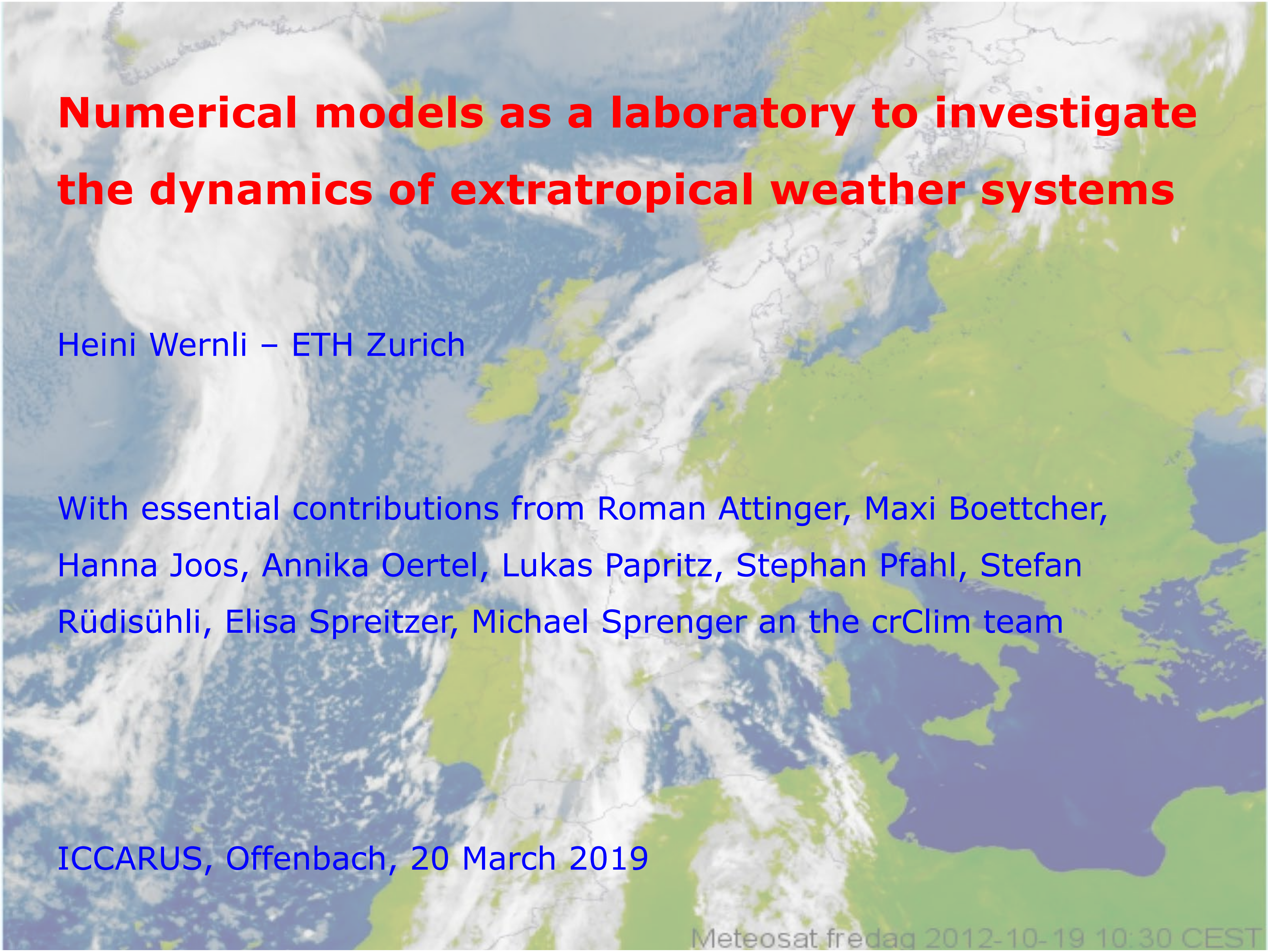


Numerical models as a laboratory to investigate the dynamics of extratropical weather systems

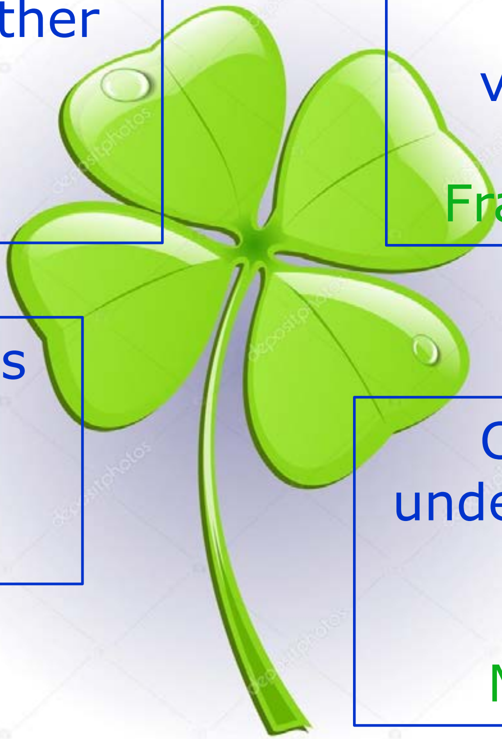
Heini Wernli – ETH Zurich

With essential contributions from Roman Attinger, Maxi Boettcher, Hanna Joos, Annika Oertel, Lukas Papritz, Stephan Pfahl, Stefan Rüdisühli, Elisa Spreitzer, Michael Sprenger an the crClim team

ICCARUS, Offenbach, 20 March 2019

Research themes of atmospheric dynamics group at ETH

4 main research themes



HALO campaigns

Diabatic processes in extratropical weather systems
Hanna Joos
Lukas Papritz

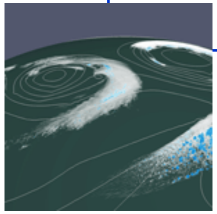
ECMWF

GLACE

High-frequency variability of stable water isotopes
Franziska Aemisegger

EUREC4A
Elucidating the role of cloud-circulation coupling in climate

Mesoscale diagnostics (foehn, fronts & precipitation)
Michael Sprenger



crClim

Characterizing & understanding extreme seasons
Maxi Böttcher
Manos Flaounas

erc

Numerical models are essential for research on weather system dynamics

(i) they help to “zoom” into a specific weather system (i.e., to increase the spatial and temporal resolution of the relevant meteorological fields compared to (re)analyses)

(ii) they enable highly detailed process analyses (e.g., by outputting physical tendency terms)

(iii) they serve to test hypotheses by performing different types of sensitivity experiments, and

(iv) they allow the modular extension of complexity (by adding modules for, e.g., water vapour tracers and stable water isotope physics).

Outline of this talk

1) Atmospheric water cycle studies with COSMO-tag

- moisture transport in subtropical North Atlantic
- case study of a cold air outbreak

2) Embedded convection in a warm conveyor belt: online trajectories in COSMO-2 simulation

3) Understanding diabatic modification of potential vorticity in extratropical cyclones: a Lagrangian PV diagnostic in the IFS

4) Towards on-the-fly diagnostics of high-resolution climate simulations: quantify frontal precipitation

Complex moisture cycle in subtropical North Atlantic

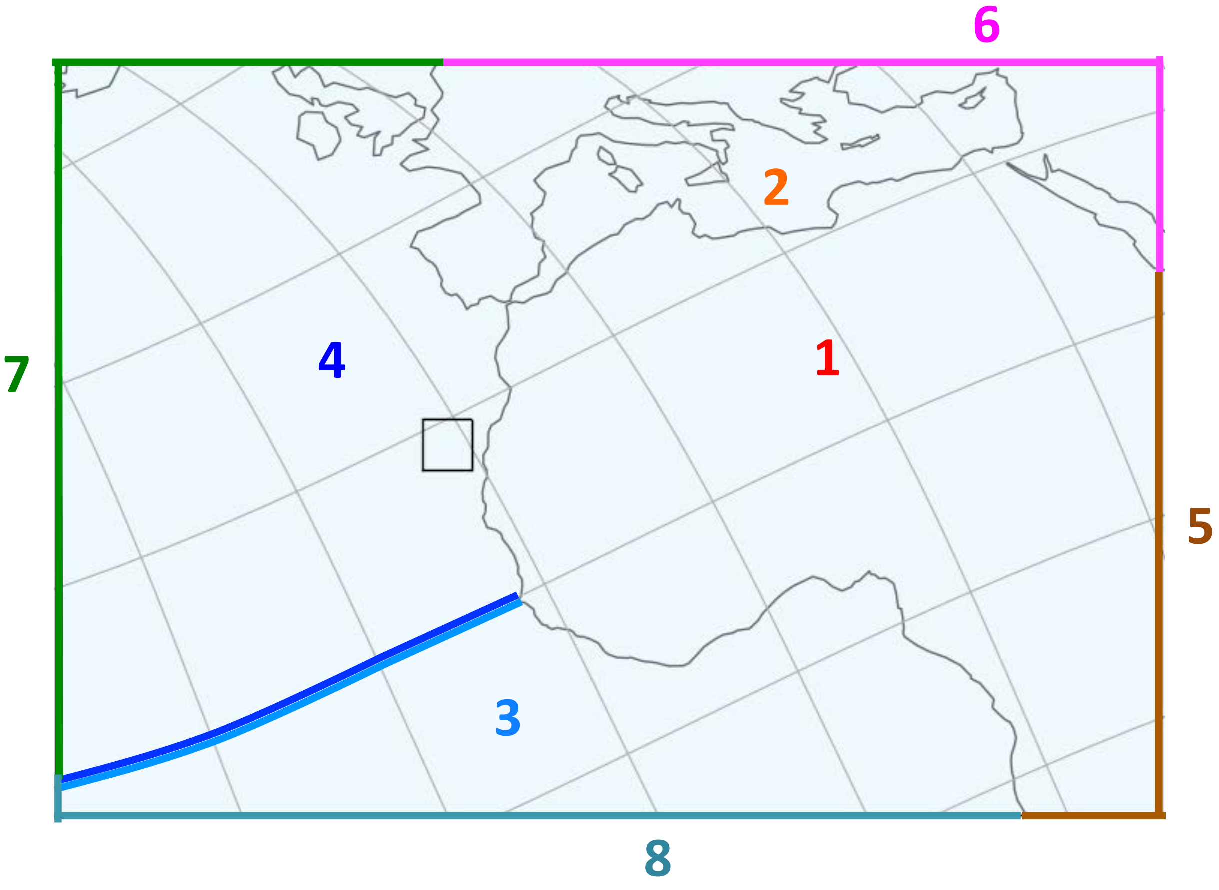
Project with KIT (M. Schneider/P. Knippertz) and FUB (S. Pfahl)

Focus on variability of water vapour and stable water isotopes in Tenerife – setup of COSMO-tag (Winschall et al. 2014, ACP)

- 2 months, nudged
- 14 km resolution
- 704 x 480 gridpoints

9 tracers:

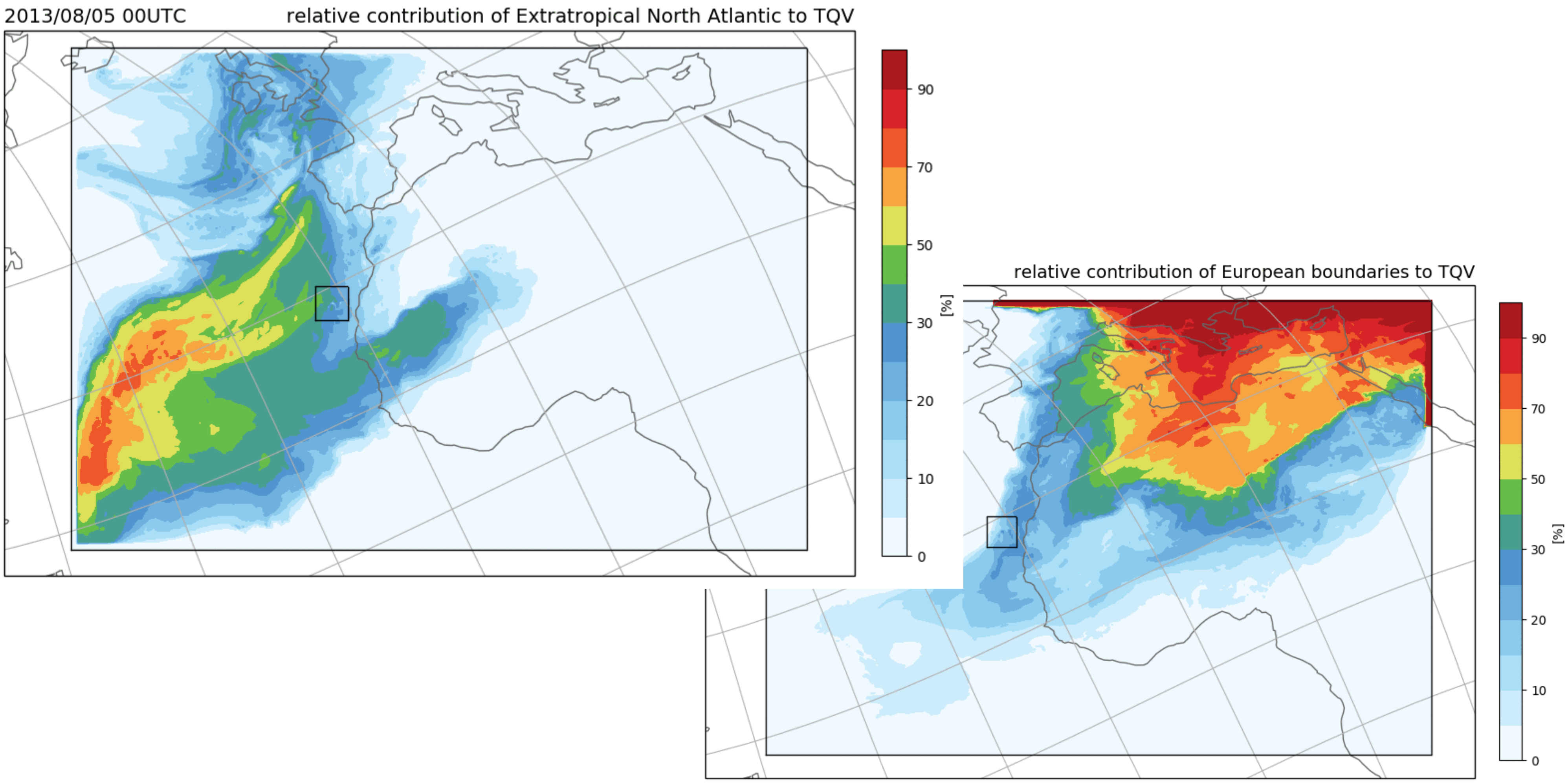
1. Africa
2. Europe & Med
3. Tropical NA (< 20°N)
4. Extratropical NA
5. African boundary
6. European boundary
7. Extratropical NA boundary
8. Tropical NA boundary
9. Initial moisture



Dahinden, Aemisegger & Pfahl

Complex moisture cycle in subtropical North Atlantic

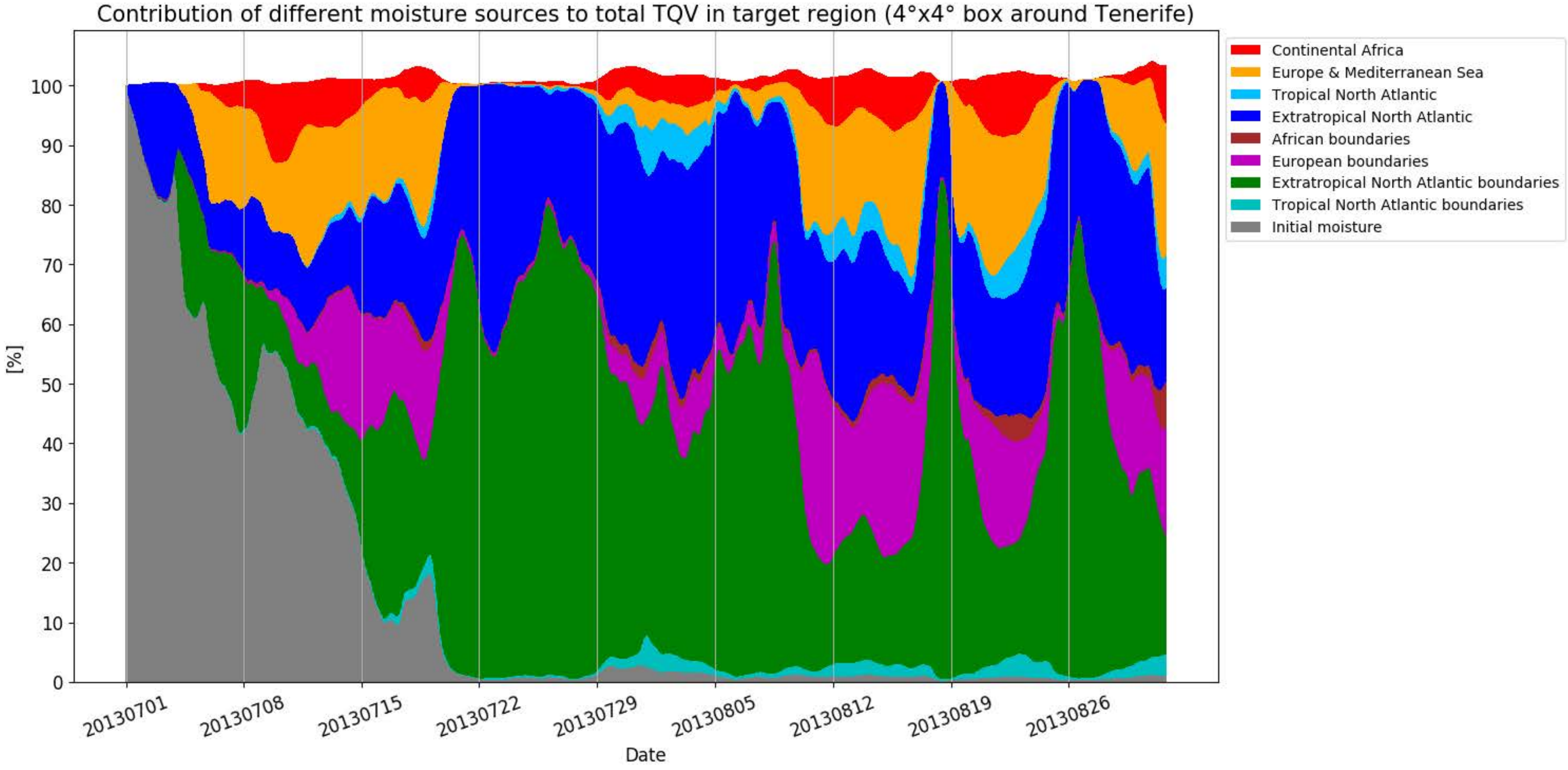
Movie with relative contributions of total QV from tracers 4 and 6



Dahinden, Aemisegger & Pfahl

Complex moisture cycle in subtropical North Atlantic

Relative contributions of moisture sources to total QV in Tenerife



Dahinden, Aemisegger & Pfahl

Typical cold air outbreak in the Nordic Seas

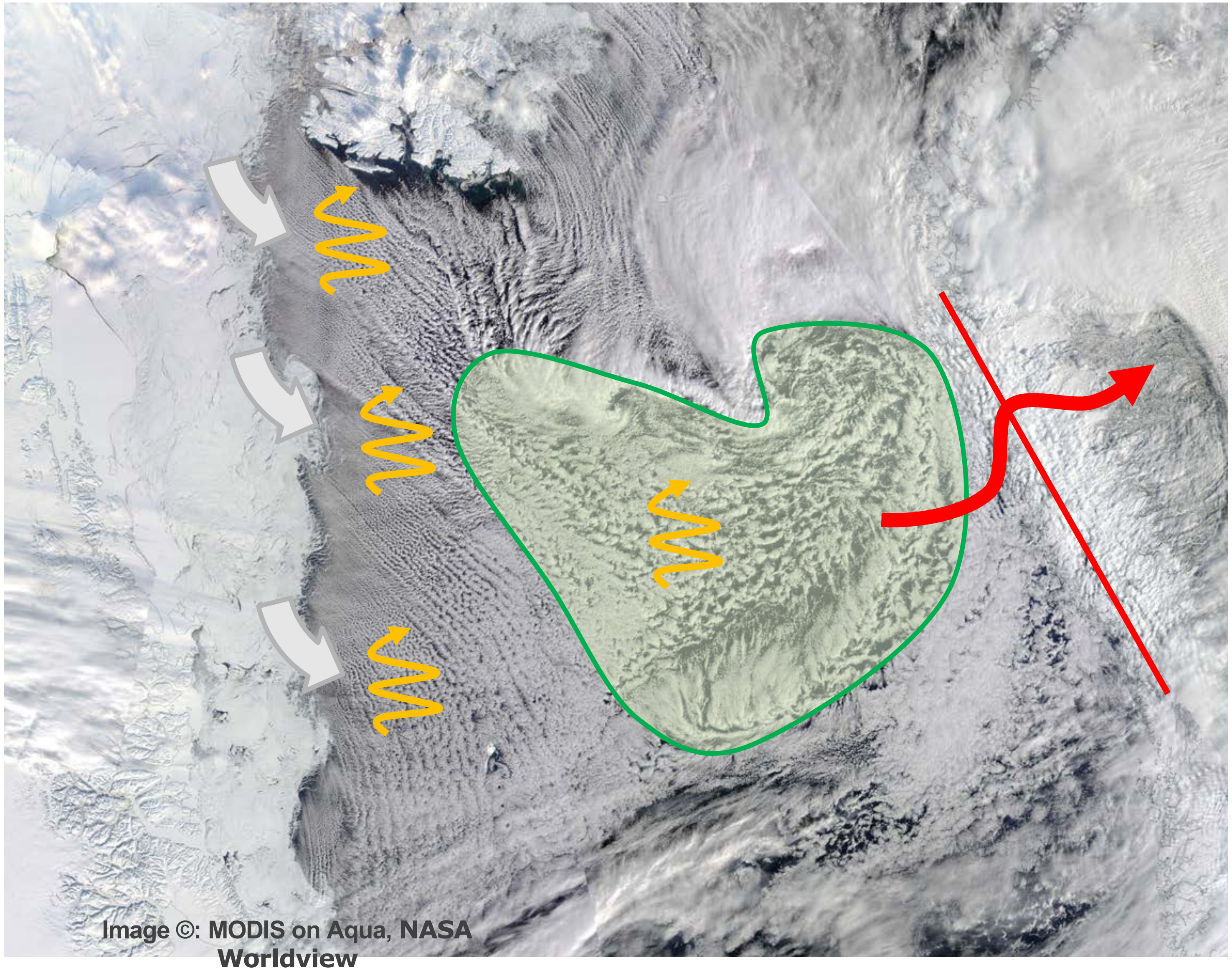


Image ©: MODIS on Aqua, NASA Worldview

Advection of cold and dry air from Fram Strait

Moisture uptake

Convection with cloud formation and precipitation

Ascent over Scandinavian topography

- ➢ **hints at an intense and local water cycle in the basin of the Nordic Seas**

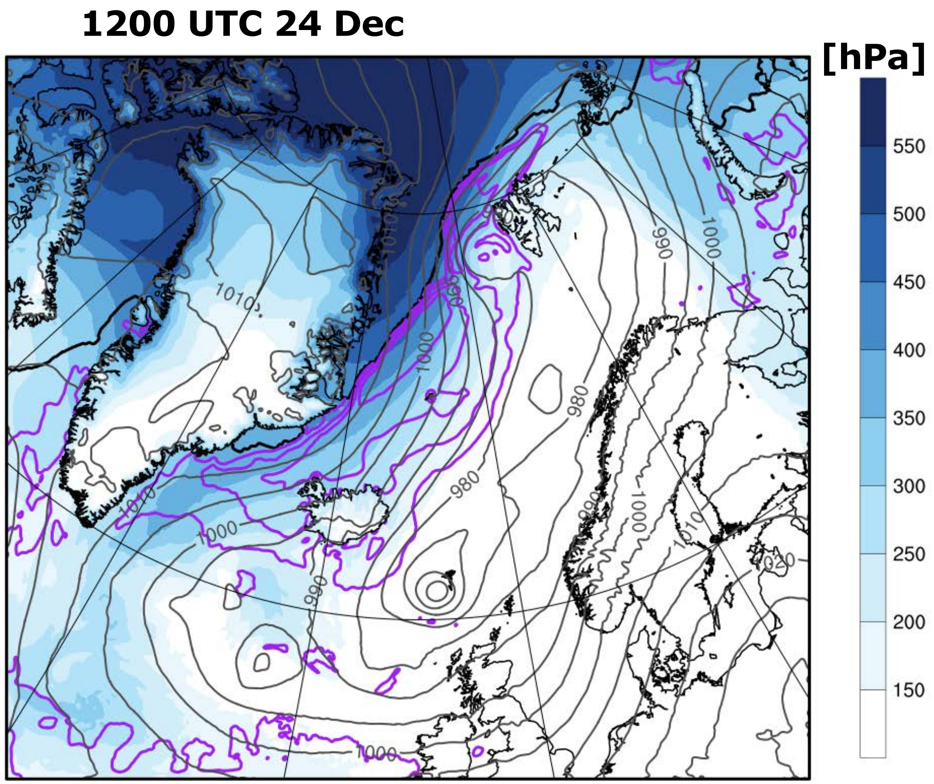
Papritz and Sodemann 2018 (MWR)

Case study: The „Christmas 2015" CAO

- 24 – 27 Dec 2015
- advection of cold airmass from Fram Strait across Nordic Seas
- 6th most severe CAO in ERA-I in terms of area averaged $\theta_{SST} - \theta_{900}$
- rather typical evolution and air mass pathway

  e.g., Papritz and Spengler 2017
- prelude to severe Arctic warm event

  e.g., Boisvert et al. 2016, Moore 2016, Binder et al. 2017



Shading: cold airmass (thickness of layer below 280 K isentrope)

— $\theta_{SST} - \theta_{900}$ from 4K every 4K

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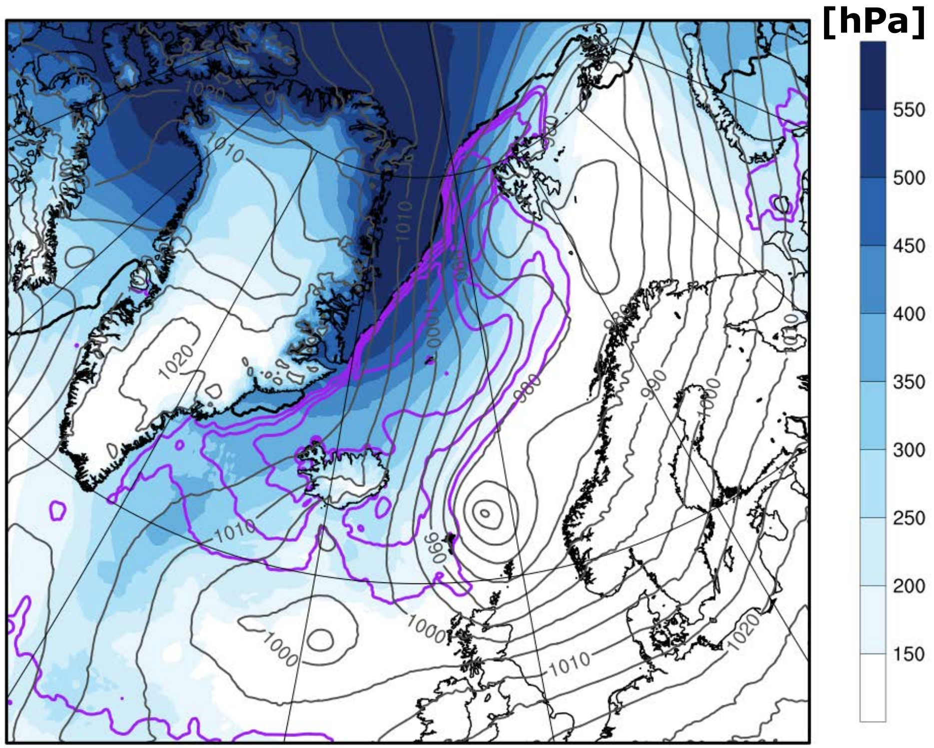
0000 UTC 25 Dec



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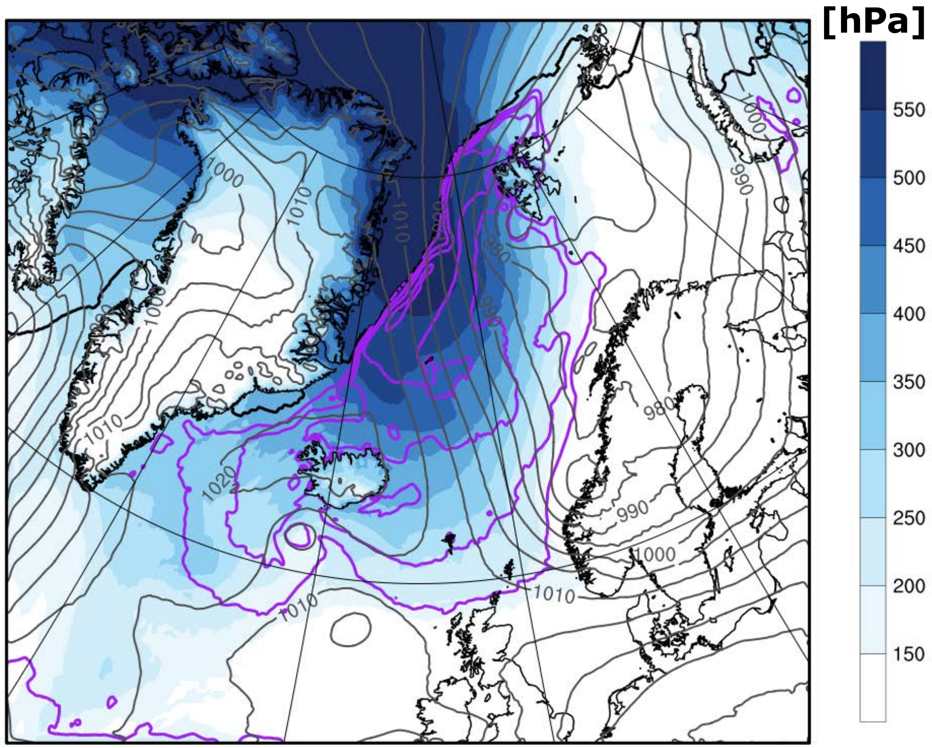
1200 UTC 25 Dec



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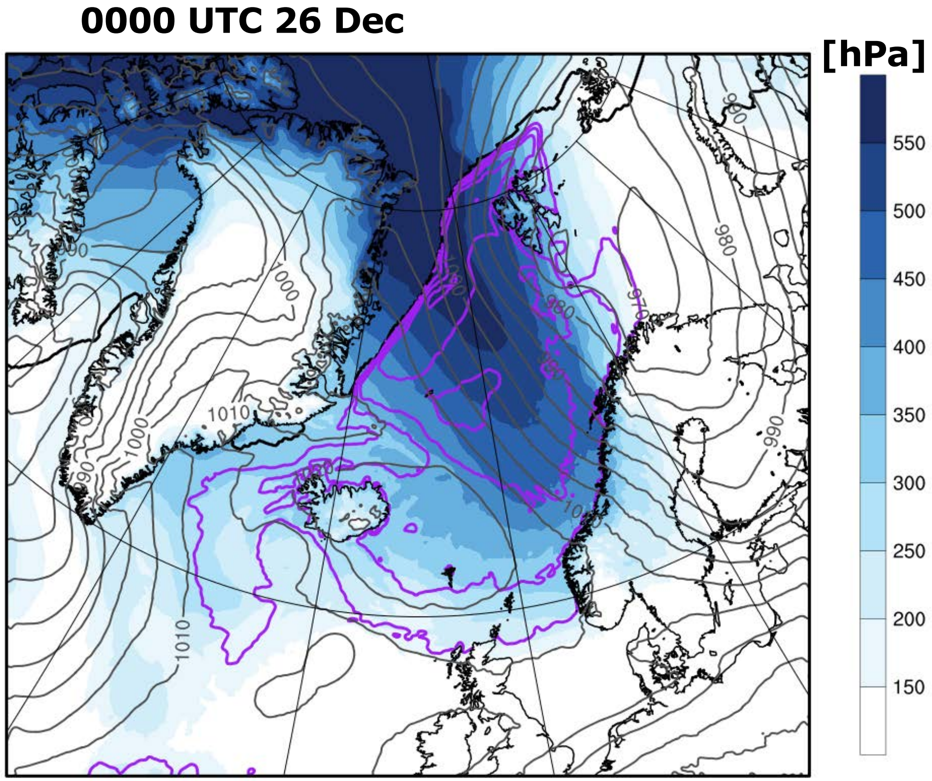

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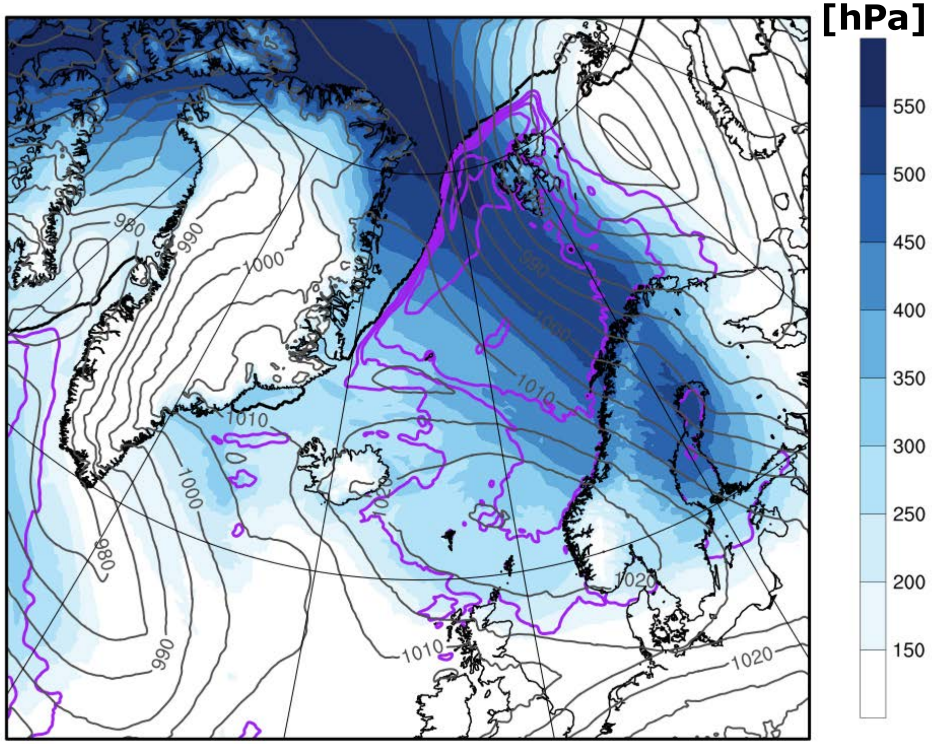
1200 UTC 26 Dec



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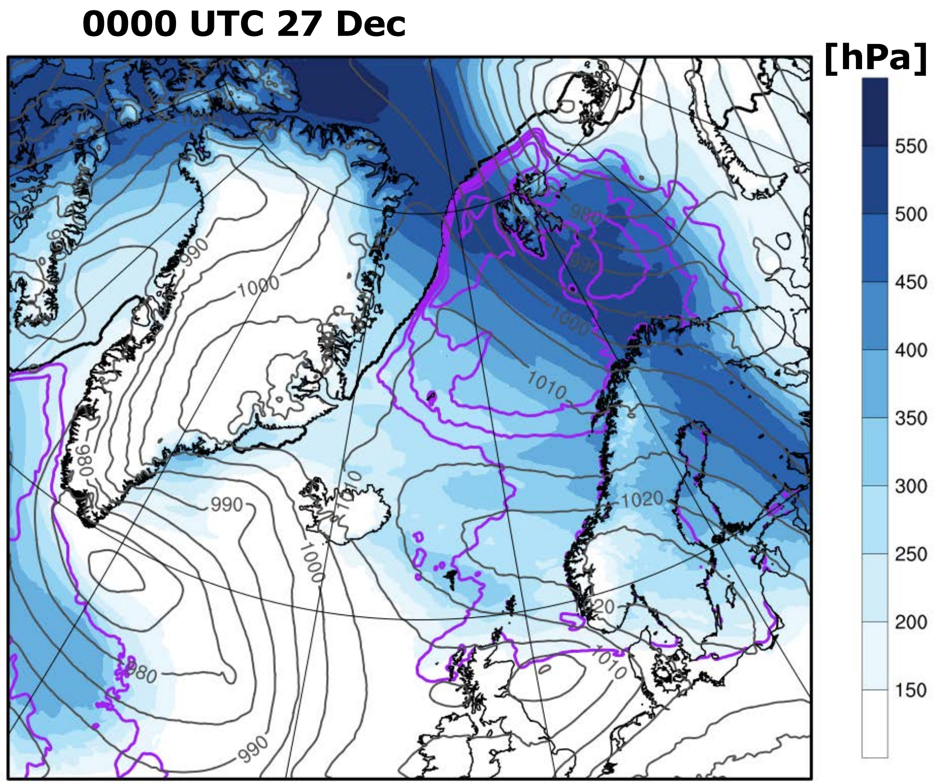

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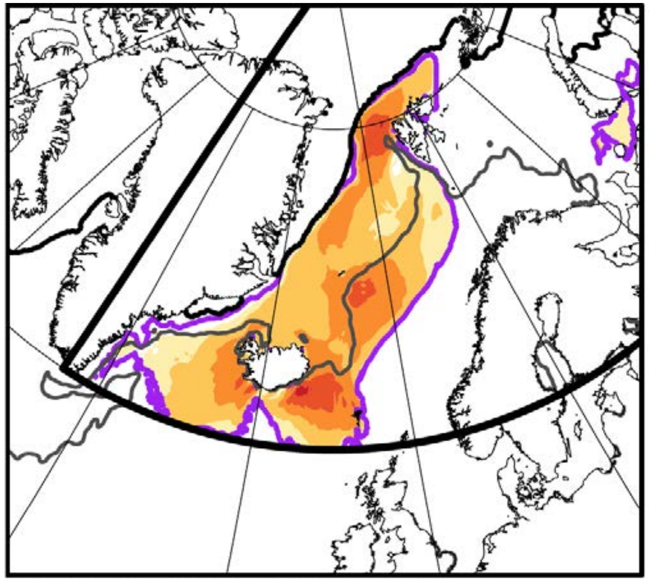
Papritz and Sodemann 2018 (MWR)

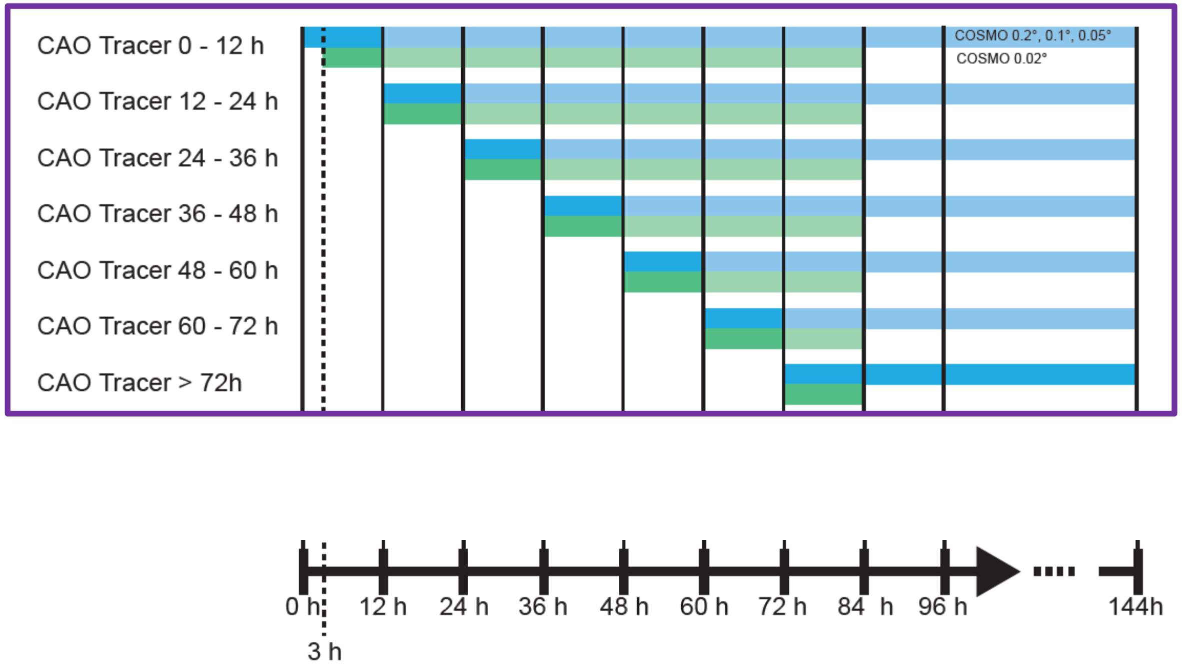
Simulations with COSMO-tag (5 km grid spacing)

Secondary water cycle representing water picked up by CAO air mass via ocean evaporation

Evaporation mask for CAO tracers: $\theta_{SST} - \theta_{900} > 4\ \mathrm{K}$



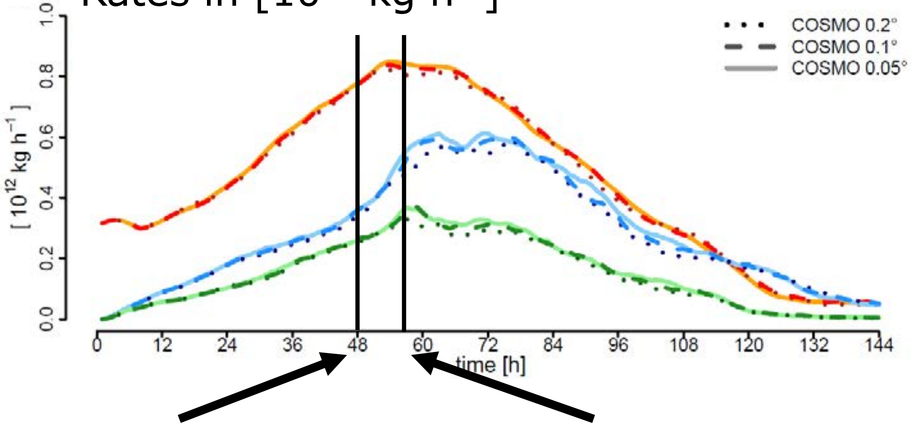
Release windows for tracers



Papritz and Sodemann 2018 (MWR)

Domain integrated CAO water budget

Rates in [10^{12} kg h^{-1}]



CAO air mass reaches into Norwegian Sea

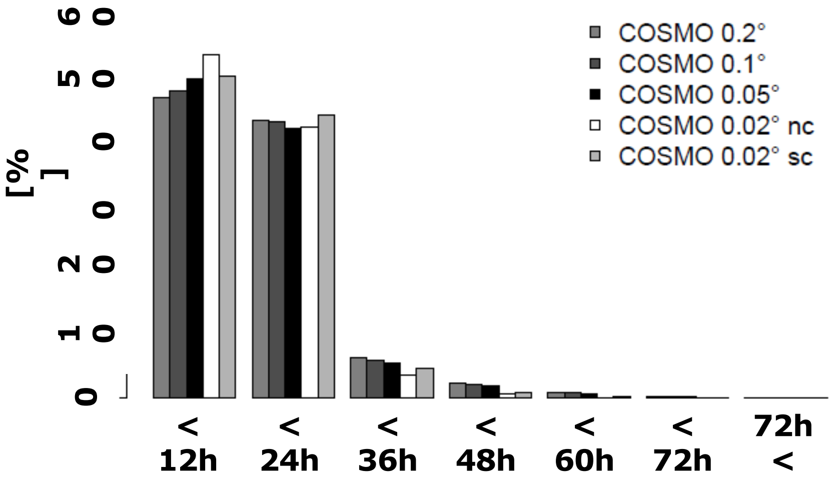
Landfall of cold front along Norway‘s coast

🟥 evaporation 🟦 precipitation

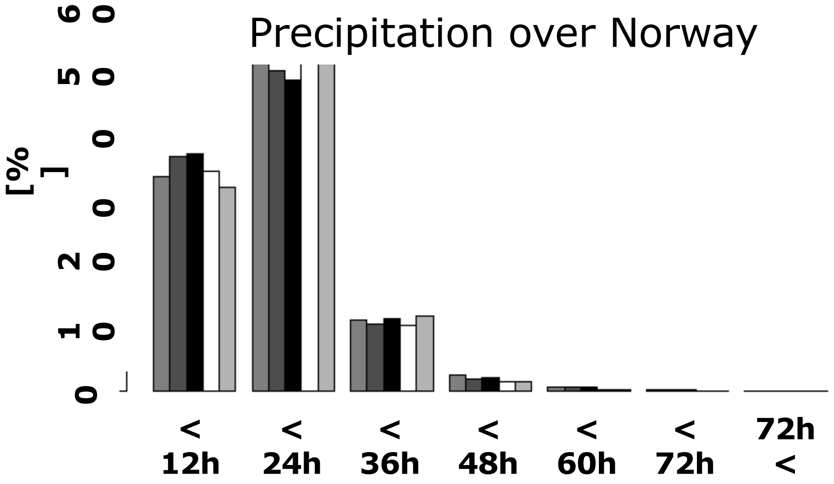
🟩 marine precipitation within CAO mask

Papritz and Sodemann 2018 (MWR)

Residence time of precipitation with CAO origin



Precipitation over ocean



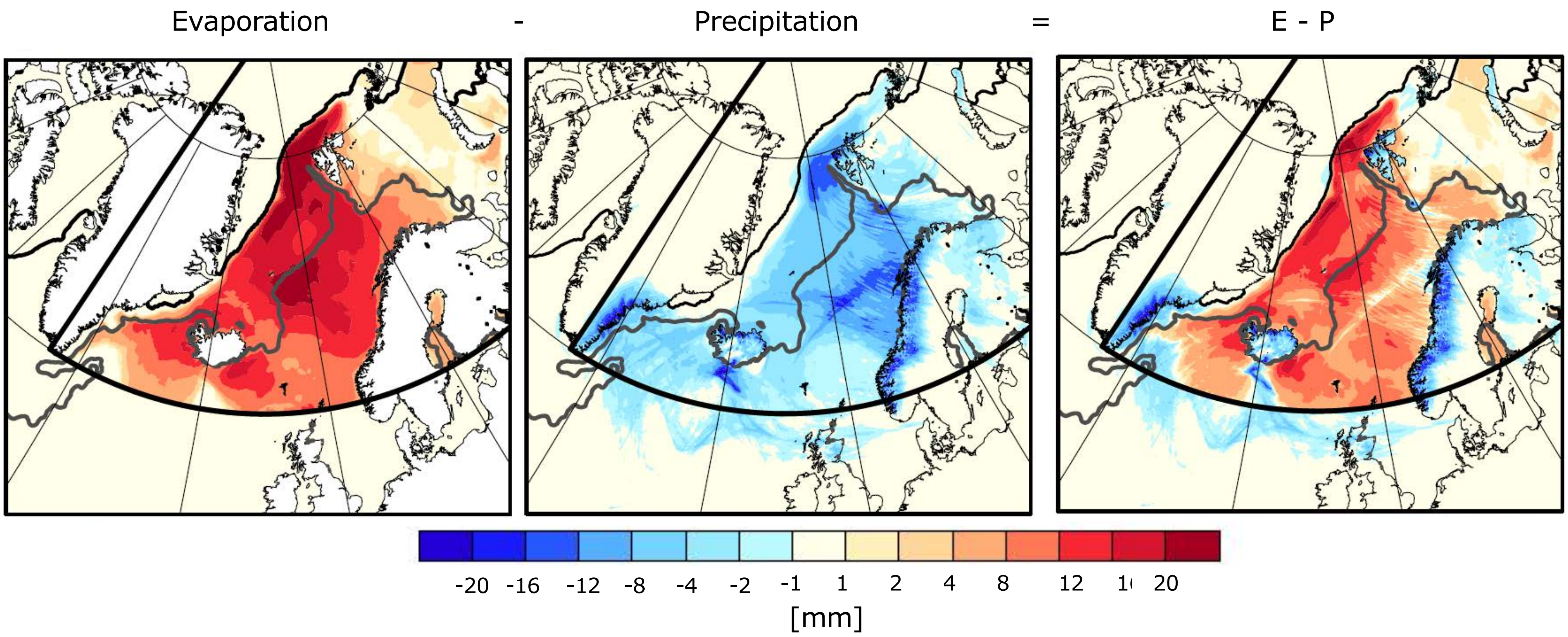
Precipitation over Norway

- fraction of precipitation with evaporation < X h ago
- lower limit due to 12-hourly release intervals of tracers
- residence time considerably shorter than climatological mean residence time:
  - Nordic Seas: 3 – 4 days
    Laederach and Sodemann 2016
  - Global: 8 – 10 days
    Bosilovich et al. 2005

Papritz and Sodemann 2018 (MWR)

Hydrological footprint of the CAO

CAO water cycle is fast and local – not much long-range transport of CAO humidity

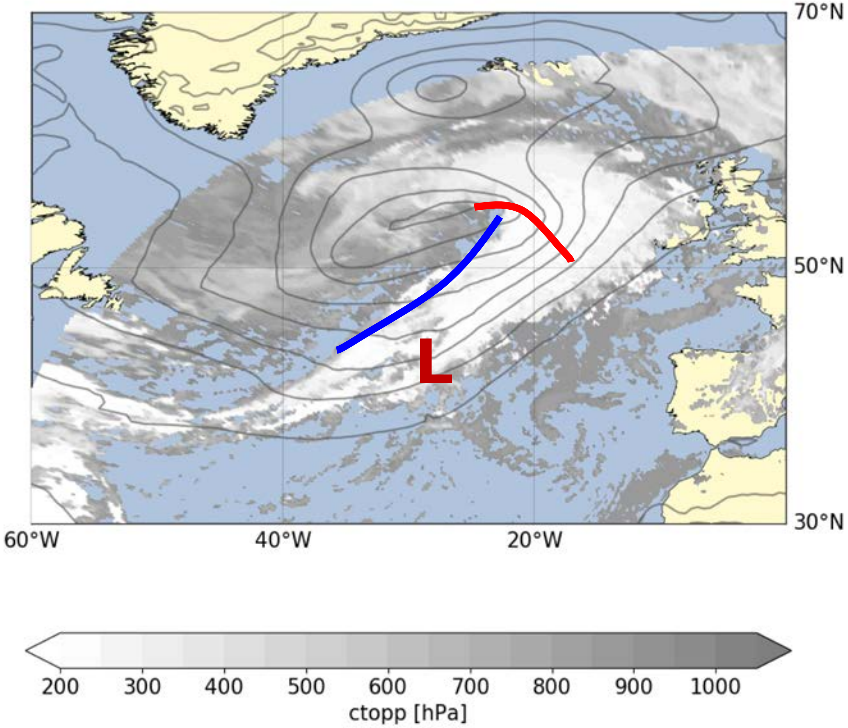


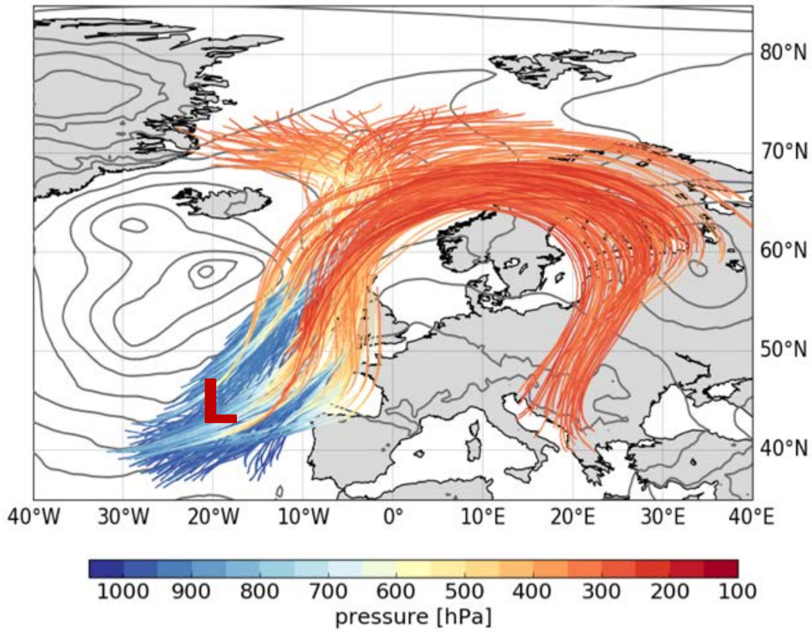
Papritz and Sodemann 2018 (MWR)

Embedded convection in a WCB (case study “Vladiana” in Sept 2016)

Warm conveyor belts (WCBs)

- Strongly ascending and main cloud producing airstreams that typically ascend ahead of the cold front, e.g. Harrold, 1973, QJ; Carlson 1980, MWR
- Lagrangian perspective: ascent rate > 600 hPa / 48 h, e.g. Madonna et al. 2014, JClim
- Convection can frequently be embedded in the WCB, e.g. Binder 2016, PhD thesis; Flaounas et al. 2017, 2018, ClimDyn; Rasp et al. 2016, MWR





Oertel et al. 2019 (QJ)

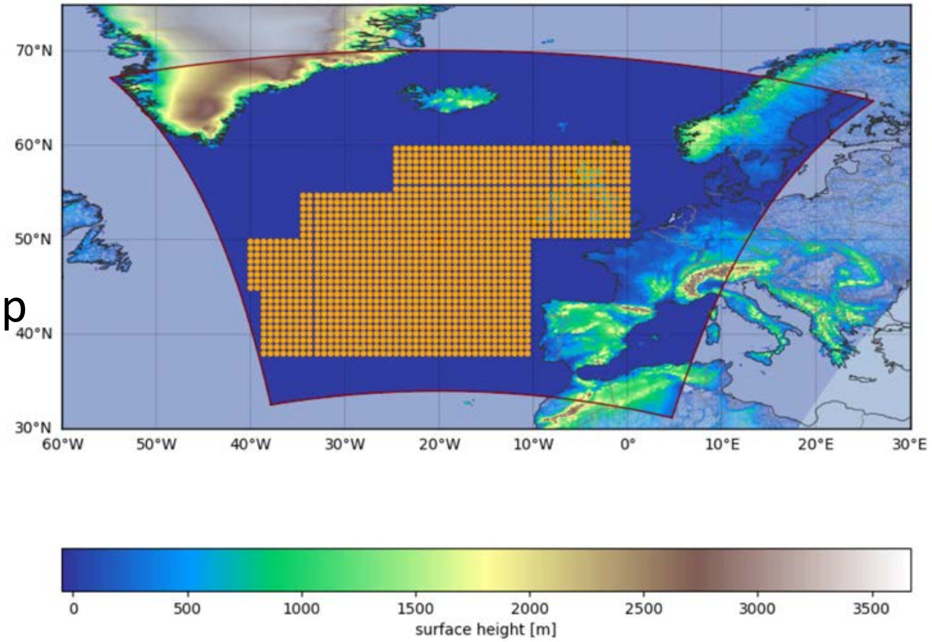
Convection-permitting COSMO simulation

convection-permitting COSMO simulation with 2 km grid spacing

calculation of about 10’000 online trajectories; calculated from 3D wind at every model timestep (Δt = 20 s)

→ explicit representation of vertical motion and convective WCB ascent

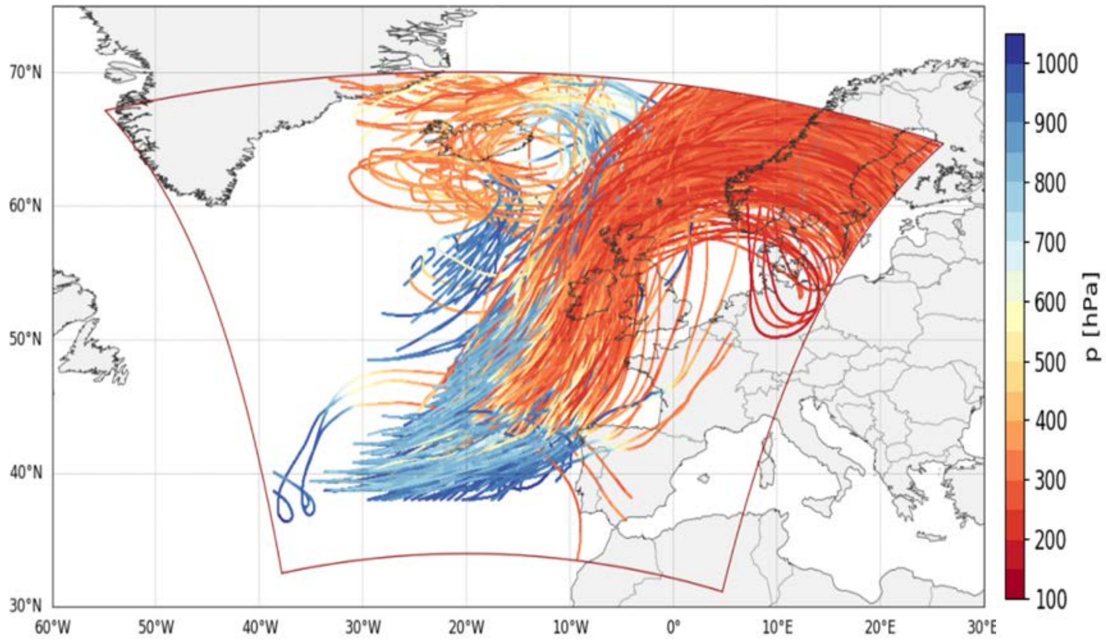
Miltenberger et al. 2013, GMD
Miltenberger et al. 2014, COSMO Technical Report



Oertel et al. 2019 (QJ)

Convective WCB ascent

WCB online trajectories



1) WCB online trajectories:
   ascent rate > 600 hPa / 48 h

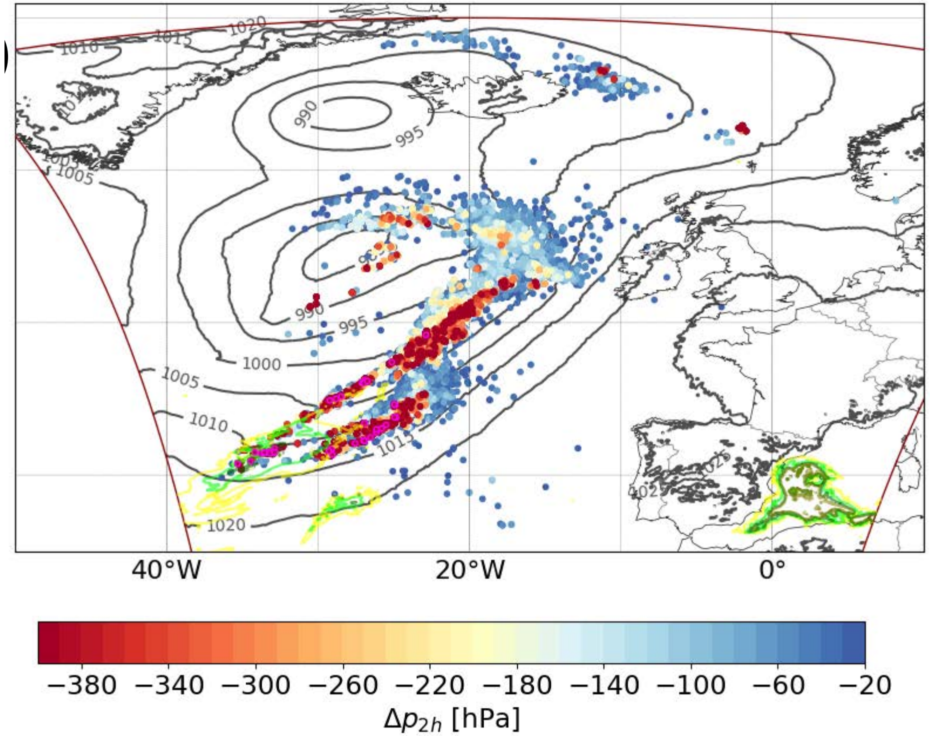
2) Select 10% fastest ascending WCB trajectories with ascent rate > 600 hPa / 3 h

→ about 2000 WCB trajectories with “convective WCB ascent”

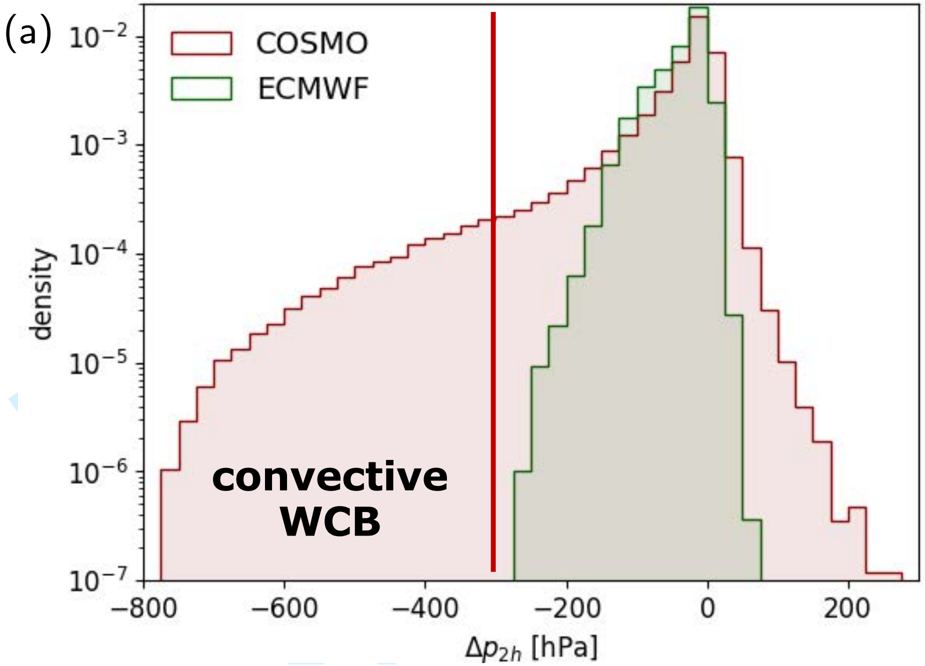
Oertel et al. 2019 (QJ)

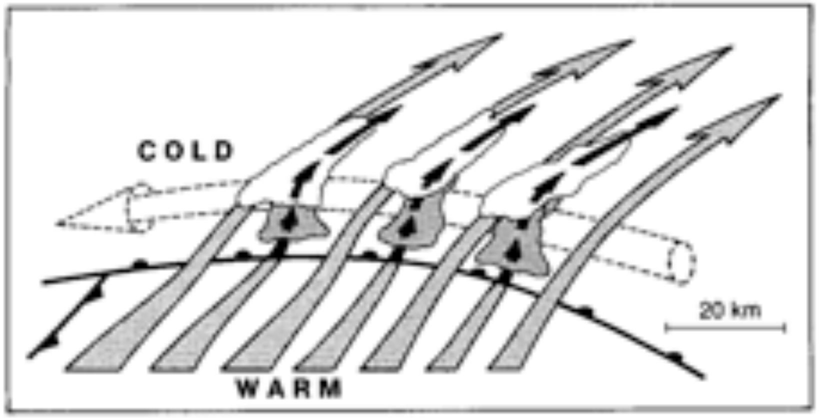
Convective WCB ascent

WCB air parcels, colored with 2-h ascent rate



Histograms of 2-h ascent rate





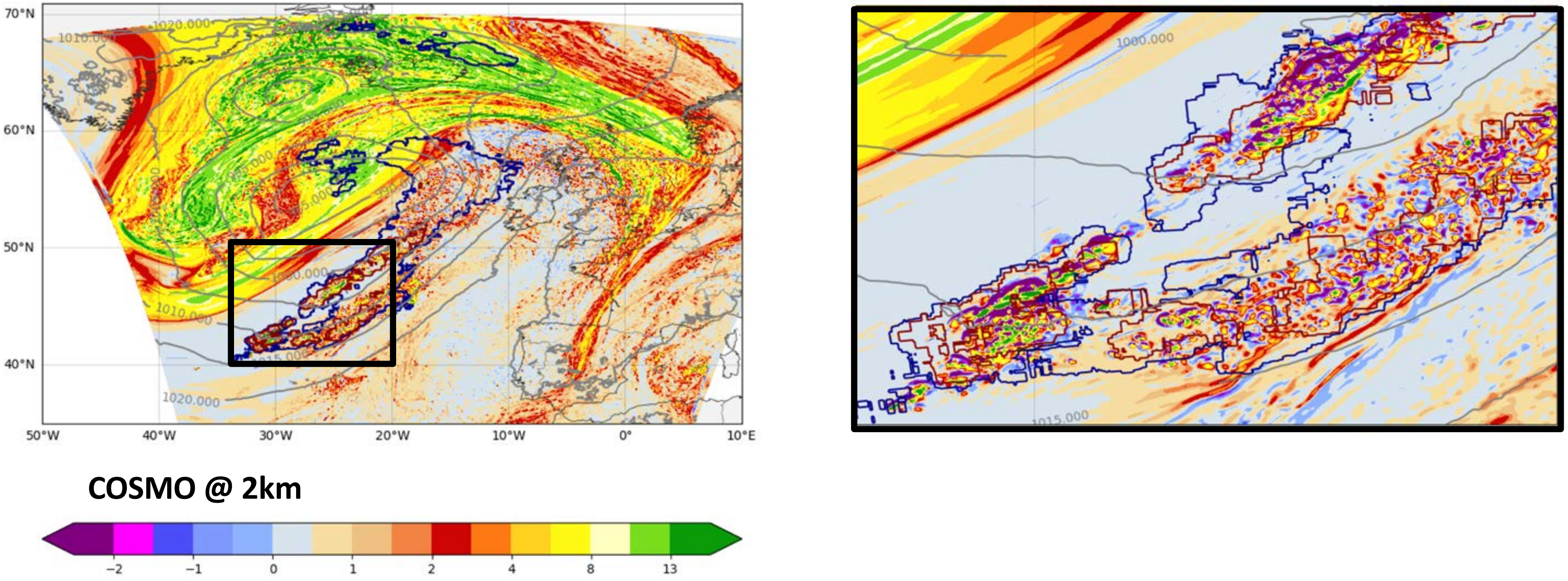
escalator–elevator concept

Neiman et al. 1993 (MWR)

Oertel et al. 2019 (QJ)

Embedded convection in a WCB (case study “Vladiana” in Sept 2016)

Upper-level PV structure above WCB looks very “noisy” → is there a consistent and dynamically relevant pattern?



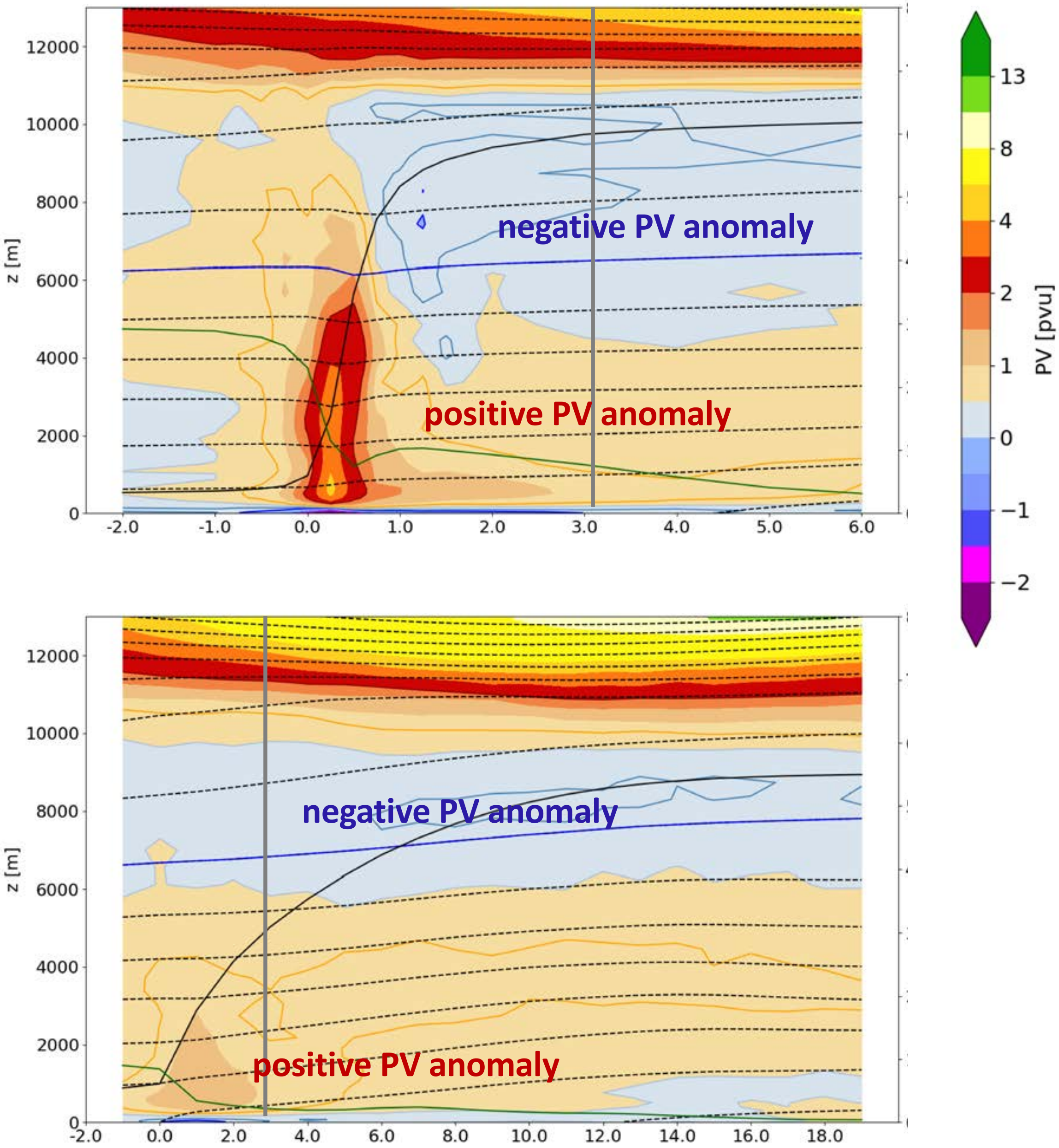
PV@325K

COSMO @ 2km

PV [PVU]

Oertel et al., in prep.

Composites of vertical PV profiles along WCB trajectories

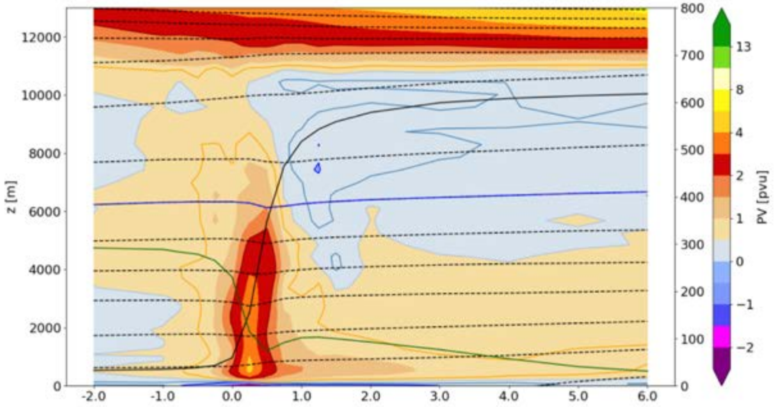


convective WCB

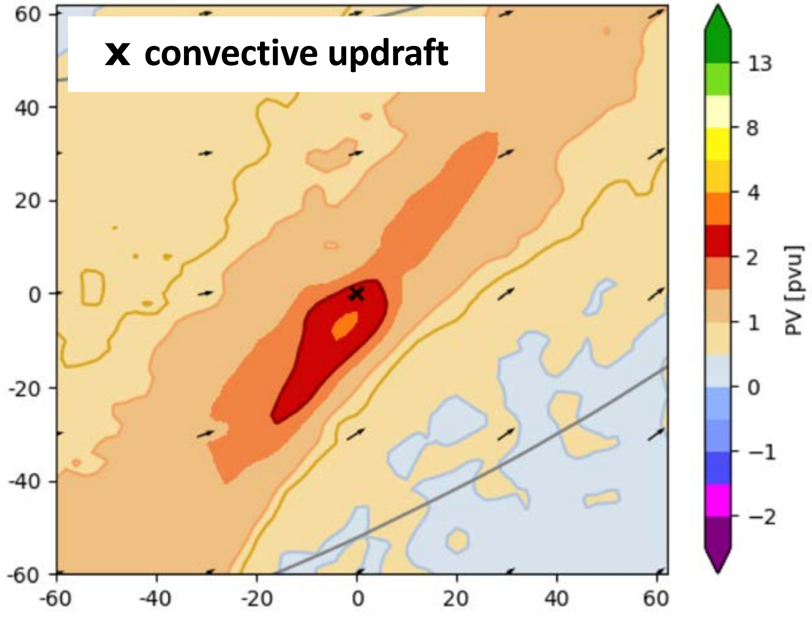
“normal” WCB with slower ascent

Oertel et al., in prep.

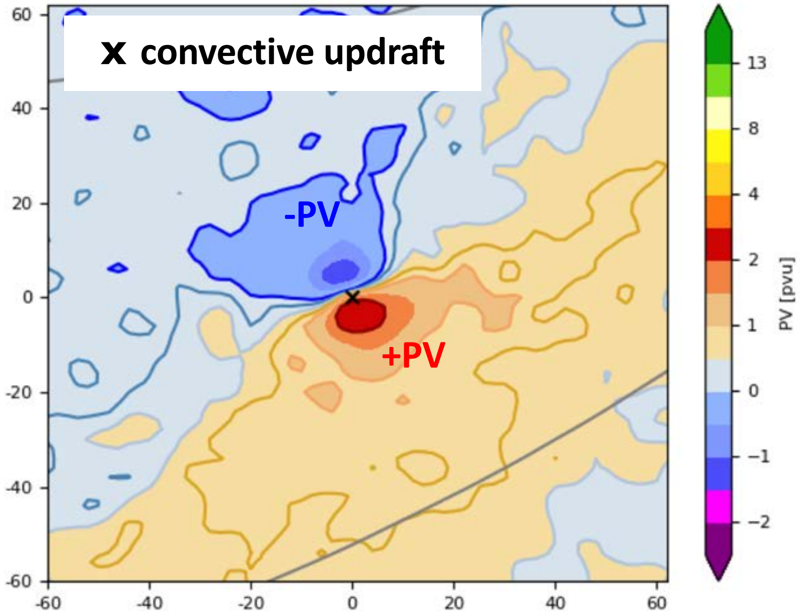
Composites of horizontal PV structure near convective WCB parcels



Low-level pos. PV anomaly



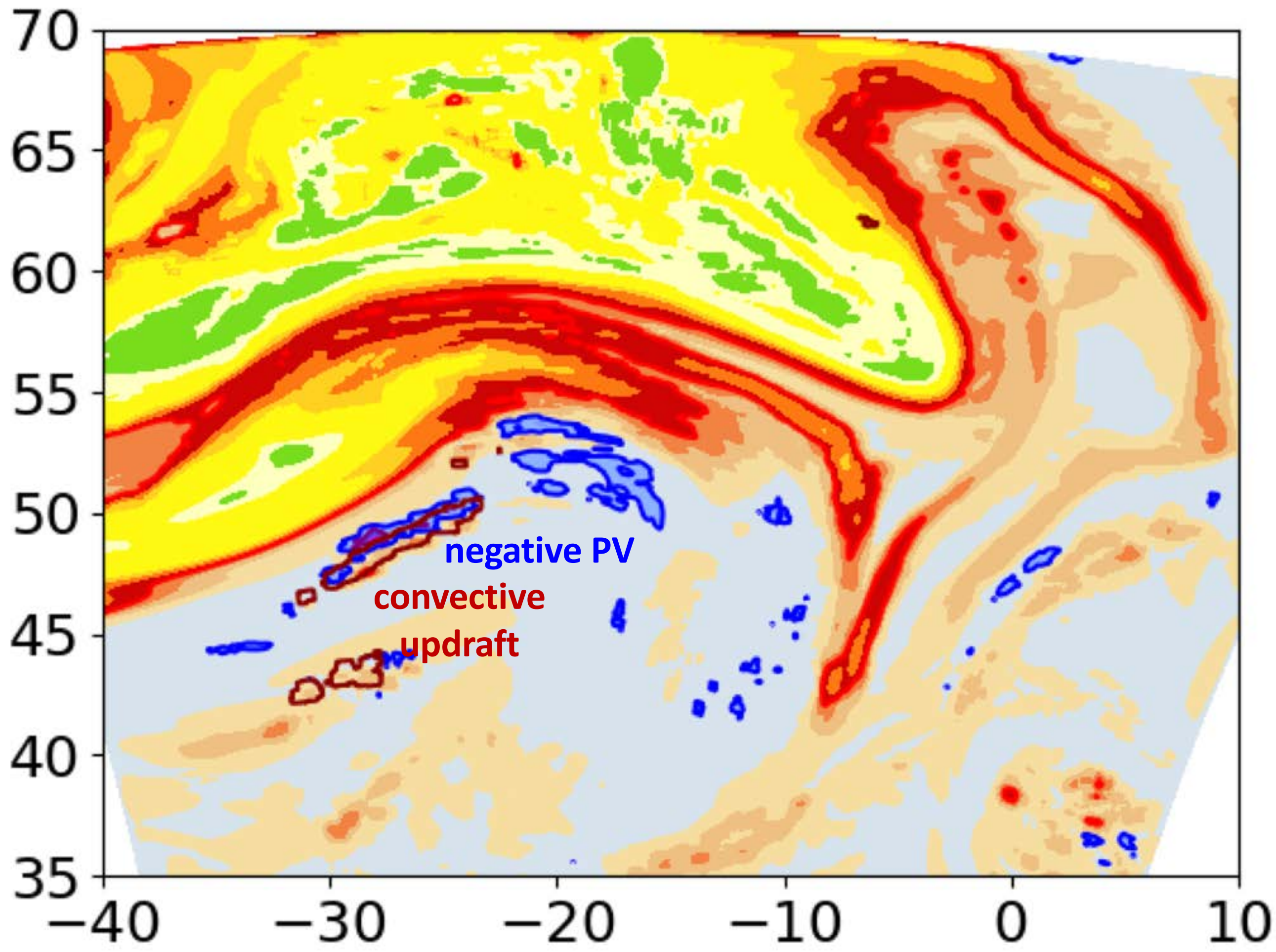
Upper-level PV dipole



Oertel et al., in prep.

Is embedded convection dynamically relevant?

1) existence of PV anomaly on a larger-scale → coarse-graining on 60 km → robust PV anomalies near ascent of convective WCB



Oertel et al., in prep.

Is embedded convection dynamically relevant?

1) existence of PV anomaly on a larger-scale
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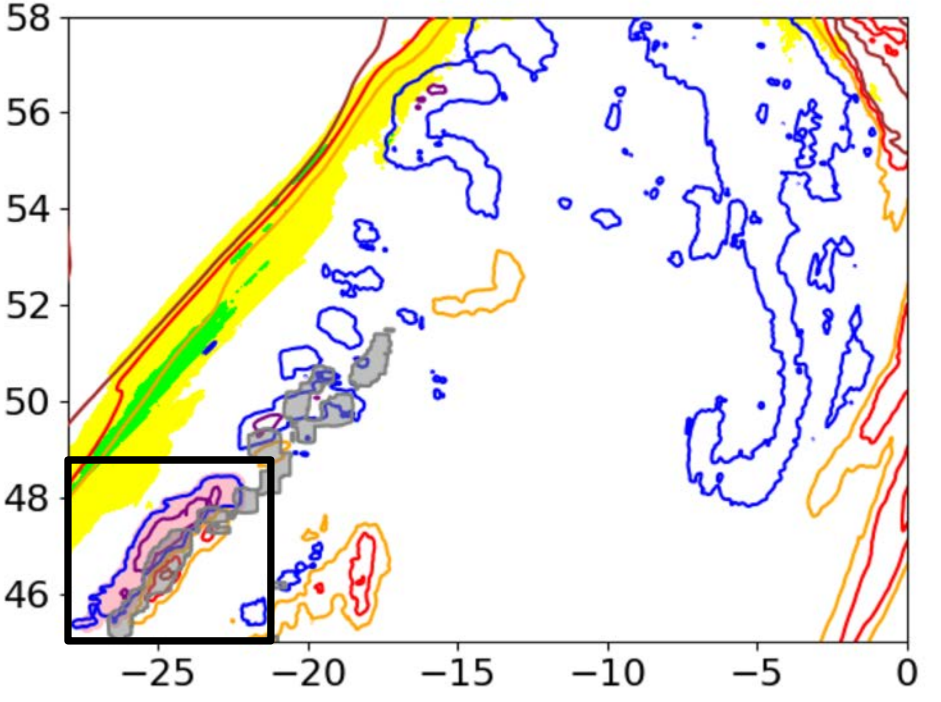
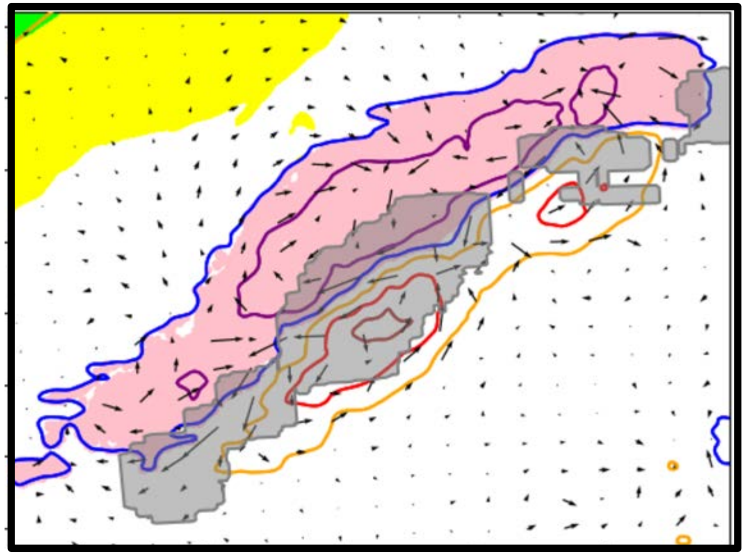
2) lifetime & interaction with upper-level waveguide
→ forward trajectories from regions of
convectively-produced negative PV





Konvektion

-1 PVU

0 PVU

1 PVU

2 PVU

3 PVU

🟨 $55\ ms^{-1}$

🟩 $60\ ms^{-1}$

🟩 $65\ ms^{-1}$

Oertel et al., in prep.

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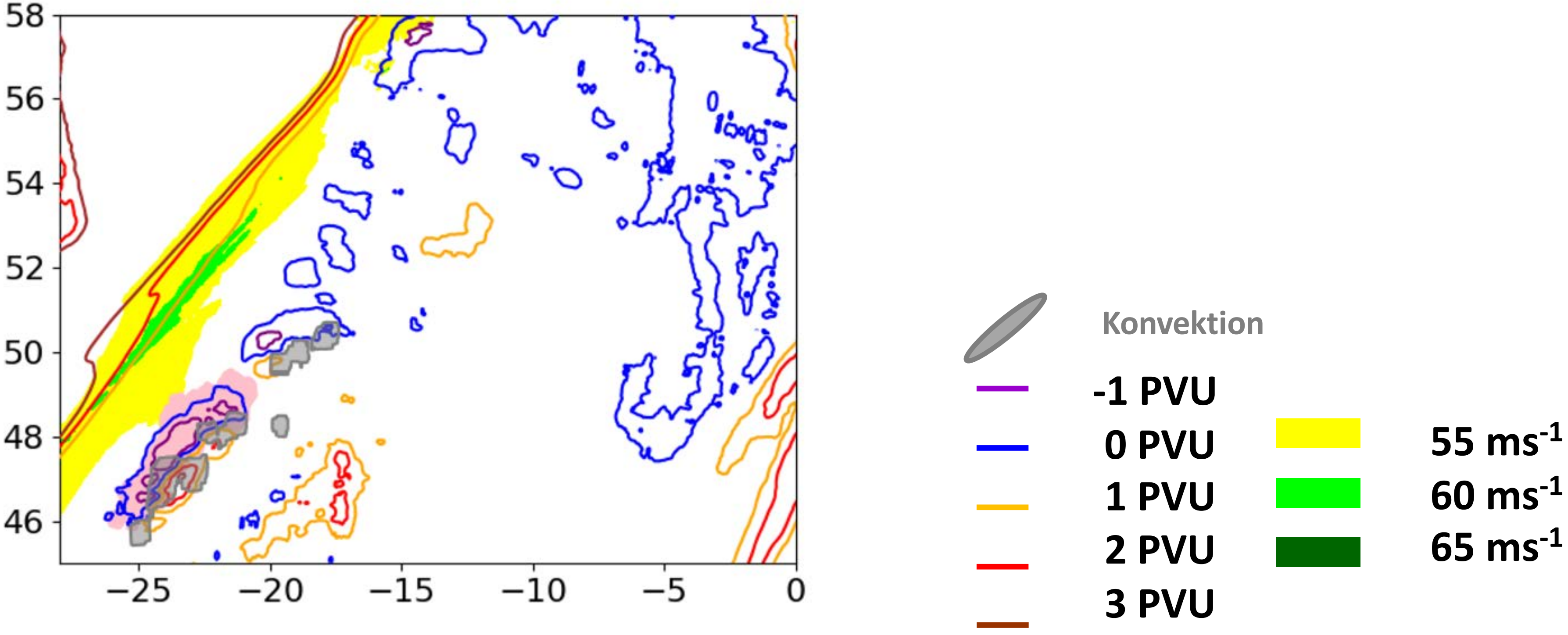

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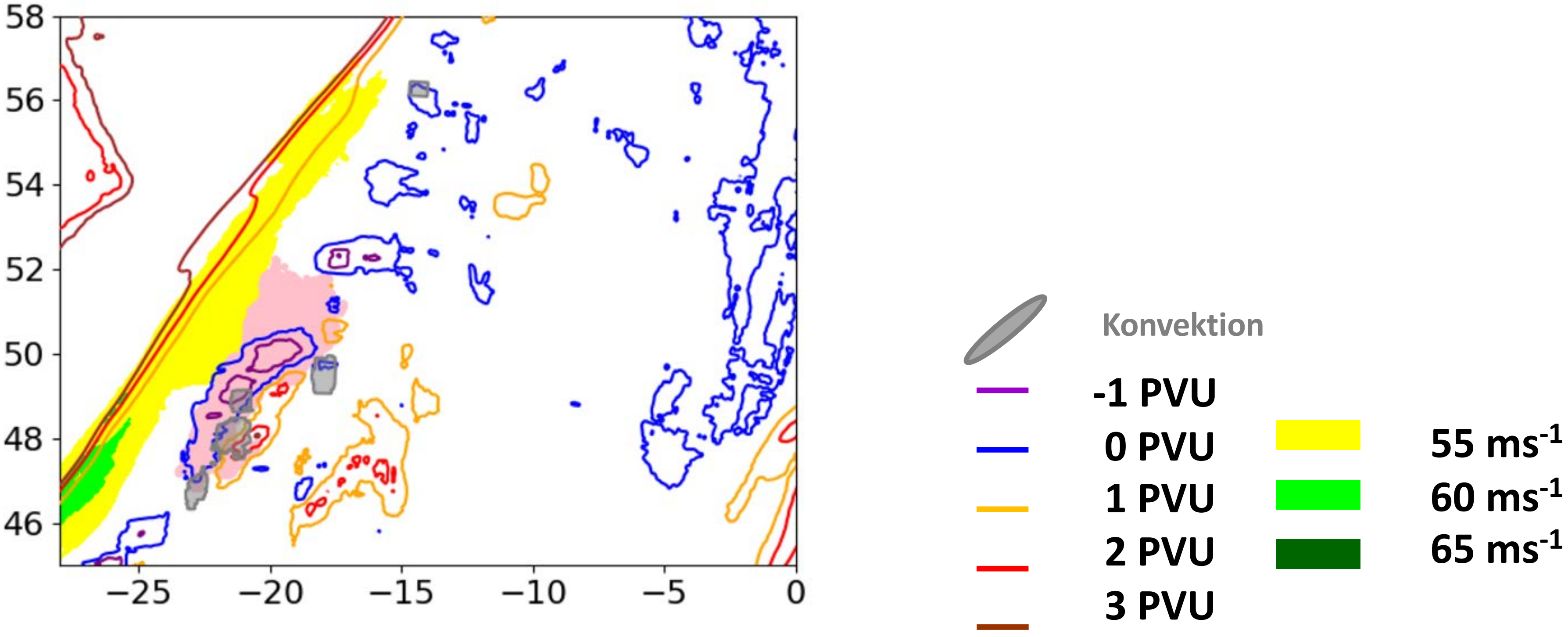

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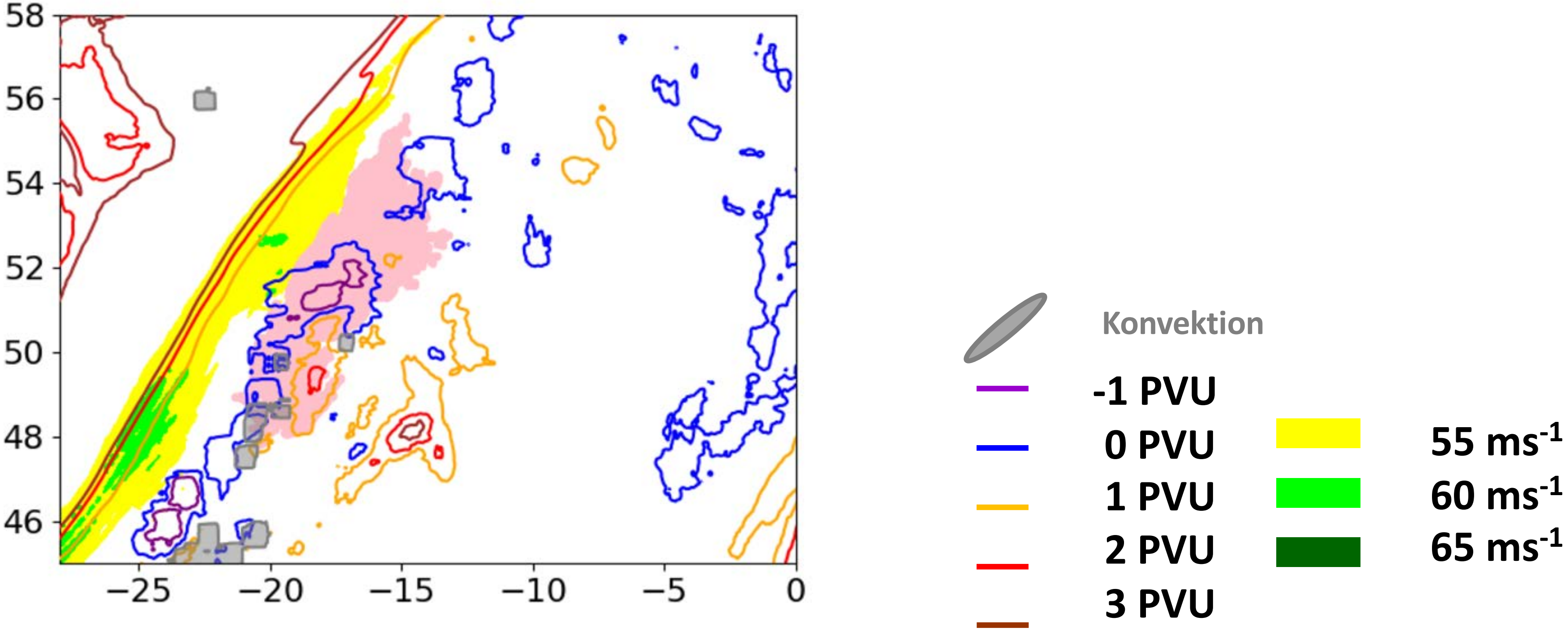

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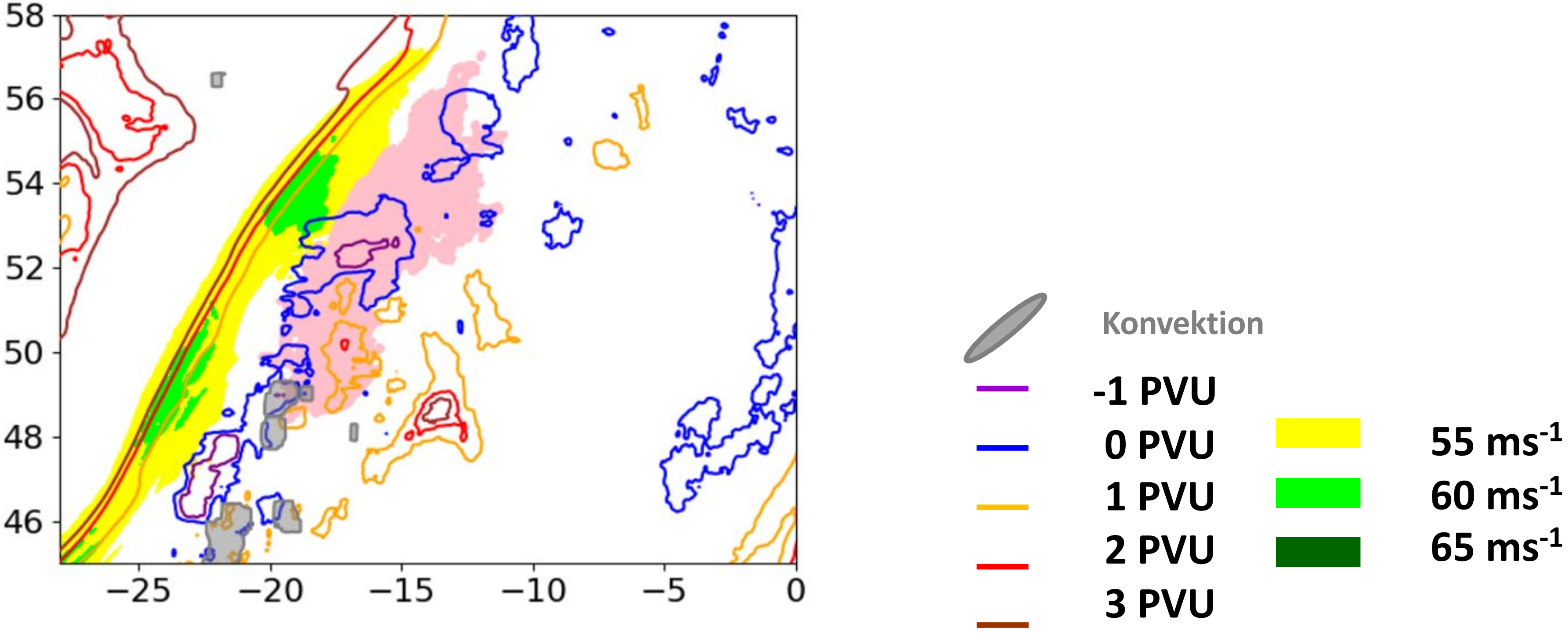

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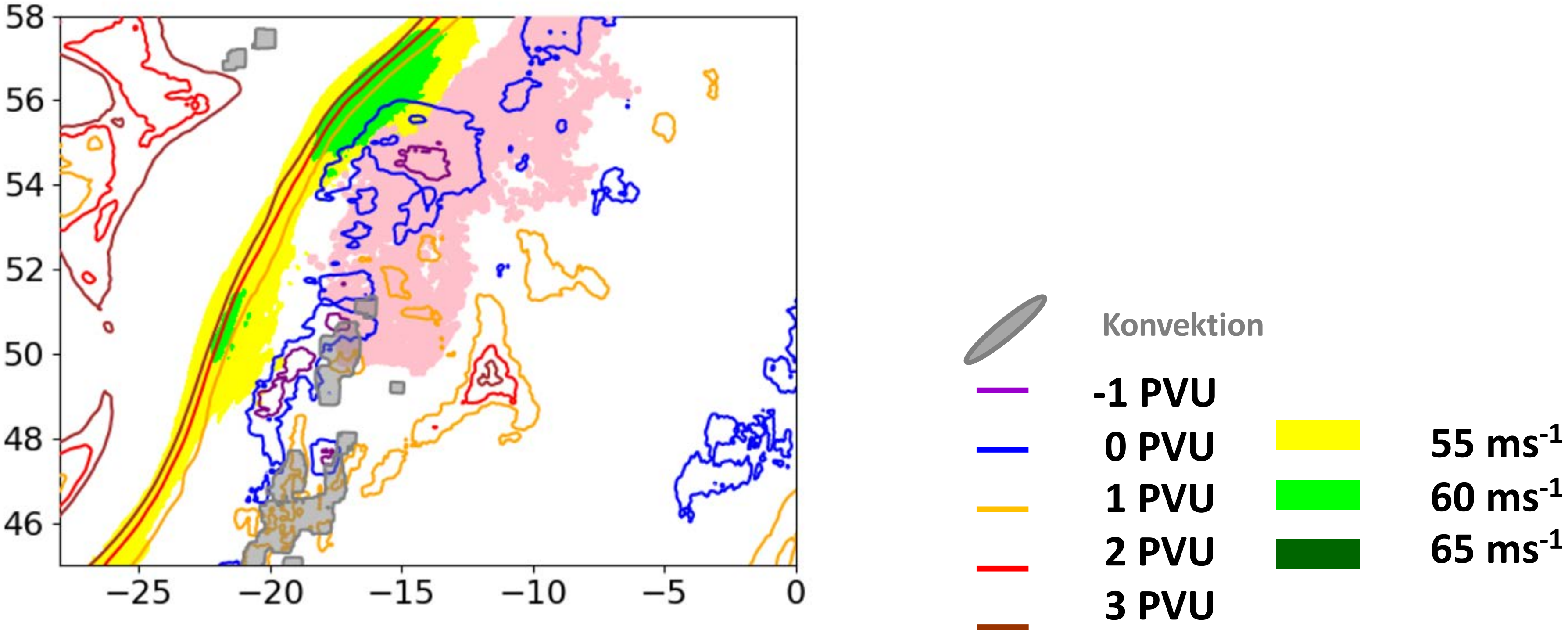

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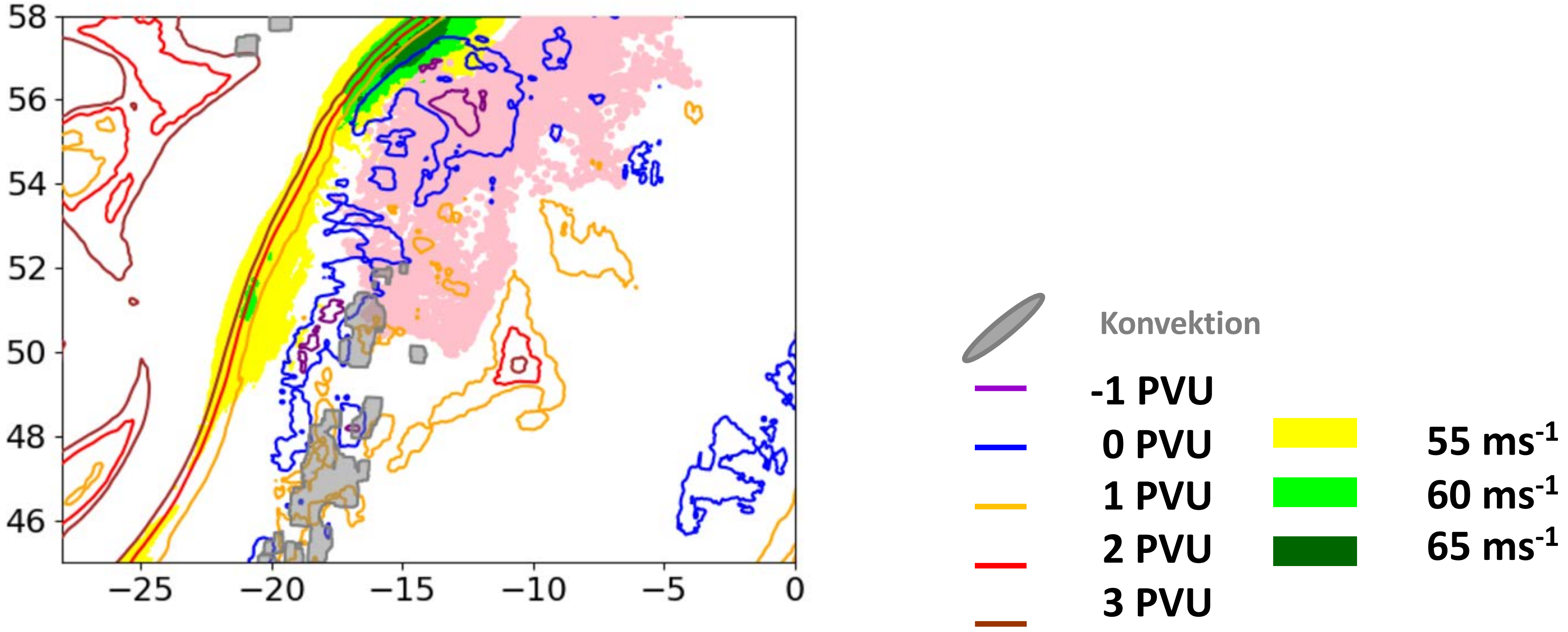


Oertel et al., in prep.

Which diabatic processes lead to form. of PV anomalies?

Material PV rate is determined by latent heating/cooling (Q) and non-conservative forces **F** (friction, turbulent processes):

$$\mathrm{PVR} = \frac{\mathrm{D}}{\mathrm{D}t}\mathrm{PV} = \frac{1}{\rho}\left(\boldsymbol{\eta}\cdot\boldsymbol{\nabla} Q + \boldsymbol{\nabla}\times\mathbf{F}\cdot\boldsymbol{\nabla}\theta\right)$$

where $Q = \frac{\mathrm{D}\theta}{\mathrm{D}t} = \left(\partial T/\partial t\right)_{\text{cloud}} + \left(\partial T/\partial t\right)_{\text{conv}} + (\ldots)_{\text{turb}} + (\ldots)_{\text{rad}}$

and $\mathbf{F} = \left(\partial \mathbf{v}/\partial t\right)_{\text{conv}} + (\ldots)_{\text{turb}}$

can be split further into individual microphysical processes

Approach

1) Output instantaneous physical tendencies from model (every hour)
2) Calculate 3D fields of instantaneous diabatic PV rates due to individual processes → $\mathrm{PVR}_{\mathrm{cloud}}$, $\mathrm{PVR}_{\mathrm{conv}}$, $\mathrm{PVR}_{\mathrm{rad}}$, etc.
3) Trace individual PV rates along backward trajectories to calculate accumulated PV changes due to diabatic processes → $\mathrm{APV}_{\mathrm{cloud}}$, $\mathrm{APV}_{\mathrm{conv}}$, $\mathrm{APV}_{\mathrm{rad}}$, etc., where

$$\mathrm{APV}(\mathbf{x}(t_0),t) = \int_t^{t_0} \mathrm{PVR}(\mathbf{x}(\tau),\tau)\,\mathrm{d}\tau$$

Joos and Wernli 2012 (QJ): COSMO WCB case study
Crezee et al. 2017 (JAS): COSMO idealized cyclones
Spreitzer et al. (JAS, in review): IFS
Attinger et al. (QJ, in review): IFS

Caveats

- Hourly output fields miss some processes
- Trajectories are not fully accurate (also due to 1-h wind fields)
- Results depend on length (in time) of backward trajectories

→ the «budget» is not closed, there will be a residual:

$$PV = \quad PV_{adv} + APV_{tot} + RES$$

where PV_{adv} is PV at end point of backward trajectory

$APV_{tot} = APV_{cloud} + APV_{rad} + \ldots$

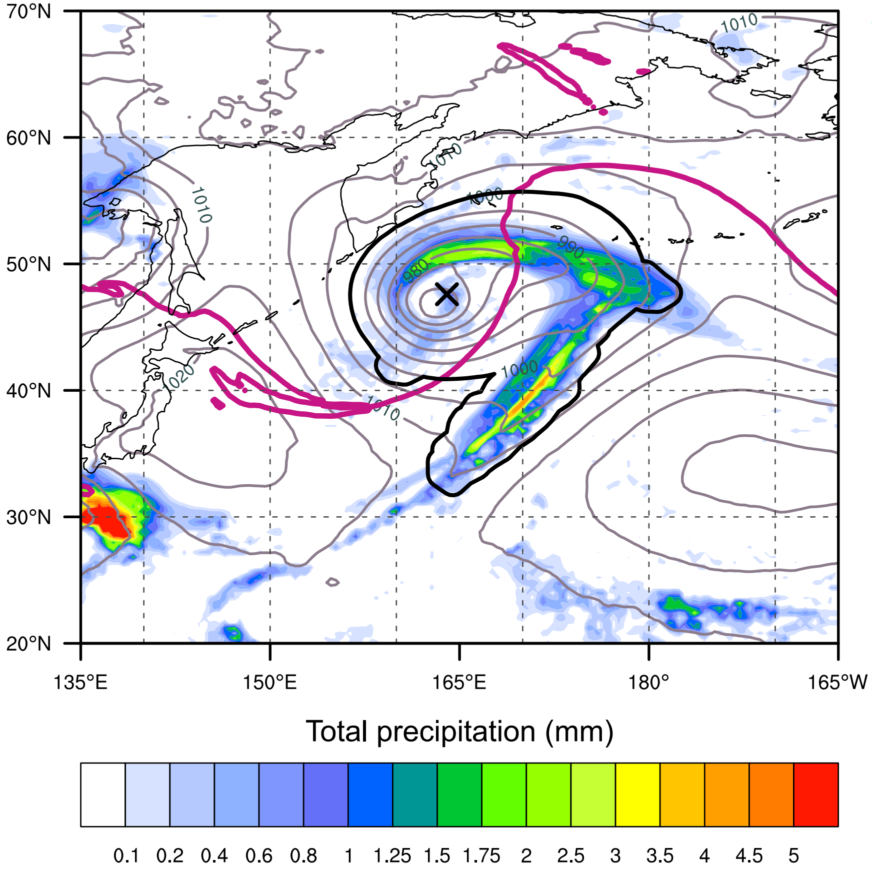
is what we are interested in (and its individ. contr.)

if RES is «small»

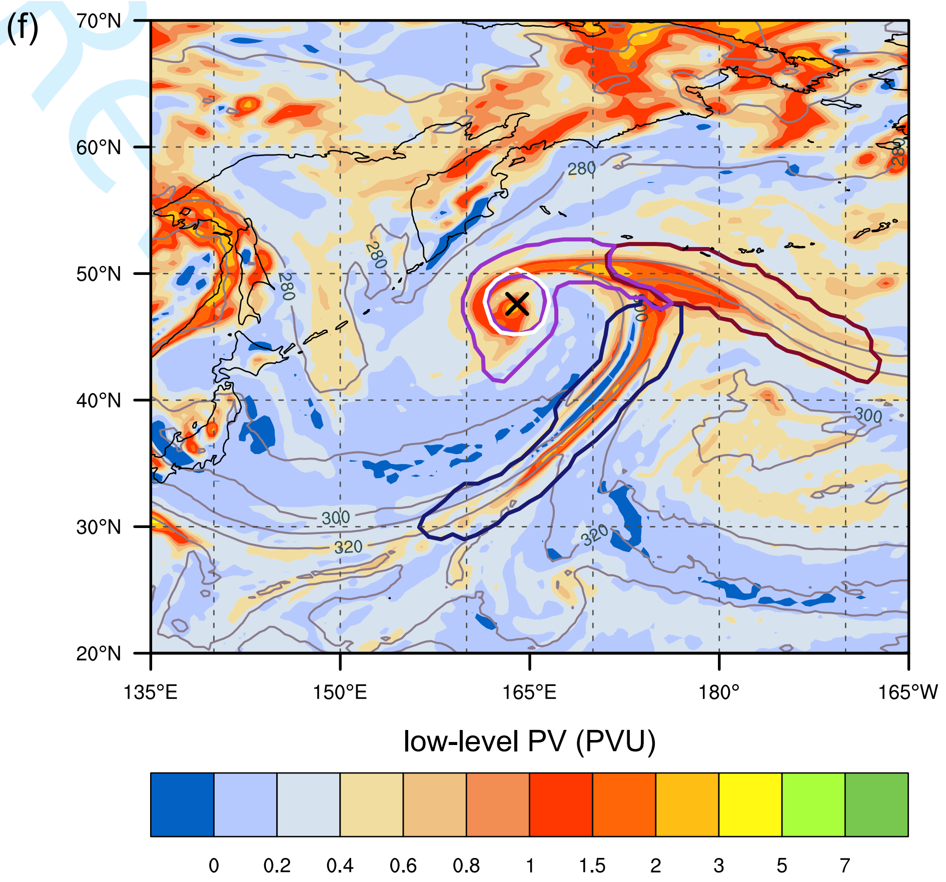
Example: Low-level PV anomalies in surface fronts

Intense North Pacific cyclone with T-bone frontal structure

hourly precipitation



low-level PV (850-950 hPa)

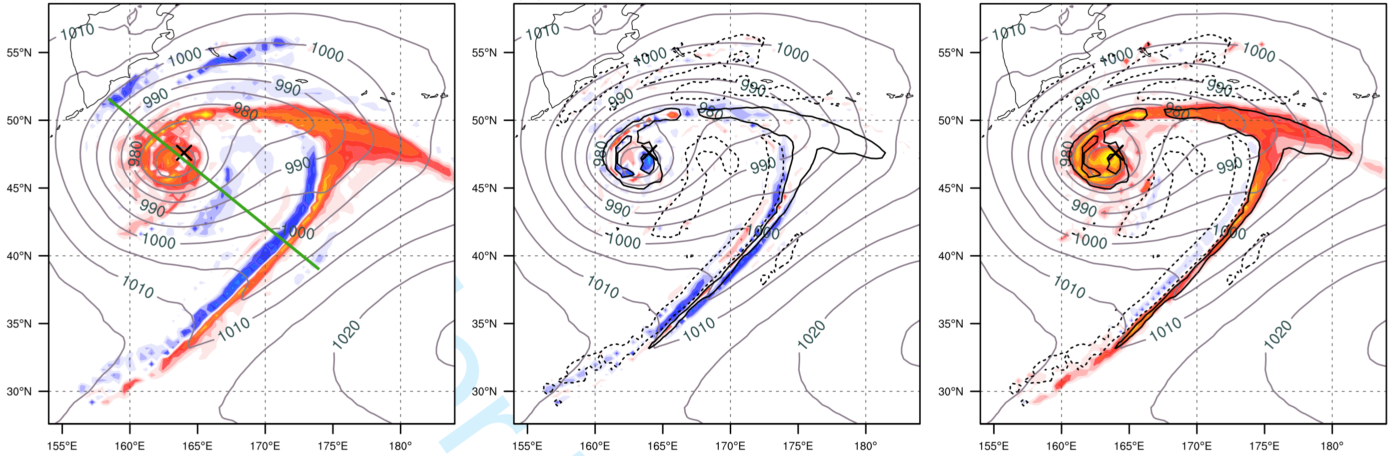


Attinger et al. (QJ, in review)

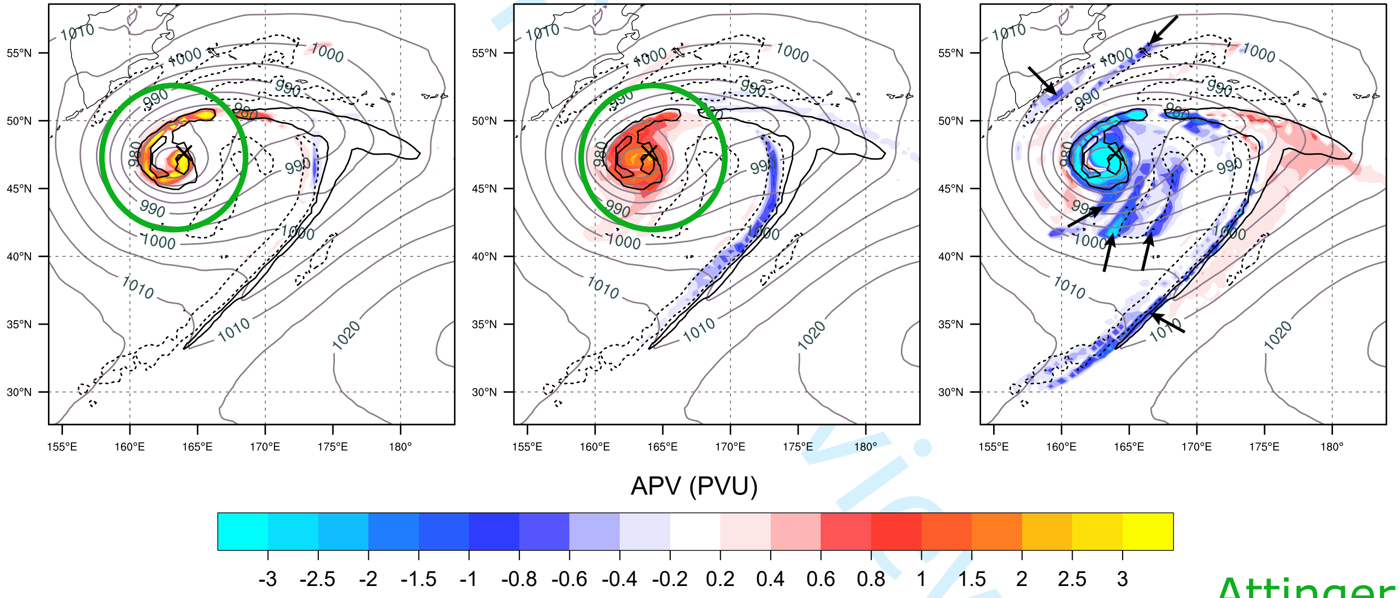
Example: Low-level PV anomalies in surface fronts

APV contributions between 950-850 hPa from different processes

(a) Total APV (b) Residual (c) Condensation



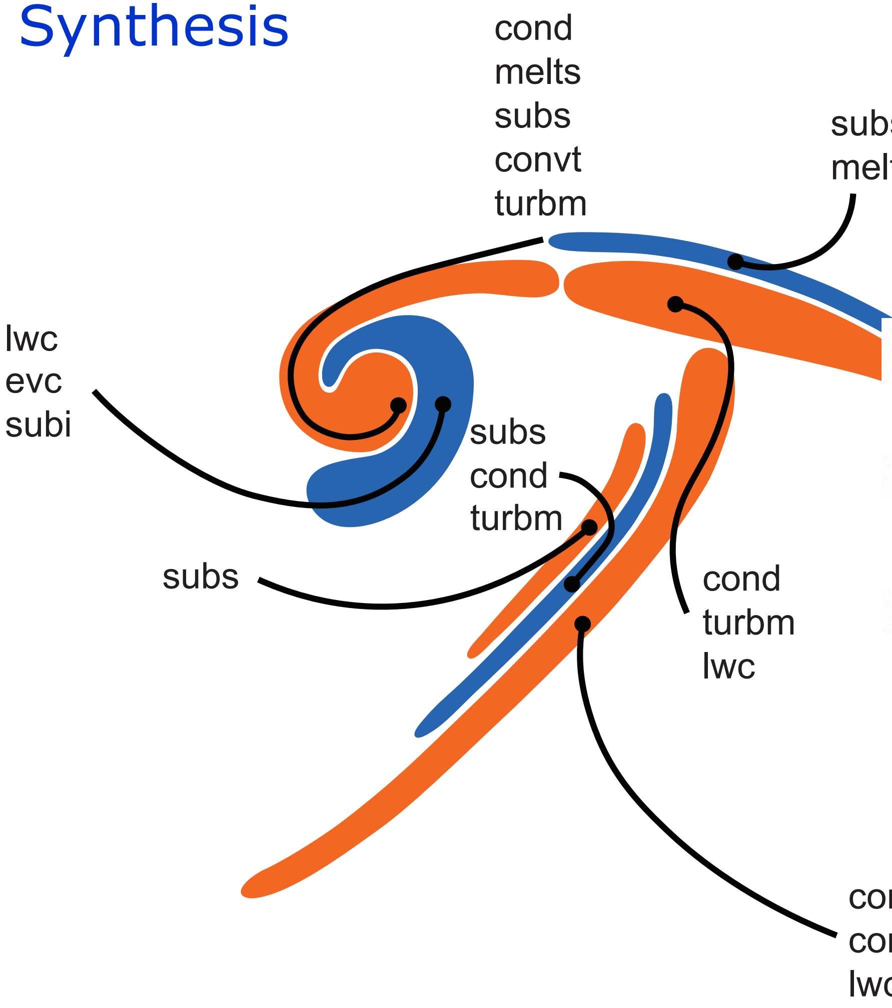
(d) Melting of snow (e) Sublimation of snow (f) Turbulence

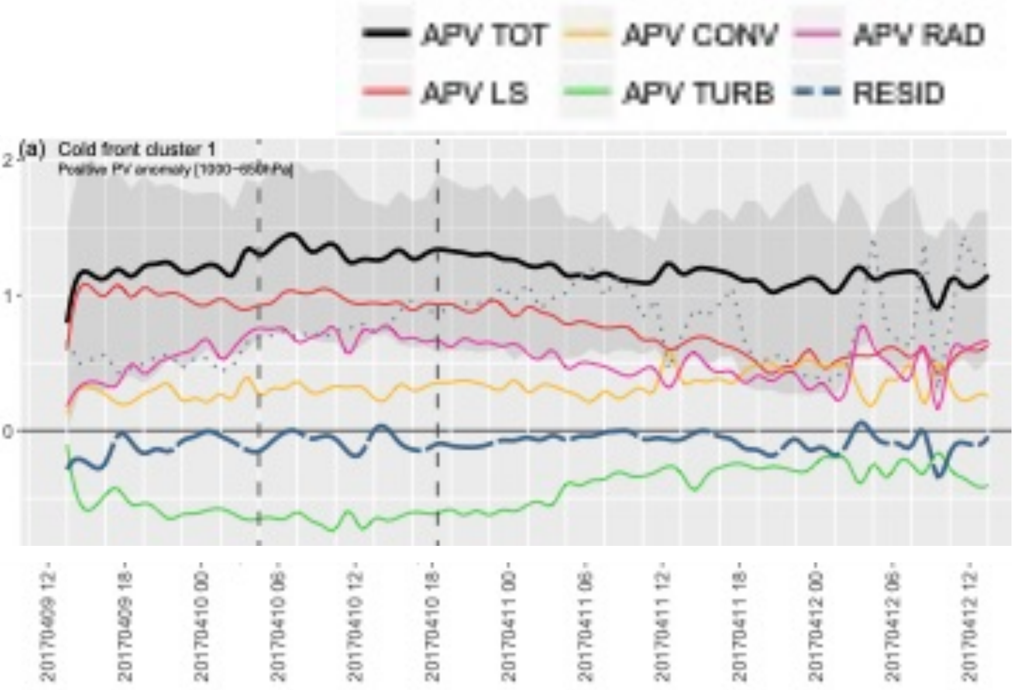


Attinger et al. (QJ, in review)

Example: Low-level PV anomalies in surface fronts

Synthesis





Consistency of major APV contributions for pos. PV anomaly along cold front during cyclone lifecycle

Attinger et al. (QJ, in review)

On-the-fly diagnostics

Standard approach to evaluate climate simulations:

- decide about diagnostics (What do we want to learn from the simulations?) and required output fields
- run simulations and write output to disk
- run diagnostics offline (i.e., using output on disk)
- advantages: simple, simulation and diagnostics fully independent
- disadvantages: you can only analyze what you planned for; very high storage demand → typically no output of 3D fields with high-temporal resolution → many interesting questions cannot be addressed

On-the-fly diagnostics

Novel approach to evaluate climate simulations:

Concept: storage becomes unfeasible and computations comparatively cheap

→ regularly rerun model with parallel simulations from checkpoints

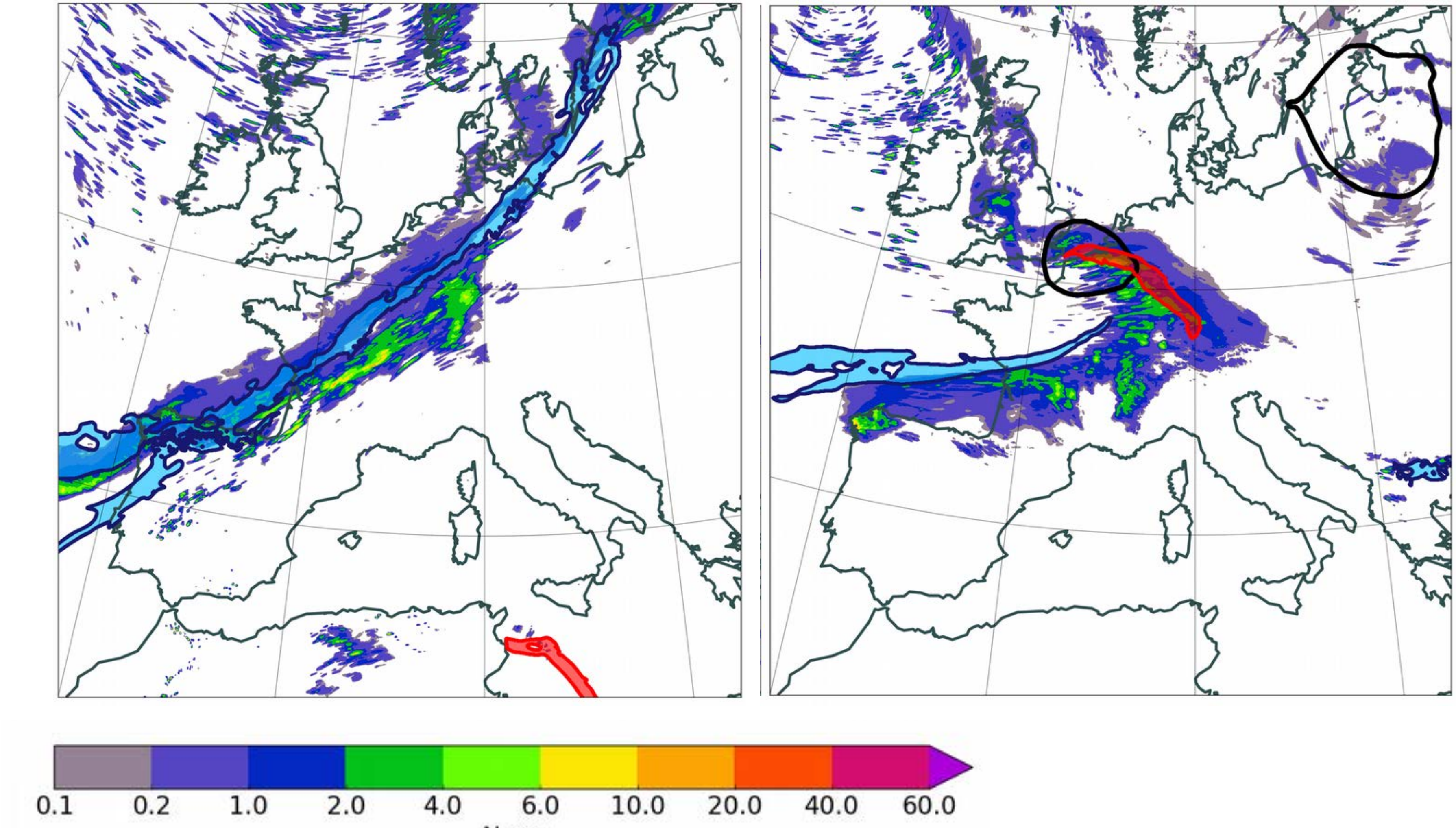
→ write recent model time steps to «fast disk» and do new diagnostics «on the fly»

→ similar to «particle physics approach with beam experiments and detectors»

- advantages: strongly reduced storage; diagnostics can access fields at very high temporal resolution → high-quality diagnostics; new insight
- disadvantages: requires bit-reproducibility; technically challenging

On-the-fly diagnostics

Example from crClim project: identify cyclones and fronts and attribute precipitation to these features



Rüdisühli et al., in prep.

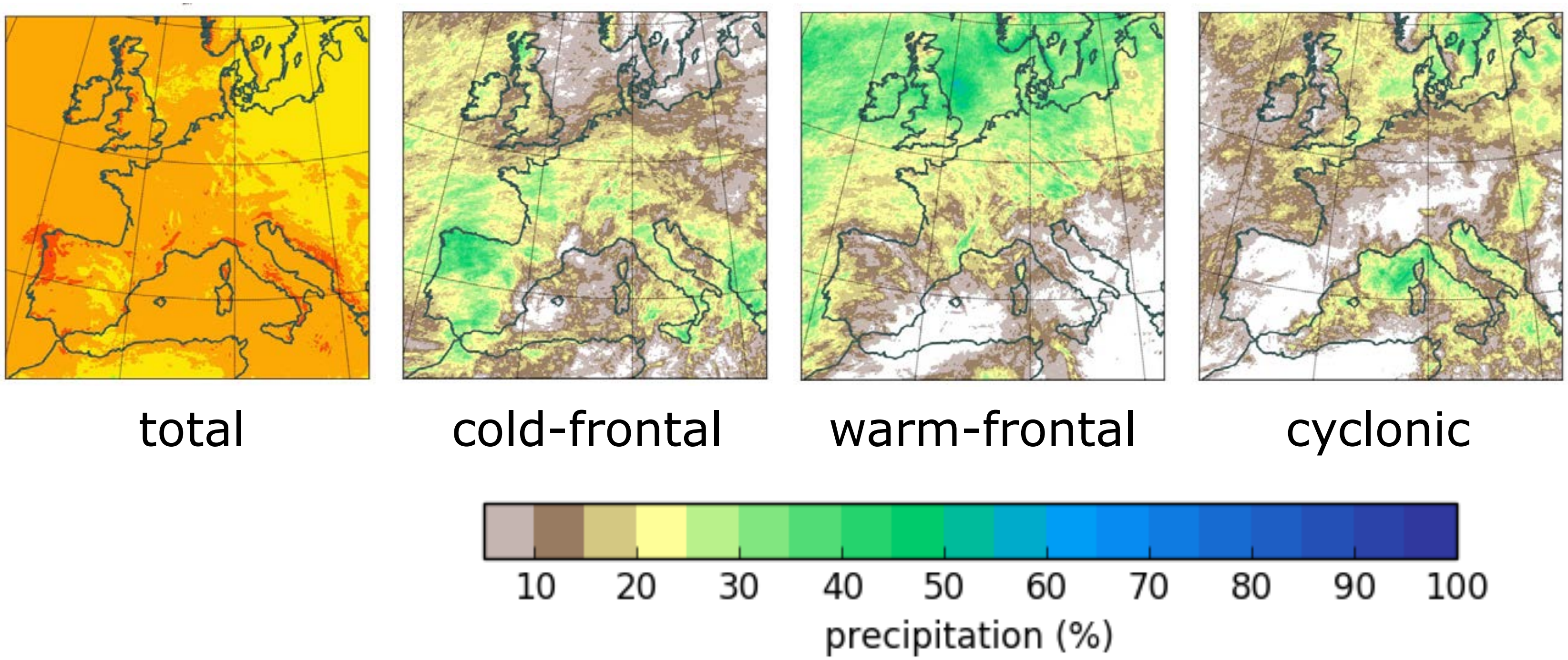
On-the-fly diagnostics

Identify cyclones and fronts and attribute rain to these features

Example: heavy precipitation in winter:

heavy

(> 99th)



total cold-frontal warm-frontal cyclonic

Rüdisühli et al., in prep.

Summary

Numerical models are essential research tools in atmospheric dynamics

The DWD support for COSMO has been extremely helpful for university reserach groups

Diagnostics can be built into the model (e.g., COSMO-tag, COSMO-iso, COSMO online trajectories) or run «on the fly» (e.g., cyclone and front identification)

Examples gave insight into

- atmospheric moisture cycle (long vs. short-range transport)
- embedded convection in WCBs and neg. PV in outflow
- role of below-cloud processes for low-level PV in cyclone centre
- novel types of analysis of «weather» in climate simulations