WAVES TO WEATHER

The importance of warm conveyor belts for (upscale) error growth

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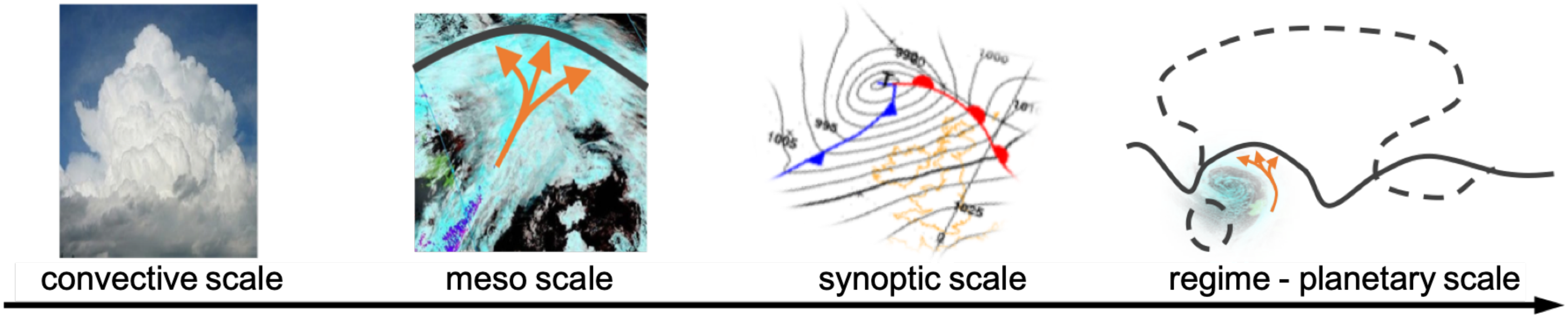
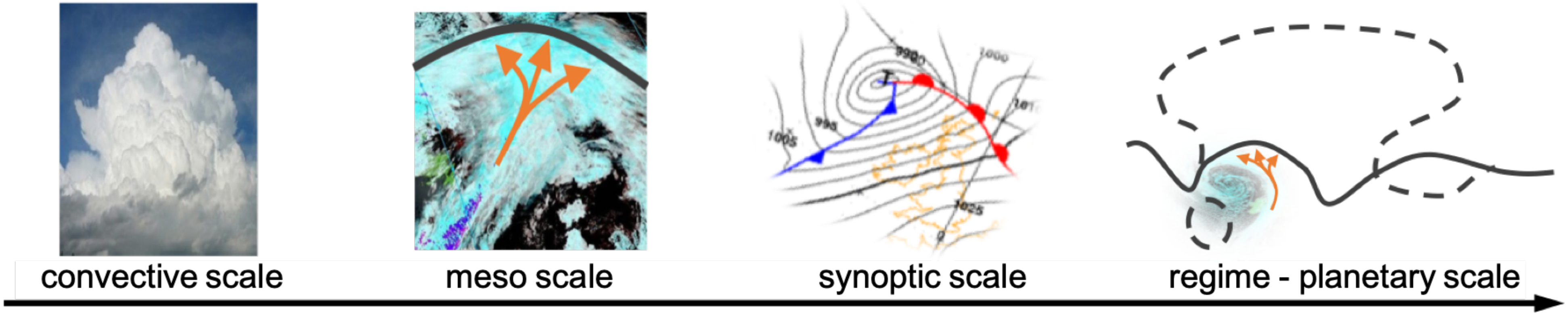
Upscale error growth



Rapid growth of unavoidable small-scale errors
→ Ultimate limit of predictability on larger scales

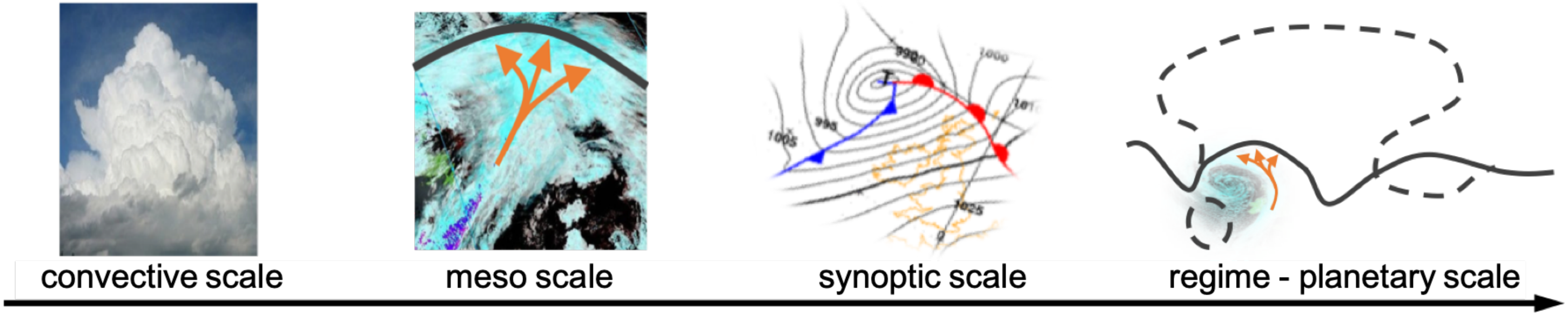
Upscale error growth



Rapid growth of unavoidable small-scale errors
→ Ultimate limit of predictability on larger scales

"Butterfly effect"

Conceptual model for upscale error growth



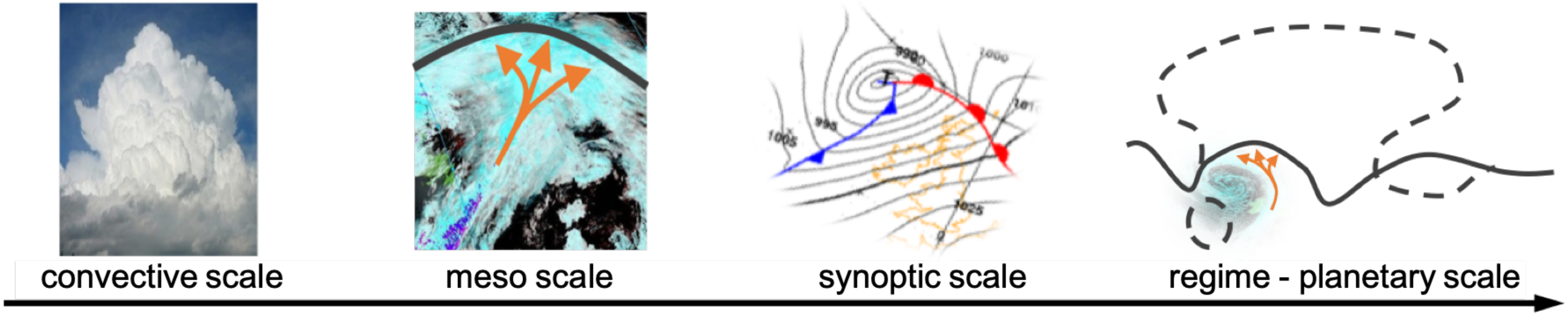
Traditional approach/ large body of literature:

- Error **energy spectra** + physical interpretation based on turbulent cascade
- Error growth on different scales **qualitatively** related to individual processes

convective instability → upscale transition / adjustment-to-balance → baroclinic instability

3-stage model (Zhang et al., 2007)

Process-based, quantitative understanding



Here:

- Focus on process-based, quantitative understanding (e.g., Snyder et al. 2003)
- Potential-vorticity framework of “error” dynamics (Davies and Didone, 2013)

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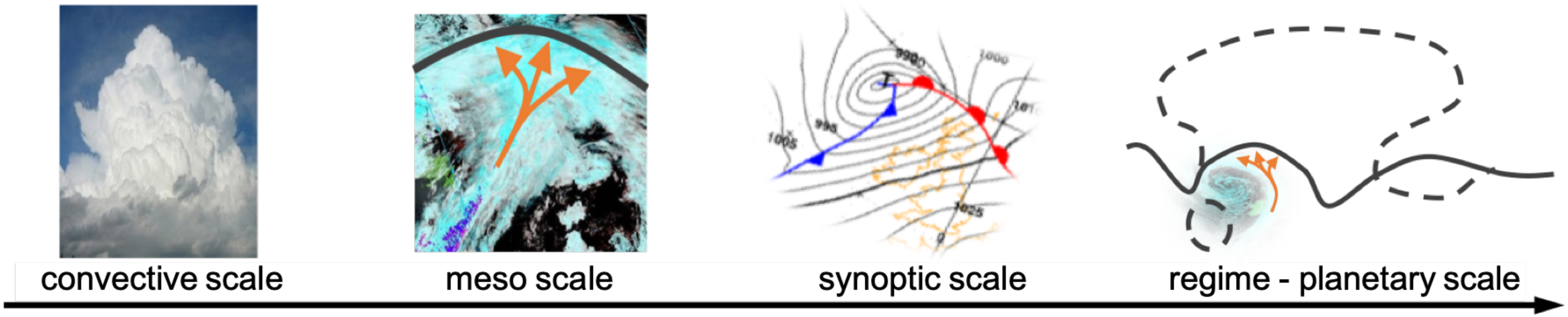

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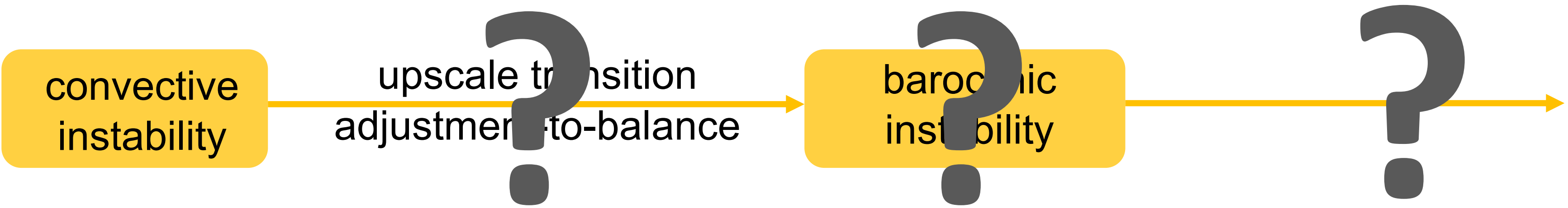

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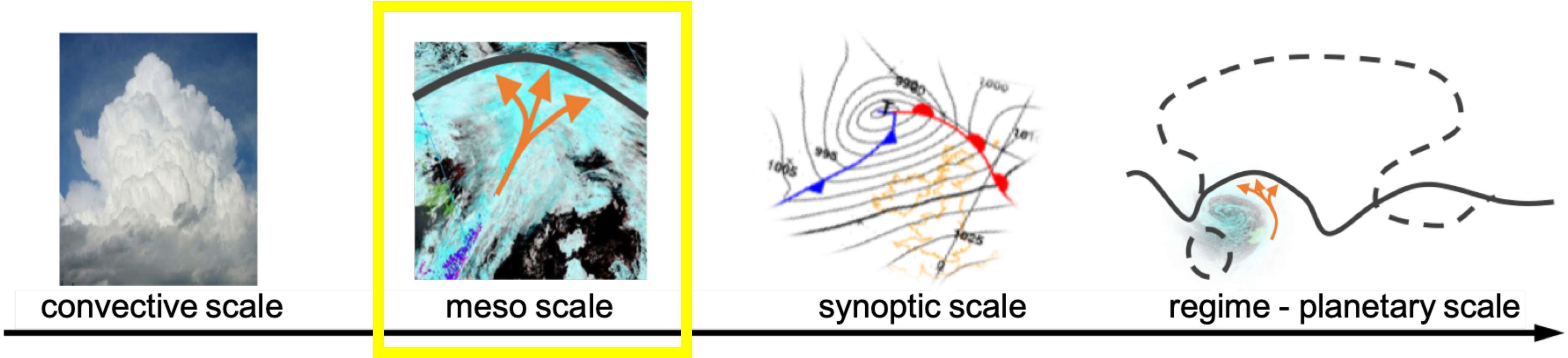

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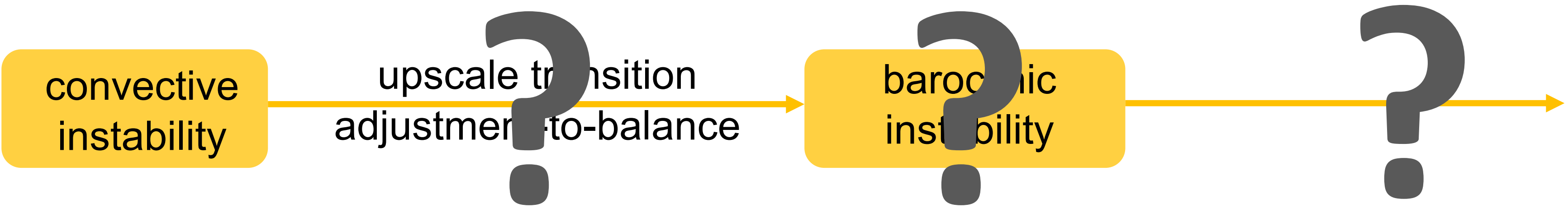
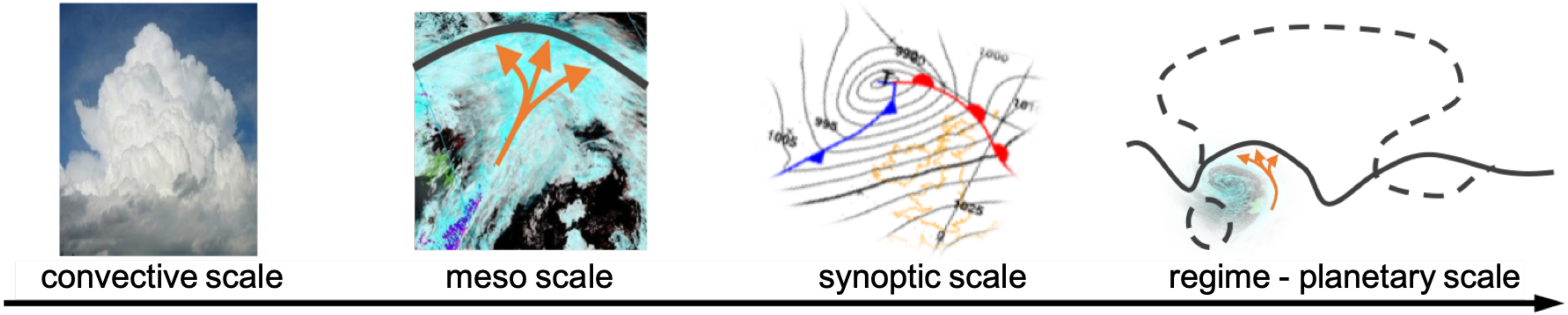
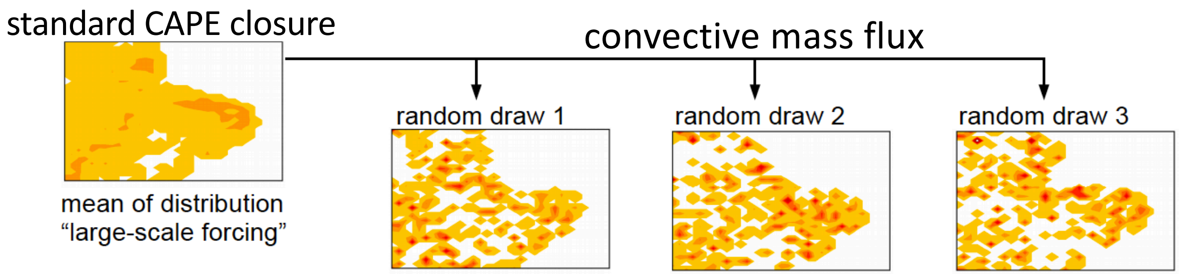


Numerical experiments using a stochastic convection scheme

Upscale error growth ICON experiments (Selz 2019)

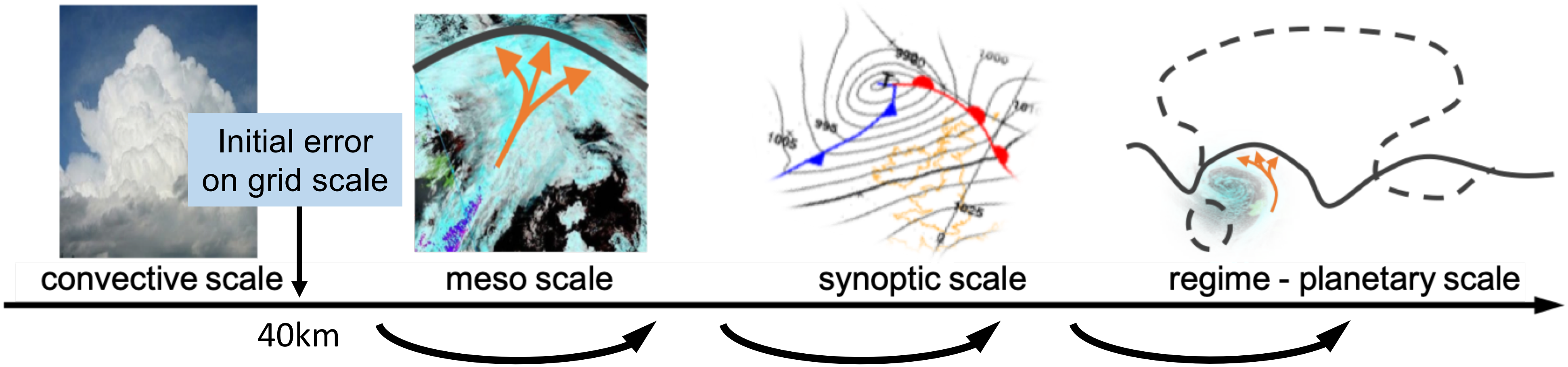


Ensembles with only initial difference in stochastic Plant-Craig convective scheme



Initial error on grid scale

Upscale error growth ICON experiments (Selz 2019)



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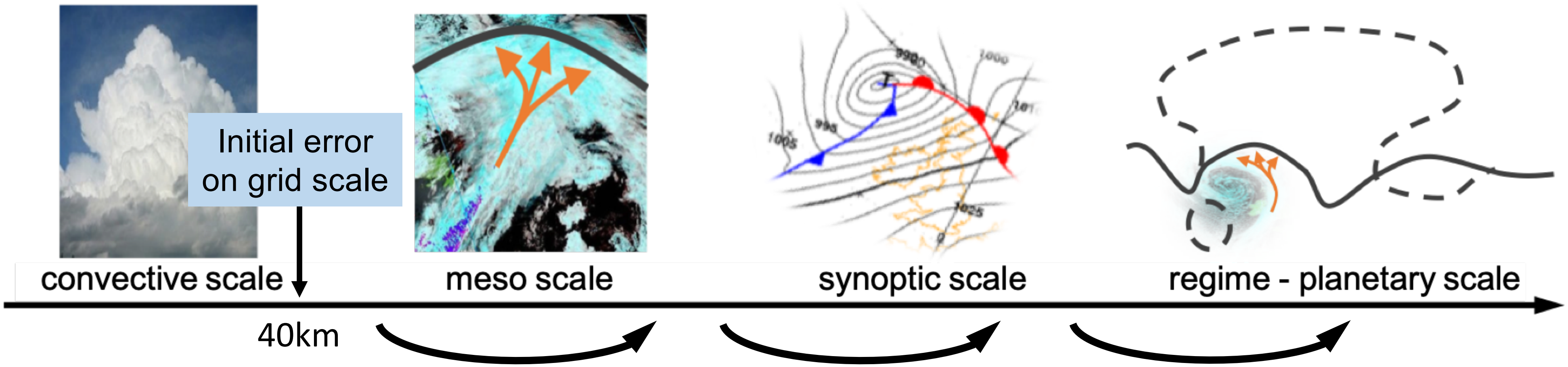


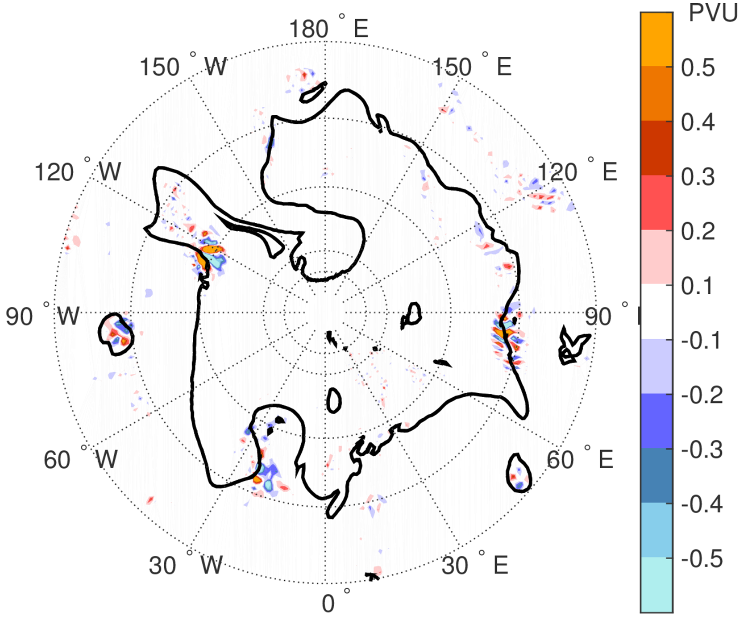
Ensembles with only initial difference in stochastic Plant-Craig convective scheme

- 5 ensemble members
- 12 different cases of real weather situations (first of each month)
- lead time of 31 days

Robust results about error growth up to regime scale

Illustration of upscale error growth

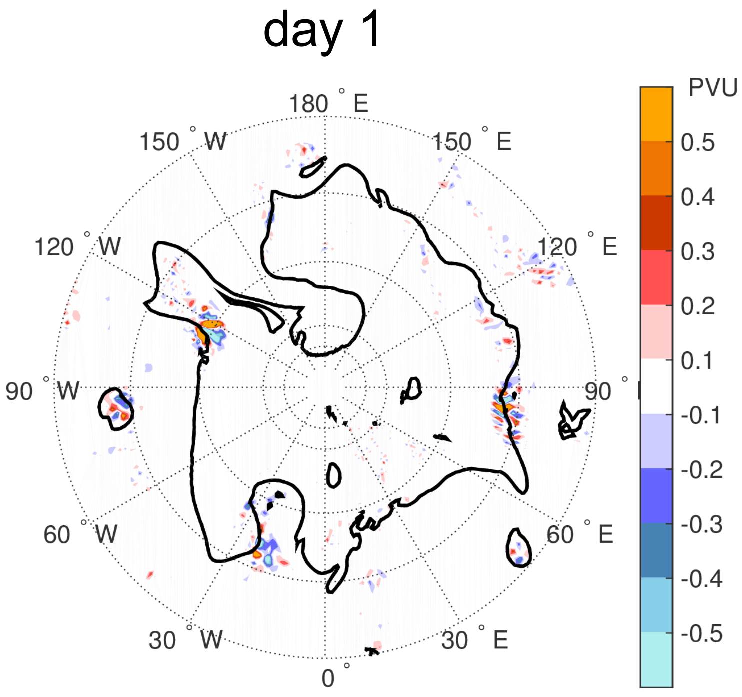
day 1



PV error on 325 K

- Errors of the midlatitude tropopause
- “Errors” := differences between two error-growth experiments

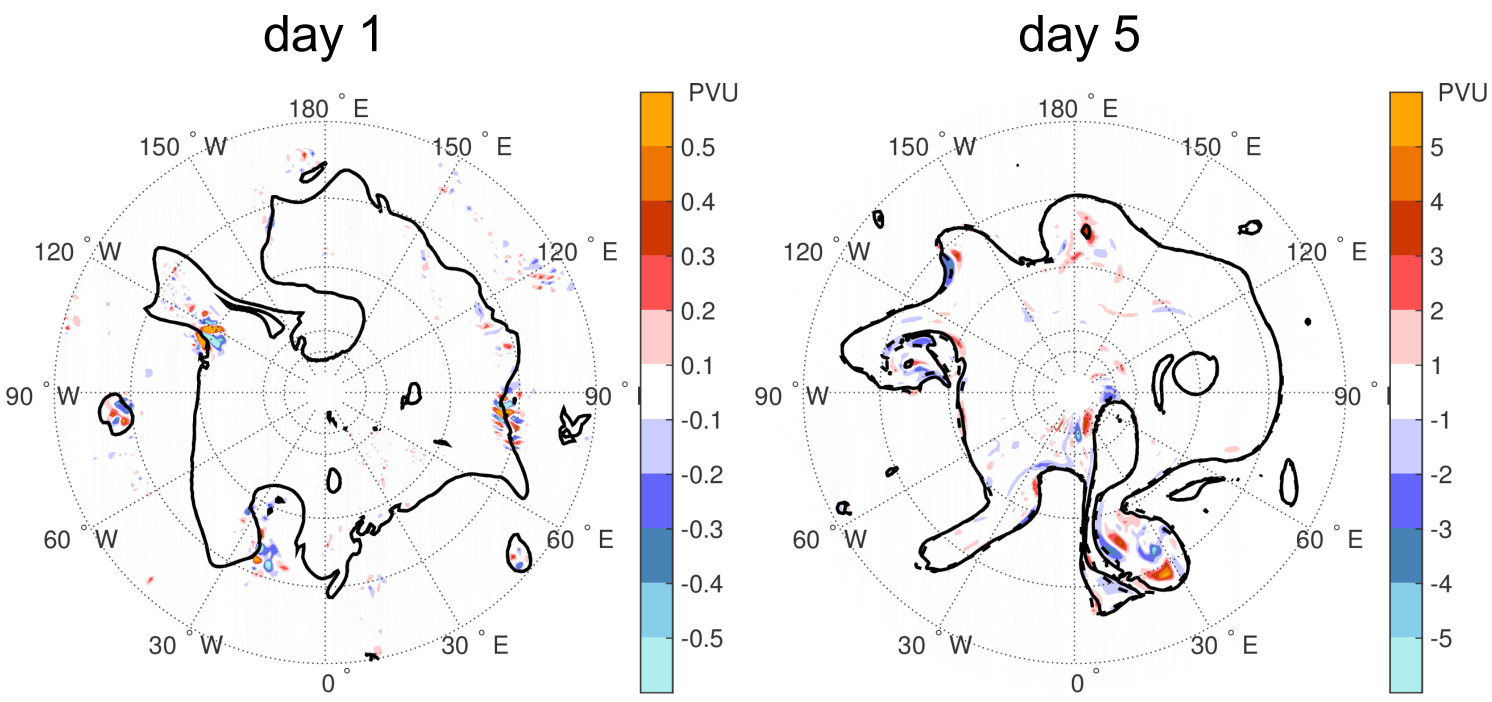
Illustration of upscale error growth



PV error on 325 K

Errors on the grid scale

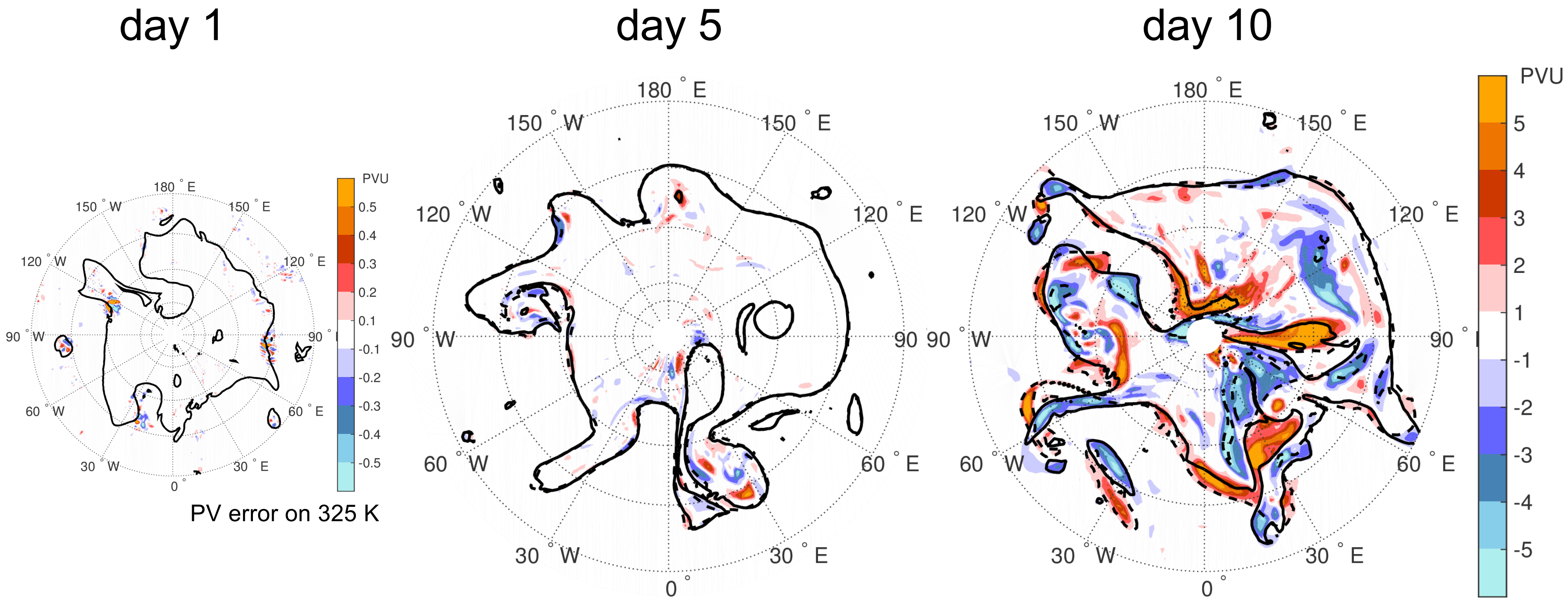
Illustration of upscale error growth



PV error on 325 K

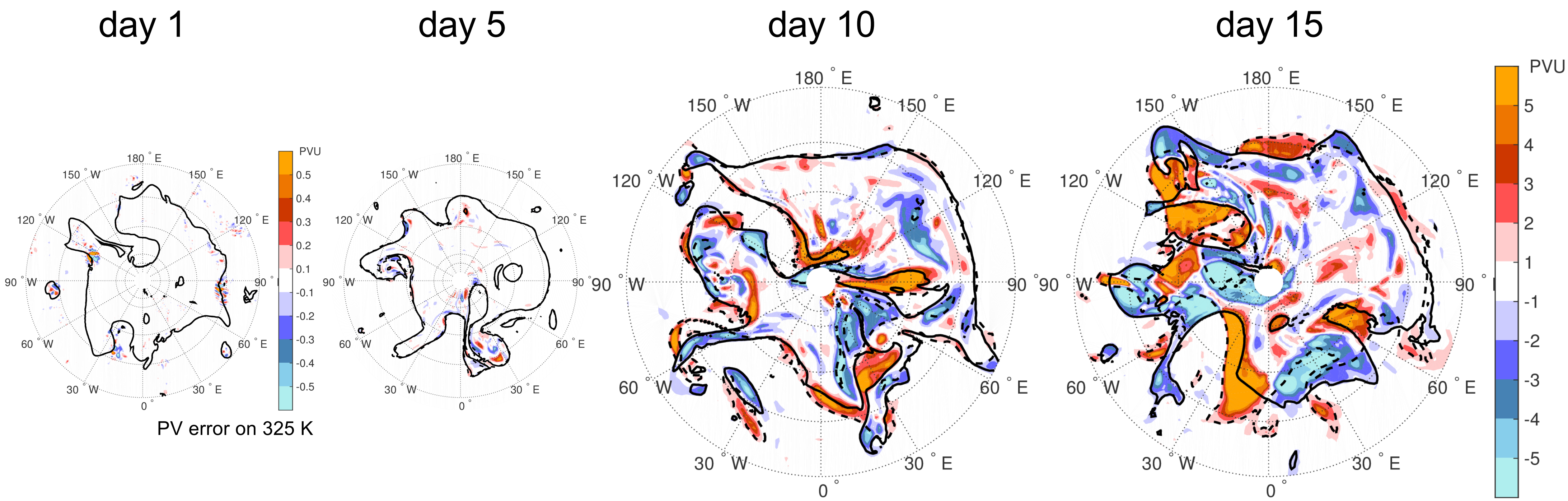
Errors on the grid scale — grow / amplify → Meso-scale coherent region

Illustration of upscale error growth



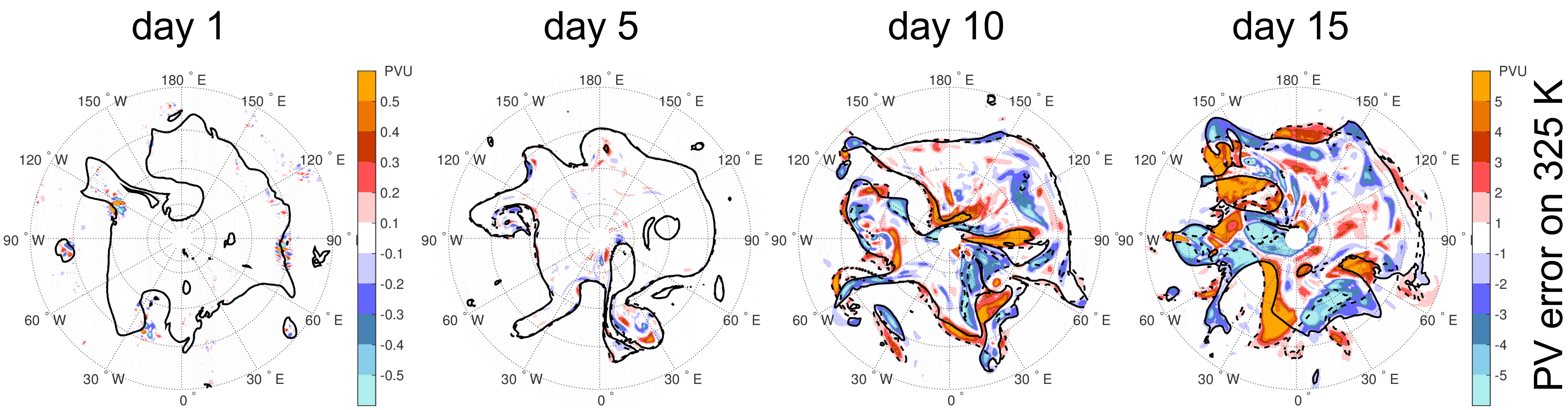
Meso-scale coherent region → grow amplify → Organized in troughs/ ridges

Illustration of upscale error growth



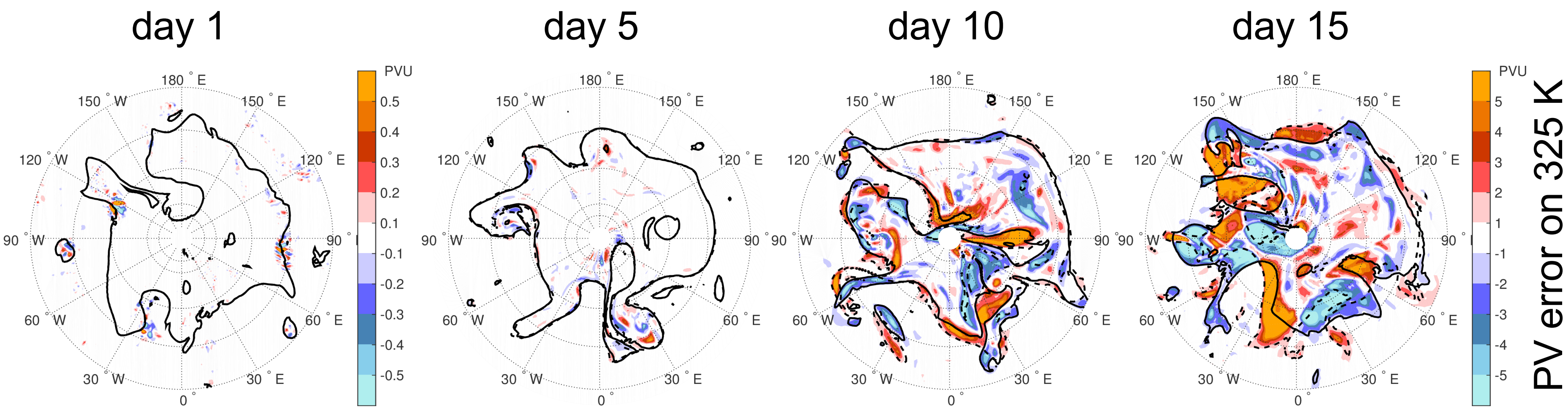
Organized in troughs/ ridges → grow (amplify) → Affect Rossby-wave scale

Illustration of upscale error growth



PV errors grow in amplitude and scale

Illustration of upscale error growth

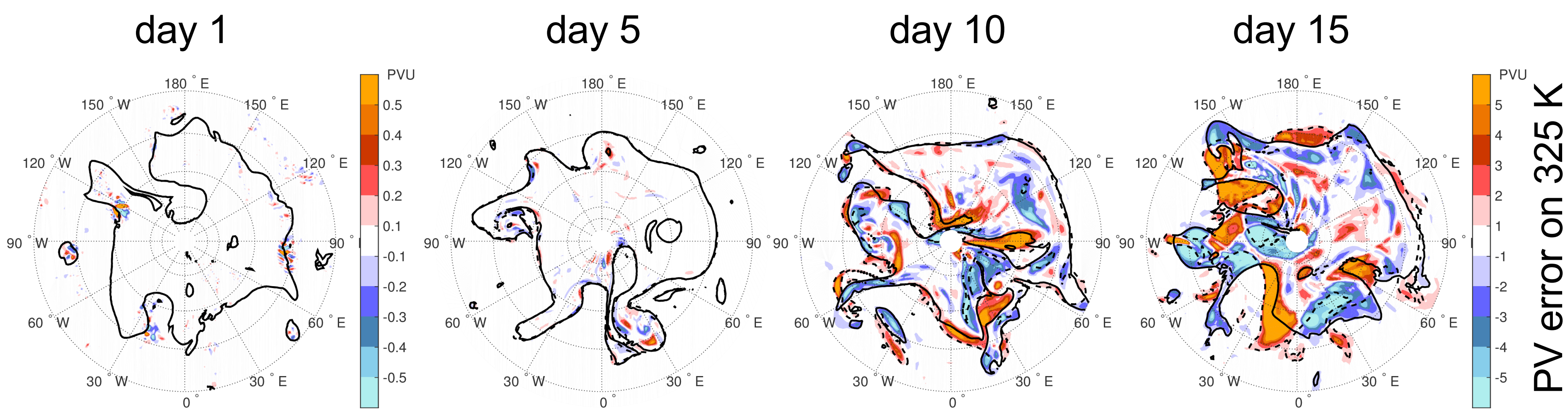


PV errors grow in amplitude and scale

→ What are the processes that govern the error evolution?

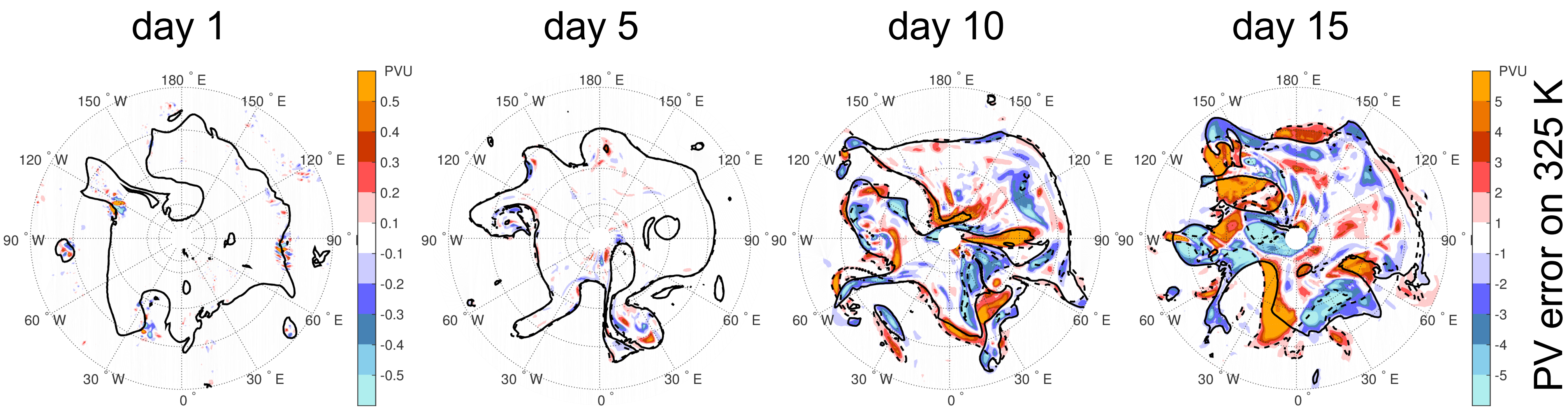
Quantitative potential-vorticity diagnostic for error growth

Error growth: Why a PV perspective?



- Potential vorticity (PV) key variable for dynamical meteorology
- PV-error tendency equation (Davies and Didone, 2013)
- Well established partition-and-attribution concept

Error growth: Why a PV perspective?



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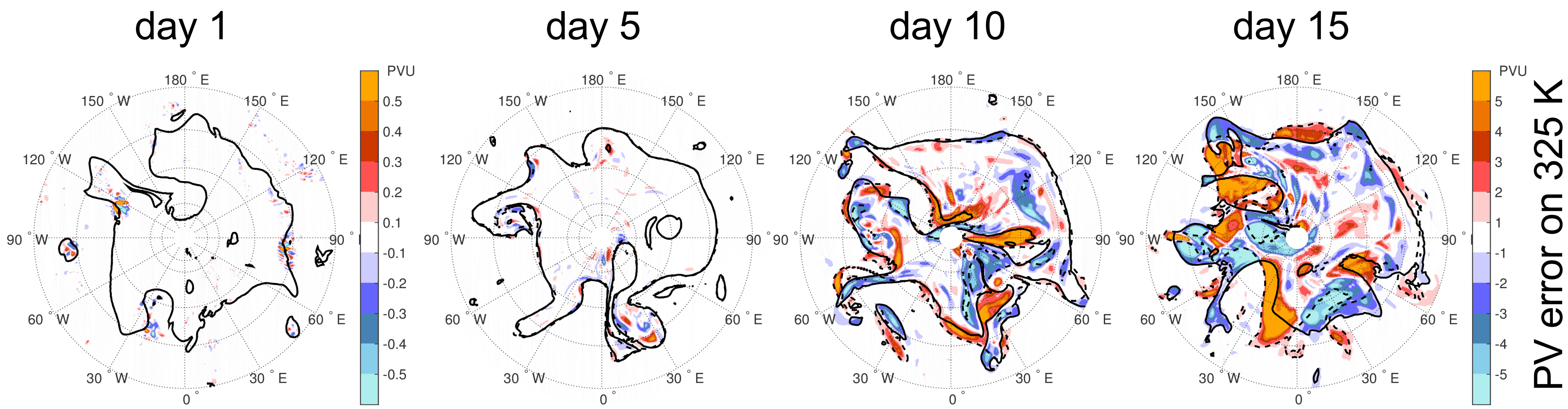
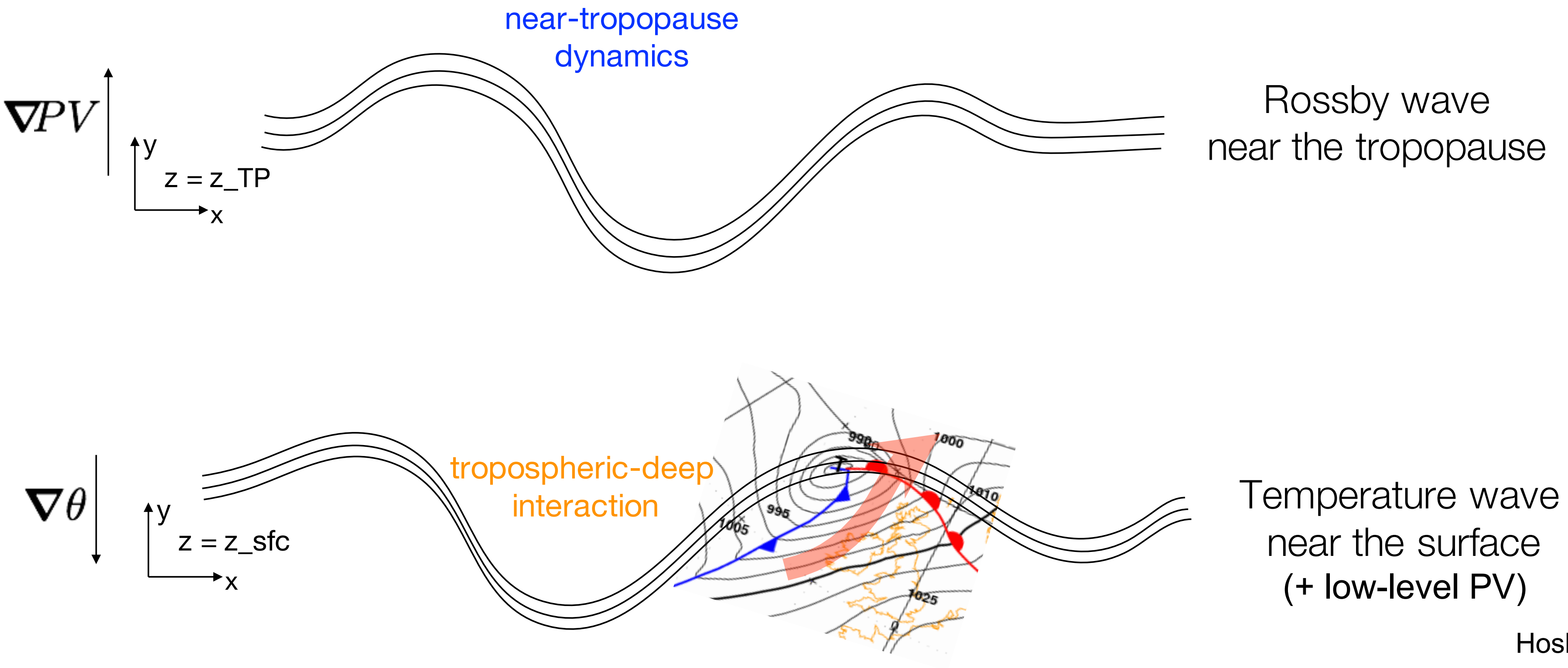


- Potential vorticity (PV) key variable for dynamical meteorology
- PV-error tendency equation (Davies and Didone, 2013)
- Well established partition-and-attribution concept
- Errors maximize near the tropopause in a PV framework

Partitioning into four processes (Teubler and Riemer, 2016)



Hoskins et al., 1985
Eady, 1949
Heifetz et al., 2004
Davis et al., 1993

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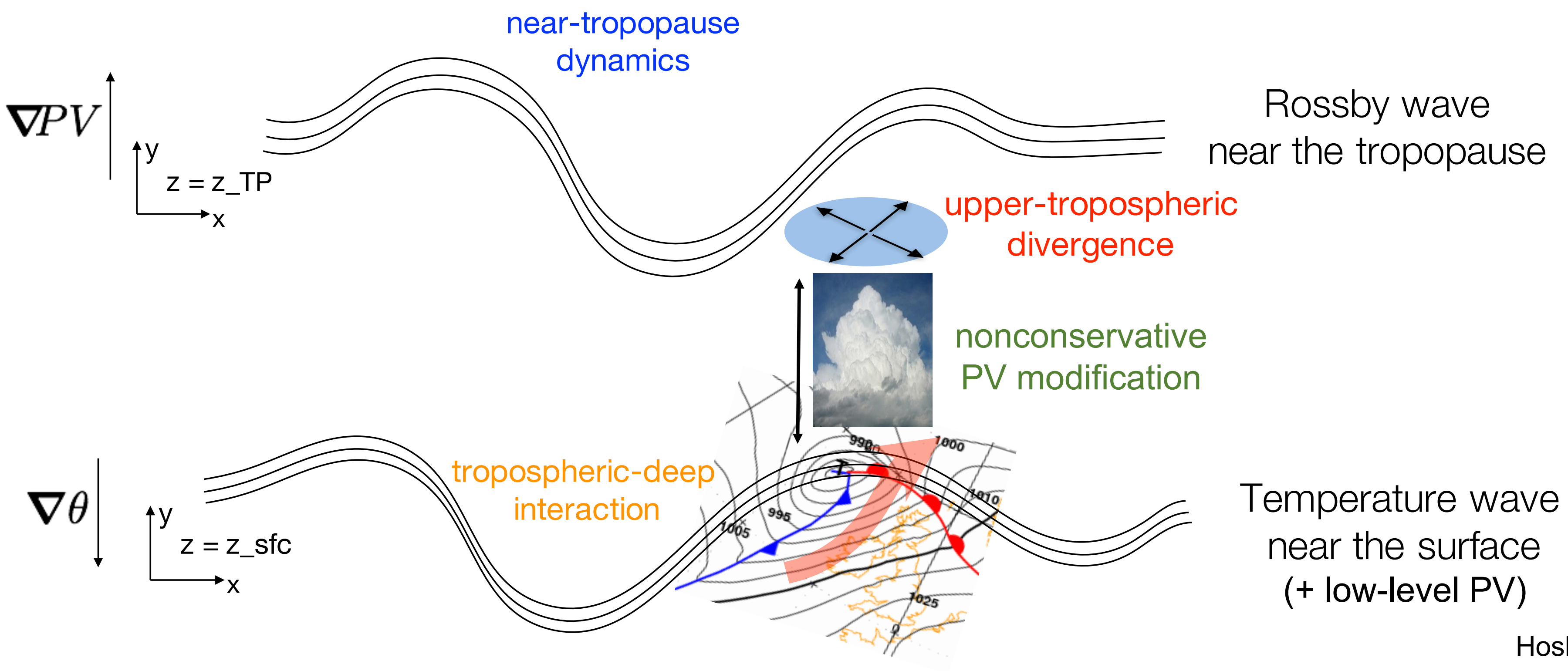

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Dynamics of PV errors

PV error: $PV^* = PV_{\text{forecast}} - PV_{\text{analysis}}$

Tendency for PV error (following Davies and Didone, 2013):

$$\frac{\partial}{\partial t} PV^* = \frac{\partial}{\partial t} PV_{\text{forecast}} - \frac{\partial}{\partial t} PV_{\text{analysis}}$$

$$= -\overrightarrow{v^*} \cdot \vec{\nabla} PV - \overrightarrow{v^*} \cdot \vec{\nabla} PV^* - \vec{v} \cdot \vec{\nabla} PV^* + NonCons^*$$

with *: error fields
without *: analysis field

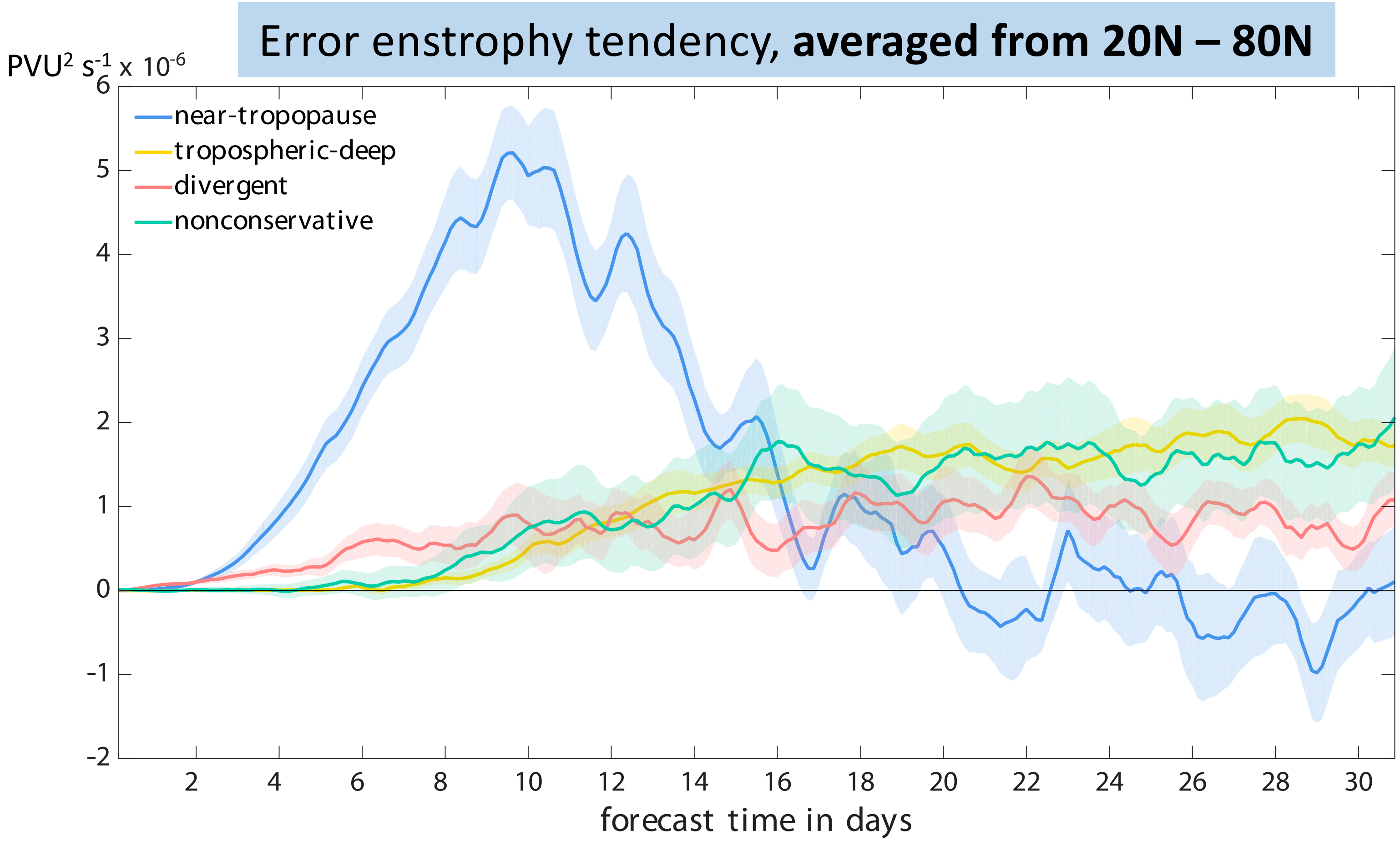
Tendency for "error enstrophy" amplification (Baumgart et al. 2018):

$$\frac{\partial}{\partial t} \frac{PV^{*2}}{2} = -PV^* \overrightarrow{v^*} \cdot \vec{\nabla} PV + \frac{PV^{*2}}{2} \vec{\nabla} \cdot \left(\vec{v} + \overrightarrow{v^*}\right) + NonCons^*$$

decompose (as shown above)

Results: Processes governing error growth

Error tendencies associated with processes



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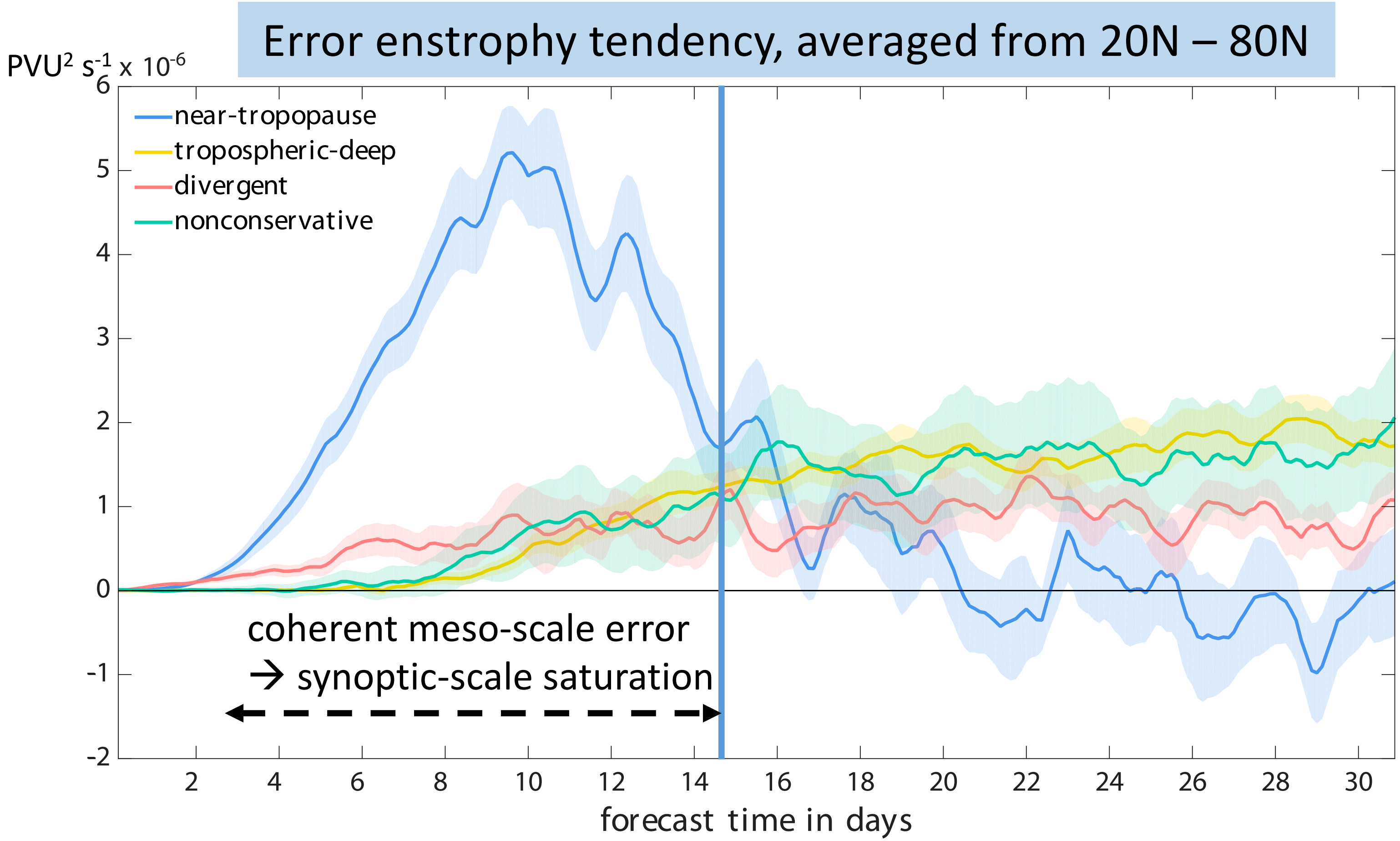
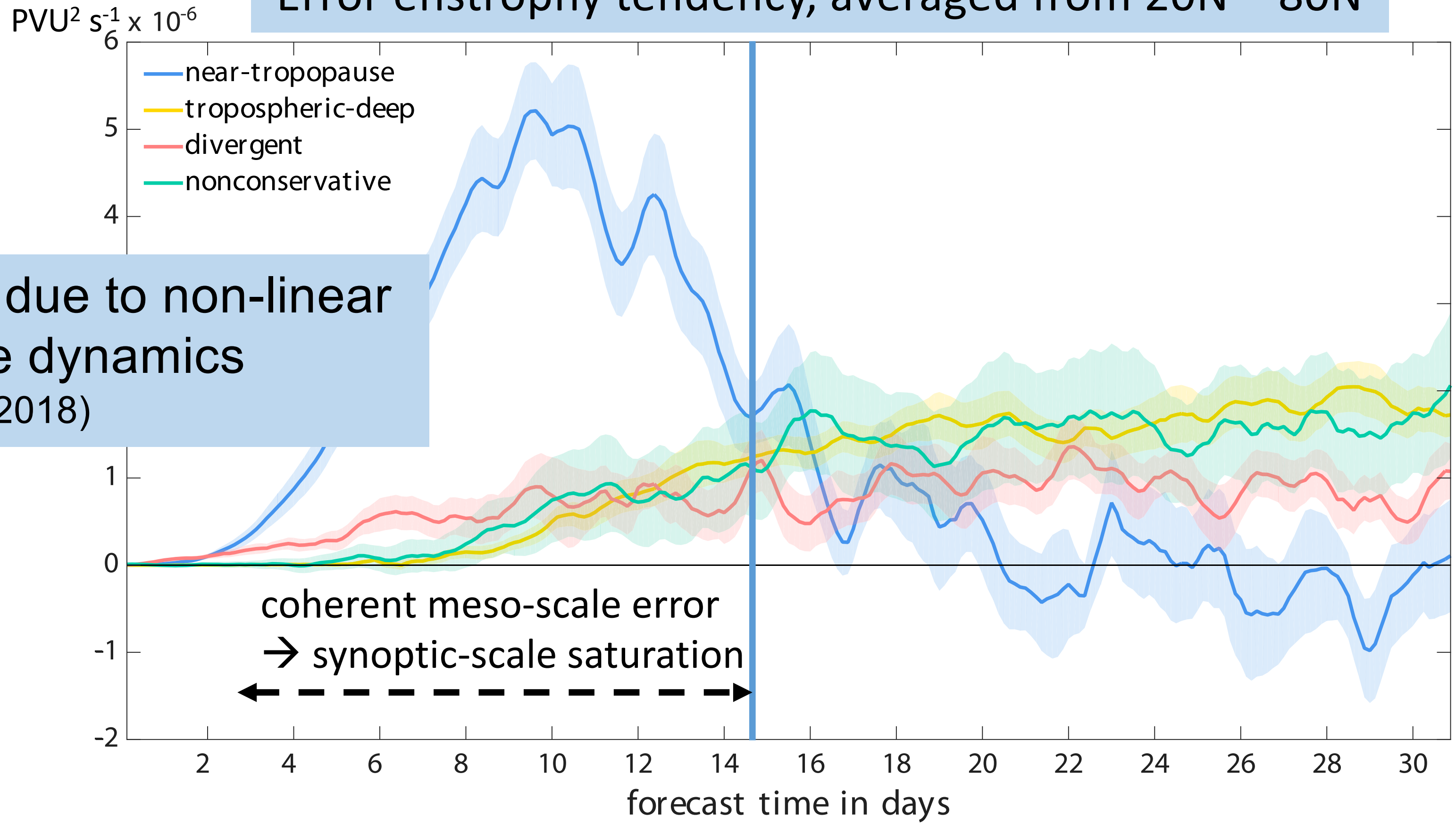


Error tendencies associated with processes

Error enstrophy tendency, averaged from 20N – 80N

Error growth due to non-linear Rossby wave dynamics
(Baumgart et al. 2018)



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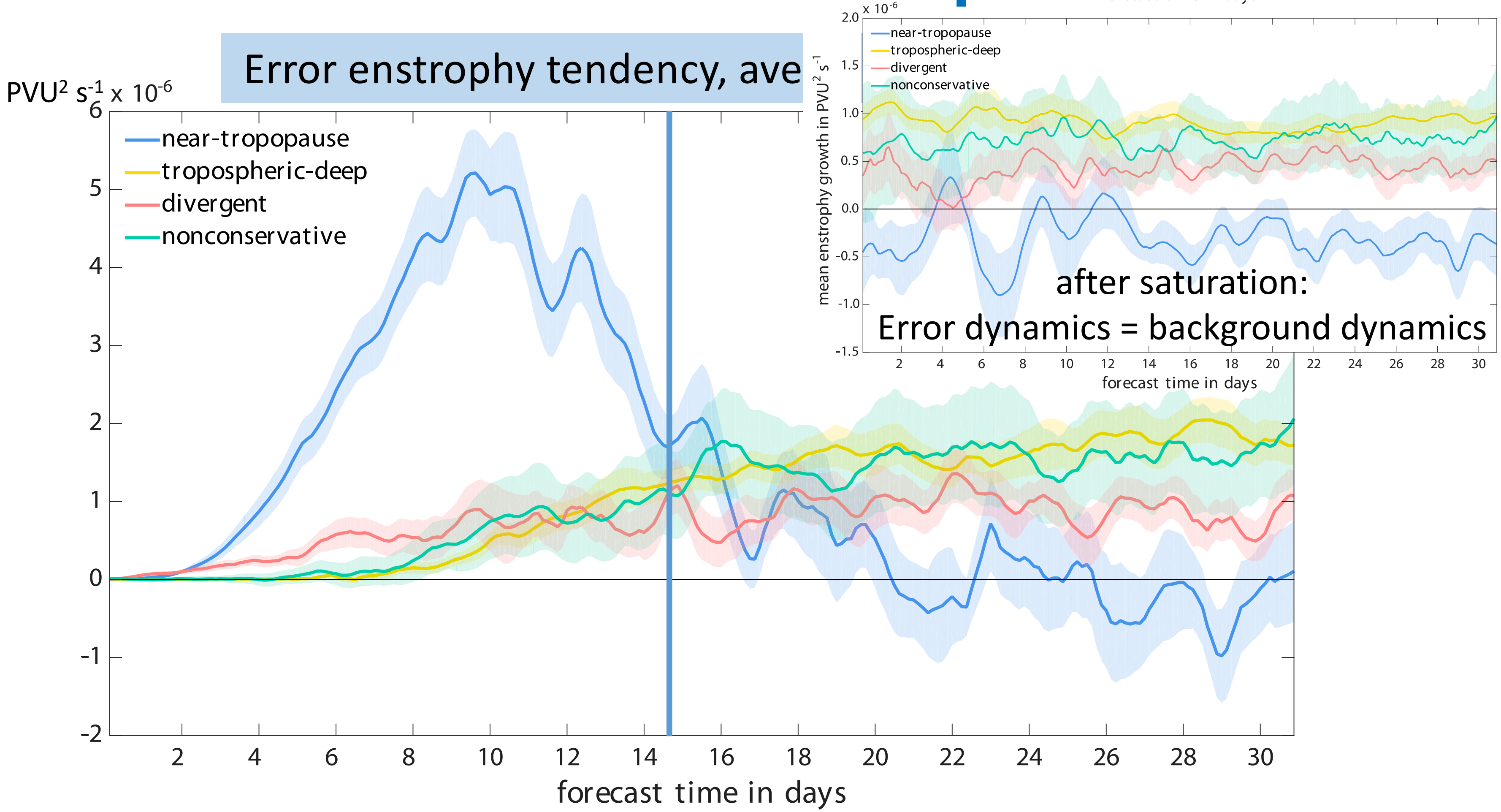

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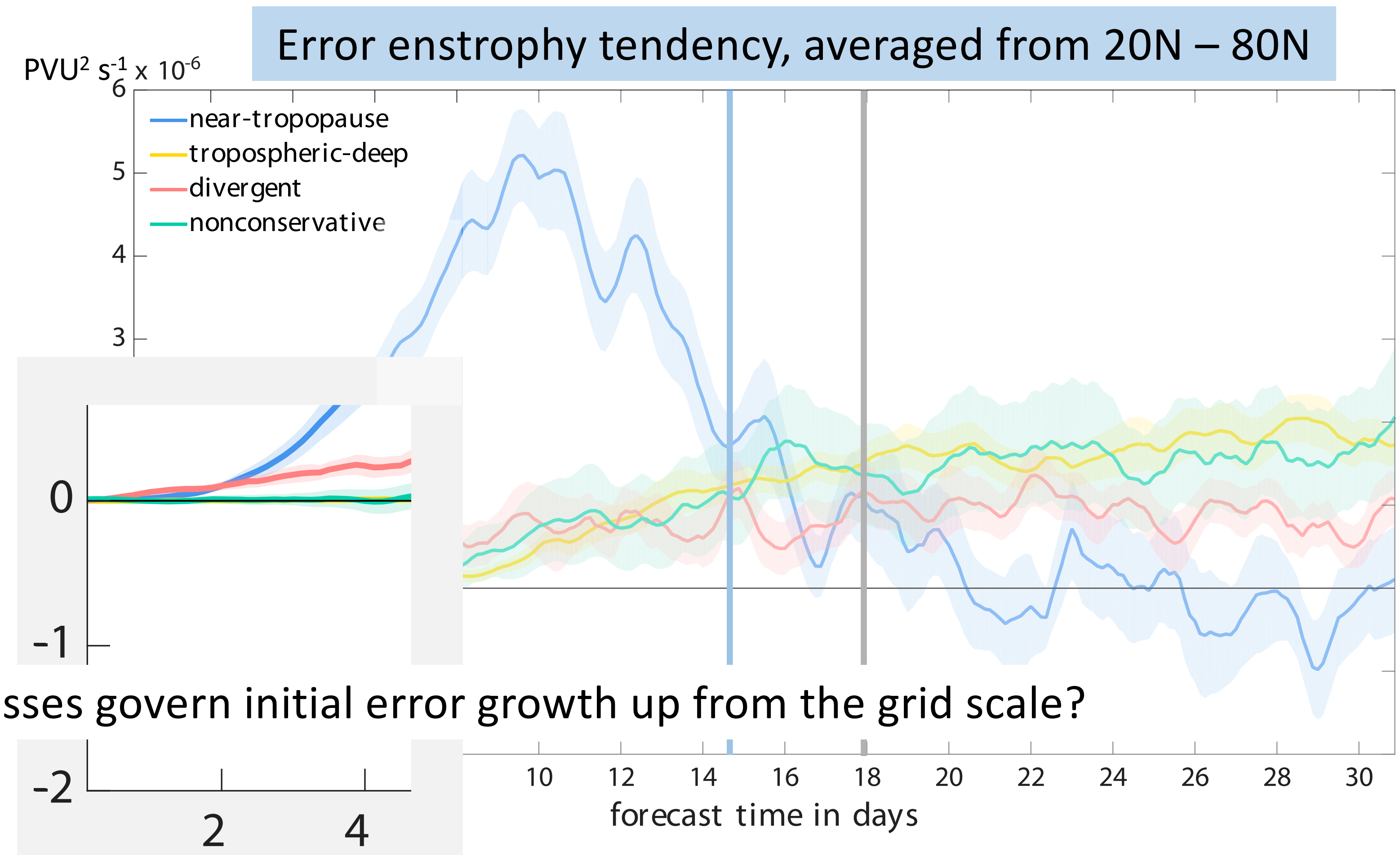
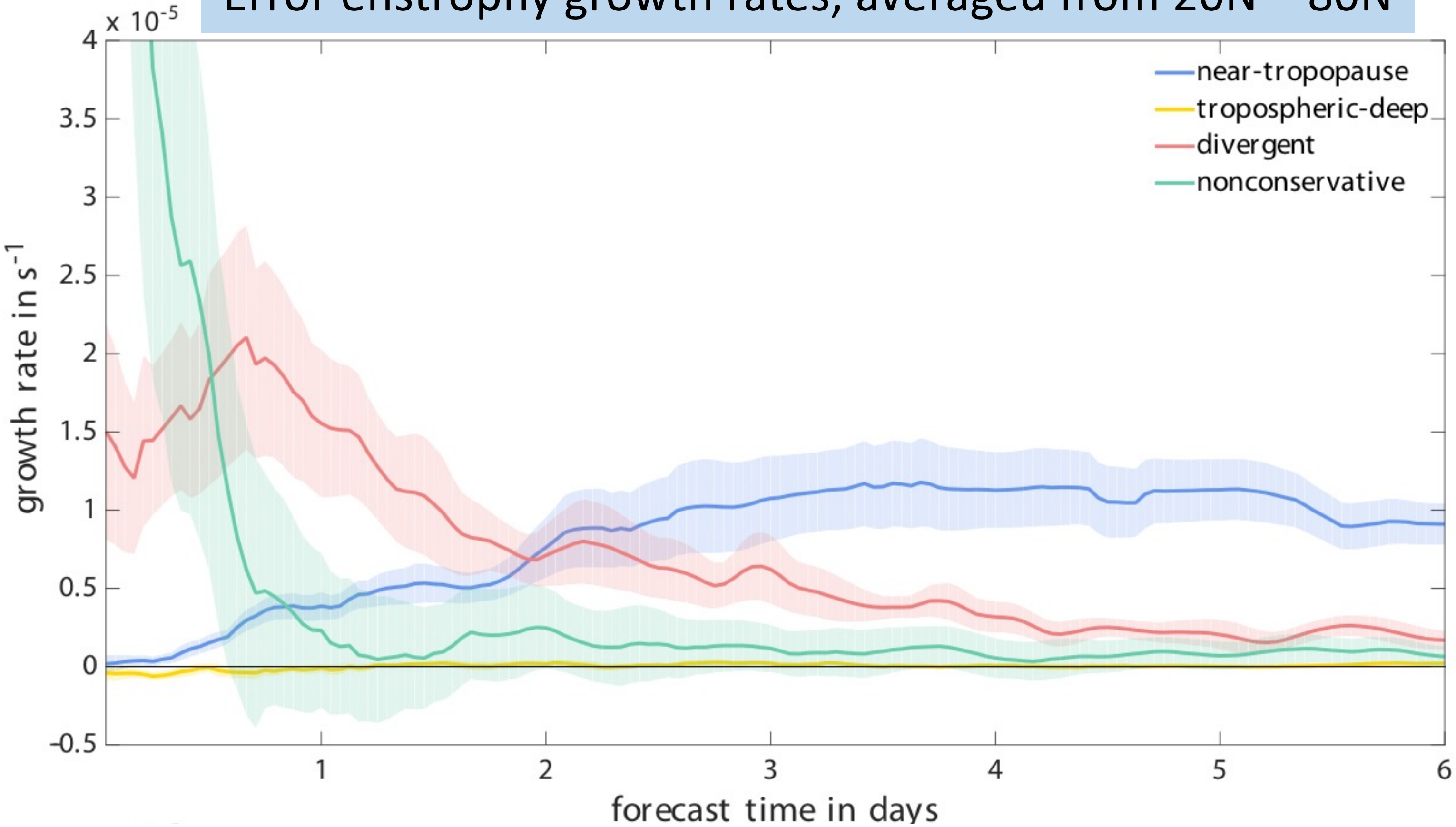


Which processes govern initial error growth up from the grid scale?

Growth rates associated with processes

Error enstrophy growth rates, averaged from 20N – 80N



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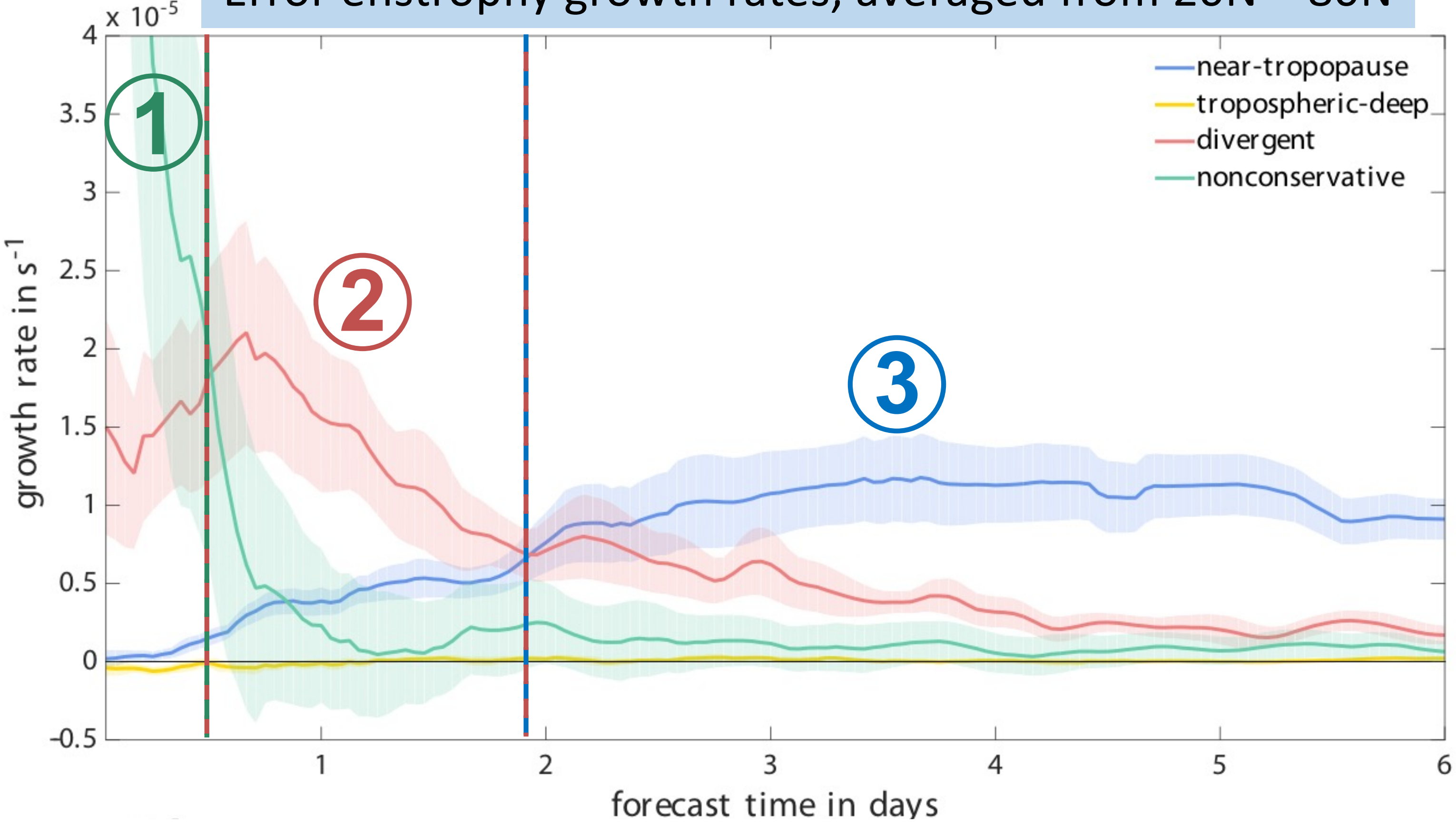
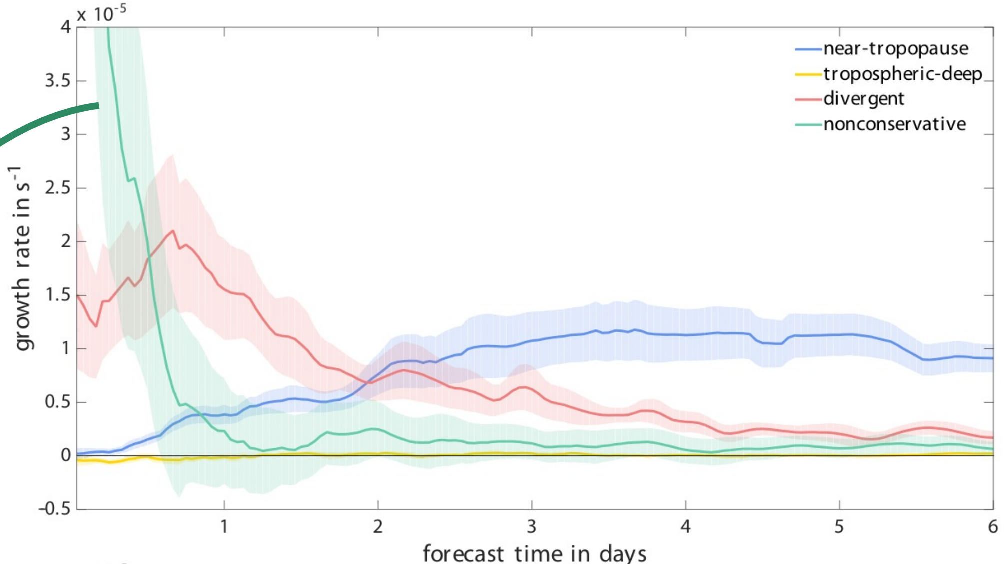
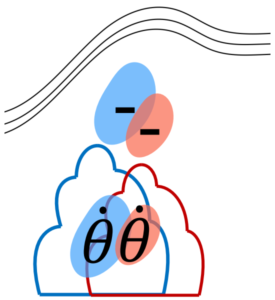


Distinct stages of upscale error growth

expected

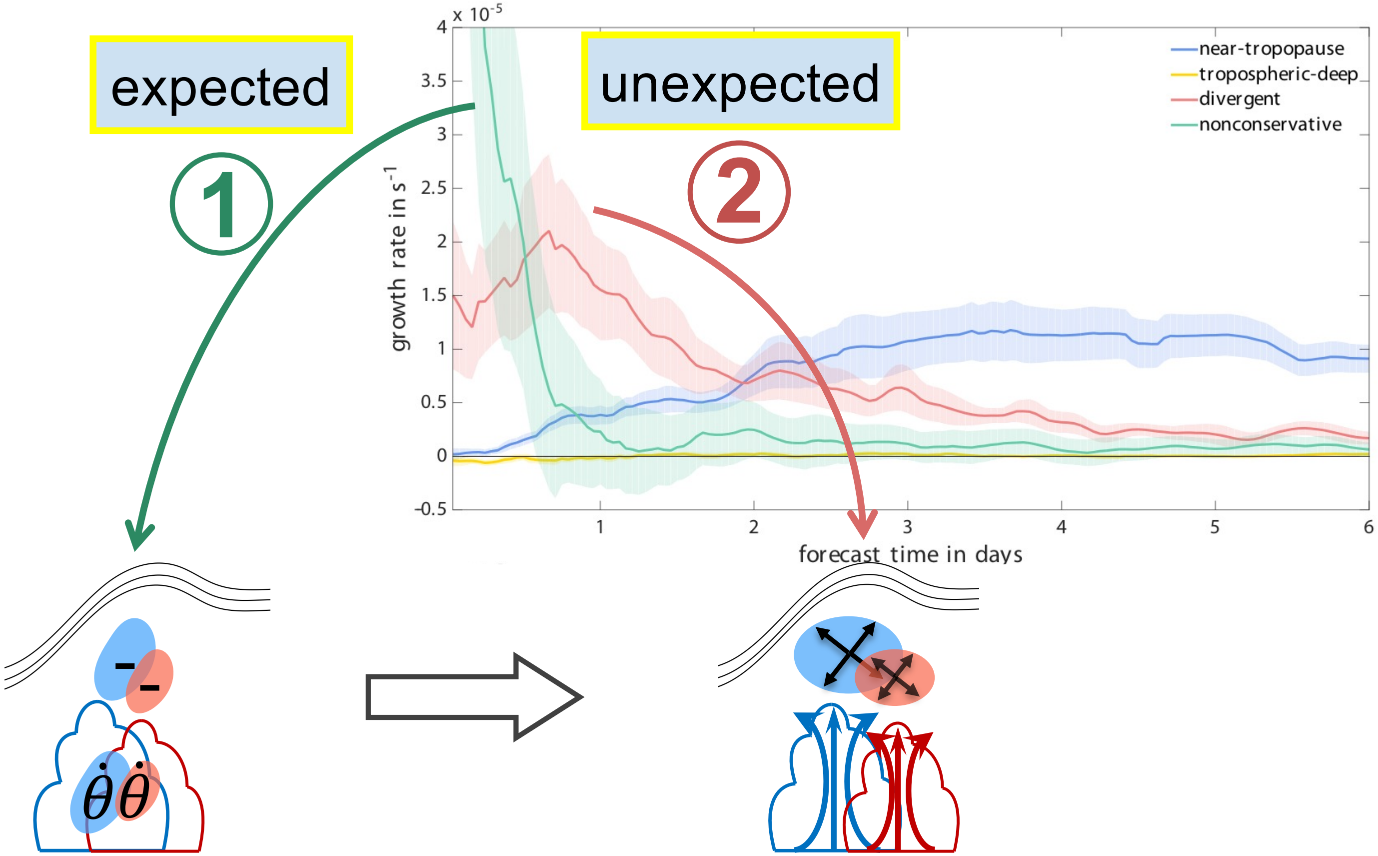
①





Error growth dominated by
latent heating

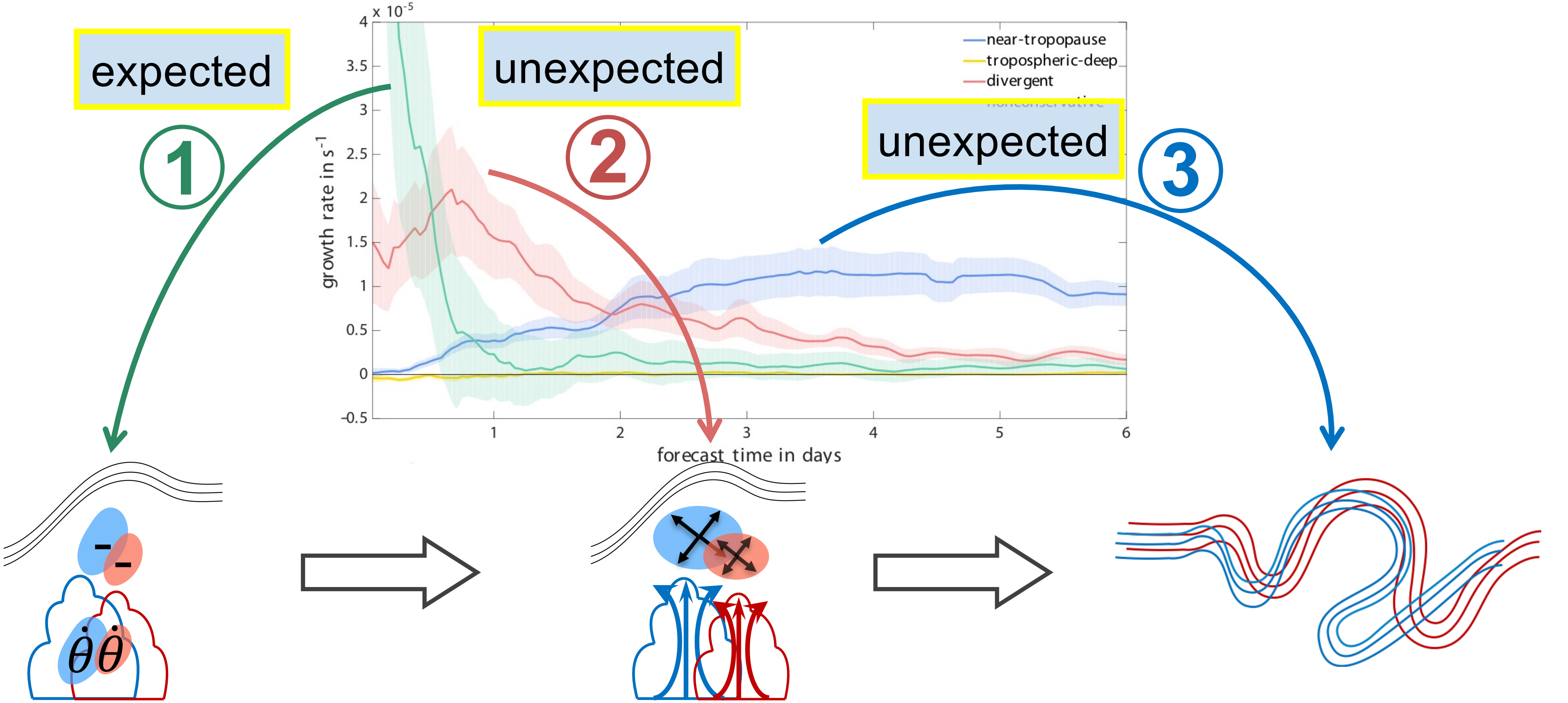
Distinct stages of upscale error growth



Error growth dominated by
latent heating

Error growth dominated by
upper-tropospheric divergence

Distinct stages of upscale error growth



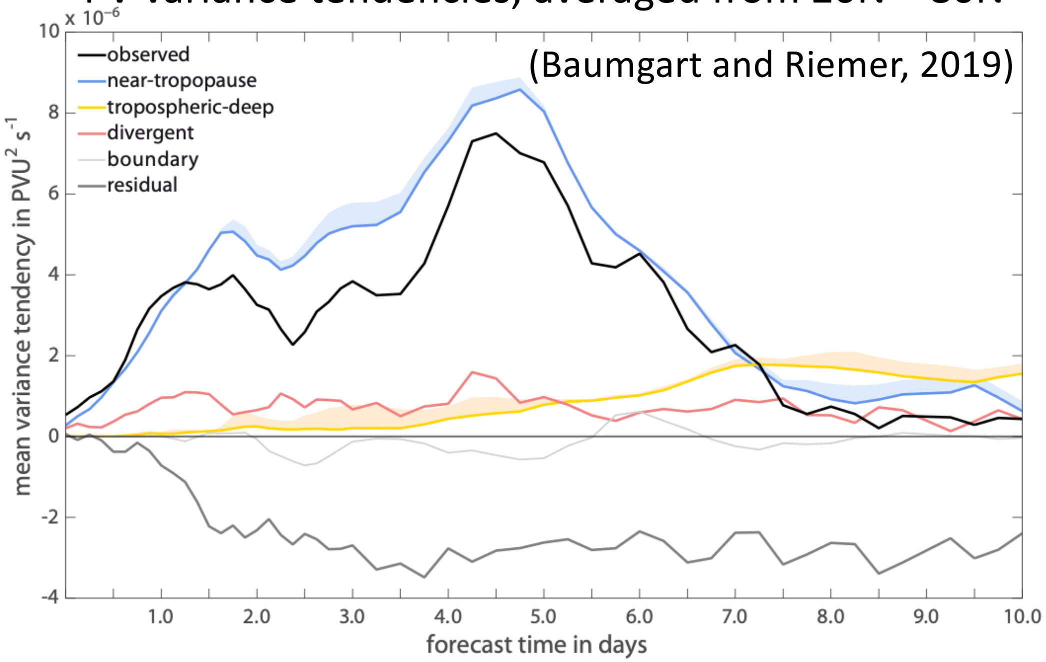
Error growth dominated by **latent heating**

Error growth dominated by **upper-tropospheric divergence**

Error growth dominated by **near-tropopause dynamics**

Error growth experiments vs. operational EC

PV variance tendencies, averaged from 20N – 80N



Initial condition uncertainty directly projects onto amplification by nonlinear tropopause dynamics.

Error growth experiments vs. operational EC

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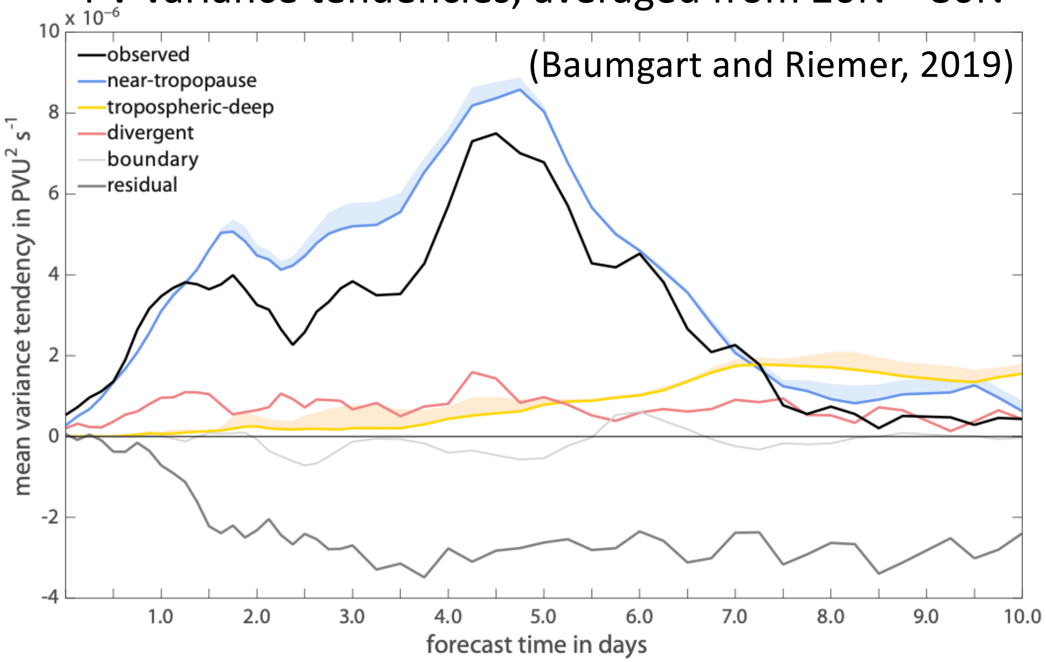
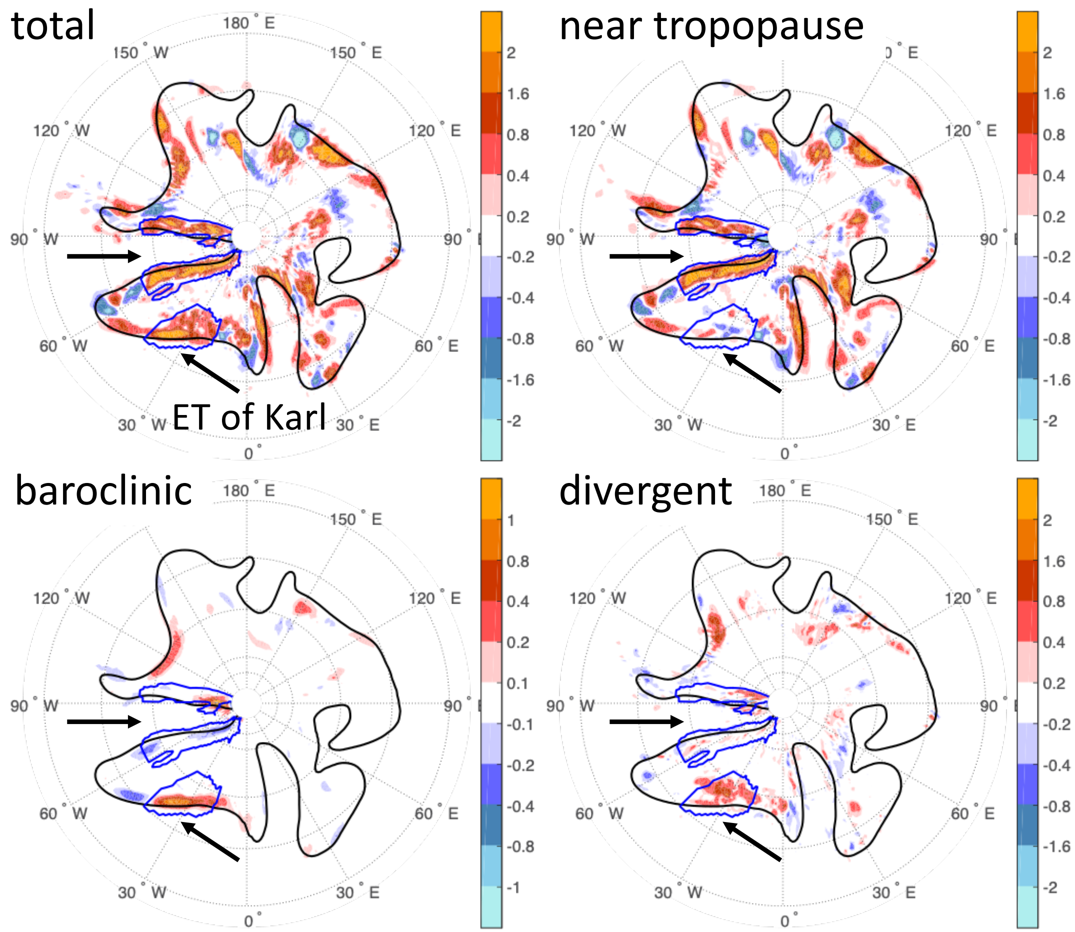


Individual PV-variance tendencies on 325K (day 4.5)



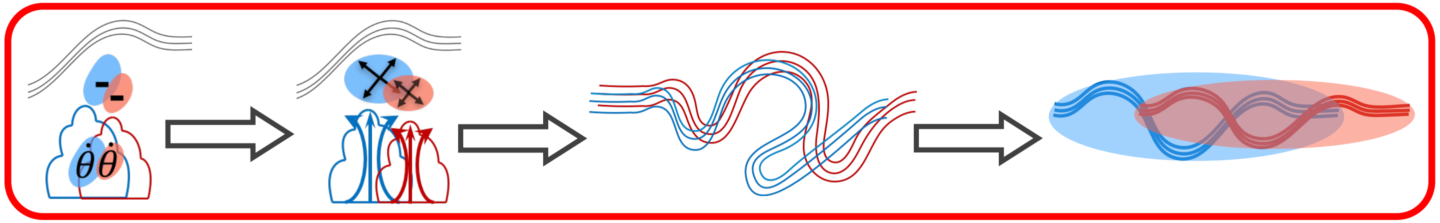
Initial condition uncertainty directly projects onto amplification by nonlinear tropopause dynamics.
Locally, however, dominant processes differ.

Summary: New insight into error growth

convective instability → upscale transition / adjustment-to-balance → baroclinic instability

Previous conceptual model

Our quantitative framework



convective scale — meso scale — synoptic scale — regime scale

10 km — 100 km — 1000 km — 10000 km

- Confirmation of multi-stage behavior of upscale error growth

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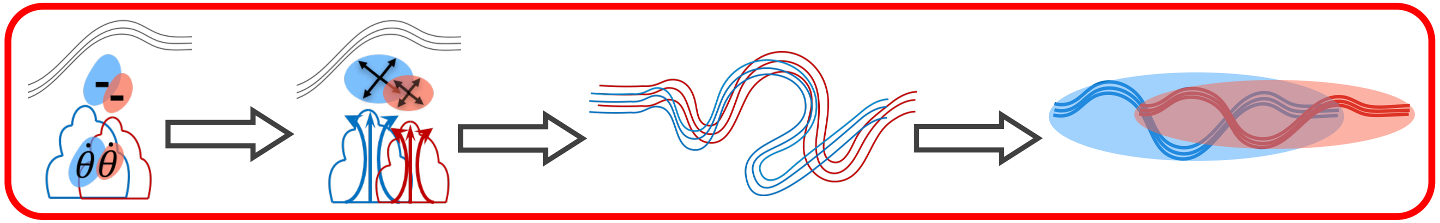

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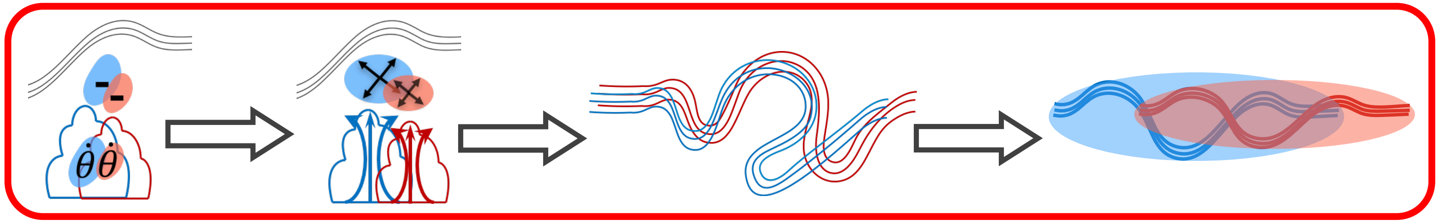
Our quantitative framework



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- Confirmation of multi-stage behavior of upscale error growth
- Novel interpretation of processes: divergent PV-advection
- Initial-condition uncertainty dominates in operational model

WAVES TO WEATHER

Interested in medium-range predictability?

Give special attention to how data (assimilation), model errors and stochastic schemes project onto <u>upper-tropospheric outflow</u> = <u>most effective trigger of medium-range</u> error and uncertainty amplification (by nonlinear tropopause dynamics).

MAY 2018 BAUMGART ET AL. 1405

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Potential Vorticity Dynamics of Forecast Errors: A Quantitative Case Study

MAY 2019 BAUMGART ET AL. 1713

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Waves to Weather (W2W)
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Quantitative View on the Processes Governing the Upscale Error Growth up to the Planetary Scale Using a Stochastic Convection Scheme

Received: 29 March 2019 | Revised: 07 June 2019 | Accepted: 01 July 2019
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RESEARCH ARTICLE

Quarterly Journal of the Royal Meteorological Society RMetS

Processes governing the amplification of ensemble spread in a medium-range forecast with large forecast uncertainty