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A Deep Learning Framework for Climate Downscaling: Focusing on Temperature Residual Patterns over the Korean Peninsula

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Global climate models (GCMs), which are widely used for long-term climate projections, typically provide outputs with a spatial resolution of around 100 km. While this is suitable for large-scale analysis, it is insufficient for applications requiring detailed regional or local information, especially in complex geographical areas such as the Korean Peninsula. To address this, downscaling (super-resolution) techniques have been employed; however, conventional methods (e.g. regional climate modelling and statistical interpolation) are computationally demanding and struggle to represent fine-scale variability.

In this study, we propose a deep learning–based climate downscaling framework that focuses on residual temperature patterns to improve spatial representation and ensure applicability to future climate data. The framework combines multiple climate variables with high-resolution terrain information to reconstruct temperature distributions at 1.5 km resolution, which is consistent with the Local Data Assimilation and Prediction System (LDAPS). Low-resolution inputs are provided by ERA5 reanalysis data, including 2-m temperature, 10-m zonal/meridional wind (U10 and V10) and surface pressure. The static variables include terrain features (90 m elevation from the Copernicus DEM and 1 km slope from SRTM) as well as the climatological leaf area index (LAI) from ERA5. Target field is the daily 1.5 m air temperature from LDAPS for the period 2013–2024.

Several deep learning architectures commonly used in weather and climate downscaling are evaluated and compared, including Convolutional Neural Network (CNN), Generative Adversarial Network (GAN), and transformer-based models. Model performance is assessed at both the snapshot level (pattern correlation, structural similarity index measurement (SSIM), bias, root mean square error (RMSE)) and the grid-wise level (spatial maps of bias, RMSE, and variability ratios), providing complementary perspectives on performance. Real observational data from Korean weather stations (ASOS, AWS) are used for independent validation.

Our results demonstrate the effectiveness of AI-based downscaling in producing reliable, high-resolution temperature estimates from coarse-resolution climate data while taking terrain into account. The proposed approach offers a scalable and computationally efficient alternative to traditional dynamical downscaling and shows promise for future applications in paleoclimate reconstruction and climate change scenario analysis.

Keywords: Korean Peninsula, Downscaling, Deep Learning, High-resolution Data