CAM-NET: An AI Foundation Model for Whole Atmosphere with Thermosphere-Ionosphere Extension

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Why AI-based model?

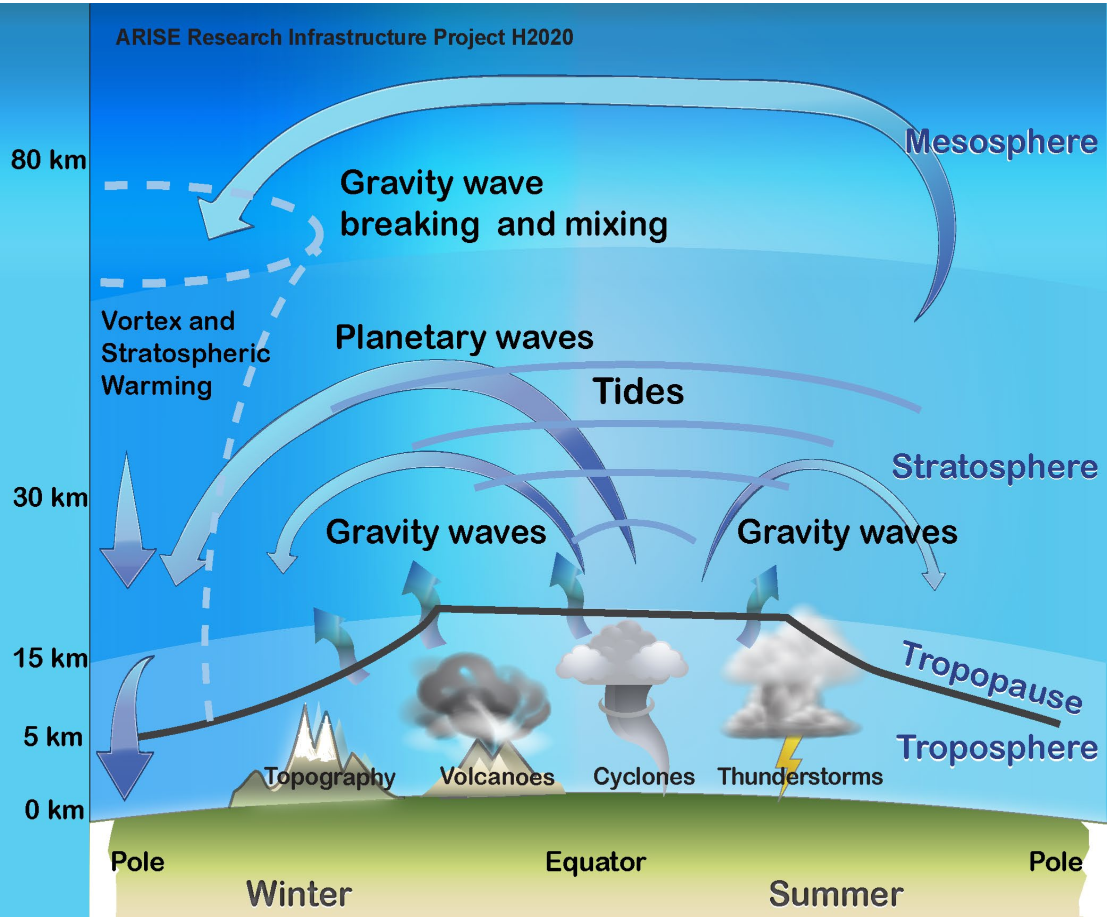


Image credit: Atmospheric Dynamics Research Infrastructure in Europe (ARISE) [1]

- **Gravity wave (GW)** modulate thermosphere winds, influence ionospheric dynamics
  - **Small-scale** modeling of GW effects is essential
- High-resolution climate models can resolve small scale waves, **BUT**
  - High computational cost
  - Time consuming
- Drives developments of AI-based models to capture atmospheric variations

From ChatGPT to climate model

- AI-foundation model
  - large-scale, pre-trained models on diverse data
  - Adaptive to many downstream tasks via fine-tuning
  - Examples: ChatGPT, Gemini, Claude
- Weather forecasting AI-foundation models
  - Based on different NN architectures: graph neural network (GNNs), vision transformer (ViT), **Fourier neural operators (FNO)**
  - Available training datasets
    - ECMWF Reanalysis v5 (ERA5)
    - Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-v2)

	Core techniques
GraphCast	GNN
ClimaX	Transformer + **FNO**
Pangu-weather	Transformer
FourCastNet	Adaptive **FNO (AFNO)**

Spherical Fourier Neural Operator

- Geometry-aware extension of FNO
  - Code package *modulus-makani* developed by NVIDIA [2]
  - Theory based on Bonev et al., 2023 [3]
- Captures long-range spatial correlations with rotational equivariances

	FNO	SFNO
Domain	Flat 2D grid (Euclidean)	Sphere ($\mathcal{S}^2$)
Transform technique	Fast Fourier	Spherical Harmonic
Spectral efficiency	$\mathcal{O}(l^2)$ filters	$\mathcal{O}(l)$ filters
Grid invariance	Partial: tied to grid resolution	Full: Generalize to new resolutions

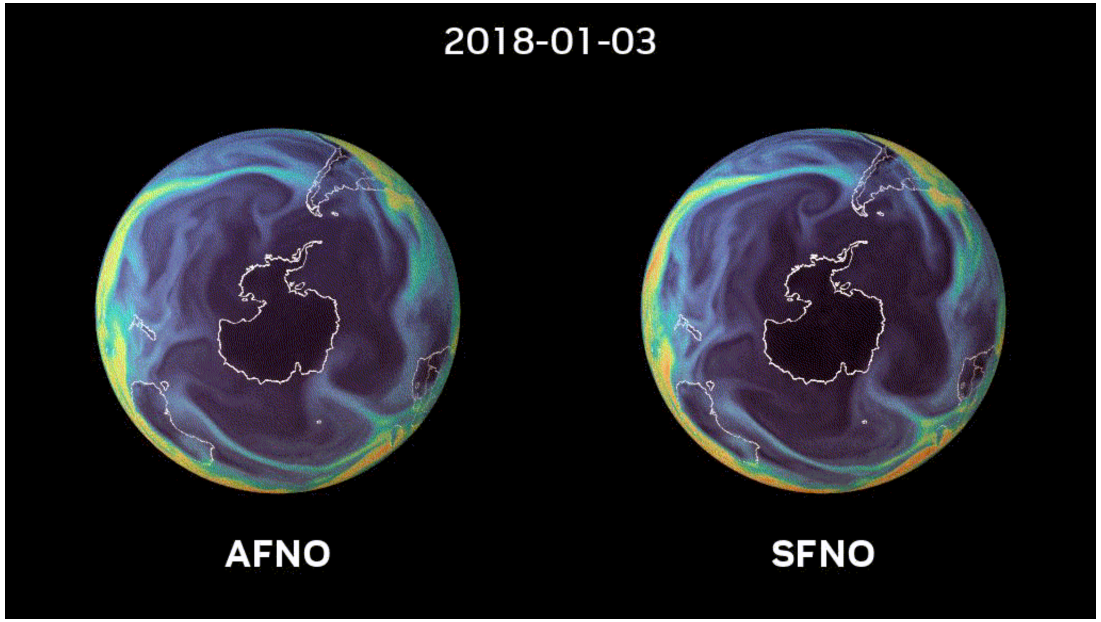
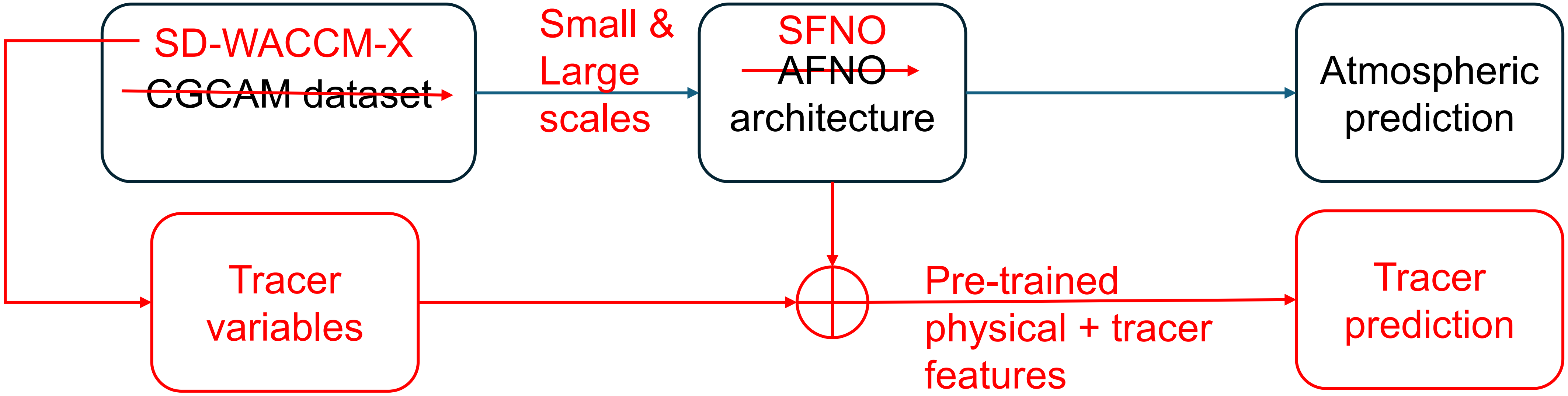


Image credit: Modeling Earth's Atmosphere with SFNO by *NVIDIA developer* [4]

Compressible Atmospheric Model -NET

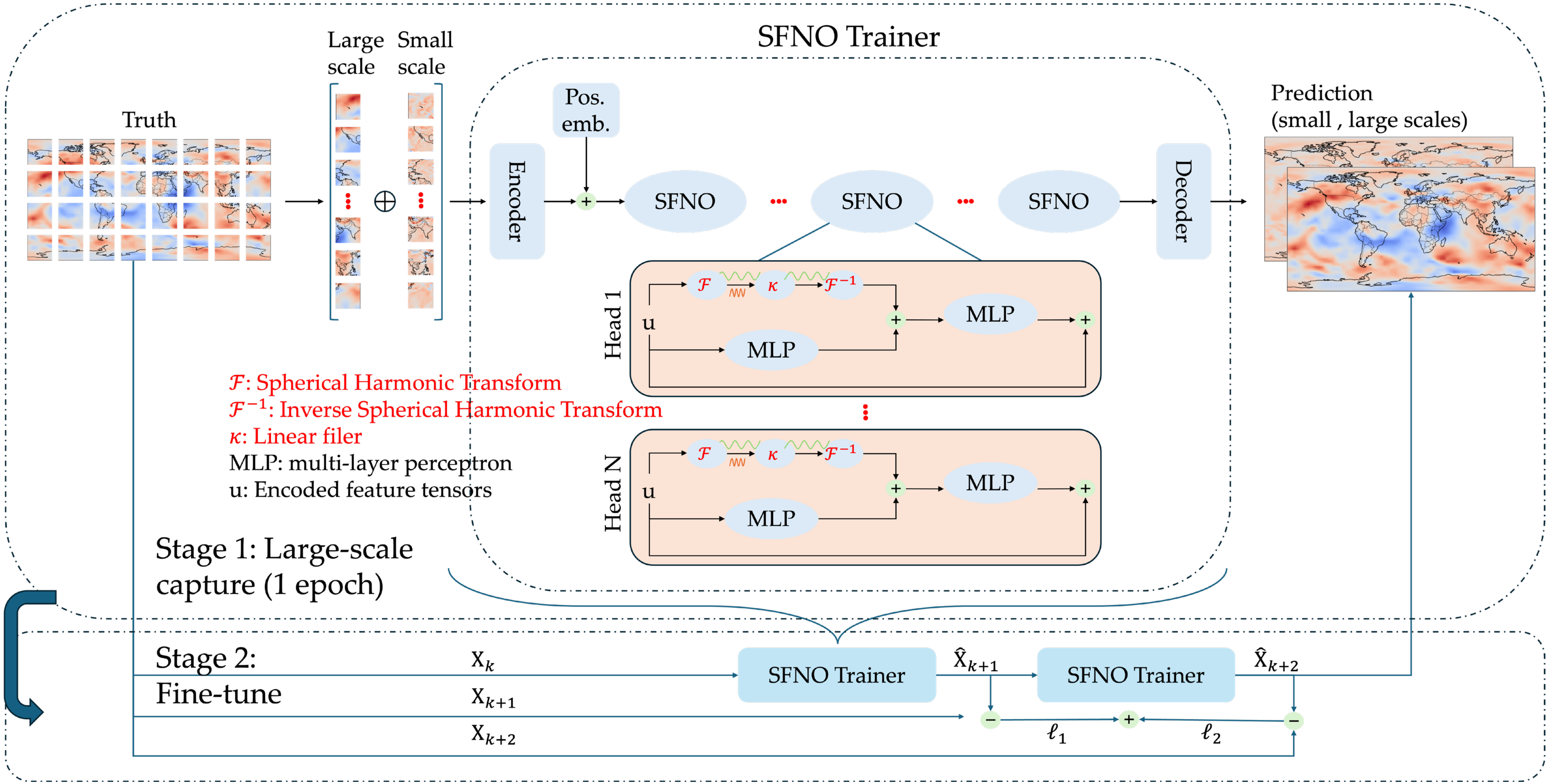
- CAM-NET developed by Dong et al., 2023 [5]
  - Simulate non-linear atmospheric GW dynamics
  - AFNO-based model trained by Complex Geometry Compressible Atmosphere Model (CGCAM) datasets
- Major developments (denoted in red)



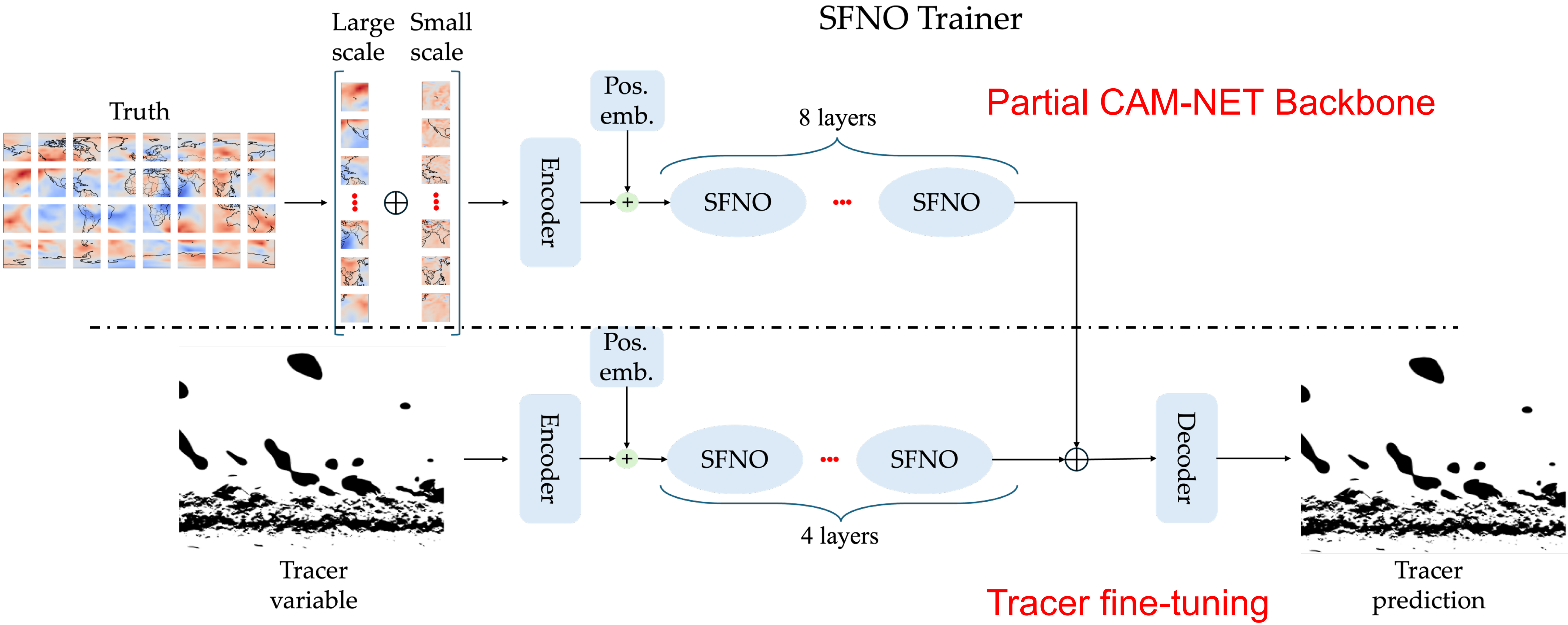
SD-WACCM-X datasets

- Extend to altitude range from earth surface to 700 km
- Nudged by external reanalysis Modern Era Retrospective-Analysis for Research and Applications Version 2 (**MERRA**)-v2 [7]
  - Lower atmosphere constraint up to 50 km
- Data Resolution
  - Lat x Lon : 0.9 x 1.25 [deg]; Vertical: ~1 [km] to 50 [km]; Time: 3 [hrs]
- Data Partition
  - Training: 10 years (2001 – 2010); Testing: 2 years (2011 - 2012); Validation: 2013

a) CAM-NET backbone flowchart

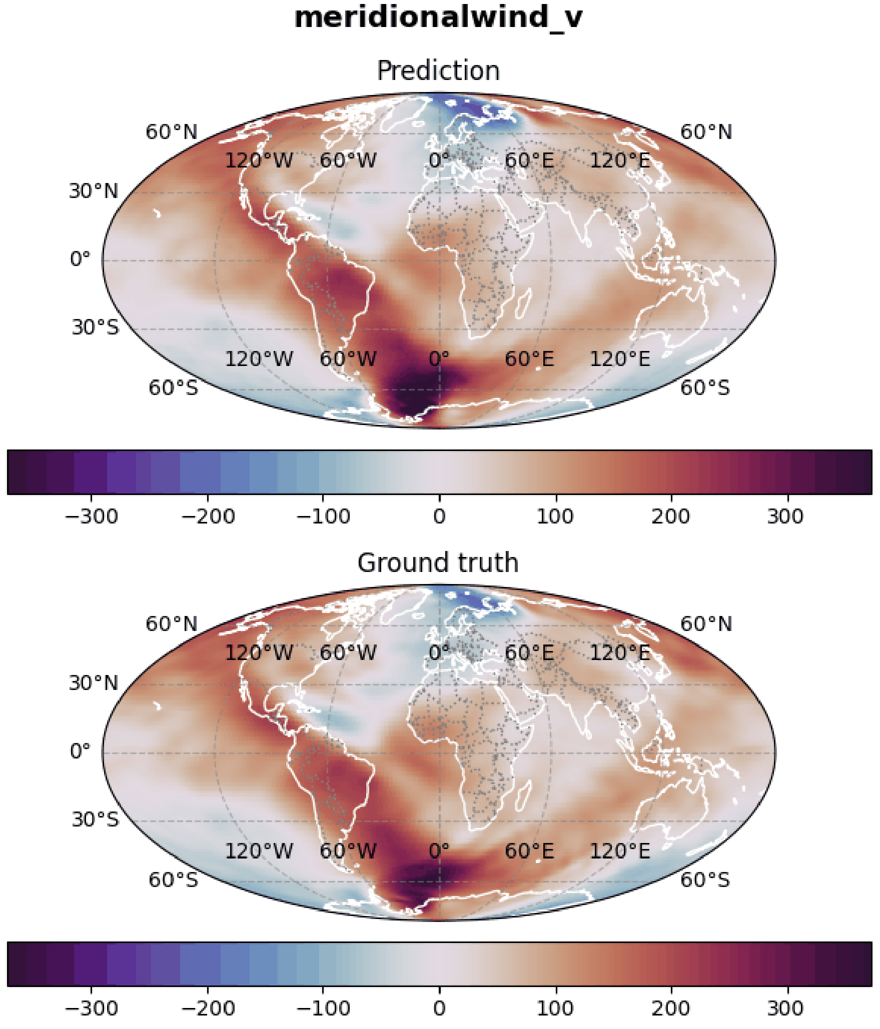


b) Tracer fine tuning schema

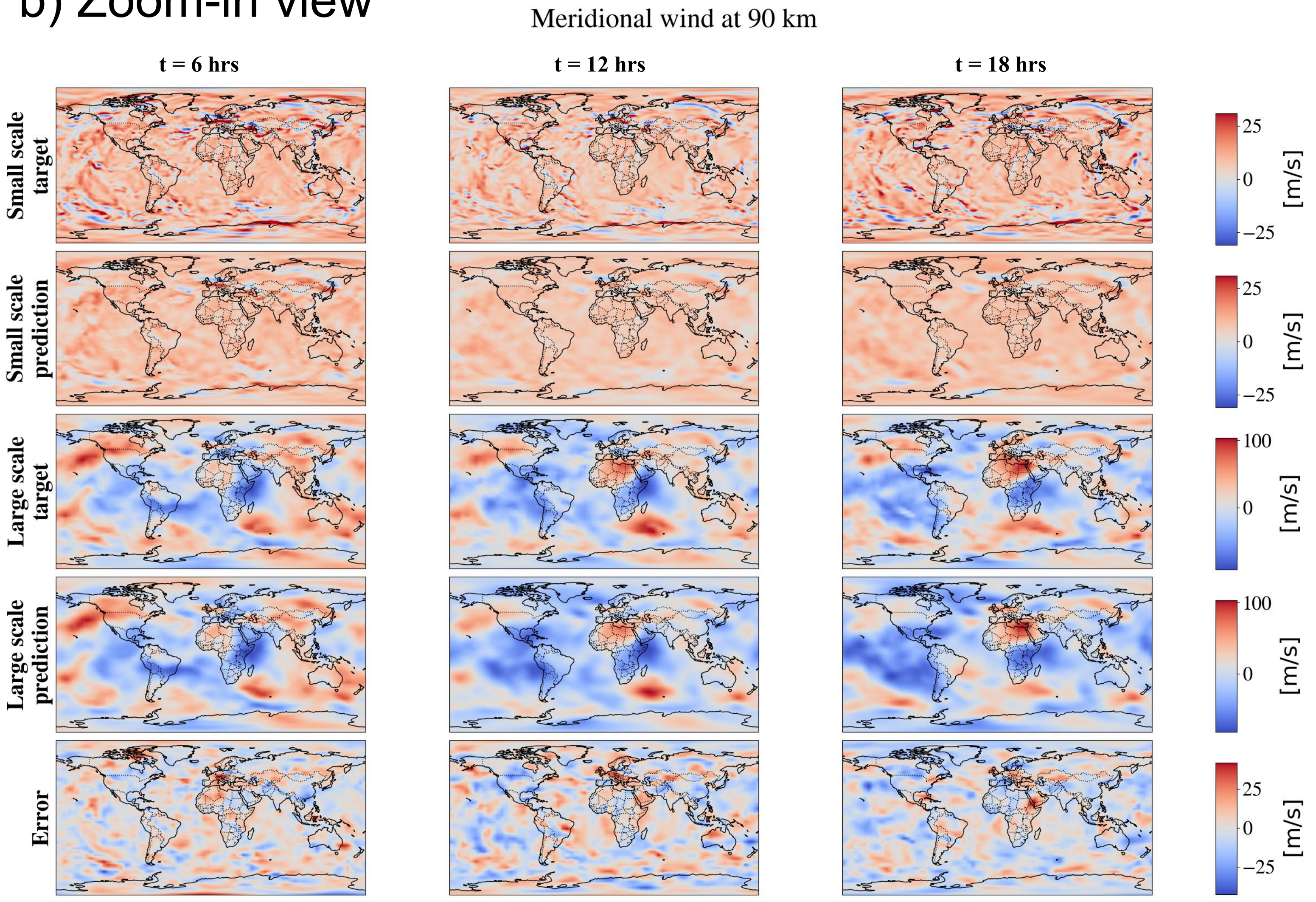


CAM-NET inference results

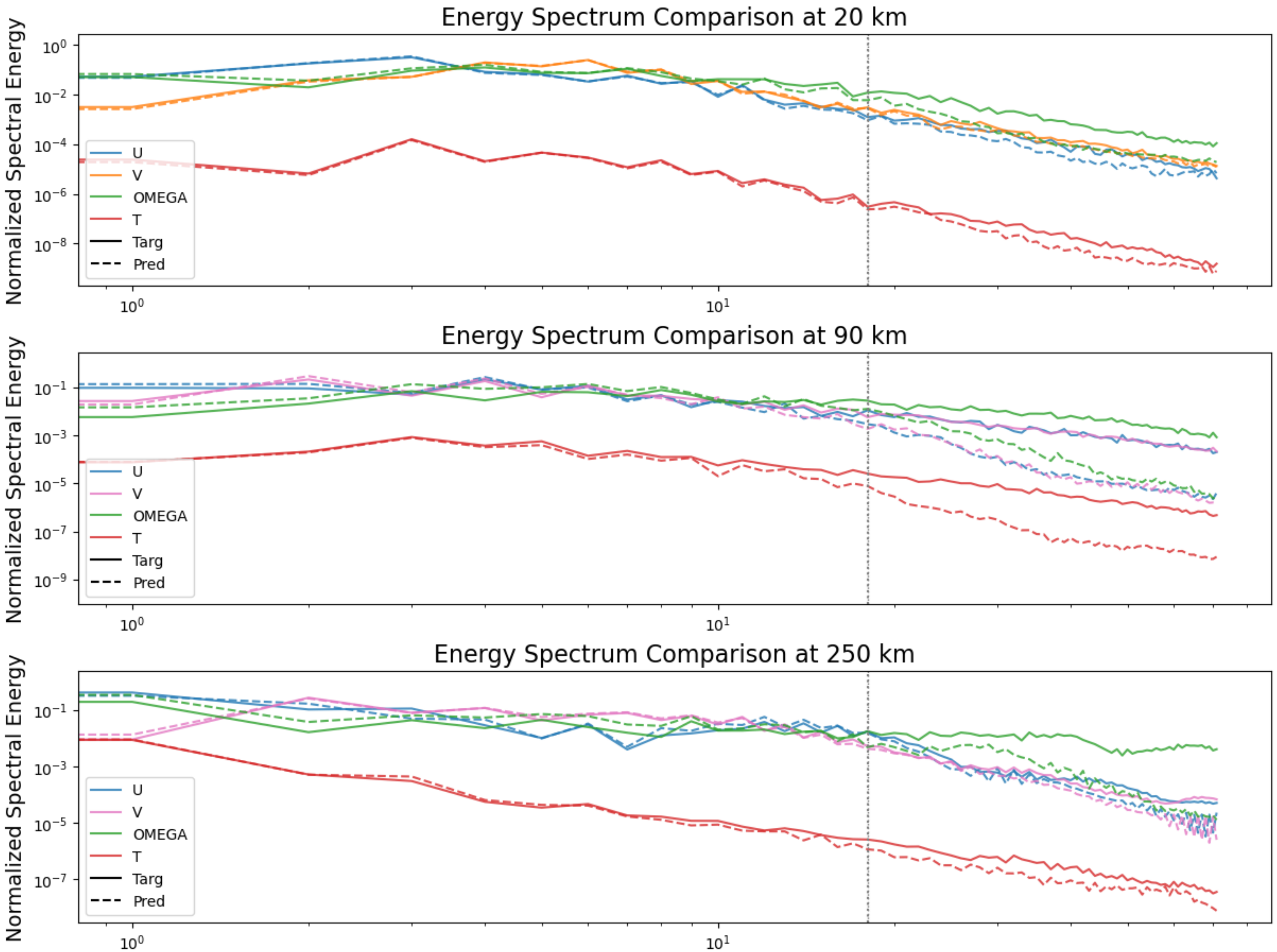
a) Animation of 18 epochs



b) Zoom-in view



Spectrum analysis



Summary and next step

- CAM-NET predictions has good alignments with WACCM-X data with 4 times faster than model run
  - ~ 5 days training for 10 years of data
  - < 12 hrs for inferencing 1 year of data
- At middle atmosphere, small-scale (high wavenumber) energy is underrepresented in predictions
- Next step
  - Integrate with diffusion model for resolving small scales [7]

Reference

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[3] NVIDIA. (2023). *Makani: Foundation models for weather and climate*. GitHub repository. https://github.com/NVIDIA/makani
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THANK YOU!