Deep learning dust forecasting from observations using partial convolutions.

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Background

Mineral dust aerosols are small particles suspended in the atmosphere emitted from soils and lifted by winds and turbulence in arid and semi-arid regions. Sand and dust storms have significant impacts on human health and large **concentrations can create hazards for vulnerable populations and industries**. Recent studies incorporate AI to leverage vast data sets for reanalysis and simulations. However, **few works directly train models on observations** due to challenges like **missing information in observations**. A widely used metric for aerosols monitoring is Aerosol Optical Depth (AOD), a measurement of the extinction of light due to interaction with aerosols in the atmosphere.

Methods

Aiming to forecast next day AOD we build a data set using **satellite retrieval of aerosols, weather forecasts, and ancillary features**:

- VIIRS satellites Deep Blue Aerosol Optical Depth (AOD) at 550 nm
- Global Forecast System weather forecasts.
- GMTED2010 elevation data map and time encoding for the day of the year.

Using the GFS lead time forecasts and previously predicted AOD images, an **autoregressive prediction framework is created** to generate multi-day forecasts.

Partial Convolutions (PConv, Liu et al 2018) are designed to handle incomplete data by masking out missing pixels. Unlike standard CNNs, PConv ensures the filters only process available observations, blocking the neurons that should interact with the masked data. **The model follows a U-Net structure**, an architecture already proven to work in the Sahara region (Nowak et al 2025) for next day forecasts, with skip connections, allowing the network to recover spatial features while filling gaps. The Partial Convolutional Neural Network model is referred as **PCNN**.

$$x' = \begin{cases} K*(X\odot M)\frac{\sum 1}{\sum M}, & \text{if } \sum M>0 \\ 0, & \text{otherwise} \end{cases} \qquad m' = \begin{cases} 1, & \text{if } \sum M>0 \\ 0, & \text{else} \end{cases}$$

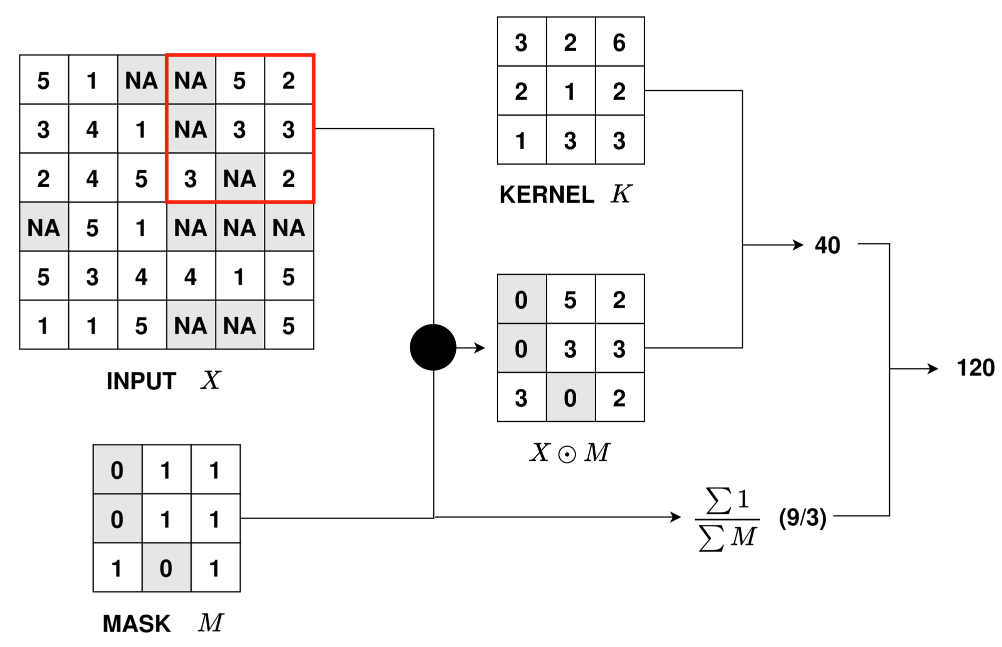

Figure 1: Partial convolution description and example.

Results

- **Validated using AERONET** ground stations observations.
- Area divided into **three zones** for regional analysis.
- Only measurements with angstrom exponent < 0.6 considered to focus on dust episodes filtering finer aerosols.
- **MONARCH dust forecast included** for benchmarking. MONARCH is a online chemical transport model developed at BSC and used operationally in the Barcelona Dust Regional Center. We use MONARCH forecasts initialised from analyses, which assimilate the same VIIRS AOD.

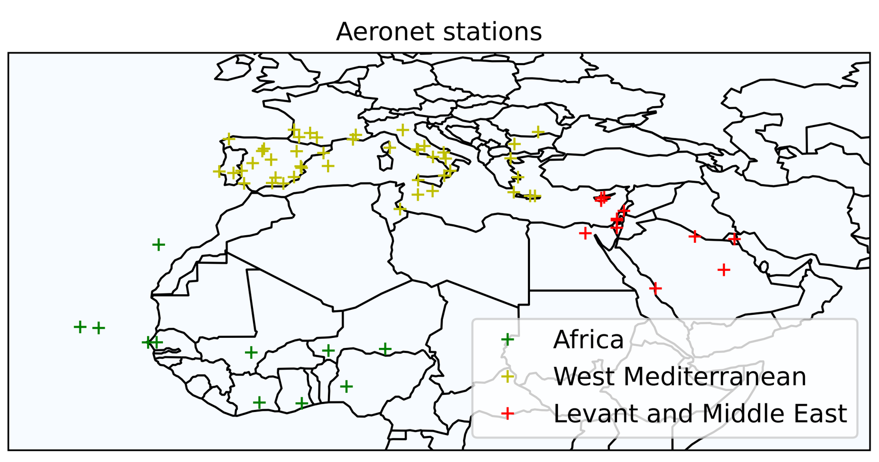

Figure 2: Location and grouping of AERONET network ground stations.

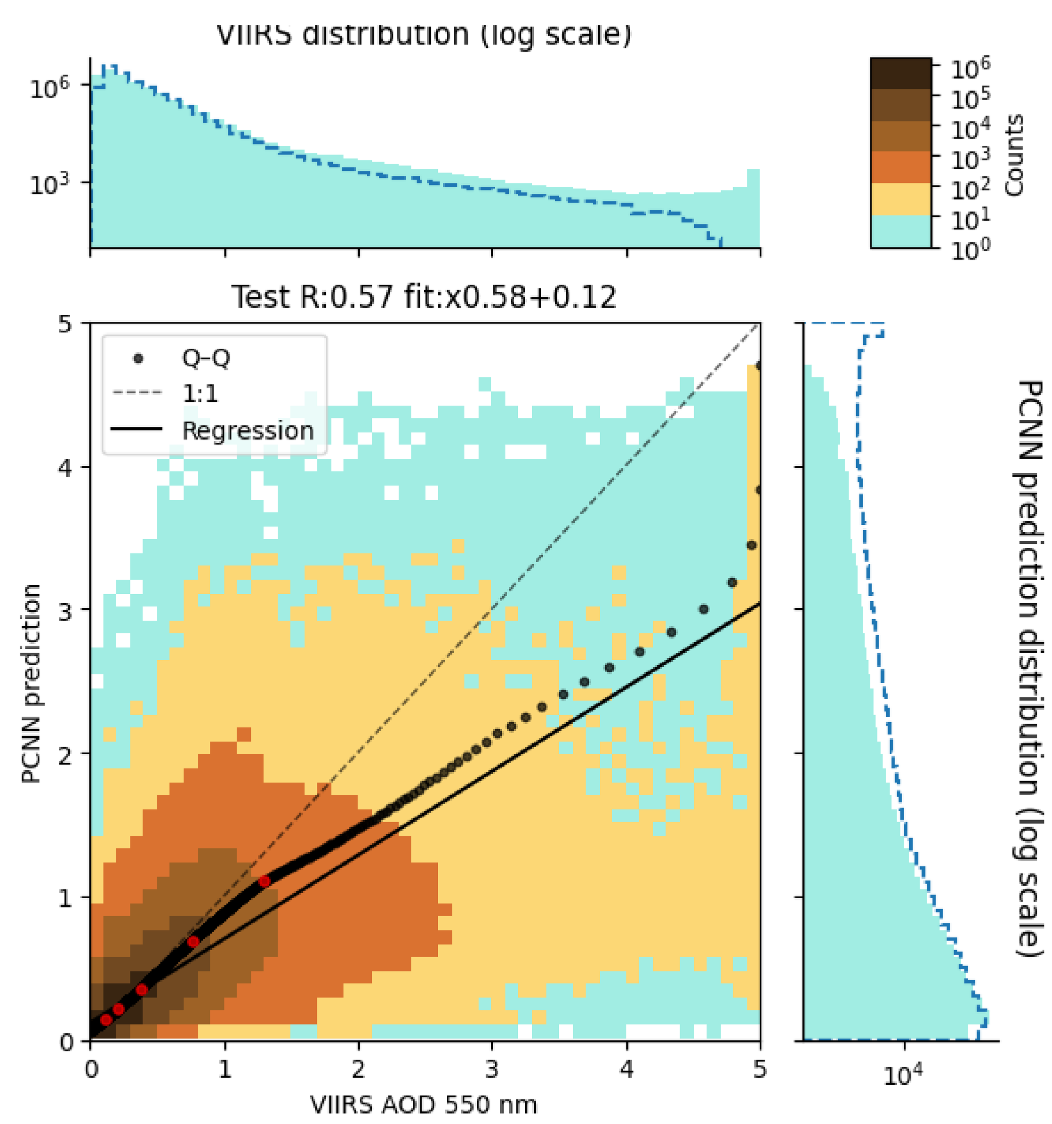

Figure 3: Validation of PCNN predictions against training target.

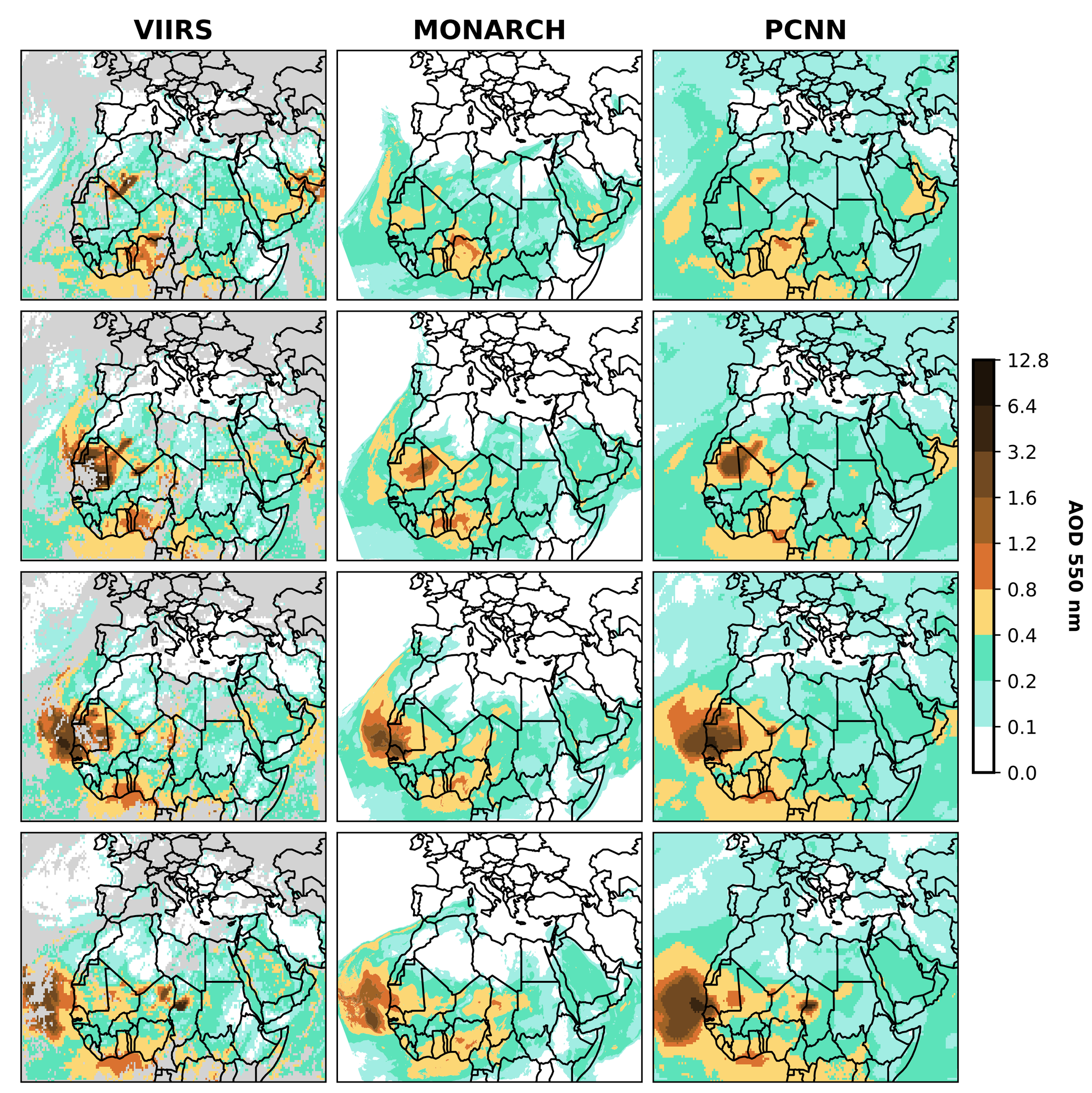

Figure 4: Next day forecast for MONARCH and PCNN compared to satellite image over an episode of dust Atlantic transport from 16-12-2024 to 19-12-2024.

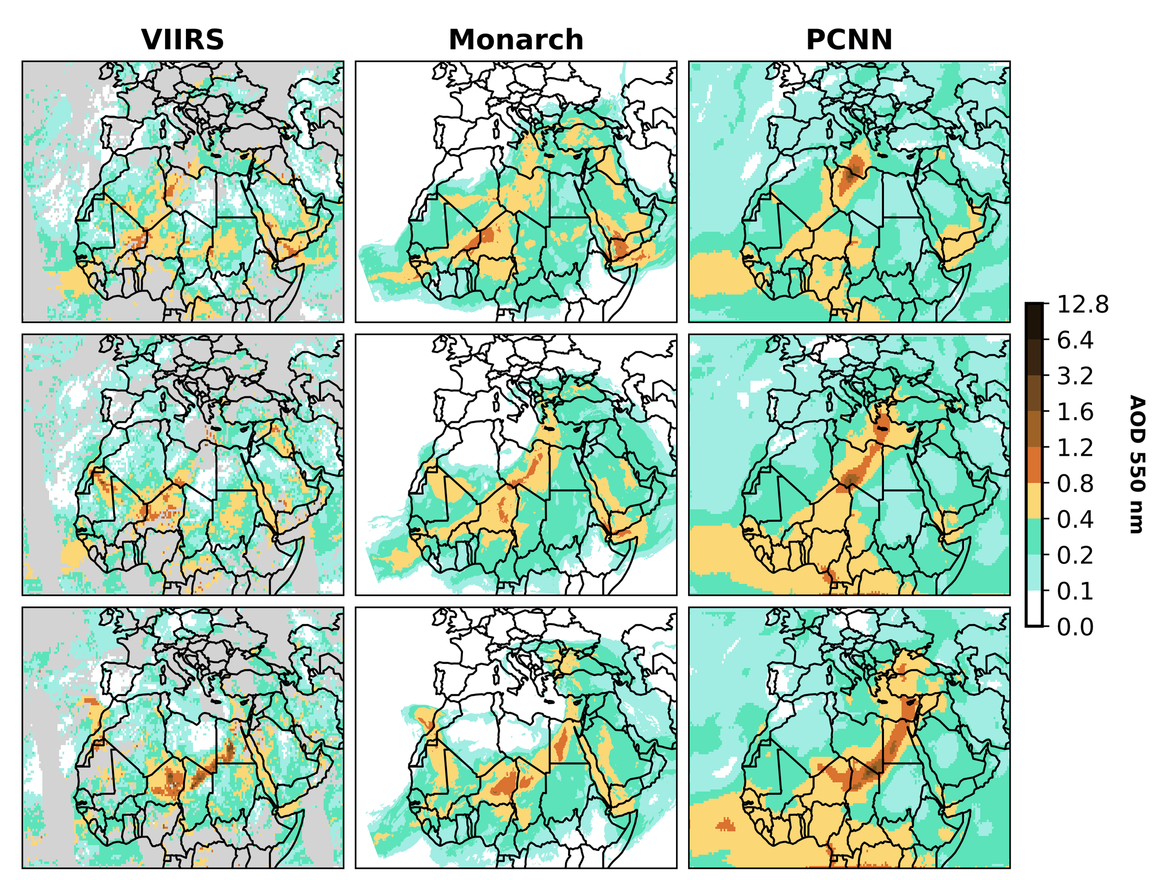

Figure 5: Lead time forecast starting on 08-10-2024.

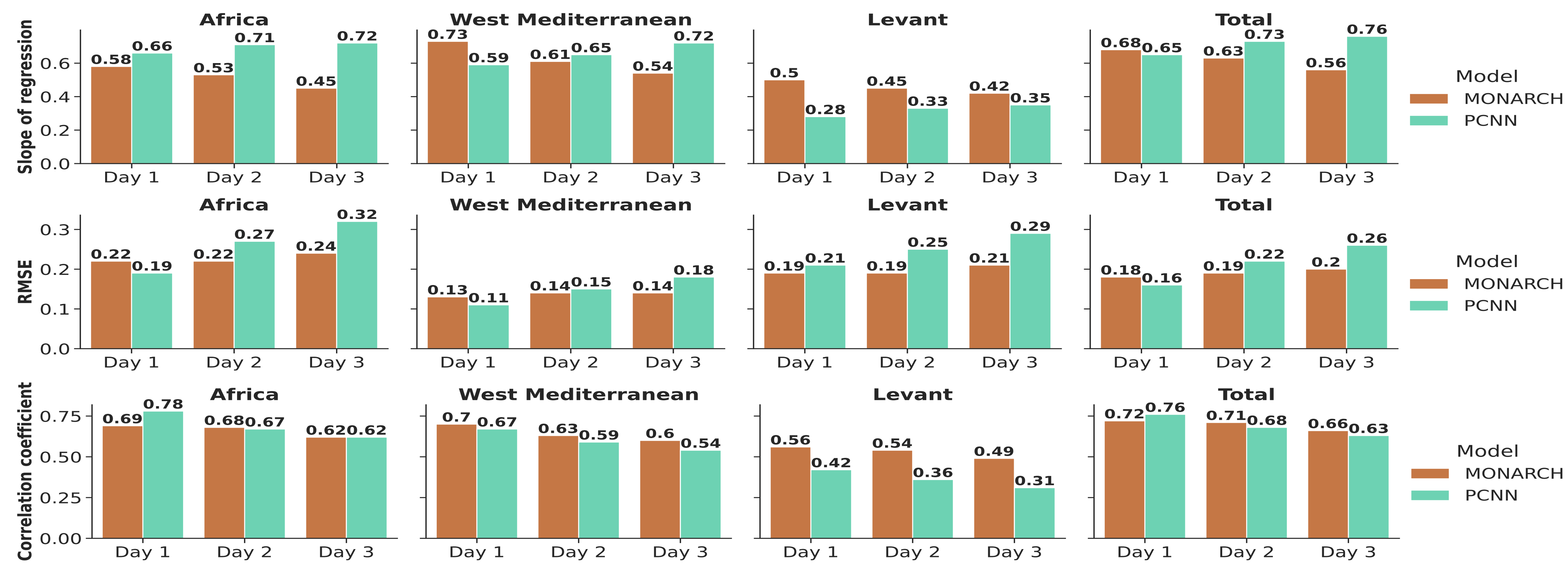

Figure 6: Validation statistics across regions and day forecasted. Red dots correspond to 25, 50, 75, 95 and 99 percentiles.

Conclusion

We present a lightweight deep learning **model that forecasts aerosols in dust-dominant regions up to three days ahead** using partial convolutions. While **performance degrades noticeably as lead time increases, early forecasts remain competitive with those of MONARCH model. Inheriting biases and errors produced by models is avoided** by learning directly from observational data rather than reanalysis products. Our approach circumvents these limitations while maintaining the computational efficiency of deep learning.

Key References

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- MONARCH forecast https://dust.aemet.es/about-us/monarch

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