Regional climate modeling using numerical simulations and artificial intelligence

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1. Project Purpose

The objective of this project is to explore regional weather patterns, focusing particularly on extreme events and the factors that influence them, especially in the context of global warming. This project employs advanced numerical modeling and artificial intelligence techniques. Specifically, the project utilizes state-of-the-art, convection-resolving numerical models such as the Weather Research & Forecasting (WRF) model and Cloud Model 1 (CM1). These models are operated at kilometer or higher resolutions over extended periods (several decades) and across multiple regions globally. Attention is paid to the impacts of terrain and land use on localized wind fields and precipitation patterns. Additionally, the project incorporates machine learning methods, such as clustering techniques, to analyze large sets of climate data. This approach is designed to unearth patterns within the data and enhance the accuracy of future predictions.

2. Results

Numerical fine-resolution climate simulation were conducted with the WRF model across various regions with diverse climatic conditions, including Japan, Vietnam, and India. The research primarily focuses on the impact of terrain on wind patterns and their subsequent effects on temperature phenomena, specifically the Foehn phenomenon. The studies thoroughly examine the dynamics and thermodynamics involved in how terrain, wind, and extreme heat interact (Kusaka et al., 2023; 2024).

The study explored another aspect of climate change, specifically how urban transformations aimed at cooling, such as the application of high-albedo materials in cities, could affect local climate patterns. The research highlighted the significant impact of urban cooling strategies on boundary layer development and lower atmosphere circulation, with the case study of the tropical city of Kolkata, India (Khan et al., 2023).

Additionally, we introduced a novel climate downscaling approach that utilizes the land surface model. This method, termed land surface physical-based downscaling (LSP-DS), has been applied in various studies, including those

examining its potential for agrometeorological predictions and interactions between heat waves and urban heat islands. Initial results from these studies have been published in SOLA (Nguyen et al., 2023).

Furthermore, we proposed a framework for evaluating clustering uncertainty using the concept of mutual information. This is the first attempt to address the uncertainty issues in clustering weather patterns, introducing a criterion that could potentially change the current framework for clustering climate data. The descriptive paper has been published in Geoscientific Model Development (Doan et al., 2023).

3. Roles of the MCRP and its significance

To thoroughly understand regional atmospheric phenomena, high-resolution numerical simulations are essential. For example, the urban heat island effect significantly influences localized thunderstorms by increasing atmospheric instability and convection. Terrain also critically affects localized wind patterns, cloud formation, and precipitation—details often missed in coarse-resolution simulations. Additionally, precipitation formation involves complex atmospheric microphysical processes, which introduce significant uncertainty in simulations. To achieve reliable results, long-term model runs are vital, as they help capture the entire spectrum of variability inherent in these phenomena.

4. Future plan

Examining the change in extreme urban precipitation and local wind is a critical task, albeit a challenging one due to significant uncertainties in simulations. To address this, it is necessary to expand the scope of research to encompass various regions with diverse climates and geographical characteristics. Additionally, investigating how extreme precipitation and local wind in different seasons responds to the effects of global warming holds substantial value and can provide valuable insights.

Additionally, we plan to utilize advanced AI and ML techniques such as Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs) for fine-scale climate prediction. The initial results will provide a foundation for addressing crucial challenges, such as developing AI systems tailored for weather forecasting.

5. Publications and conference presentations

(1) Journal papers

- Kusaka H, Imai Y, Kobayashi H, Doan Q-V, Ngo-Duc T. 2024. Influence of foehn winds of Truong Son Mountains on the high temperatures observed in North-

Central Vietnam during May 31-June 5, 2017. *Journal of Applied Meteorology and Climatology*. American Meteorological Society, 1(aop). https://doi.org/10.1175/JAMC-D-23-0010.1.

- Kusaka H, Nishiba S, Asano Y. 2024. Why Does Japan's South Foehn, "Jintsu-Oroshi," Tend to Onset during the Night?: An Investigation Based on Two Case Studies. *Journal of Applied Meteorology and Climatology* 63 (2). https://doi.org/10.1175/JAMC-D-23-0063.1.
- Nguyen D-M, Doan Q-V, Trinh HD, Nguyen T-H, Khanh DN, Phan DC, Tran T-T, Nguyen H-V, Bui T-M. 2023. Land Surface Physics-Based Downscaling Approach for Agricultural Meteorological Prediction: Applicability for Tropical-Monsoon Region, the Red River Delta, Vietnam. *SOLA*, 19: 298–306. https://doi.org/10.2151/sola.2023-039.
- Khan A, Carlosena L, Khorat S, Khatun R, Das D, Doan Q-V, Hamdi R, Aziz SM, Akbari H, Santamouris M, Niyogi D. 2023. Urban cooling potential and cost comparison of heat mitigation techniques for their impact on the lower atmosphere. *Computational Urban Science*, 3(1): 26. https://doi.org/10.1007/s43762-023-00101-1.
- Doan Q-V, Amagasa T, Pham T-H, Sato T, Chen F, Kusaka H. 2023. Structural *k*-means (S *k*-means) and clustering uncertainty evaluation framework (CUEF) for mining climate data. *Geoscientific Model Development*. Copernicus GmbH, 16(8): 2215–2233. https://doi.org/10.5194/gmd-16-2215-2023.

(2) Presentations

- Chen F, He C, Doan QV, Niyogi D, Di L, 2023. Extreme Precipitation Trend in Multiple Urban Systems. *104th American Meteorological Society Annual Meeting*, Baltimore, USA.
- Chen F, He C, Doan QV, Niyogi D, 2023. Investigate Extreme Precipitation in Multiple Urban Systems. *Asia Oceania Geosciences Society 2023 Annual Meeting*, Singapore.
- Xue L, Doan QV, Kusaka H, He C, Chen F, 2023. Performance Evaluation of a Land-surface-physics-based Downscaling Approach for Urban Thermal Environment Prediction. *Asia Oceania Geosciences Society 2023 Annual Meeting*, Singapore.
- Doan QV, et al., 2023. Fine-scale Climate Change Information to Assist Decision Making: The CORDEX SEA Urban Climate Initiative. *Asia Oceania Geosciences Society 2023 Annual Meeting*, Singapore.

- Angela Monina Ticobay Magnaye, Hiroyuki Kusaka, 2023. Sensitivity tests of WRF-UCM simulations of extreme heat events in Metro Manila. Nonhydrostatic Workshop, Sapporo, Japan.

(3) Others

Supercomputer	Use	Allocated resources*		
		Initial resources	Transferred resources**	Additional resources
Cygnus	Yes/No	10,000		
Pegasus	Yes/No			
Wisteria/BDEC-01	Yes/No	100,000		
	*in units of node-hour product ** If the budget transfer was performed, fill in here, such as "+2000" and "−1000".			