ClimAI: Meteorological Predictions with Vision Transformers

NAML NAVAL APPLICATIONS OF MACHINE LEARNING

noblis

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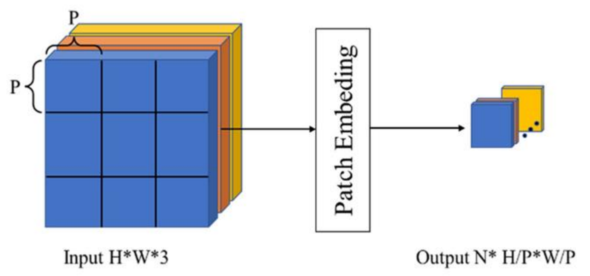
KEY POINTS

- **Extreme and unpredictable weather conditions are worsening existing security risks.**
- **Existing numerical weather prediction (NWP) models are computationally intensive and expensive, requiring long processing times and significant compute resources.**
- **Foundational machine-learning (ML) based methods require less time and less computationally expensive resources.**

BACKGROUND

- Department of Defense (DoD) incurred estimated damages of **$4 to $5 billion from extreme weather events.** (Hauptman 2022)
- Ensemble forecasts represent the majority of computational expenses at NOAA R&D and operations **($4.55 Billion)** (NOAA 2024)

Damaged incurred by Hurricane Michael at Tyndall Air Force Base, Florida. (DVIDS, n.d.)

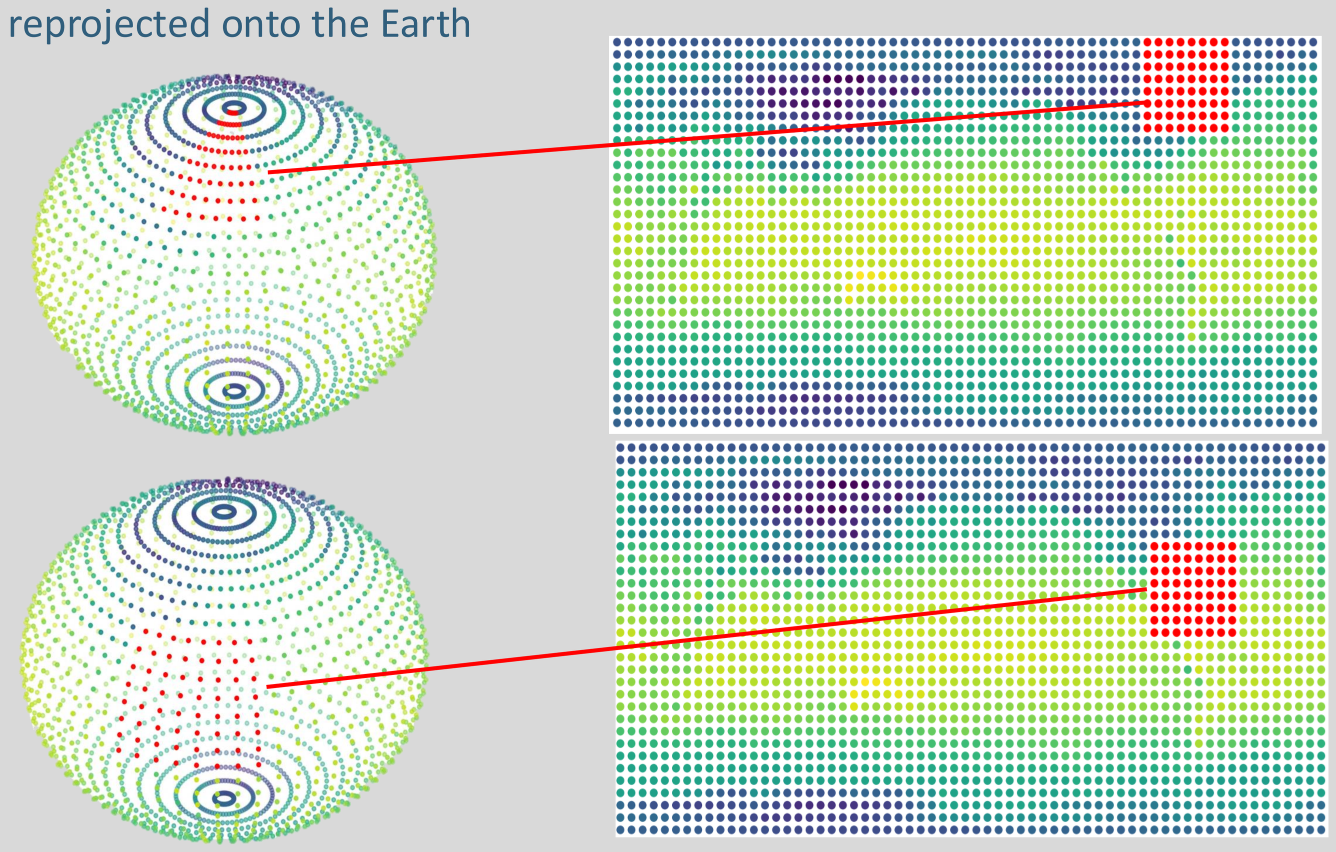


DATA & METHODS

- We introduce a novel method for processing regions that overlap the anti-meridian by utilizing cylindrical layers within a Vision Transformer neural network.
- Using the ERA5 dataset at 5.625° resolution for 2-meter air temperature (in Kelvin), formatted as a global rectangular grid, we hypothesize that our cylinder-based patch embedding approach will perform as well as or better than traditional NWP models (Hersbach 2020). Unlike NWP methods, which are equation-based and rely on computationally intensive ensemble calculations, our method tokenizes small sections of data through cylindrical convolutional layers, optimizing processing efficiency and reducing compute demands.
- This approach leverages the Vision Transformer architecture, where cylindrical convolutional layers embed patches across the globe, allowing the model to process geospatial data with high precision and adaptability.

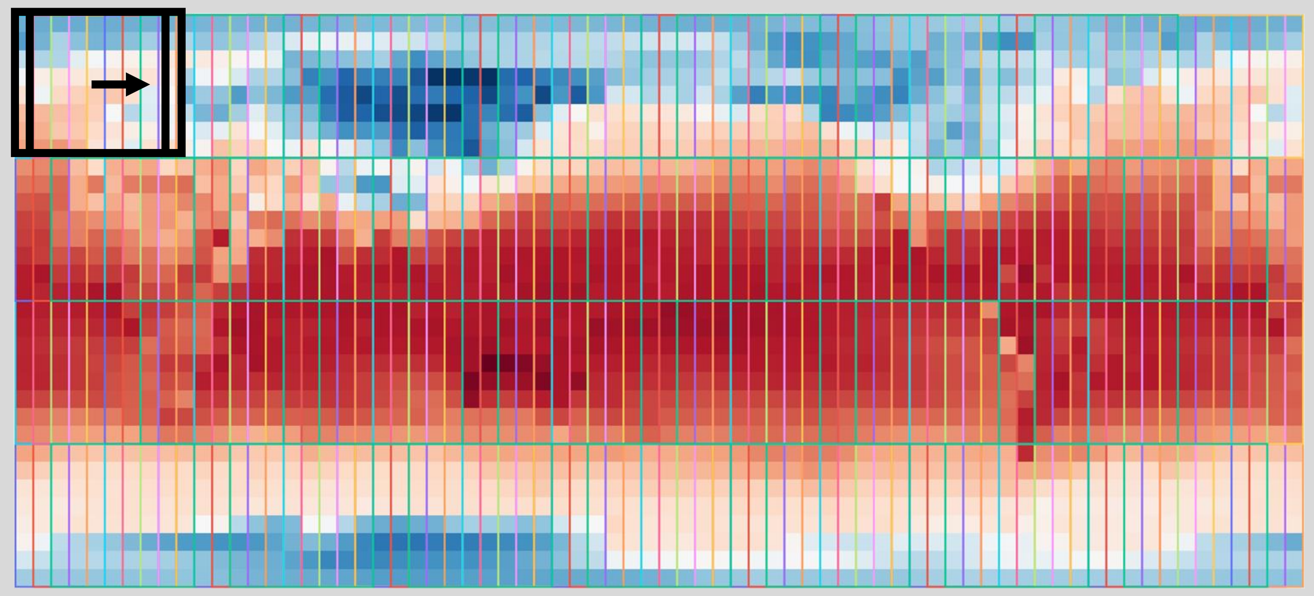
References:
Hauptman, 2022. Extreme weather is costing the military billions in damages and it's only getting worse. Task & Purpose
Nguyen et al., 2023. ClimaX: A foundation model for weather and climate. Proceedings of the 40th International Conference on Machine Learning
Cheon et al., 2024. - https://ar5iv.labs.arxiv.org/html/2208.05419
Frolov et al., 2024 - https://journals.ametsoc.org/view/journals/bams/aop/BAMS-D-24-0062.1/BAMS-D-24-0062.1.xml?tab_body=pdf
Kurth et al., 2024 - https://arxiv.org/pdf/2402.08185
NOAA, 2024 - https://www.youtube.com/watch?v=WLbnrLufQwQ
DVIDS, n.d. - https://taskandpurpose.com/wp-content/uploads/2022/04/21/Tyndall-Damage.jpg
Hersbach et. al., 2020 - https://doi.org/10.1002/qj.3803.

A square 8x8 patch reprojected onto the Earth

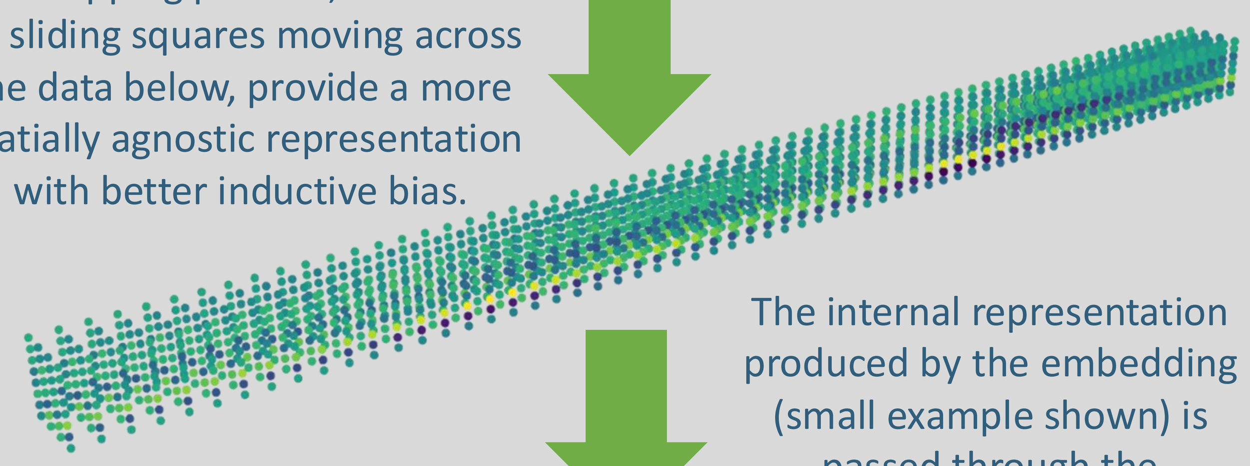


The 5.625° resolution ERA5 temperature data

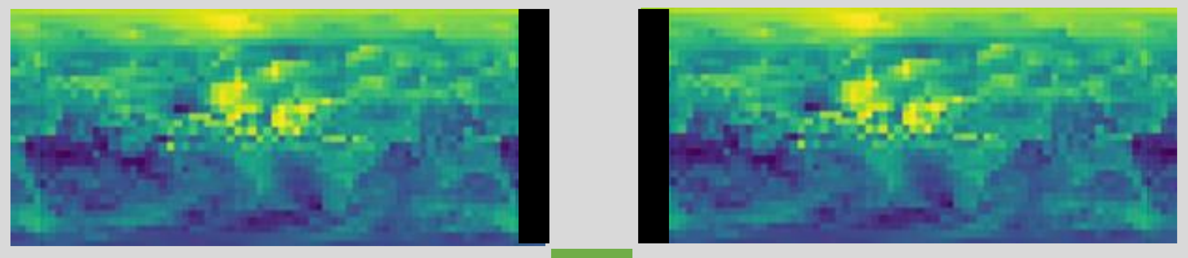
GeoStride – Proposed Patch Embedding



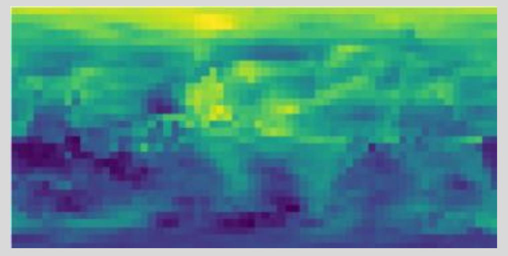
Overlapping patches, indicated by sliding squares moving across the data below, provide a more spatially agnostic representation with better inductive bias.



The internal representation produced by the embedding (small example shown) is passed through the transformer backbone.

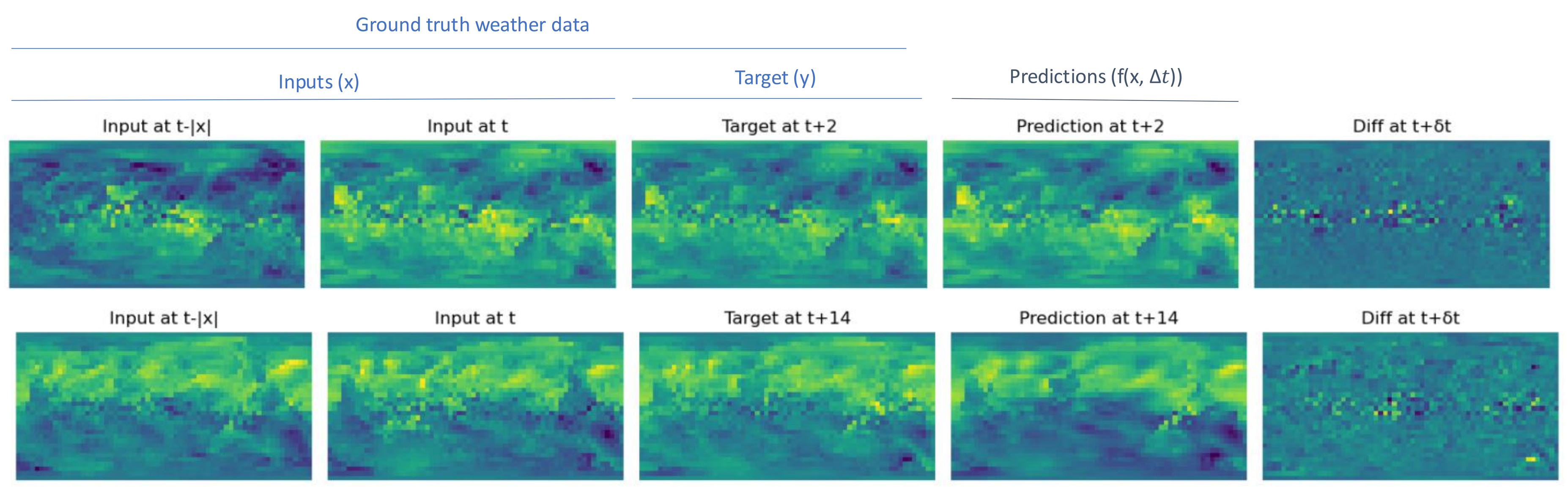


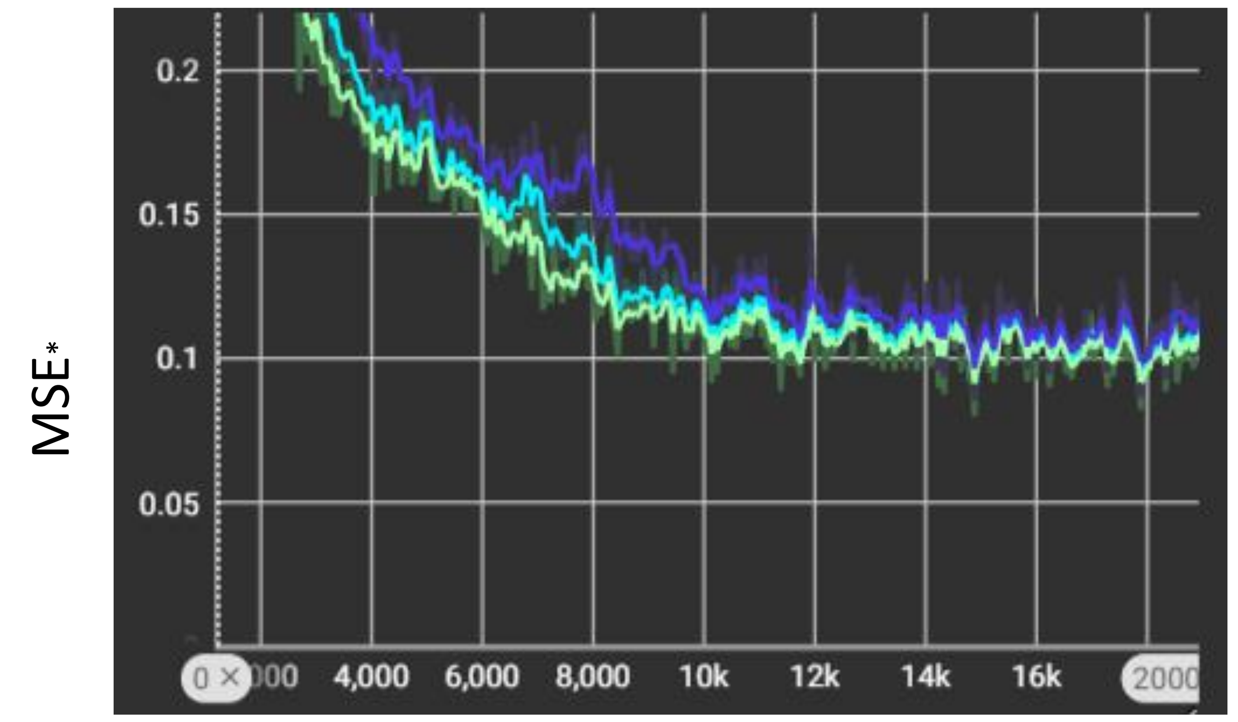
Accumulate



RESULTS AND EVALUATION

- Equivalent ViT architectures optimize more quickly with GeoStride, providing especially improved results for undertrained models.
- Darker colors represent actual values; lighter colors are averaged over iterations.





*Latitude-weighted mean squared error after global normalization

Sampling uniformly from Δt=U[6, 168] after 50 training epochs, we obtain average validation mean squared error (MSE) of:

Full Stride (Traditional ViT)	Half Stride	Min Stride
0.0753	0.0747	0.0760

FUTURE EFFORTS

- Apply patch embedding to similar architectures, e.g., convolutional vision transformers, U-net/residual connections.
- Increase resolution to down scale predictions for regional localities.
- Increase trustworthiness of the model by developing communication of the model's uncertainty.
- Adjust size of patches based on latitude.
- Apply to other domain areas of geospatial data, including infectious diseases and wildfires.
- Develop a GUI to lower barrier of entry to AI/ML predictions.

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