Environmental Computational Science
and Earth Observation Laboratory

Semester project subject

Topography-aware Weather Forecasting in Europe: A Focus on Heatwaves

<u>Context</u>

Weather and climate extremes strongly affect many aspects of our society and the environment surrounding us. In recent years, the probability and intensity of extreme events have been amplified in a warming world, leading to devastating consequences for economies and communities. Therefore, we are in urgent need of reliable predictions of weather conditions, particularly extreme events, on time scales from hours to months ahead[1].

Traditionally, weather forecasting has been approached using numerical methods based on general circulation models (GCMs) by representing systems of differential equations across the globe. However, GCMs suffer from the challenge in representing physical processes at fine resolutions, as well as the tremendous computation burden in data assimilation and computational simulations[2]. In contrast, data-driven methods show a steady rise in recent years. By training deep neural networks on large-scale datasets (e.g., the ERA-5 reanalysis dataset[3]) to predict target atmospheric variables, these models[2, 4, 5] now achieve not only competitive accuracy but also faster inference speed compared to numerical methods.

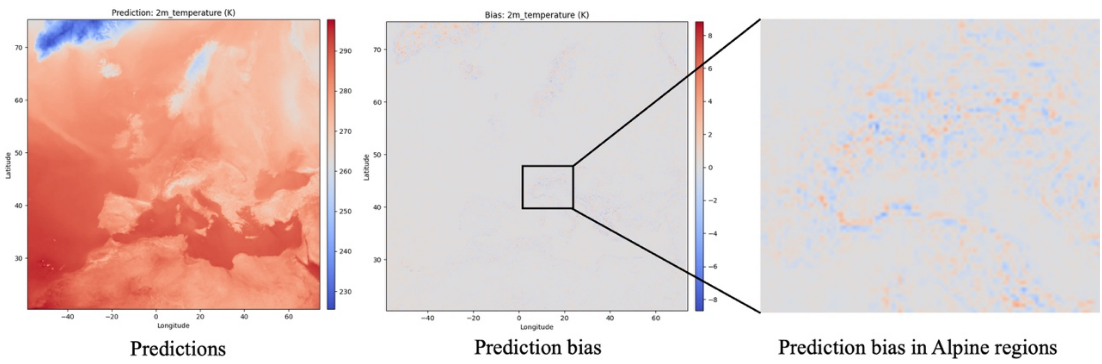

Figure 1: An illustration of temperature predictions, prediction bias and regional bias in the CERRA datasets. This figure illustrates the strong prediction bias related to geo-locations in deep neural networks (ViT).

However, when solving high-resolution weather forecasting in local regions with deep learning, significant errors often arise due to topographic variability. Most current deep learning models operate in a topography-agnostic manner: they typically treat forecasting as a standard time

ECEO

EPFL ENAC IIE
Devis Tuia, Prof.
Rue de l'Industrie 17
Case Postale 440
CH – 1951 Sion

Téléphone : +41 21 69 382 83 (secr).
E-mail : devis.tuia@epfl.ch

series prediction task, overlooking the intrinsic topography that influences atmospheric conditions, leading to errors in regions with complex terrain. As illustrated in Figure 1, a prediction map over Europe reveals severe biases in the Alpine regions with errors that are closely related to the mountain's complex terrain. This motivates us to think about leveraging the topography prior to enhance the forecasting performance of deep neural networks. Understanding the value of topography information in weather forecasting not only enhances model performance but also lays the foundation for broader deep learning-based climate modelling applications, including downscaling, climate projections, and extreme event analysis.

Project

In this project, we are going to explore *topography-aware weather forecasting in Europe* by first evaluating the relationship of elevation map with atmospheric variables. We will then design strategies to incorporate topography prior into the deep neural network to enhance the forecasting results (Figure 2). Specifically, this project will:

• Assess the relationship between topography information (elevation map) and the forecasting of atmospheric variables (2m temperature), as well as the prediction of heatwaves.

• Implement deep learning methods for weather and heatwave forecasting, design methods to incorporate elevation maps into these models through two main strategies: feature fusion[6] and physics-informed constraints[7].

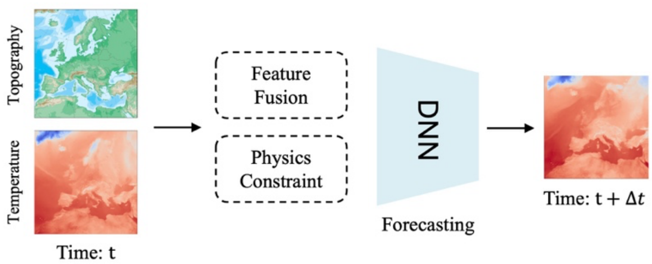

Figure 2: Overview of this project. We will explore the utility of topography information for weather forecasting with feature fusion strategies and physics constraint.

The project will primarily involve climate data processing, model design, training, and evaluation. By taking this study, the project will provide valuable insights into the utility of topography for weather forecasting and help advance the use of geographic prior for climate modelling in a broader field of study.

Requirements

• Experience or strong interest in remote sensing, climate modelling, and deep learning.

• Proficiency in Python and relevant libraries (e.g., pytorch, netcdf4, numpy, matplotlib).

• Strong willingness to learn and ability to work independently and interest in contributing to projects with real-world environmental impact.

Literature

[1] Materia, Stefano, et al. "Artificial intelligence for climate prediction of extremes: State of the art, challenges, and future perspectives." *Wiley Interdisciplinary Reviews: Climate Change* 15.6 (2024): e914.

[2] Nguyen, Tung, et al. "ClimaX: A foundation model for weather and climate." International Conference on Machine Learning. PMLR, 2023.

ECEO

EPFL ENAC IIE
Devis Tuia, Prof.
Rue de l'Industrie 17
Case Postale 440
CH – 1951 Sion

Téléphone : +41 21 69 382 83 secr.
E-mail : devis.tuia@epfl.ch

[3] Hersbach, Hans, et al. "The ERA5 global reanalysis." Quarterly journal of the royal meteorological society 146.730 (2020): 1999-2049.
[4] Gao, Zhihan, et al. "Earthformer: Exploring space-time transformers for earth system forecasting." Advances in Neural Information Processing Systems 35 (2022): 25390-25403.
[5] Nguyen, Tung, et al. "Climatelearn: Benchmarking machine learning for weather and climate modeling." Advances in Neural Information Processing Systems 36 (2023): 75009-75025.
[6] Lian, Jie, et al. "TerraWind: A deep learning-based near-surface winds downscaling model for complex terrain region." Geophysical Research Letters 51.23 (2024): e2024GL112124.
[7] Harder, Paula, et al. "Hard-constrained deep learning for climate downscaling." Journal of Machine Learning Research 24.365 (2023): 1-40.

Contact
Chang Xu, chang.xu@epfl.ch
Prof. Devis Tuia, devis.tuia@epfl.ch