Cold-pool-driven convective initiation and its representation in convection-permitting models

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1) Summary in text form

2) Presentation

Convective cold pools are volumes of negatively buoyant air that originate from precipitating downdraughts. Evaporation of precipitation in the sub-cloud layer, combined with the weight of the condensed water, creates negative buoyancy and accelerates the downdraught. When these cold, moist air masses hit the surface, they spread in near-circular patterns, often led by a gust front, where lifting fosters the initiation of new convection.
Cold pools are essential for organizing convection and play a particular role in convective initiation in the afternoon and evening. Both aspects are deficient in current convection-permitting models and a better understanding and representation of cold pools is likely necessary to overcome these deficiencies.

In a recent publication (Hirt et al., 2020), we detected cold pools and convective initiation within hectometer simulations for four days over Germany (ICON-LEM, HDCP2 simulations) and identified several sensitivities of cold-pool-driven convective initiation to model resolution. Mostly, cold pools are more frequent, smaller and less intense in lower-resolution simulations and their gust fronts are weaker and less likely to trigger new convection. Using a causal graph analysis, we were able to estimate the relevance of several indirect effects, as displayed in Fig 1.
We identify one single dominant pathway (the RGP path): a reduced model resolution (R) directly causes gust front upward massflux (G) to be weaker which then also reduces convective initiation (P). Pathways involving cold pool intensity or buoyancy anomaly were found to be unimportant. It is particularly the cold pool gust fronts that are too weak in km-scale models to trigger sufficient, new convection.

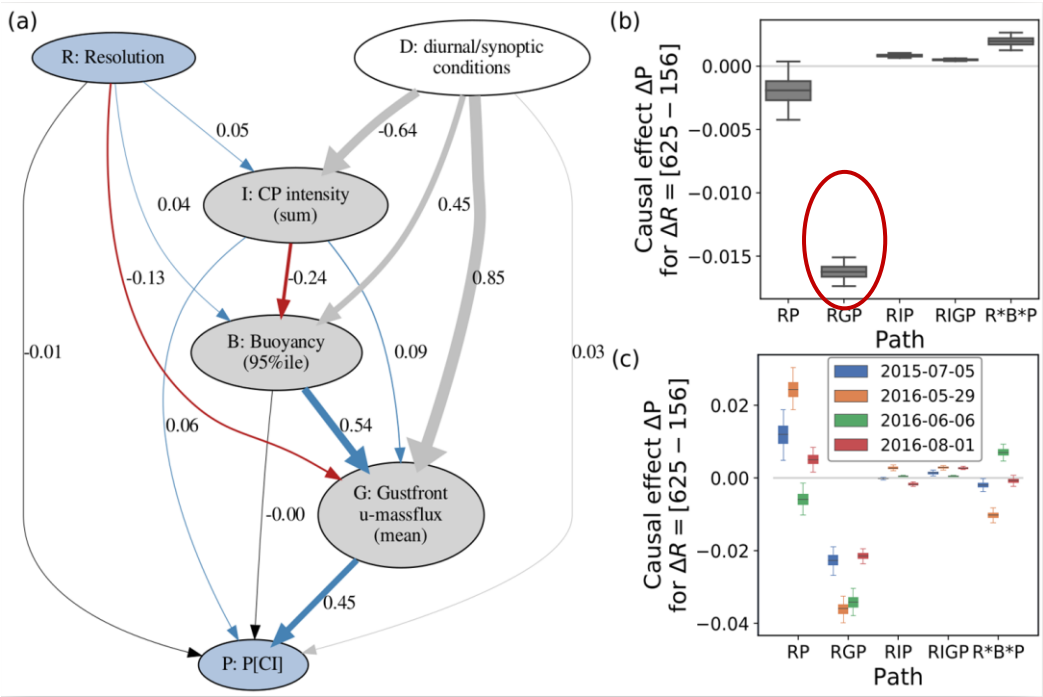

Figure 1: (a) Causal graph with estimated causal effects (normalized) to understand how model resolution (R) impacts cold-pool-driven convective initiation (P). (b) De-normalized causal effects of different pathways from model resolution (R) to convective initiation (P). (c) as (b), but the

causal analysis is applied for the four considered days separately. As (b) shows, the RGP path dominates. Further details can be found in Hirt et al. (2020).

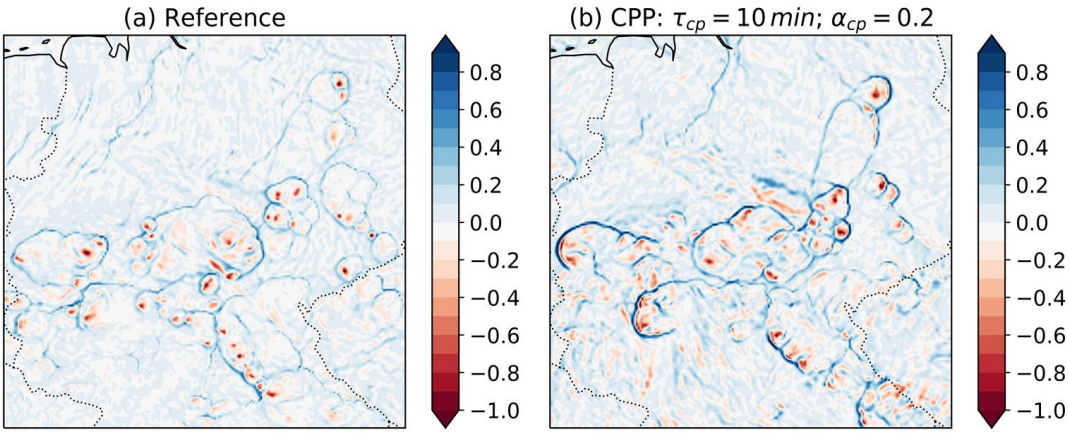

Figure 2 *Vertical velocity for an unperturbed reference simulation (a) and a perturbed, CPP simulation (b) with COSMO is displayed. Fields are displayed for the 5th model level (~200m) above surface at 15 UTC and a selected region with several cold pool gust fronts over central Germany.*

To address this deficiency, we develop a parameterization for the convection-permitting COSMO model to improve the representation of cold pool gust fronts, the CPP scheme. A target vertical velocity scale for cold pool gust fronts is derived using dimensional analysis and approximated based on local buoyancy gradients. Vertical velocity perturbations were then imposed so that the model vertical velocity at cold pool gust fronts converges towards this target scale. In addition, horizontal wind components were perturbed in a 3d non-divergent manner as in Hirt et al. 2019. Our results show that cold pool gust fronts are indeed strengthened by CPP (Fig. 2) and - to all appearances - enhances cold pool driven convective initiation. As anticipated, the late afternoon/evening precipitation is improved for weakly forced situations (Fig. 3, amplitude and Fraction Skill Score) and indications for enhanced organization were found.
In addition, we evaluated the combination of CPP with PSP2, a physically based, stochastic perturbation scheme to account for variability in boundary layer turbulence (Kober and Craig, 2016, Hirt et al., 2019). Such a combined simulation revealed the benefits of both schemes, with an earlier onset of convection and improved afternoon/evening precipitation (Fig. 3).

Overall, the results from the CPP scheme are promising and the development is still ongoing.

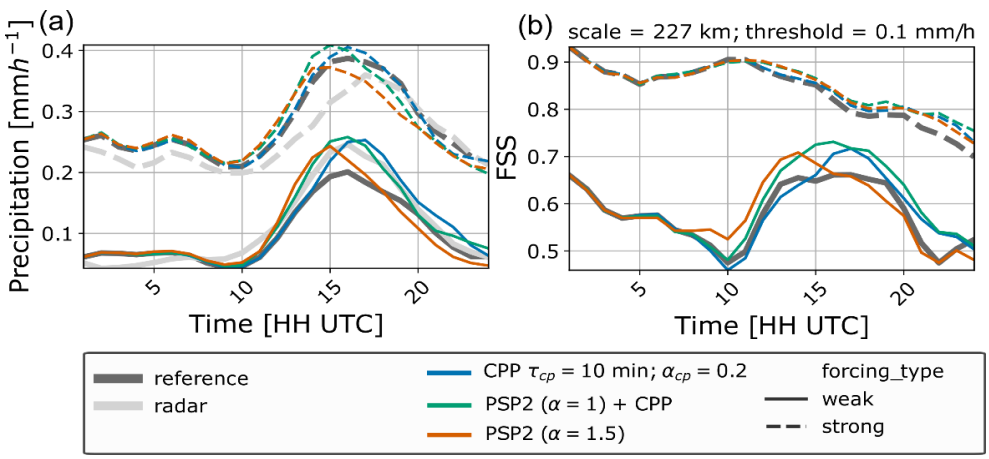

Figure 3 Diurnal evolution of hourly accumulated, domain averaged precipitation (a) and Fraction Skill Score (b) for five weakly forced days and five more strongly forced days (29.5-7.6.2016).

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Hirt, M., S. Rasp, U. Blahak, and G.C. Craig, 2019: Stochastic Parameterization of Processes Leading to Convective Initiation in Kilometer-Scale Models. *Mon. Wea. Rev.*, **147**, 3917–3934, doi:10.1175/MWR-D-19-0060.1

Hirt, M., Craig, G.C., Schäfer, S.A.K., Savre, J. and Heinze, R. (2020), Cold pool driven convective initiation: using causal graph analysis to determine what convection permitting models are missing. *Q J R Meteorol Soc*. Accepted Author Manuscript. doi:10.1002/qj.3788

Cold pool driven convective initiation: How can we improve its representation in km-scale models?

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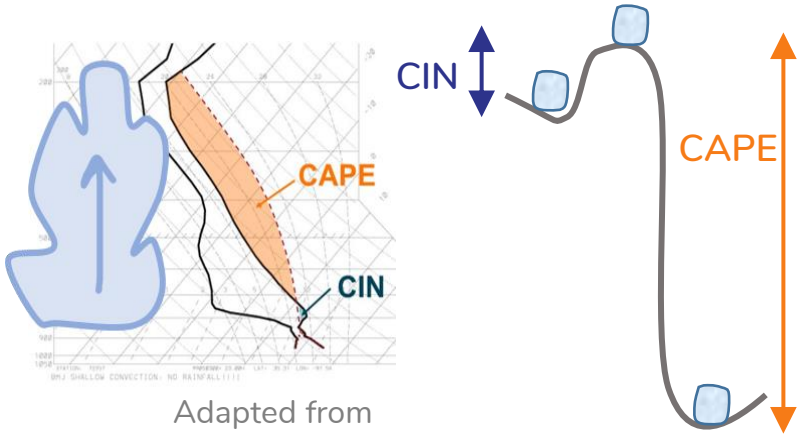
Motivation:

- Km-scale models are now widely used for numerical weather prediction
- Still struggle in capturing **realistic diurnal cycles** and **organization** of convection
- Partially related to **unresolved convection initiation**
- Kober and Craig, 2016 (JAS) and Hirt et al. 2019 (MWR): **Physically based stochastic perturbations (PSP)** for PBL turbulence
- But **organization** and **evening precipitation** is not addressed



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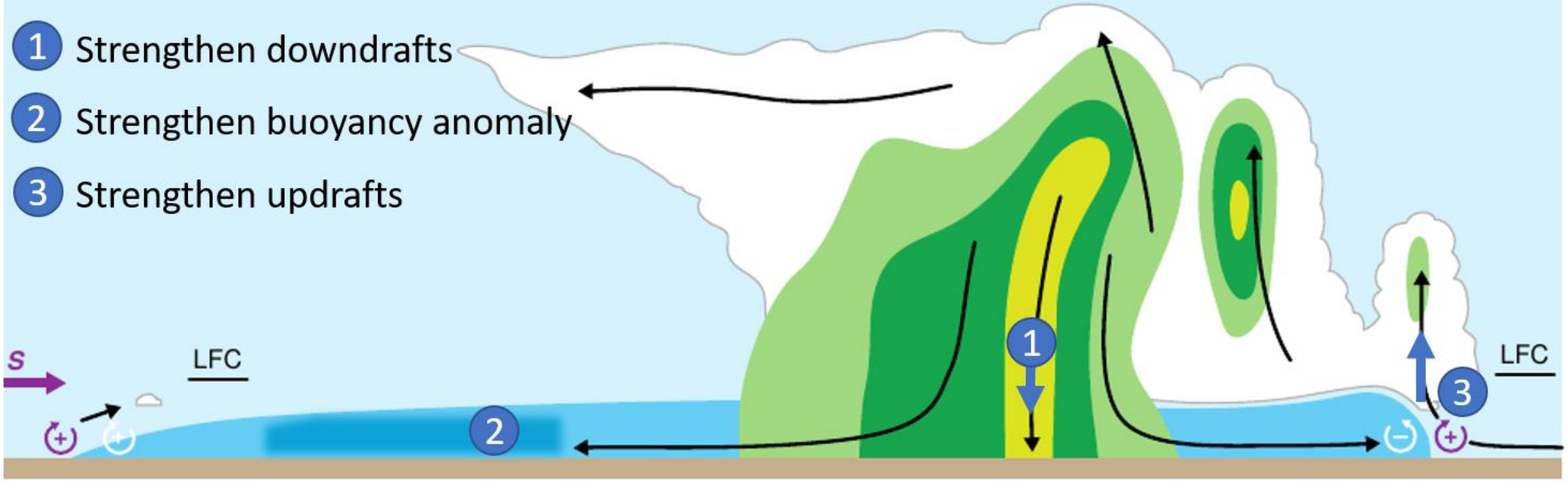
→ Parameterization to account for Cold pool driven convection initiation?

CPP: cold pool perturbations

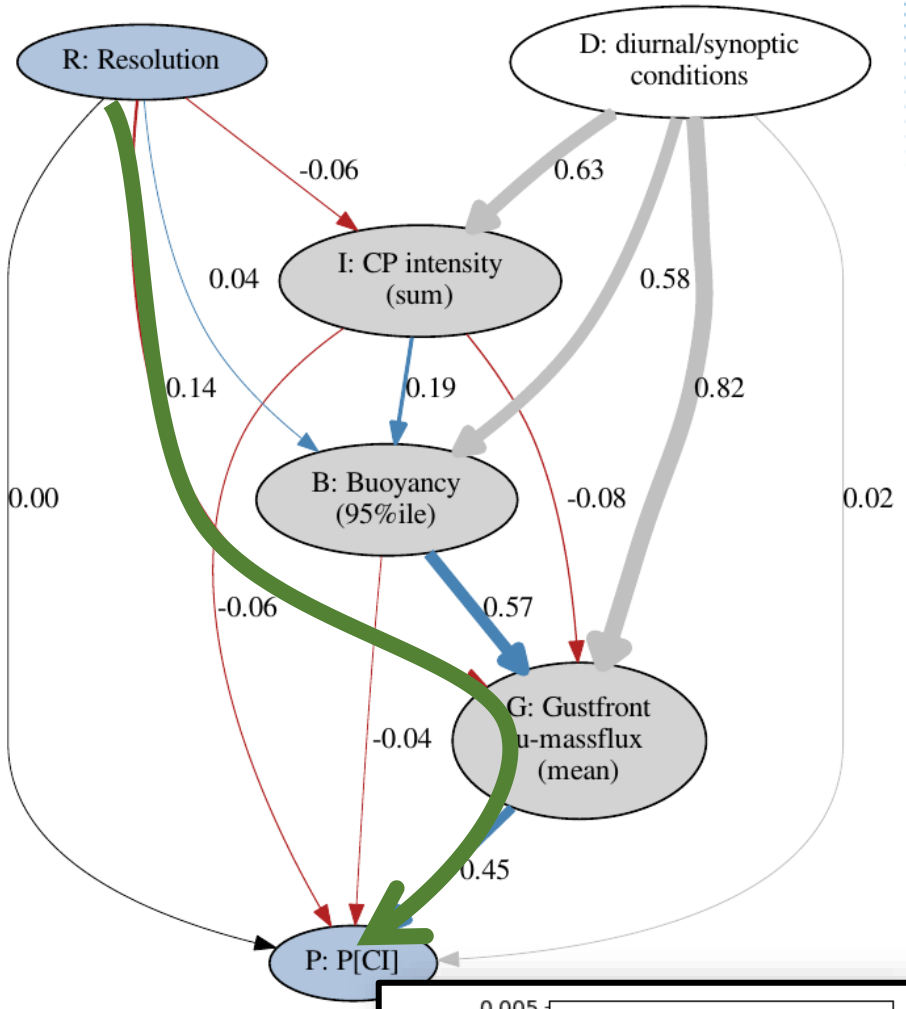


From Markowski and Richardson (2011), modified

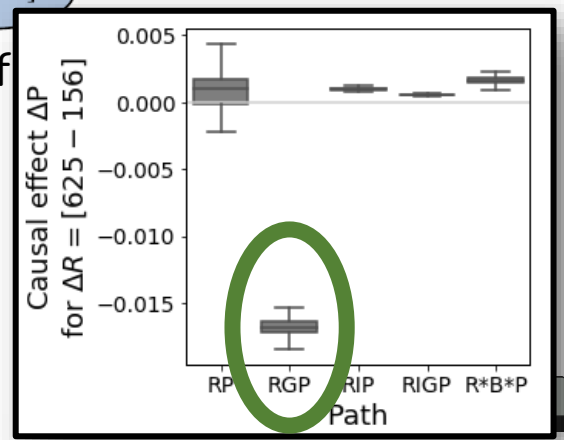
Summary Hirt et al. 2020, QJRMS:

- Cold pools are **more frequent**, **smaller** and **less intense** in lower resolutions (156m – 612m; HDCP2 ICON-LEM simulations).
- Their **gust fronts** are **weaker** and **trigger less** new convection in lower resolutions.
- **Causal graph analysis**: RGB path dominates: Lower model resolution causes weaker gustfronts, which reduces convective initiation.

→**Develop perturbations to strengthen cold pool gust fronts**



Probability of convective initiation



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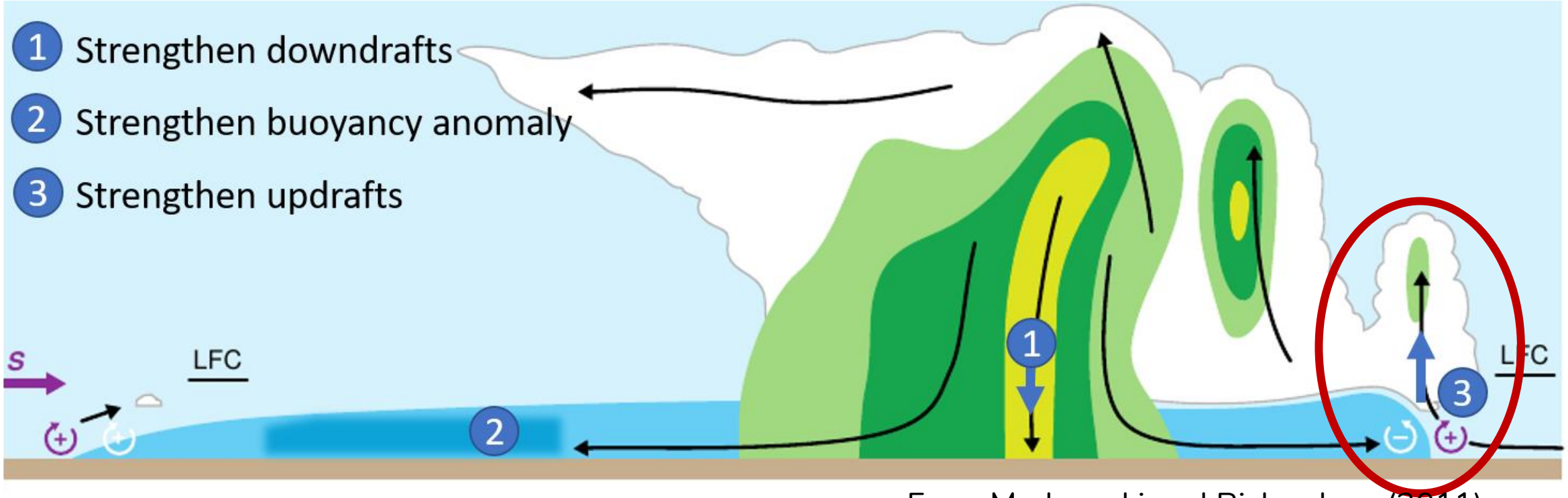
CPP: cold pool perturbations



From Markowski and Richardson (2011), modified

Cold Pool Perturbations (CPP) to strengthen cold pool gust fronts

Theoretical explanation:

- Vorticity – Streamfunction system (xz-plane, inviscous, Boussinesque-approximated)
- Dimensional analysis gives gust front vertical velocity **w**

$$\rightarrow \qquad \mathbf{W} = \sqrt{\frac{\mathbf{BH}}{1+\frac{\mathbf{L}^2}{\mathbf{H}^2}}}$$

B: Cold pool buoyancy

L: horizontal length scale (limited by Δx)

H: vertical length scale

Fully **resolved case**: L/H=1

$$\rightarrow \qquad \mathbf{w_0} = \sqrt{\frac{\mathbf{BH}}{2}}$$

Similar relationships have also been derived for:

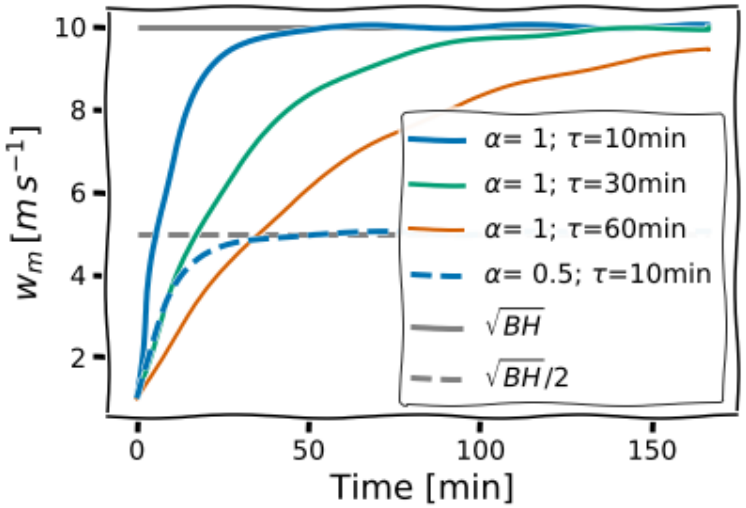
- the horizontal propagation speed of a density current ($\mathrm{U} = \sqrt{2\mathrm{BH}}$)
- Rising warm bubbles (resolution dependency)
  - Jeevanjee 2017, JAMES
  - Morrison 2015, JAS
  - Pauluis and Garner 2006, JAS
  - Weisman et al. 1997, MWR

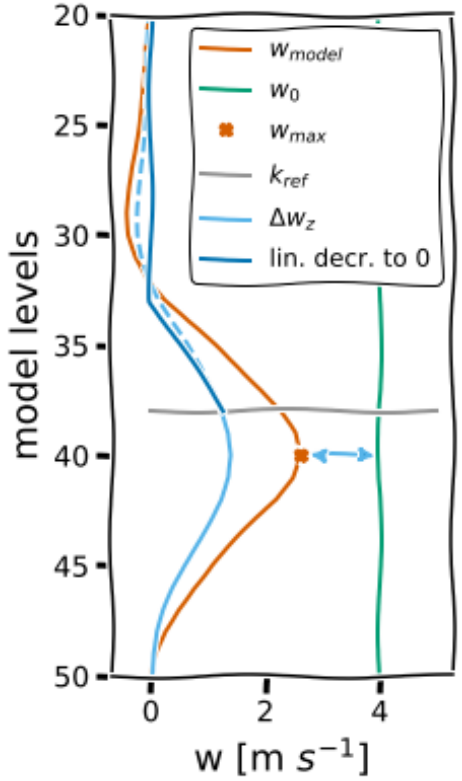
CPP Basic design

- Nudging gust front vertical velocity towards $\mathbf{w_0} = \sqrt{\mathbf{BH}/2}$

$$\left.\frac{\partial w}{\partial t}\right|_{cp} = \frac{w_0 - w}{\tau_{cp}}$$

- Details:
  - Estimation of $\sqrt{BH}$ based on local buoyancy gradients $(B = \frac{|\nabla \bar{\theta}}{\theta}$ $g\ 5\Delta x, H = 200m)$
  - $\boldsymbol{\alpha}_{cp}$ for tuning w_0
  - Vertical profile from model → w_{max}
  - Identifying cold pool gust fronts in the model
  - Time scale τ_{cp} = 10-30 min
  - u, v are perturbed in 3d-non-div. way (see Hirt et al. 2019, MWR)

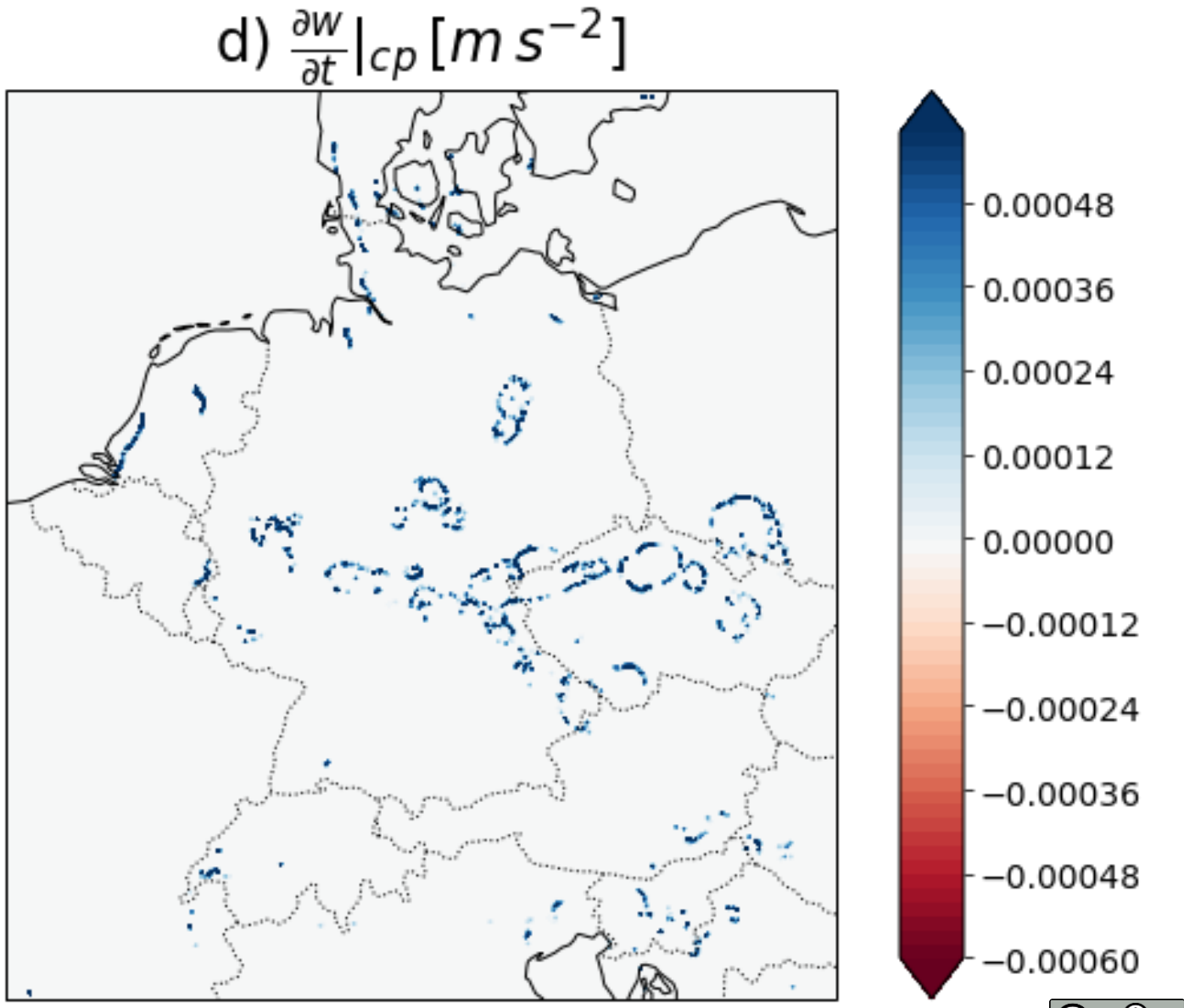




$$\left.\frac{\partial w}{\partial t}\right|_{cp} = \frac{1}{\tau_{cp}} \frac{(\boldsymbol{\alpha}_{cp}\sqrt{BH} - w_{max})}{w_{max}} \cdot w(z)$$

Horizontal constraints to select gust fronts

- $|\nabla\theta_v| >$ threshold
- $w_{max} >$ threshold
- SSO $<$ threshold
- $(w_0 - w_{max}) > 0$

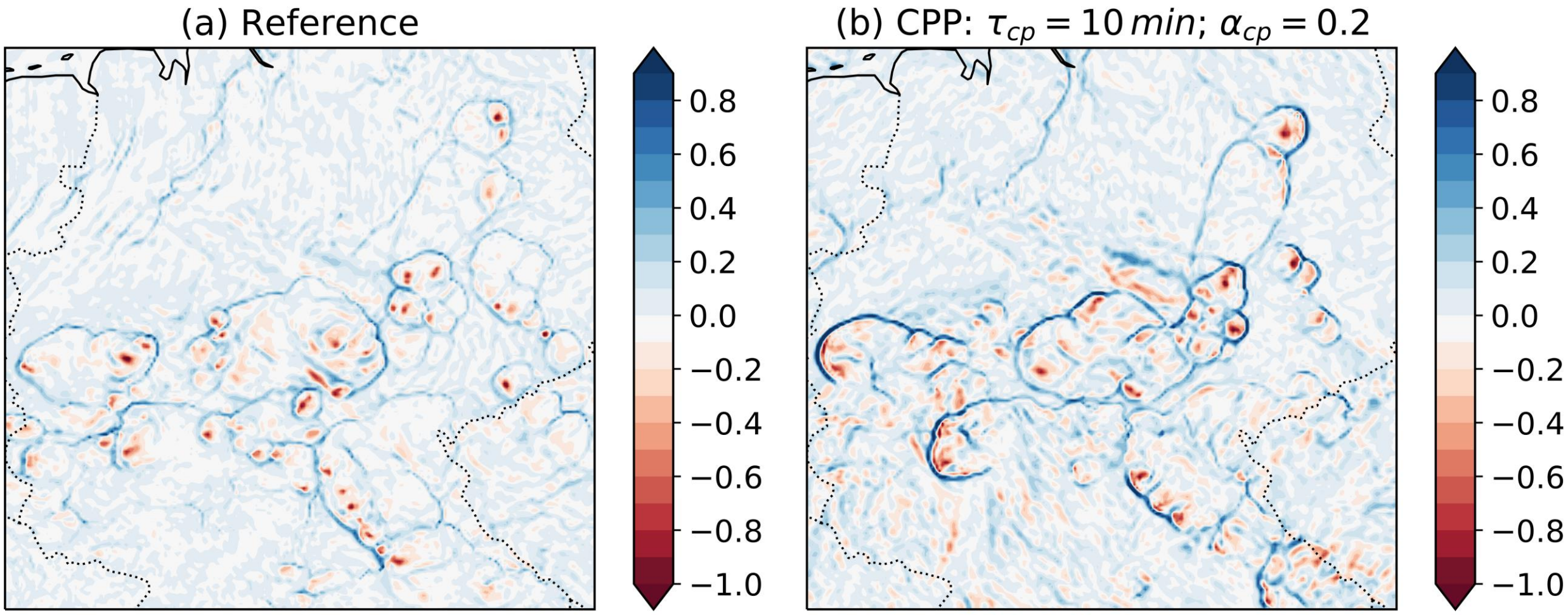


Simulations and model setup

- **COSMO-DE**, $\Delta x = 2.8\ \mathrm{km}$, operational setup (except tur_len=500)
- Test case: **5 June 2016** with many cold pools
- Longer evaluation period: **29 May -7 June 2016**
- 24 h, deterministic simulations

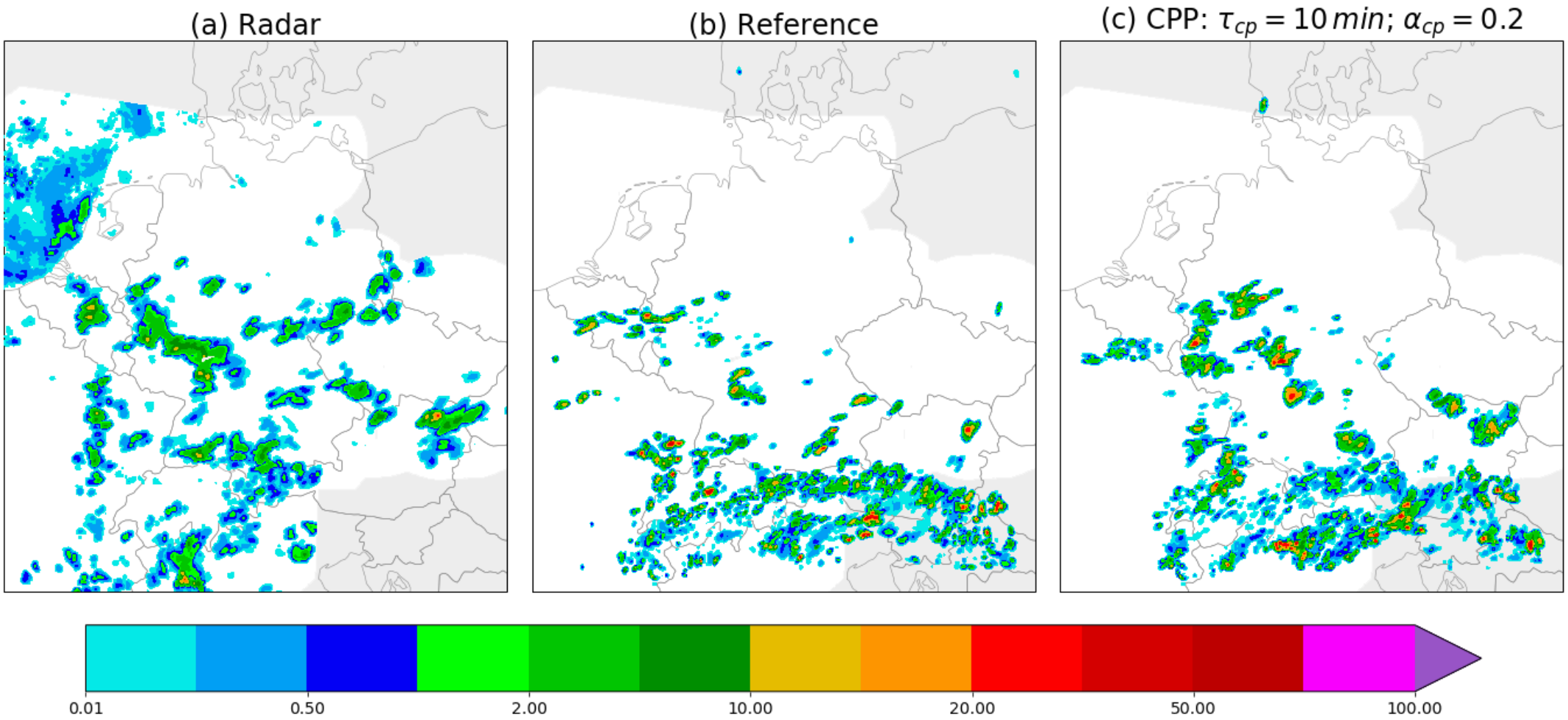
Impact of cold pool perturbations (CPP)

Vertical velocity [m/s]



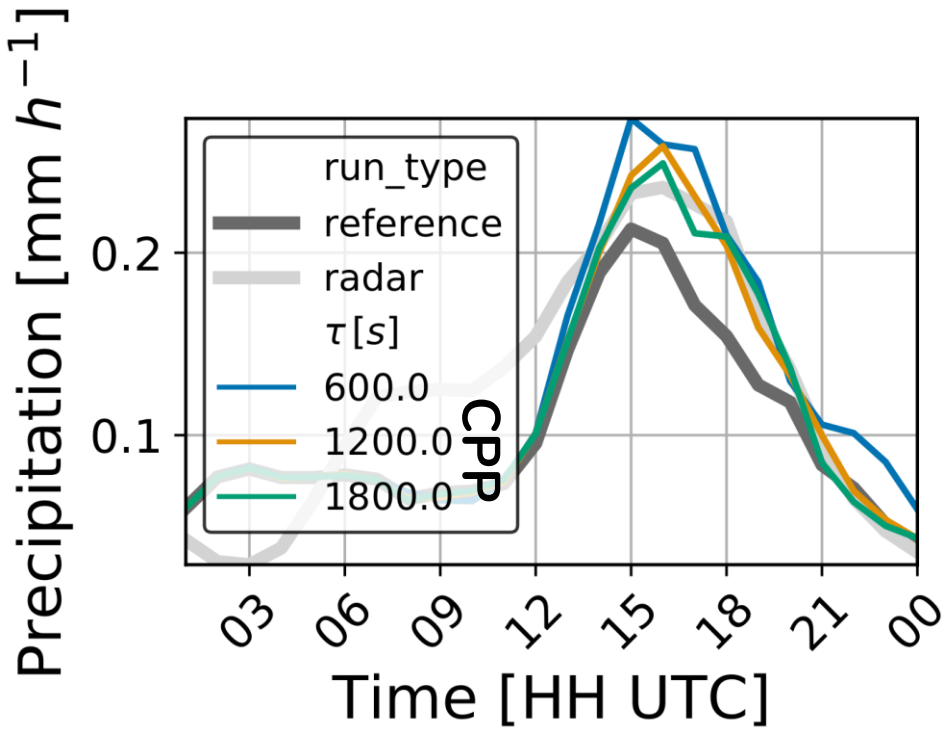
5th level above surface, 15 UTC
5 June 2016, 15:00 UTC

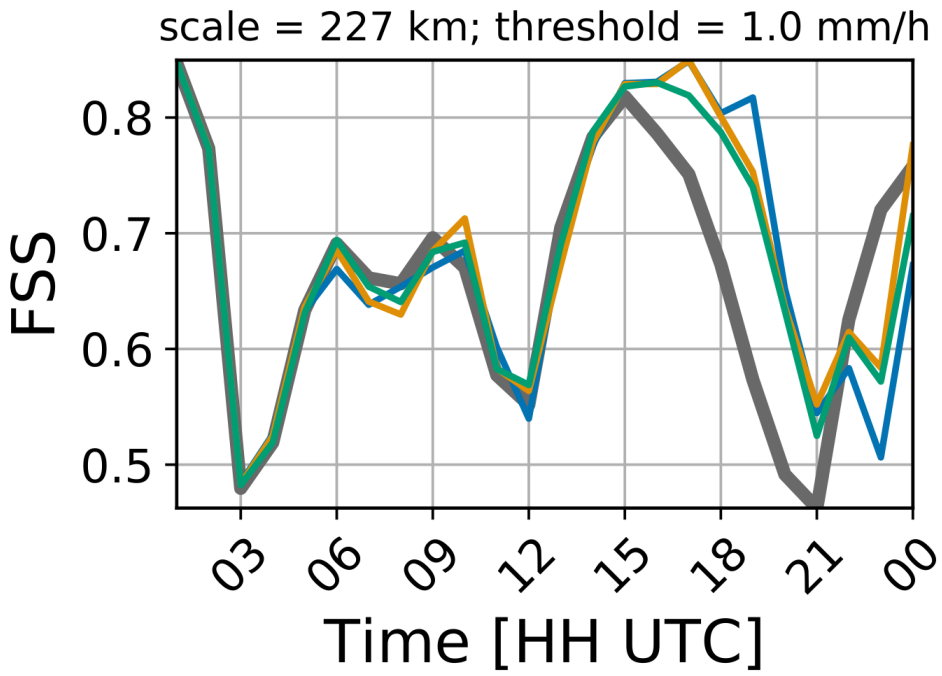
Precipitation [mm/h]

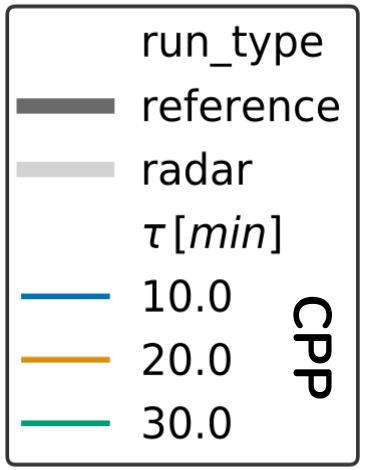


5 June 2016, 19:00 UTC

Precipitation - diurnal cycle

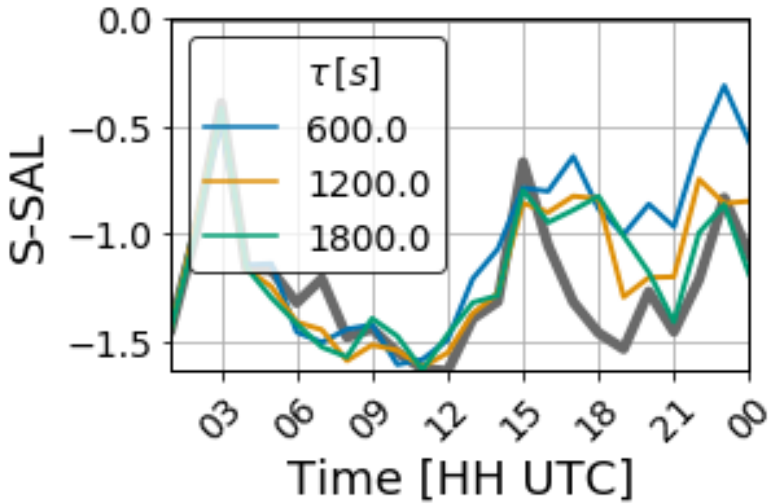


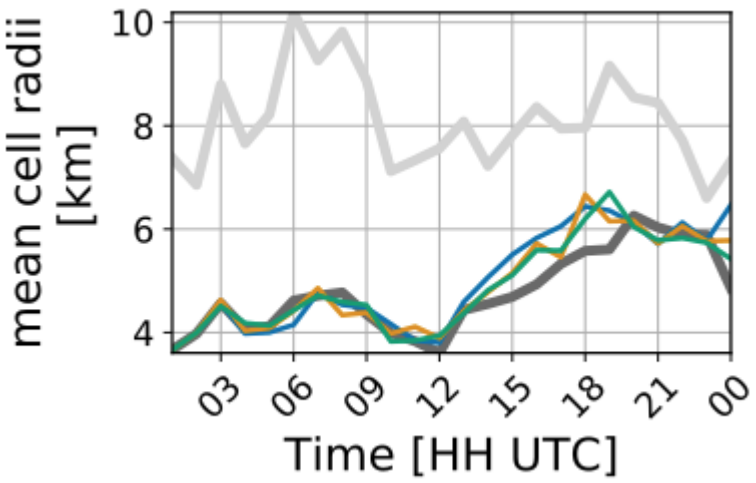


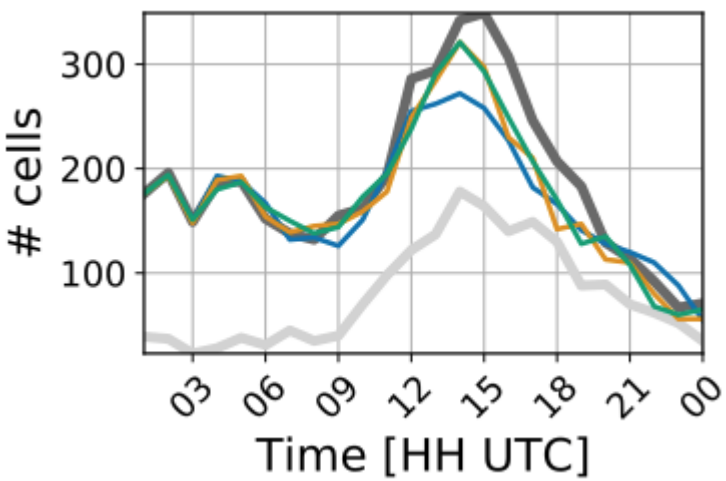


5 June 2016

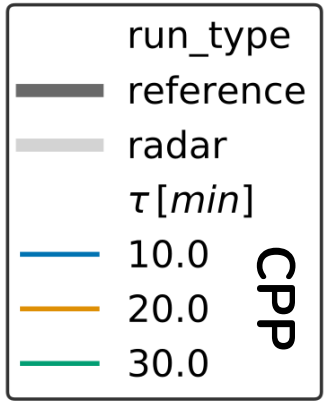
Precipitation - organization



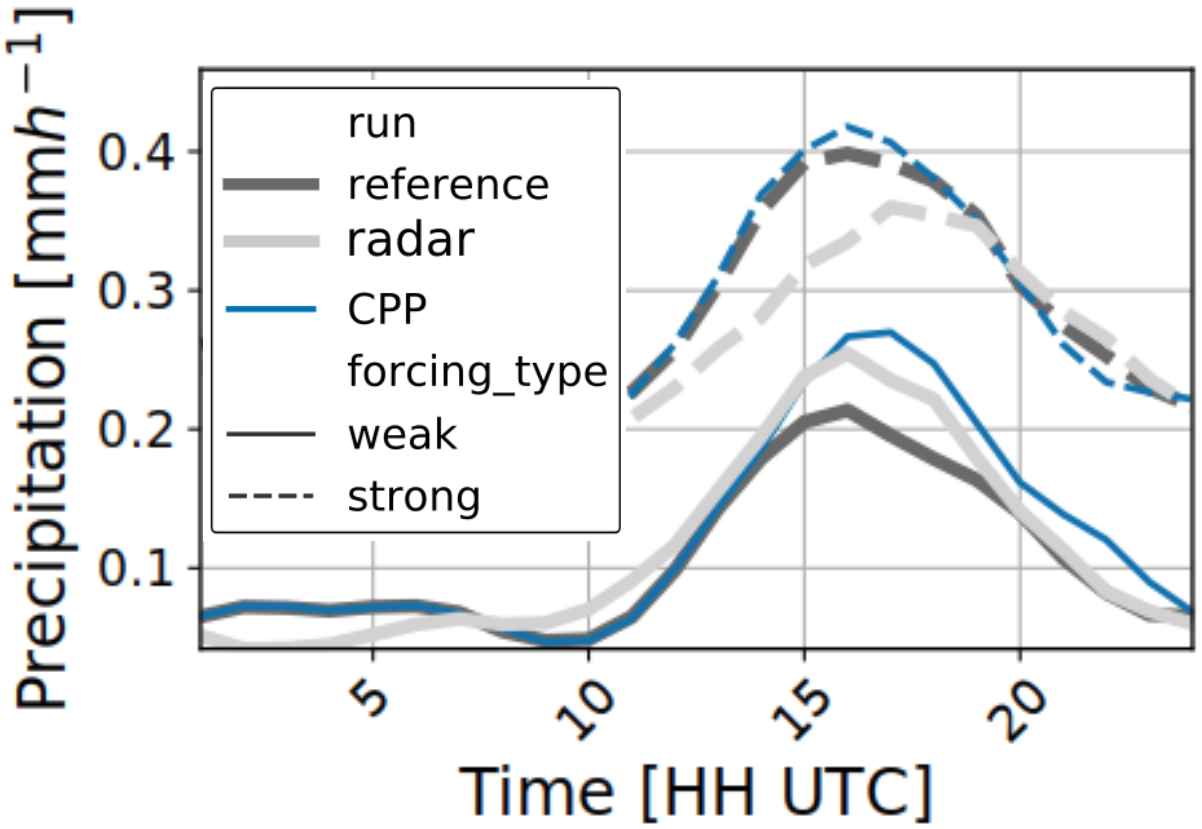


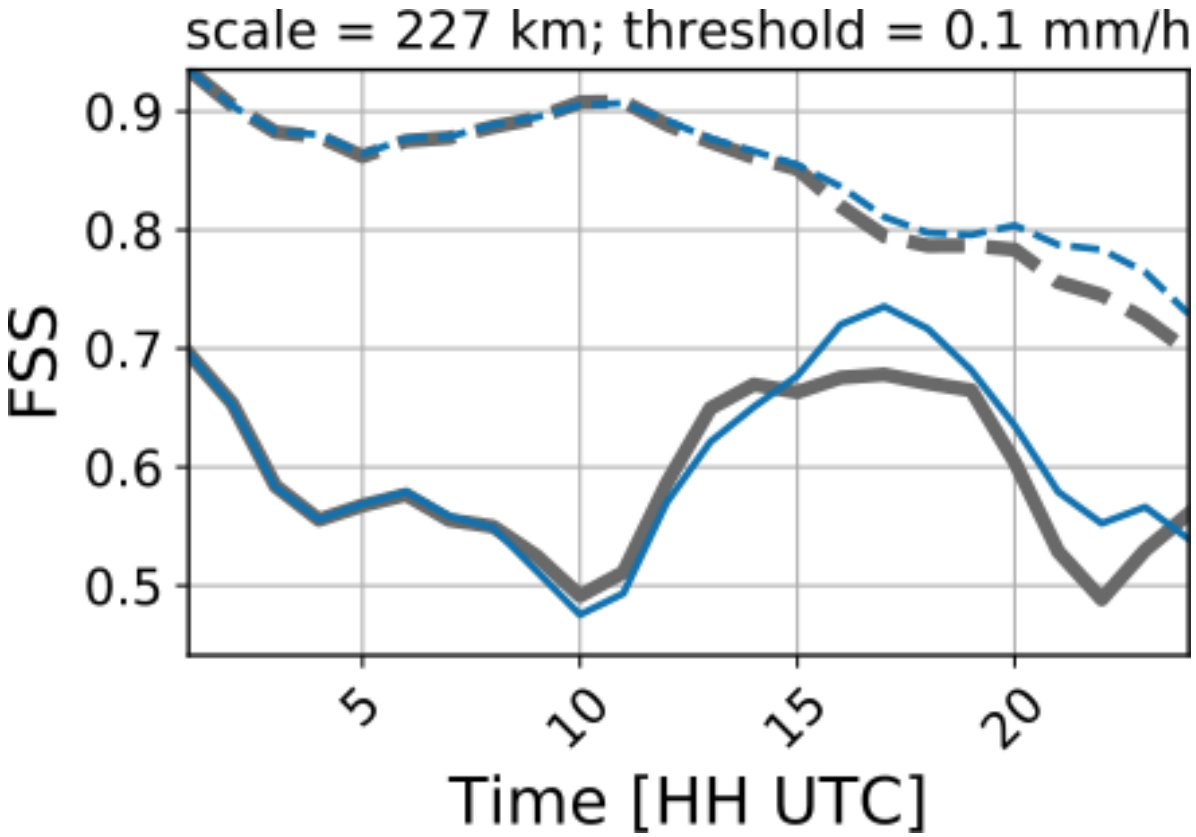


- S-SAL is improved (more wide, less peaked)
- Cell get bigger and less frequent
- Area based metrics: indirect measures for organization
- Distance based metrics (RDF; I-org): Interpretation more difficult



10 day period

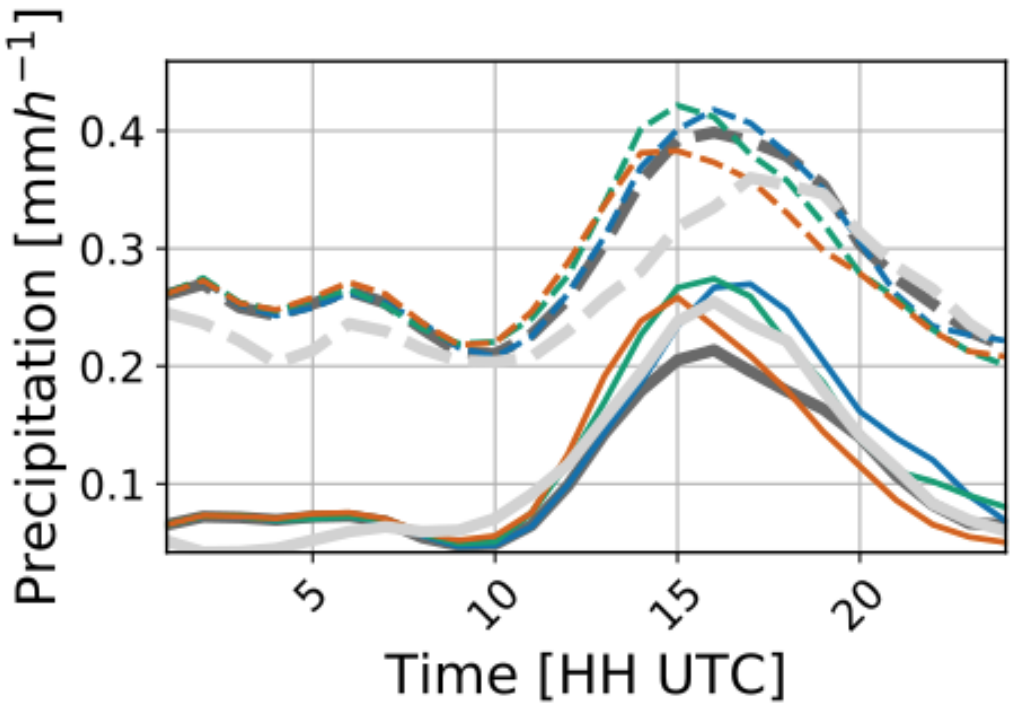


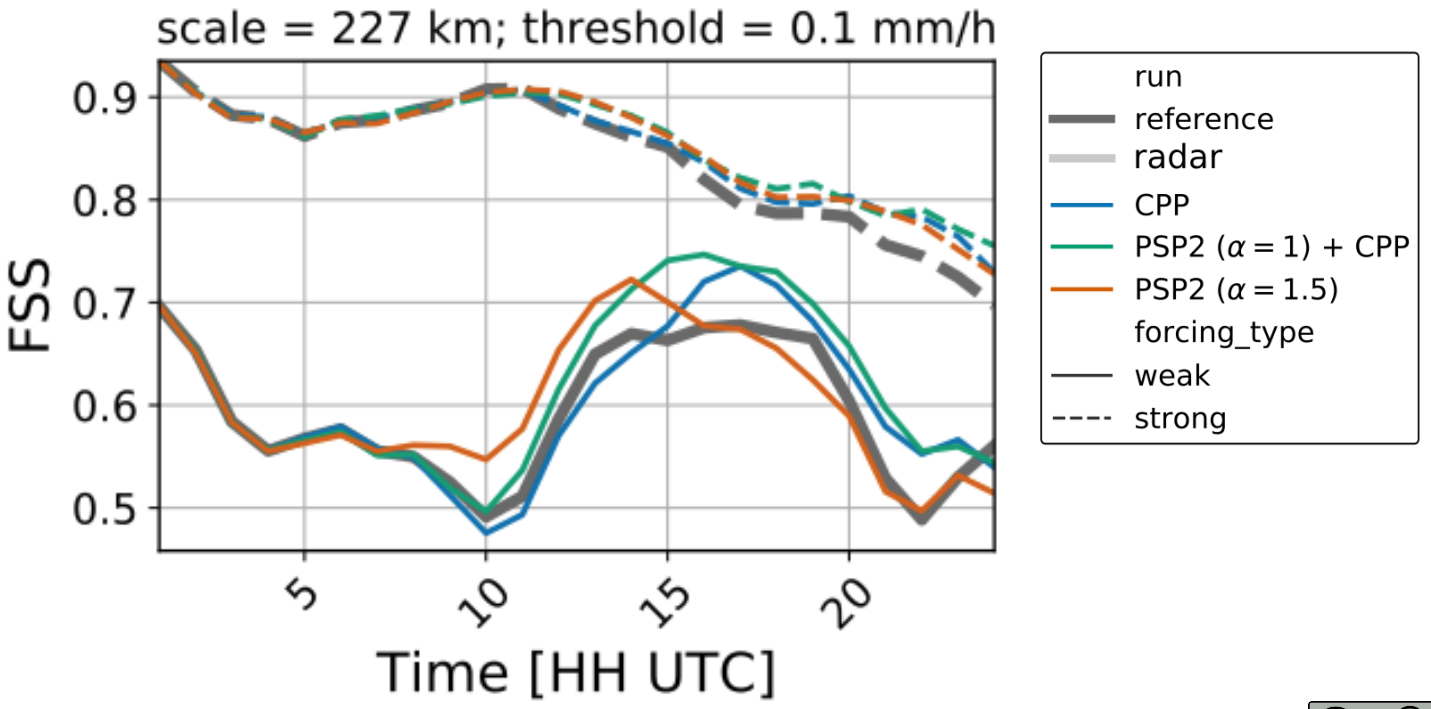


CPP + PSP2: “effects add up”

PSP2: Stochastic perturbations to account for **subgrid variability of boundary layer turbulence**;

PSP: Kober and Craig, 2016 (JAS); PSP2: Hirt et al. 2019 (MWR)



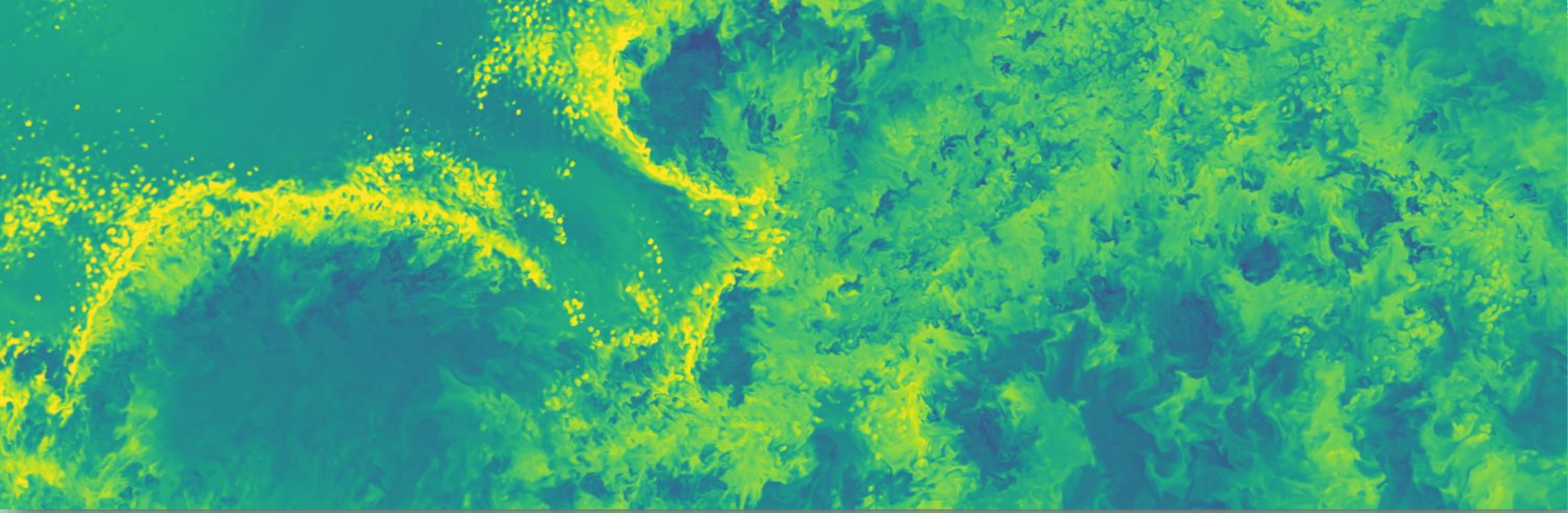


Summary

- CPP **strengthens cold pool gust fronts** by increasing w towards some target w_0
- **Precipitation** in afternoon/evening is strengthened and **FSS improved**
- **Organization** seems to be **improved**
- **Flow dependent** behavior
- **PSP2 + CPP**: Effects of PSP2 and CPP “add up”

Possible next steps

- Enable scale adaptivity (within km-scale range)
  - Thresholds need to be defined in a scale-adaptive way
  - Simulations with different resolutions are required
- Identify impact of CPP on other aspects, e.g. land-sea breeze
- Physically based: → retuning of other parameters may be necessary?
- Improve computational efficiency
- Implement in ICON



Thank you for your attention!

References

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