

Ensemble weather forecasting? Sensitivity analysis would help

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This paper explores the integration of Sensitivity Analysis (SA) with ensemble weather forecasting to improve uncertainty quantification (UQ) in Numerical Weather Prediction (NWP).

Ensemble weather forecasting plays a crucial role in meteorology by representing uncertainty through multiple model simulations, accounting for variability in initial conditions, model dynamics, and external influences. Widely used techniques, such as Stochastically Perturbed Parameterization Tendencies (SPPT) [Buizza et al., 1999, Leutbecher and Palmer, 2008], Stochastically Perturbed Parameterization (SPP) [Ollinaho et al., 2017], Ensemble Data Assimilation (EDA) [Houtekamer and Mitchell, 1998, Bonavita et al., 2012], Singular Vectors (SV) [Buizza and Palmer, 1995] have been fundamental in addressing uncertainties within ensemble forecasting frameworks. However, these methods often operate under assumptions of linearity and Gaussian error distributions, which limit their capacity to fully capture the non-linearities, interdependencies, and broader range of uncertainties inherent in complex atmospheric systems.

Sensitivity analysis [Saltelli, 2008, Saltelli et al., 2004, Iooss and Lemaître, 2015] offers a robust and complementary technique to overcome these limitations by systematically identifying, ranking, and quantifying the influence of input parameters on model outputs. Unlike traditional ensemble methods, SA provides a structured approach for understanding how variations in model parameters impact forecast outcomes, enabling a more comprehensive analysis of non-linear interactions and parameter dependencies. Sensitivity analysis has long been recommended and widely applied for UQ across various scientific domains, including hydrological modeling [Ratto et al., 2007] and environmental studies [Saltelli et al., 2004]. These applications demonstrate the effectiveness of global sensitivity analysis in exploring the multidimensional space of the input parameters and capturing the effects of non-linearity and of interactions among parameters in the model, thereby improving model evaluation and calibration. Its successful implementation in other fields emphasises the potential benefits of integrating SA into ensemble weather forecasting, enhancing the robustness and accuracy of uncertainty representation in meteorological models.

This paper explores the integration of SA into ensemble weather forecasting, demonstrating how this synthesis enhances UQ in NWP models. By integrating SA into ensemble forecasting, we discuss the representation of multivariate uncertainties, how to improve the accuracy of parameter perturbations, and refine probabilistic forecasts. We detail the current ensemble techniques, emphasising how SA can inform the adjustment of perturbation strategies and better capture non-Gaussian error structures. Additionally, SA enables a more accurate representation of joint distributions [Mara et al., 2015], leading to improved identification of critical thresholds and tipping points in model behaviour, particularly for extreme weather events [Bousquet and Bernardara, 2021, Allen et al., 2017]. The integration of SA has the potential to refine stochastic perturbation techniques, such as SPPT and SPP, by providing evidence-based parameter ranges and interdependencies. By incorporating SA, meteorologists can better capture the complexities of atmospheric systems, advancing the accuracy and reliability of probabilistic weather predictions. This work emphasises the need for adopting SA techniques in ensemble forecasting to achieve more comprehensive uncertainty quantification in NWP models while offering meteorologists a more nuanced understanding of model uncertainties, and improving the communication of forecast uncertainty to stakeholders.

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