. doi: 10.1002/qj.4464.
[2] T. Nomokonova, P. J. Griewank, U. Löhnert, T. Miyoshi, T. Necker, and M. Weissmann. Estimating the benefit of Doppler wind lidars for short-term low-level wind ensemble forecasts. Quarterly Journal of the Royal Meteorological Society, 149(750):192–210, 2023. doi: 10.1002/qj.4402.
[3] B. Ancell and G. J. Hakim. Comparing adjoint-and ensemble-sensitivity analysis with applications to observation targeting. Monthly Weather Review, 135(12):4117–4134, 2007. doi: 10.1175/2007MWR1904.1.
[4] R. D. Torn and G. J. Hakim. Ensemble-based sensitivity analysis. Monthly Weather Review, 136(2):663–677, 2008. doi: 10.1175/2007MWR2132.1.
[5] LIDAR and DIAL instruments at ground stations – LIDIA project – personal communication German Meteorological Service / D. Khordakova
[6] https://www.vaisala.com/en/products/weather-environmental-sensors/atmospheric-profiling/dial-atmospheric-profiler-da10 (accessed on March 17, 2026) and Google My Maps
[7] Tikhonov regularization – A. N. Tikhonov. Ill-conditioned problems in linear algebra and their robust method solution. Doklady Akademii Nauk SSSR, 163:591–594, 1965.
[8] Ensemble Square-Root Kalman filter – J. S. Whitaker and T. M. Hamill. Ensemble data assimilation without perturbed observations. Monthly Weather Review, 130(7):1913–1924, 2002. doi: 10.1175/1520-0493(2002)130<1913:EDAWPO>2.0.CO;2.
[9] Gaspari-Cohn function – G. Gaspari and S. E. Cohn. Construction of correlation functions in two and three dimensions. Quarterly Journal of the Royal Meteorological Society, 125(554):723–757, 1999. doi: 10.1002/qj.49712555417. – introduces weights 1 to 0 (at cut-off $c = 2\sqrt{10/3}\, l$), $l = 50$ km (horizontal) / $0.1 \ln(\mathrm{hPa})$ (vertical) (following [11])
[10] T. Matsunobu, C. Keil, and C. Barthlott. The impact of microphysical uncertainty conditional on initial and boundary condition uncertainty under varying synoptic control. Weather and Climate Dynamics, 3(4):1273–1289, 2022. doi: 10.5194/wcd-3-1273-2022.
[11] D. Reinert, F. Prill, H. Frank, M. Denhard, M. Baldauf, C. Schraff, C. Gebhardt, C. Marsigli, J. Förstner, G. Zängl, and L. Schlemmer, 2024: Report "DWD Database Reference for the Global and Regional ICON and ICON-EPS Forecasting System", https://www.dwd.de/DWD/forschung/nwv/fepub/icon_database_main.pdf (accessed on December 22nd, 2024)
[12] recent investigations in the Pilotstation project (similar as, e.g., C. Knist, M. Kayser, F. Lauermann, M. Löffler, V. Lehmann, and R. Lehtinen, 2022: Conference contribution (DACH2022-188) at DACH2022, Leipzig, Germany, March 21-25, 2022 "Assessment of a Broadband Differential Absorption Lidar (DIAL) for use in a ground-based measurement network", https://doi.org/10.5194/dach2022-188 (accessed on November 9, 2025)) – personal communication German Meteorological Service / C. Knist
[13] G. H. Golub, M. Heath, and G. Wahba. Generalized Cross-Validation as a method for choosing a good ridge parameter. Technometrics,. 21(2):215-223, 1979. doi: 10.1080/00401706.1979.10489751

ECMWF Annual Seminar 2026, Reading, September 14 – 18, 2026