Diabatic processes in extratropical cyclones

Heini Wernli – ETH Zurich

With contributions from: Roman Attinger, Hanin Binder, Maxi Boettcher, Christian Grams, Hanna Joos, Erica Madonna, Elisa Spreiter, Andreas Schäfler and the NAWDEX team

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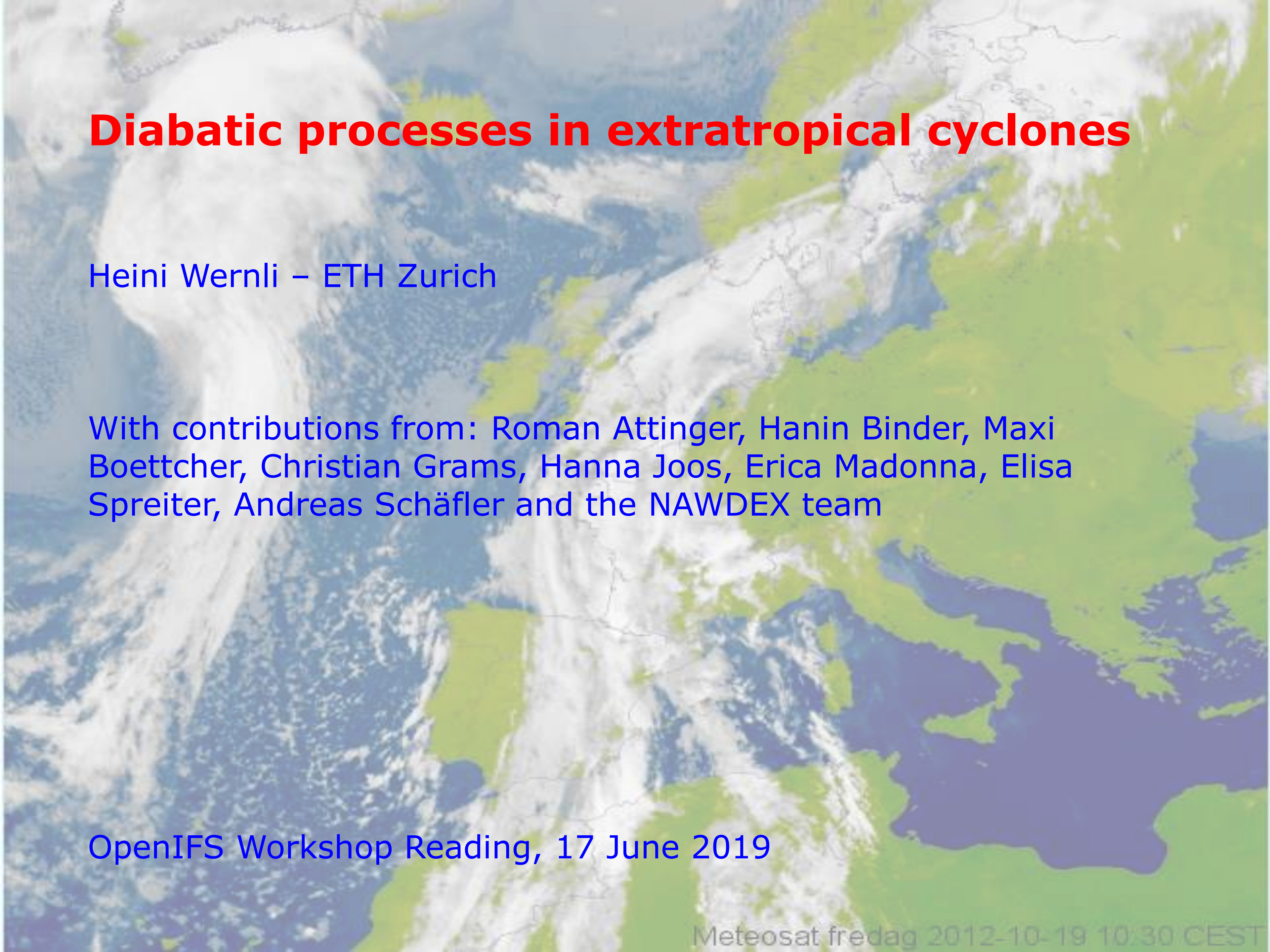


What are diabatic processes?

Momentum equations:

dynamical core, "dry dynamics"

$$\underbrace{\frac{\partial u}{\partial t}}_{\text{local time change}} = \underbrace{-u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z}}_{\text{advection}} - \underbrace{\frac{1}{\rho}\frac{\partial p}{\partial x}}_{\text{pressure gradient force}} + \underbrace{fv}_{\text{Coriolis force}}$$

$$+ \underbrace{\frac{uv}{r_e}\tan(\alpha)}_{\text{curvature term}} + \underbrace{\frac{\partial u}{\partial t_{\text{conv}}}}_{\text{convective transport}} + \underbrace{\frac{\partial u}{\partial t_s}}_{\text{eddy transport}}$$

parameterized momentum tendencies
due to convection and turbulence

What are diabatic processes?

Temperature equation:

nonlinear advection; adiabatic warming/cooling

$$\frac{\partial T}{\partial t} = -u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} - \omega\left(\frac{\partial T}{\partial p} - \frac{RT}{c_p p}\right) + \frac{H}{c_p}$$

parameterized temperature tendencies
due to clouds, convection and radiation

What are diabatic processes?

Diabatic processes = PV non-conservative processes

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 $Q = \frac{\mathrm{D}\theta}{\mathrm{D}t} = \left.\frac{\mathrm{D}\theta}{\mathrm{D}t}\right|_{\text{cloud}} + \left.\frac{\mathrm{D}\theta}{\mathrm{D}t}\right|_{\text{conv}} + (\ldots)_{\text{turb}} + (\ldots)_{\text{rad}}$

and $\mathbf{F} = \left(\partial \mathbf{v}'/\partial t\right)_{\text{conv}} + (\ldots)_{\text{turb}}$

Outline

A) Does cloud latent heating impact cyclone intensity?

B) Where does maximum latent heating occur in cyclones?

C) What is the PV evolution along WCBs?

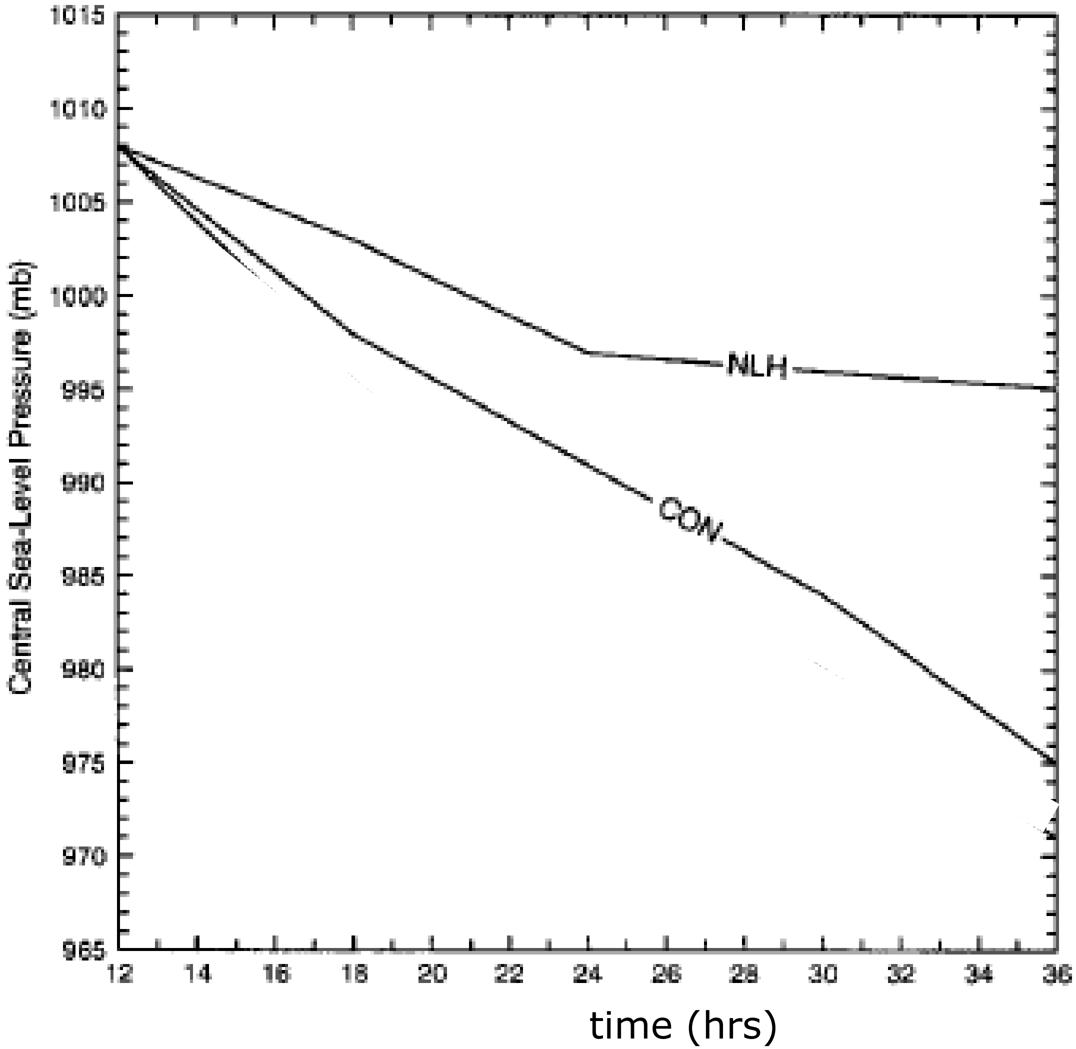
D) How do WCBs influence cyclone intensity and upper-level Rossby wave dynamics?

E) How can we observe diabatic processes?

F) How can we analyse diabatic processes in models?

Latent heat release and cyclone intensification

Classical „dry“ sensitivity experiments



ΔSLP=13 hPa / 24 h

without latent heat release

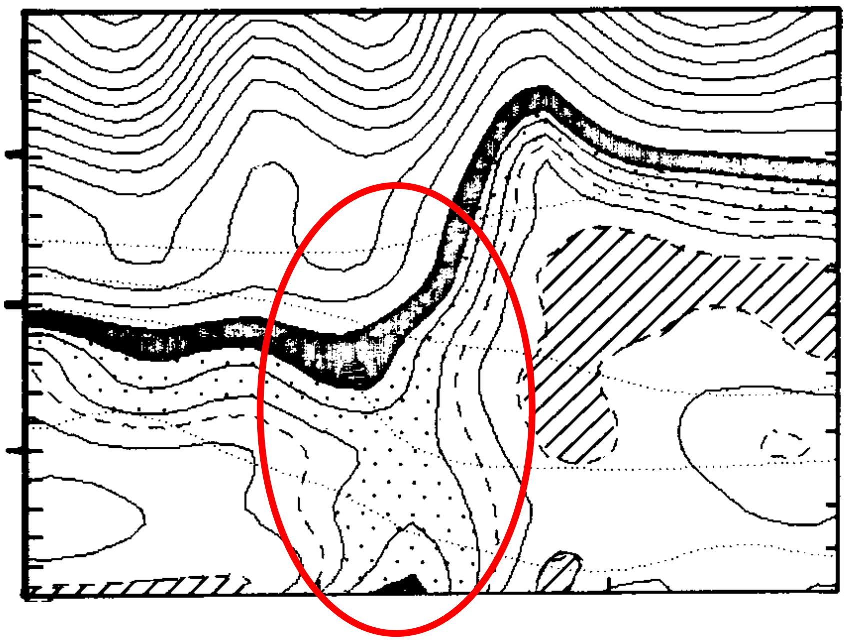
ΔSLP=20 hPa / 24 h
contribution to cyclone
deepening from LHR

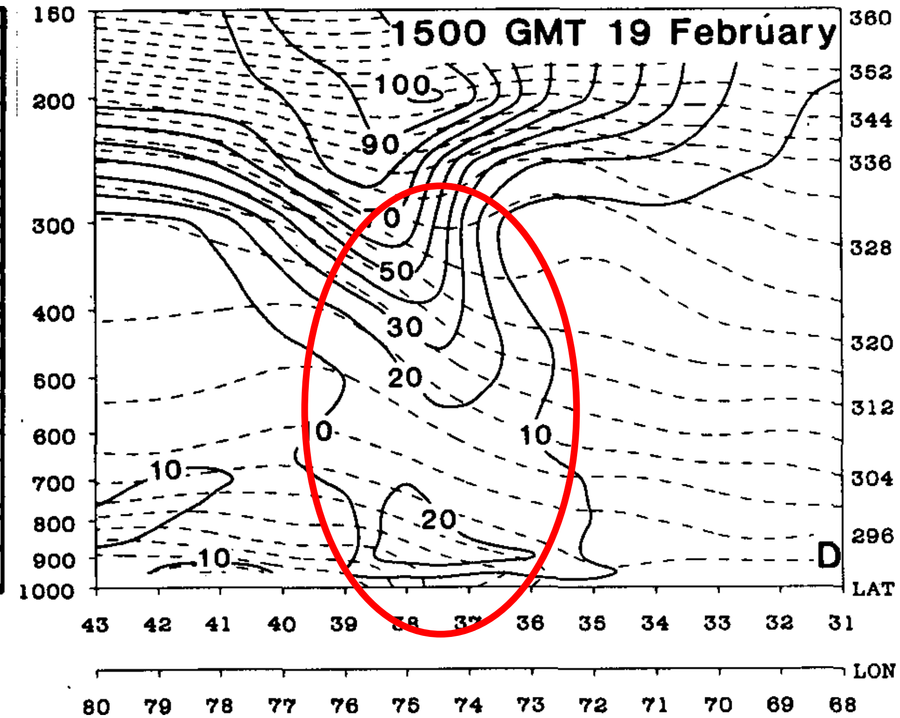
with latent heat release

Stoelinga 1996 (MWR)

The PV-tower perspective of cyclogenesis

Historic examples (vertical sections across cyclones)





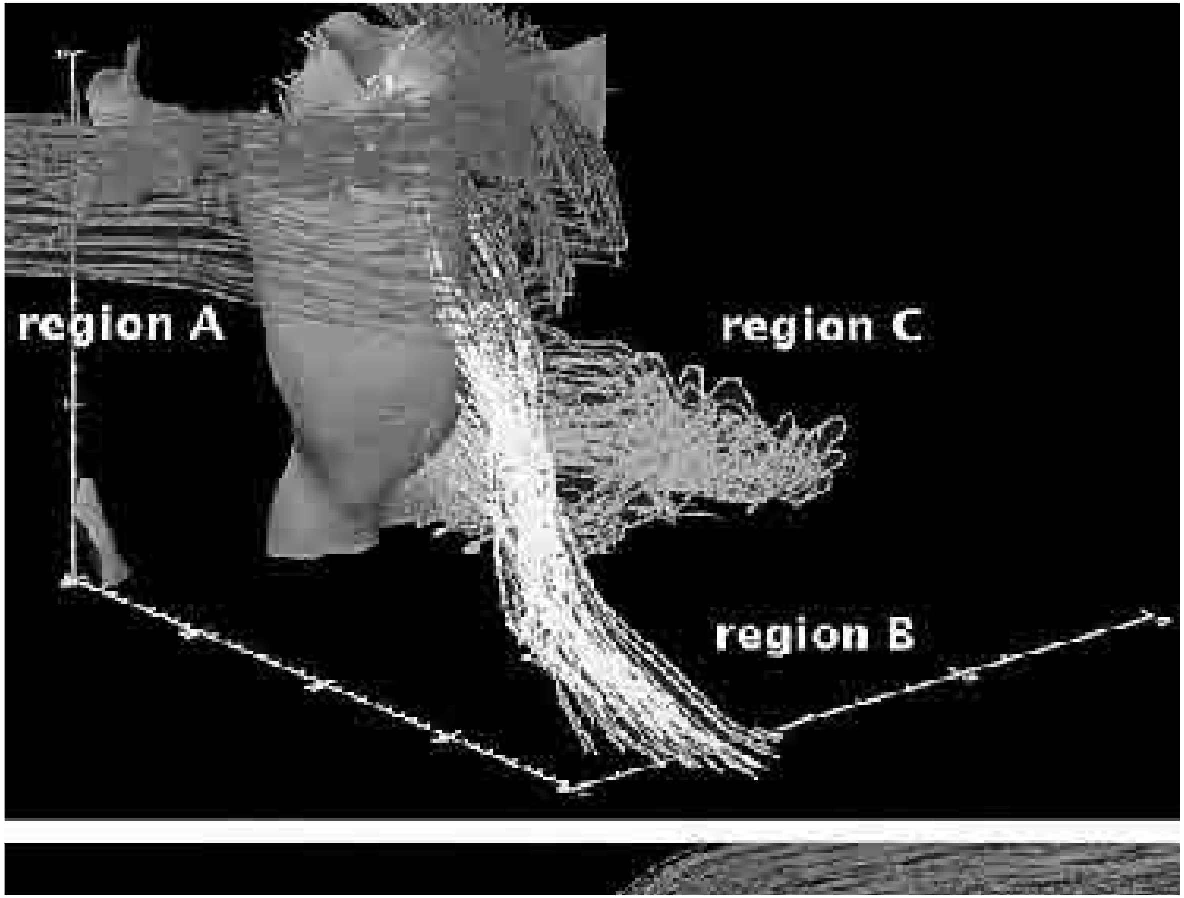
„October Storm"
(UK, October 1989)
Hoskins and Berrisford 1991

„President Day's Storm"
(USA, February 1979)
Whitacker et al. 1988

→ intense cyclones have vertical „tower" of anomalously high PV

The PV-tower perspective of cyclogenesis

Different airstreams contribute to PV tower



view from SW towards mature cyclone near Iceland

gray shading = 1 pvu

backward trajectories from different segments of the tower

→ lower part of PV tower is formed in ascending flow where latent heating occurs

Rossa et al. 2000 (MAP)

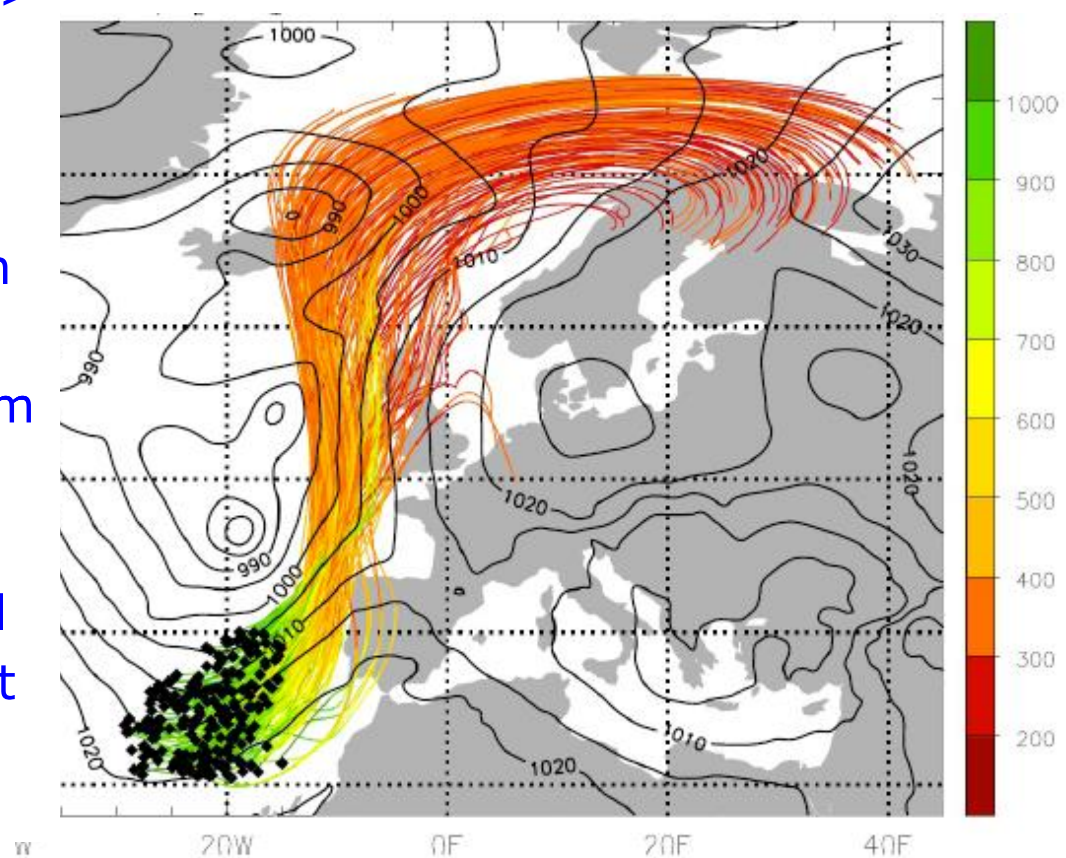
Where does maximum latent heating occur?
In warm conveyor belts …

selection criterion: ascent of > 600 hPa in 2 days

→ coherent bundle of trajectories, „airstream", with

- polew. transport > 3500 km
- latent heating > 20 K

flow structure in extratropical cyclones with strongest latent heat release & precipitation
Browning 1990

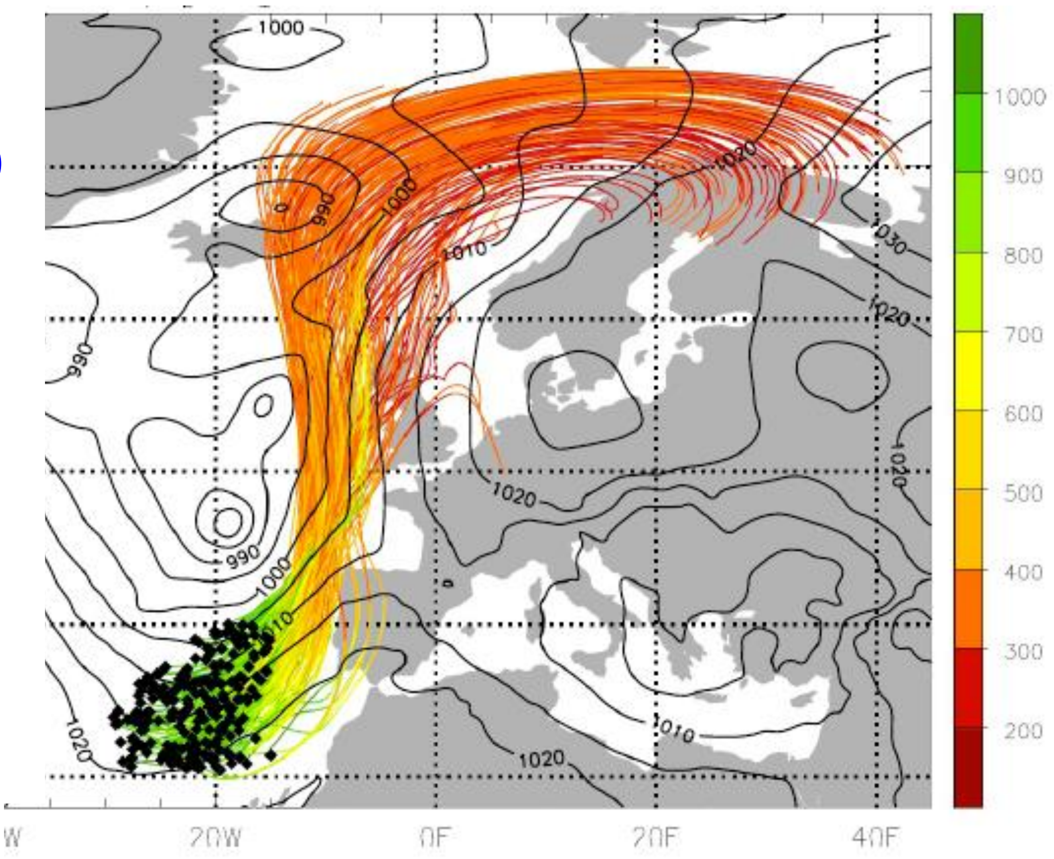


Joos and Wernli 2012 (QJ)

Where does maximum latent heating occur?
In warm conveyor belts …

Terminology:

- WCB outflow (p < 400 hPa)
- WCB ascent
- WCB inflow (p > 700 hPa)



Joos and Wernli 2012 (QJ)

PV evolution along WCB

Kleinschmidt 1950 (Met. Rundsch.)
Hoskins et al. 1985 (QJ)

$$\frac{D}{Dt}PV \approx \frac{1}{\rho}(f+\zeta)\cdot\frac{\partial\dot{\theta}}{\partial z}$$

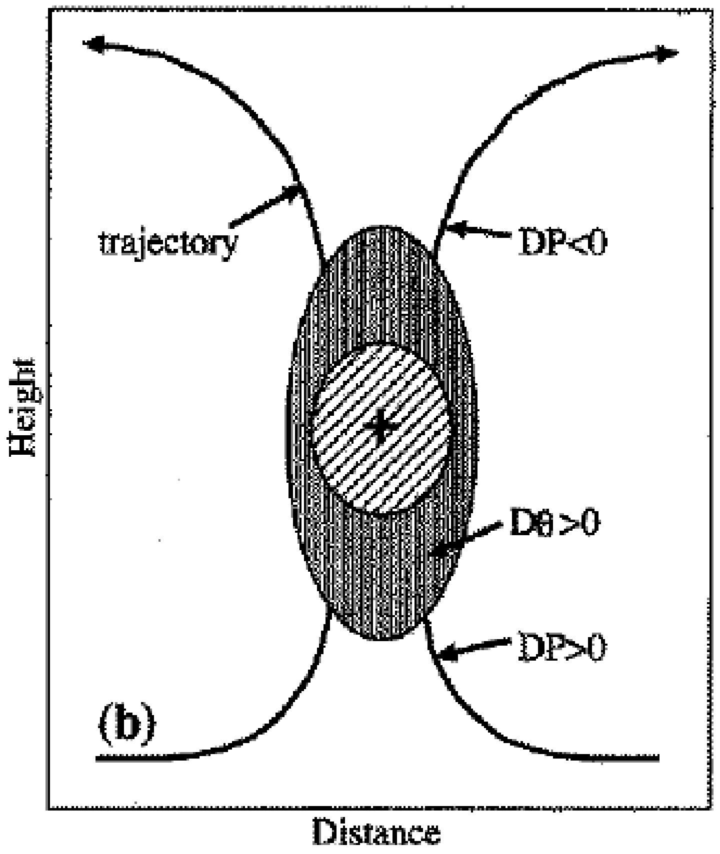
PV is materially produced/destroyed below/above level of max. heating

PV evolution along WCB

Kleinschmidt 1950 (Met. Z.)
Hoskins et al. 1985 (QJ)
PV is materially produced/destroyed below/above level of max. heating

Wernli & Davies 1997 (QJ)

empirically from case study:
PV(outflow) ≈ PV(inflow)



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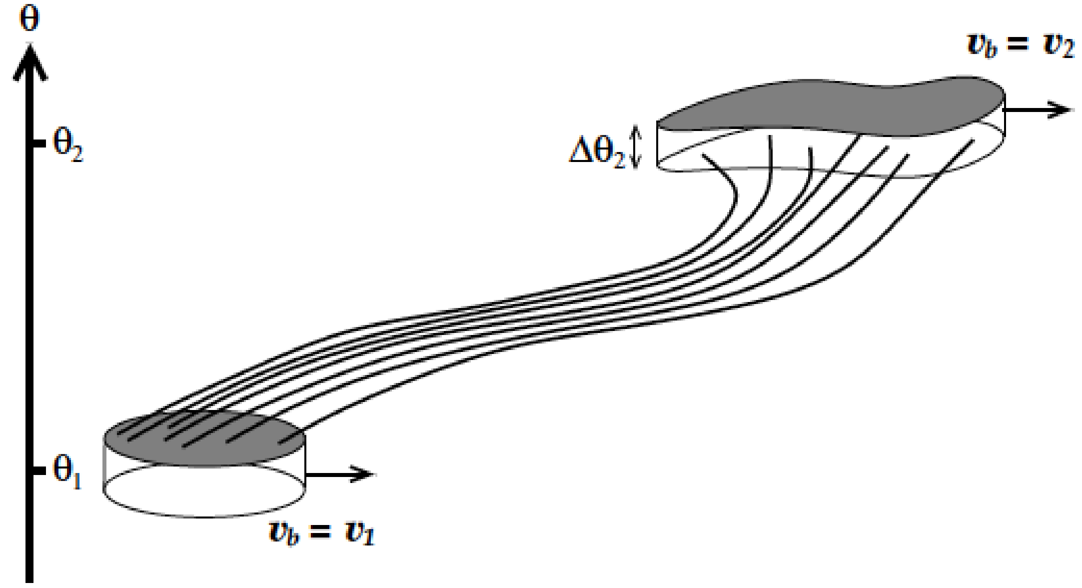

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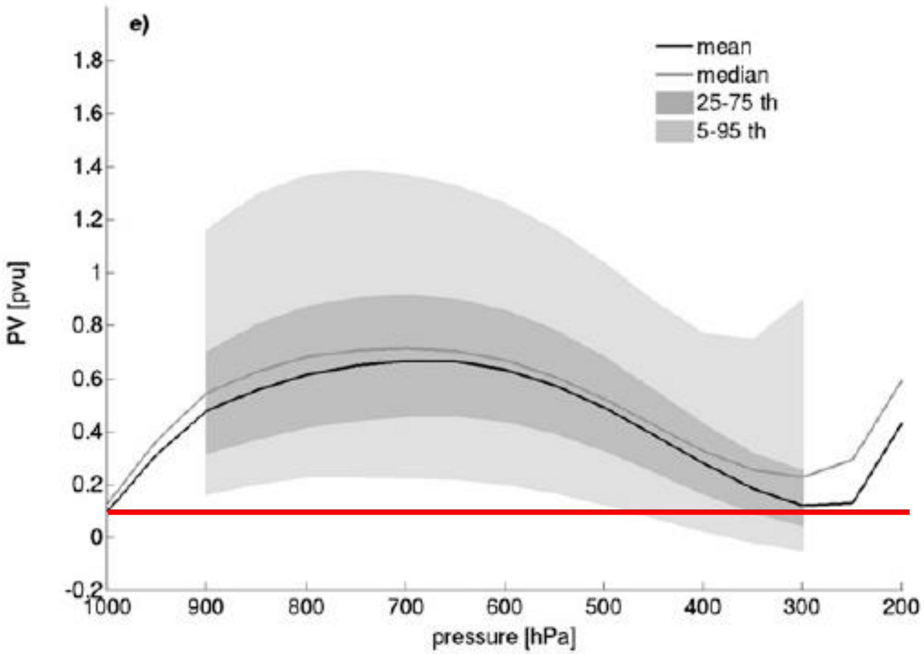
theoretically:
PV(outflow) = PV(inflow)

Madonna et al. 2014 (JClim)
empirically from WCB climatology:
PV(outflow) ≈ PV(inflow)
≈ 0.1-0.3 pvu



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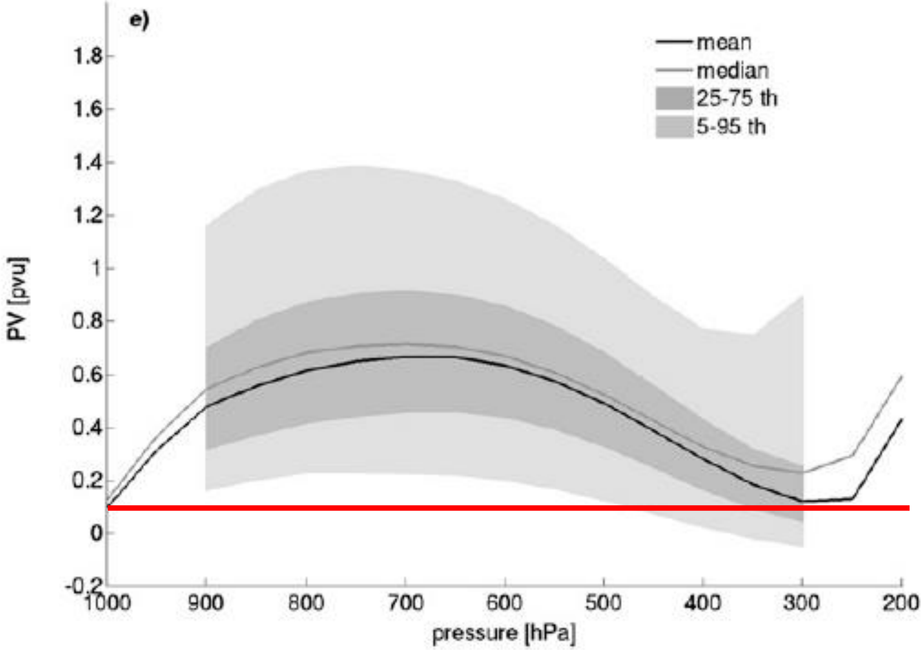
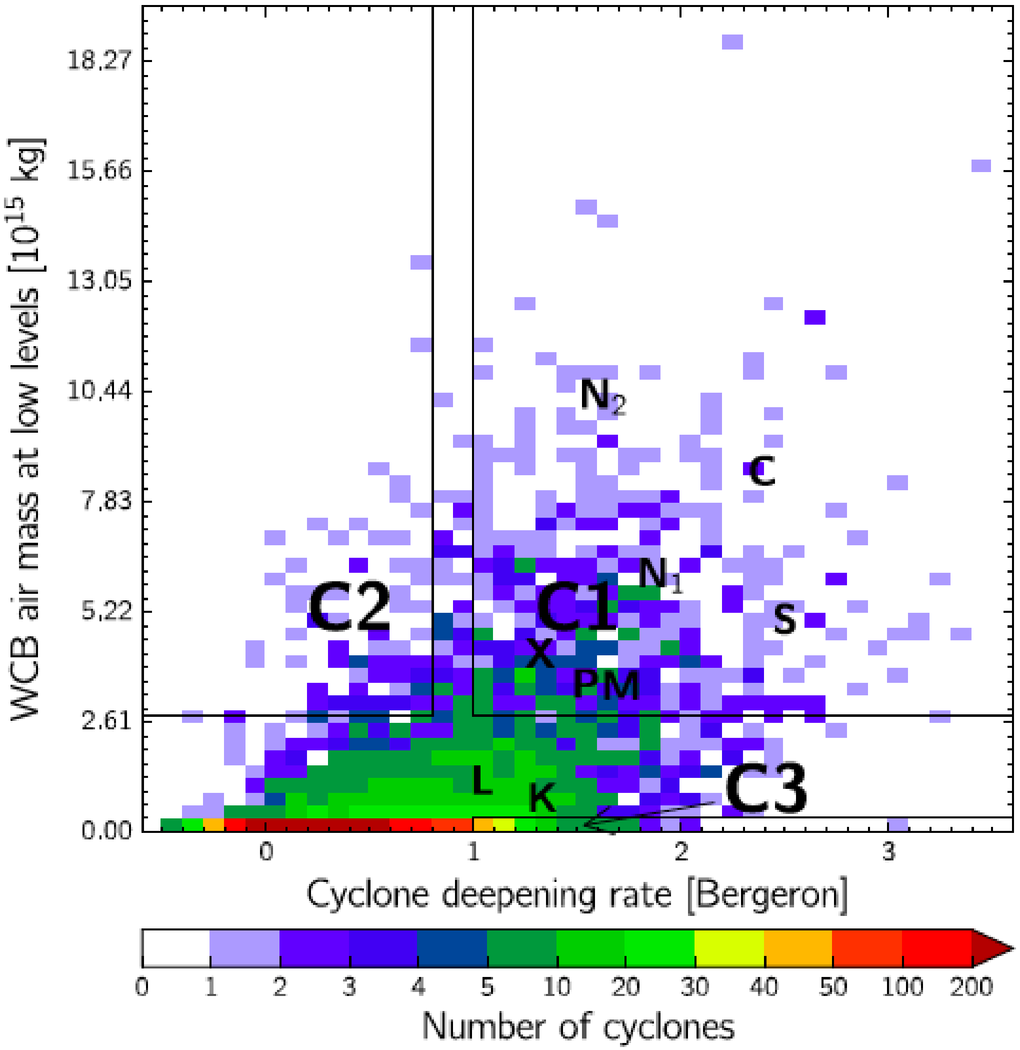
Madonna et al. 2014 (JClim)
empirically from WCB climatology:
PV(outflow) ≈ PV(inflow)
≈ 0.1-0.3 pvu
PV(ascent) ≈ 0.4-0.9 pvu



Is PV production in WCB ascent important for cyclone intensification?

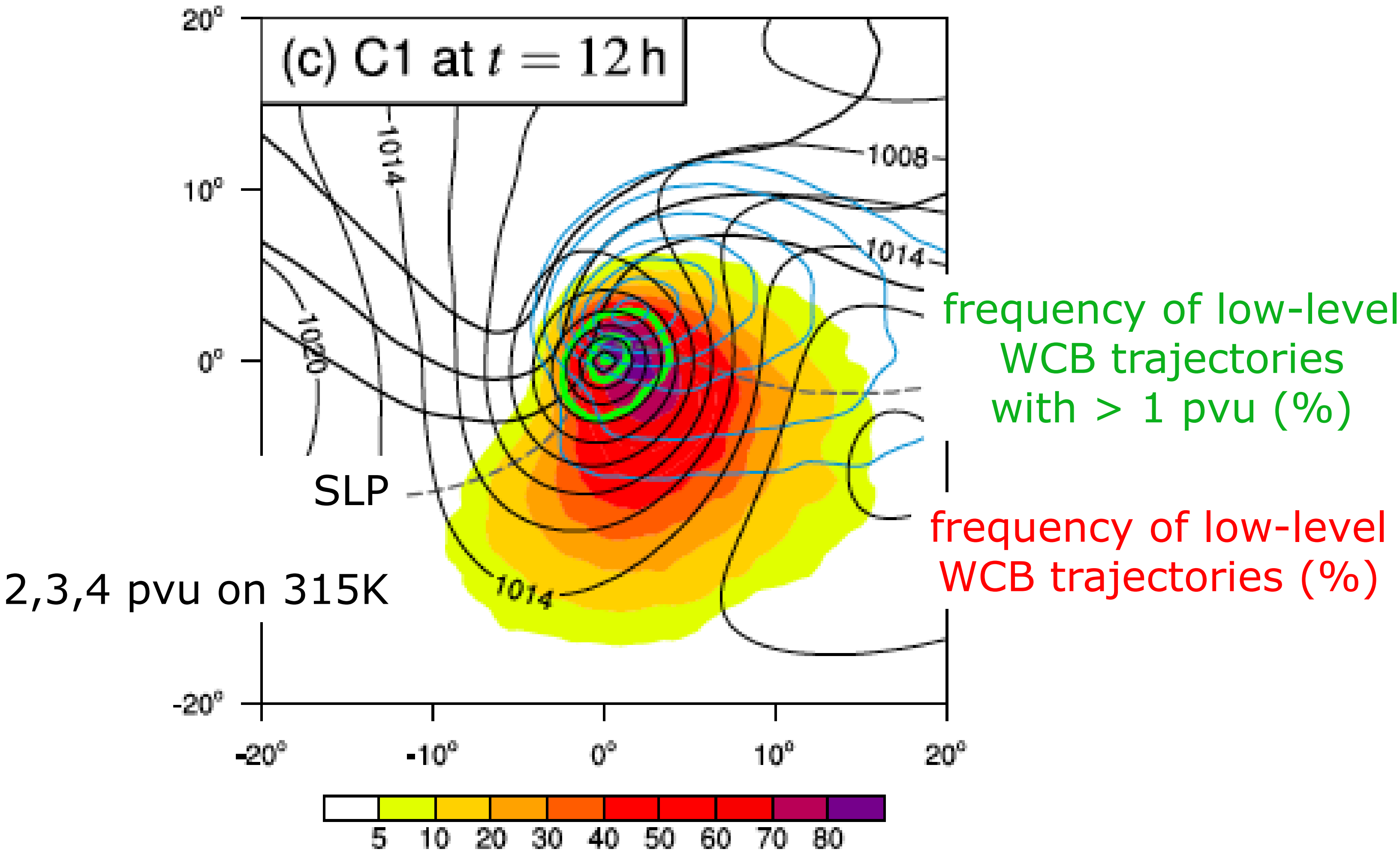
2D histogram of cyclone intensification vs. strength of WCB (number of WCB trajectories)



Spearman rank correlation of 0.68

Binder et al. 2016 (JAS)

Composites of C1 cyclones

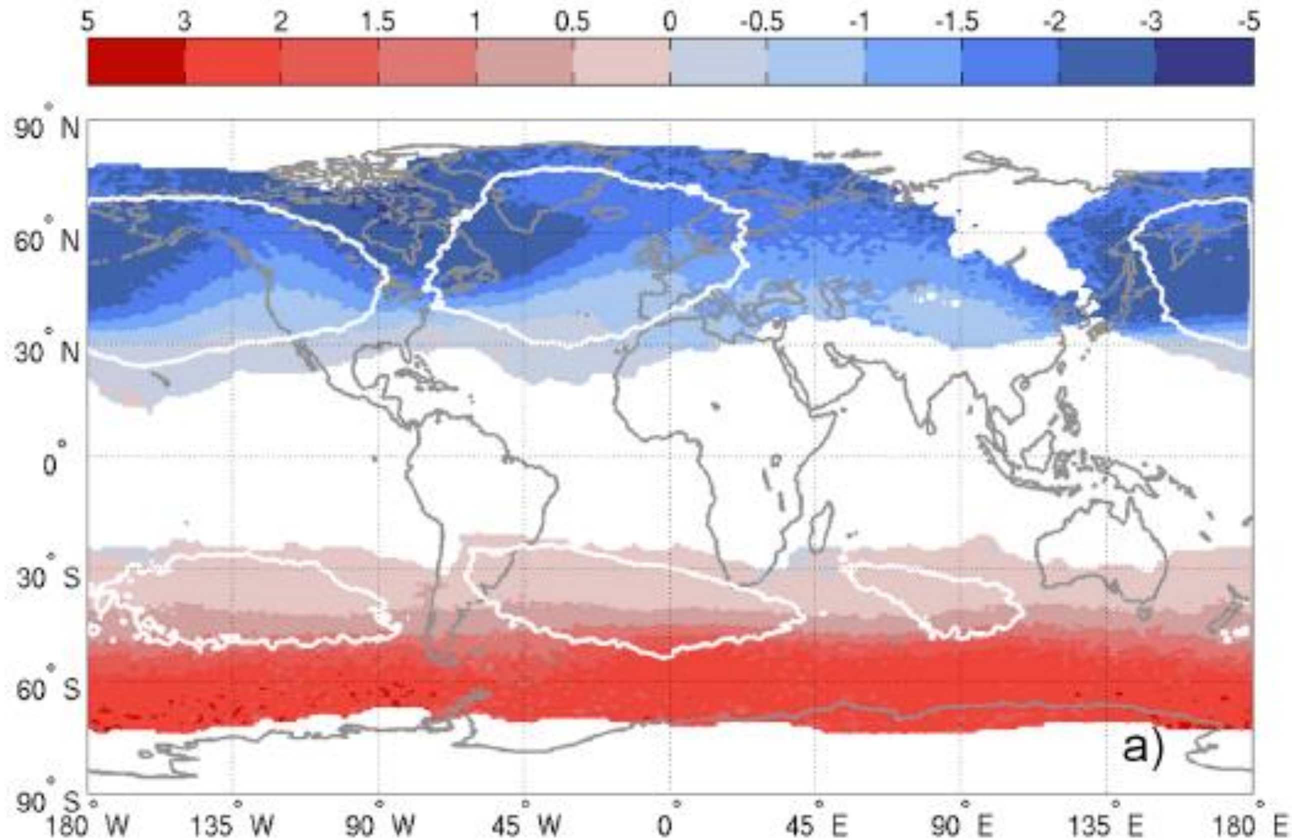


→ diabatic PV production in WCB ascent close to cyclone center contributes to explosive cyclone deepening

Binder et al. 2016 (JAS)

Is low PV in WCB outflow important for Rossby wave dynamics?

PV(outfl.)≈0.1–0.3 pvu – what does this mean in terms of **PV anomaly**?

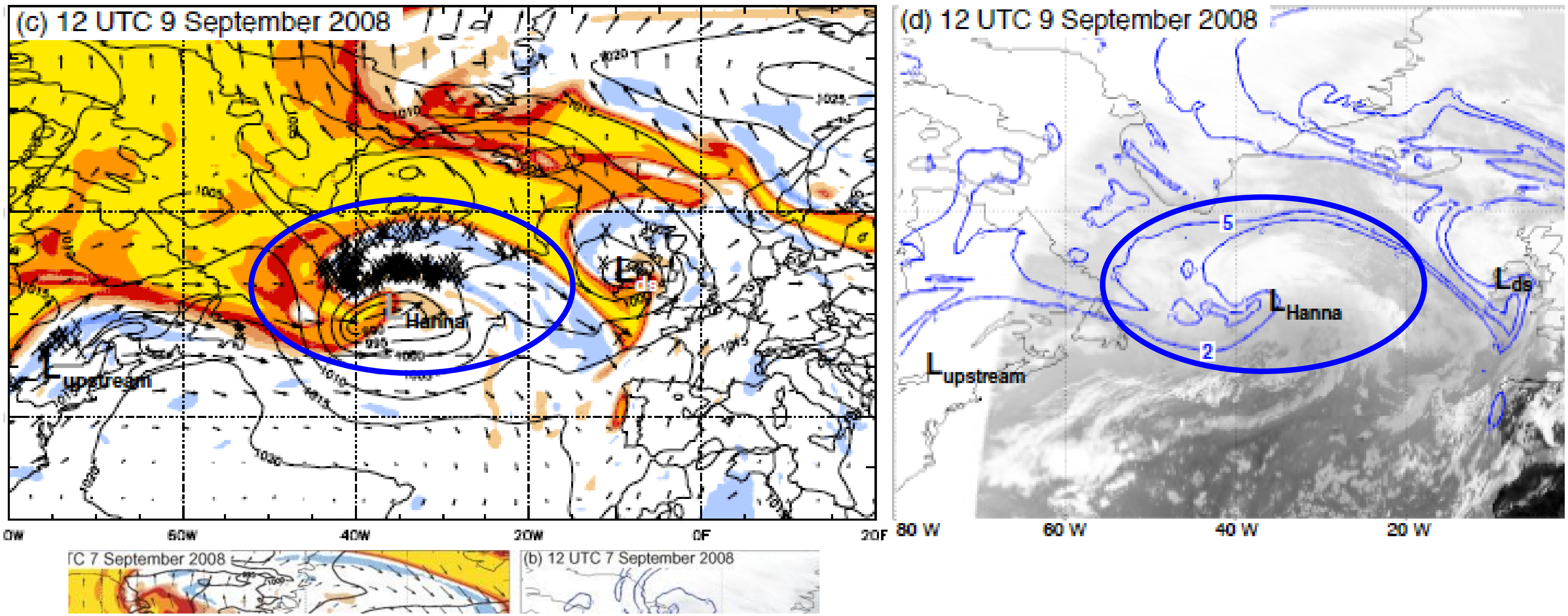


PV anomaly (deviation from climatology) in WCB outflows, averaged between 280-340 hPa in DJF, amounts to –1 … –3 pvu

Madonna et al. 2014 (JClim)

Is low PV in WCB outflow important for Rossby wave dynamics?

PV on 320 K

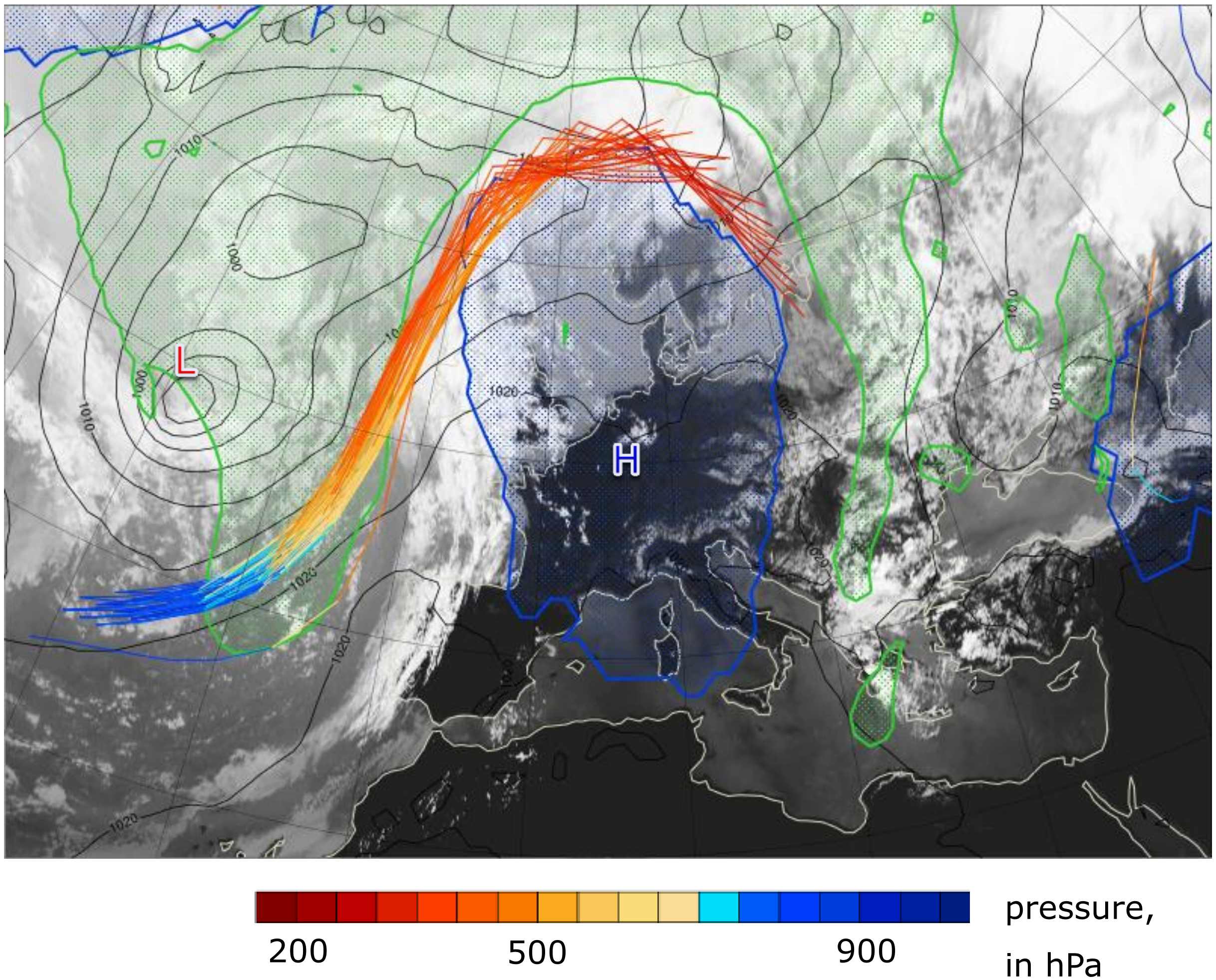


→ WCB outflow (is cloudy and) amplifies upper-level ridges

Grams et al. 2011 (QJ)

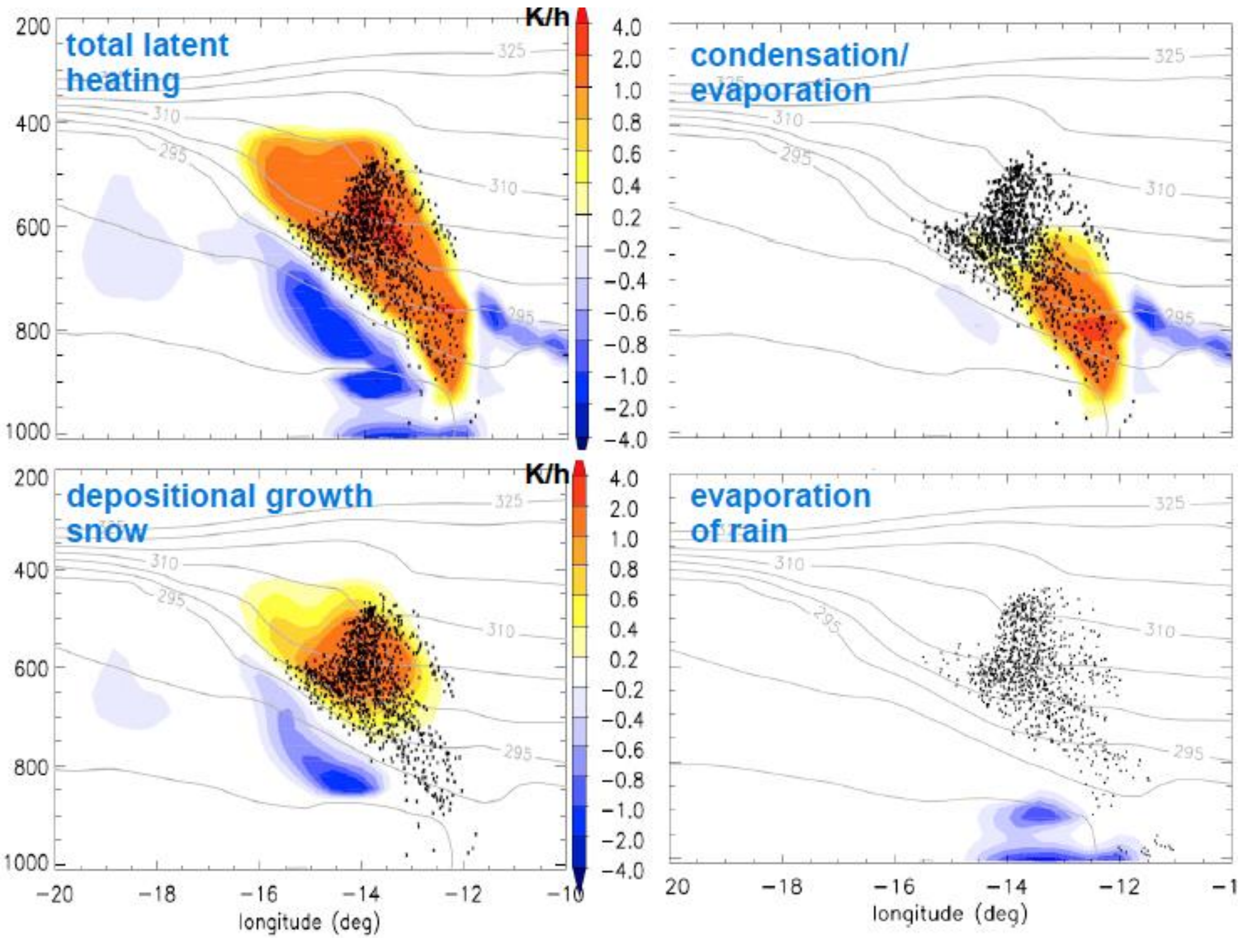
WCB outflows, blocking and heat waves …

→ see more in presentation by Christian Grams



Warm conveyor belts: microphysical processes

Vertical section across WCB in COSMO simulation



→ Latent heating in WCB occurs due to both condensation and depositional growth of snow (note also latent cooling below WCB!)

Joos and Wernli 2012 (QJ)

Observing how diabatic processes influence dynamics

What would we like to observe?
e.g. 2D sections (x-z plane) of T, **v**, q (+ latent heating in clouds) in regions where …

(i) WCB ascent intensifies cyclone
(ii) WCB outflow impinges on jet stream
(iii) WCB has maximum ice water content

Ground-based instruments?
Not many places (islands, ships), not flexible; lidar measurements blocked by clouds; no radar available in main storm track region

Airborne instruments?
Flexible, but aircraft have limited range; limited payload (not everything can be measured by one aircraft); lidar measurements blocked by clouds; dropsondes not allowed in air traffic corridor; expensive; requires international collaboration → FASTEX 1997 and **NAWDEX in 2016**

Observing how diabatic processes influence Rossby wave dynamics

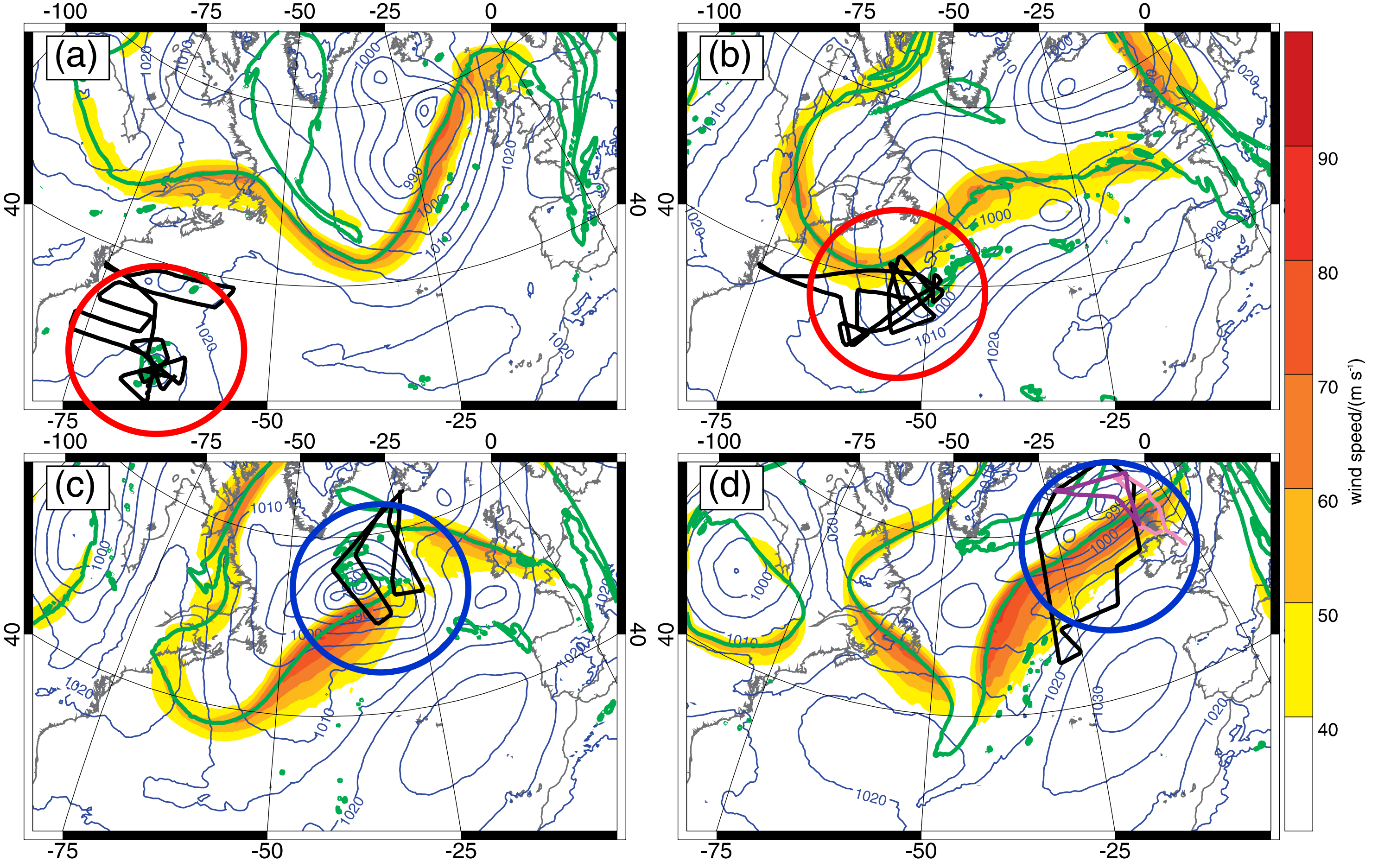
NAWDEX: 4-week field experiment in Iceland with 4 aircraft (HALO, two Falcons, FAAM) in Sept/Oct 2016

HALO (flight duration up to 9 hours)
- Cloud radar and H2O lidar (downward looking)
- In situ measurements (high-frequency T, q, winds, …)

DLR-FALCON (flight duration up to 3.5 hours)
- Wind and aerosol backscatter lidar – works only in not too-clean air and very thin clouds!
- In situ measurements (T, q, winds, …)

NAWDEX IOP4 “ex-Karl” – 26/27 September 2016

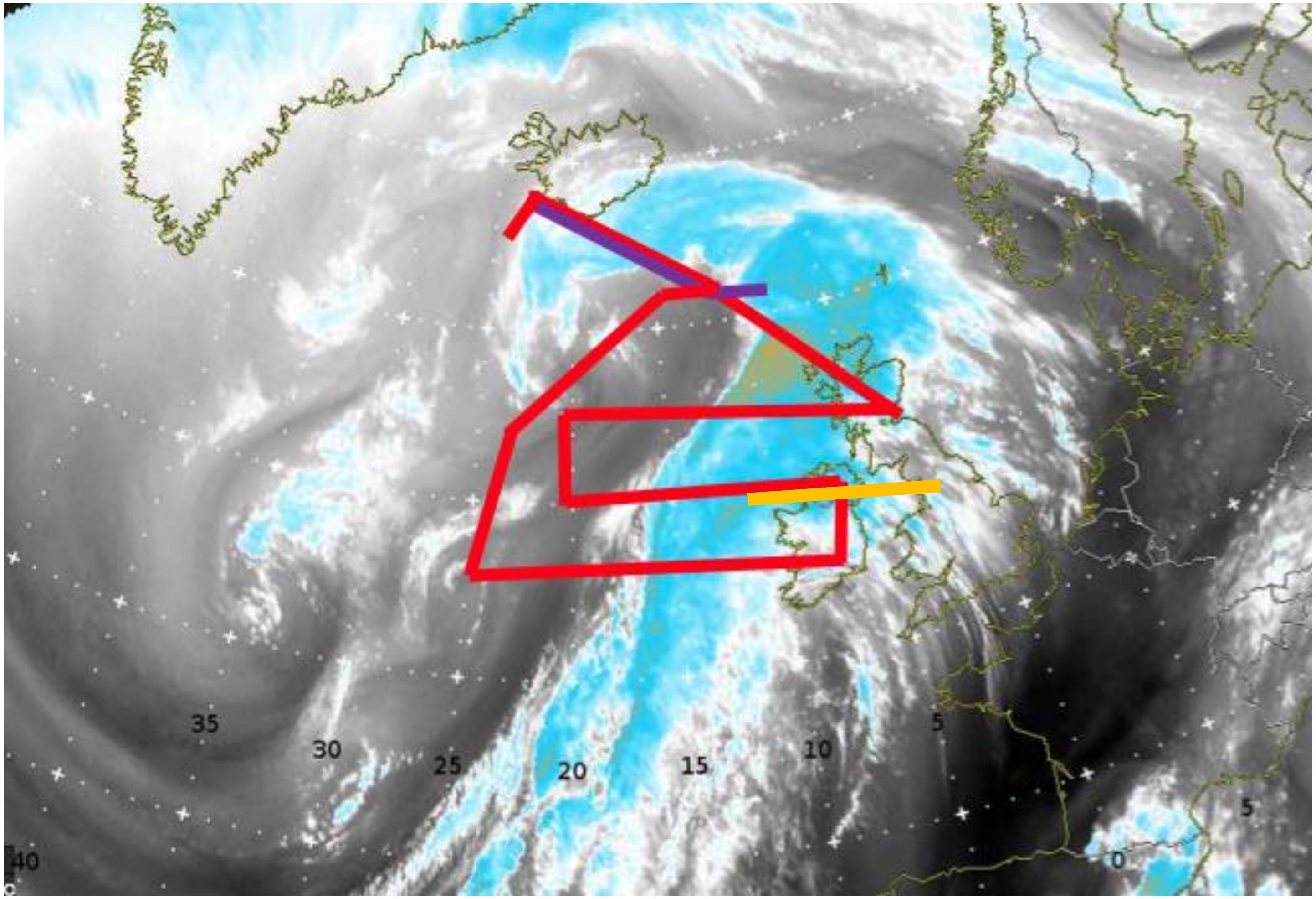
First-ever observations of a TS from tropical phase and ET (SHOUT observations) through midlatitude re-intensification, jet-streak formation, ridge enhancement, and HIW over Scandinavia (NAWDEX observations)



Schäfler et al. 2018 (BAMS)

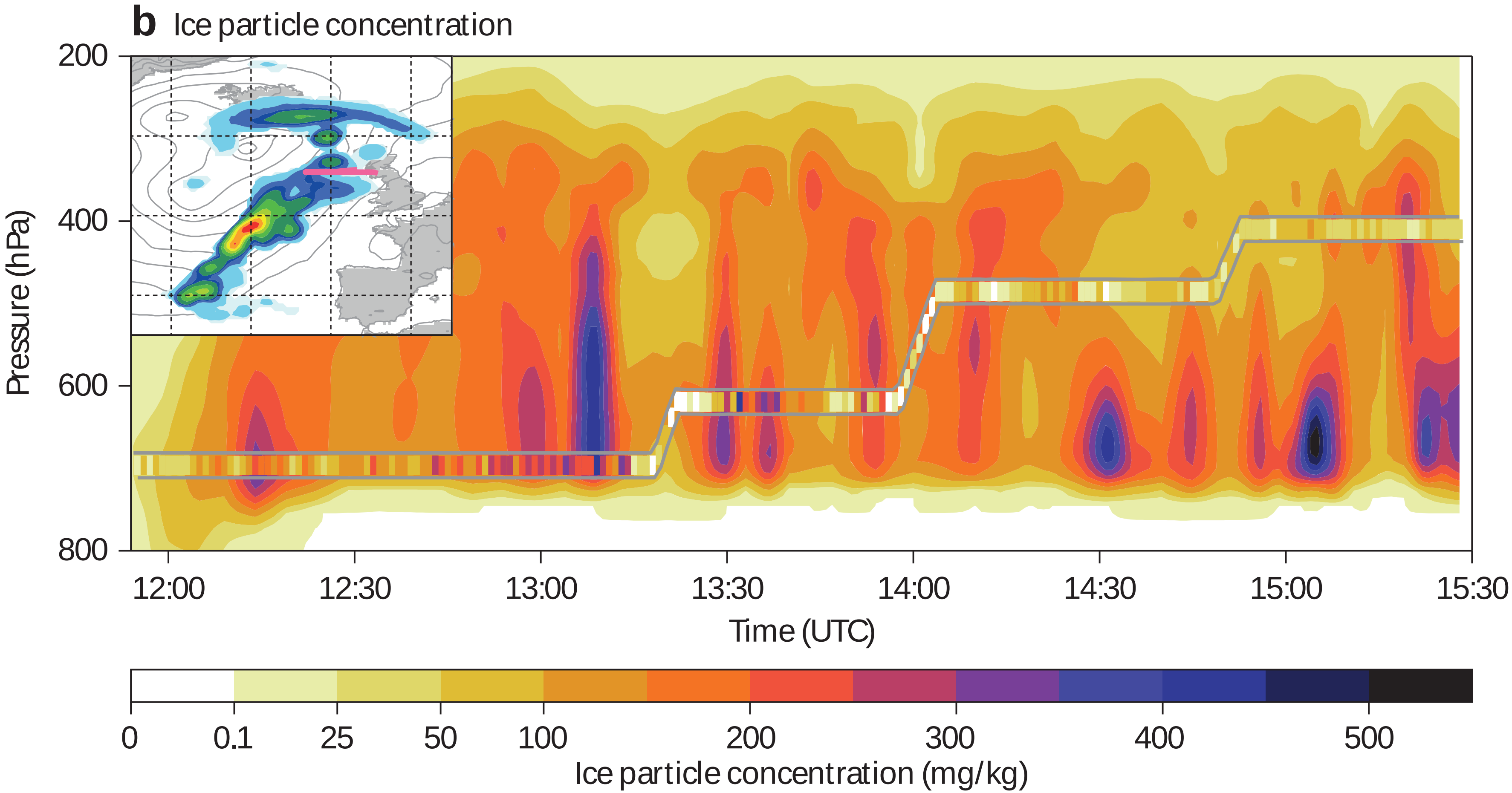
NAWDEX IOP3 “Vladiana” – 23 September 2016

Coordinated flights of HALO, DLR-FALCON and FAAM



NAWDEX IOP3 “Vladiana” – 23 September 2016

Comparison ice concentration (IWC+SWC) of IFS with in situ aircraft (Nevzorov probe onboard FAAM BAe146)



from Elisa Spreitzer, aircraft data from G. Vaughan & C. Deardon (U Manchester)

How to diagnose diabatic processes?

Approach 1: PV tracers in model

Advect PV c_i produced by source term S_i (parameterization i) during model integration

$$\frac{Dc_i}{Dt} = S_i,$$

→ full PV field q can be decomposed into

$$q = c_{\mathrm{adv}} + \sum_i c_i.$$

Davis et al. 1993 (MWR); Stoelinga 1996 (MWR)
Gray 2006 (JGR); Chagnon and Gray 2009 (QJ); Chagnon et al. 2013 (QJ);
Martinez-Alvarado and Plant (2014); Chagnon and Gray 2015 (MWR);
Saffin et al. 2016 (QJ), 2017 (JGR)

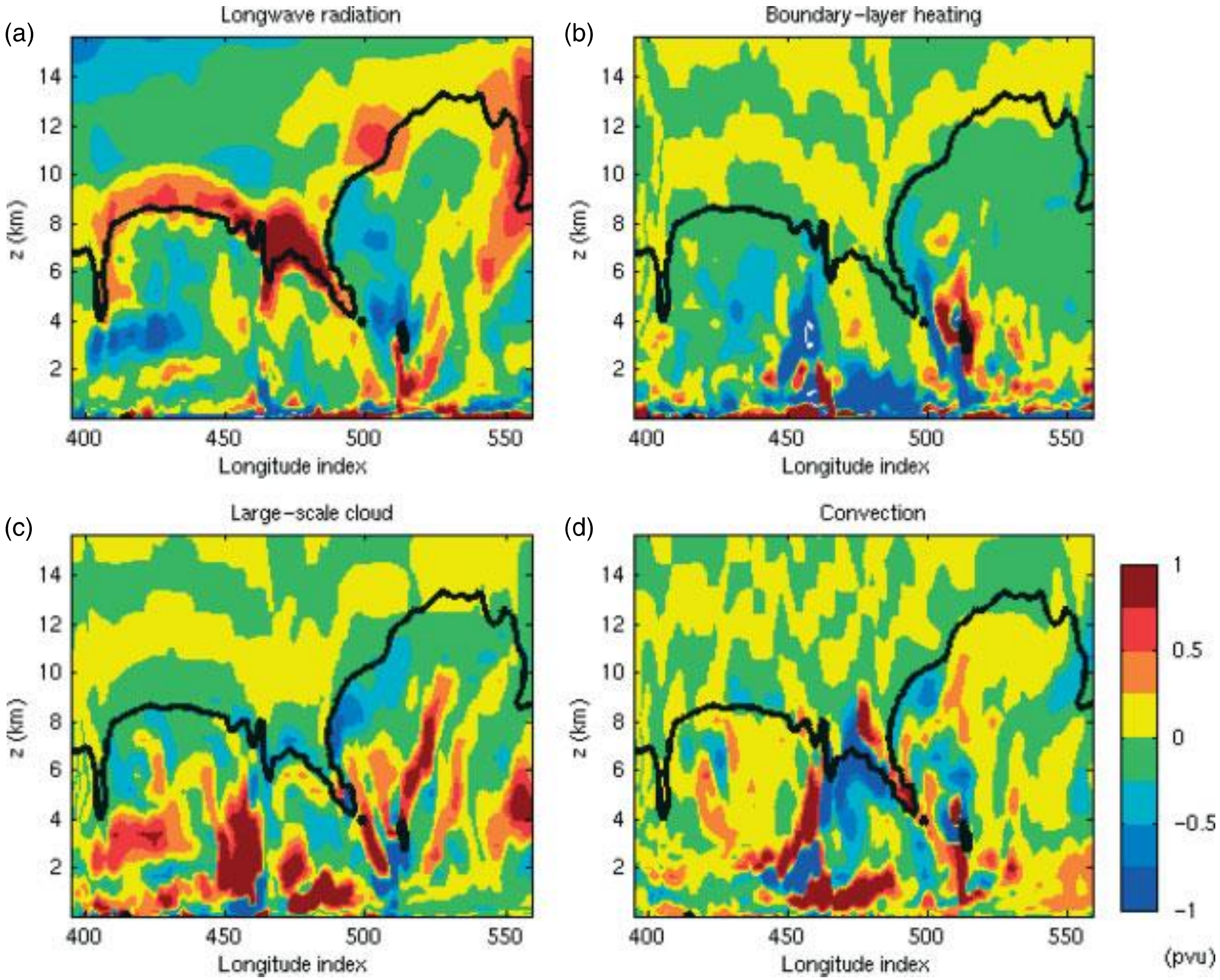
Strength

- Diagnostic is fully consistent with model simulation
- High accuracy due to online implementation
- Provides full 3D fields

Caveats

- Not straightforward to diagnose where PV modification occurred
- Implementation is technically involved

Example: diabatic PV tracers in vertical section across North Atlantic cyclone



Chagnon et al. 2013 (QJ)

Approach 2: Lagrangian method

1) Output instantaneous physical tendencies from model (every hour)

2) Calculate 3D fields of instantaneous diabatic PV rates due to individual processes → PVR_{cloud} , PVR_{conv} , PVR_{rad} , etc.

3) Trace individual PV rates along backward trajectories to calculate accumulated PV changes due to diabatic processes → APV_{cloud} , APV_{conv} , APV_{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. 2019 (JAS): IFS
Attinger et al. (QJ, accepted): 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»

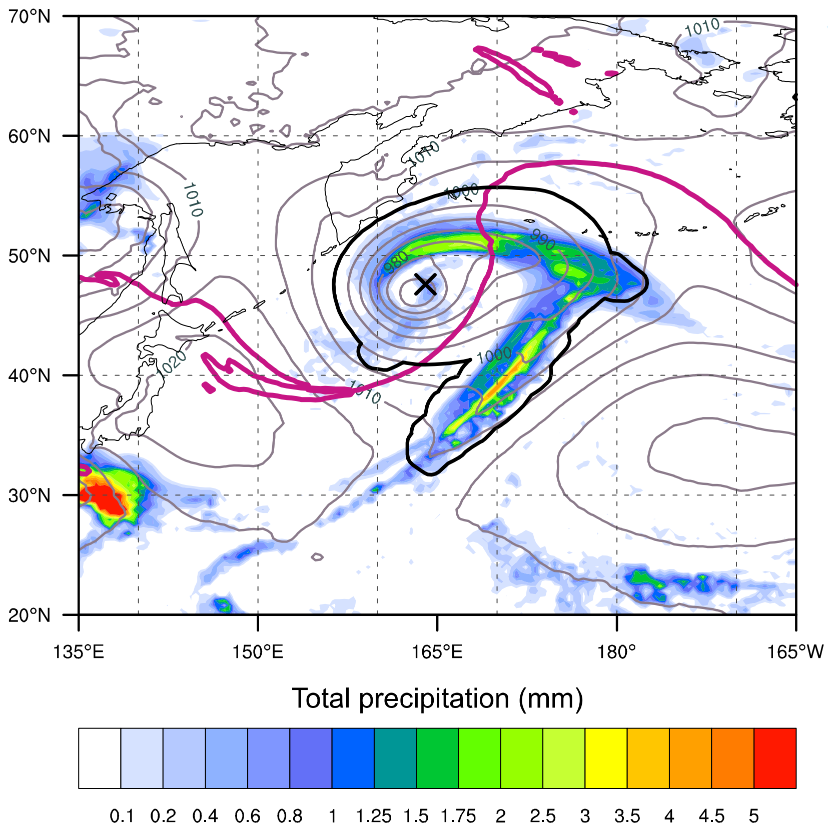
Strength

- Identifies also where PV modification occurs
- Method is relatively versatile (output additional fields from any model; not much model intervention needed)

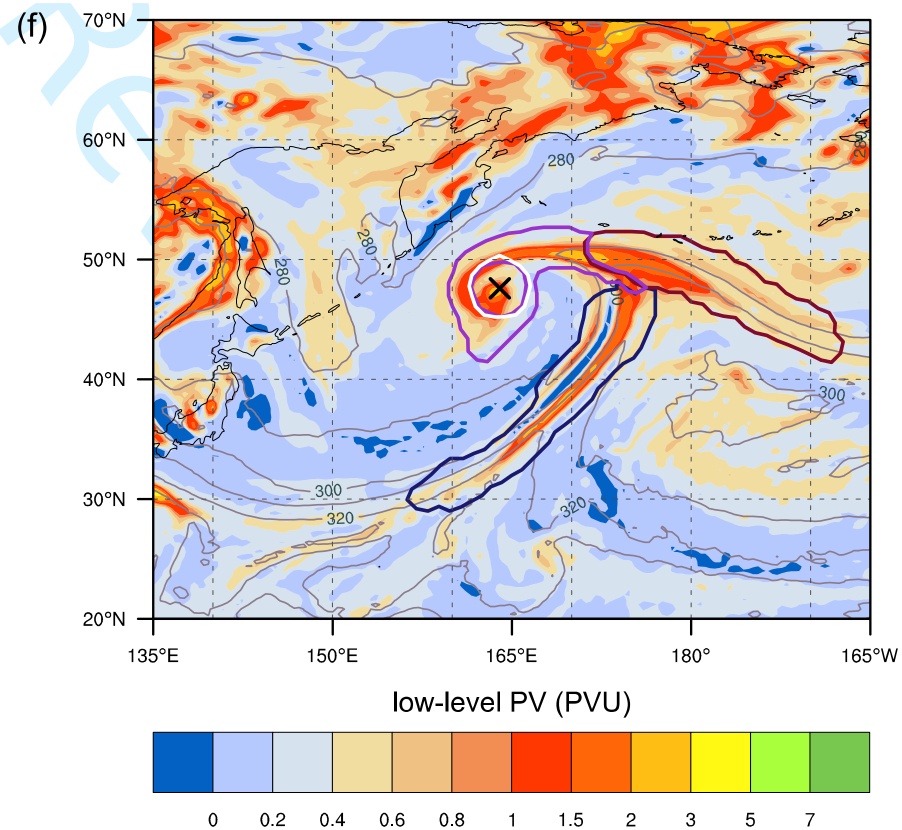
Example: Low-level PV anomalies in surface fronts

Intense North Pacific cyclone with T-bone frontal structure

hourly precipitation



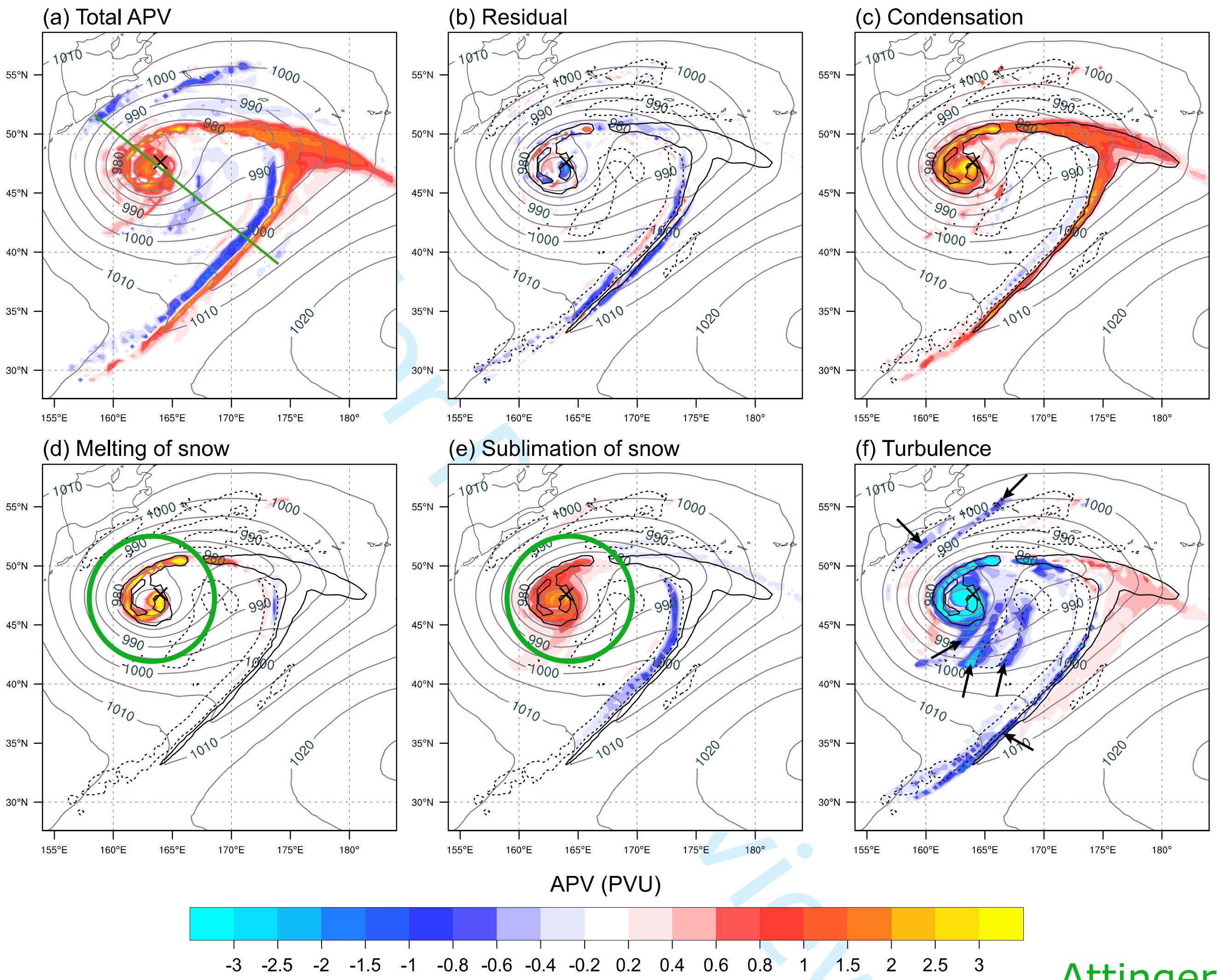
low-level PV (850-950 hPa)



Attinger et al. (QJ, accepted)

Example: Low-level PV anomalies in surface fronts

APV contributions between 950-850 hPa from different processes



Attinger et al. (QJ, accepted)

Wrap up

A) Does latent heating impact cyclone intensity? yes

B) Where does maximum latent heating occur in cyclones? in WCBs

C) What is the PV evolution along WCBs? increase and decrease

D) How do WCBs influence cyclone intensity and upper-level Rossby wave dynamics? pos and neg PV anomalies in WCB ascent and outflow, respectively

E) How can we observe diabatic processes? aircraft field experiments …

F) How can we analyse diabatic processes in models? PV tracers, trajectory method