WAVES TO WEATHER

Case Study Of Error-growth From Mesoscale Convection Near The Intrinsic Limit: Combining Potential Vorticity Error Growth Tendencies With Ensemble Sensitivity Analysis

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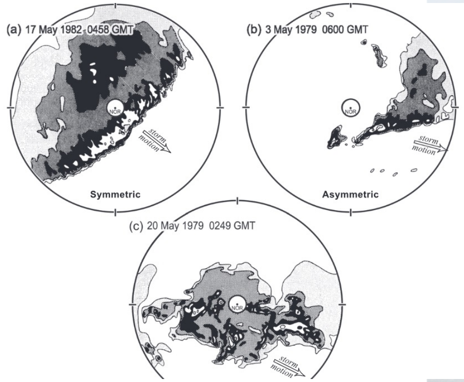
Collaborators: Michael Riemer, Tobias Selz

September 12, ECMWF, Reading

Why variability of deep moist convection?

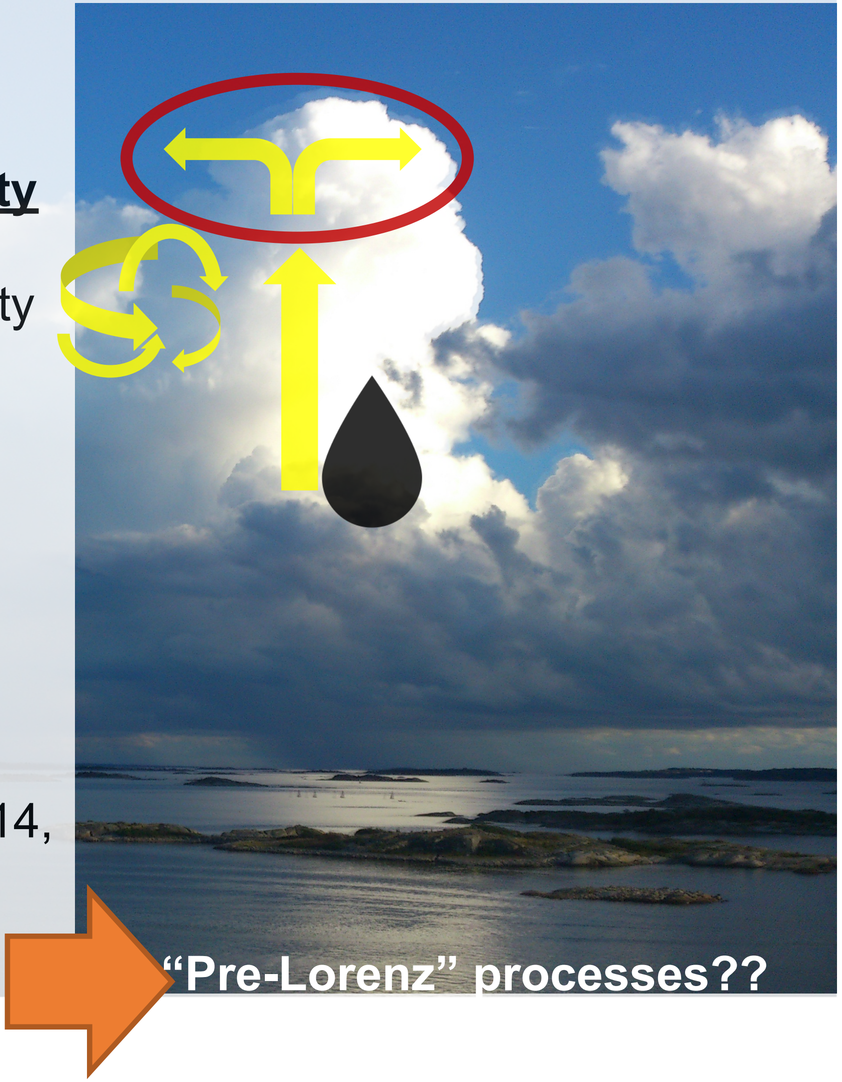
Since Lorenz' works we have been chasing "butterflies"

- **Convective instability** as important instability
- Lorenz (1963, 1969) **"deterministic chaos" & finite predictability horizon**
- Convective organisation and outflow affecting weather predictability (Rodwell et al. 2013, Baumgart et al. 2019)



- Do the "butterflies" actually exist as such? (Durran & Gingrich, 2014, Lorenz 1969)

➔ Investigate error cascade and its spread evolution!!



"Pre-Lorenz" processes??

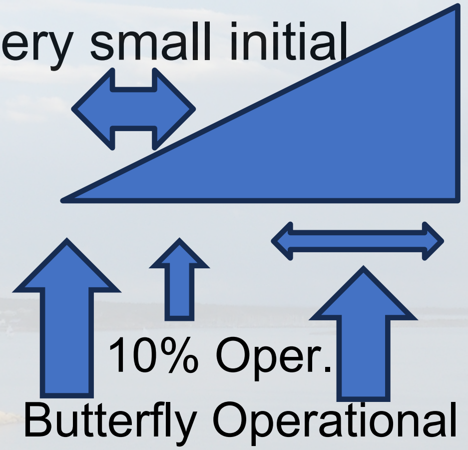
Why variability of deep moist convection?

Since Lorenz’ works we have been chasing “butterflies”

➔ Investigate error cascade and its spread evolution!!

1. Error-growth stages from Zhang et al. 2007,
2. Mean evolution from Baumgart et al. studies, Selz et al. 2022/Tobias’ talk:

- Spread growth from diabatic tendencies at very small initial condition uncertainty
- Convection seems to dominate
- Convective heating → outflow
  → DIV pert → non-linear winds?
- < 10-20% operational uncertainty
- Dominant days 1 & 2
- Near-tropopause dynamics

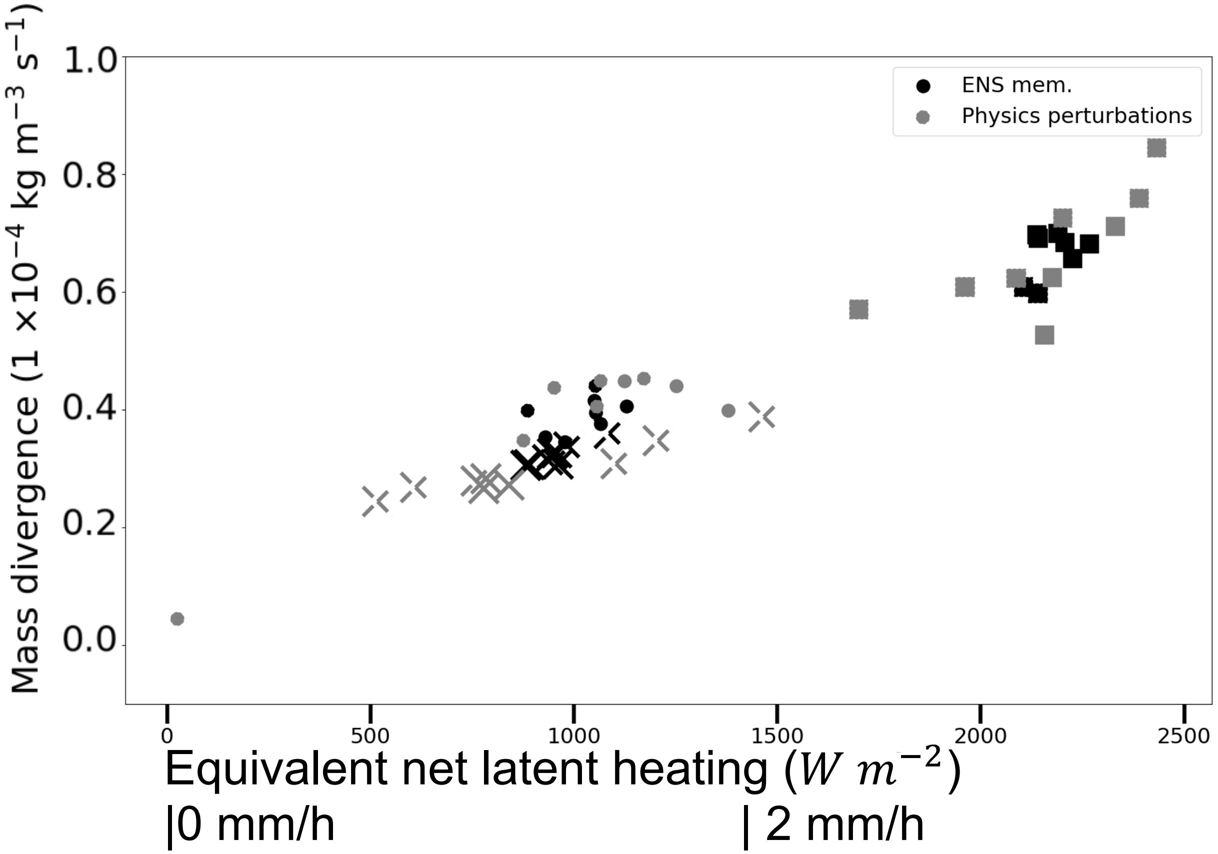


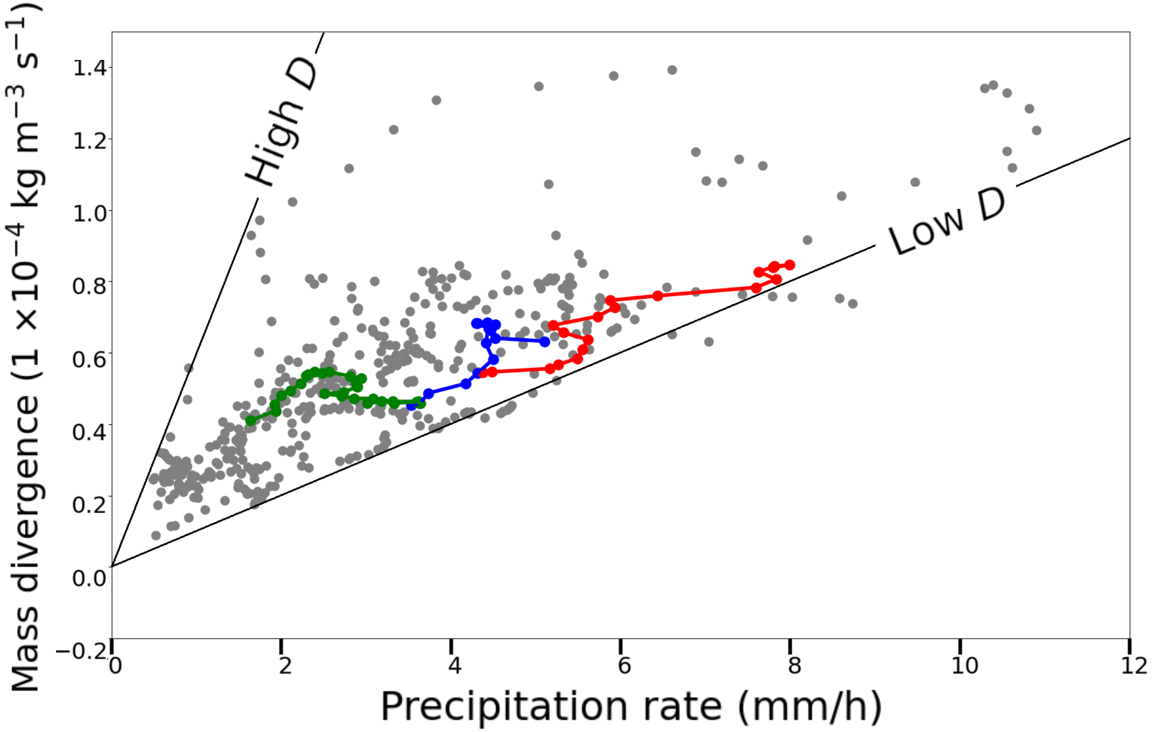
“Pre-Lorenz” processes??

What about case-to-case variability and individual cases?

Handy ”tool” from earlier work…

13 km parameterized deep conv. | 1 km conv.-permitting





See Groot, Kuntze, Miltenberger & Tost (2024), WCD

Summary earlier work on convective outflow

Upper tropospheric divergent outflow in ICON depends

Parameterised set-up (13 km)

- ⚡ Linearly on (net) latent heating
- ✗ Weak variation around linear relation

Convection-permitting set-up (1 km)

- ⚡ On (net) latent heating
- ⚡ On convective aggregation
- ? Possibly on outflow dimensionality

LES-study, CM1

←This ICON-study

Large-scale sensitivity to the outflows

Hypothesis: **convective systems** of event **can induce** a subsequent **jet stream shift** in a much underdispersed ensemble*

*(Rescaled initial uncertainty →→ Lorenz' "butterflies", n = 50)

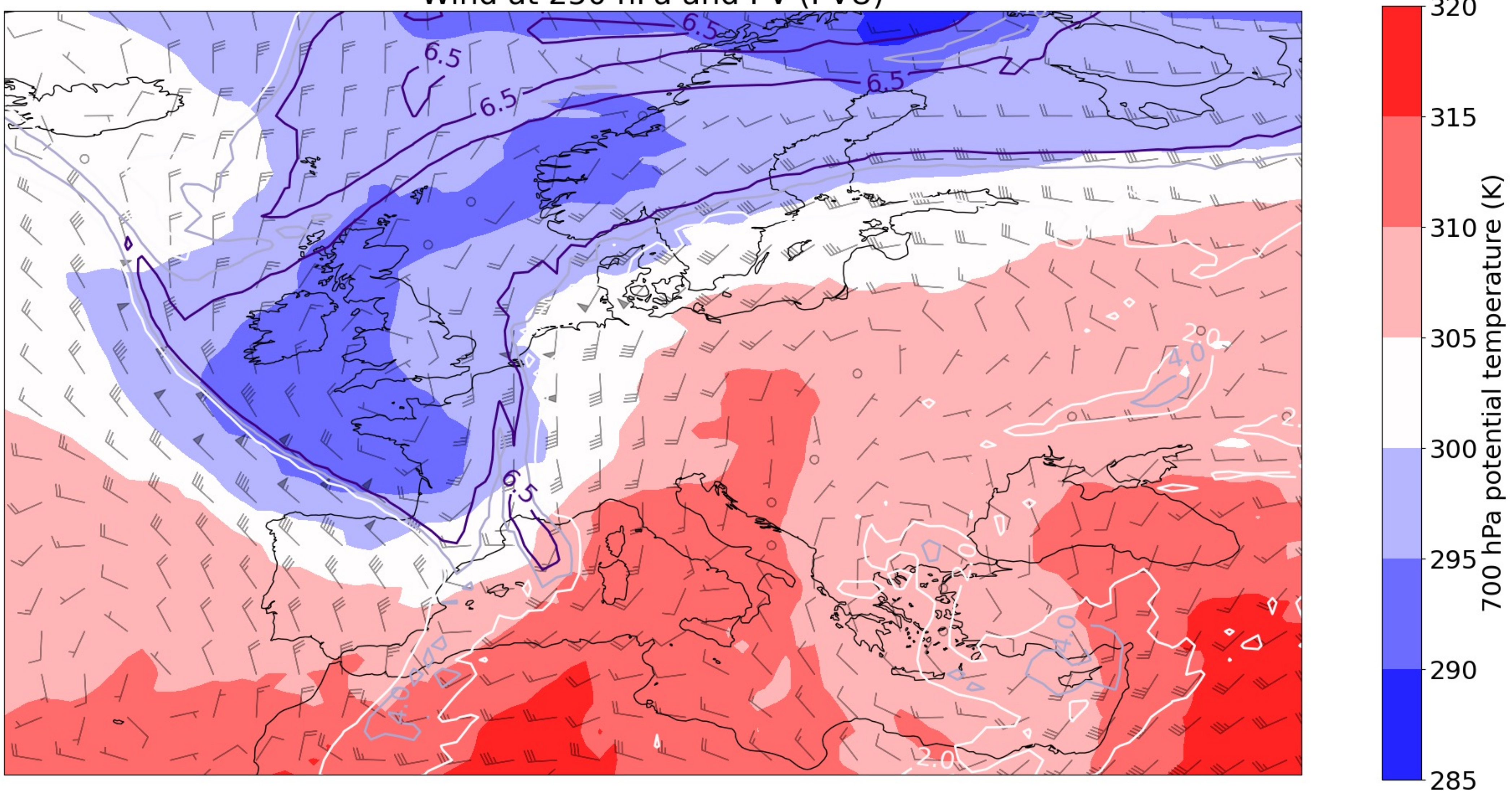
Methods:

1. Ensemble sensitivity analysis (regression)
2. Spread growth diagnostics for attribution (Selz et al. 2022; Baumgart et al. 2019)

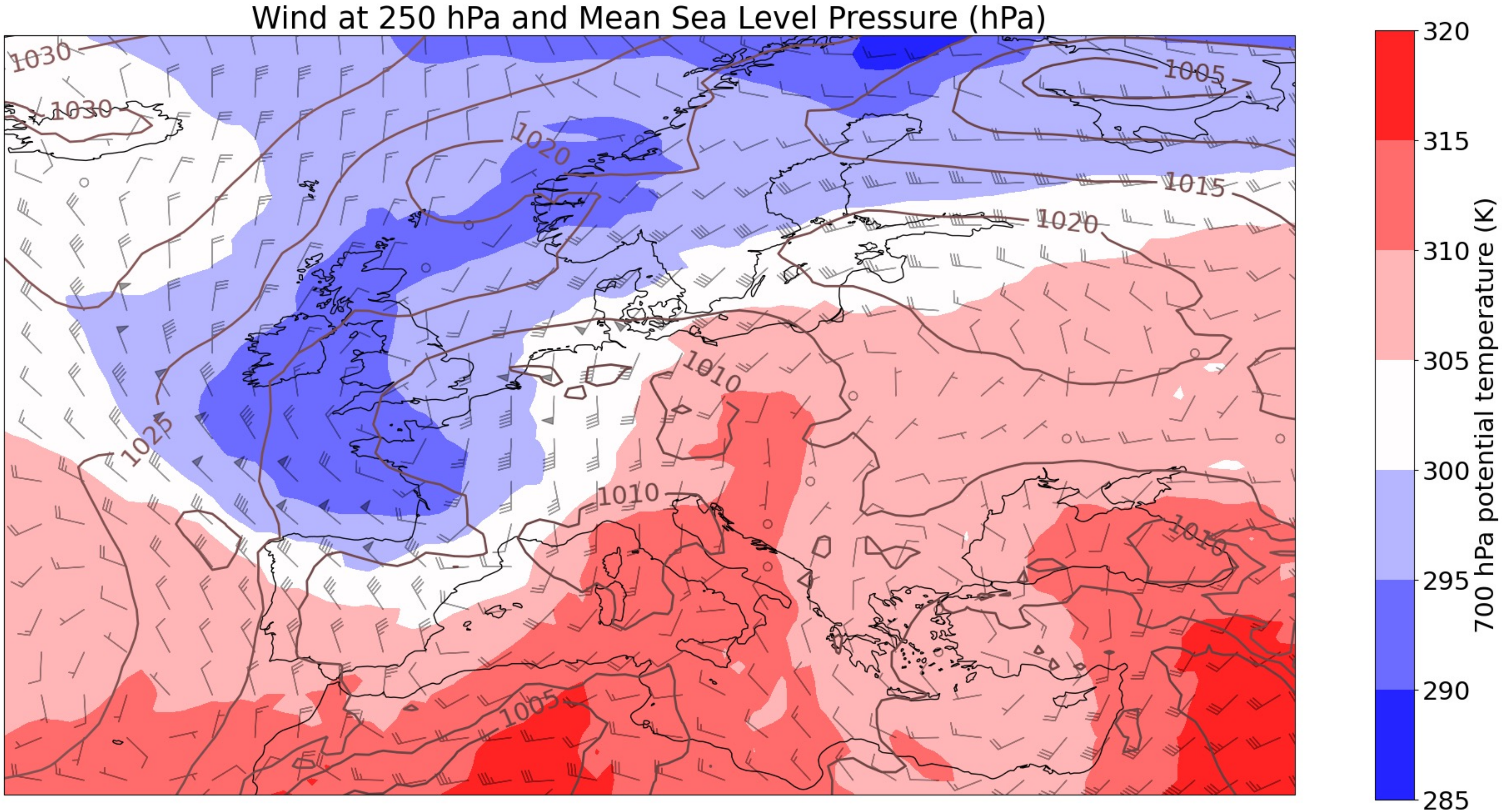
A convective event

Synoptic setting

Wind at 250 hPa and PV (PVU)



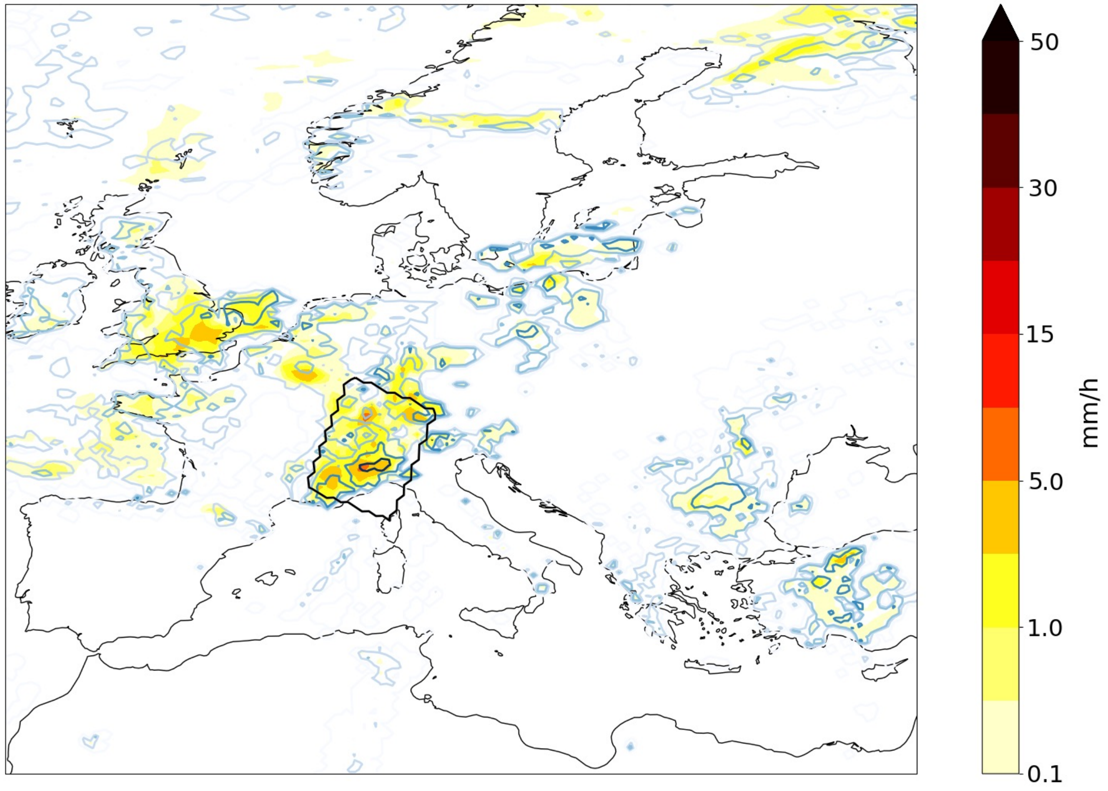
Synoptic setting


Wind at 250 hPa and Mean Sea Level Pressure (hPa)

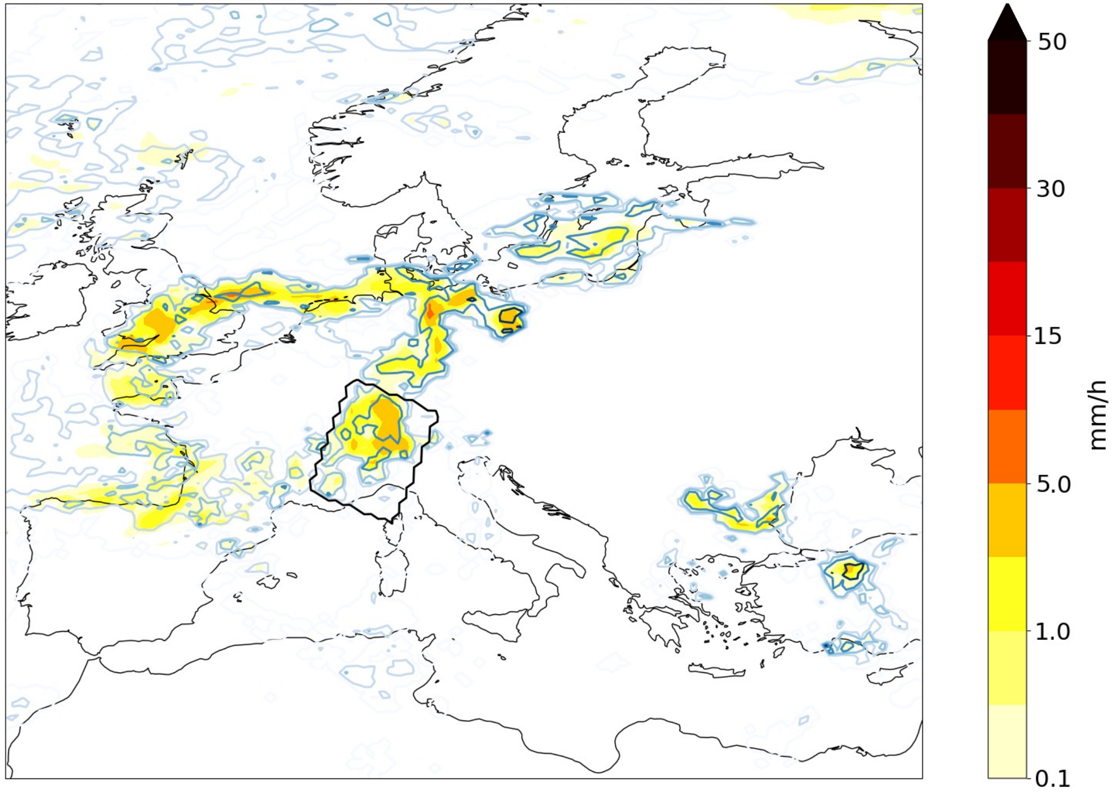
Convective systems

"Alps system":

2-13 h forecast time



Rescaled IFS-ens, hourly $\mu_{preciprate}$ and $\sigma_{preciprate}$
003 hours since 10-06-2019 12 UTC



Rescaled IFS-ens, hourly $\mu_{preciprate}$ and $\sigma_{preciprate}$
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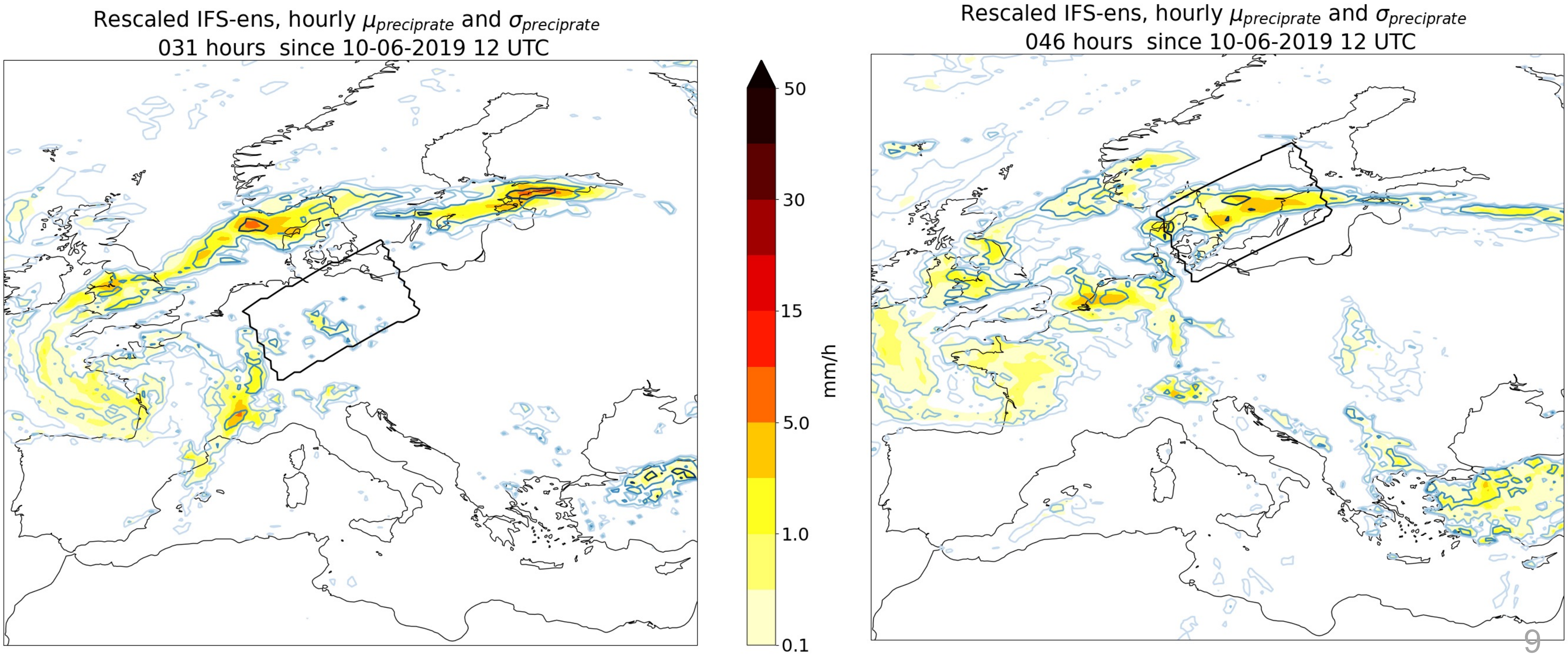
Convective systems

“Day 2” system:

31-46 h forecast time



Rescaled IFS-ens, hourly $\mu_{preciprate}$ and $\sigma_{preciprate}$
031 hours since 10-06-2019 12 UTC

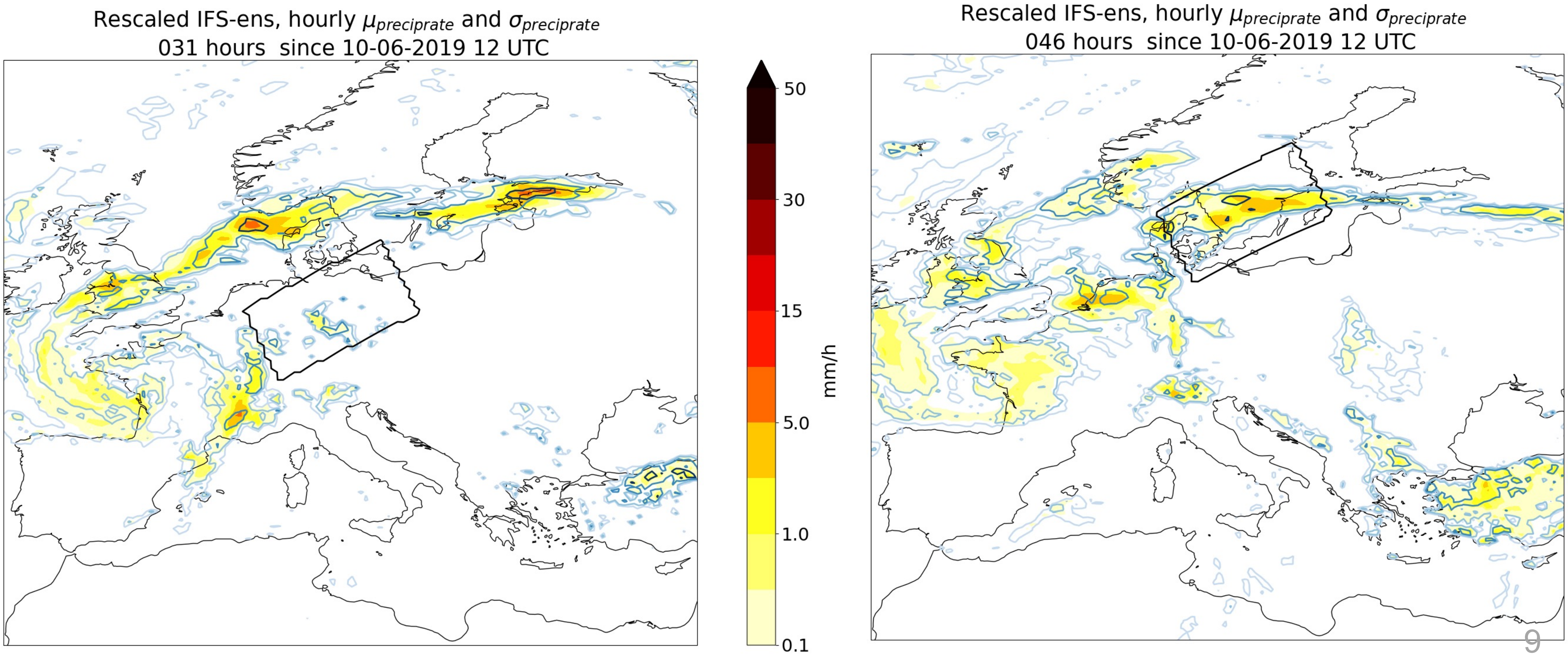
Rescaled IFS-ens, hourly $\mu_{preciprate}$ and $\sigma_{preciprate}$
046 hours since 10-06-2019 12 UTC

Convective systems

“Day 2” system:

31-46 h forecast time

Both convective systems have a total range in area mean precipitation accumulation of roughly 1-10%!



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Rescaled IFS-ens, hourly $\mu_{preciprate}$ and $\sigma_{preciprate}$
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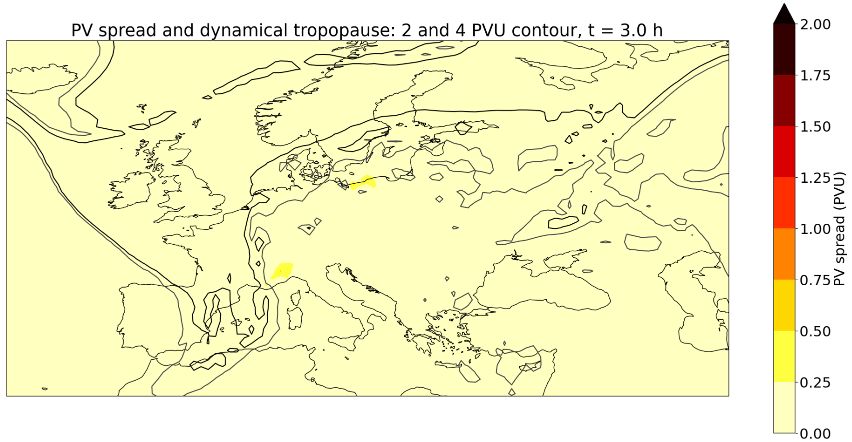
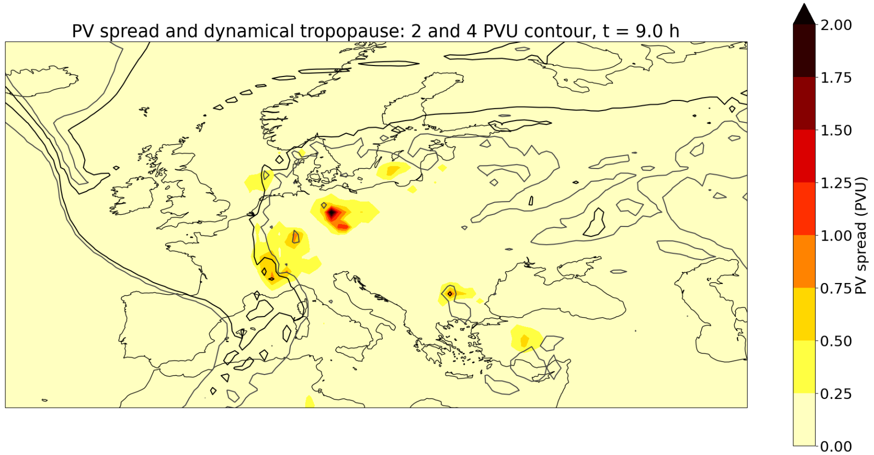
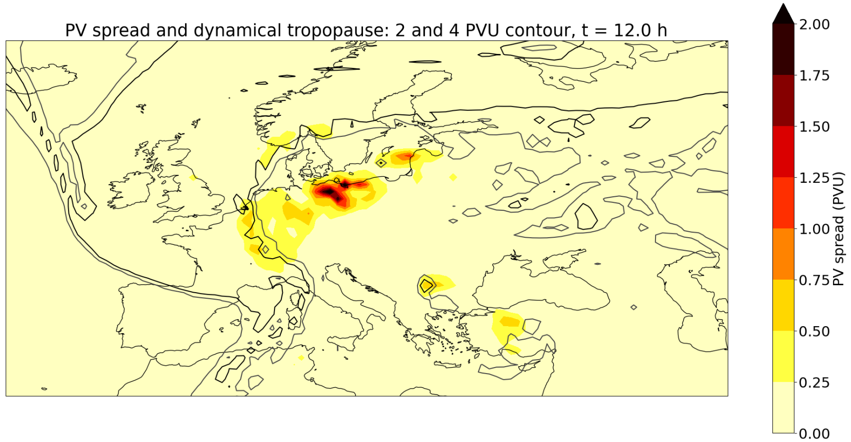
Methods sensitivity analysis

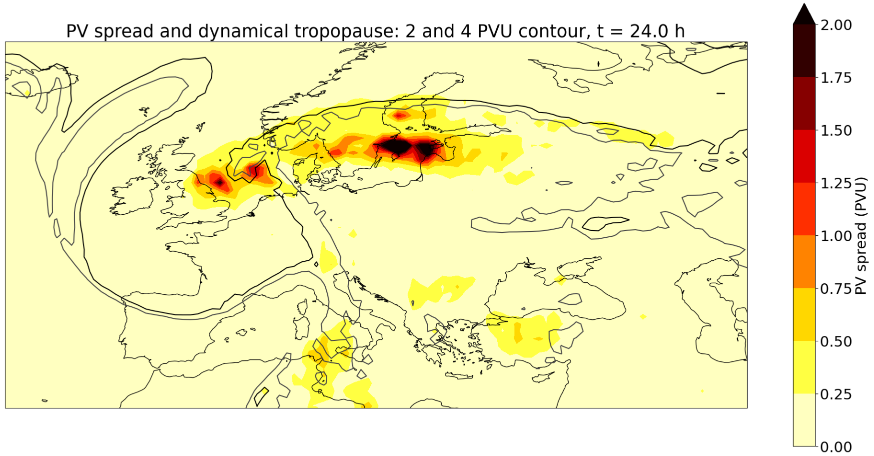
Quantification of **lateral outflow** at the top of convective systems

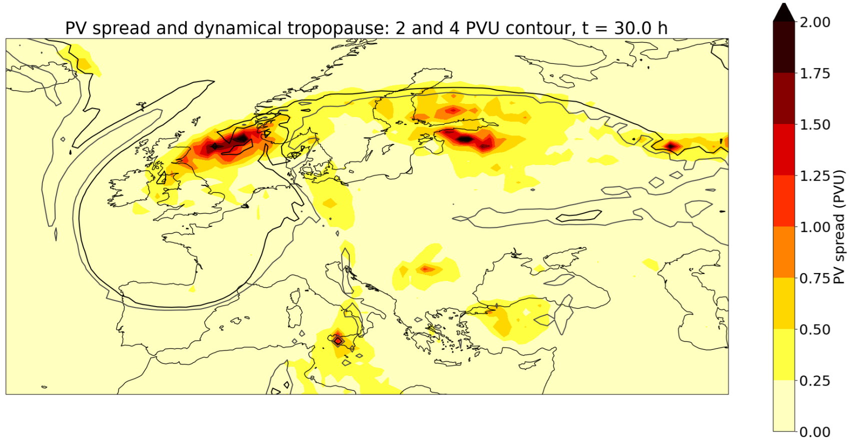
- Volume integration of mass divergence
- Compared to PV variability for sensitivity analyses

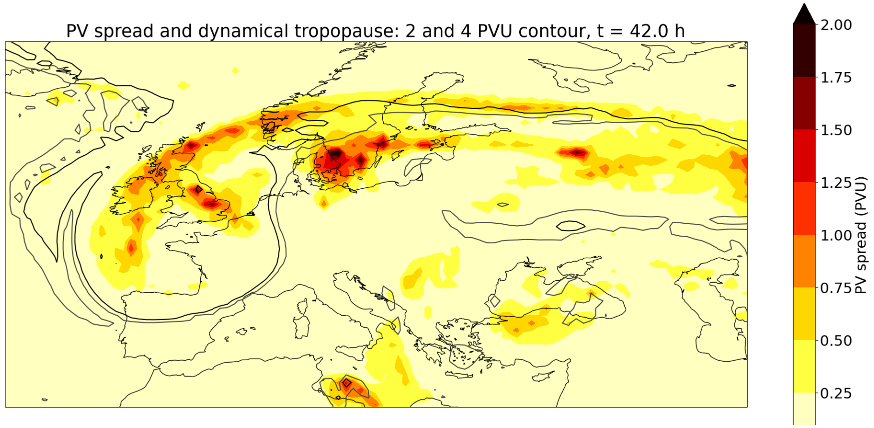

PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 3.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 9.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 12.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 24.0 h

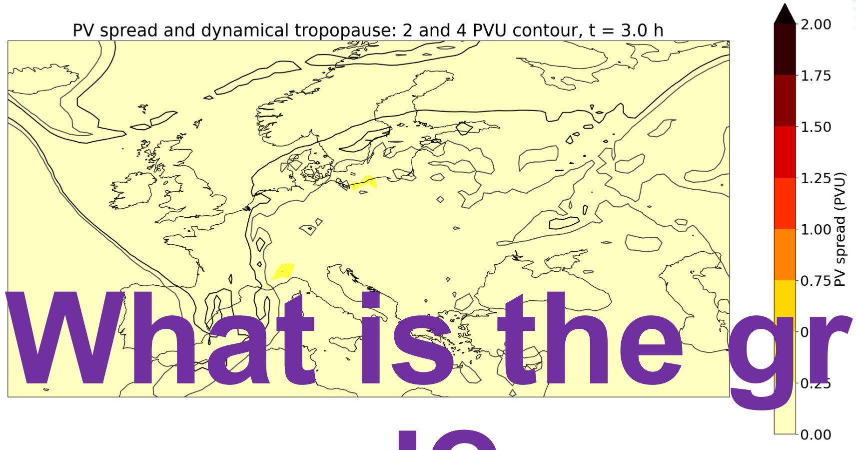

PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 30.0 h

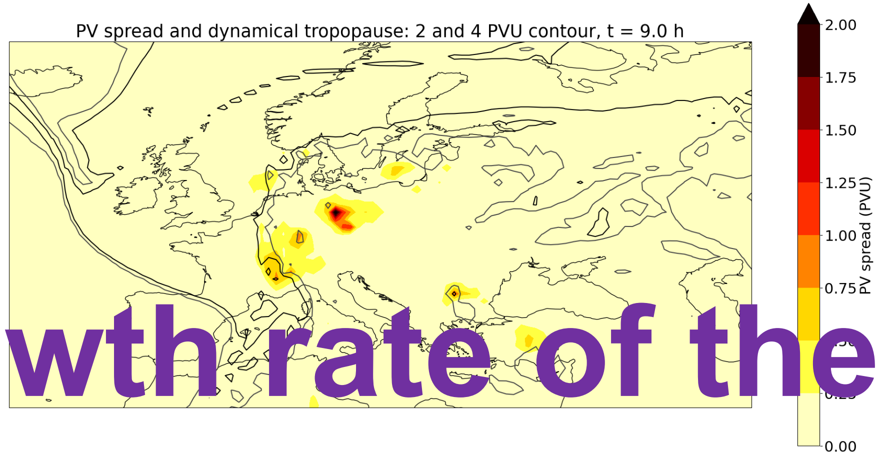

PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 42.0 h

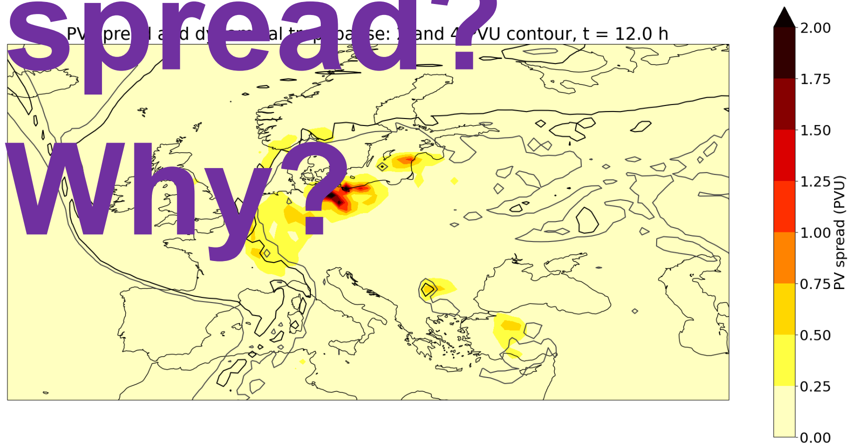
What is the growth rate of the spread?

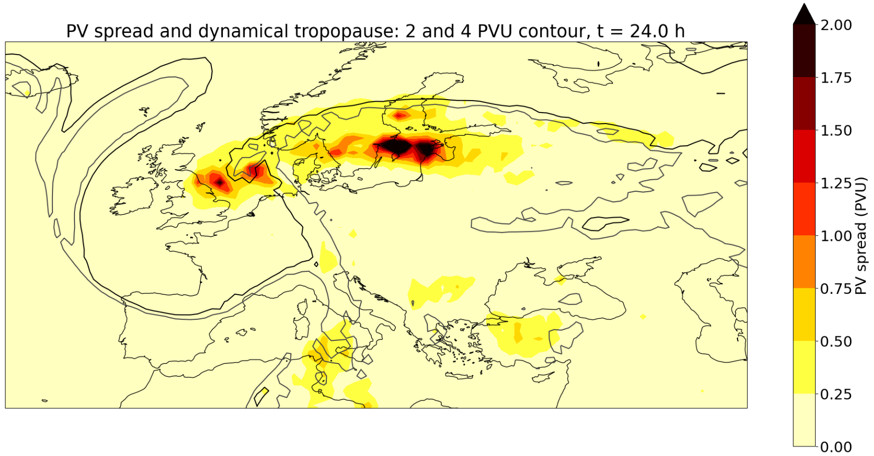
Why?

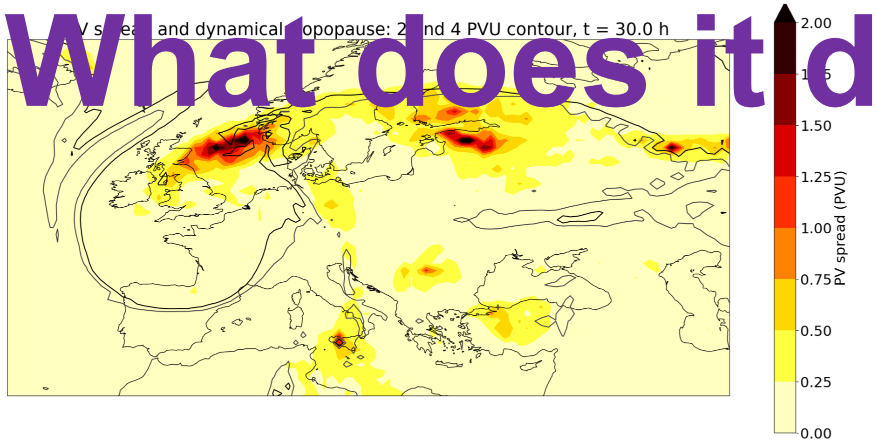
What does it depend on?

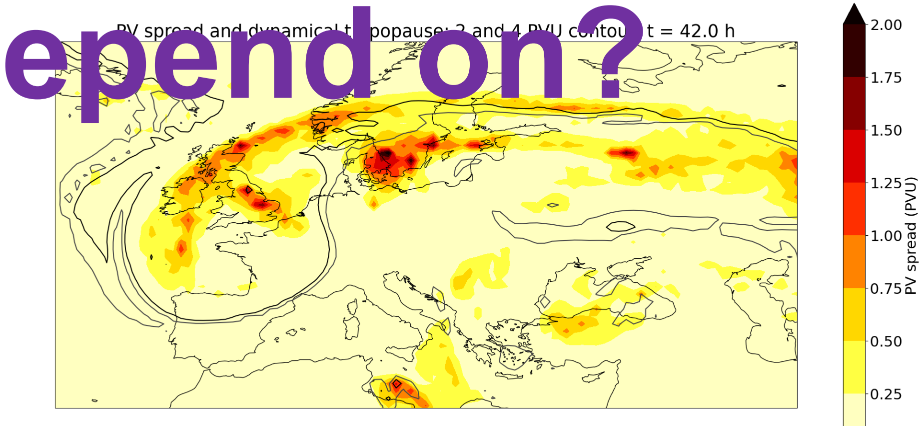

PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 3.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 9.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 12.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 24.0 h

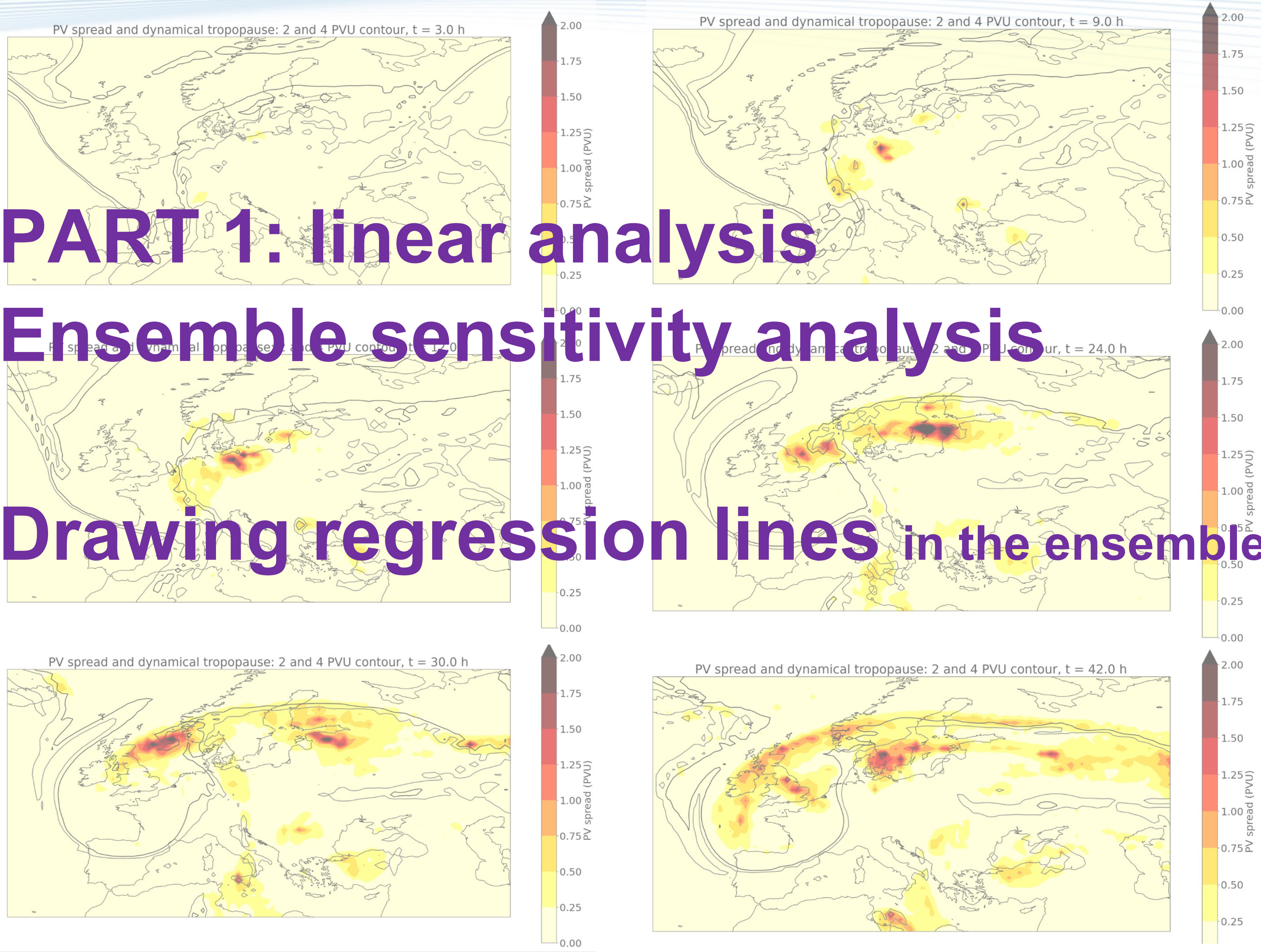

PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 30.0 h


PV spread and dynamical tropopause: 2 and 4 PVU contour, t = 42.0 h

PART 1: linear analysis

Ensemble sensitivity analysis

Drawing regression lines in the ensemble covariance

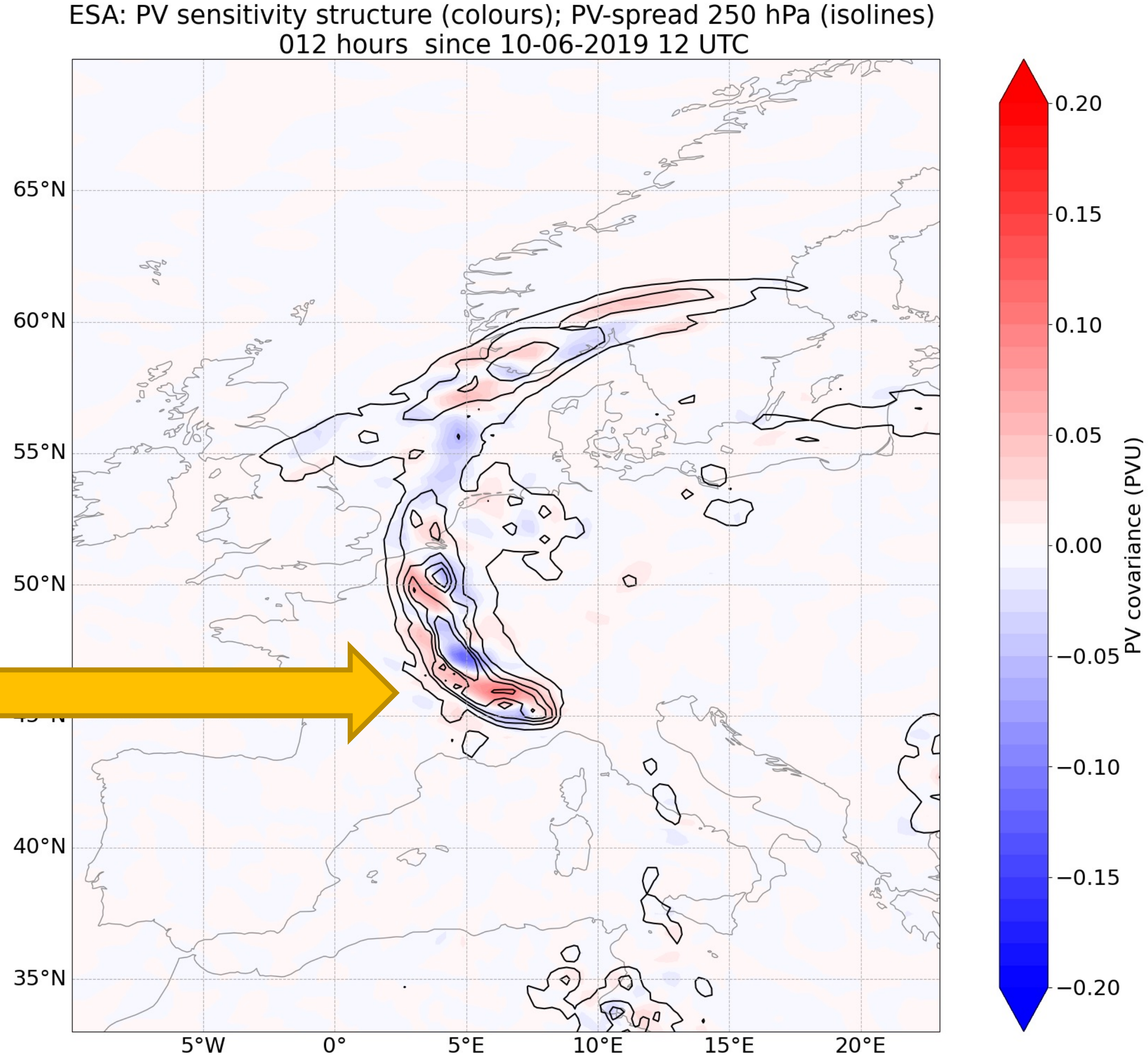


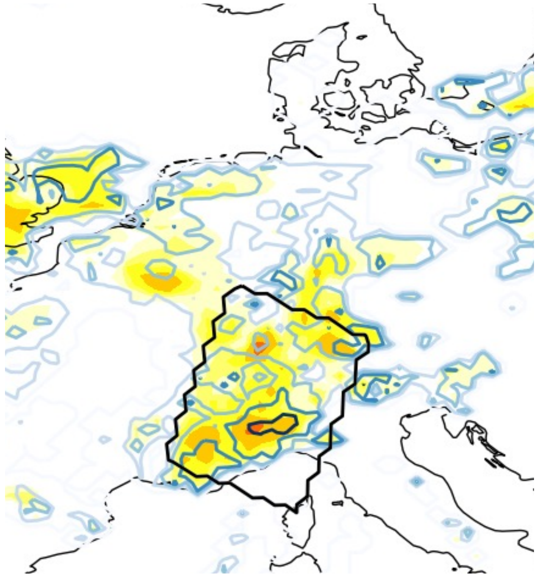
Methods sensitivity analysis

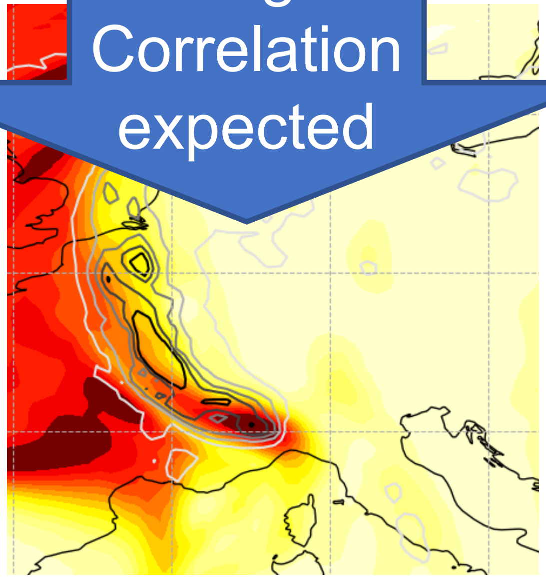
Quantification of **lateral outflow** at the top of convective systems

- Volume integration of mass divergence
- Compared to PV variability for sensitivity analyses

“Alps system” +12h

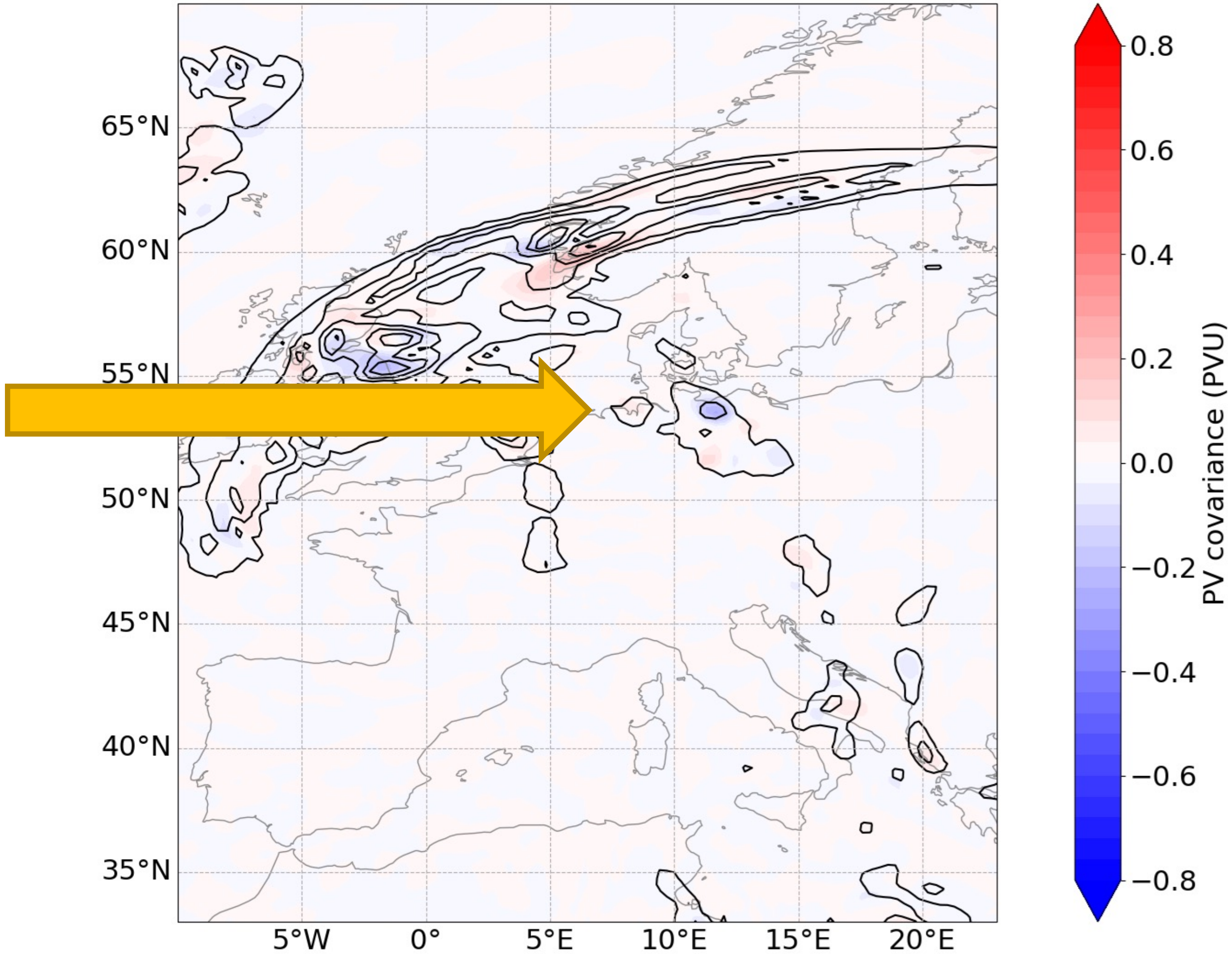

ESA: PV sensitivity structure (colours); PV-spread 250 hPa (isolines)
012 hours since 10-06-2019 12 UTC



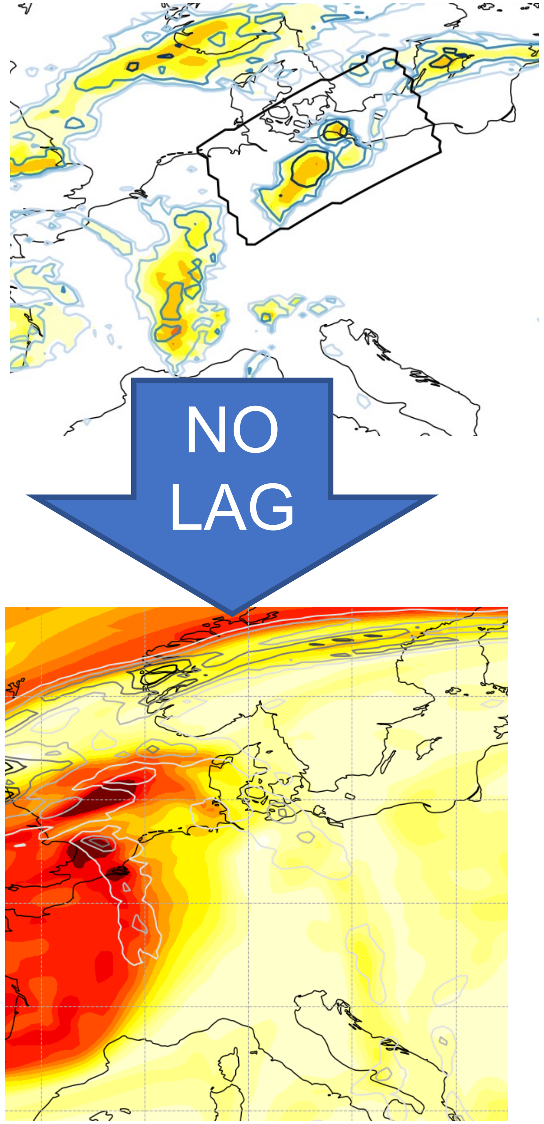


Neg. Correlation expected

“Day 2 system” +34h

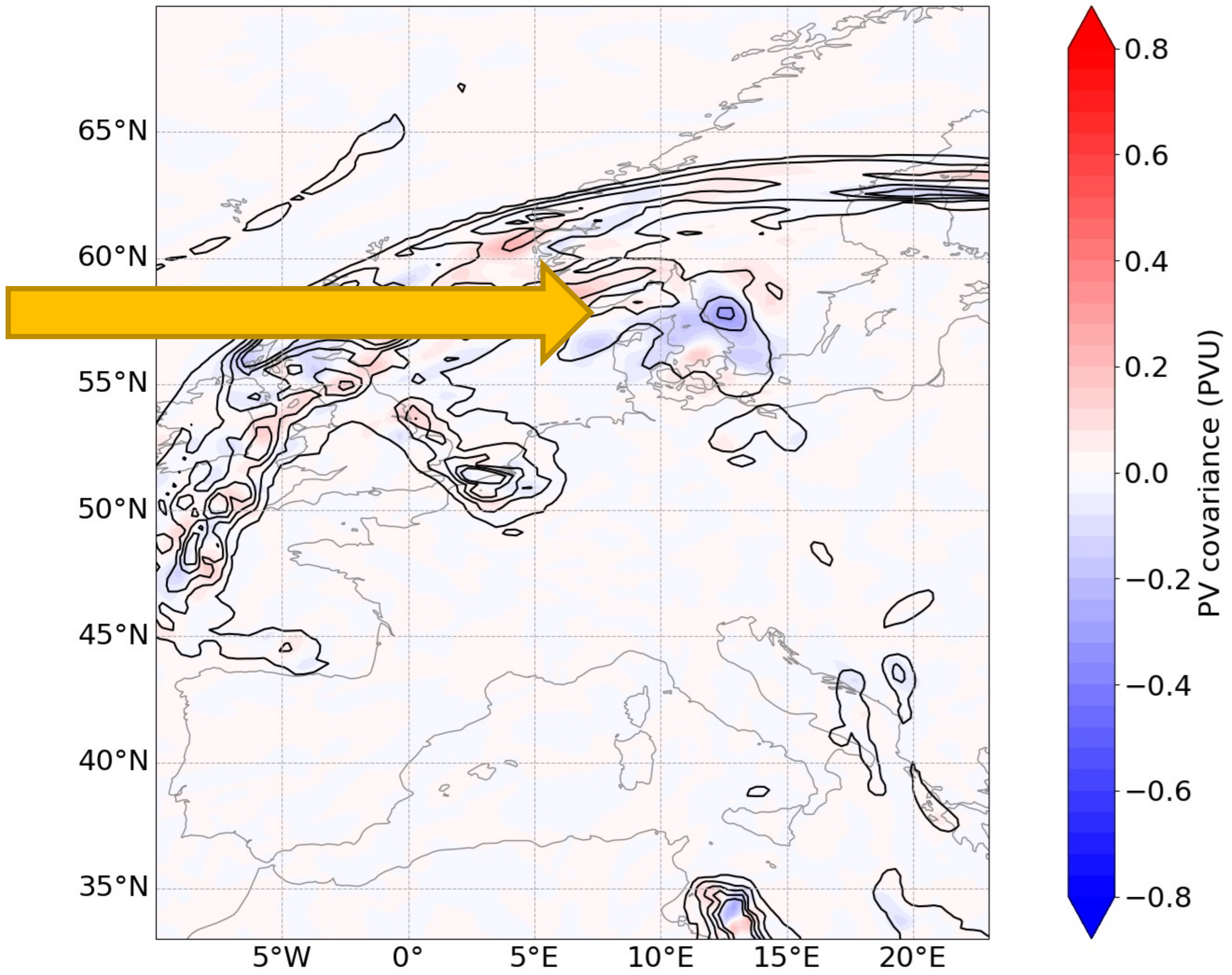


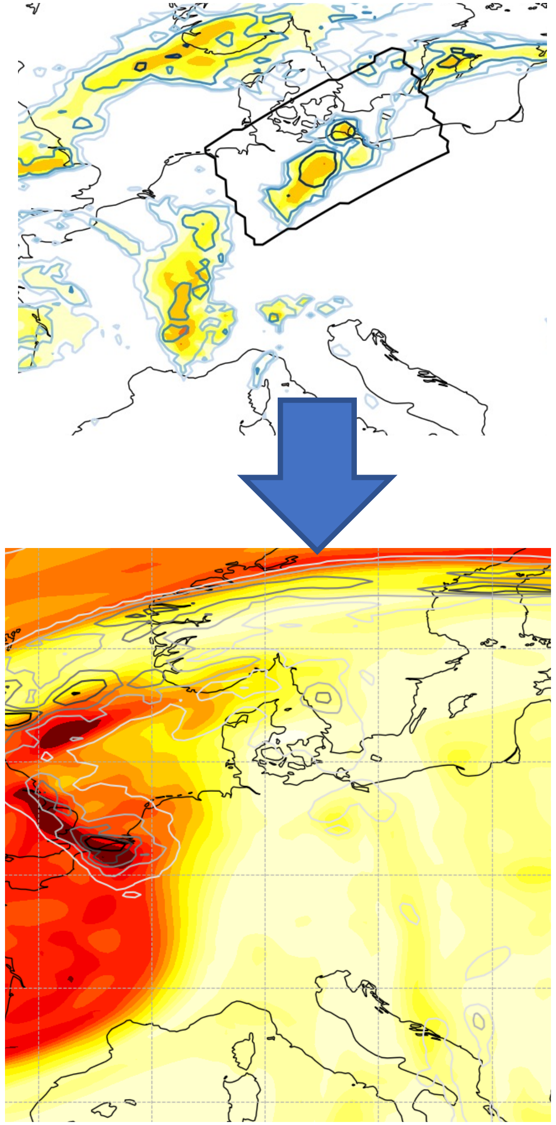
ESA: PV sensitivity structure (colours); PV-spread 250 hPa (isolines)
034 hours since 10-06-2019 12 UTC



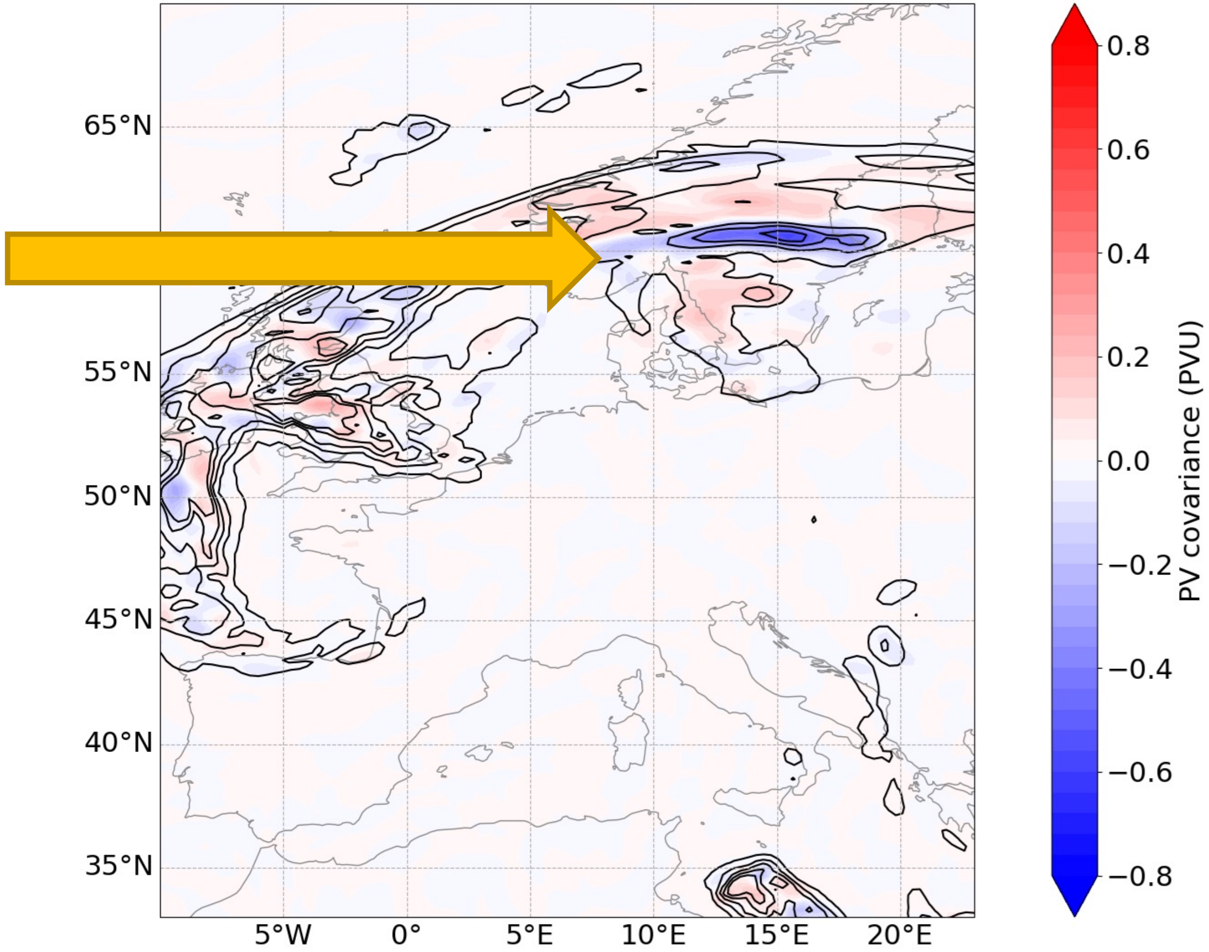
“Day 2 system” +39 h

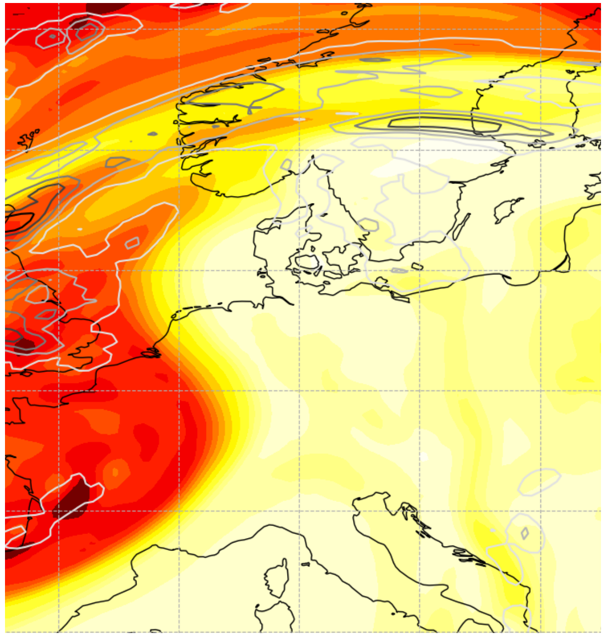
ESA: PV sensitivity structure (colours); PV-spread 250 hPa (isolines)
039 hours since 10-06-2019 12 UTC



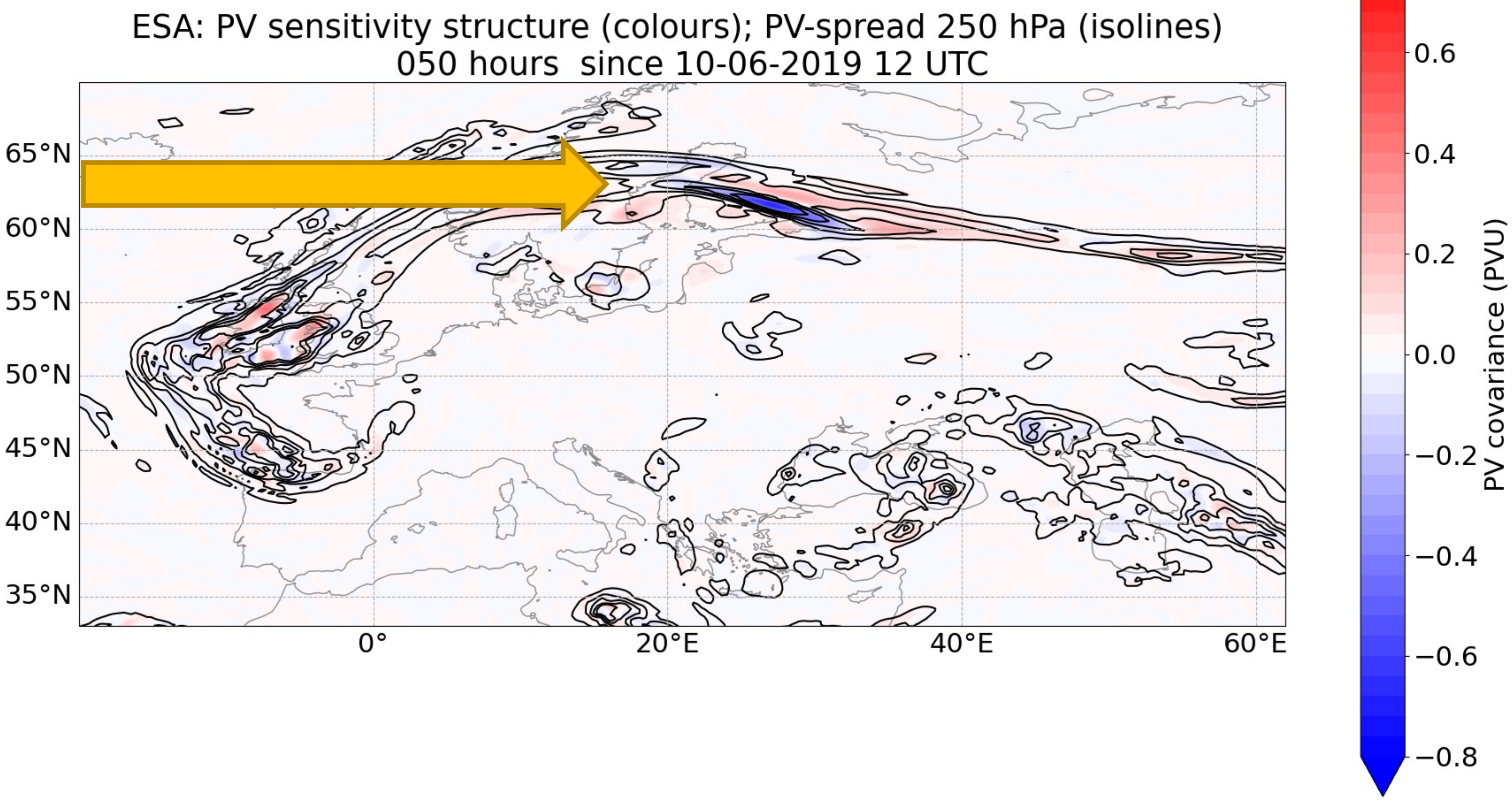


“Day 2 system” +44 h


ESA: PV sensitivity structure (colours); PV-spread 250 hPa (isolines)
044 hours since 10-06-2019 12 UTC



“Day 2 system” +50 h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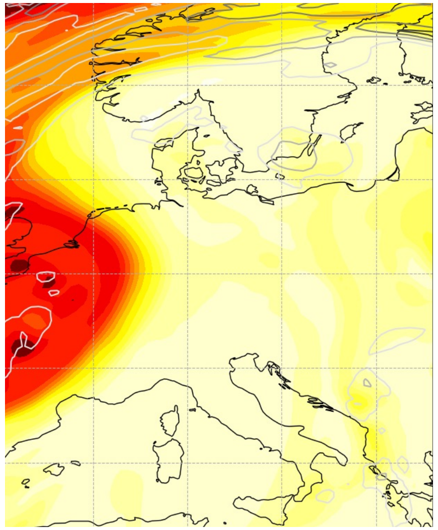
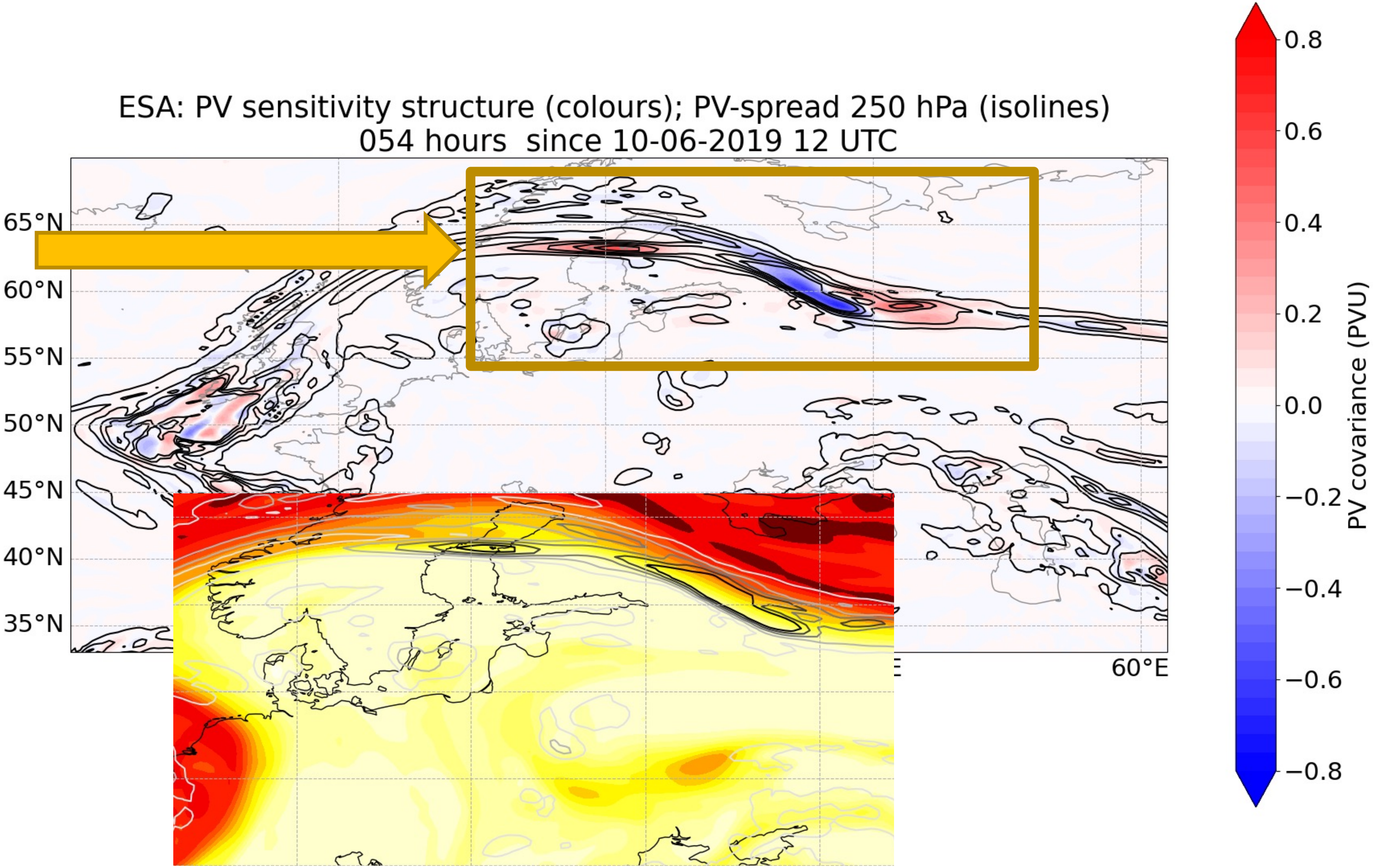
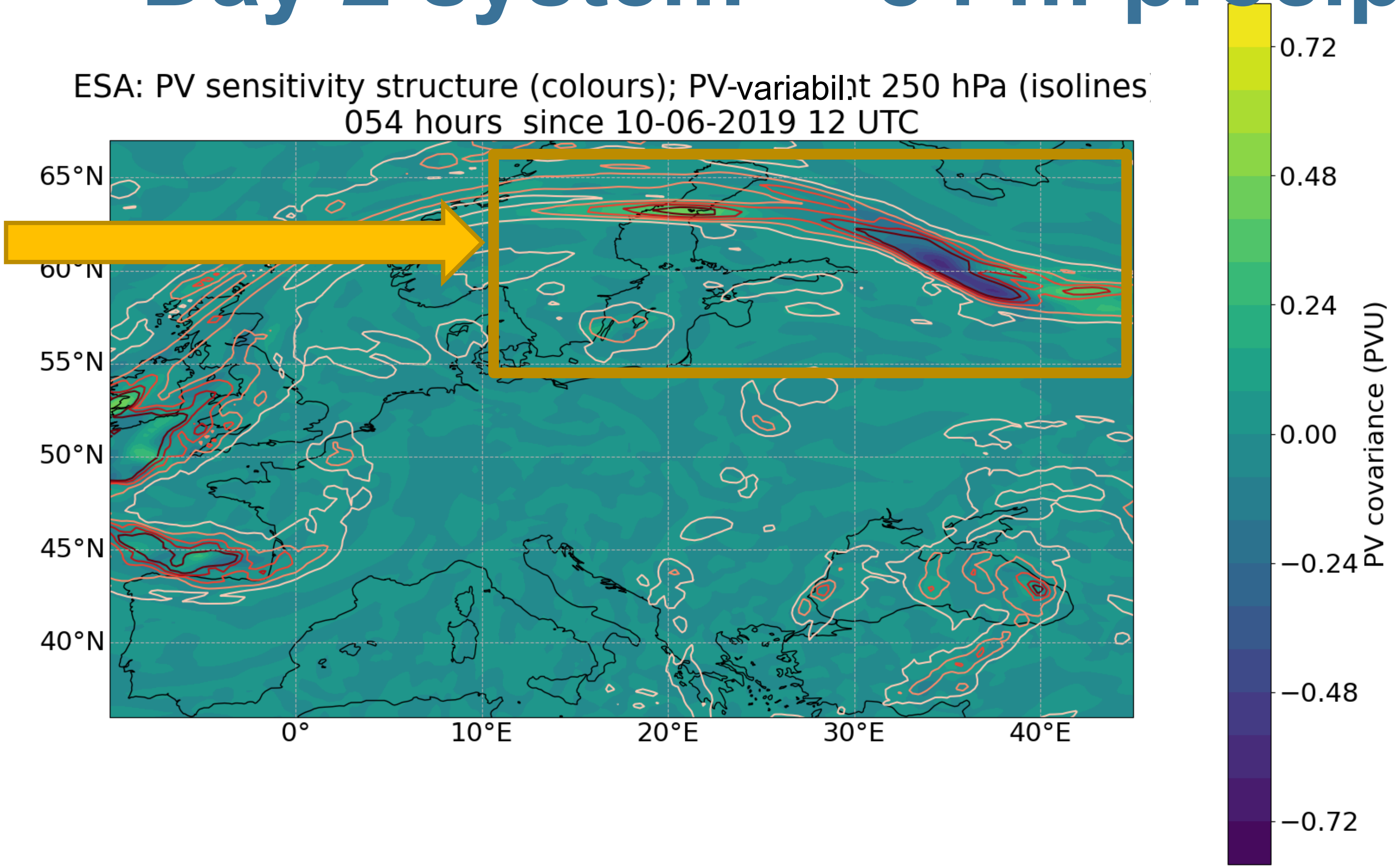




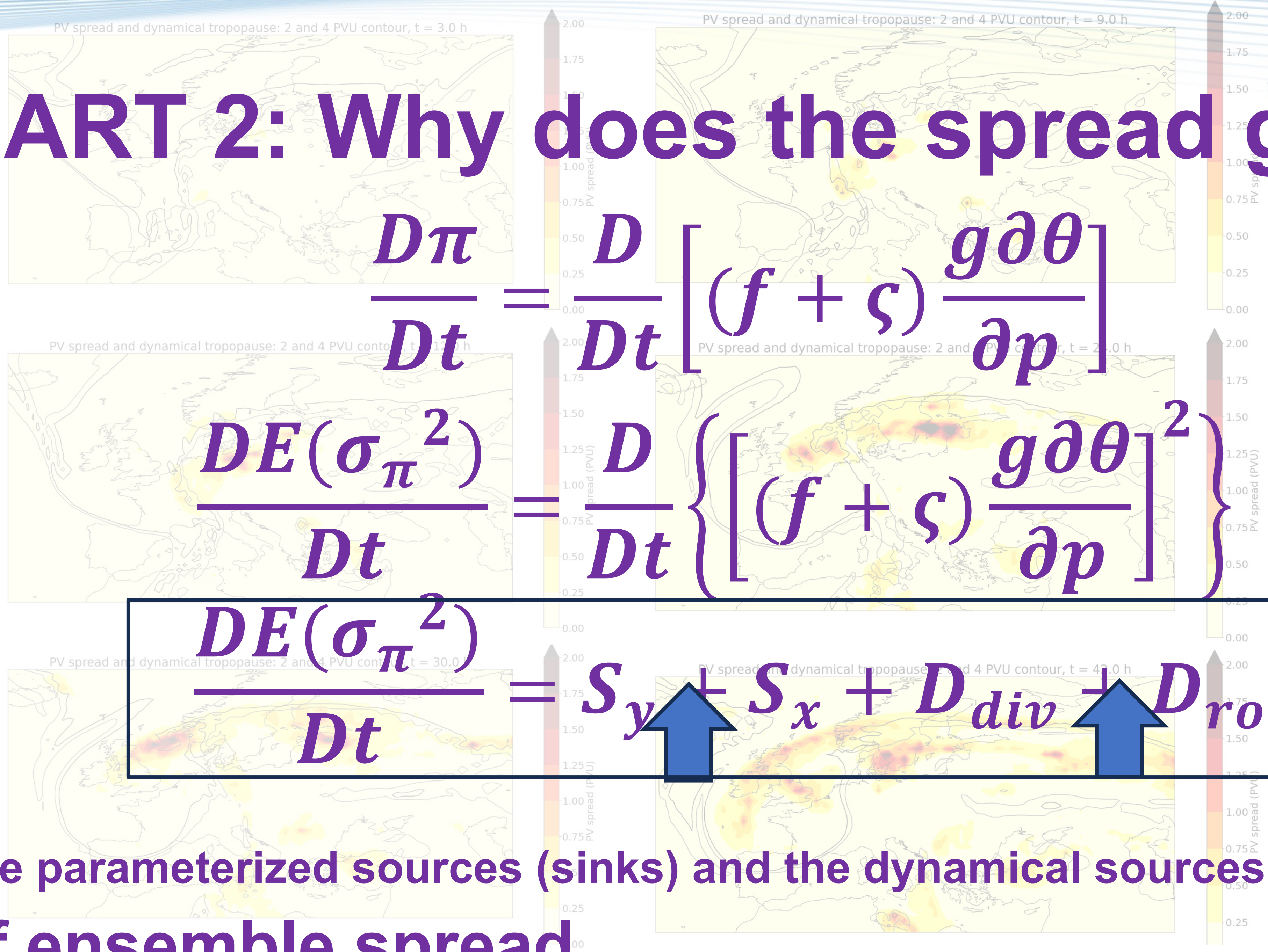
ESA: PV sensitivity structure (colours); PV-spread 250 hPa (isolines)
054 hours since 10-06-2019 12 UTC

“Day 2 system” +54 h: precipitation rate



ESA: PV sensitivity structure (colours); PV-variabilit 250 hPa (isolines
054 hours since 10-06-2019 12 UTC

PART 2: Why does the spread grow?



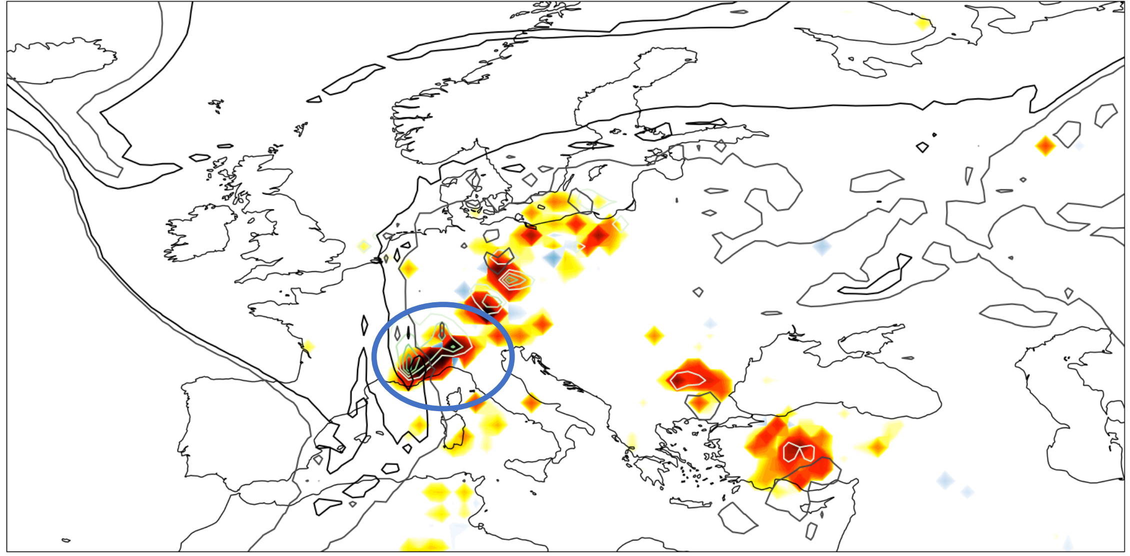
$$\frac{D\pi}{Dt} = \frac{D}{Dt}\left[(f+\varsigma)\frac{g\partial\theta}{\partial p}\right]$$

$$\frac{DE({\sigma_\pi}^2)}{Dt} = \frac{D}{Dt}\left\{\left[(f+\varsigma)\frac{g\partial\theta}{\partial p}\right]^2\right\}$$

$$\boxed{\frac{DE({\sigma_\pi}^2)}{Dt} = S_y \Uparrow + S_x + D_{div} + \Uparrow D_{rot}}$$

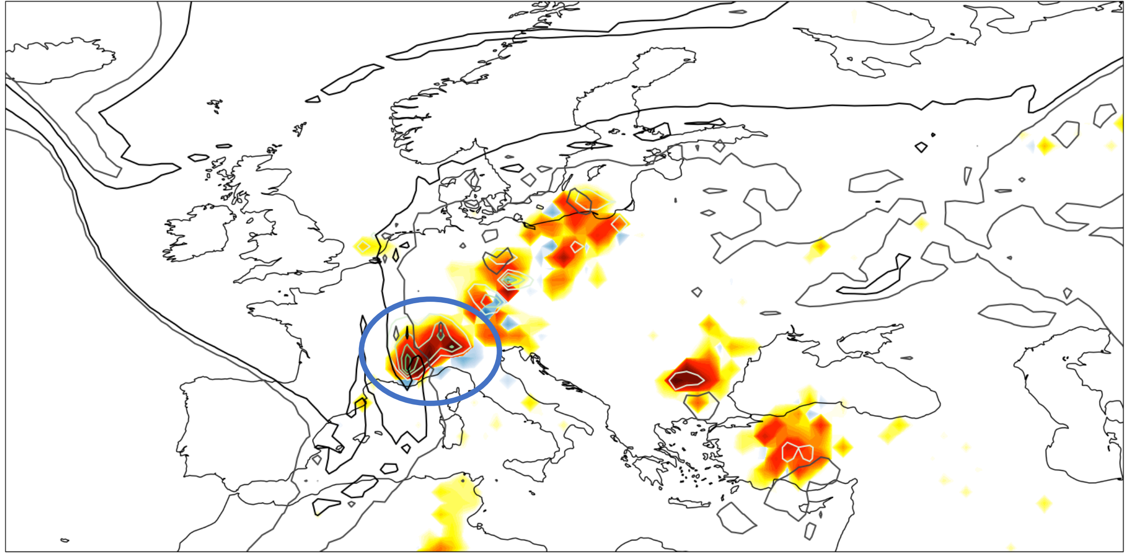
The parameterized sources (sinks) and the dynamical sources (sinks) <u>of ensemble spread</u>

T_{conv}, 3hr mean enstrophy tendency, t = 6.0 h



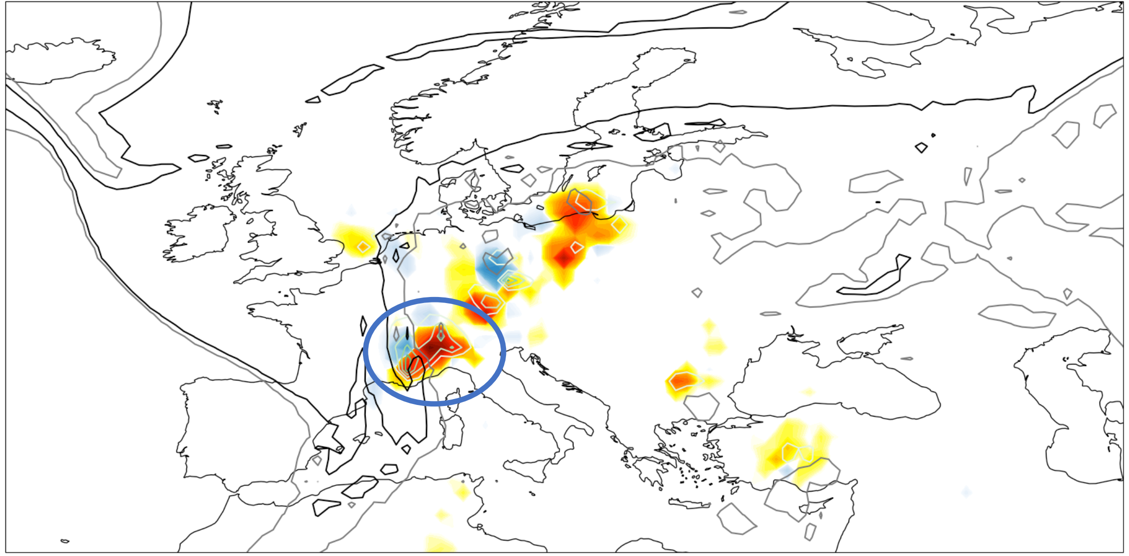
Convective heating

T_{lw}, 3hr mean enstrophy tendency, t = 6.0 h



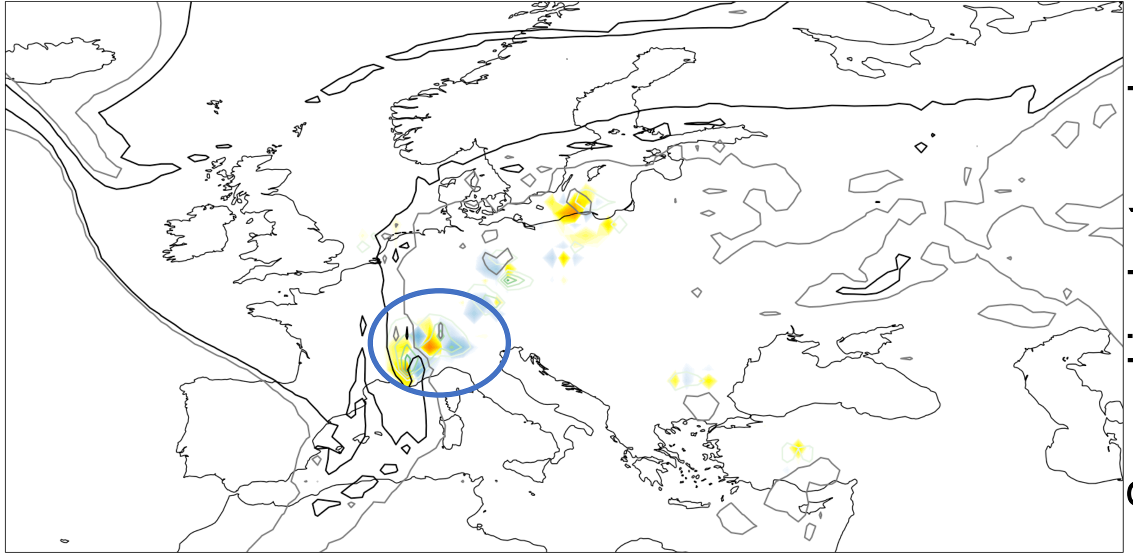
Longwave radiation

T_{div}, 3hr mean enstrophy tendency, t = 6.0 h

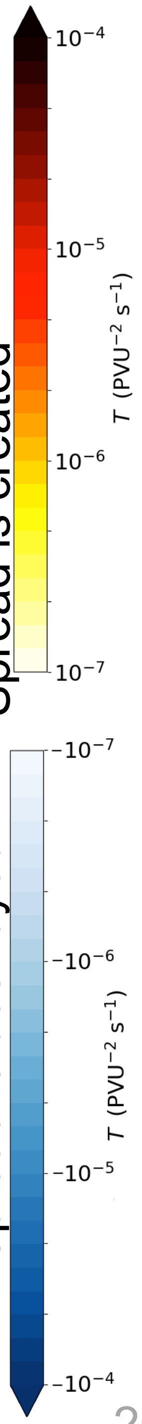


Divergent advection

T_{rot}, 3hr mean enstrophy tendency, t = 6.0 h

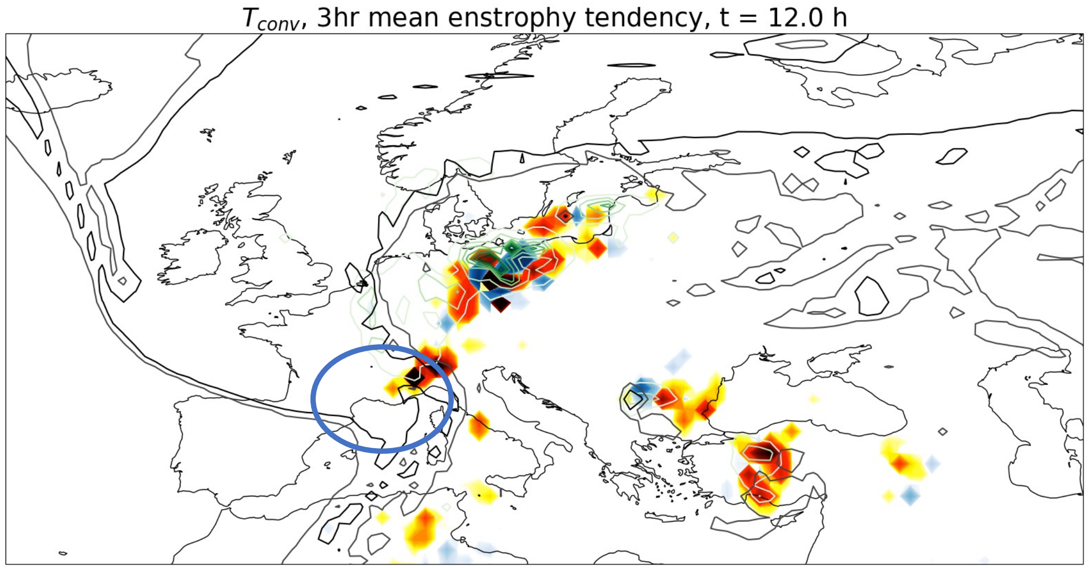


Rotational advection

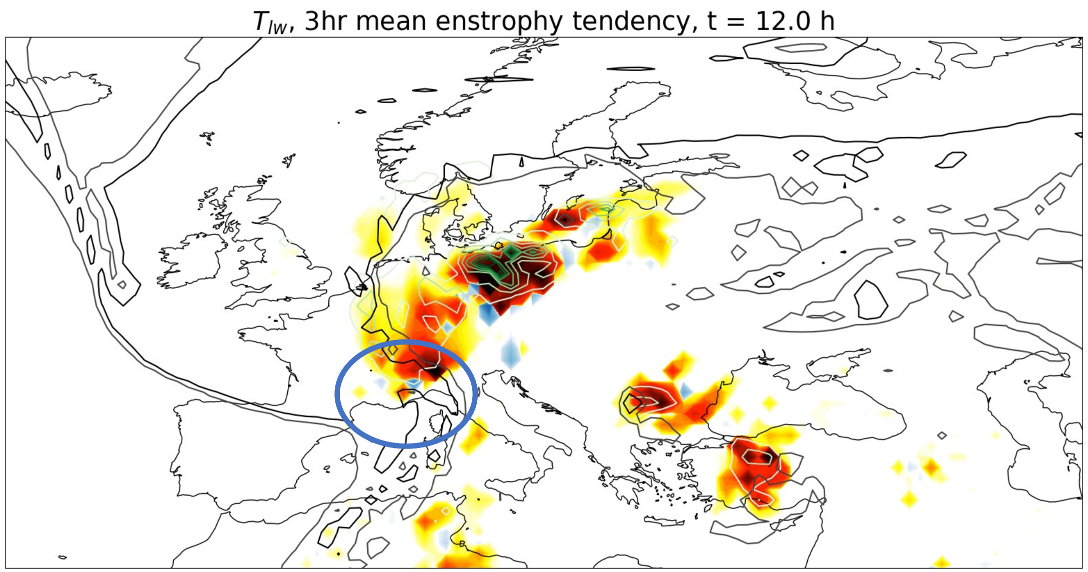


Spread is created

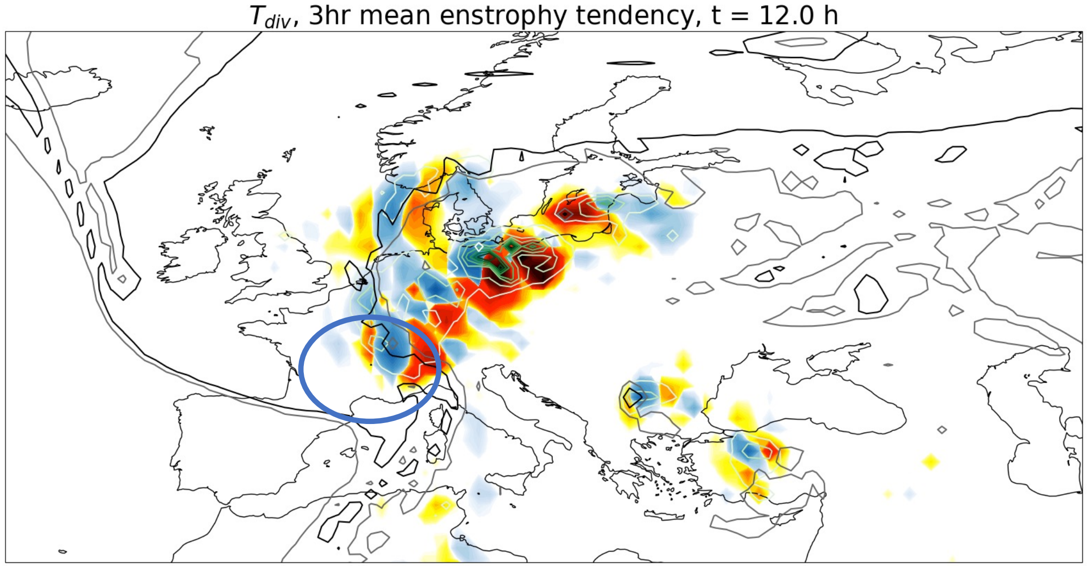
Spread is destroyed



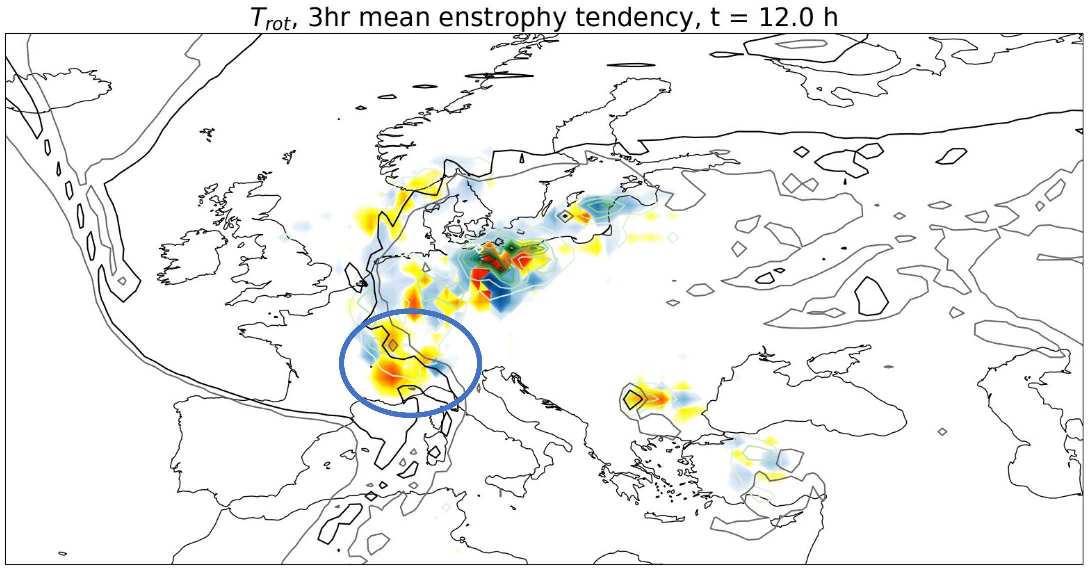
Convective heating



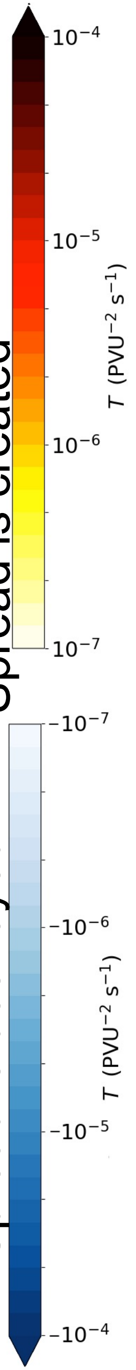
Longwave radiation



Divergent advection



Rotational advection



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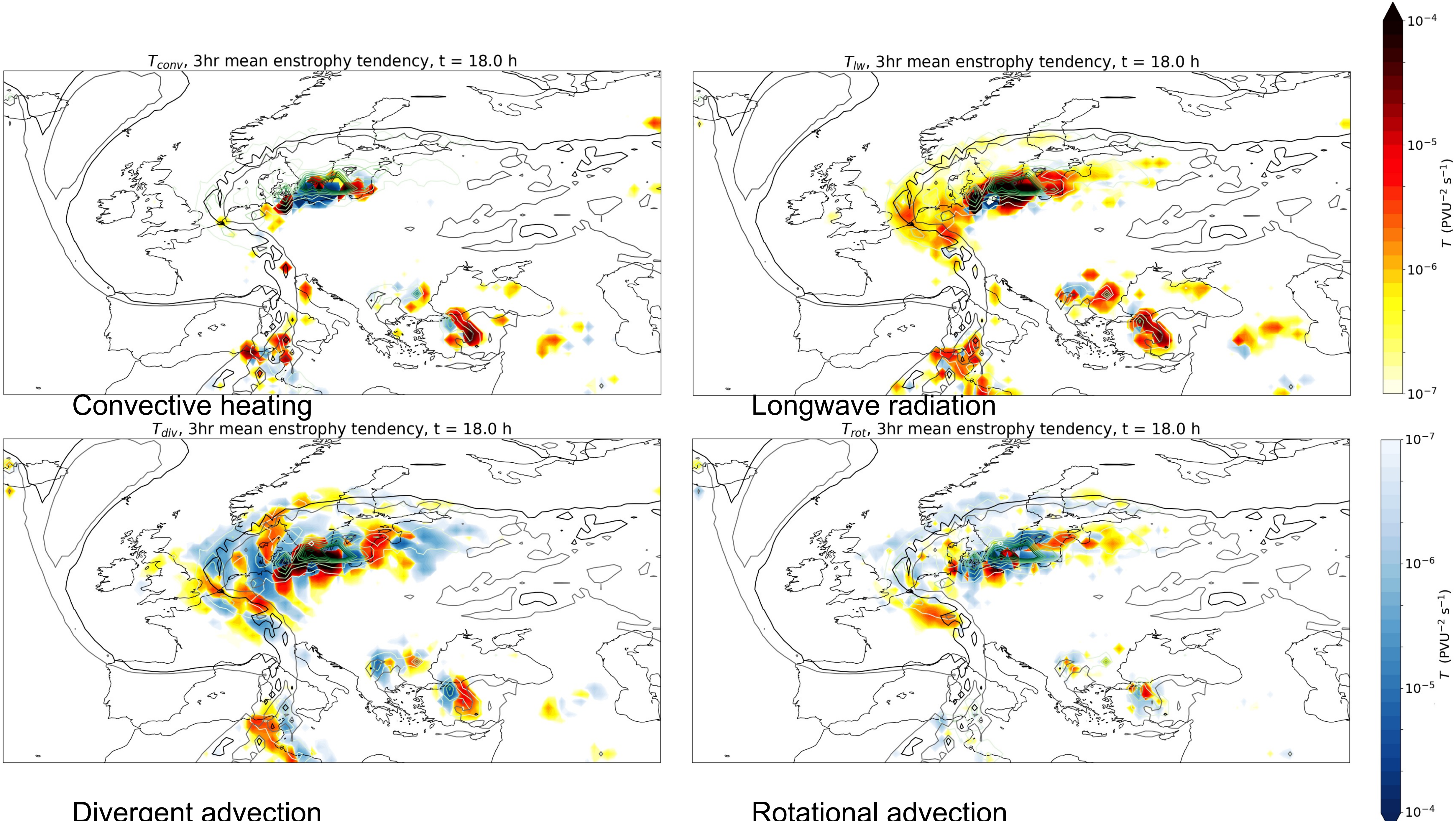


T_{conv}, 3hr mean enstrophy tendency, t = 18.0 h

Convective heating

T_{lw}, 3hr mean enstrophy tendency, t = 18.0 h

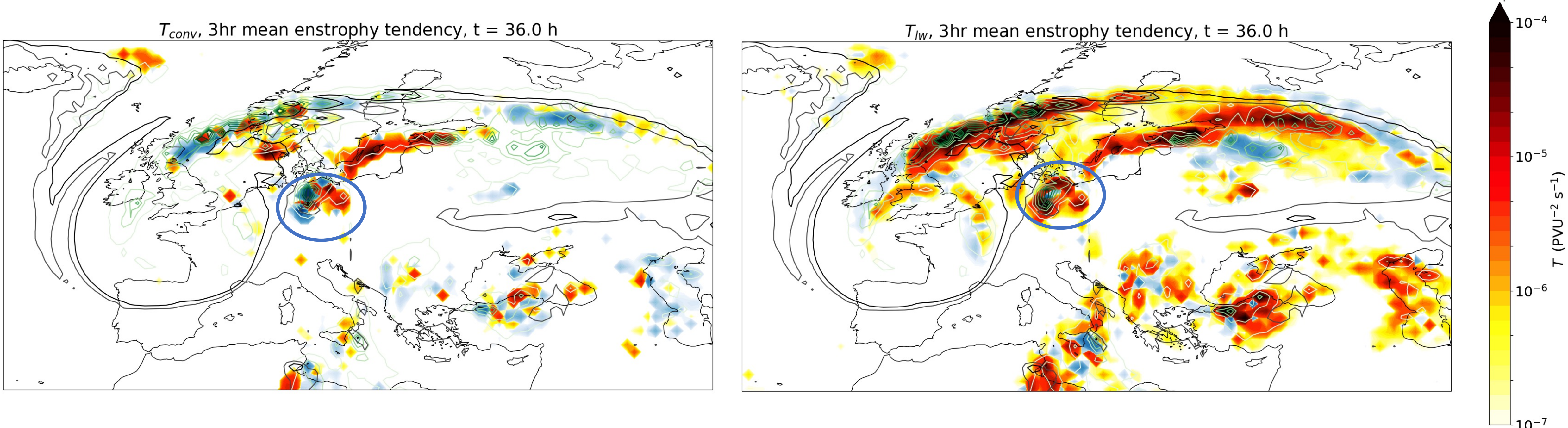
Longwave radiation

T_{div}, 3hr mean enstrophy tendency, t = 18.0 h

Divergent advection

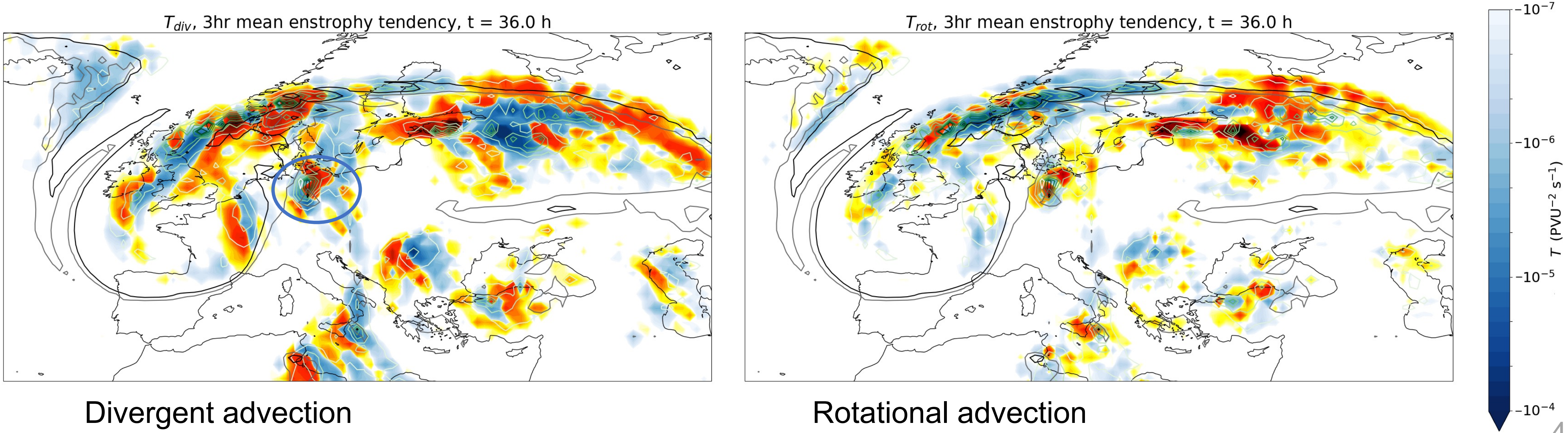
T_{rot}, 3hr mean enstrophy tendency, t = 18.0 h

Rotational advection



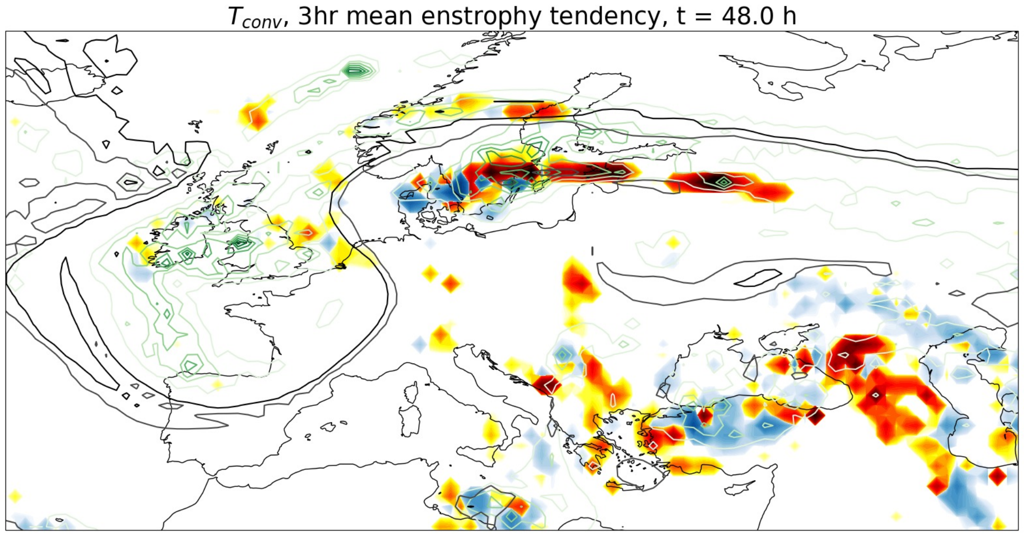
Convective heating

Longwave radiation

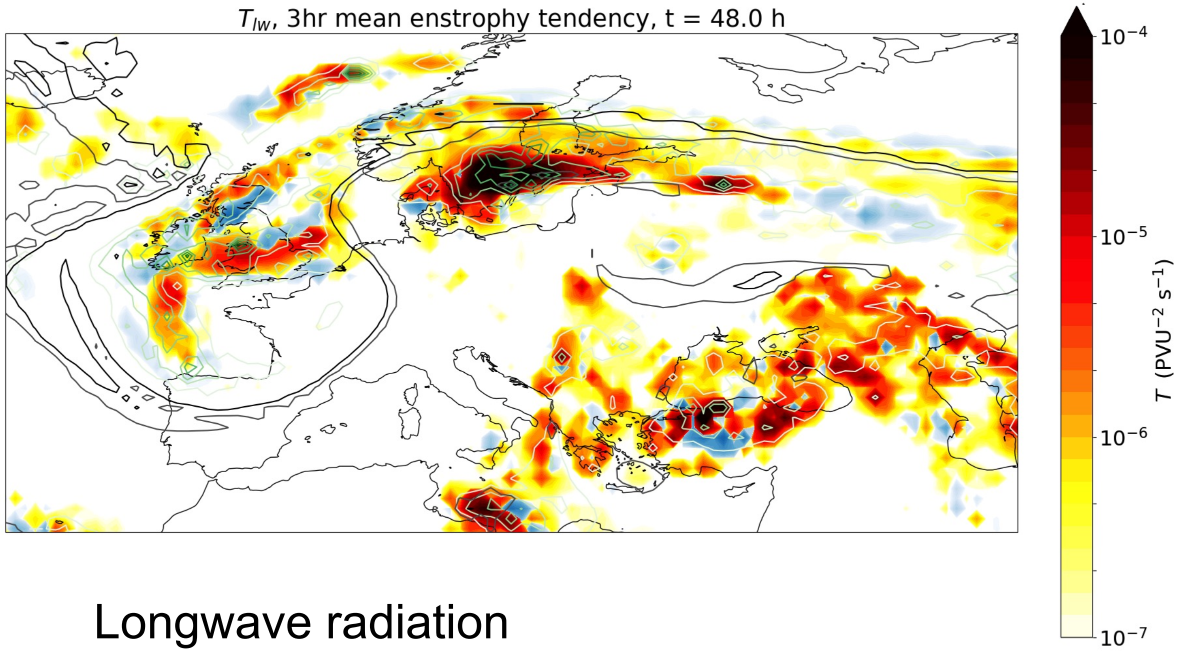


Divergent advection

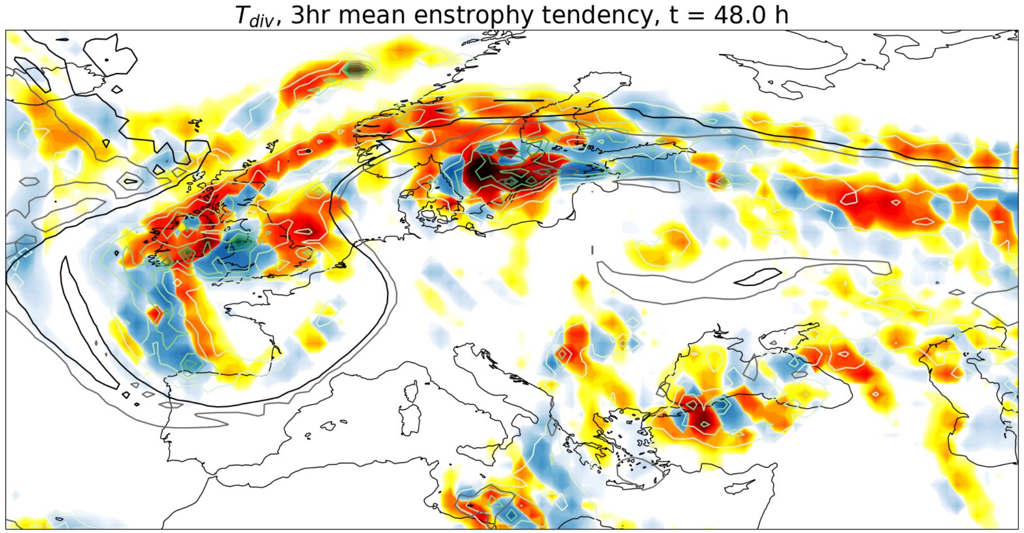
Rotational advection



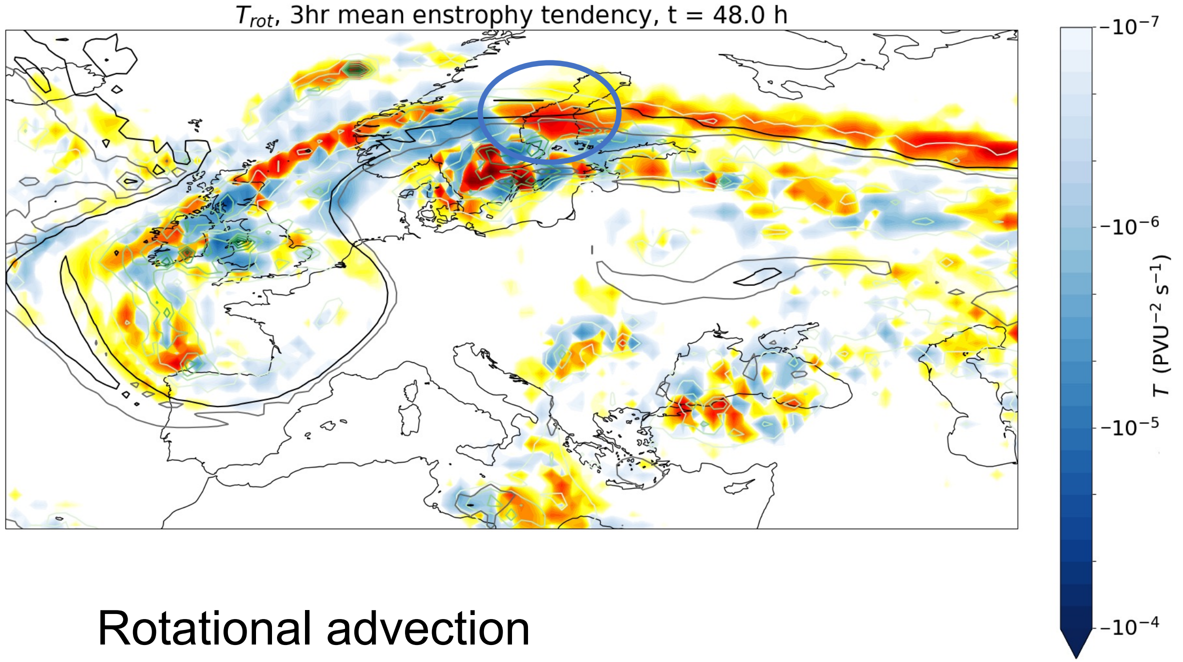
Convective heating



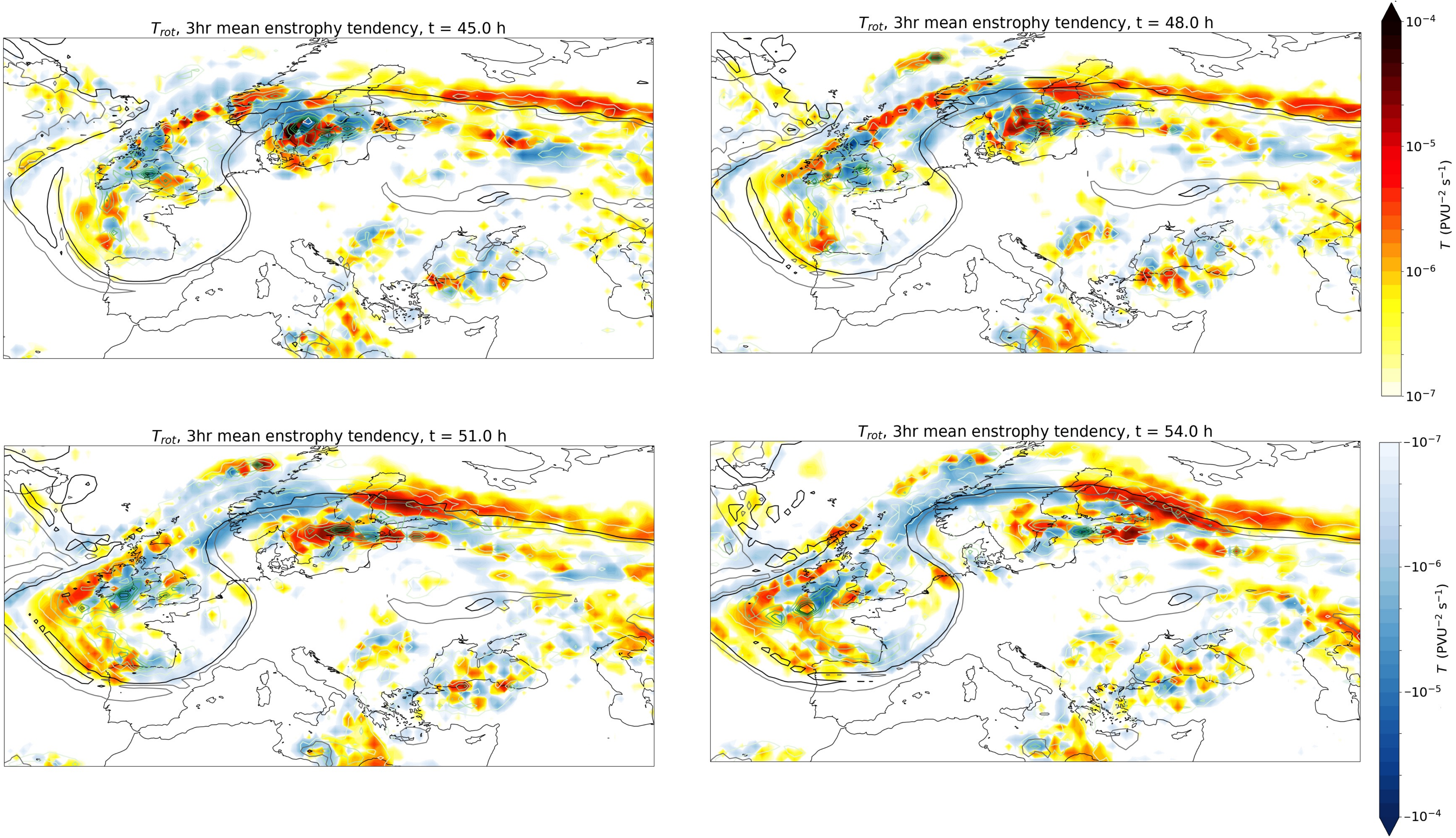
Longwave radiation



Divergent advection



Rotational advection


T_{rot}, 3hr mean enstrophy tendency, t = 45.0 h
T_{rot}, 3hr mean enstrophy tendency, t = 48.0 h
T_{rot}, 3hr mean enstrophy tendency, t = 51.0 h
T_{rot}, 3hr mean enstrophy tendency, t = 54.0 h
10^{-4}
10^{-5}
10^{-6}
10^{-7}
T (PVU^{-2} s^{-1})
-10^{-7}
-10^{-6}
-10^{-5}
-10^{-4}
T (PVU^{-2} s^{-1})

Summary & conclusions II

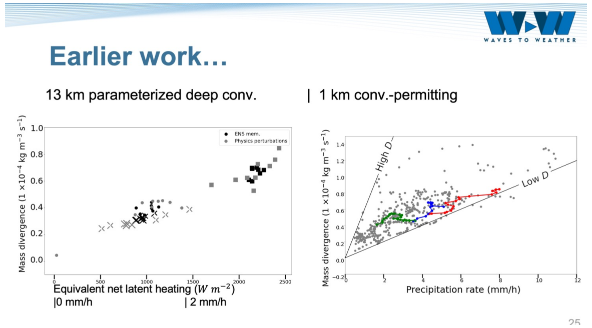
Jet stream winds in an <u>underdispersed ensemble</u> are sensitive to convective variability, where

- Small uncertainties in precipitation can rapidly induce forecast uncertainty downstream
- Convective latent heating/mass divergence variability can **<u>but does not always</u>** propagate downstream and upscale
- Combining two methods enables us to quantify and attribute forecast uncertainty

Take home messages

Modelling of deep convection

- Representation of convective outflow variability is more advanced at higher resolution

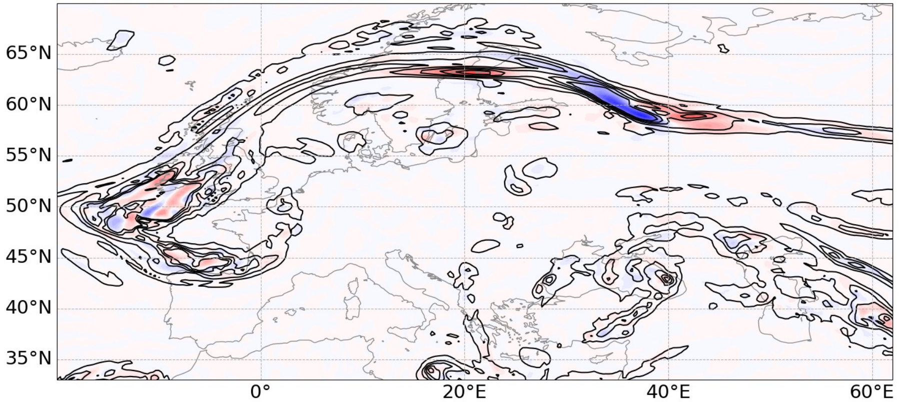


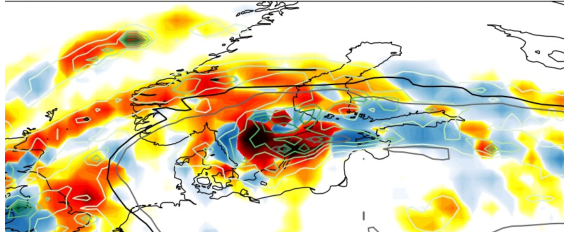
Earlier work…

13 km parameterized deep conv. | 1 km conv.-permitting

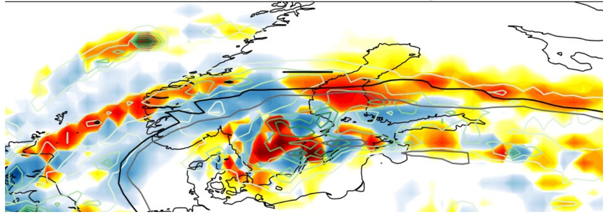
Downstream effect of deep convection

- Convective variability can **<u>but does not always</u>** propagate downstream and upscale





T_{div}, 3hr mean enstrophy tendency, t = 48.0 h



T_{rot}, 3hr mean enstrophy tendency, t = 48.0 h

Thank you for your attention!