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Deep Learning Approach to Estimating Uncertainty in the Copernicus Arctic Regional Reanalysis (G2): A Prototype

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Introduction

The **Copernicus Arctic Regional Reanalysis Second Generation (CARRA-2)** is a high-resolution climate data product that covers the pan-Arctic region. It assimilates an extensive time series of observations into the **Harmonie-AROME** model and employs a **3D-VAR** data assimilation system to provide the most accurate estimates of the atmospheric state. Copernicus is the Earth observation component of the European Union's space program. The European Centre for Medium-Range Weather Forecasts (**ECMWF**) has been appointed by the European Commission, with funding from the **EU,** to operate the Copernicus Climate Change Service on its behalf. A key requirement for **CARRA-2** is to compute potential ensemble uncertainties for essential climate variables. This research aims to extend uncertainty estimation to important climate variables within model spaces. Extensive investigations utilizing large ensemble datasets explore the potential relationship between **ERA5-EDA** ensembles and the **CARRA-2** ensemble, particularly regarding ensemble spread. The ultimate goal of this research is to develop an empirical relationship using a machine learning (ML) approach, leveraging both coarser-resolution **ERA5-EDA** data and high-resolution **CARRA-2** data. For uncertainty quantification (**UQ**) between the ensembles, a **deep learning (DL) diffusion model (DM)** has been developed over the **CARRA-2** domain to generate **HUGE** ensemble.

Model: Harmonie-AROME Ensemble, CY46

Data Assimilation: 3D Variational Data Assimilation

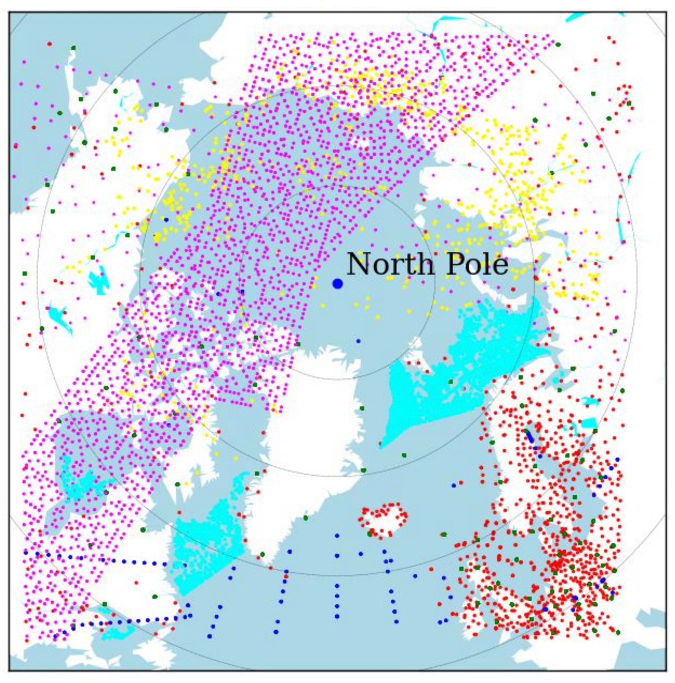
Horizontal Resolution: 2.5 km

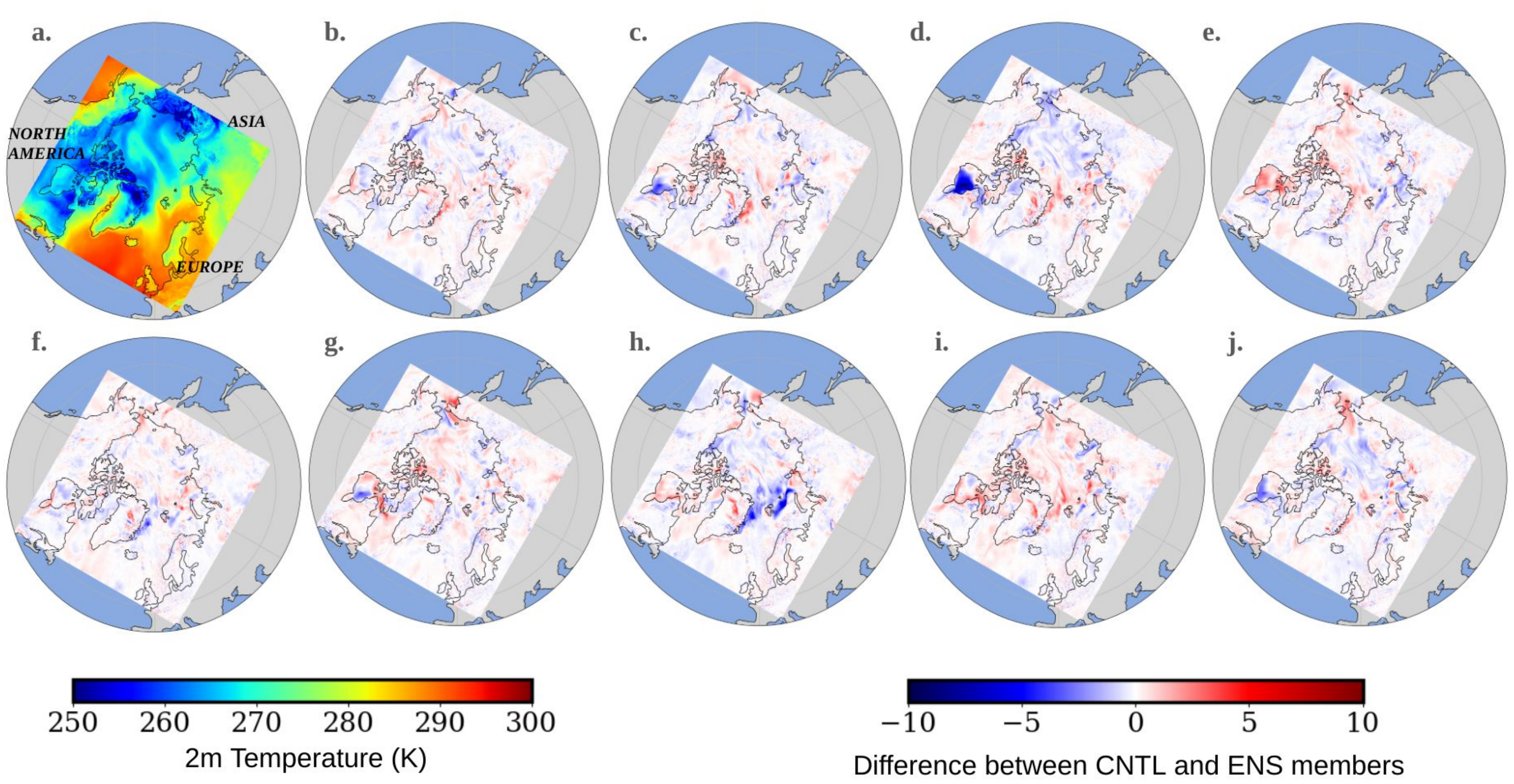
Grid Points: 2880x2880

Vertical levels : 65

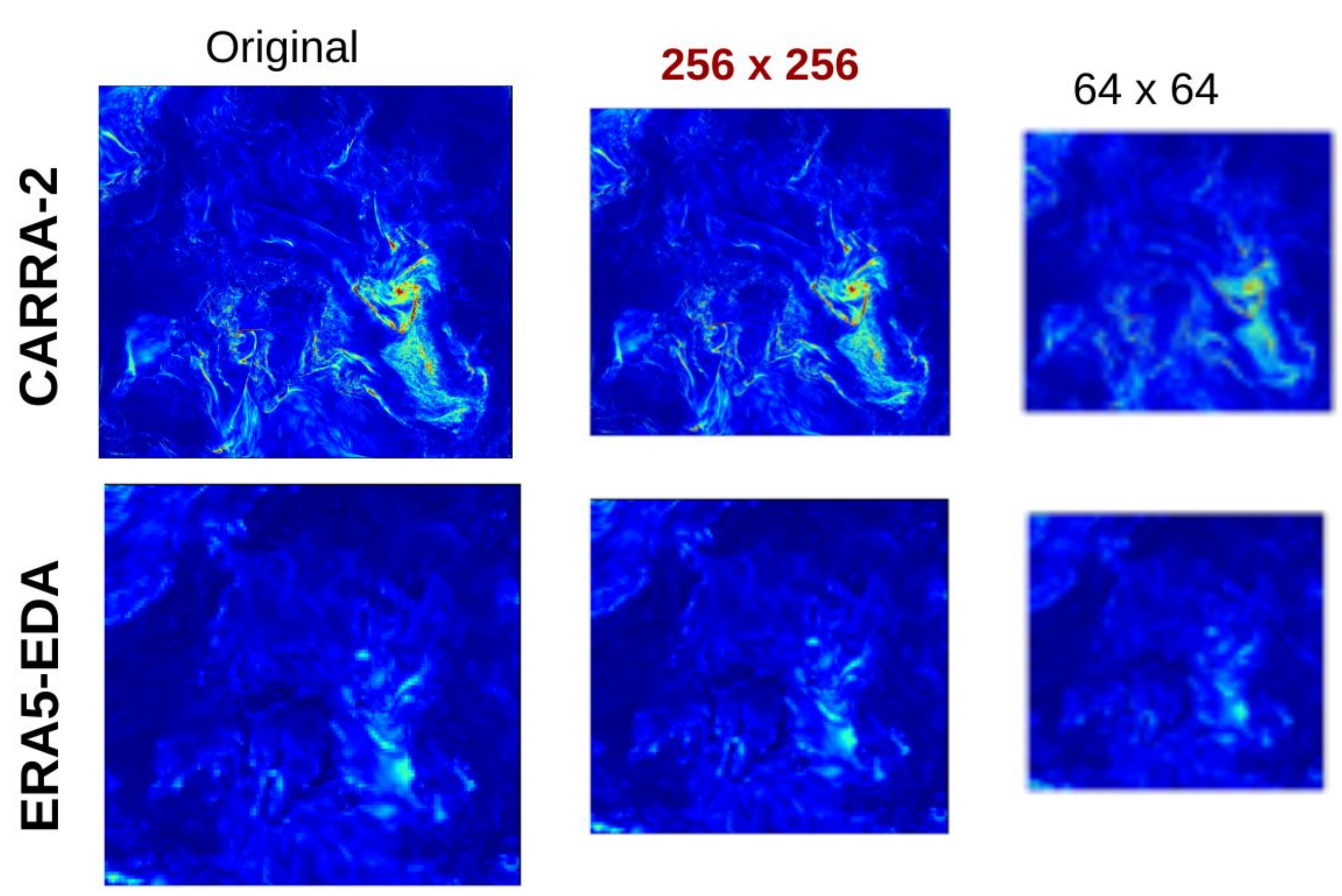
IC/BC: ERA5-EDA

Spatial distribution of assimilated conventional and satellite observations across the study domain valid on 20220101 at 00 UTC.





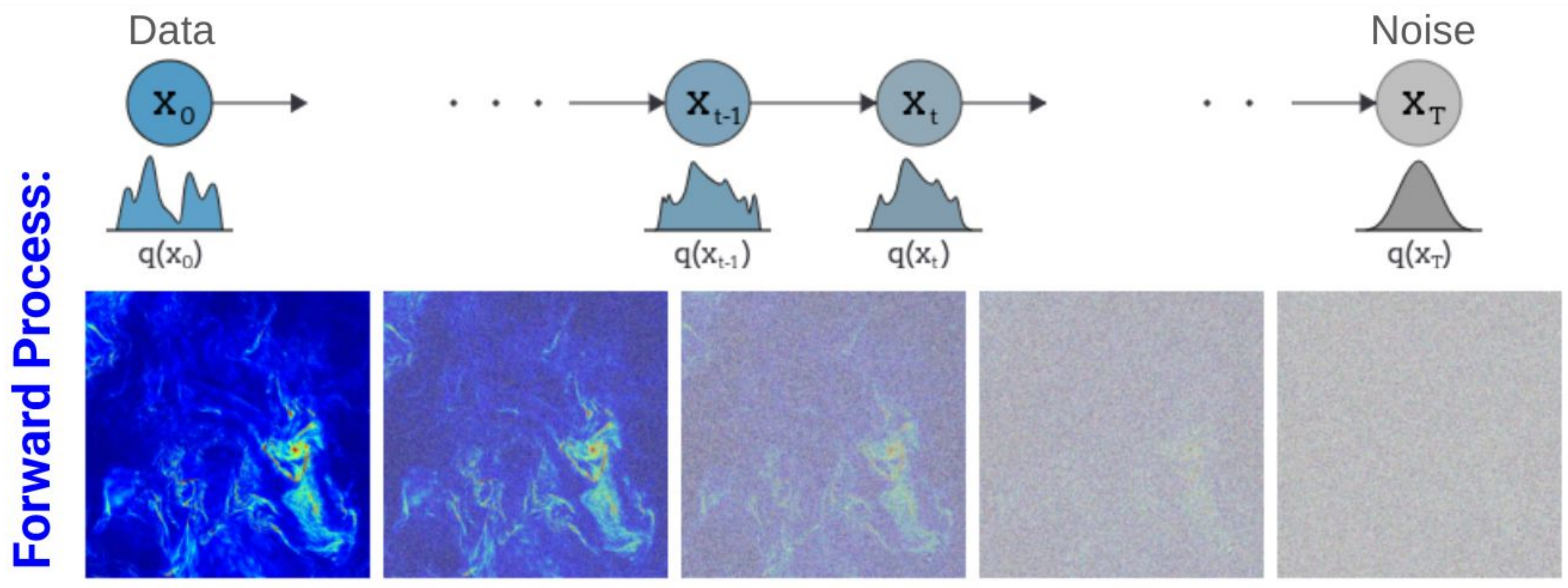
Uncertainty Quantification



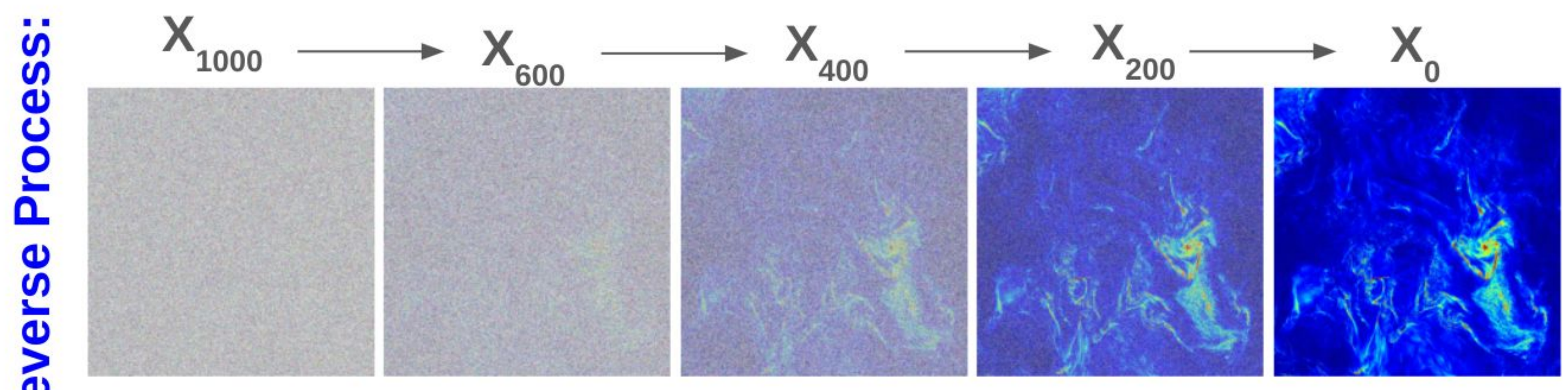
A visual depiction illustrating the conversion of various pixel sizes from the original grid size of (2869 x 2869) to (256 x 256) and to (64 x 65) pixel sizes for the uncertainty images of CARRA2 (shown in the top three panels) and ERA5-EDA (shown in the bottom three panels).

Deep Learning Diffusion Model (DL ⊂ ML ⊂ AI)

Denoising Diffusion Probabilistic Models (DDPM) with Convolutional Neural Networks (**CNN**) utilize CNNs to learn the process of removing noise from data in multiple steps. The CNN helps in capturing spatial patterns effectively, making DDPMs well-suited for generating high-quality ensembles and high-resolution data by progressively refining them through learned noise-reversing transformations.



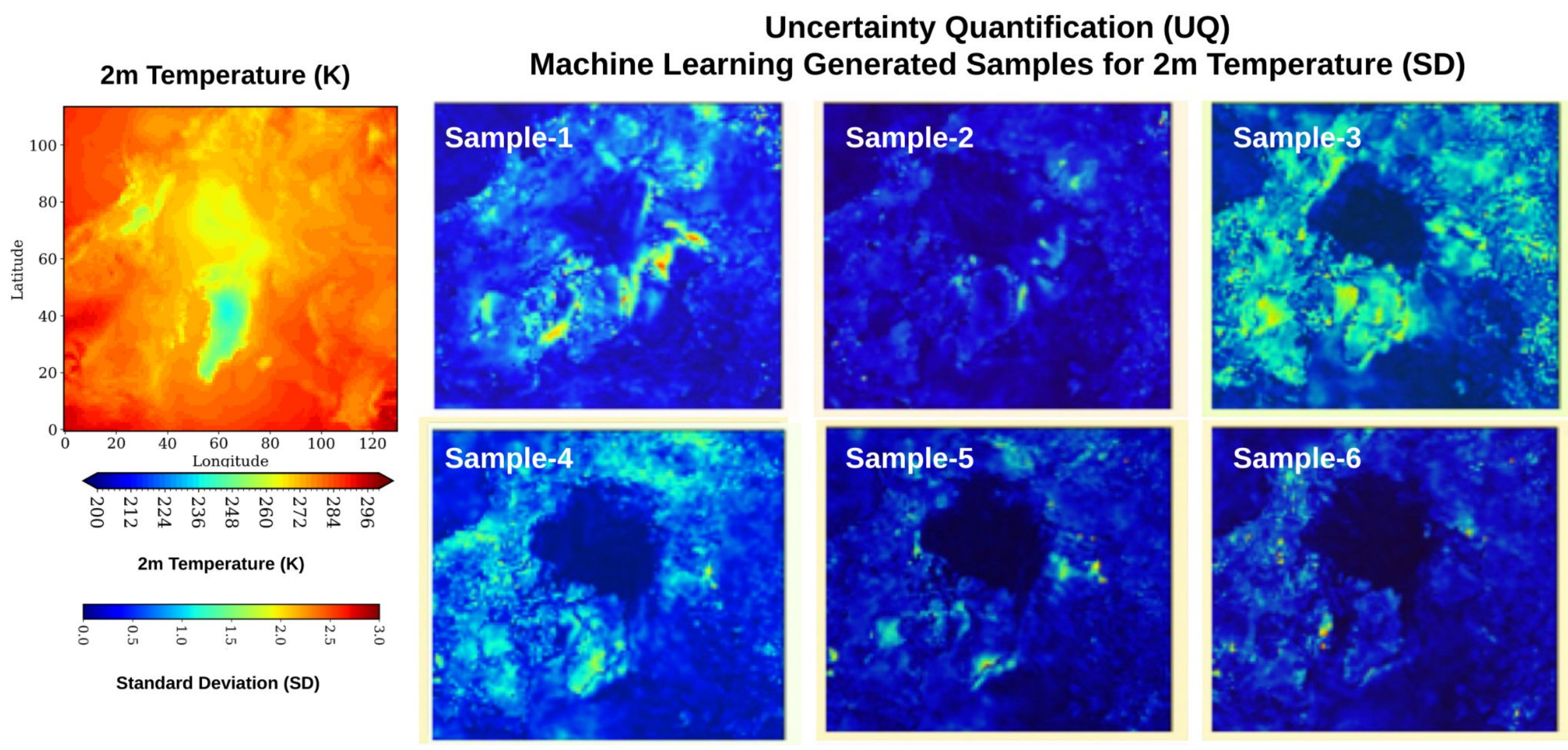
$$q(x_t|x_{t-1}) := \mathcal{N}(x_t; \sqrt{1-\beta_t}x_{t-1}, \beta_t I)$$



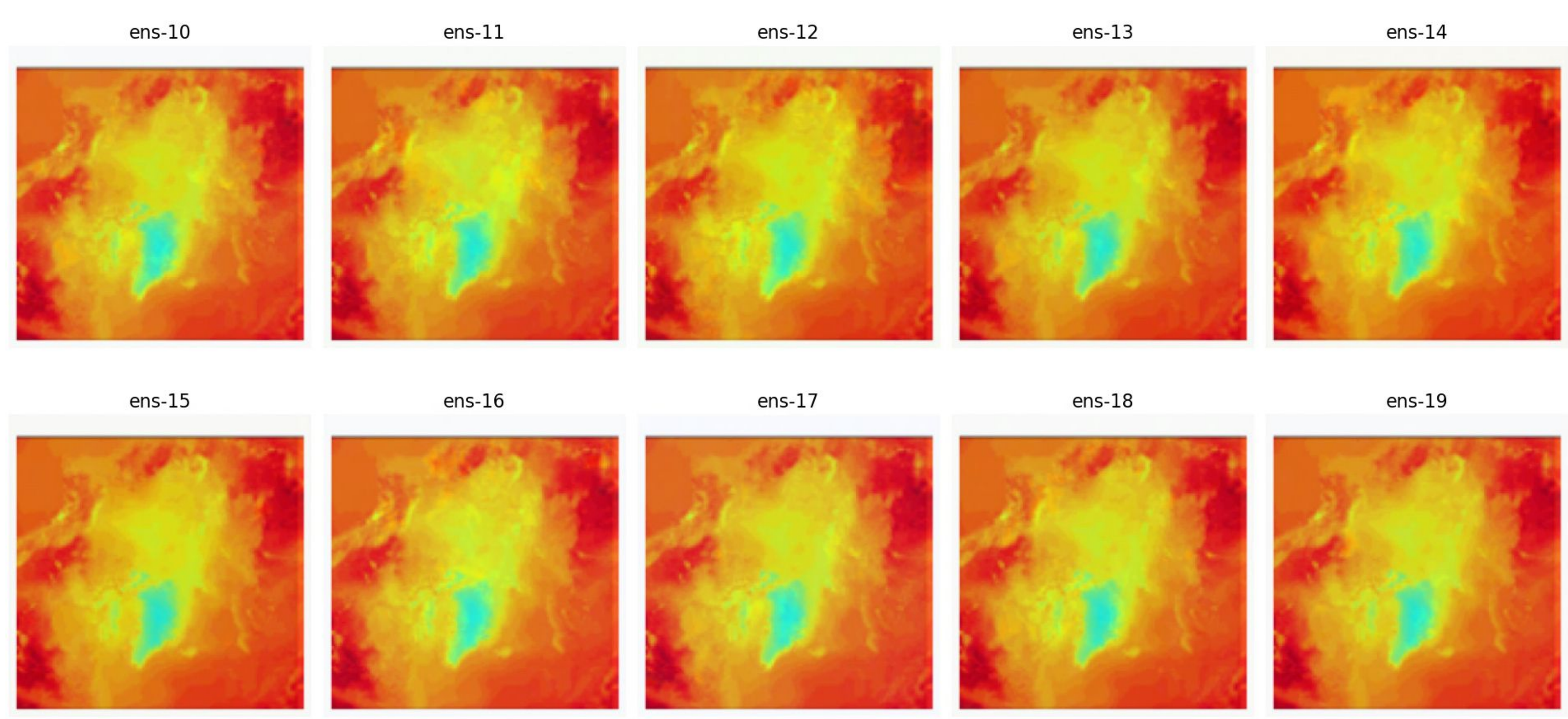
$$p_\theta(x_{t-1}|x_t) := \mathcal{N}(x_{t-1}; \mu_\theta(x_t), \Sigma_\theta(x_t))$$

when $t = 0$, we want to derive a sample x_t based on the clean sample x_0 The purpose of the reverse process P_θ is to approximate the previous step x_{t-1} in the diffusion chain based on a sample x_t. A parameterizable prediction model with parameters ε is used to estimate the error. The reverse process will be **gaussian** if the diffusion steps are large enough. For that reason we will used **4000** step of diffusion step t both **forward and reverse process**.

Results



ML Generated HUGE Ensemble



Next, the process of hyperparameter tuning, particularly when applied to extensive datasets in conjunction with score-based data assimilation (SDA), is crucial for improving the efficacy of machine learning (ML) models.

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