Ensemble-variational approach to environmental risk assessment of particulate matter

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Air pollution caused by particulate matter (PM) remains a critical environmental and public health risk in urban areas, with particularly severe impacts observed in Chisinau, one of the most polluted cities in the region. This study develops and applies a four-dimensional ensemble-variational (4DEnVar) data assimilation and quasi-dynamic simulations of particulate matter concentrations, specifically designed to support environmental risk assessment through improved monitoring, modeling, and short-term forecasting of PM concentrations. By integrating observational data for PM1, PM2.5, and PM10 collected at the eALERT research monitoring station in Chisinau, the framework enables dynamic estimation of pollution exposure and associated health risks under evolving atmospheric conditions. The 4DEnVar methodology plays a central role in enhancing risk assessment capabilities by providing flow-dependent background error covariance, incorporating anisotropic ensemble-based uncertainty, and eliminating the need for adjoint models. These features allow for robust representation of nonlinear atmospheric processes and uncertainty propagation, which are essential for reliable identification of high-risk pollution episodes. Compared to traditional four-dimensional variational (4DVar) approaches, the 4DEnVar system improves both computational efficiency and the physical consistency of simulated PM fields, making it particularly suitable for operational risk assessment in data-limited or resource-constrained computational environments. Implemented in a cost-effective Python-based environment, the integrated system combines real-time data assimilation, quasi-dynamic simulations, ensemble forecasting, and statistical diagnostics tailored to environmental risk evaluation. Correlation analyses reveal strong interdependencies among PM fractions, indicating common emission sources and compounding exposure risks. Diurnal cycle patterns highlight elevated pollution levels during morning hours, corresponding to increased human exposure and heightened health risk. Model validation demonstrates improved predictive performance, with reduced root mean square error (RMSE) and positive forecast skill, enabling more accurate detection and anticipation of hazardous air quality conditions. Importantly, the 4DEnVar framework supports probabilistic risk assessment by quantifying uncertainty in pollutant concentrations and enabling ensemble-based evaluation of extreme pollution scenarios. The integration of correlation-driven diagnostics further refines background error structures, leading to more reliable forecasts of pollution peaks and duration - key factors in public health risk management.

Reference:

Paladi A., Sprincean V., Leu A., Paladi F. An integrated air quality modeling and forecasting framework using 4DEnVar-based simulations of particulate matter: A case study in Chisinau. Water, Air, & Soil Pollution: An International Journal of Environmental Pollution. 2026, in press.