Tracking Extreme Weather in a Changing Climate: The Role of Remote Sensing and Data Assimilation in ALADIN

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Abstract Remote sensing enhances numerical weather prediction by providing critical atmospheric data, essential in a changing climate. In the ALADIN model, SEVIRI radiances were assimilated using 3D-Var with Variational Bias Correction (VarBC), requiring a warm-up phase for bias initialization. Radar Doppler wind data underwent preprocessing and spatial filtering before assimilation. Challenges included aliasing and non-Gaussian observation errors, impacting forecast accuracy. Results showed improved alignment between observations and model fields. As extreme weather events intensify with climate change, refining bias correction, optimizing VarBC initialization, and improving radar data quality control are crucial for more accurate forecasting and early warning systems.

Satellite observations

Provide coverage of atmospheric conditions **Improve initial conditions and forecast accuracy** **Require careful bias correction and quality control**

The basic quantity describing the recorded electromagnetic radiation is radiance. Radiance expresses the specific radiance of a surface source and refers to a specific part of the electromagnetic spectrum. Assuming that there is no scattering of the emitted radiation, a relationship can be derived to calculate the amount of radiance. This prerequisite is met in the pure atmosphere and when scanning in the infrared and microwave spectrum.

Satellite Meteosat Second Generation (MSG), with imaging radiometer **SEVIRI**, do not measure the state variables used in the model (temperature, humidity,..) but the **radiances** L_λ (with spectral channels VIS (+ HRV), NIR, IR emitted by the surface & atmosphere system.

$$L_\lambda(z_x;\Theta) = \varepsilon_{S,\lambda}\, B_\lambda\big(T_B(z_0)\big)\tau_\lambda(0;z_x;\Theta)$$

$$+\int_{z_0}^{z_x} B_\lambda\big(T_B(z)\big)\frac{d\tau_\lambda(z;z_x;\Theta)}{dz}dz$$

The thus obtained radiances are used in the assimilation process. However, if the model background x_b or observations y contain systematic errors (**biases**), then the available data are not used optimally in the assimilation scheme and the analysis is biased.

Variational bias correction (**VarBC**) is a sophisticated statistical approach that adjusts for these biases during the assimilation process. Started with zero coefficients and used **daily cycling strategy** of β_i . By dynamically estimating bias parameters β_i alongside the model state x. Provided the independence between the model state error and the bias coefficients error, the cost function $J(x;\beta)$ (which minimum of it, is the aim of variational assimilation system) becomes

$$J(x;\beta) =$$

$$\frac{1}{2}\Big(y - H(x) - \sum_{i=0}^{N}\beta_i p_i(x)\Big)^T R^{-1}\Big(y - H(x) - \sum_{i=0}^{N}\beta_i p_i(x)\Big)$$

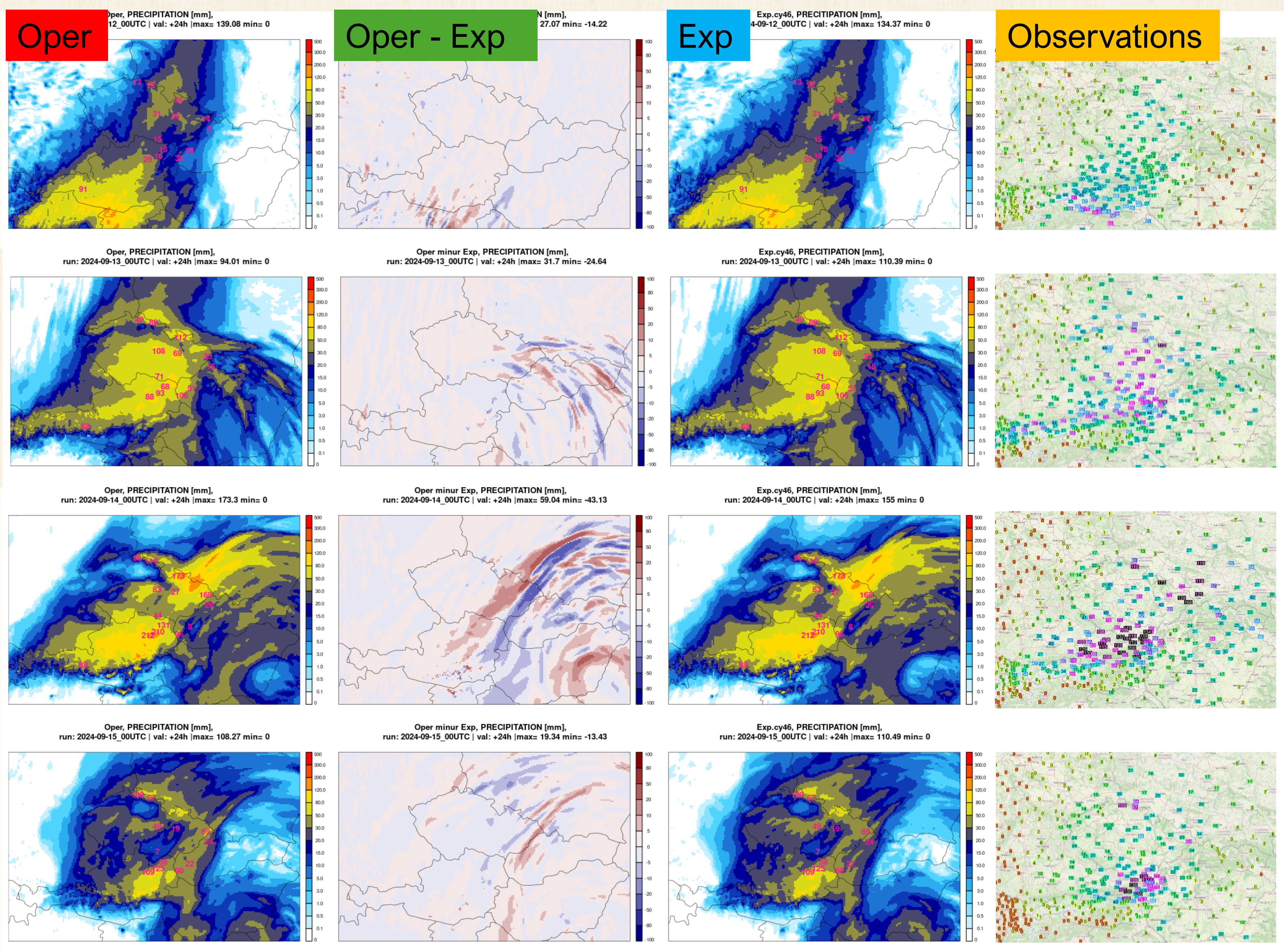
$$+\frac{1}{2}(x_b - x)^T B_x^{-1}(x_b - x) + \frac{1}{2}(\beta_b - \beta)^T B_\beta^{-1}(\beta_b - \beta)$$

Case Study: The low Boris (Sept 11–15, 2024)

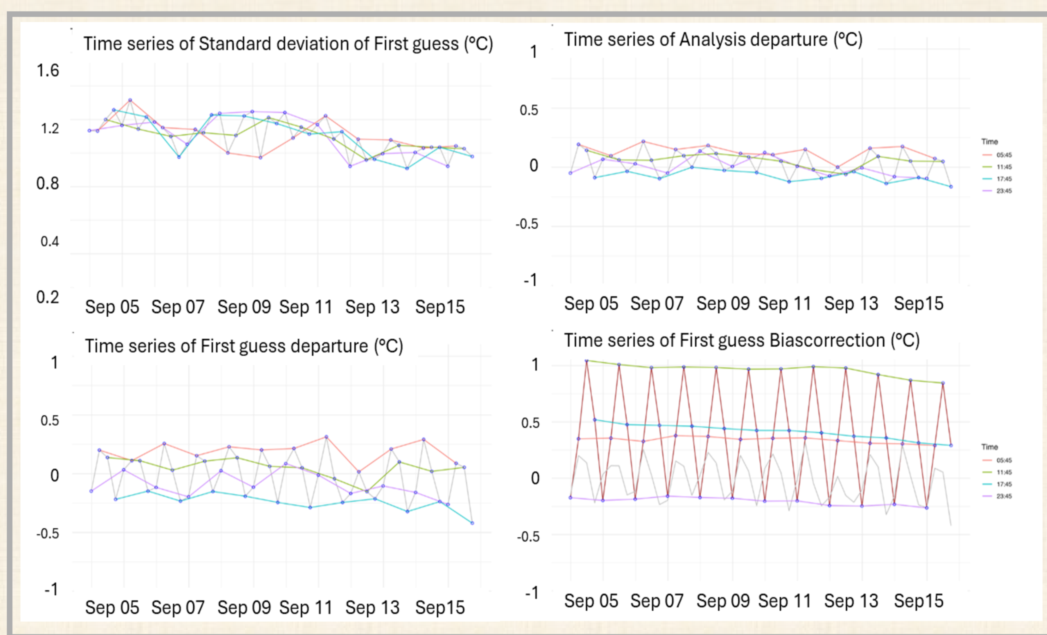
Cold air intrusion from the UK → Mediterranean → strong temperature contrast over Europe.

Low-pressure system formed over Italy, evolving into a cut-off low.

High-pressure ridges trapped the system, causing prolonged heavy rainfall.

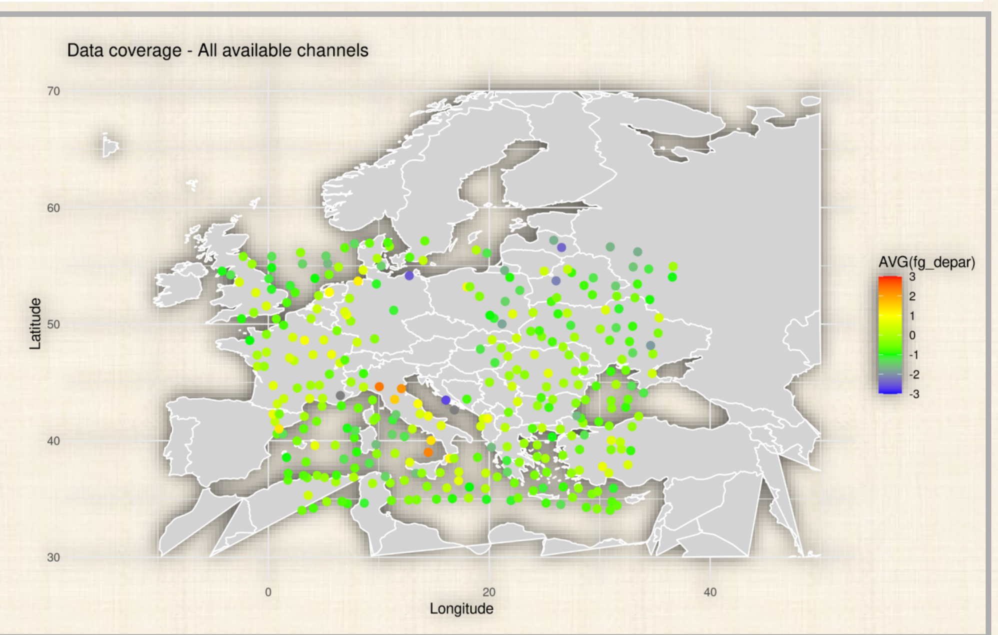


Comparison of prediction of cumulative precipitation (24h) : of operative model ALADIN/SHMU (Oper), experimental copy of Oper with Seviri and VarBC (Exp), difference the latest two setups and Observations.



Evaluating data assimilation quality :

- **FG Depar:** Difference between observations & model's first guess (smaller = better)
- **ANA Depar:** Reduction vs. FG Depart indicates successful assimilation
- **STD FG Depar:** Measures variability of FG departures (lower = more reliable)
- **Biascorr:** Correction for systematic errors in observations



Conclusion I

The assimilation of SEVIRI radiances in the ALADIN model. Used the **3D-Var method** with bias correction through VarBC, where daily cycling of weighting coefficients allowed for dynamic adaptation to systematic errors in satellite measurements.

This correction led to a better agreement between the model background and satellite observations, improving input data quality and potentially enhancing extreme weather forecasts.

Results from the case study (September 11–15, 2024) suggest that incorporating satellite measurements improves atmospheric predictions, especially in areas with limited conventional observations. The role of remote sensing in numerical weather prediction is increasingly important in a changing climate, but further verification is needed to fully assess the impact on extreme weather forecasting.

DEE, D. P., 2005. *Bias and data assimilation.*

BENÁČEK, P. & MILE, M. 2019. *Satellite Bias Correction in the Regional Model ALADIN/CZ: Comparison of Different VarBC Approaches*

Observations. *www.ogimet.com*

Radar observations

Improves convective storm & precipitation forecasting **Provides high-resolution wind and reflectivity data** **Enhances monitoring of dynamic atmospheric processes**

Radars use electromagnetic waves to detect and measure the speed of moving objects. After the signal is sent, part of the energy reflected from the object is recorded. These reflections make it possible to measure the reflectivity and radial component of the wind, i.e. the speed of the object along the imaginary line between the radar and the target. The key variable in the case of assimilation of the radial component of the wind is the Nyquist velocity.

Frequency change Δf between emitted f_0 and received signal is proportional to radial velocity:

$$v_r = \frac{\Delta f.\, c}{2f_0}$$

where c is the speed of light. **Nyquist velocity** v_{NI} helps ensure that these measurements are reliable and accurate. If the radial velocity v_r, exceeds v_{NI}, aliasing occurs, where the speed appears less or opposite than it is. The Nyquist velocity :

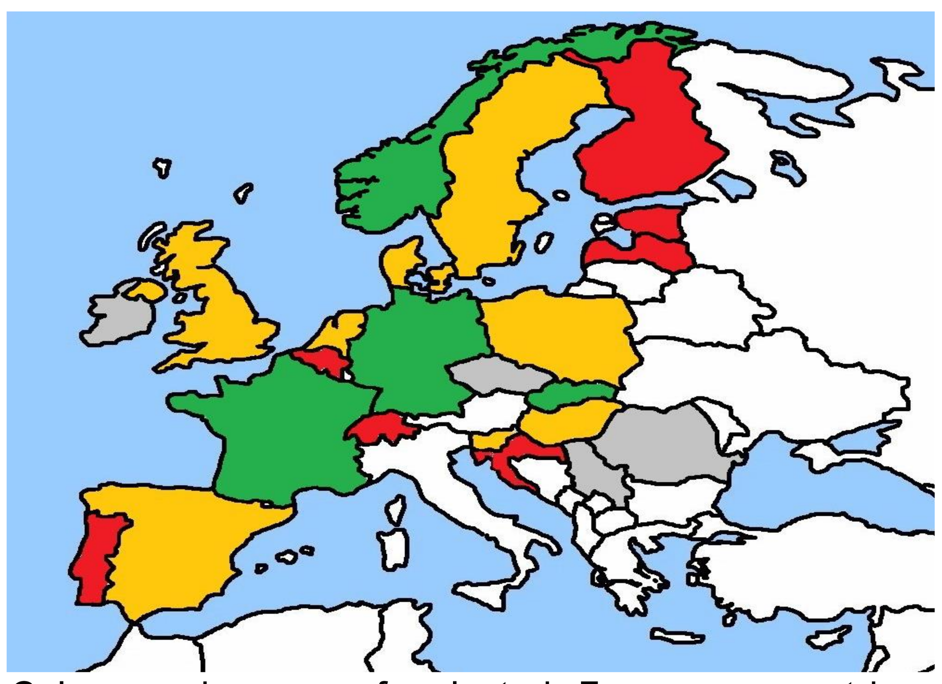
$$v_{NI} = \frac{f_s \cdot \lambda}{4}$$

where λ is the wavelength of radar signal and f_s is limited sampling rate.

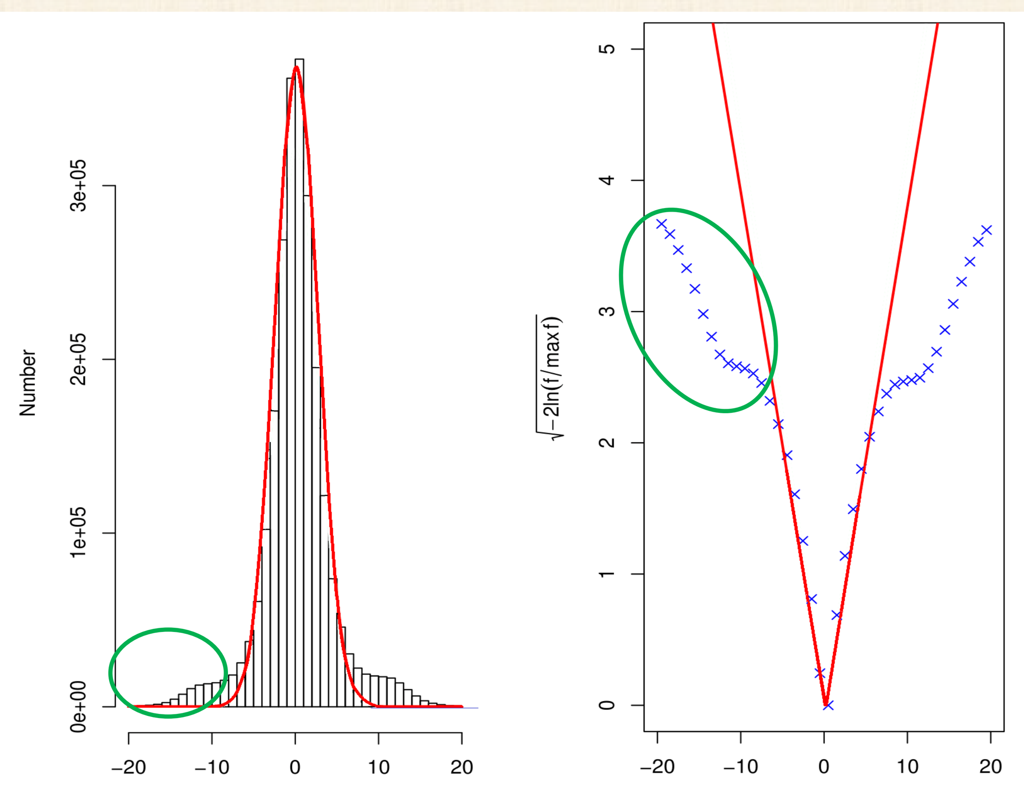
In meteorology, a higher Nyquist velocity is beneficial for observing fast-moving weather phenomena, while a lower Nyquist velocity may be better suited for detecting slower-moving objects.

Radar data preprocessing:

- **Homogenization:** Standardizes datasets for assimilation
- **Filtering & subsampling:** Removes noise and spurious values
- **Validation:** First-guess departures check data quality



Colour code map of selected European countries based on Nyquist velocity value. Green = datasets contained only NI =>30 m/s, Red = NI < 30 m/s, Yellow = higher and lower than 30 m/s, Grey = missing either the value of NI or the entire dataset.



Histogram of FG departures of active data (left) and **transformed histogram** by Anderson and Järvinen method (right).

The FG departures follow a Gaussian behaviour up to 5-6 m/s, but for higher values they form tails, indicating a non-Gaussian distribution. This is believed to be one of the reasons why the assimilation of radial velocity had a detrimental impact on the forecasts.

Conclusion II

Focus was on the assimilation and validation of radar radial wind data within the ALADIN model. Data preprocessing using HOOFv1.9 identified issues with incomplete quality flags, which were addressed through a correction method. The spatial filtering effectively reduced artefacts and improved data quality prior to assimilation.

Passive assimilation results demonstrated a strong agreement between radar radial winds and the NWP model, with histogram-based analysis providing insights into data departures from theoretical distributions.

ANDERSON, E. & JÄRVINEN, H. 1999. *Variational quality control.*

RIDAL, M. et al. 2024. *Optimal use of radar radial winds in the HARMONIE numerical weather prediction system.*

PETROVIČ, M. 2024. *Data assimilation and validation of radar radial winds observations*

FINAL CONCLUSION: The study demonstrates how advanced data assimilation techniques in model ALADIN, incorporating both satellite radiances (SEVIRI) and radar radial winds, contribute to improving extreme weather prediction. As climate change increases the frequency and intensity of extreme meteorological events, better integration of remote sensing data will be essential for enhancing forecast accuracy and supporting effective early warning systems. February 2025