A Novel Physics-Informed Neural Network Approach for Downscaling Local Circulation in Taiwan

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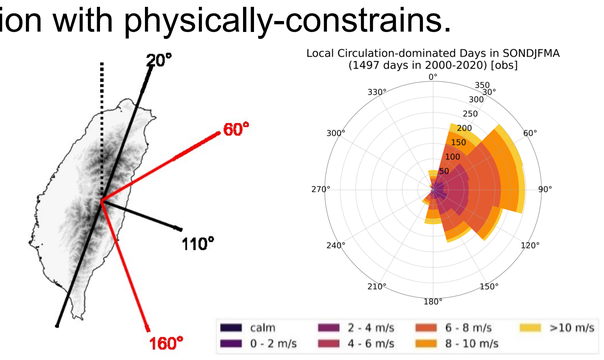
Abstract

Data-driven Artificial Intelligence (AI) and Deep Learning (DL) models have revolutionized weather forecasting by reducing computational costs, offering a promising alternative to numerical weather prediction (NWP) models. However, concerns persist regarding the accurate representation of scientific relationships in purely data-driven DL models. We address these challenges by employing physically-constrained training data derived from semi-realistic TaiwanVVM large ensemble simulations, focusing on local circulation-dominated days influenced by diverse synoptic factors. Through VAE, we learn the representation of training data, effectively conveying the physics of vortex formation and variability under various synoptic conditions. Our findings reveal that the learned latent manifold in VAE corresponds to controlling synoptic flow regimes. As a reduced-order model, VAE efficiently evaluates Taiwan's high-fidelity local circulation, offering a valuable tool for assessing local impacts under different future climate scenarios. This approach is particularly advantageous for applying machine learning neural network models to scientific inquiries, ensuring transparency, interpretability, and explainability.

TaiwanVVM Semi-Realistic Large Ensemble

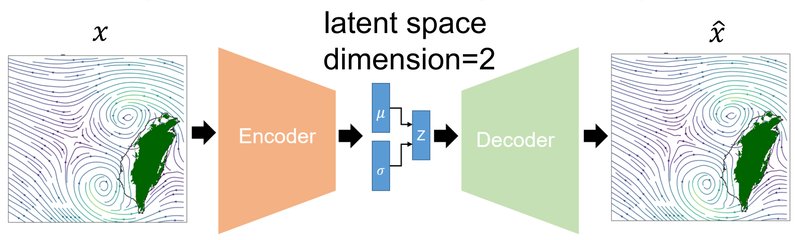
- Previous studies suggested that the local circulation associated with the lee vortex is sensitive to slight changes in synoptic wind directions. (Lai and Lin, 2020; Hsieh et al., 2022, Hsu et al., 2023)
- By excluding strong synoptic forcing weather regimes, we identify the local circulation-dominated days to examine the variability of the synoptic conditions.
- The windrose indicates that the prevailing winds of local circulation-dominated days favor the formation of the lee vortex.
- We select 197 semi-realistic TaiwanVVM (Wu et al., 2019) simulations to generate a dataset that depicts the variability of local circulation with physically-constrains.



Physics-Informed Variational Autoenocder

Variation Autoencoder:

- VAE (Kingma & Welling,2014; 2019) is a unique neural network framework that creates a continuous latent space in which the representation of the variability of the input data can be captured.
- As we take the semi-realistic simulations as the training data of the VAE, the model physics of TaiwanVVM can be informed to the VAE so that the VAE can learn physics instead of overfitting the training data.

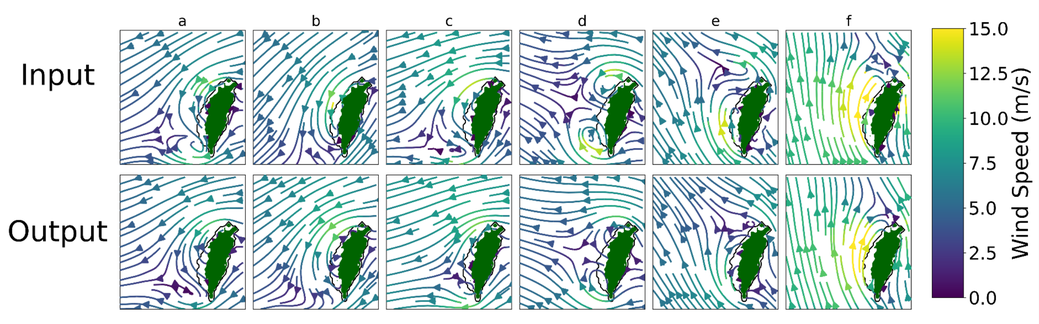


$$loss_{VAE} = loss_{reconstruction} + \beta loss_{regularization}$$

$$= \sum_{x \in X} \|x - \hat{x}\| + \beta D_{KL}[\mathcal{N}(Z_\mu, Z_\sigma) || \mathcal{N}(0, I)]$$

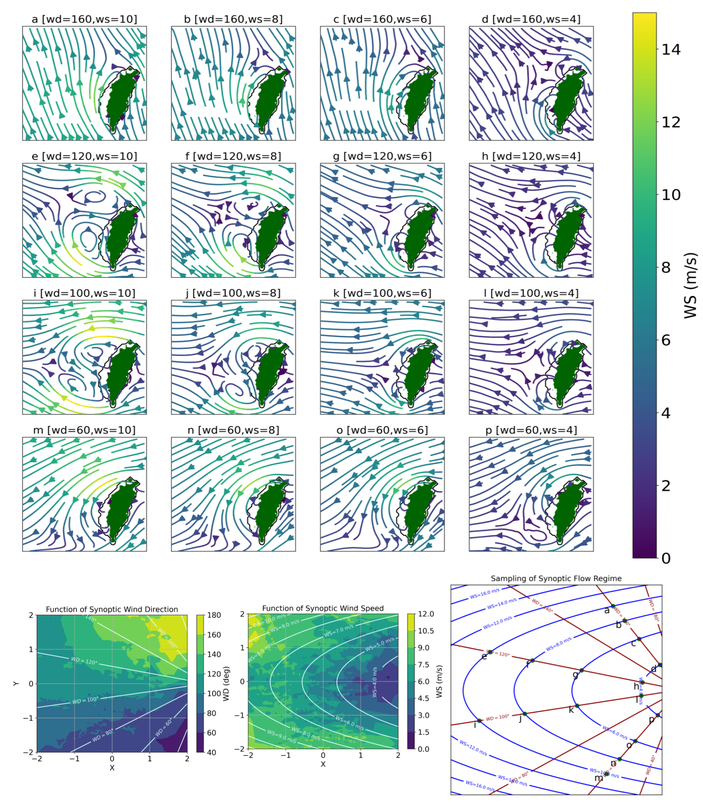
Reconstruction performance:

- The reconstructed local flow exhibits a pattern akin to the corresponding input data, showing that the VAE has the capability to generate plausible local circulations that adapt to distinct prescribed synoptic flow regimes, a feature evident from our scrutiny of the semi-realistic simulations.

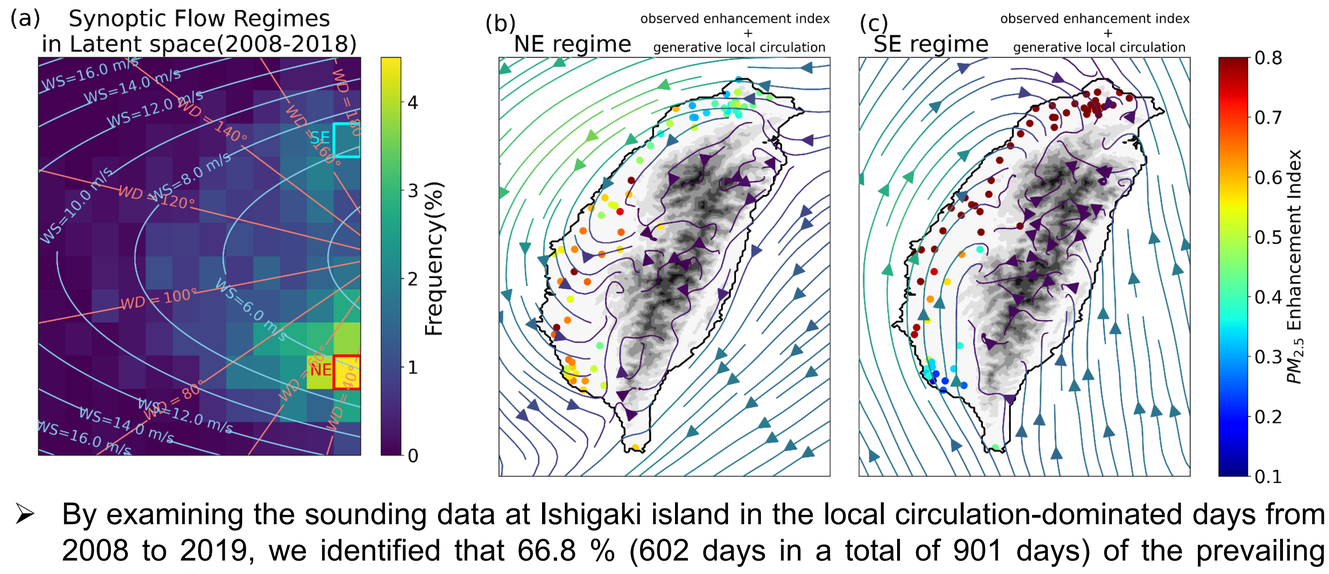


Physically-interpretable Latent Space

- VAE learned from semi-realistic simulations can generate reasonable flow patterns associated with the lee vortex.
- In the 2-dimensional latent space, the different characteristics of the prescribed synoptic winds of the simulations are separated, highlighting the role of synoptic variability on the local circulations.
- We transform the latent space into physical parameters-based coordinates, which are synoptic wind speed and direction.
- The essential factors responsible for the variability of the local circulation in the training data are aligned with the synoptic flow regimes that drive the diverse local circulation scenarios in the semi-realistic ensemble simulations, indicating that the physical mechanism of the local turbulence associated with the topography induced by synoptic conditions is extracted by the VAE.



VAE serves as a Reduced-Order Model



- By examining the sounding data at Ishigaki island in the local circulation-dominated days from 2008 to 2019, we identified that 66.8 % (602 days in a total of 901 days) of the prevailing synoptic flow regimes are encompassed within the latent space.
- The generated high-fidelity local circulation provides a physical interpretation of the local $PM_{2.5}$ deteriorated by local transport.
- The VAE serves as a reduced-order model(ROM) that is explainable for human interpretation to increase the trustworthiness of prediction by the neural network model.
- This ROM can evaluate the local circulation of Taiwan under various warming scenarios with much higher efficiency and save much computation resources.

Reference

- Hsieh, M.-K., Chen, Y.-W., Chen, Y.-C., & Wu, C.-M. (2022). The Roles of Local Circulation and Boundary Layer Development in Tracer Transport over Complex Topography in Central Taiwan. Journal of the Meteorological Society of Japan. Ser. II, 100(3), 555–573. https://doi.org/10.2151/jmsj.2022-028
- Hsu, T.-H., Chen, W.-T., Wu, C.-M., & Hsieh, M.-K. (2023). The Observation-Based Index to Investigate the Role of the Lee Vortex in Enhancing Air Pollution over Northwestern Taiwan. Journal of Applied Meteorology and Climatology, 62(3), 427–439. https://doi.org/10.1175/JAMC-D-22-0102.1
- Kingma, D. P., & Welling, M. (2019). An Introduction to Variational Autoencoders. Foundations and Trends® in Machine Learning, 12(4), 307–392. https://doi.org/10.1561/2200000056
- Kingma, D. P., & Welling, M. (2022). Auto-Encoding Variational Bayes (arXiv:1312.6114). arXiv. http://arxiv.org/abs/1312.6114
- Lai, H.-C., & Lin, M.-C. (2020). Characteristics of the upstream flow patterns during PM2.5 pollution events over a complex island topography. Atmospheric Environment, 227, 117418. https://doi.org/10.1016/j.atmosenv.2020.117418
- Wu, C.-M., Lin, H.-C., Cheng, F.-Y., & Chien, M.-H. (2019). Implementation of the Land Surface Processes into a Vector Vorticity Equation Model (VVM) to Study its Impact on Afternoon Thunderstorms over Complex Topography in Taiwan. Asia-Pacific Journal of Atmospheric Sciences, 55(4), 701–717. https://doi.org/10.1007/s13143-019-00116-x

Acknowledgment: This material is based upon work supported by the National Science and Technology Council under 國科會卓越領航計畫--山區雲氣候計畫NSTC-112-2123-M-002-006.