PEAR

Equal Area Weather Forecasting on the Sphere

Hampus Linander 20/8 - 2025, GeUmetric Deep Learning, Umeå

UNIVERSITY OF GOTHENBURG

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PEAR: Equal Area Weather Forecasting on the Sphere

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HEAL-SWIN: A Vision Transformer On The Sphere

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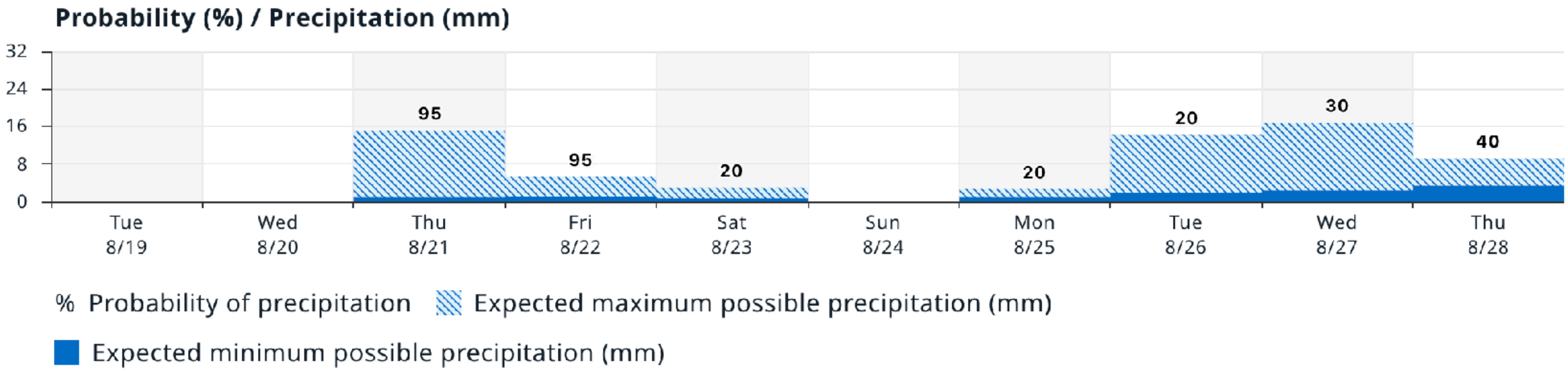
Christoffer Petersson[e][a] Daniel Persson[a]

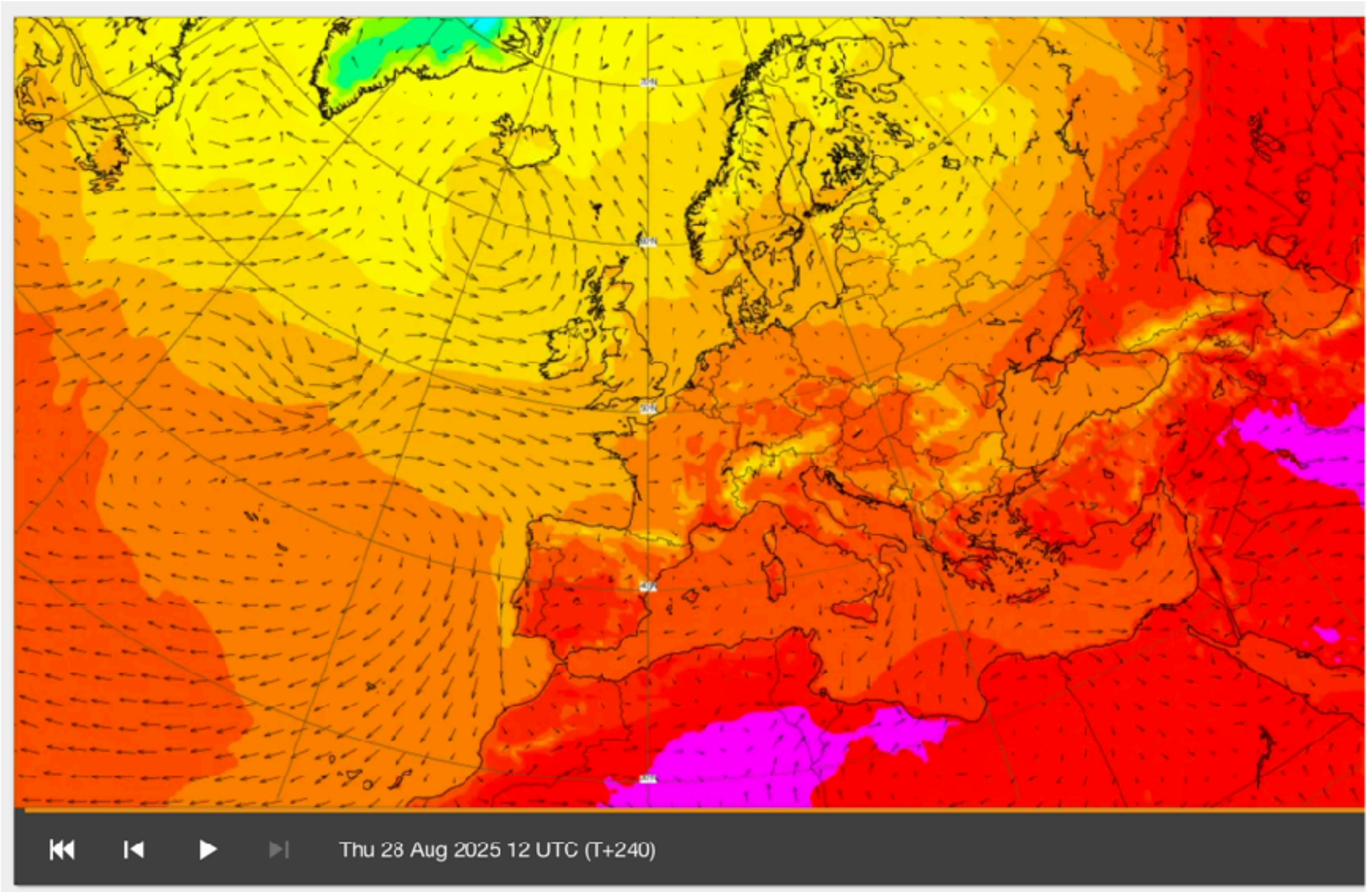
CVPR 2024

Weather forecasting

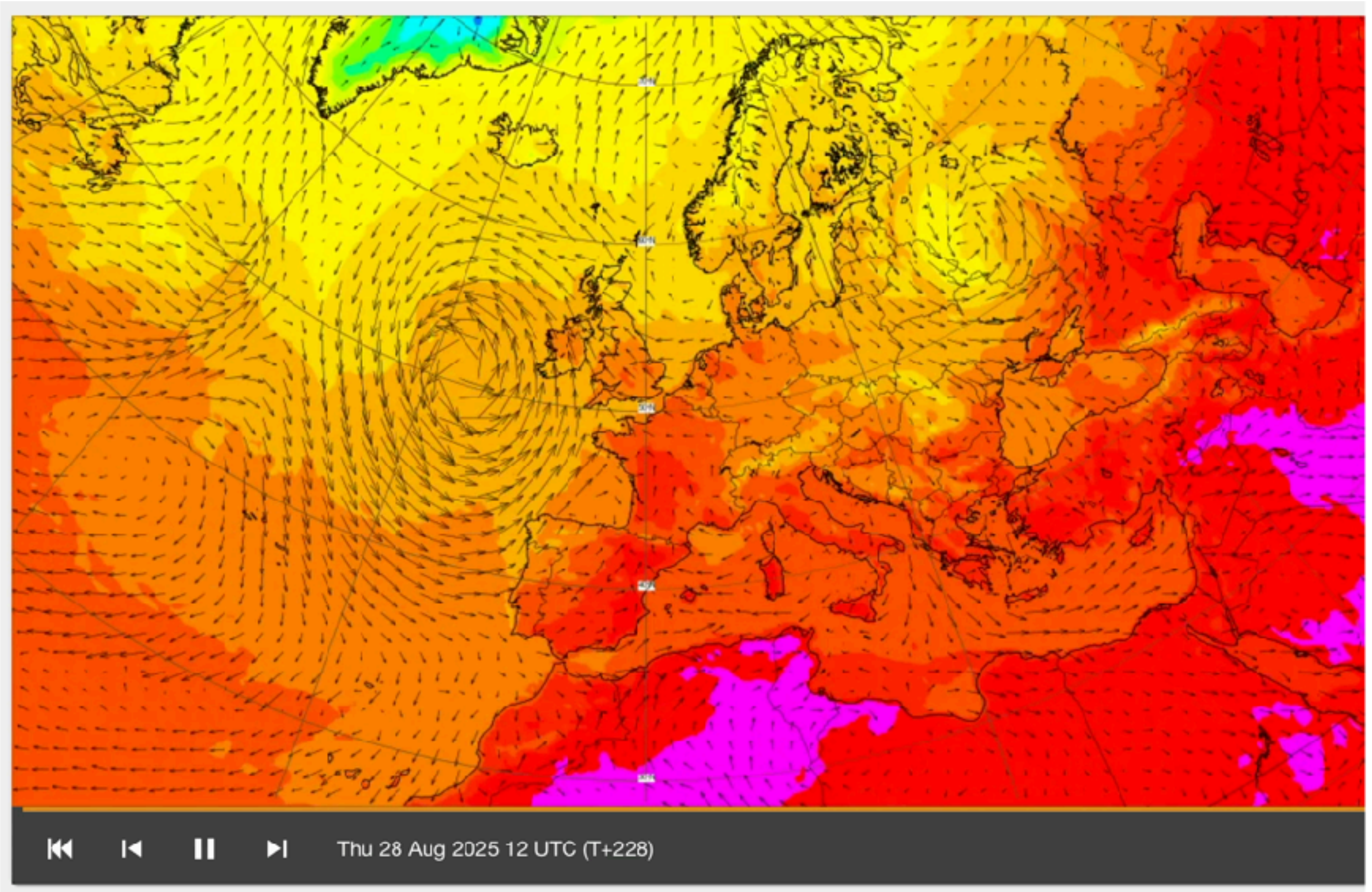


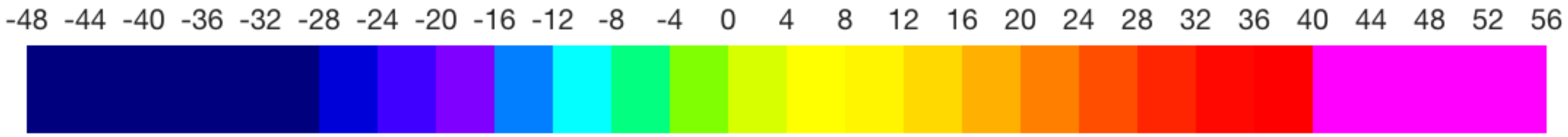
Weather forecasting

Graphcast



ECMWF ex-HRES





Lam, Remi, et al. "Learning skillful medium-range global weather forecasting." *Science 2023*

ECMWF charts (charts.ecmwf.int)

Problem

Medium-range forecasting

Predict future global atmospheric state at medium-range timescales

$$\Delta t \leq 15 \text{ days}$$

Traditional method: Solve Navier-Stokes numerically

Problem

Medium-range forecasting

Predict future global atmospheric state at medium-range timescales

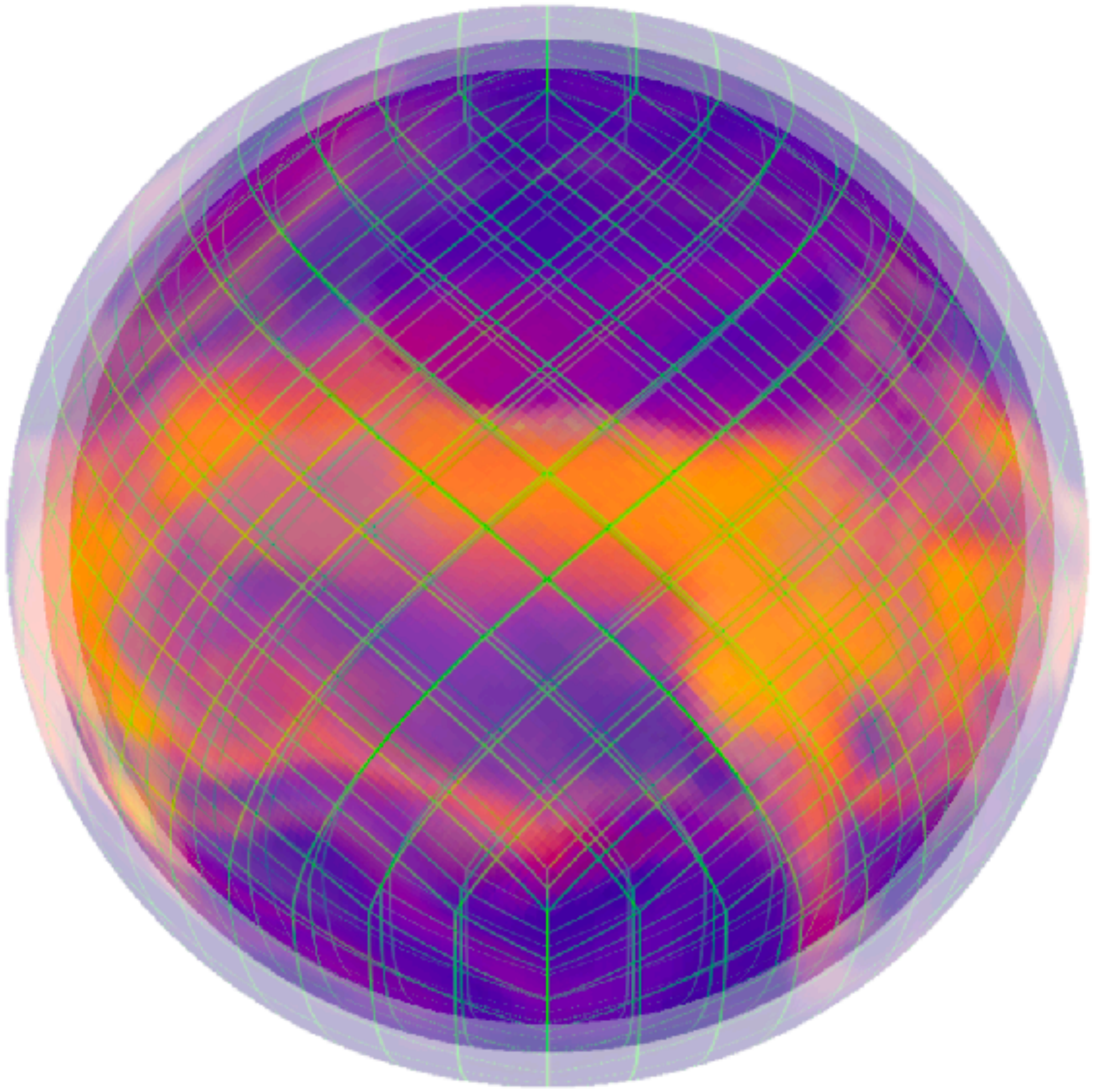
$$\Delta t \leq 15 \text{ days}$$

Traditional method: Solve Navier-Stokes numerically 😅

Global weather forecasting

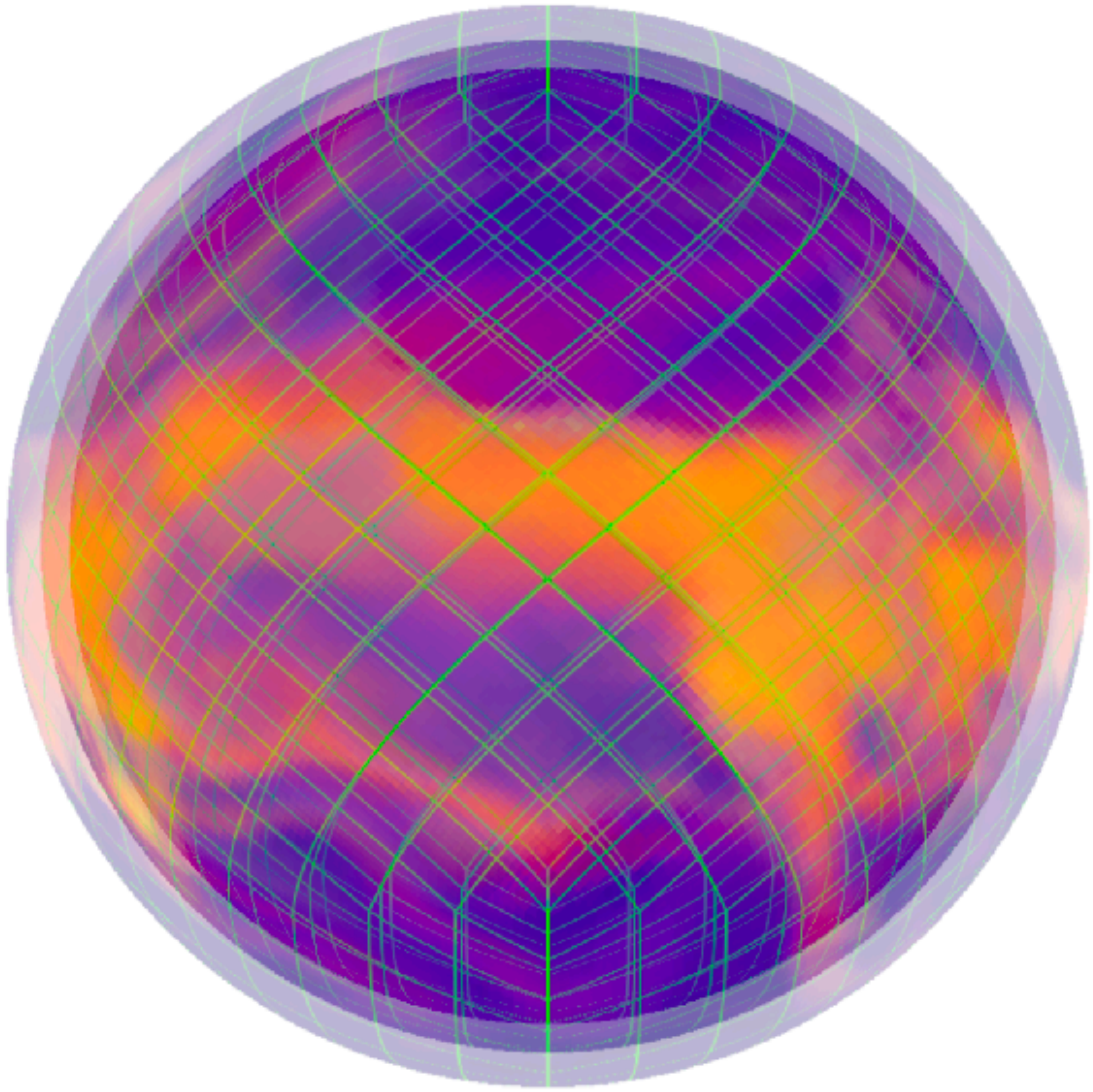
as a regression task

t_0



Input

$t_0 + \Delta t$



Target

ERA5

ECMWF reanalysis 1940-present

Hourly global grid (0.25 degrees, 31km resolution)
from surface up to height of 80km

Surface

temperature

pressure

wind velocity

…

Atmosphere

temperature

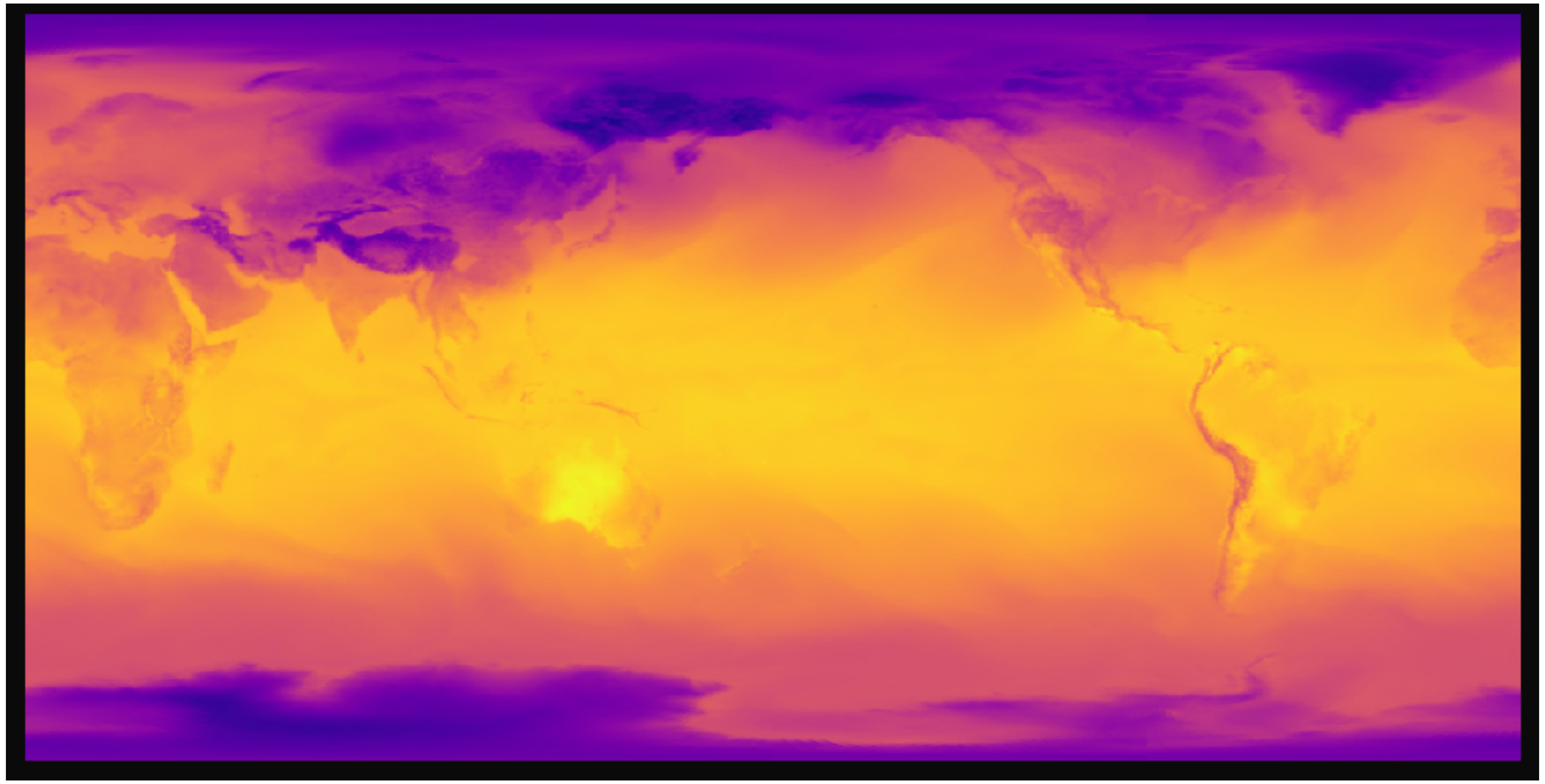
geopotential

wind velocity

humidity

…

5 petabytes



ERA5 lite

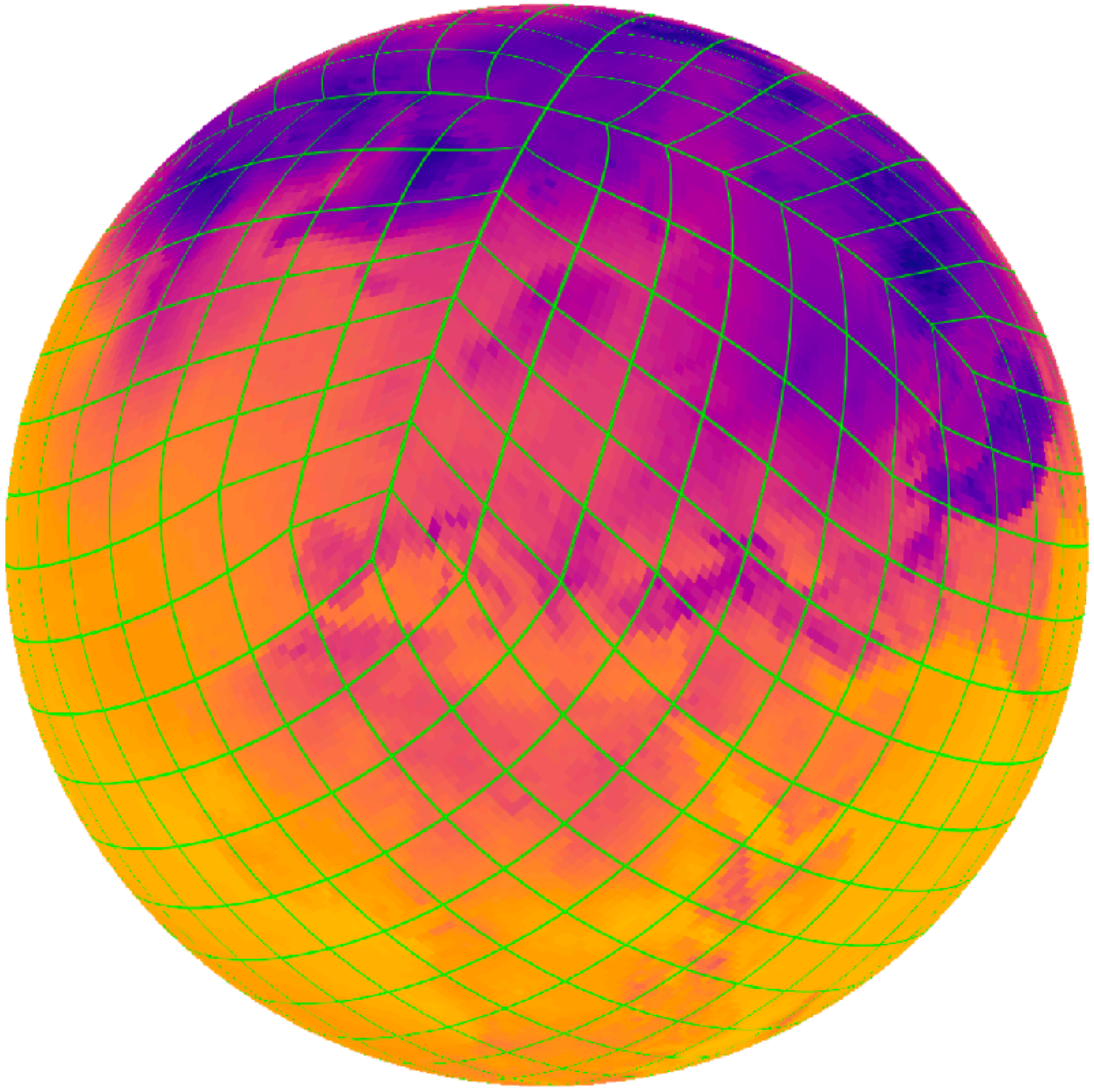
reduced resolution

Daily global grid (0.92 degrees, 300km resolution)
with 13 height levels

2007 - 2017

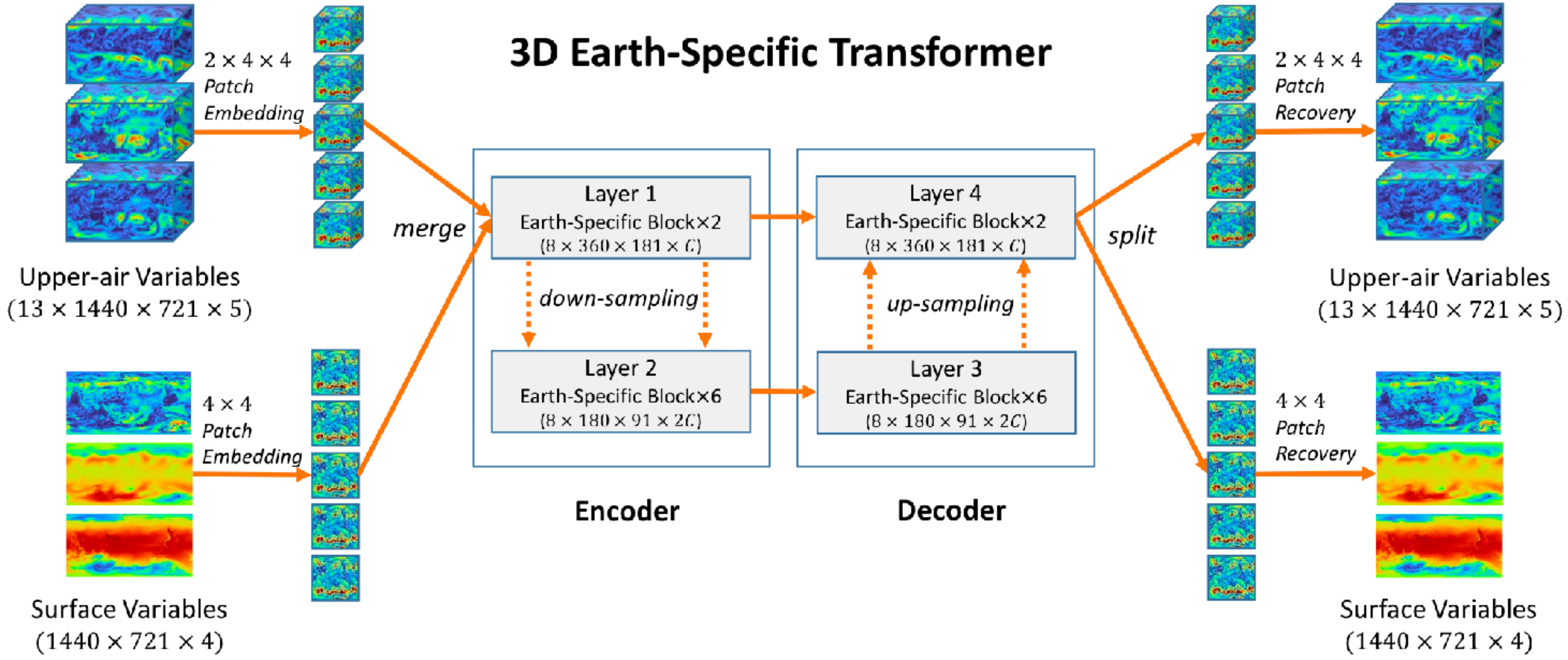
Surface	Atmosphere
temperature	temperature
pressure	geopotential
wind velocity	wind velocity
	humidity

1 terrabyte



Pangu Weather

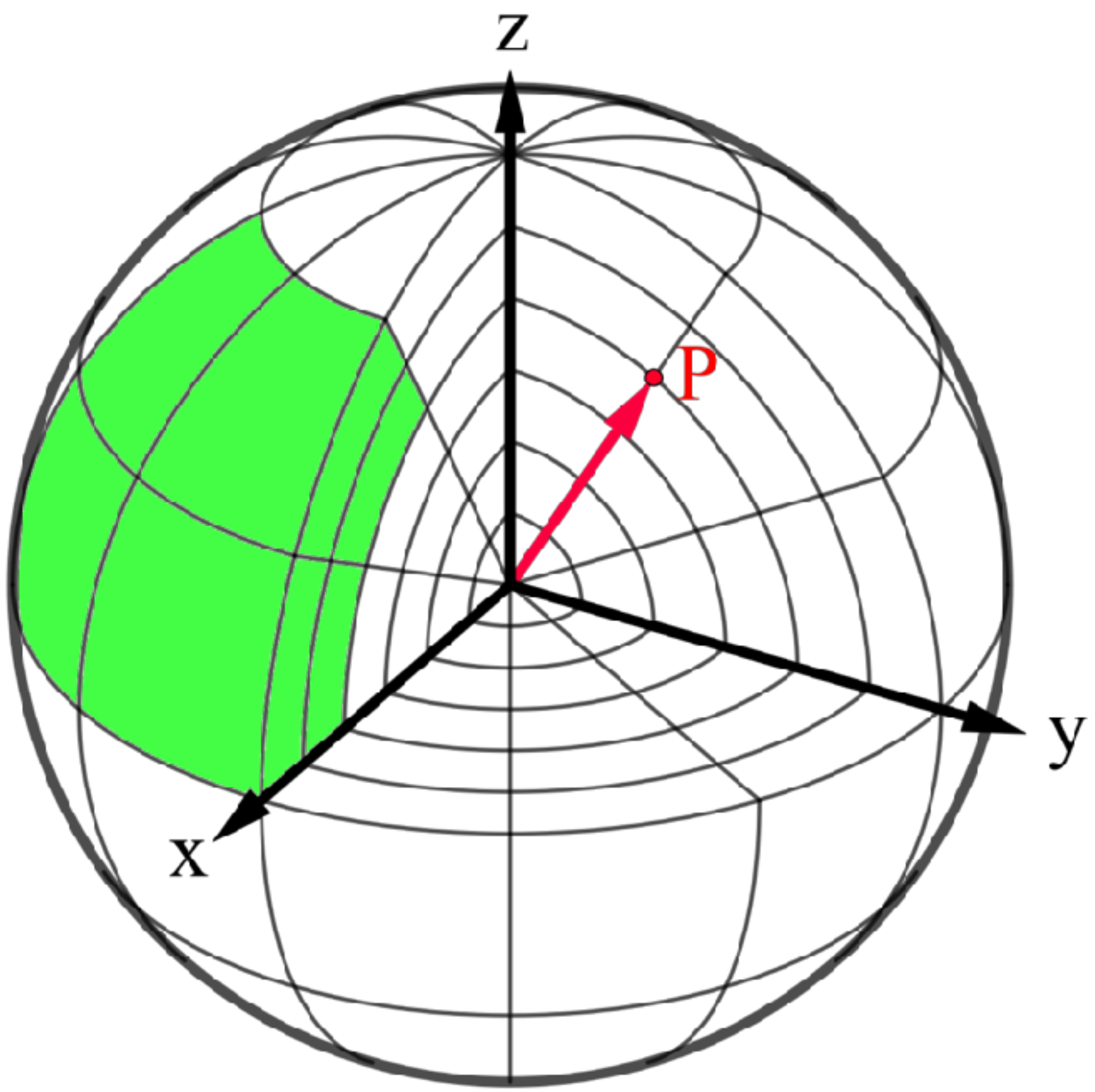
volumetric transformer



Bi et al. "Accurate medium-range global weather forecasting with 3D neural networks." *Nature 2023*

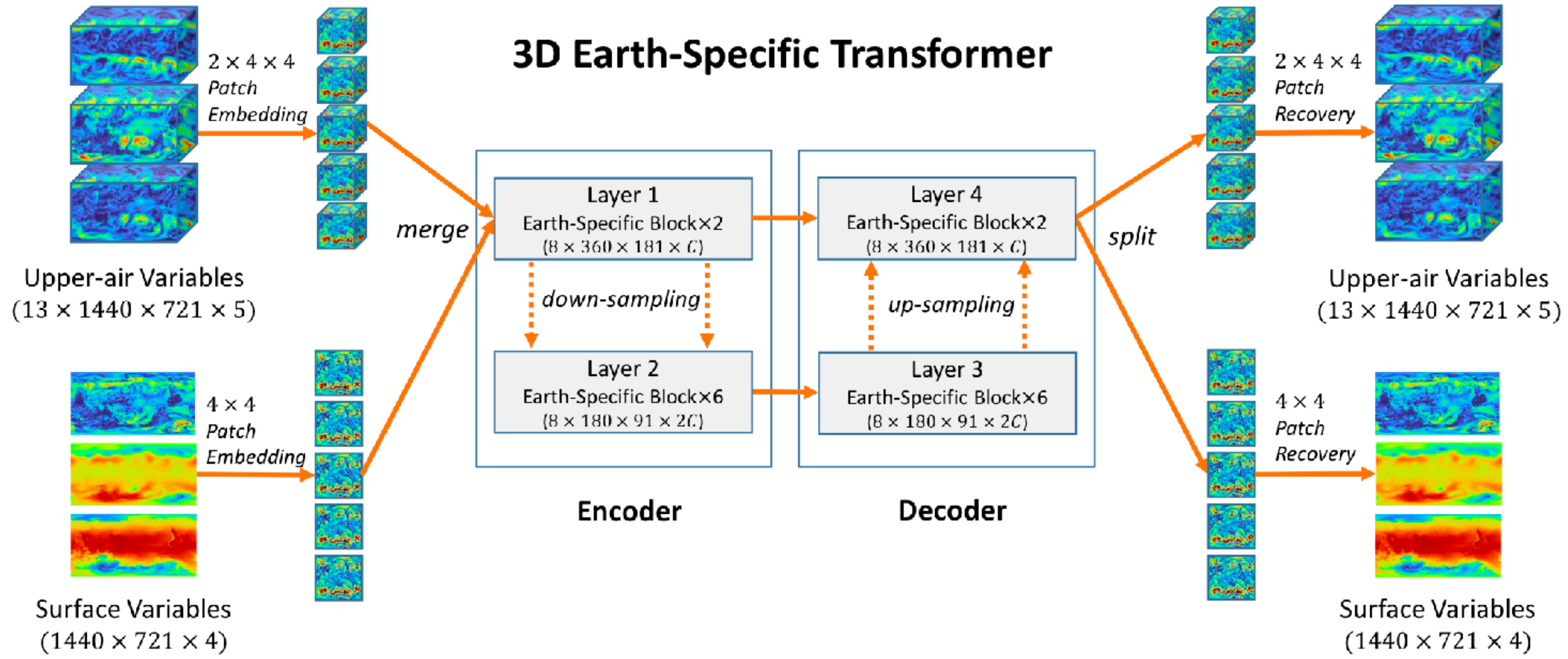
Pangu weather

Shifted windowed attention



SharkD 2018

Liu et.al. “Swin Transformer: Hierarchical Vision Transformer using Shifted Windows”, CVPR 2021



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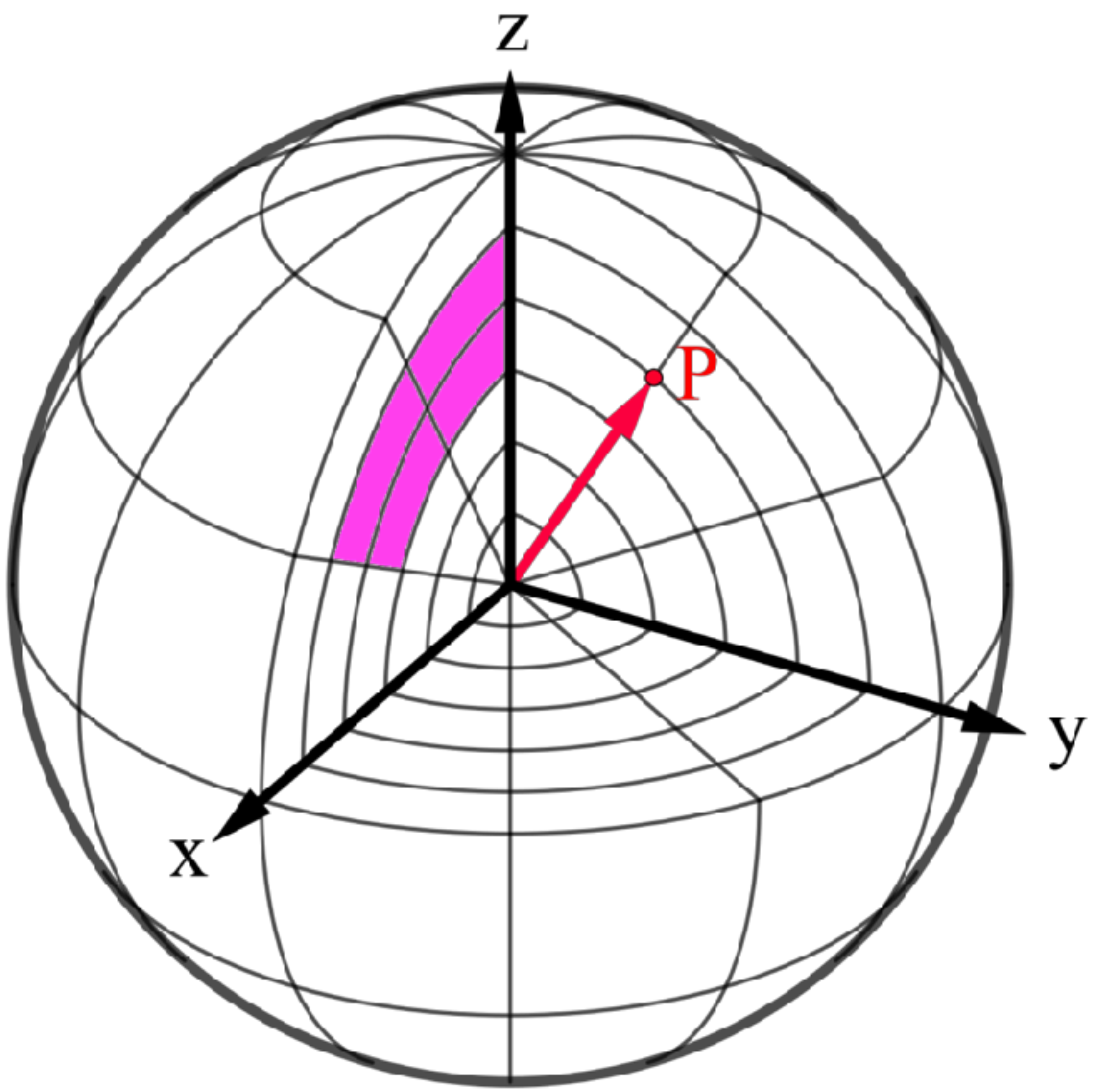
Pangu weather

Shifted windowed attention



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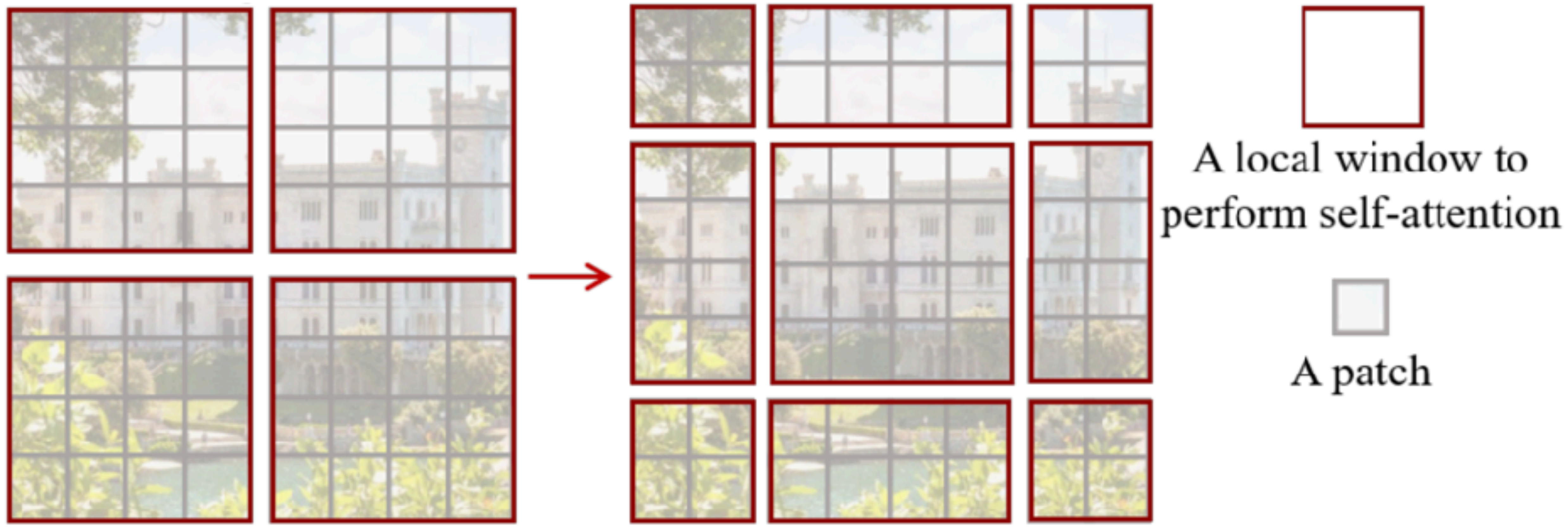

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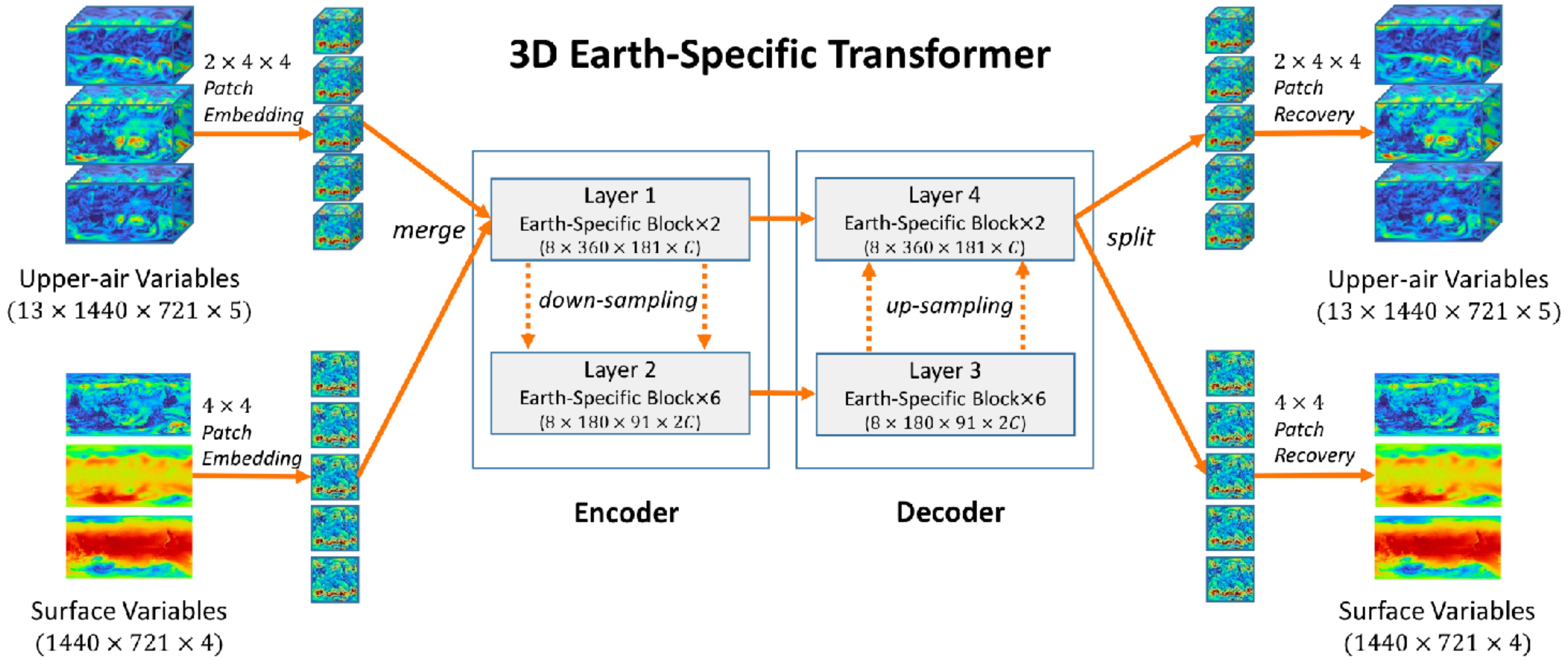
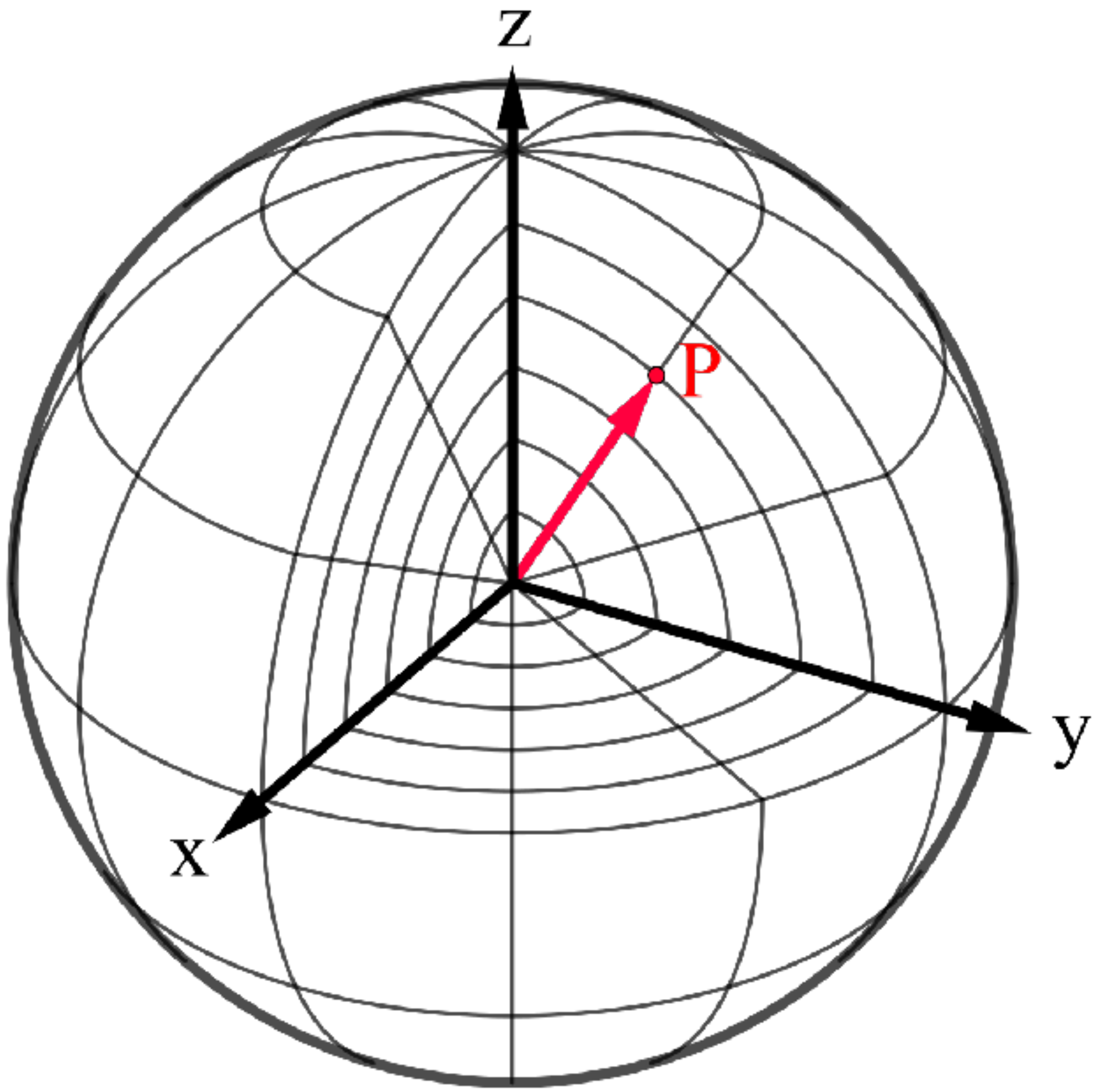
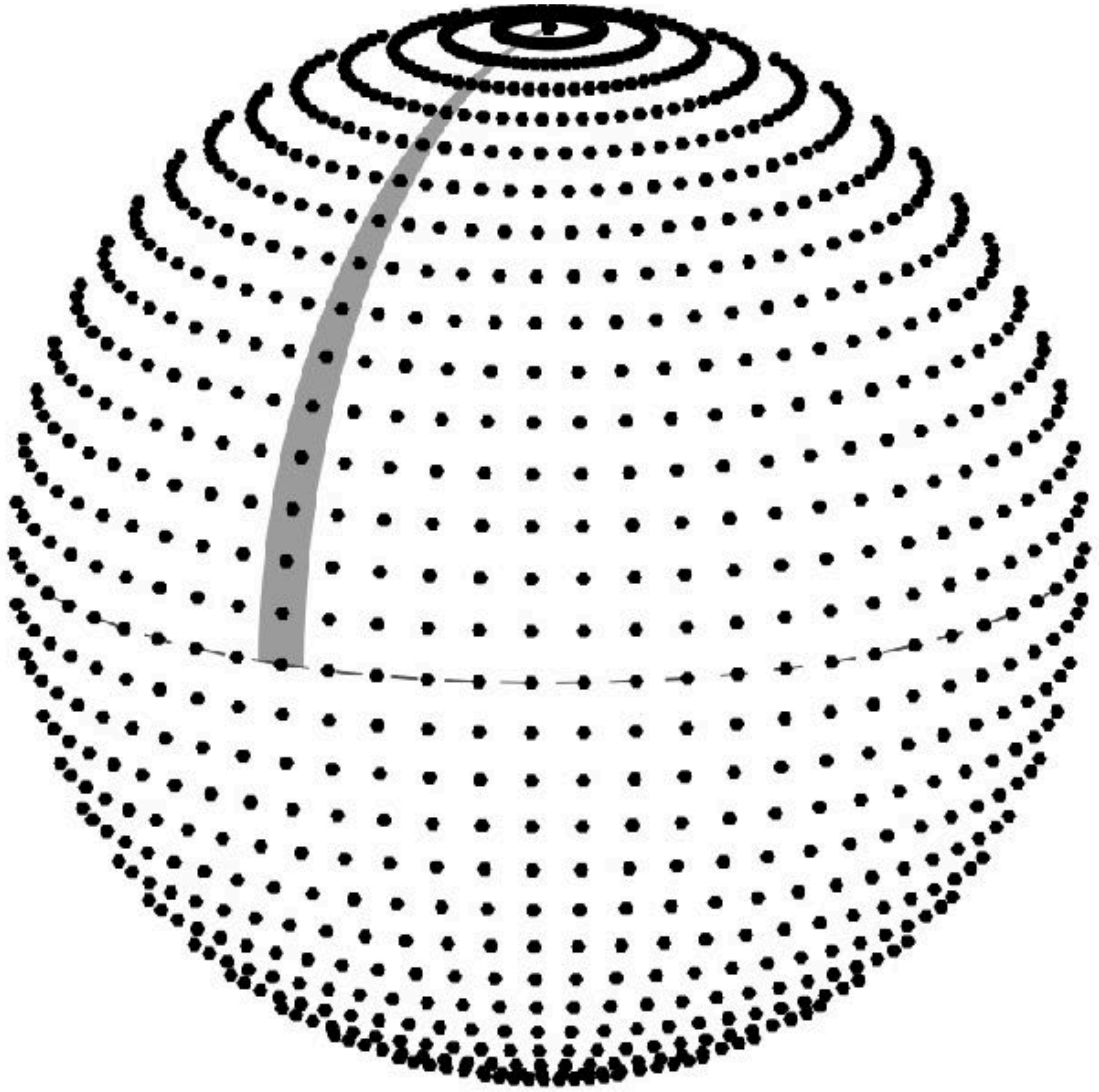


Bi et al. "Accurate medium-range global weather forecasting with 3D neural networks." *Nature 2023*

Grids on the sphere

Equiangular grids





SharkD 2018

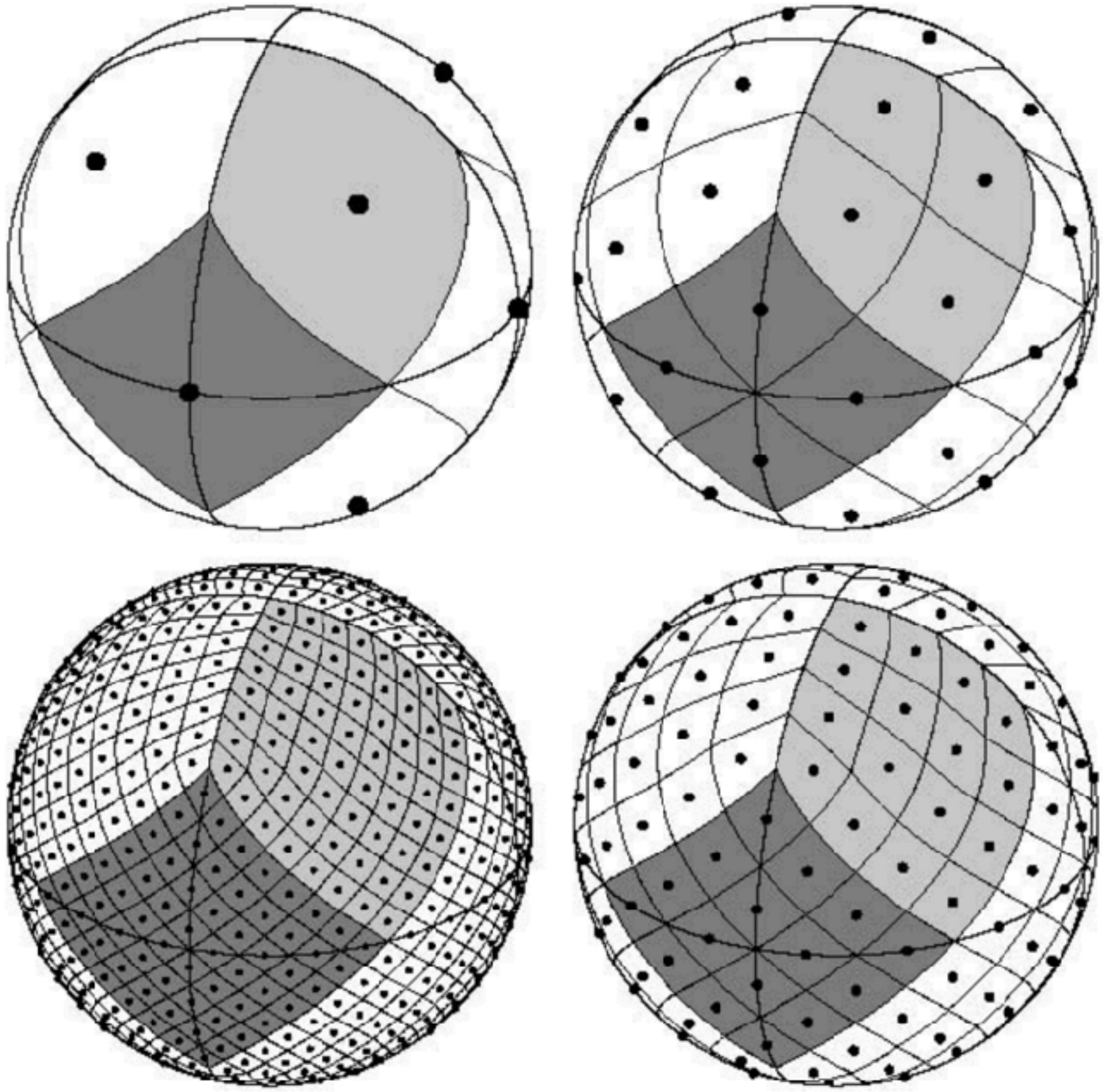
Górski et.al. “HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere” ApJ 2005

Grids on the sphere

Hierarchical Equal Area isoLatitude Pixelation (HEALPix)

Equal area grid with pixels on isolatitude bands

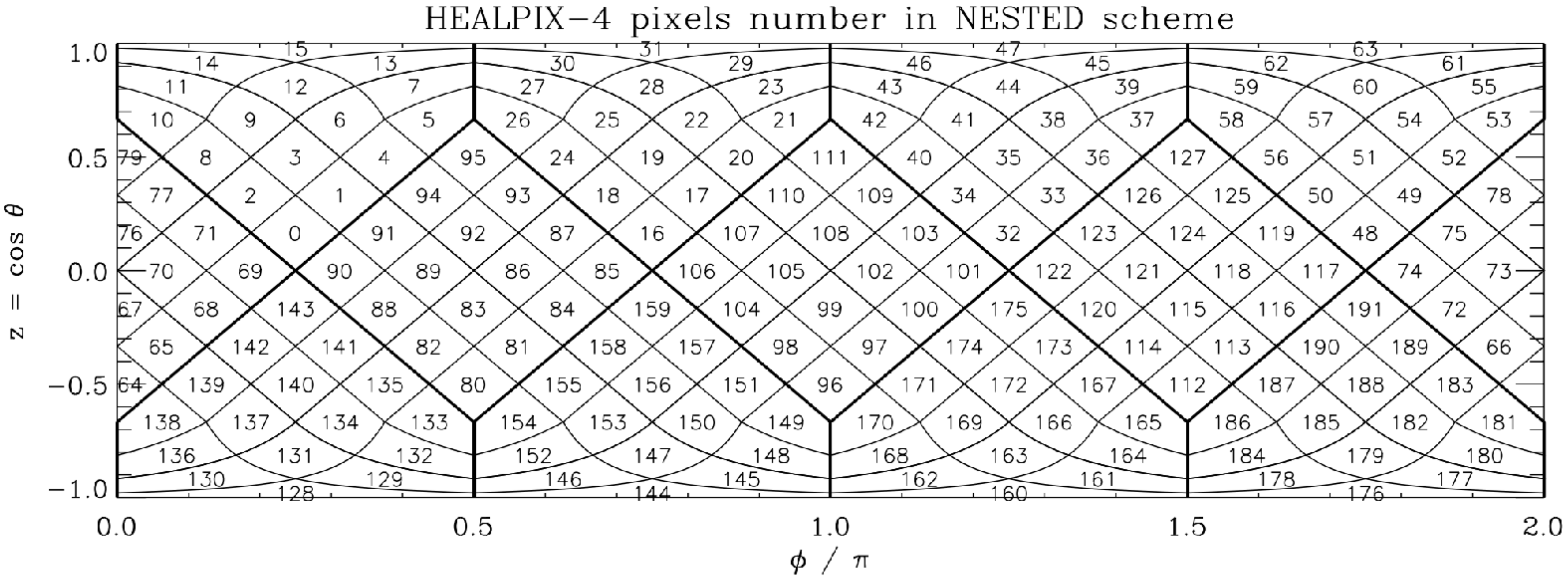
Originally developed for cosmic microwave background data



Górski et.al. “HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere” ApJ 2005

HEALPix

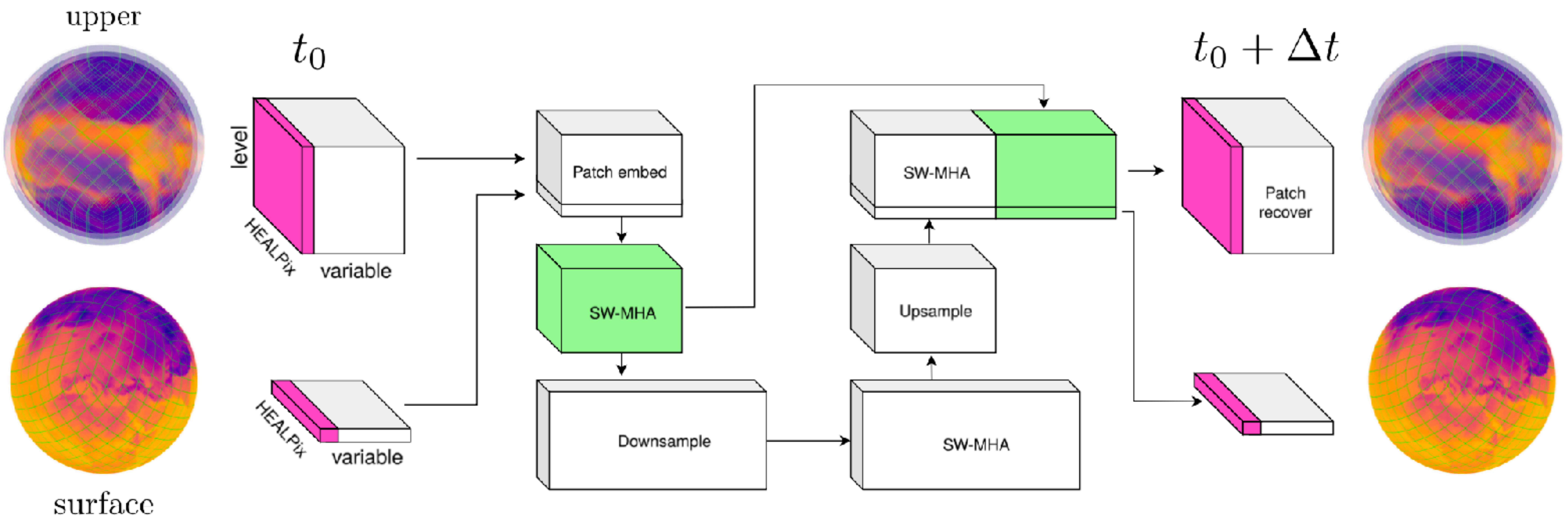
Nested indexing



Górski et.al. “HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere” ApJ 2005

PEAR 🍐

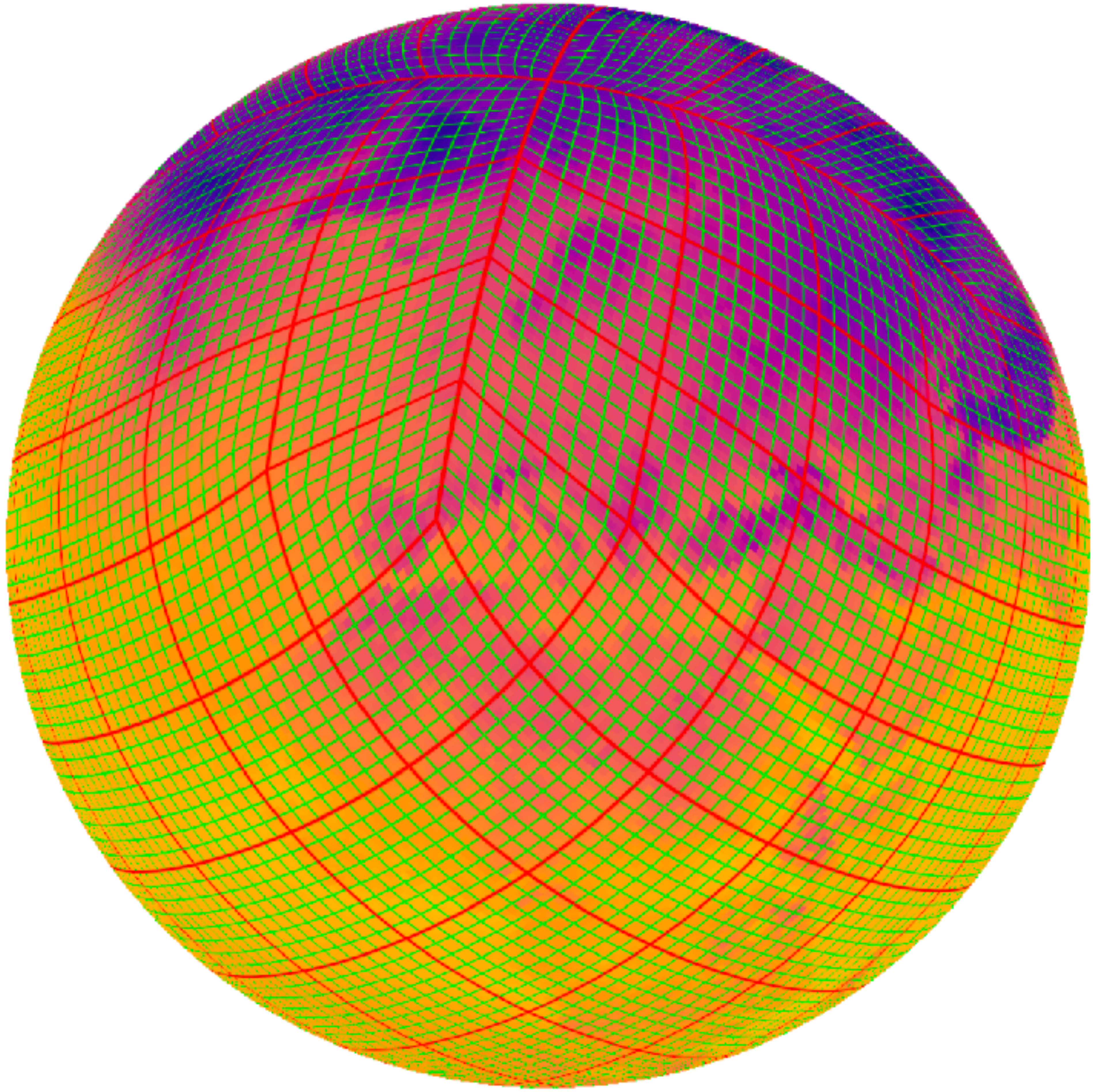
Pangu Equal ARea model



HL, Christoffer Petersson, Daniel Persson, and Jan E. Gerken. "PEAR: Equal Area Weather Forecasting on the Sphere." arXiv:2505.17720

PEAR

Windows and patches



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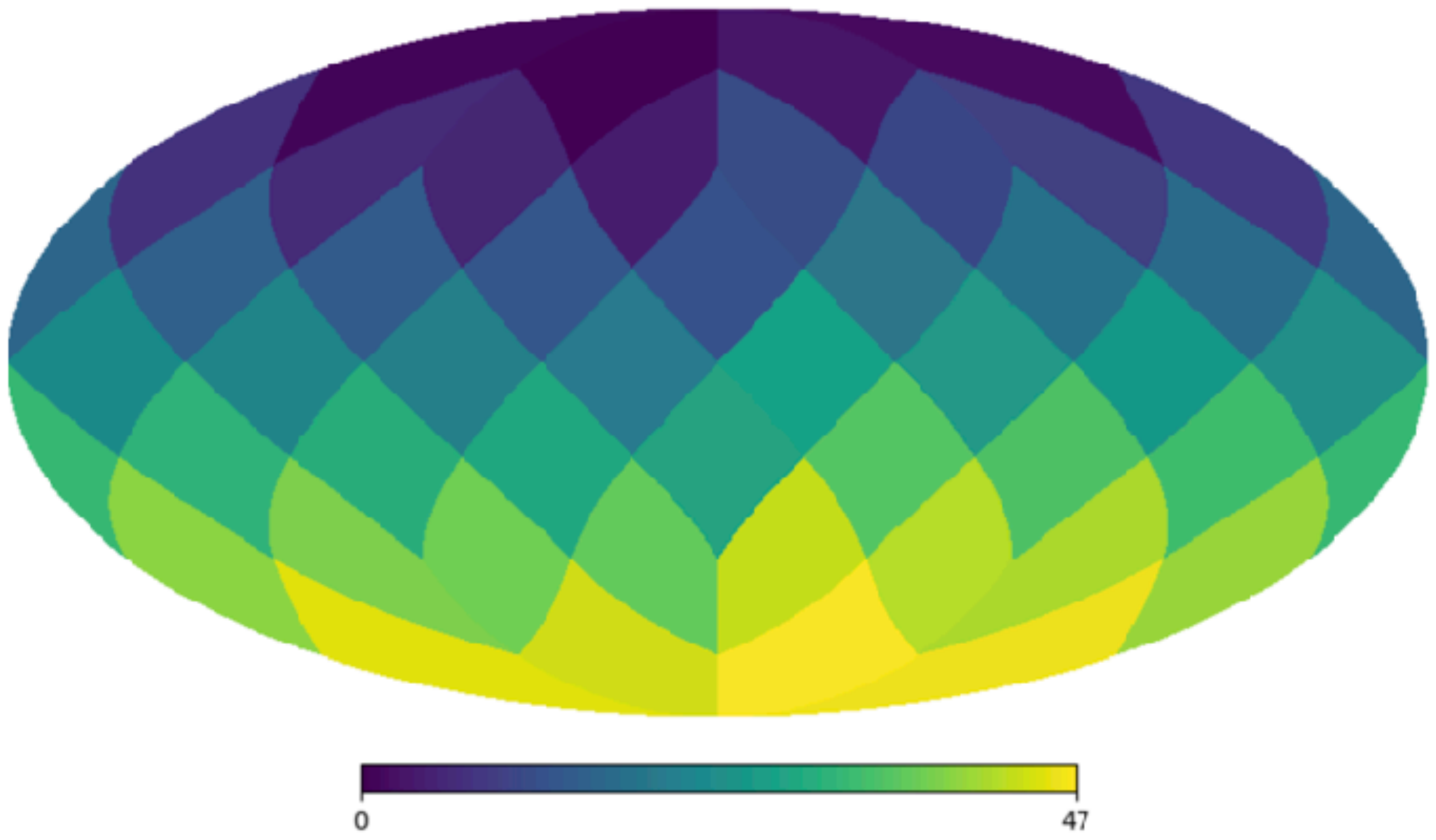
PEAR

Window shifting



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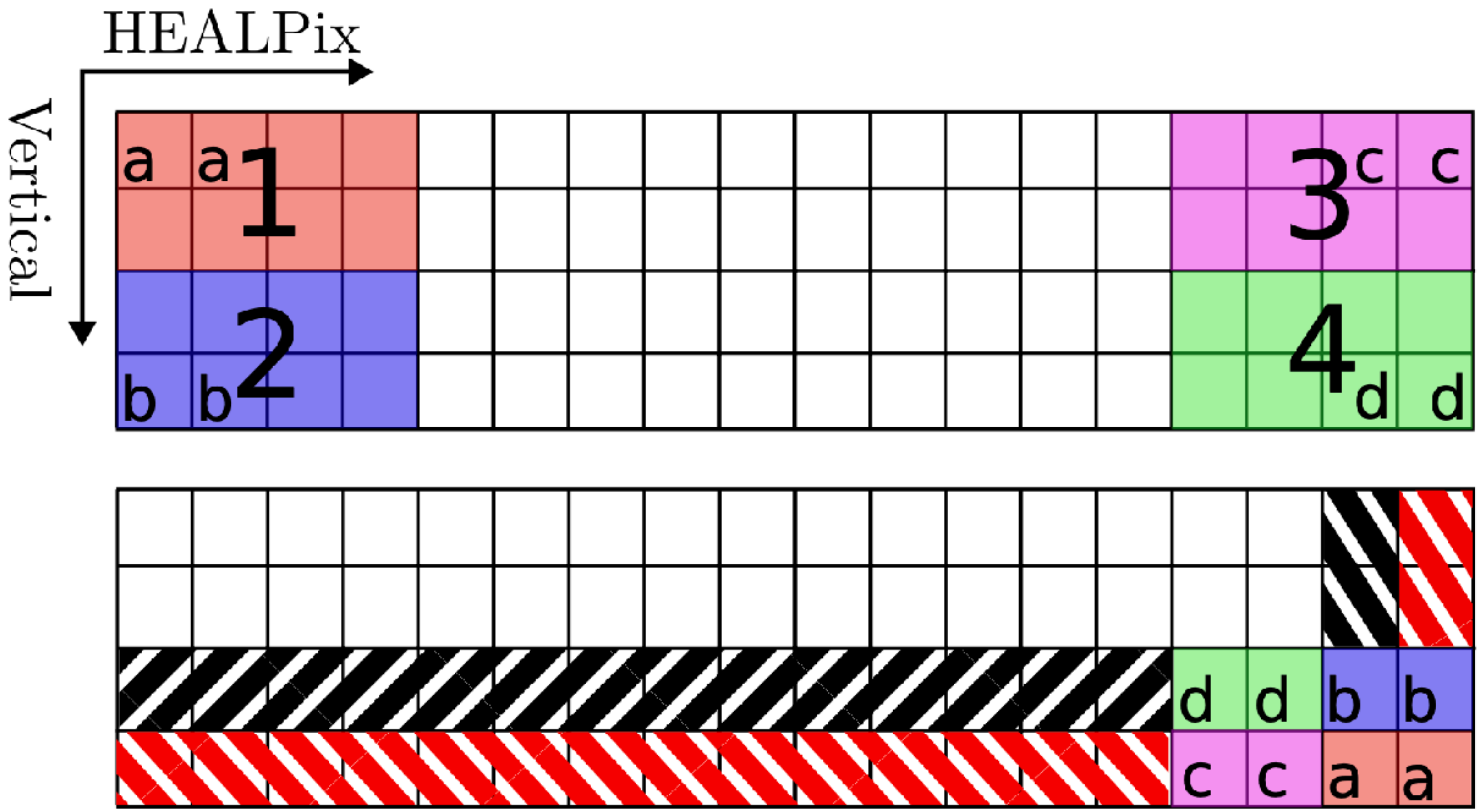
PEAR

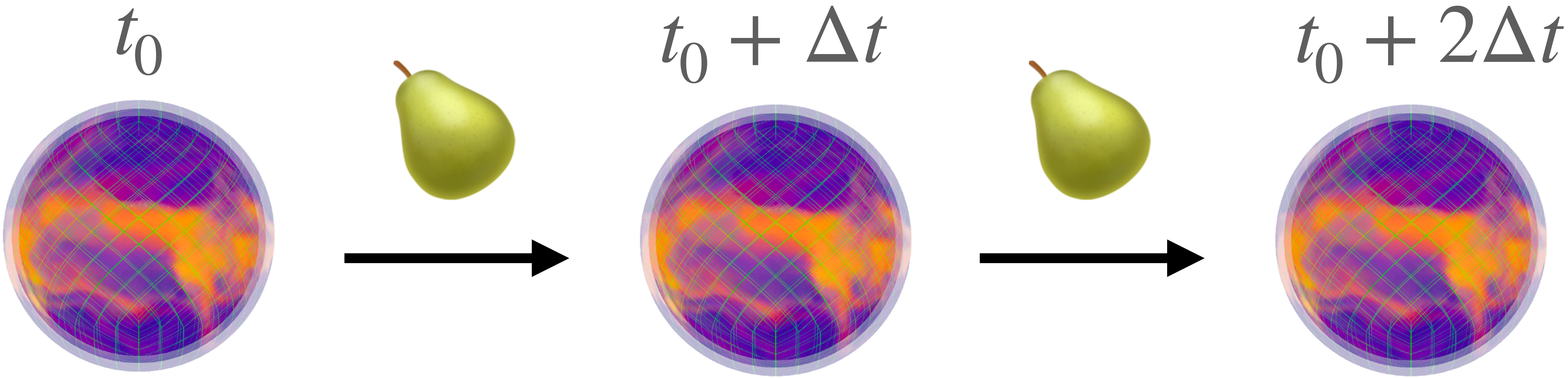
Window shifting



HL, Christoffer Petersson, Daniel Persson, and Jan E. Gerken. "PEAR: Equal Area Weather Forecasting on the Sphere." arXiv:2505.17720

PEAR

Longer forecast time



HL, Christoffer Petersson, Daniel Persson, and Jan E. Gerken. "PEAR: Equal Area Weather Forecasting on the Sphere." arXiv:2505.17720

Evaluation

Metrics

HEALPix

$$\mathrm{RMSE}(y, \hat{y}) = \sqrt{\frac{1}{12n_{\mathrm{side}}^2} \sum_{i=0}^{12n_{\mathrm{side}}^2} (y^i - \hat{y}^i)^2}$$

Equiangular

$$\mathrm{RMSE}(v, t) = \sqrt{\frac{\sum_{i=1}^{N_{\mathrm{lat}}} \sum_{j=1}^{N_{\mathrm{lon}}} L(i)(\hat{\mathbf{A}}_{i,j,t}^{v} - \mathbf{A}_{i,j,t}^{v})^2}{N_{\mathrm{lat}} \times N_{\mathrm{lon}}}}$$

$$L(i) = N_{\mathrm{lat}} \times \frac{\cos \phi_i}{\sum_{i'=1}^{N_{\mathrm{lat}}} \cos \phi_{i'}}$$

Evaluation

Metrics

Anomaly Correlation Coefficient (ACC)

$$\mathrm{ACC}(y, \hat{y}) = \frac{\sum_i^{12n_{\mathrm{nside}}^2} \Delta y^i \Delta \hat{y}^i}{\sqrt{\left(\sum_i^{12n_{\mathrm{nside}}^2} (\Delta y^i)^2\right)\left(\sum_i^{12n_{\mathrm{nside}}^2} (\Delta \hat{y}^i)^2\right)}}$$

$$\Delta y = \underset{\text{yearly}}{E}\left[\hat{y}\right] - y$$

Correlation between deviation from “climate average” between data and model predictions

PEAR

Quantitative evaluation

Variable	Δt (days)	ACC PEAR	ACC Pangu	RMSE PEAR	RMSE Pangu	unit
msl surface	1	**0.984**	0.979	**84.6**	97.9	Pa
	3	**0.924**	0.860	**175**	230	
	5	**0.790**	0.675	**282**	355	
t2m surface	1	**0.886**	0.876	**0.792**	0.846	K
	3	**0.779**	0.728	**1.11**	1.31	
	5	**0.650**	0.551	**1.41**	1.77	
u10 surface	1	**0.930**	0.923	**1.05**	1.1	$\frac{m}{s}$
	3	**0.819**	0.759	**1.59**	1.8	
	5	**0.647**	0.557	**2.17**	2.42	
v10 surface	1	**0.932**	0.922	**1.07**	1.13	$\frac{m}{s}$
	3	**0.820**	0.750	**1.64**	1.87	
	5	**0.638**	0.528	**2.26**	2.54	

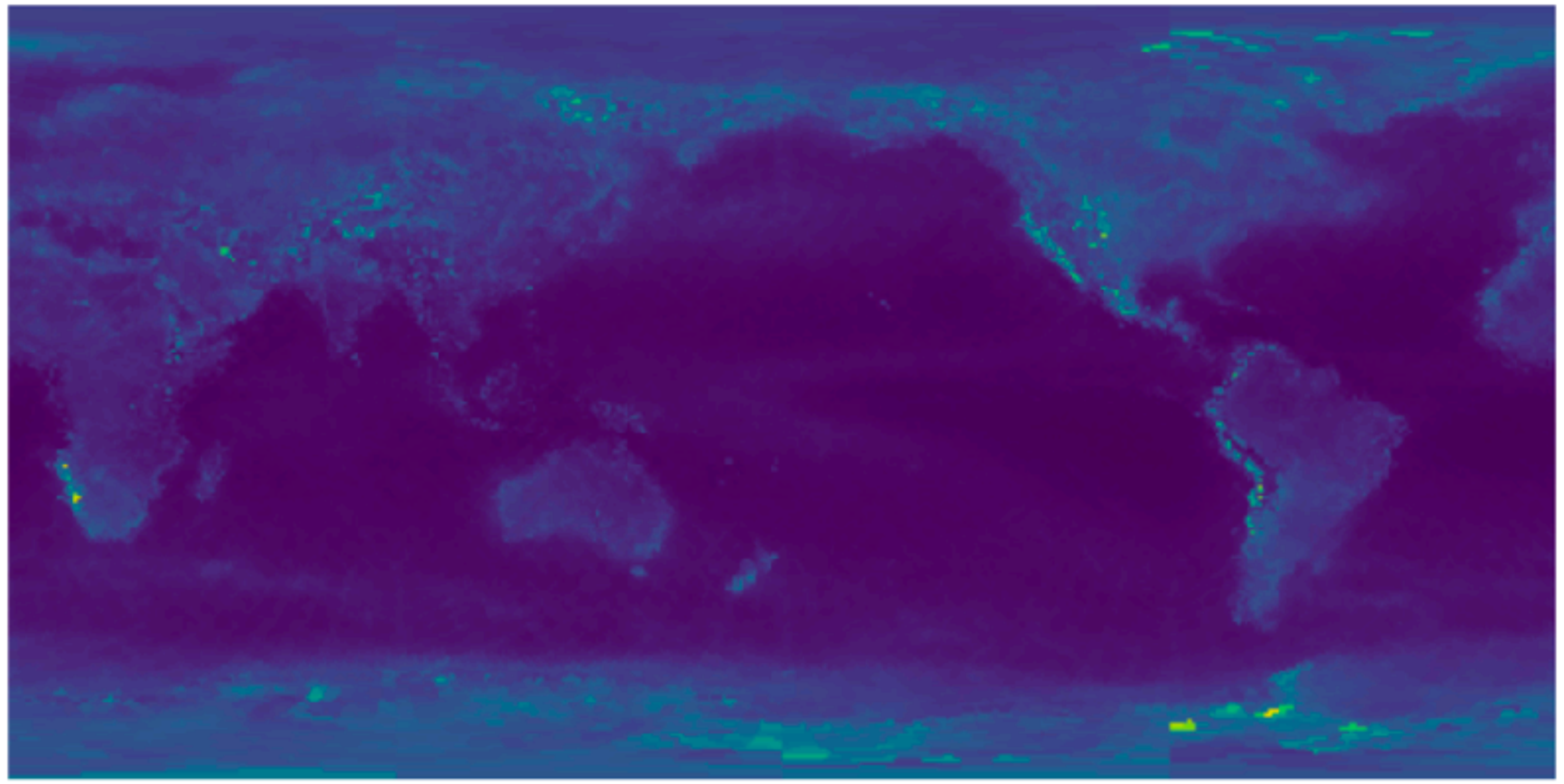
PEAR

Quantitative evaluation

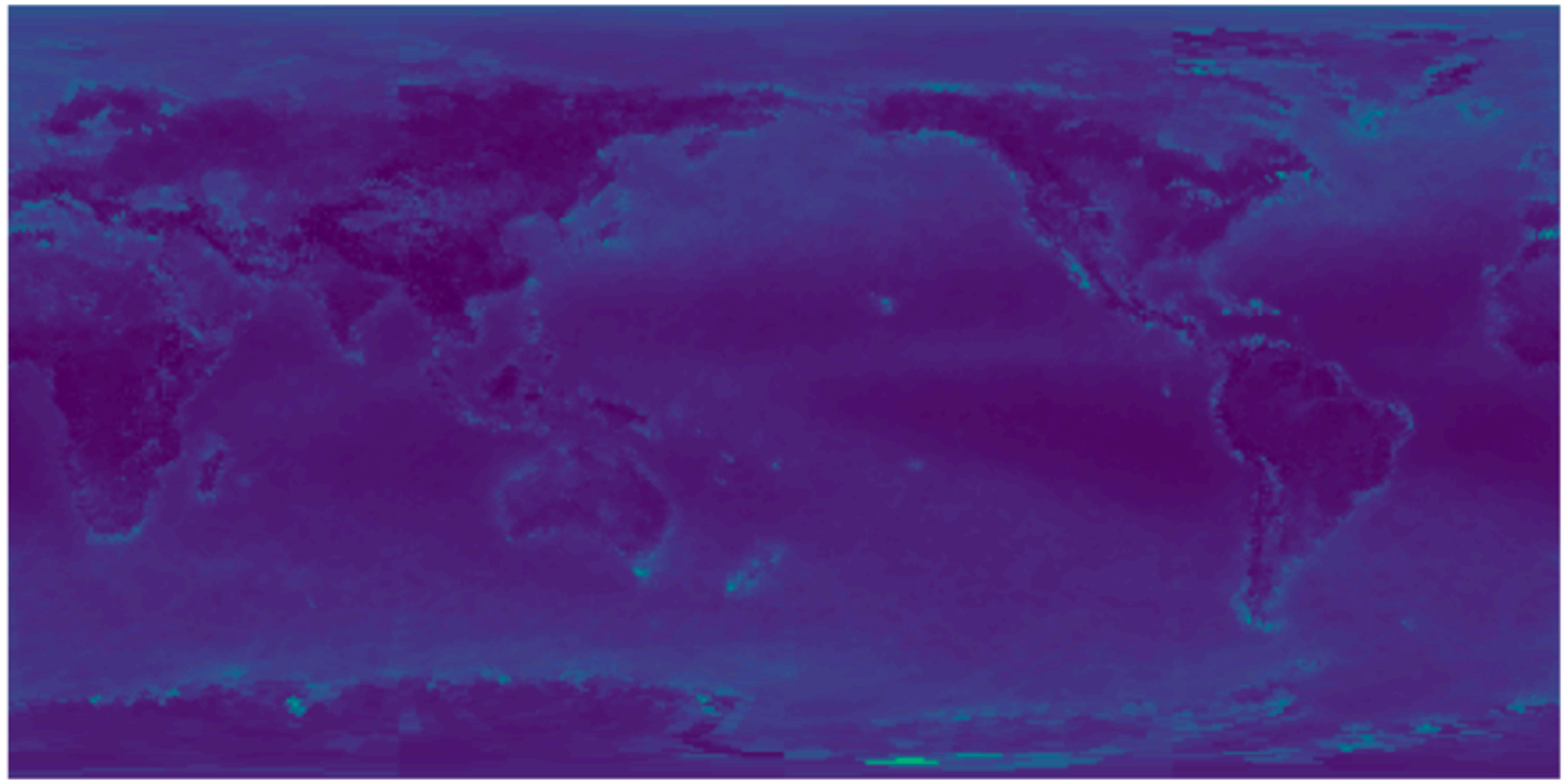
Variable	Δt (days)	ACC PEAR	ACC Pangu	RMSE PEAR	RMSE Pangu	unit
q_{upper}	1	**0.824**	0.792	$\mathbf{2.87 \times 10^{-4}}$	3.1×10^{-4}	$\frac{g}{kg}$
	3	**0.706**	0.647	$\mathbf{3.69 \times 10^{-4}}$	4.09×10^{-4}	
	5	**0.584**	0.510	$\mathbf{4.52 \times 10^{-4}}$	5.03×10^{-4}	
t_{upper}	1	**0.945**	0.938	**0.756**	0.809	K
	3	**0.877**	0.822	**1.11**	1.3	
	5	**0.763**	0.664	**1.51**	1.77	
u_{upper}	1	**0.944**	0.937	**2.04**	2.17	$\frac{m}{s}$
	3	**0.866**	0.812	**3.12**	3.6	
	5	**0.739**	0.648	**4.31**	4.92	
v_{upper}	1	**0.941**	0.931	**2.02**	2.16	$\frac{m}{s}$
	3	**0.859**	0.787	**3.07**	3.61	
	5	**0.717**	0.595	**4.26**	4.92	
z_{upper}	1	**0.991**	0.985	**79**	98.8	gpm
	3	**0.949**	0.889	**175**	251	
	5	**0.850**	0.734	**291**	393	

PEAR

spatially resolved prediction errors



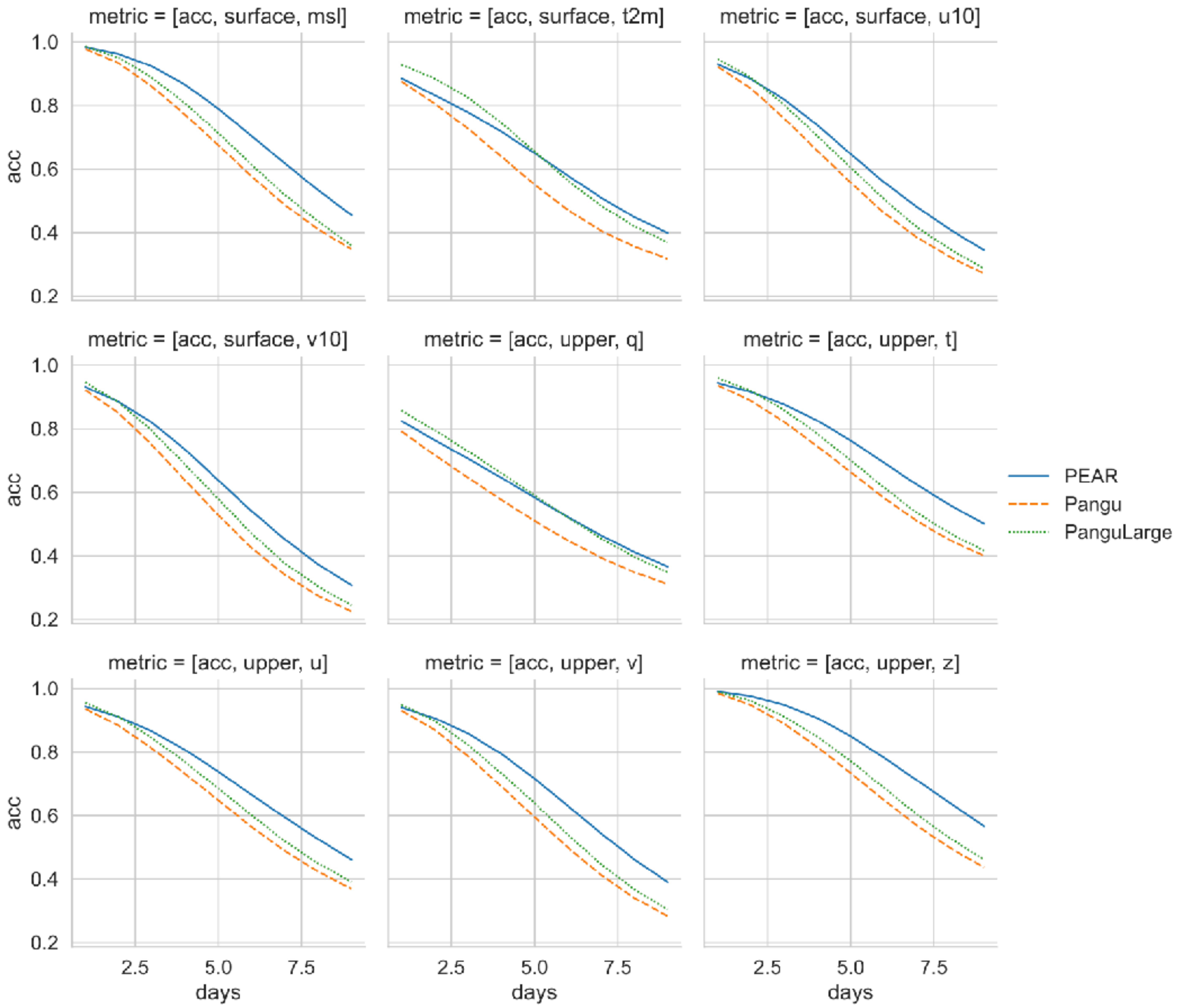
temperature
error (RMSE)



wind speed
error (RMSE)

PEAR

ACC


metric = [acc, surface, msl]
metric = [acc, surface, t2m]
metric = [acc, surface, u10]
metric = [acc, surface, v10]
metric = [acc, upper, q]
metric = [acc, upper, t]
metric = [acc, upper, u]
metric = [acc, upper, v]
metric = [acc, upper, z]
acc
days
1.0
0.8
0.6
0.4
0.2
2.5
5.0
7.5
PEAR
Pangu
PanguLarge

PEAR

compute

Model	Trainable parameters (M)	Inference time (ms)
PEAR	4.3	17 ± 0.12
Pangu	11.4	25 ± 0.05
Pangu-Large	33.7	54 ± 0.02

Outlook

Azimutal equivariance

Full ERA5 dataset

Increased resolution

gapindnns.github.io

PEAR

Data shape

Tensor	Shape
surface	$(49152, 4)$
upper	$(49152, 13, 5)$