Interpretability of AI weather models via intermediate decoding

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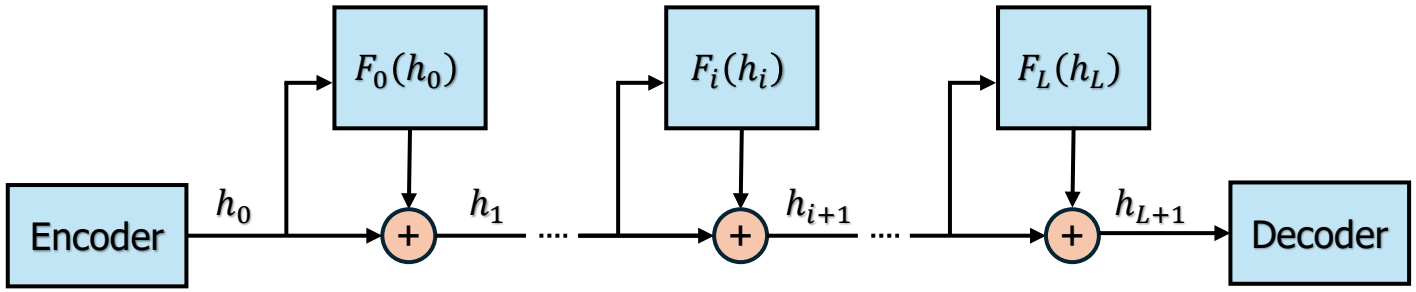
Introduction

- AI weather models are still black boxes
- Apply method of Intermediate Decoding to three different models:
  - Graphcast (Graph Neural Network)
  - Aurora (Transformer model)
  - ArchesWeather (Transformer model)
- How does the forecast evolve with increasing model depth?
  - Model loss
  - Spatial scale progression
  - Physical balances

Methods

- Models employ a residual network architecture:

$$\mathbf{h}_{\mathrm{i}+1} = \mathbf{h}_{\mathrm{i}} + F_{\mathrm{i}}(\mathbf{h}_{\mathrm{i}})$$



- Send intermediate model states to the decoder to create a prediction $\hat{X}^{t+1}$:

$$\hat{X}^{t+1}(\mathrm{i}) = Decoder(\mathbf{h}_{\mathrm{i}})$$

- Apply linear transformation (translator) before decoding:

$$\hat{X}^{t+1}(i) = Decoder(\mathbf{h}_{\mathrm{i}}\mathrm{W}_{\mathrm{i}} + \mathbf{b}_{\mathrm{i}})$$

Methods

- Models generate a global forecast:

$$\hat{X}^{t+1} = Model(X^{t}, X^{t-1}), \qquad \Delta t_{GC,\,Au} = 6h, \Delta t_{Ar} = 24h$$

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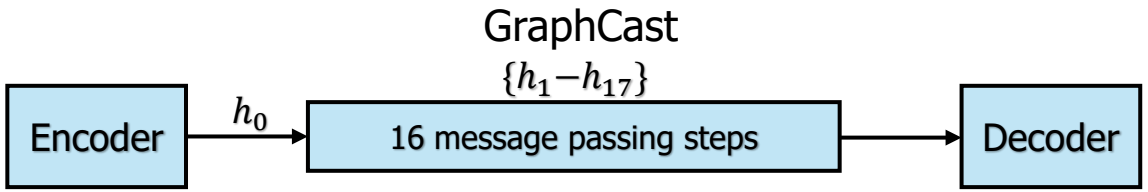

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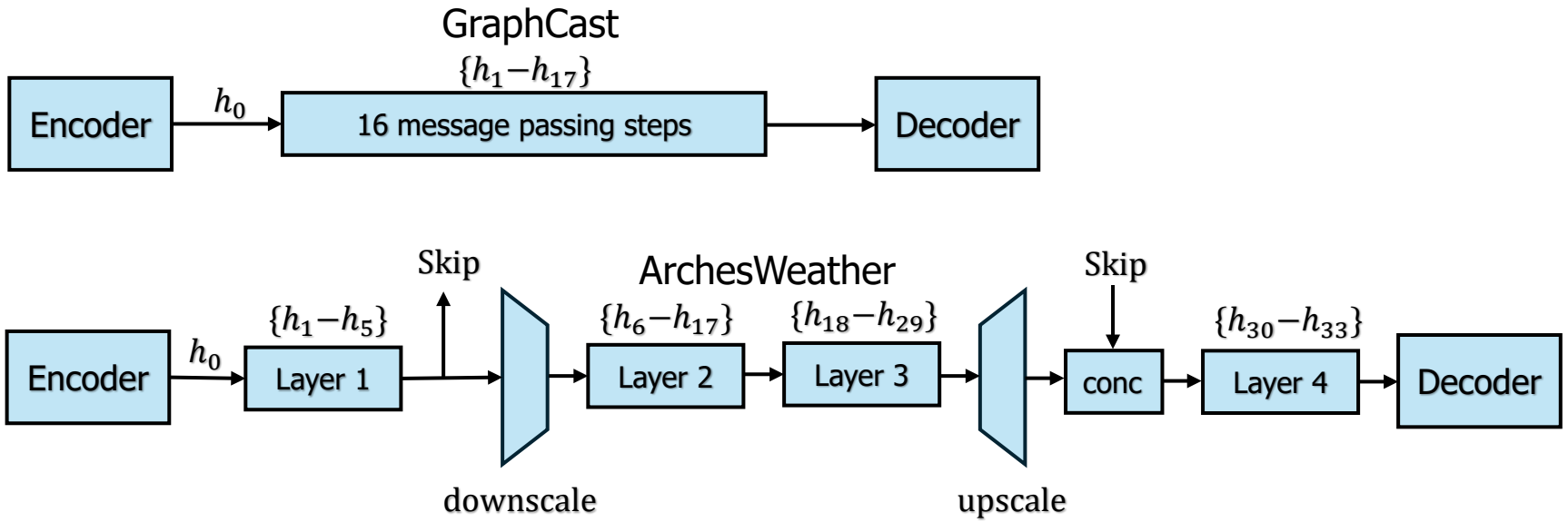

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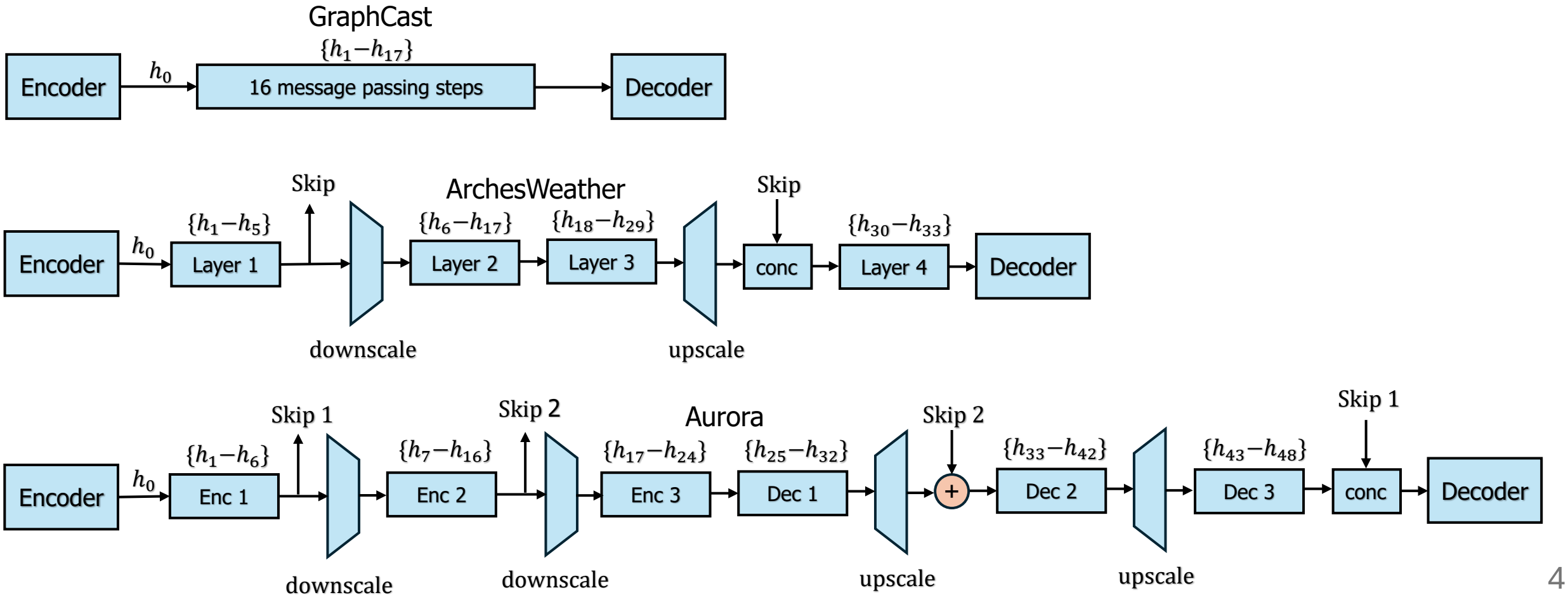
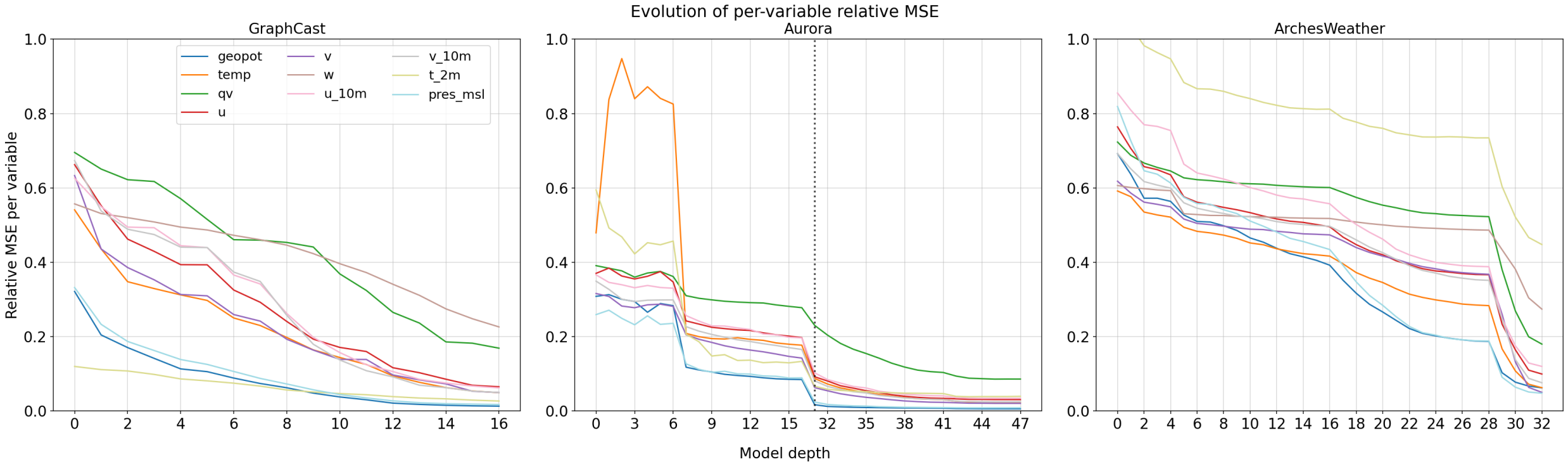


Forecast performance

- Calculate MSE for intermediate decodings:

$$MSE_{rel}(i) = \frac{MSE\left(\hat{X}_i^{t+1}, X^{t+1}\right)}{MSE(X^t, X^{t+1})}$$



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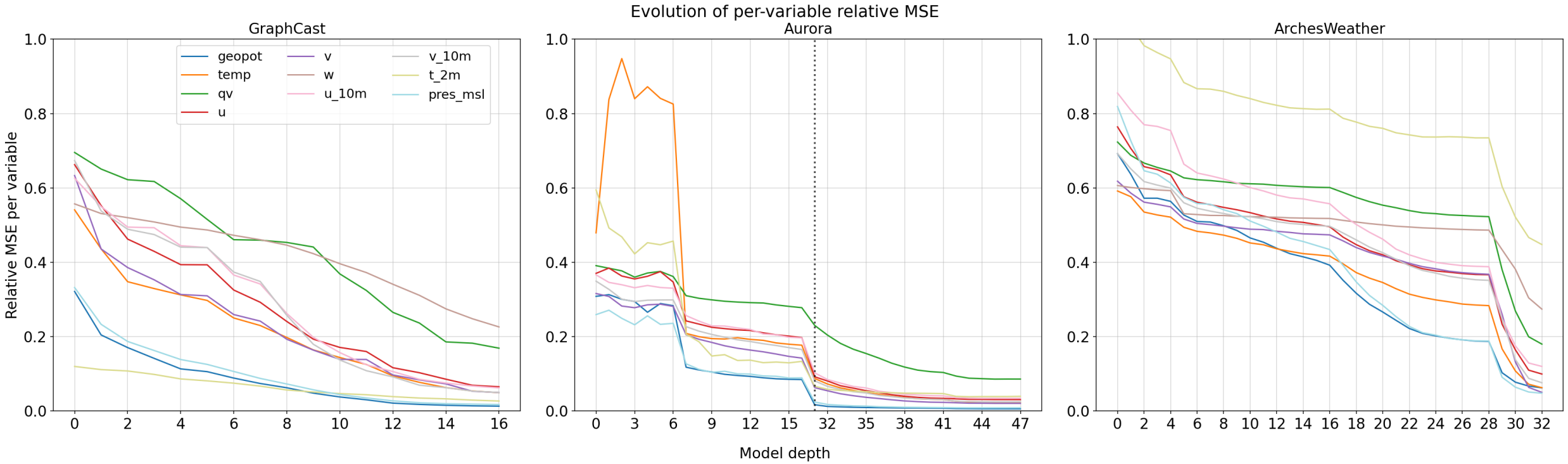
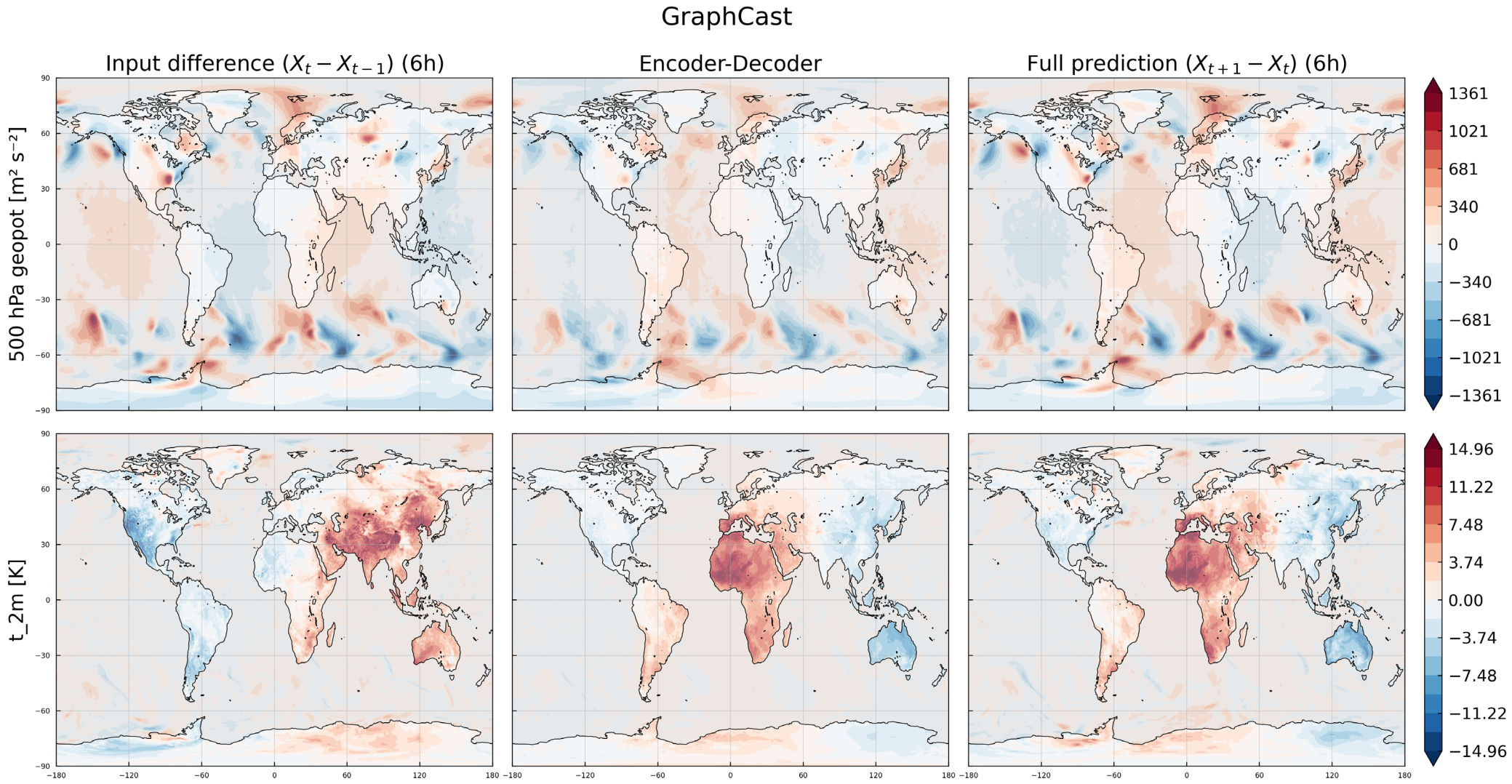
- ➢ Encoder immediately creates prediction
- ➢ Stage structure evident
- ➢ Gradual convergence towards final prediction within consistent stages



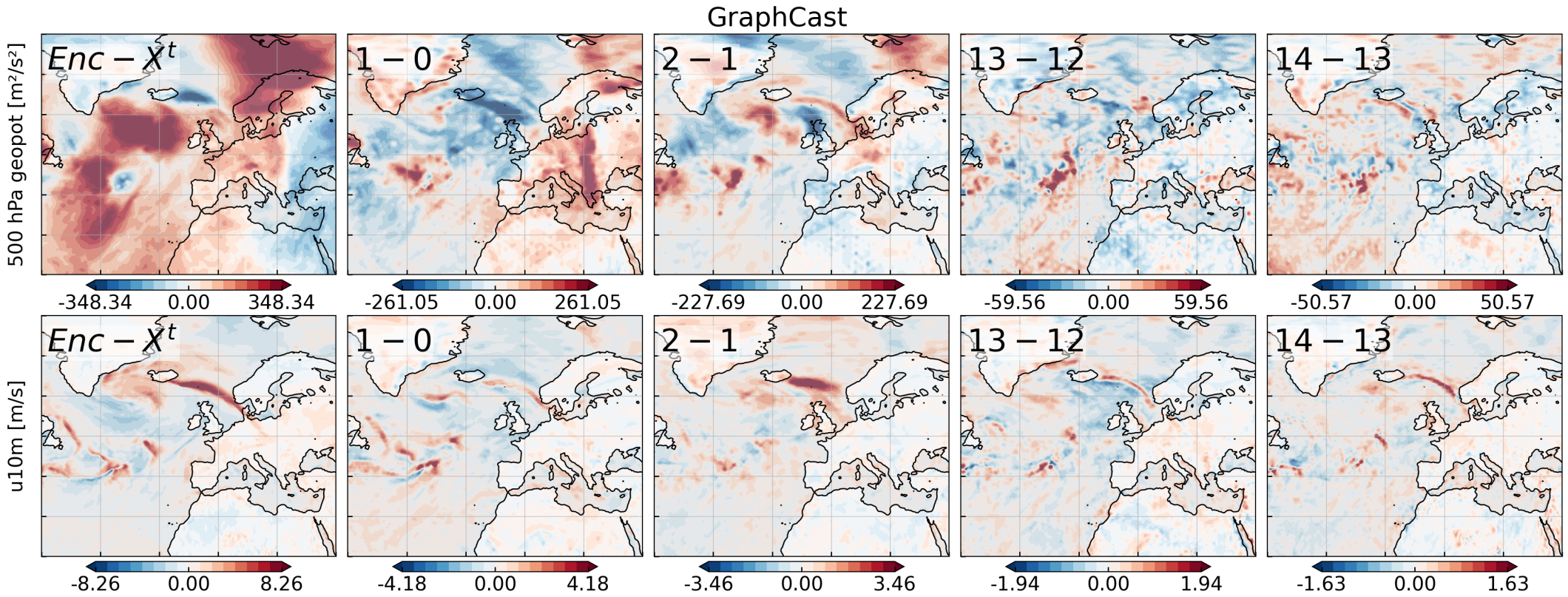
Encoder-Decoder only forecast



Forecast progression

- Calculate increment between intermediate decodings:

$$\Delta\hat{X}^{t+1}(i) = \hat{X}^{t+1}(i) - \hat{X}^{t+1}(i-1)$$



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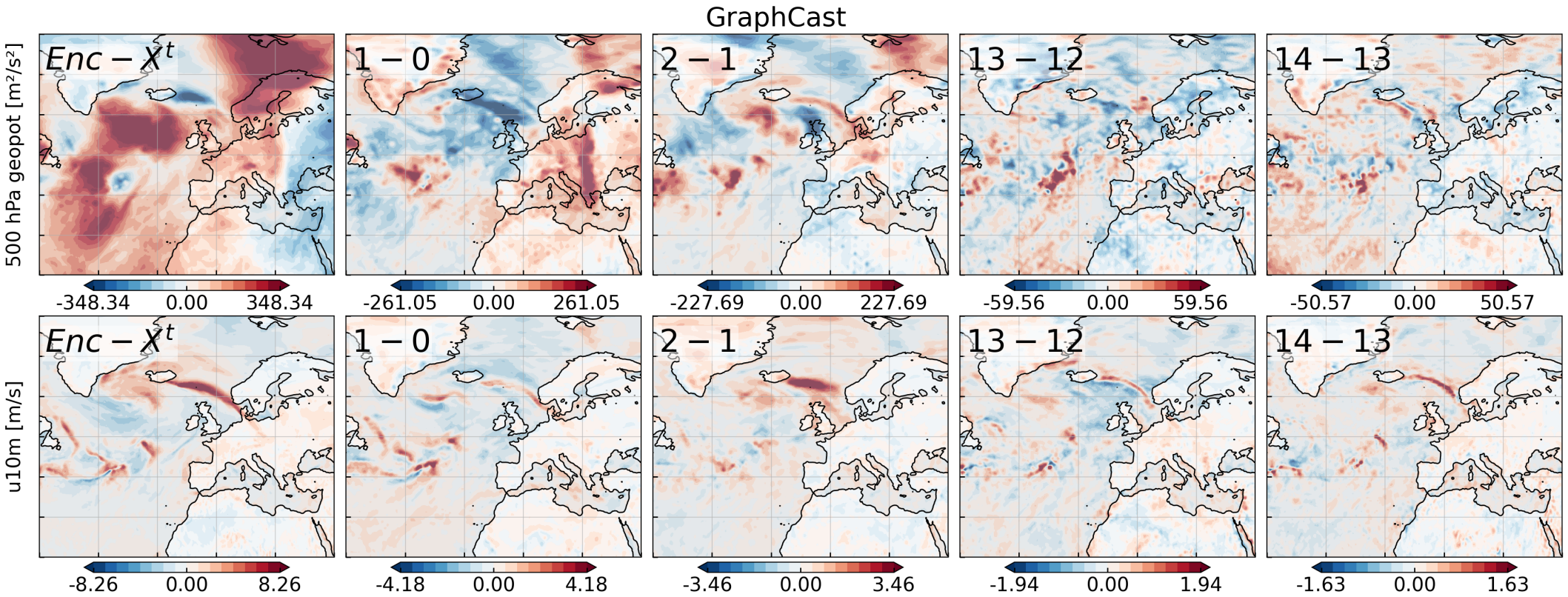
$$\Delta\hat{X}^{t+1}(i) = \hat{X}^{t+1}(i) - \hat{X}^{t+1}(i-1)$$

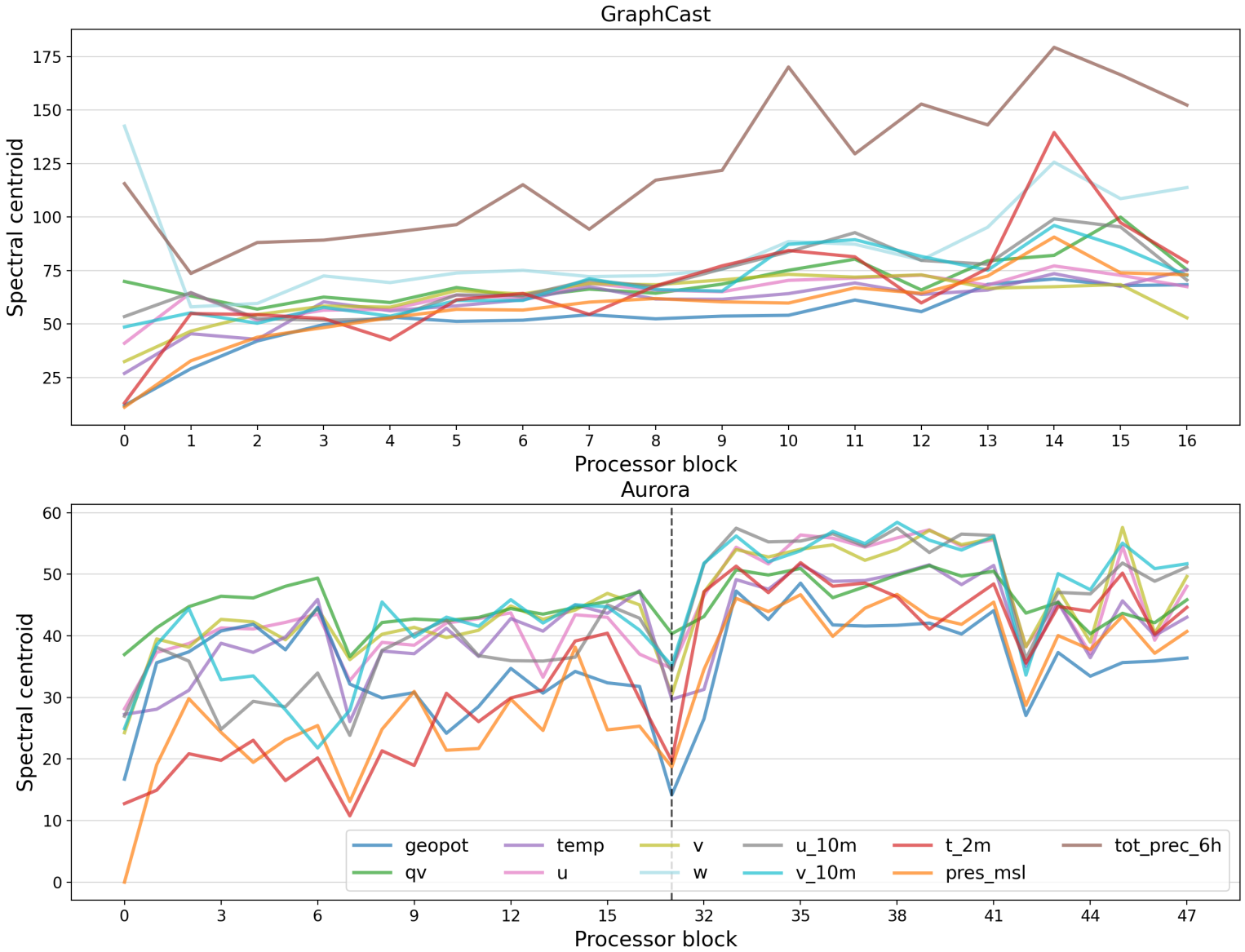
- ➢ Progression toward smaller spatial scales and reduced amplitudes with increasing model depth
- ➢ Features are iteratively refined



Forecast progression: Scales

- Calculate spectral centroids of increment fields:

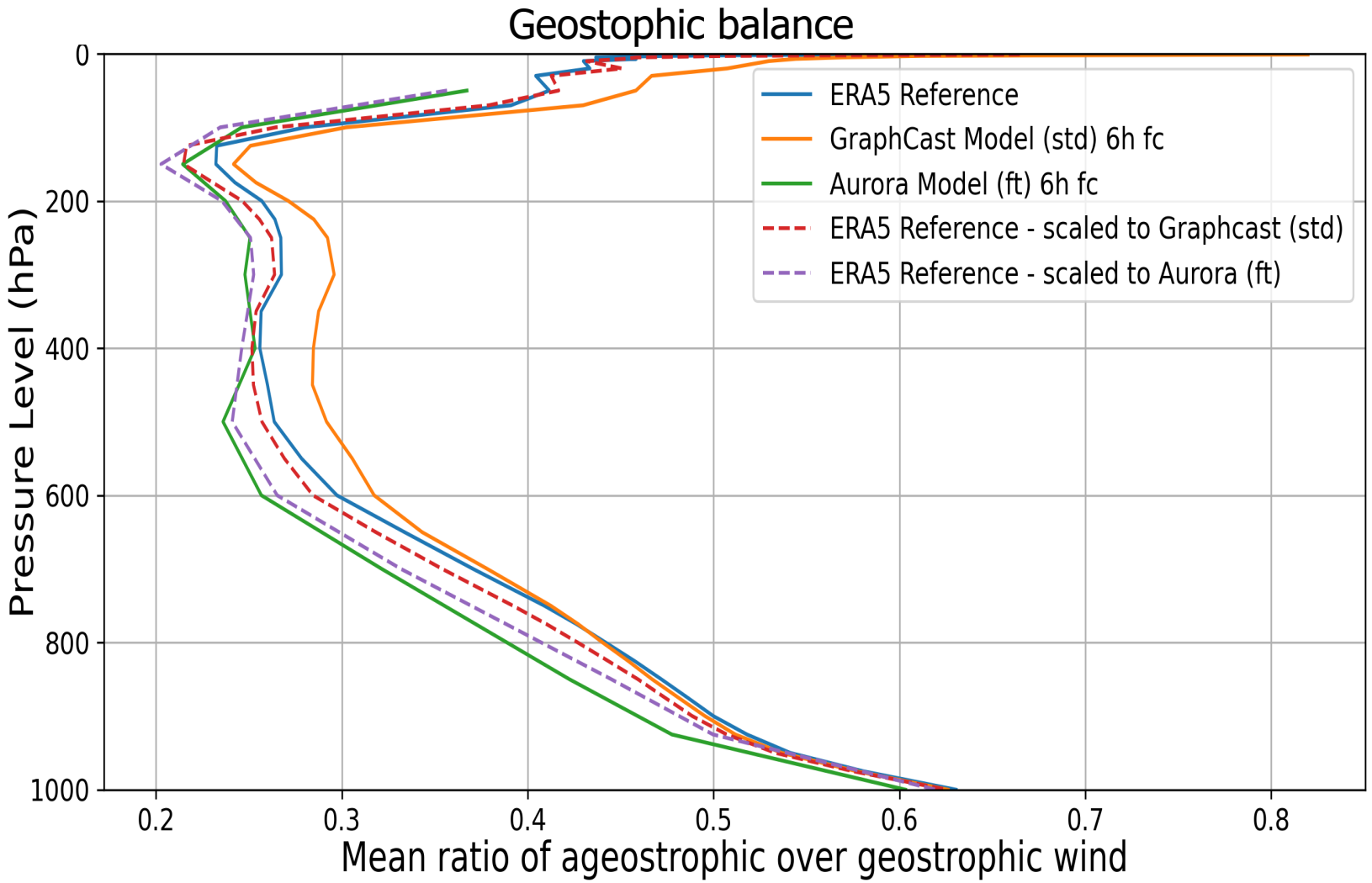
$$\mathrm{l}_{centroid} = \frac{\sum l\, P_l}{\sum l}$$



Geostophic balance

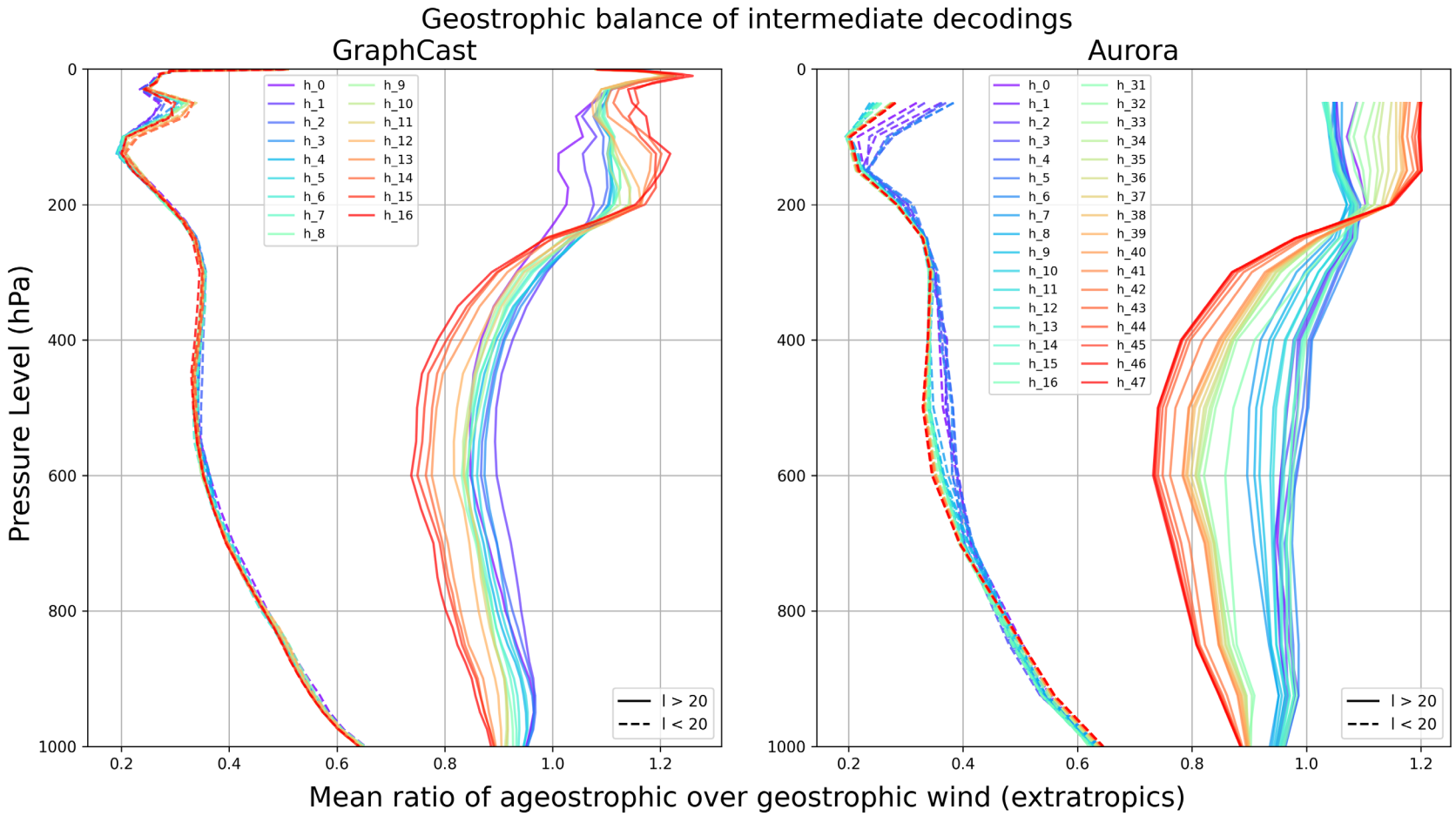
- Calculate geostrophic balance of model forecasts and compare to ERA5

$$r = \frac{\|\mathbf{u}_{\text{ageo}}\|}{\|\mathbf{u}_{\text{geo}}\|}, \quad lon > 20\,°$$



Geostophic balance: intermediate decodings

- Create intermediate decoding forecasts and filter scales:
  - Planetary/synoptic ($l \leq 20$)
  - Meso ($l > 20$)
- Calculate geostrophic balance on scale seperated intermediate decoding forecasts



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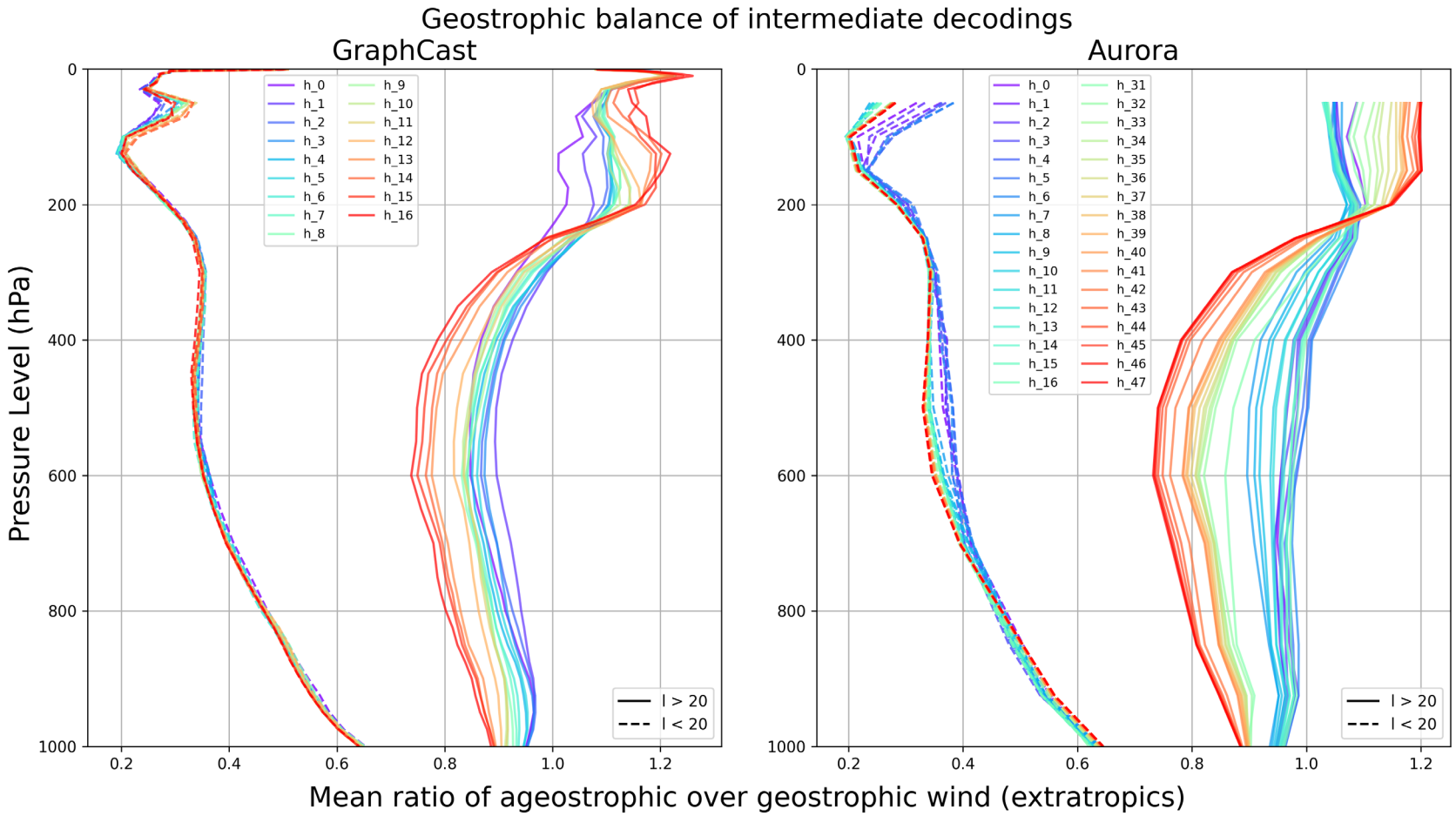


➢ Geostrophic balance increases with model depth, driven by small scales

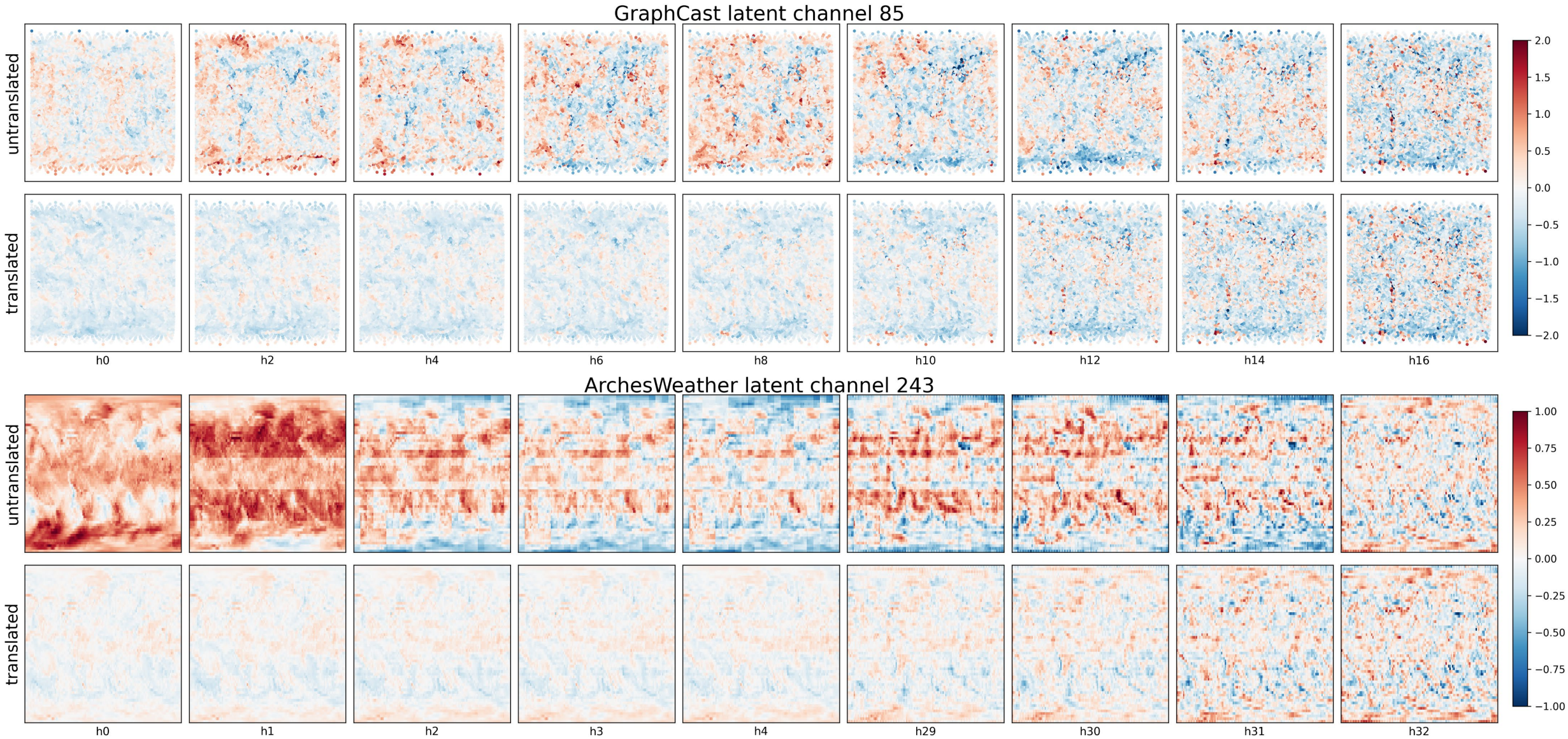
Conclusion

- We apply a method to track how forecasts evolve in physical space:
  - Stage structure relevant for forecast construction
  - Encoder-Decoder create sensible first guess
  - Progression to smaller scales
  - Geostrophic balance with later layers
- However: No direct access to interpretable latent features
- Next steps: Examine latent space directly, PCA, sparse autoencoders, Interactive tool (https://github.com/ktempestuous/latent_space_visualiser_weather_models)

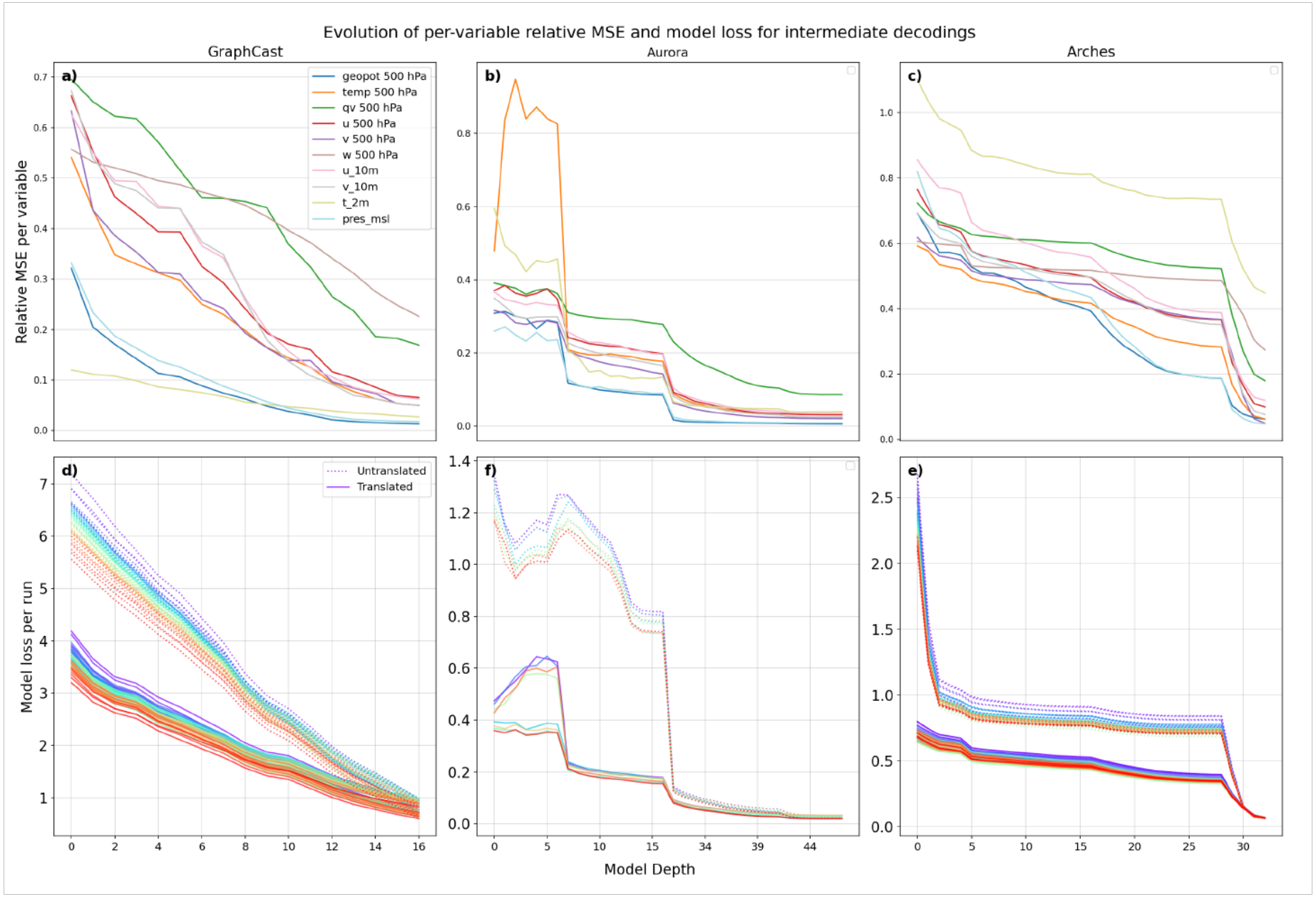
(k.tempest@physik.uni-muenchen.de)

Appendix

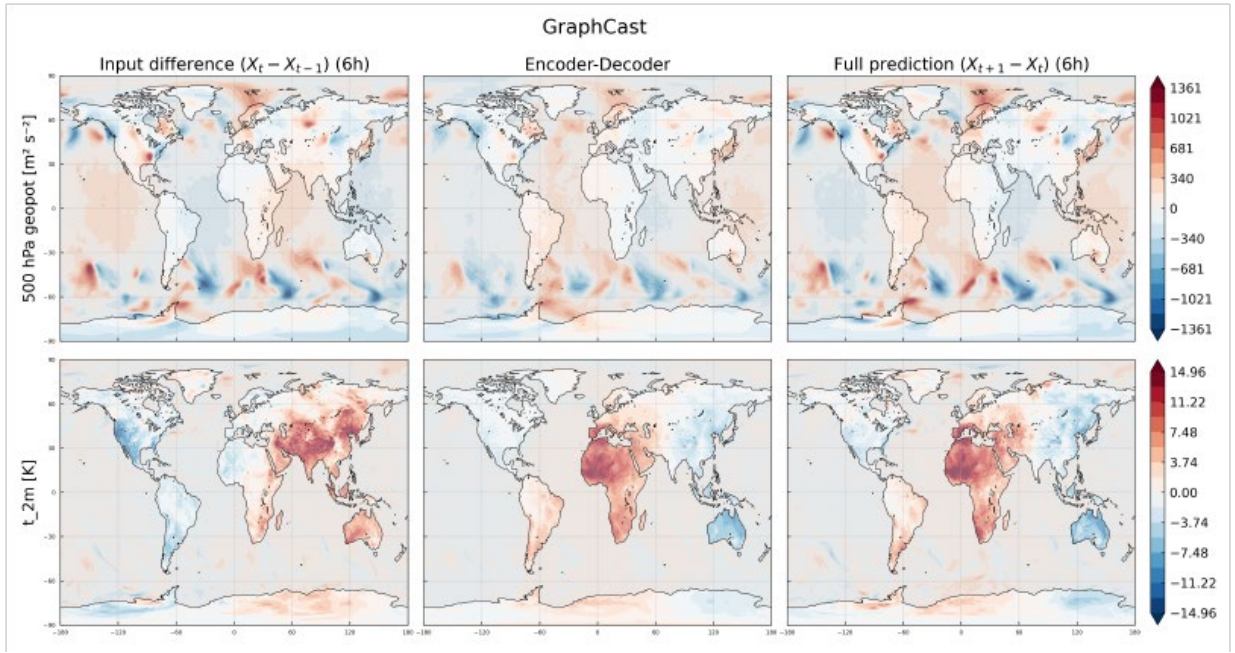
Latent channel developement

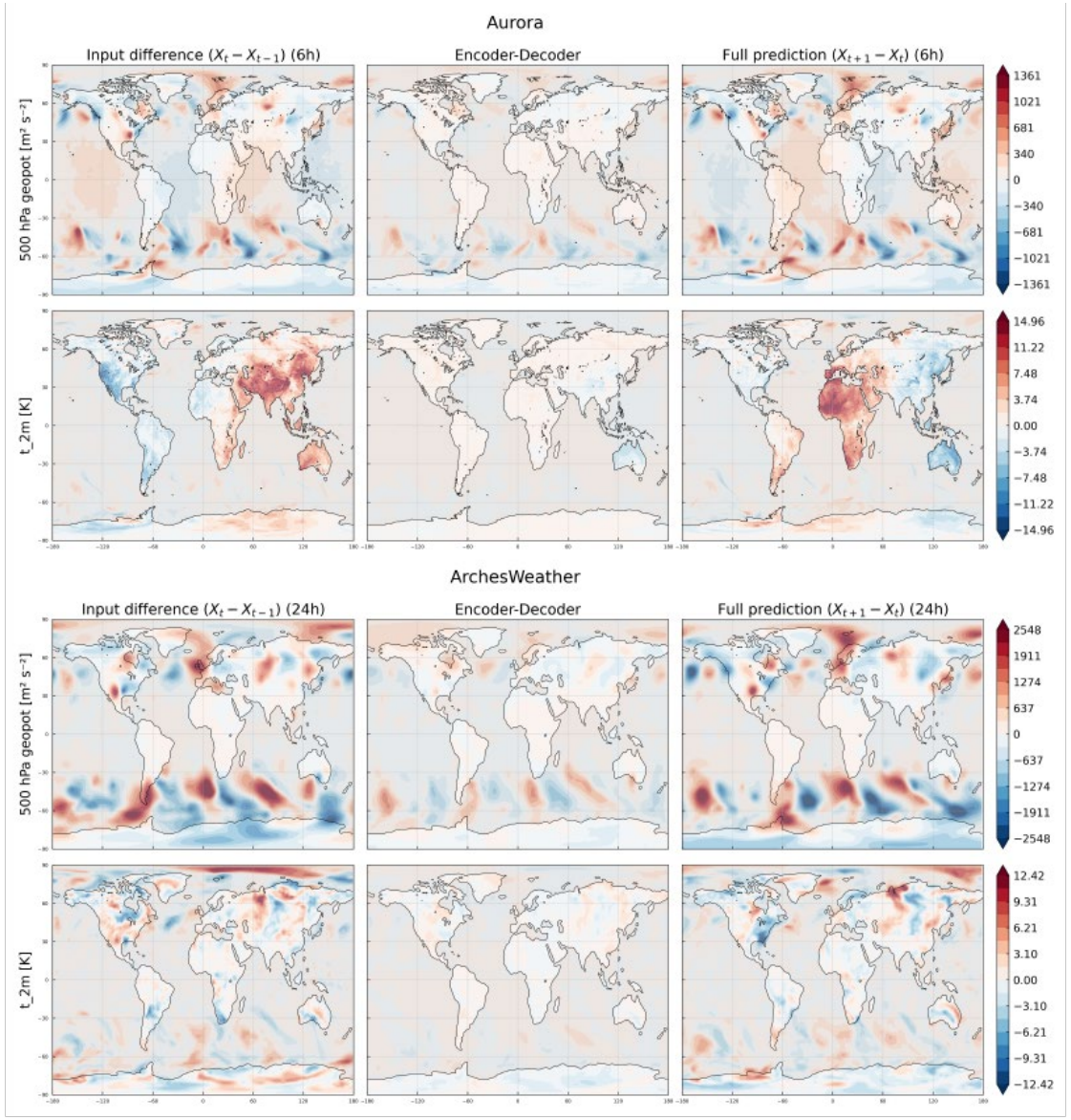


Forecast progression

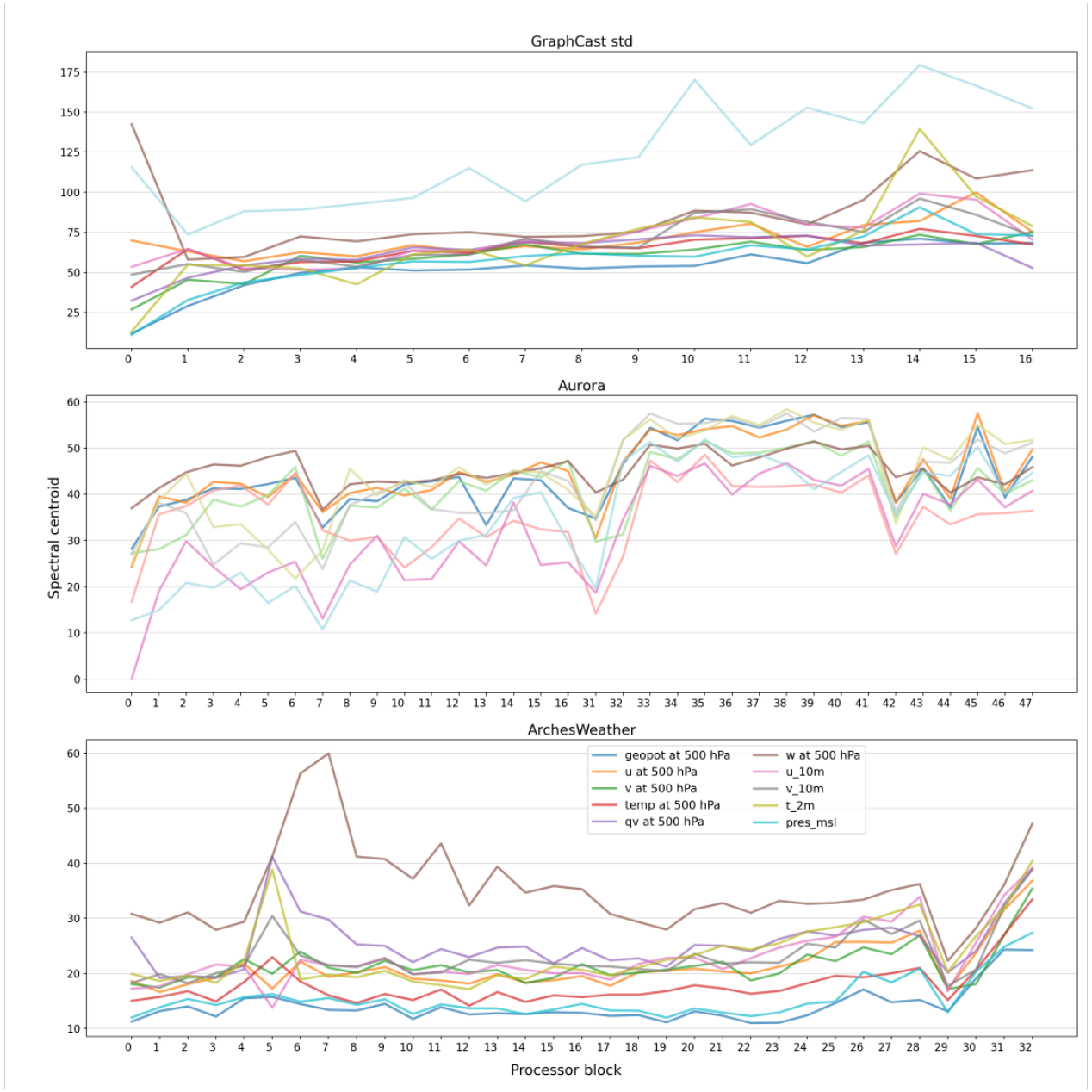


Encoder-Decoder

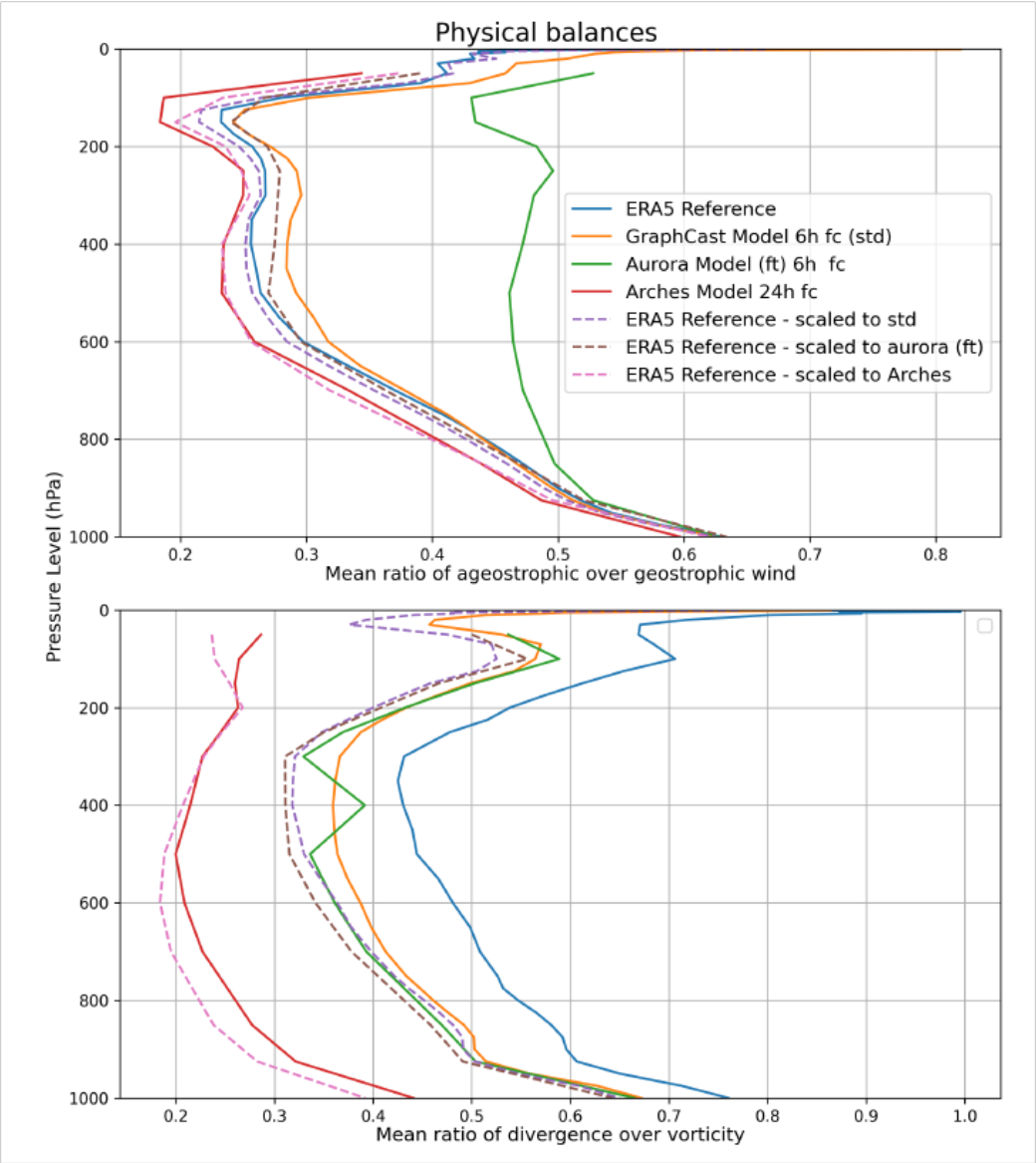




Scales


GraphCast std
Aurora
Spectral centroid
ArchesWeather
geopot at 500 hPa
u at 500 hPa
v at 500 hPa
temp at 500 hPa
qv at 500 hPa
w at 500 hPa
u_10m
v_10m
t_2m
pres_msl
Processor block

Physical balance



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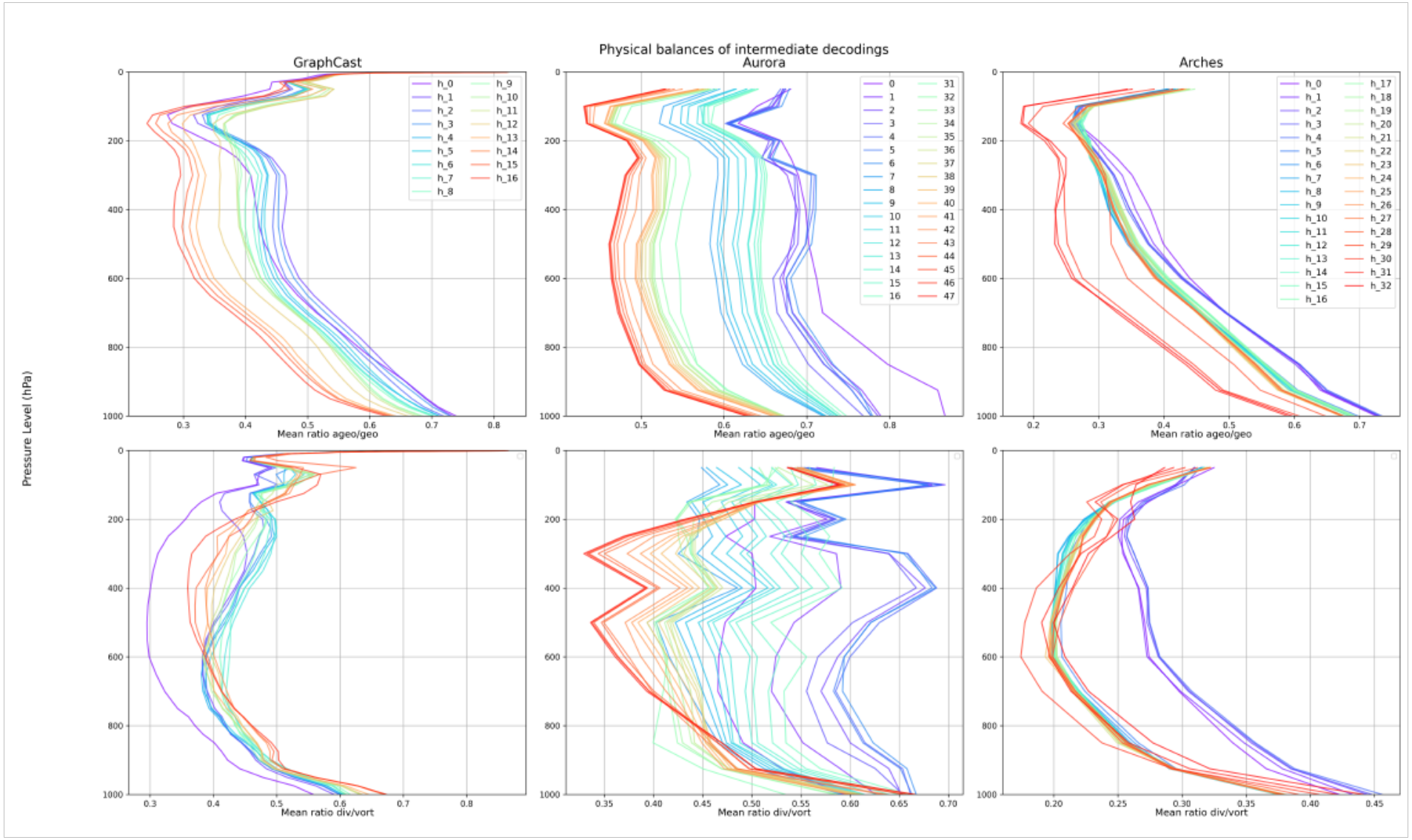

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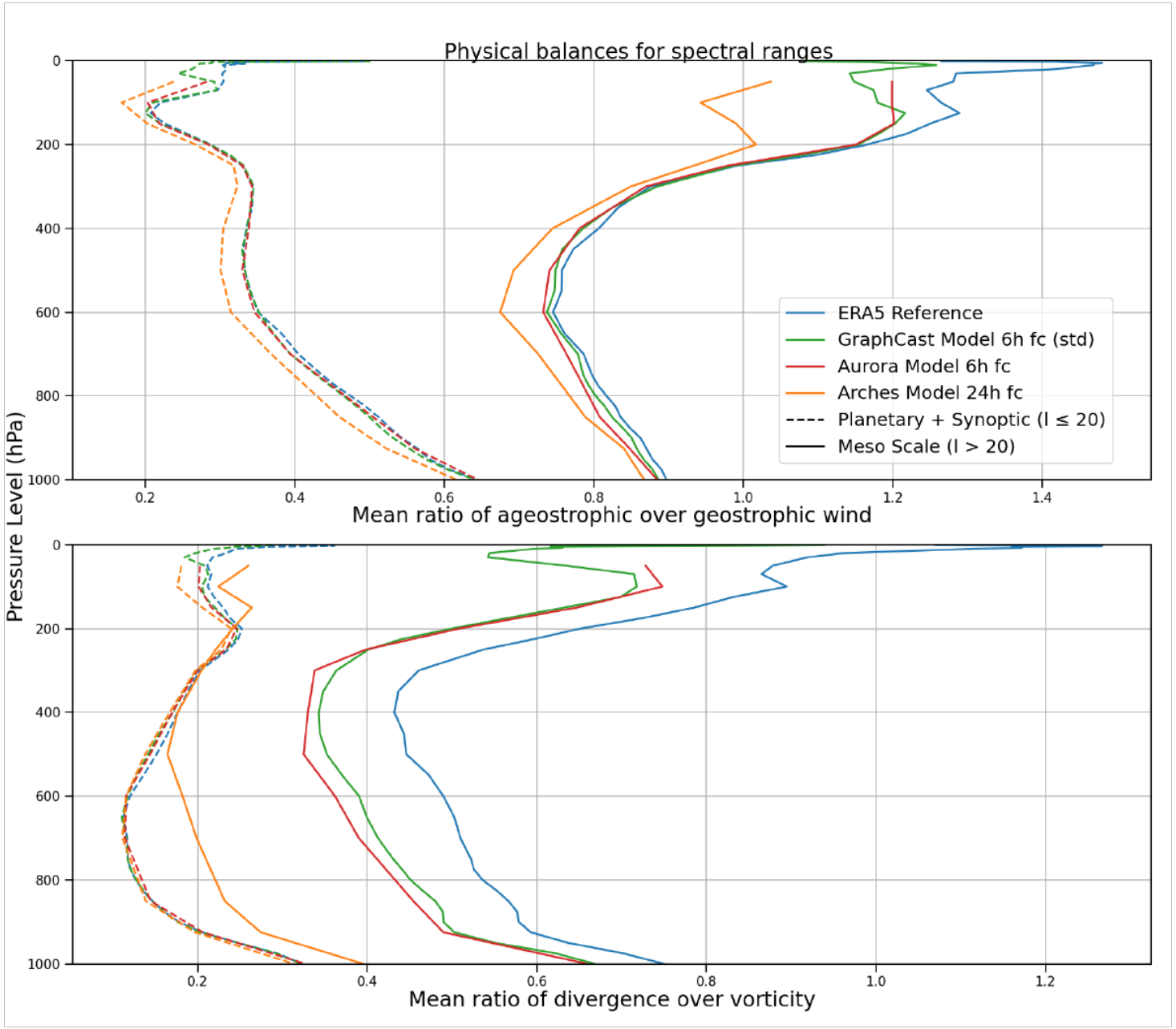

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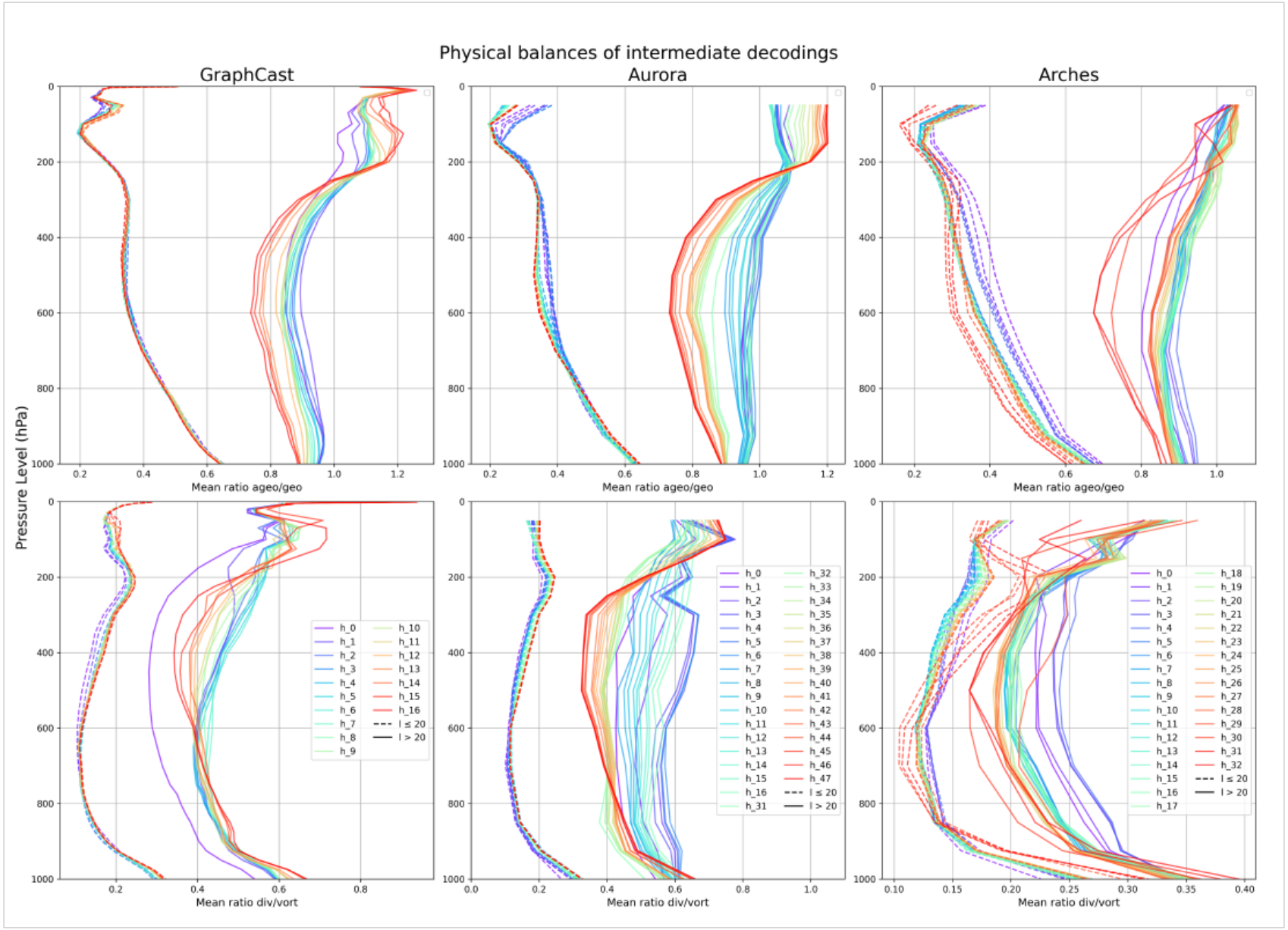
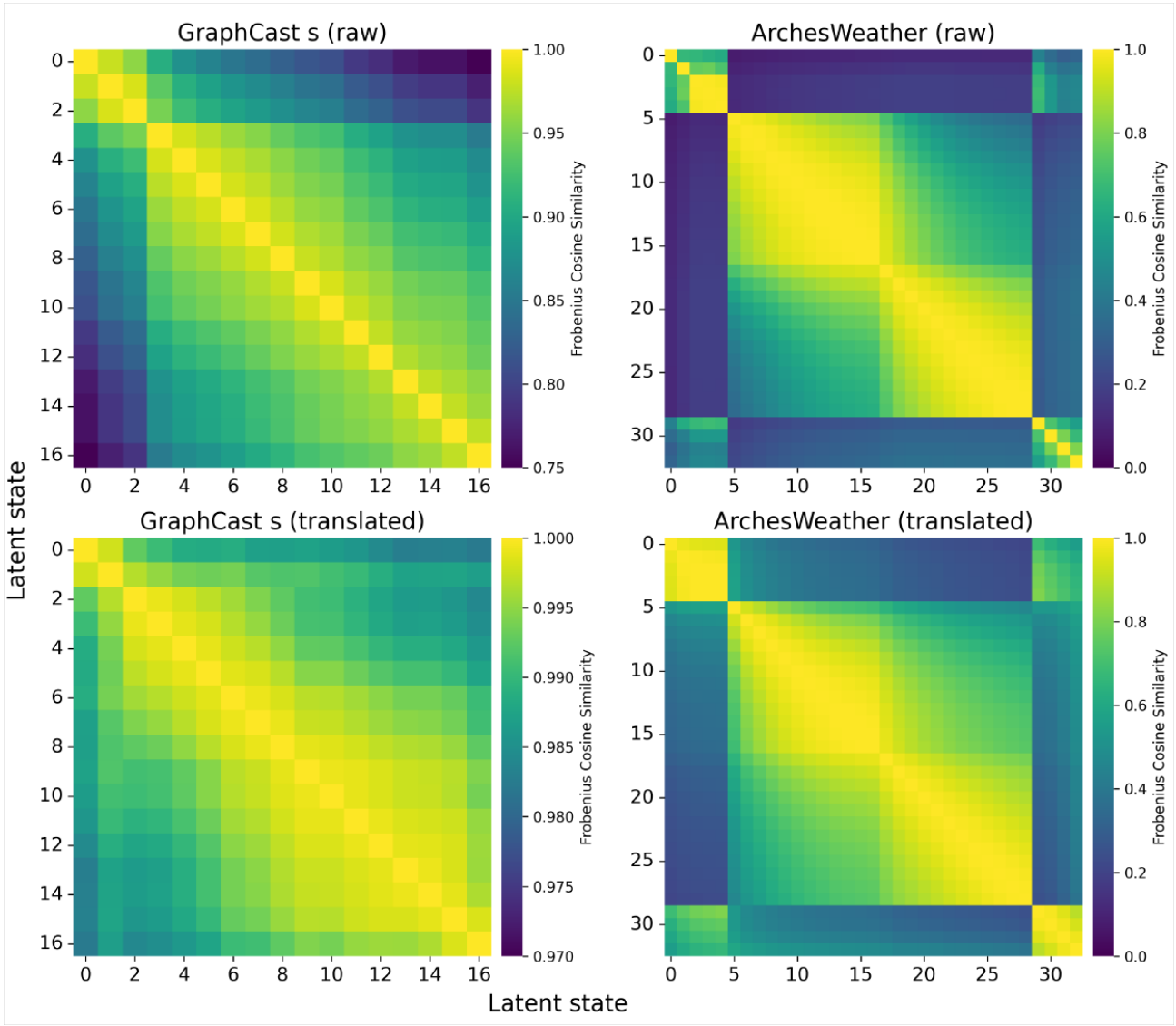
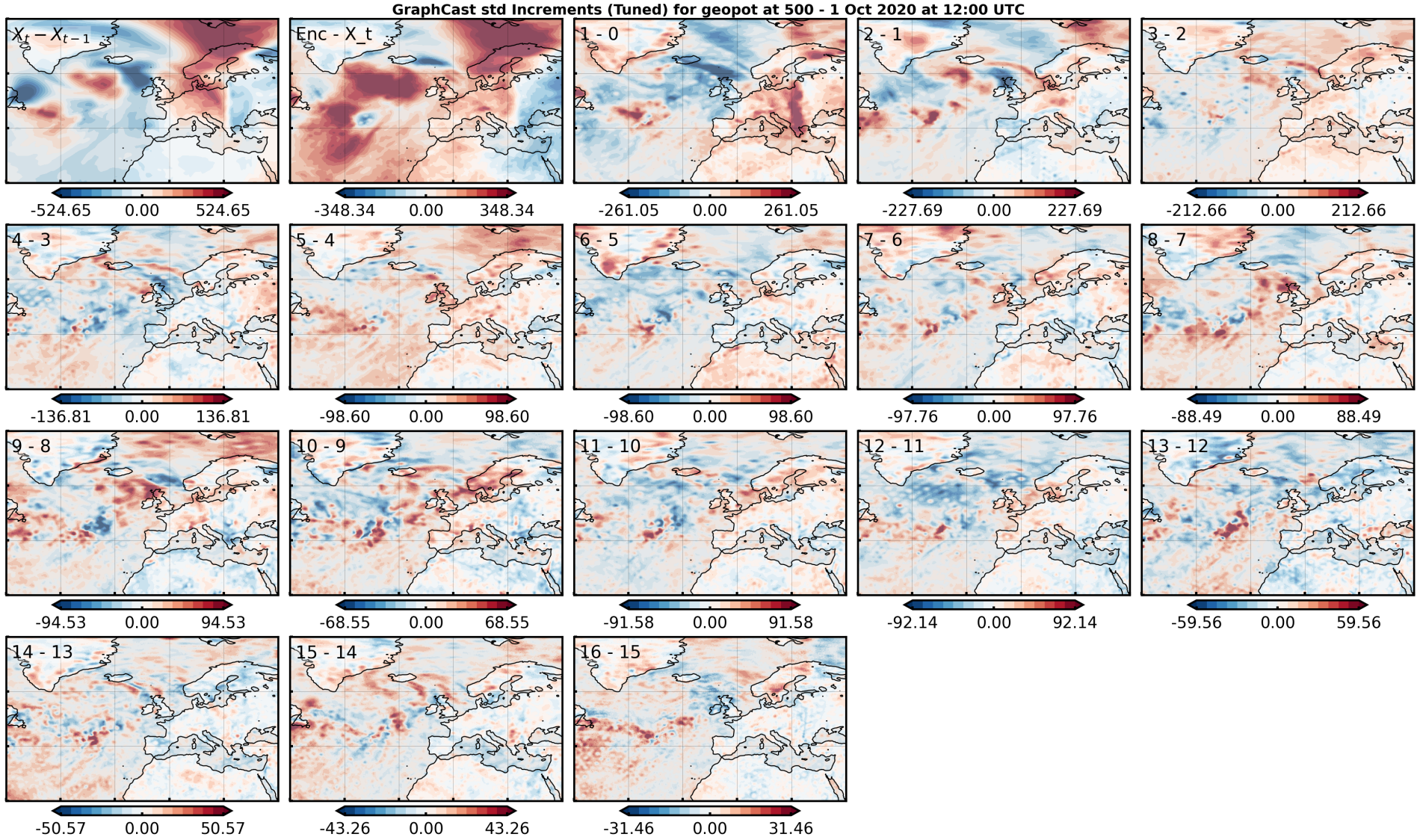


Representational stability



$$\cos_F(A,B) = \frac{\langle A,B\rangle_F}{\|A\|_F\,\|B\|_F},$$

GraphCast all increments



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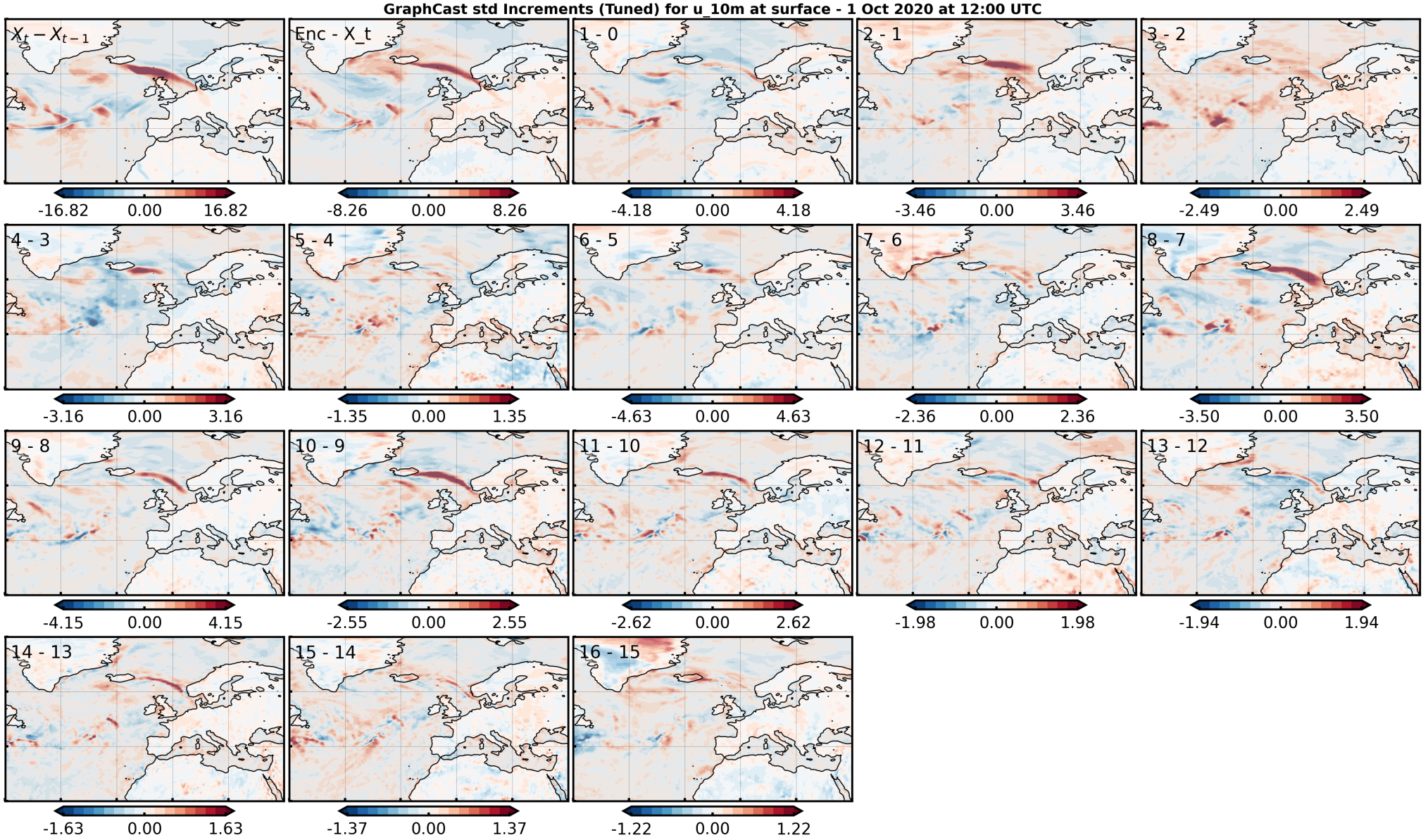

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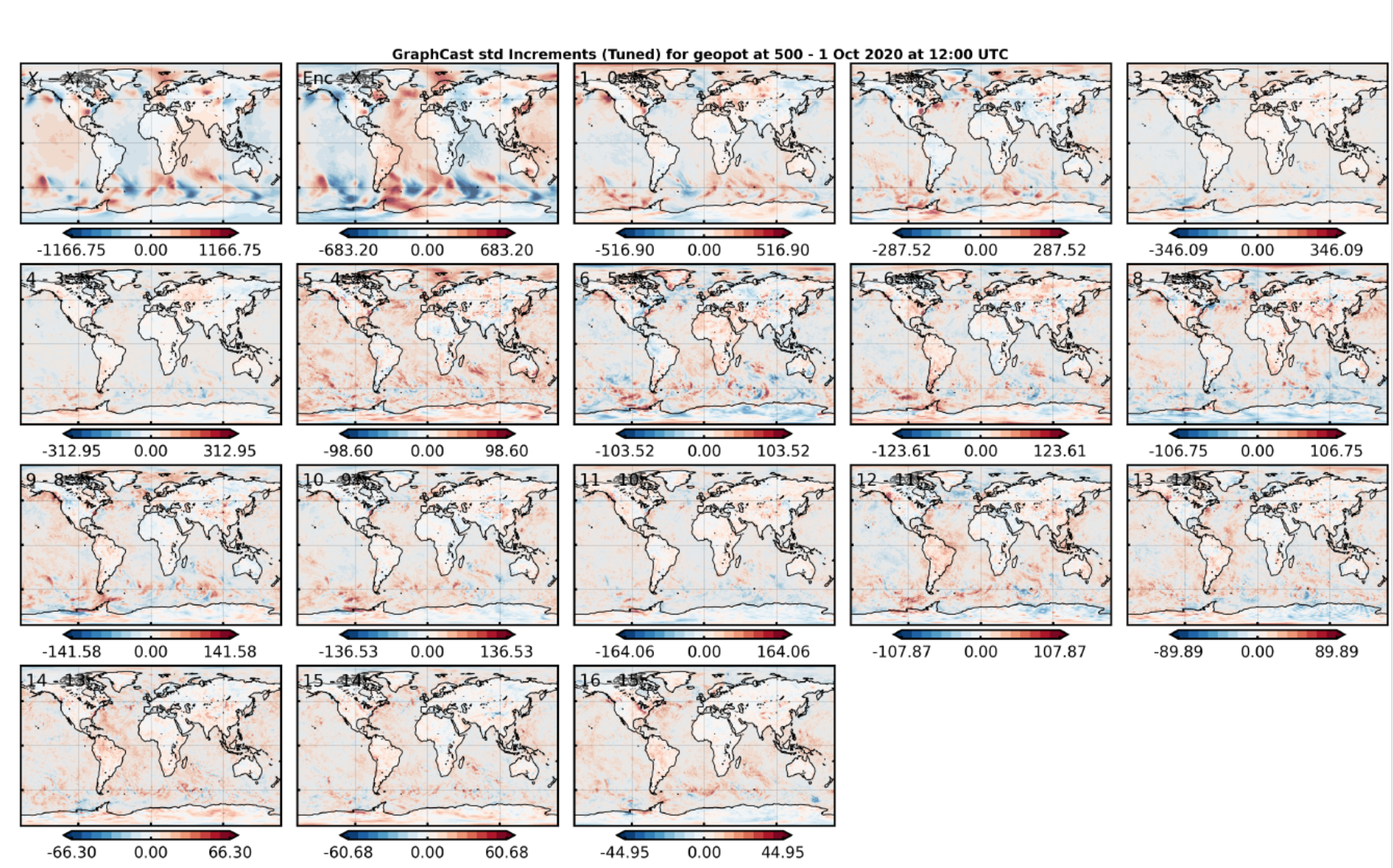
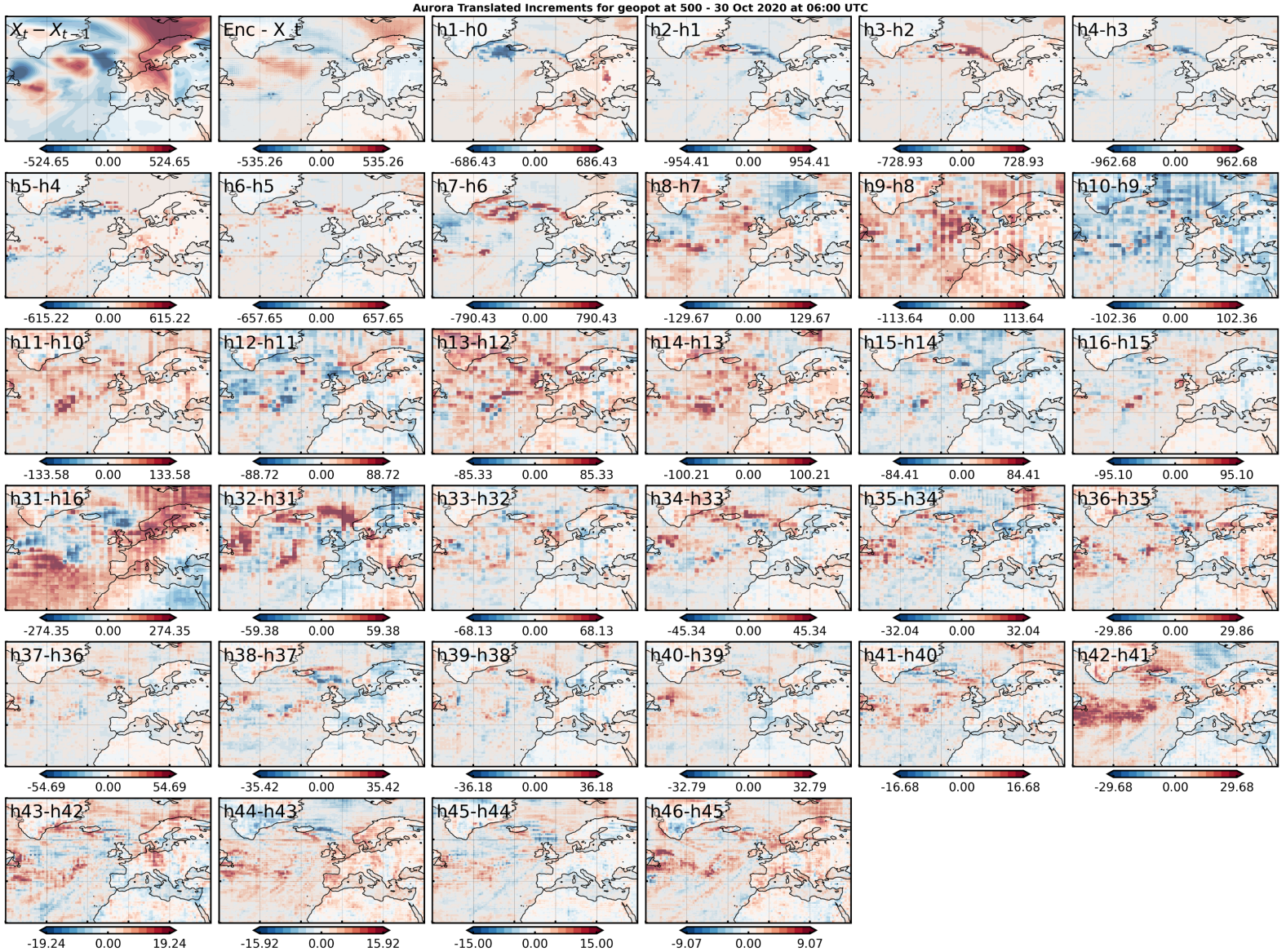


Aurora all increments



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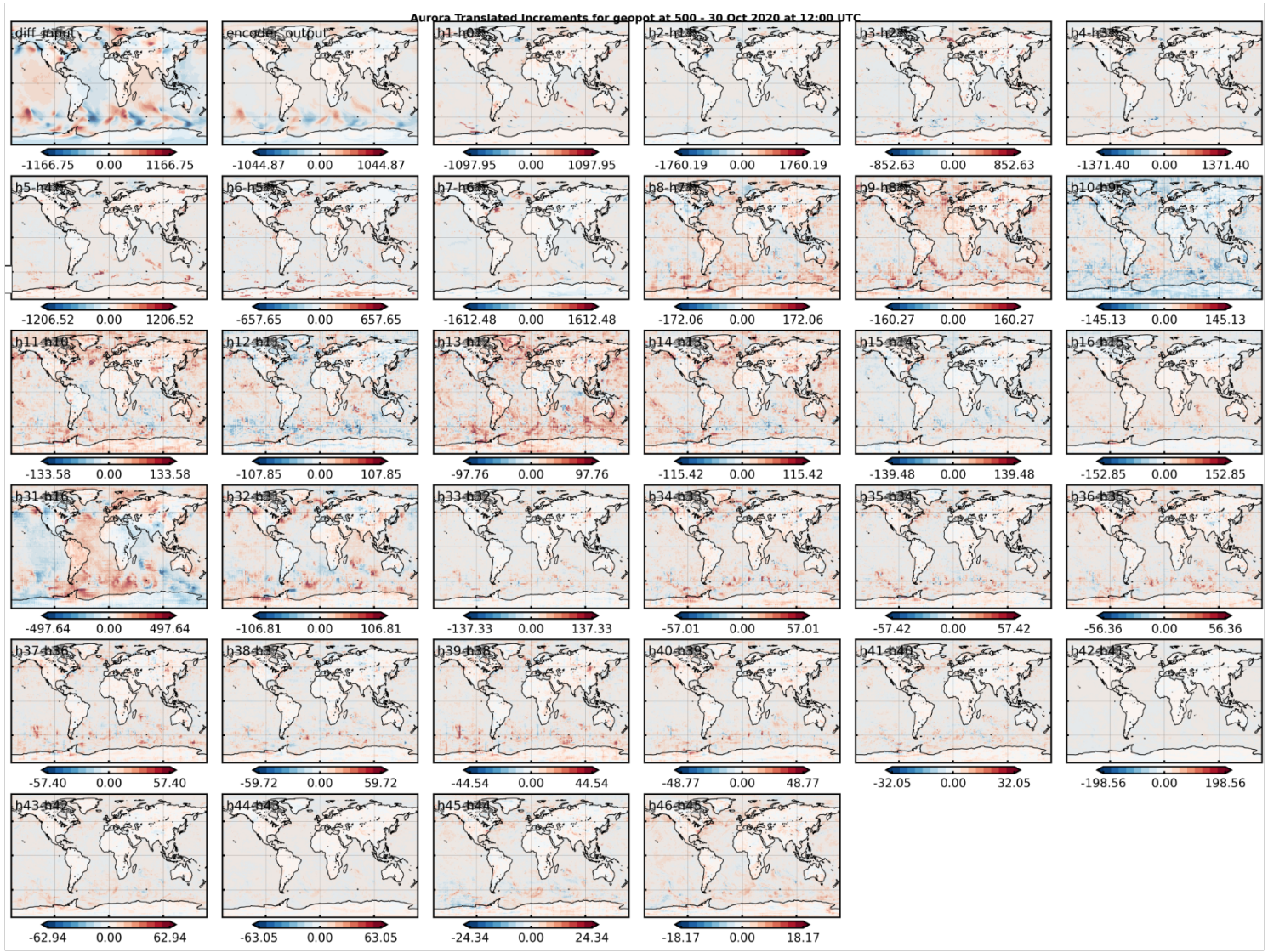

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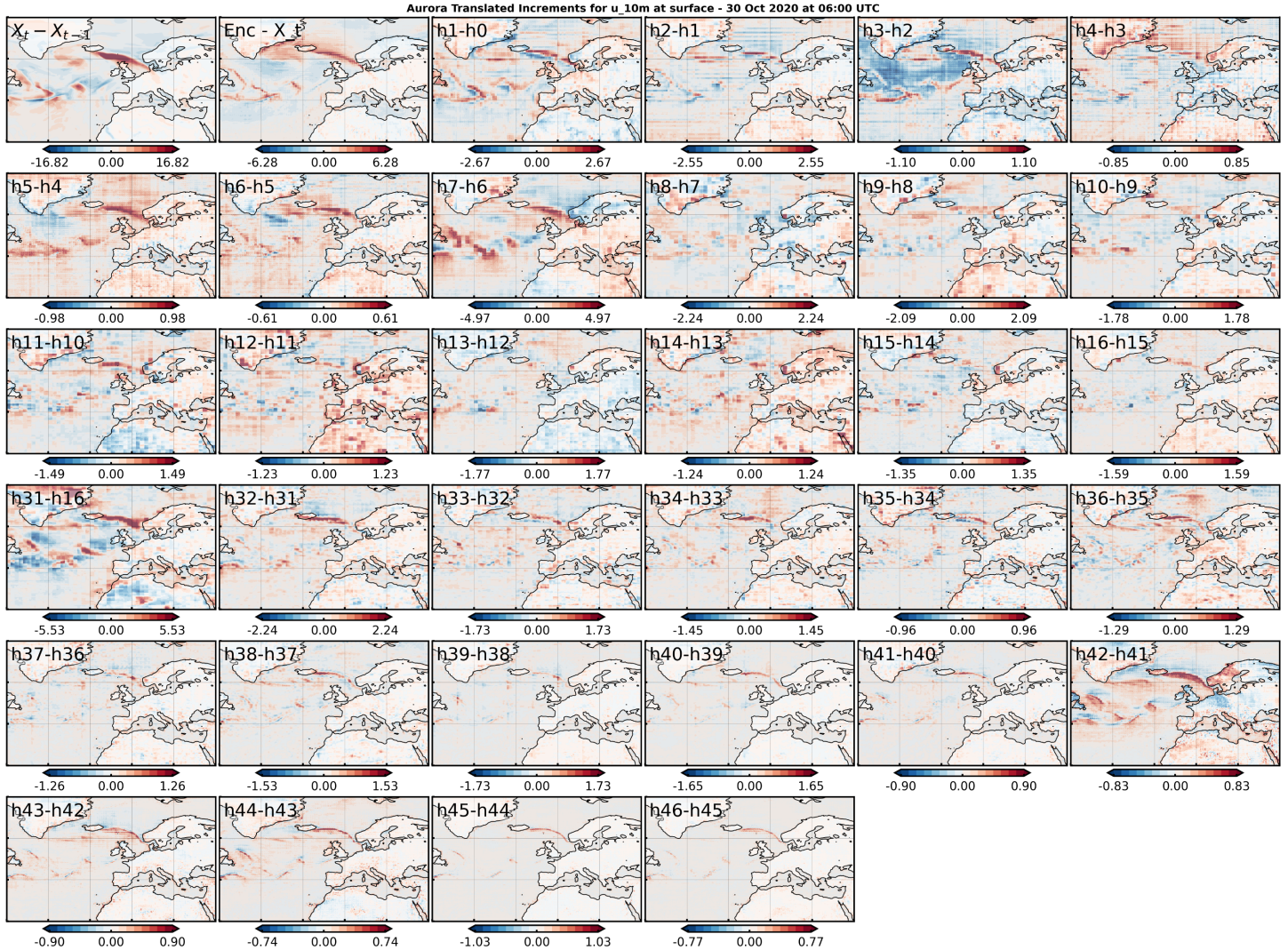

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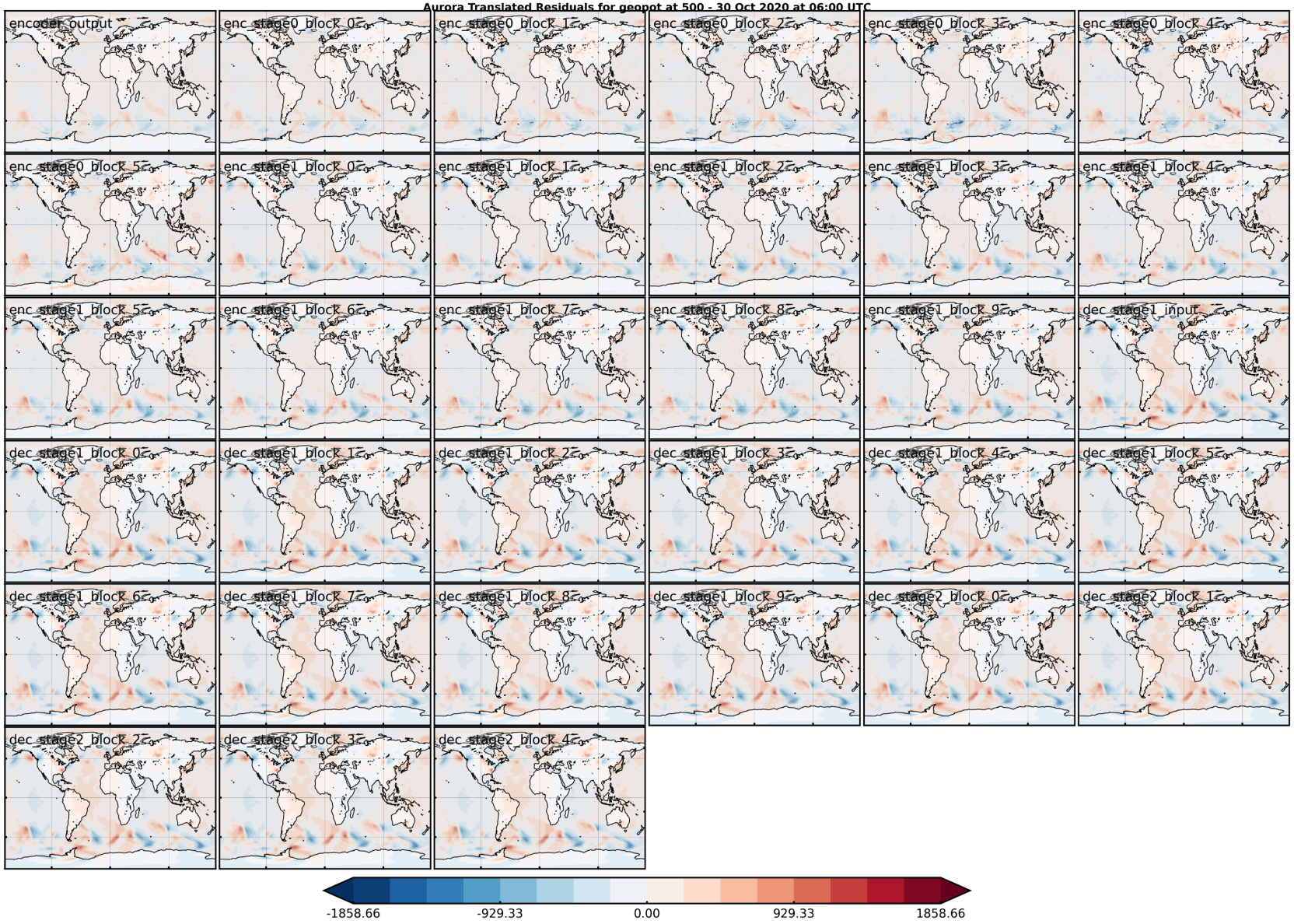

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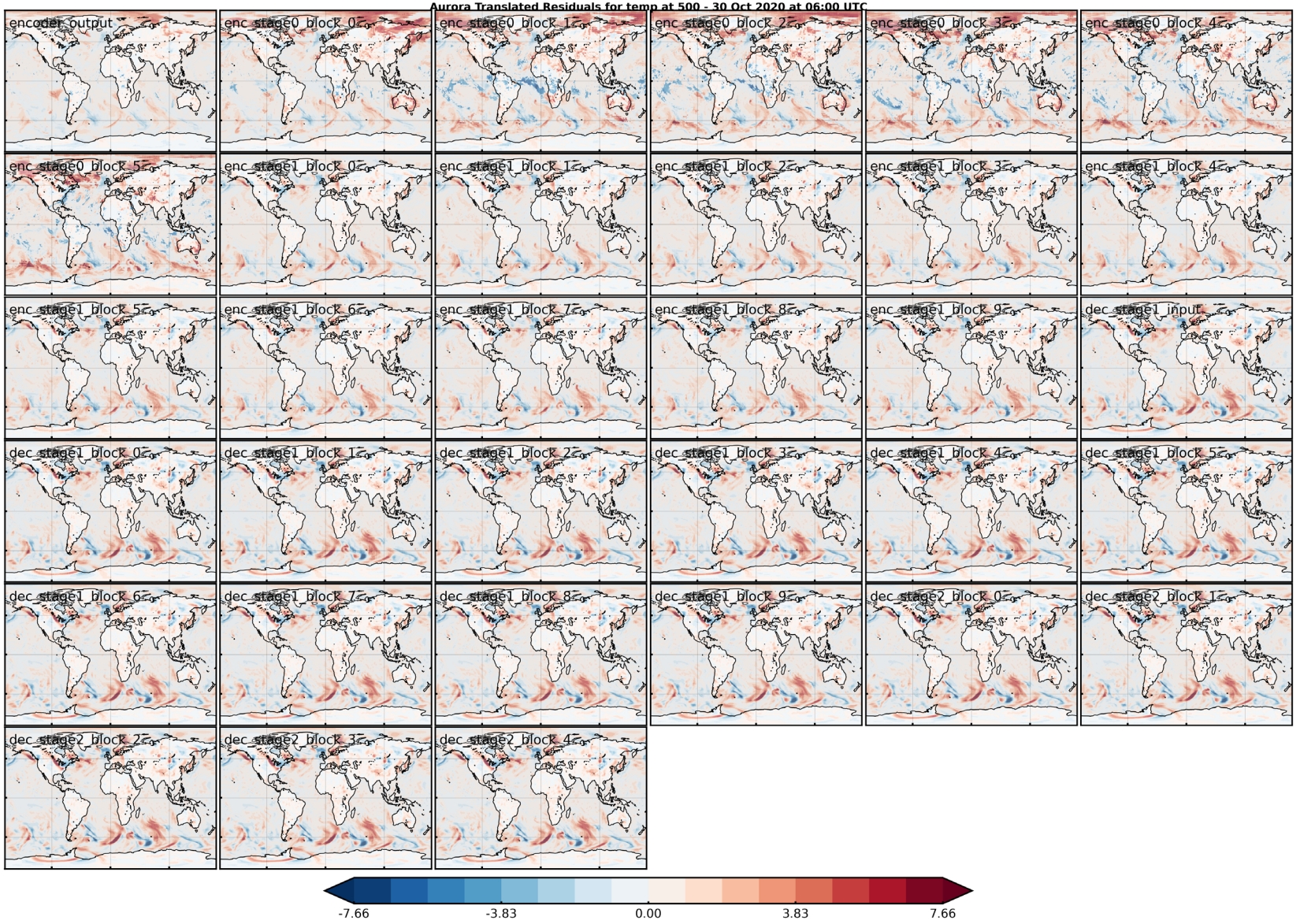

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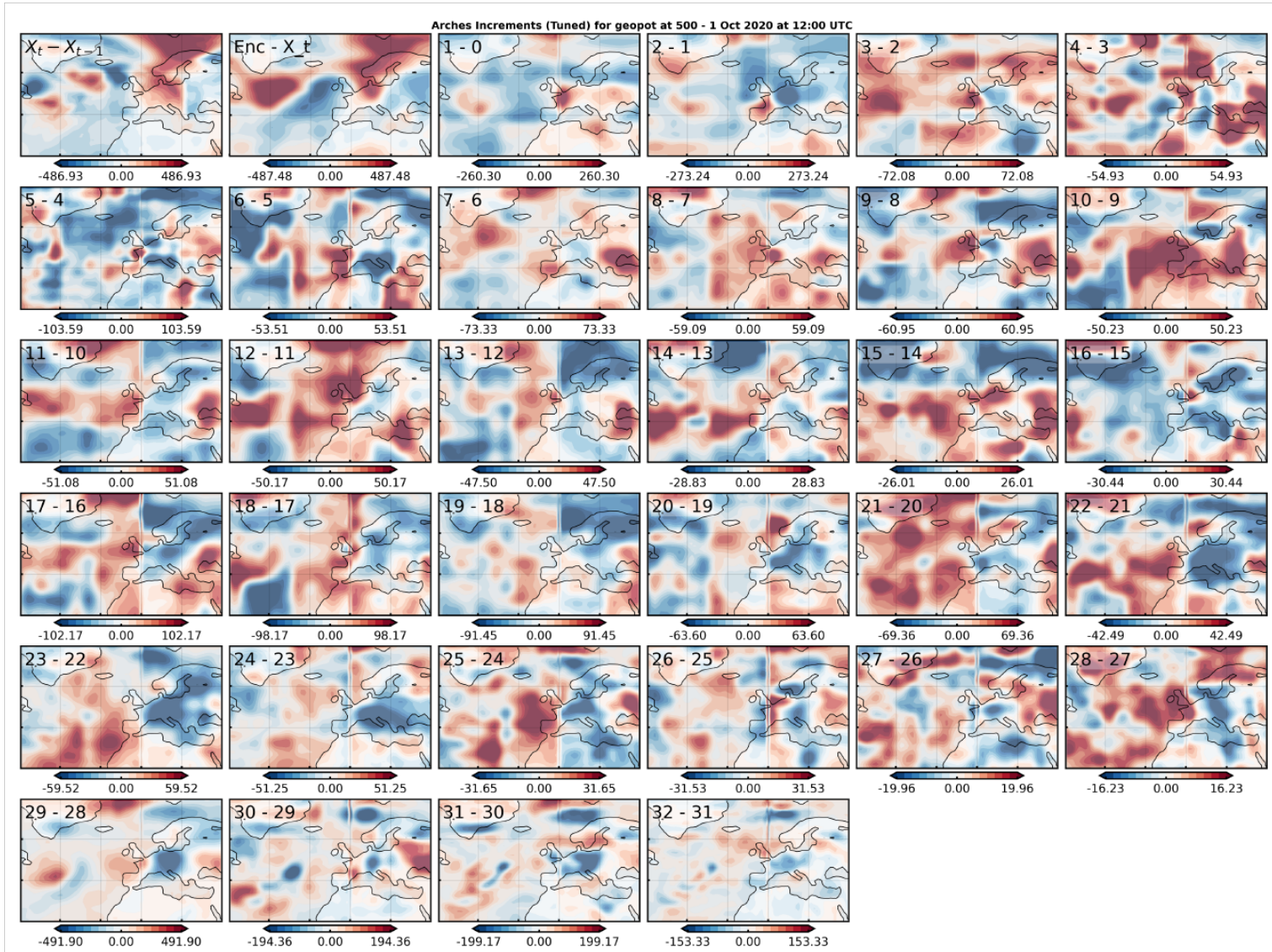

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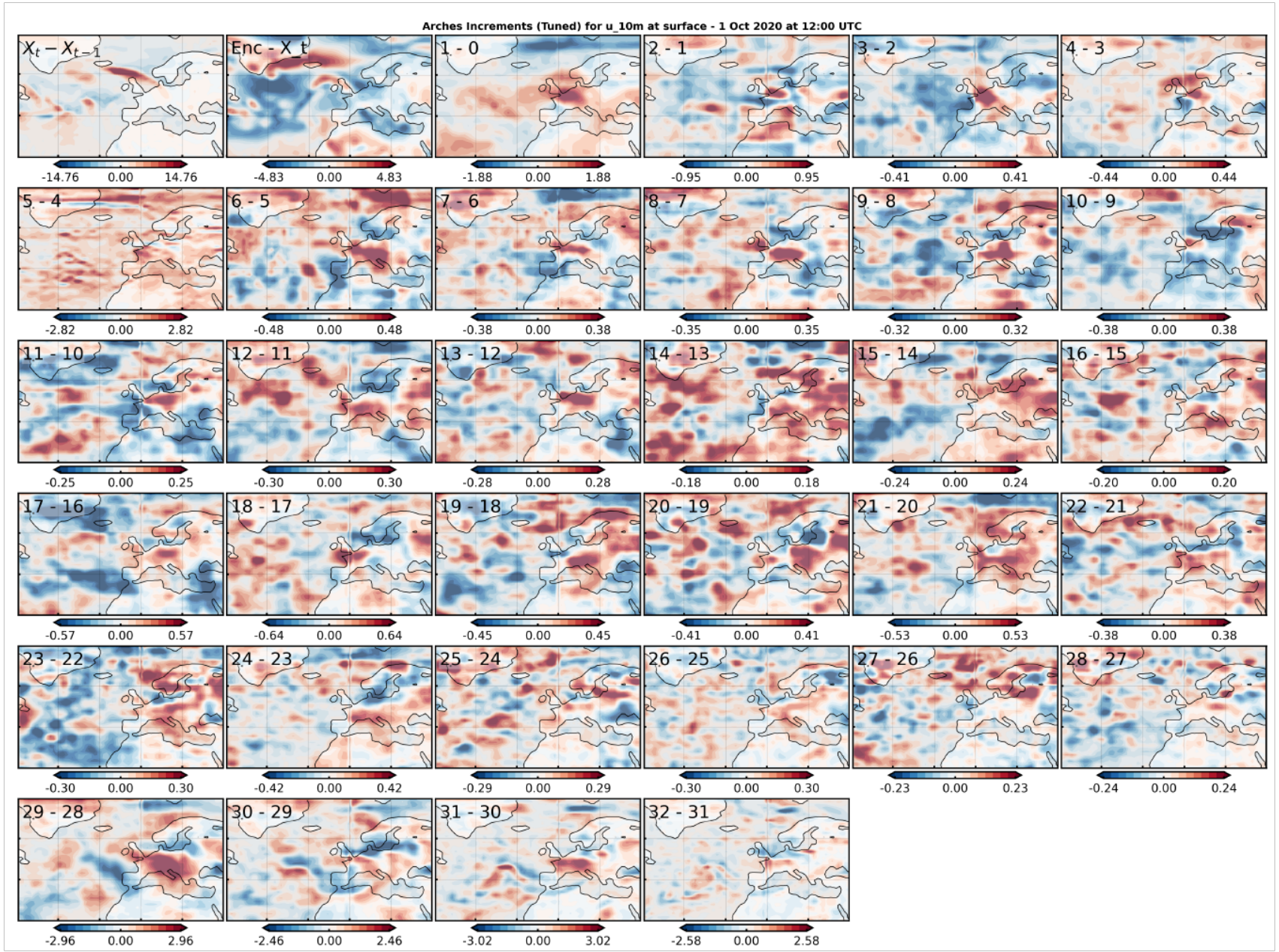

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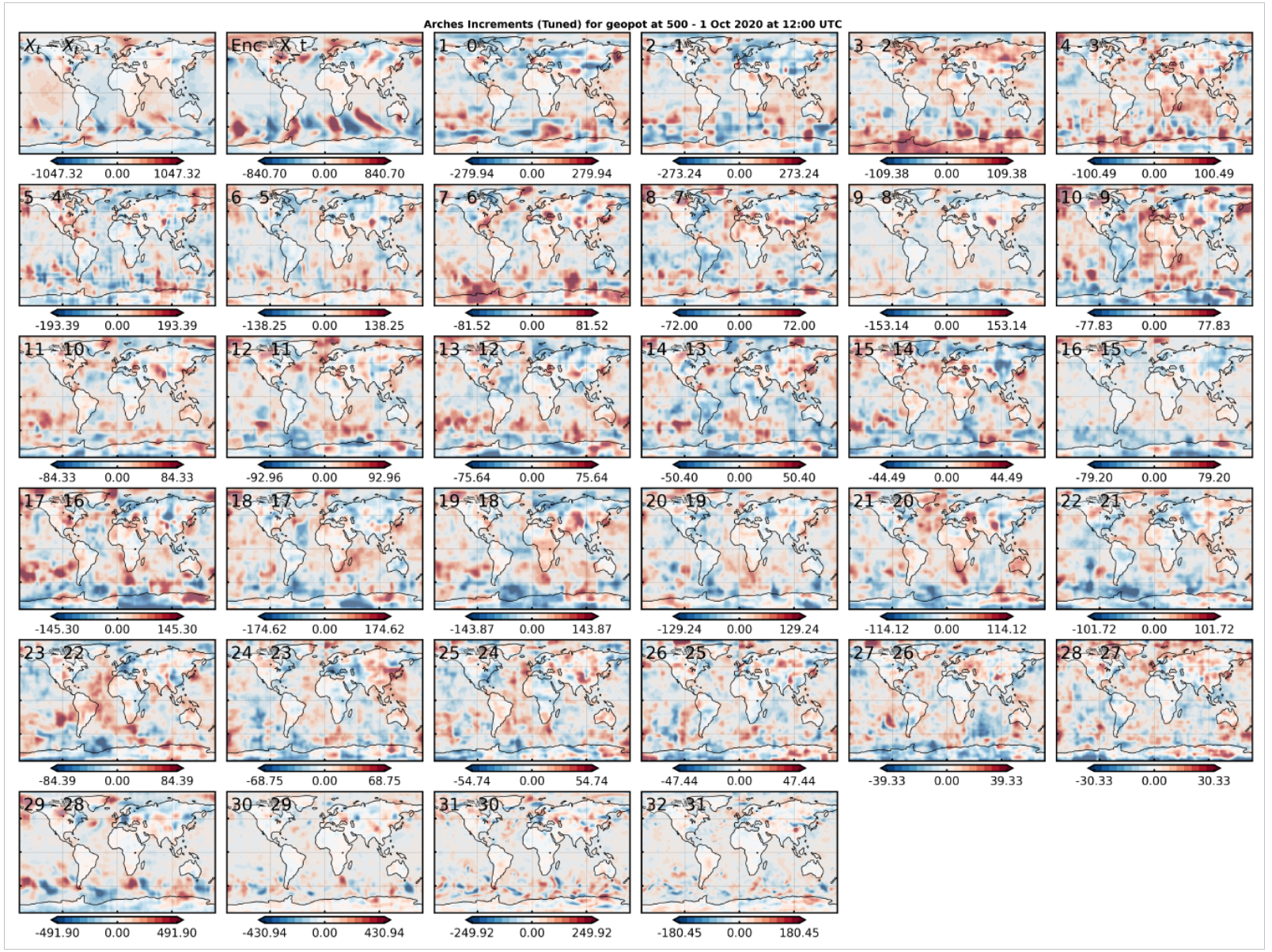

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