The Impact of Microphysical Processes on the Potential Vorticity in a Diabatic Rossby Wave

Master's Thesis

Daniel Steinfeld

Supervision:

Dr. Maxi Böttcher, IACETH

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Motivation

Blick zurück

NZZ

Der wütende Lothar

René Zeller 29.12.2014, 05:30 Uhr

Bäume, von «Lothar» geknickt wie Mikadostäbchen: Wald bei Binz im Kanton Zürich am 27. Dezember 1999. *(Bild: Walter Bieri / Keystone)*

Mit dem Namen «Lothar» sind ungute Erinnerungen verknüpft. Der Sturm hinterlässt nach den Weihnachtstagen 1999 Todesopfer, zerlegt Bauten und richtet die grössten je in der Schweiz festgestellten Waldschäden an.

Winterstorm Lothar 1999, Europe (CH, D, FR):

- Extremely high wind velocities
- 110 casualties
- Losses: 40 bn Dollars (Swiss Re)
- Forecast error

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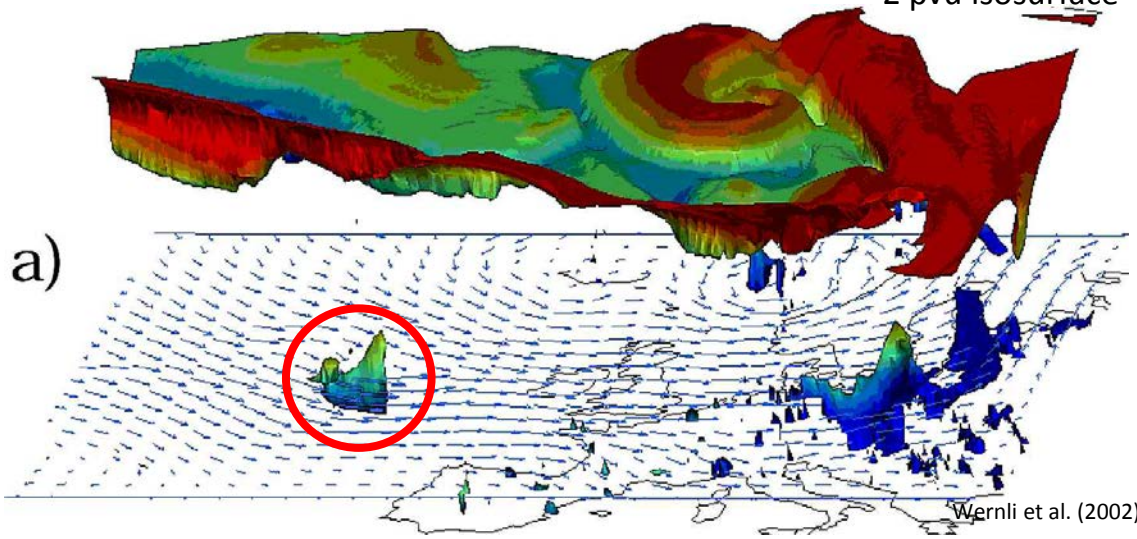
2 pvu isosurface



Wernli et al. (2002)

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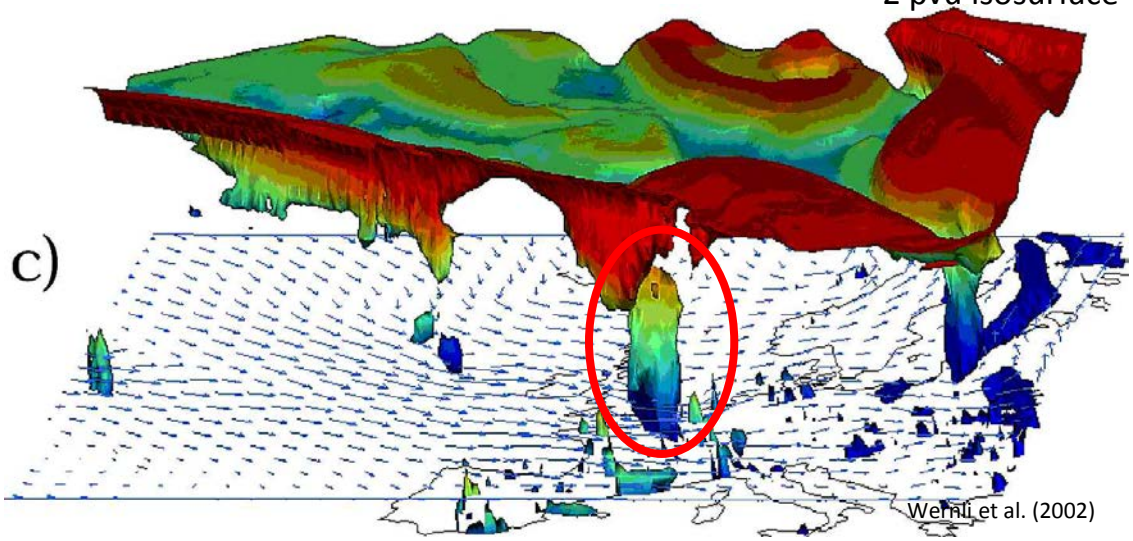

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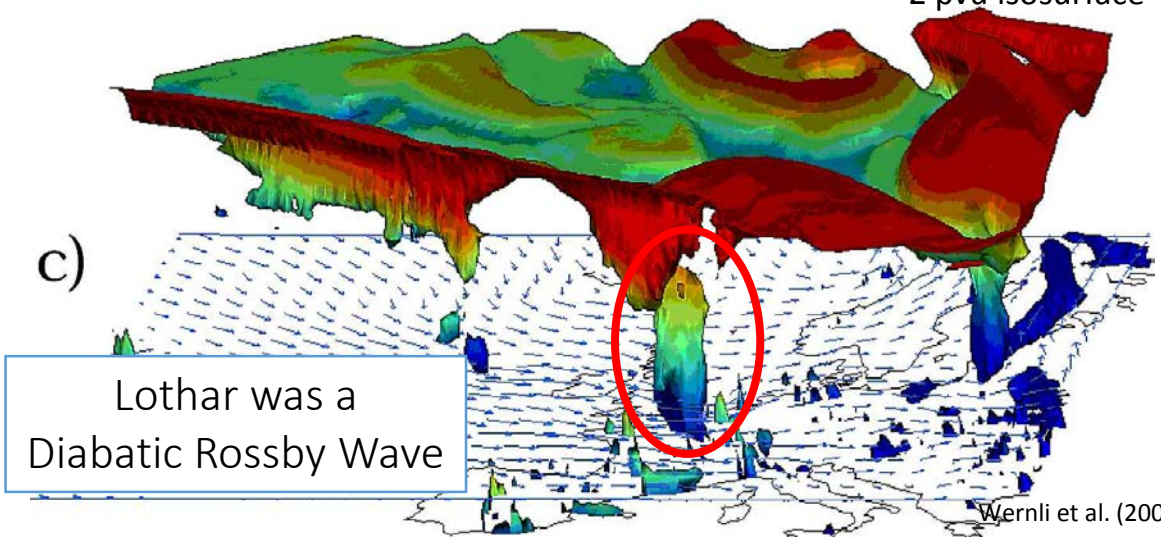

Lothar was a Diabatic Rossby Wave

Wernli et al. (200

Outline

1. What is Potential Vorticity (PV)?
2. The diabatic Rossby Wave mechanism
3. Objectives
4. Data and Tools
5. Case study of a DRW
6. Results
7. Limitations
8. Summary
9. References

What is Potential Vorticity (PV)?

- A powerful tool for understanding large- and mesoscale atmospheric dynamics
- evolution/prediction of synoptic weather systems, atmospheric waves and cyclones
- Ertel's PV (1942):

$$PV = \frac{1}{\rho}(2\boldsymbol{\Omega} + \boldsymbol{\nabla} \times \boldsymbol{u}) \cdot \boldsymbol{\nabla}\theta$$

absolute vorticity static stability

PV Unit:
[1 pvu $=10^{-6}\,\mathrm{K\,m^2\,s^{-1}\,kg^{-1}}$]

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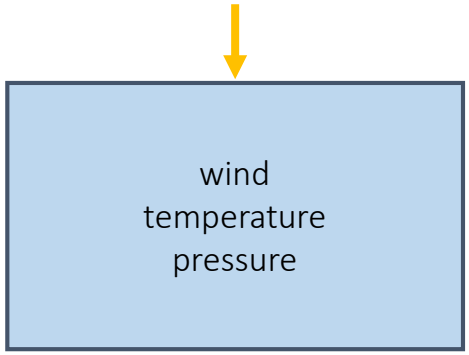
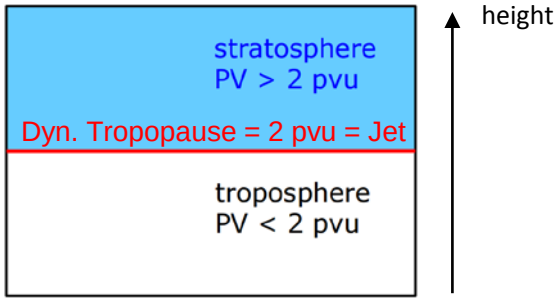
1) PV-Inversion



2) Material Conservation for adiabatic flow

$$\frac{D}{Dt}PV = 0$$



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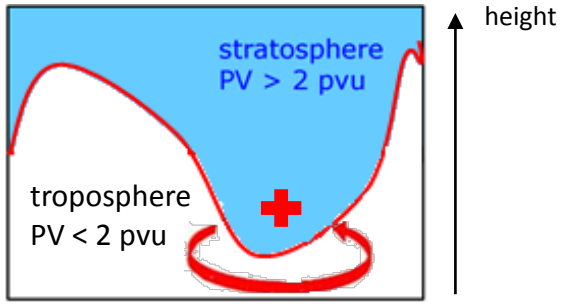
1) PV-Inversion

wind
temperature
pressure

Positive PV anomaly associated with:
- Cyclonic wind field

2) Material Conservation for adiabatic flow



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Cold front, Bern 13.05.2014

But the atmosphere is not dry!

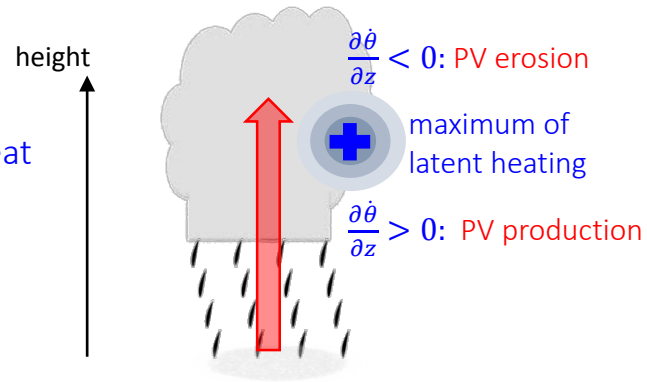
What is Potential Vorticity (PV)? non-conservation

- However, in the presence of cloud-diabatic processes, PV is no longer conserved!
- Diabatic PV rate (DPVR):

$$\frac{D}{Dt}PV = \frac{1}{\rho}[\underbrace{(2\boldsymbol{\Omega} + \boldsymbol{\nabla} \times \boldsymbol{u}) \cdot \boldsymbol{\nabla}\dot{\theta}}_{\text{diabatic processes}} + \underbrace{\nabla\theta \cdot (\nabla \times \mathbf{F})}_{\text{frictional terms}}]$$

Diabatic heating rate (DHR): release and consume latent heat

Microphysical processes



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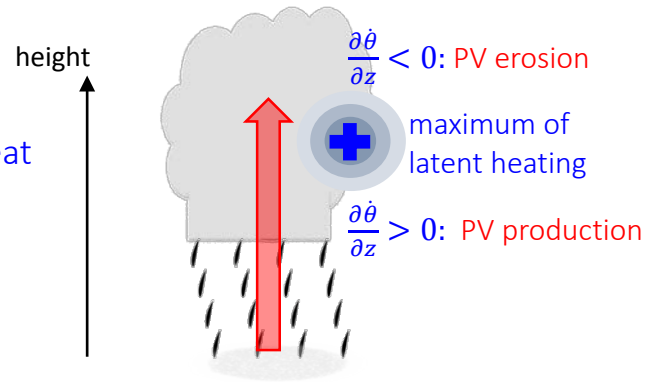
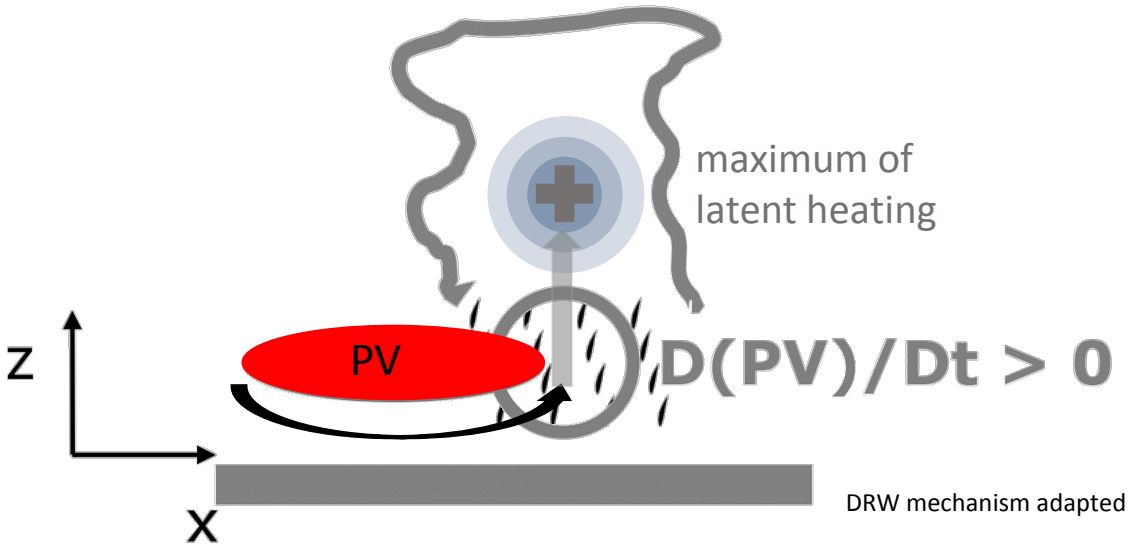


- Essential is
  - vertical gradient of diabatic heating rate (not the heating itself)
  - Diabatic PV production in lower troposphere → positive PV anomaly

What is a diabatic Rossby wave (DRW)?

- Low-level positive PV anomaly over baroclinic zone; sufficient moisture supply



DRW mechanism adapted by Parker and Thorpe (1995)

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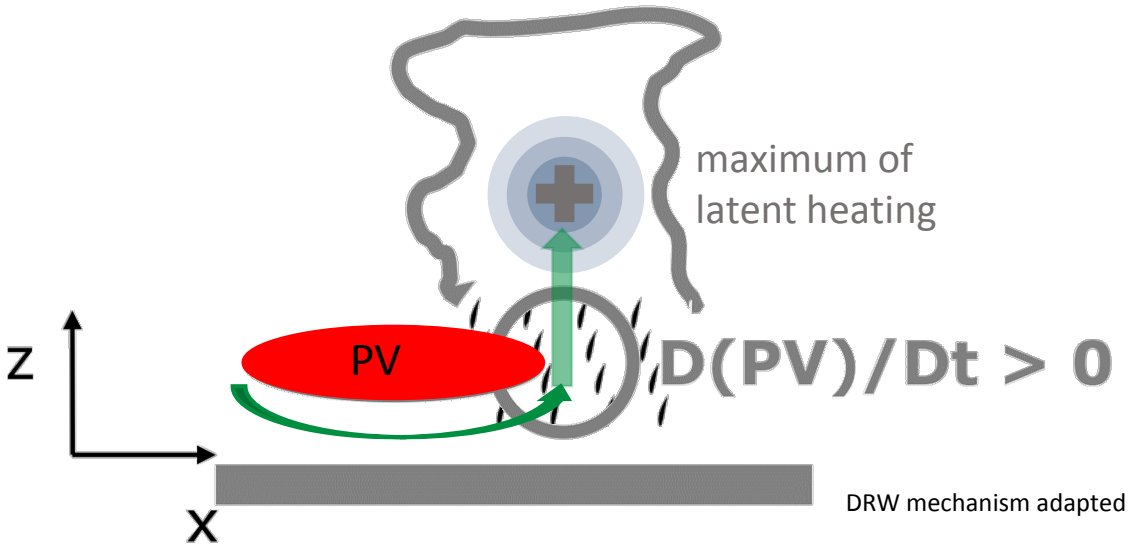

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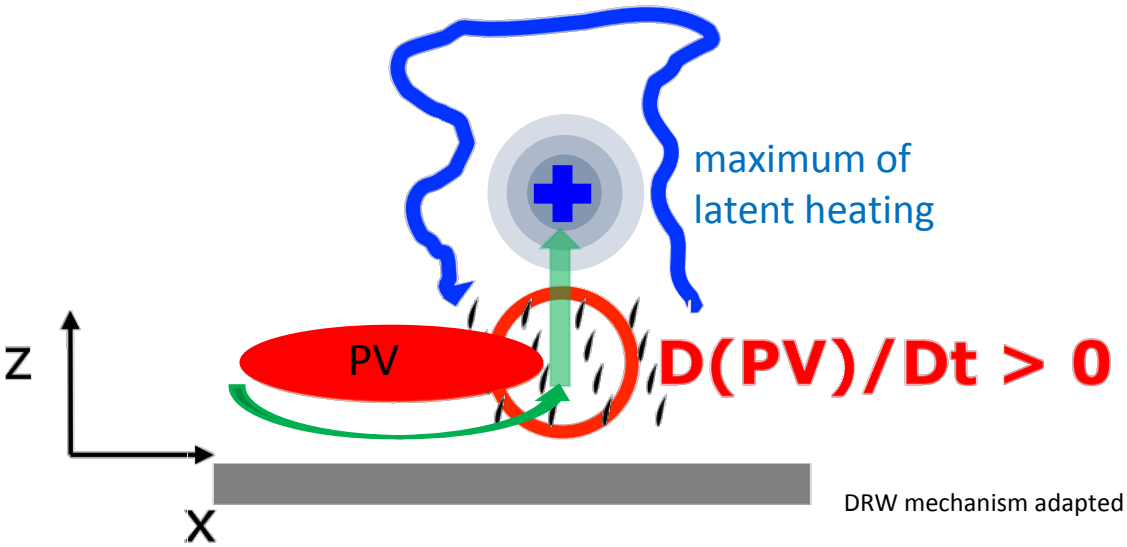

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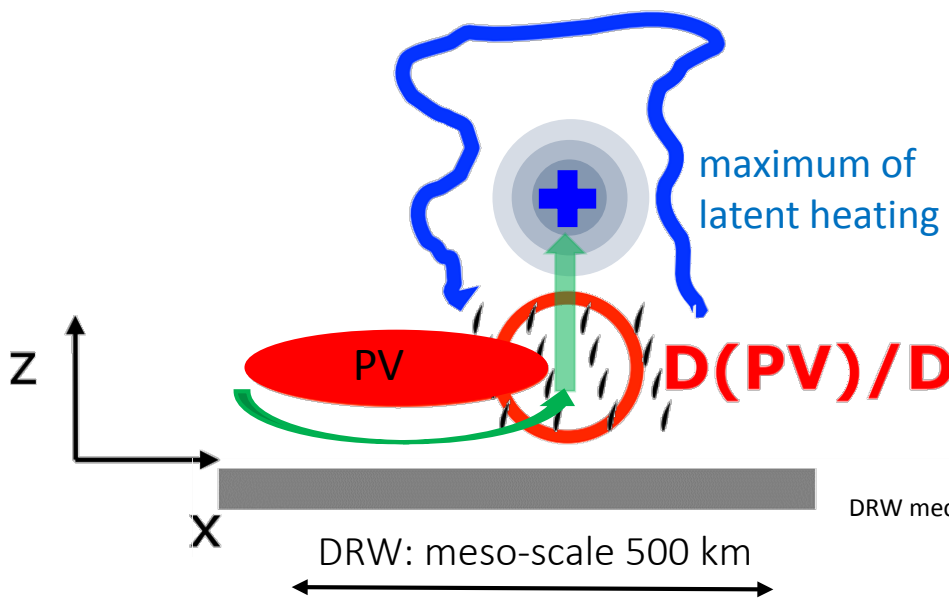

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Diabatic Rossby waves (DRW) are a special type of fast propagating low-level cyclone associated with a cyclonic low-level positive potential vorticity (PV) anomaly, which is continuously reproduced due to diabatic processes

- Rapid propagation
- Potentially huge impact (Boettcher and Wernli, 2011)
- Poor predictability
- Absence of upper-level forcing

Rossby wave: synoptic-scale 2000 km

Objectives

- Which microphysical processes contribute most to the heating (DHR) and PV modification (DPVR) in a DRW?
- Is the DRW associated with coherent air streams like WCB?
- Combination of Lagrangian and Eulerian framework to understand the 3D clouds, heating and PV structure of the DRW.

Data & Tools

ECMWF IFS – model

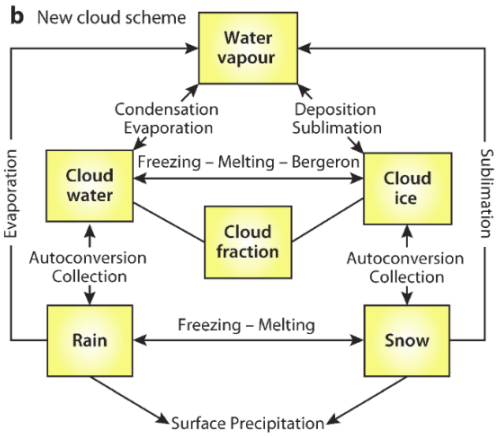
- forecast of a DRW case over the North Atlantic
- with 28 km horizontal resolution and hourly output

- detailed IFS microphysical cloud scheme (thanks to Richard Forbes) with prognostic equations for cloud water, cloud ice, rain and snow
- change in temperature due to transfers between the hydrometeor species:

$$DHR_{tot} = \frac{\partial T}{\partial t} = \sum_{x=1}^{m} \frac{L(x)}{C_p} \frac{\partial q_x}{\partial t}$$

$$= DHR_{cond./evap.} + DHR_{dep.\ growth\ of\ snow} + DHR_{melting\ of\ snow} + \ldots\ldots$$

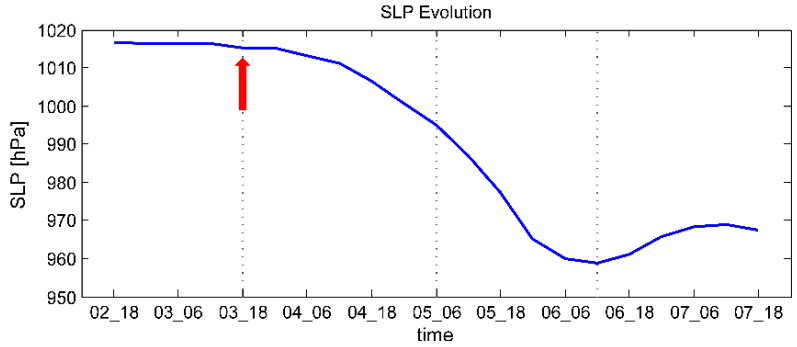
$$DPVR_{cond./evap.} + DPVR_{dep.\ growth\ of\ snow} + DPVR_{melting\ of\ snow} + \ldots\ldots$$

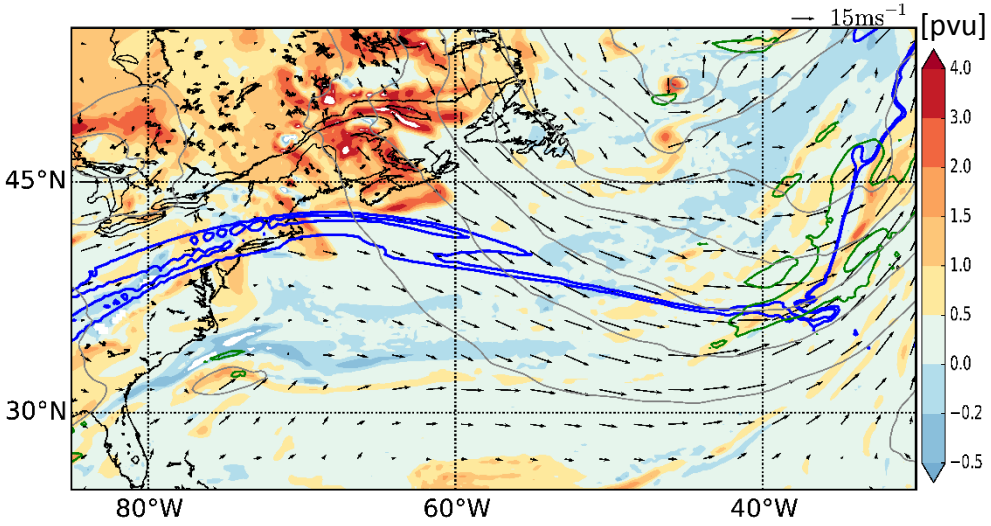


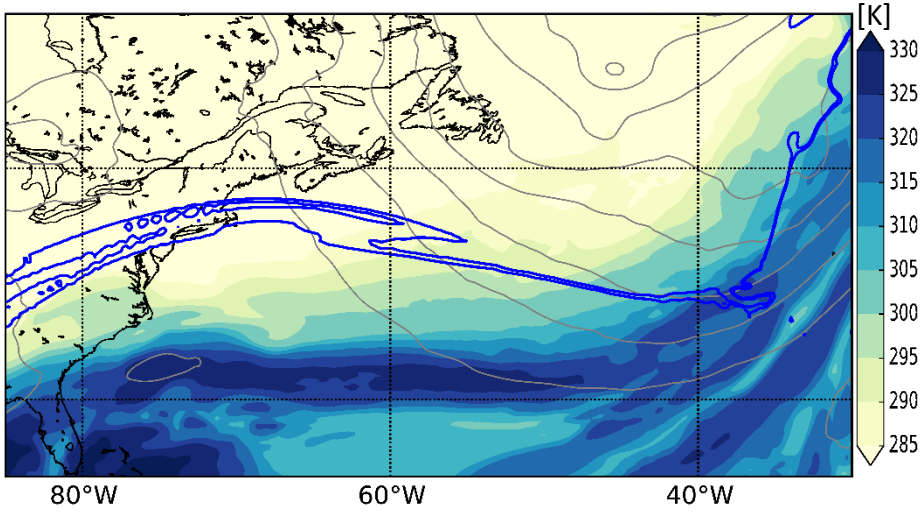
- calculation of trajectories - Based on the IFS output (Lagranto, Wernli and Davies, 1997)
- DHR and DPVR are tracked along the trajectories

Case study synoptic overview and general characteristics of the DRW

03 Jan 2013 18 UTC
generation phase





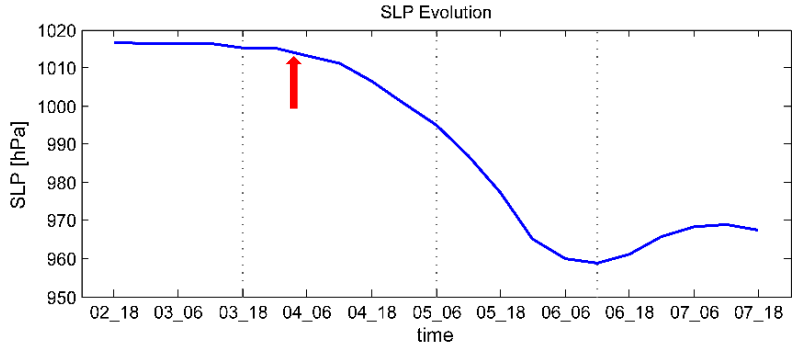


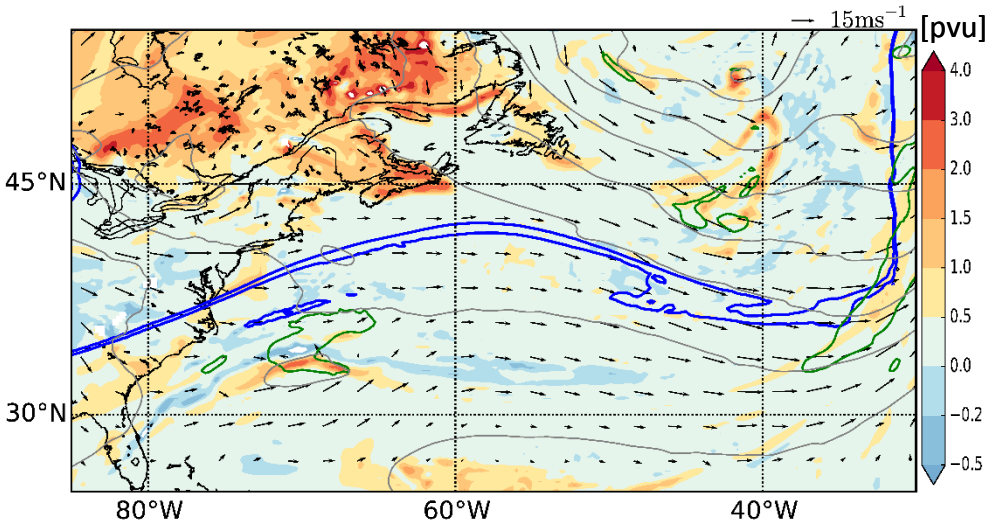
PV at 900 hPa
SLP grey, Rain green
1.5 and 2 pvu at 250hPa blue

θ_e at 900 hPa

Case study synoptic overview and general characteristics of the DRW

04 Jan 2013 04 UTC
propagation phase (DRW)





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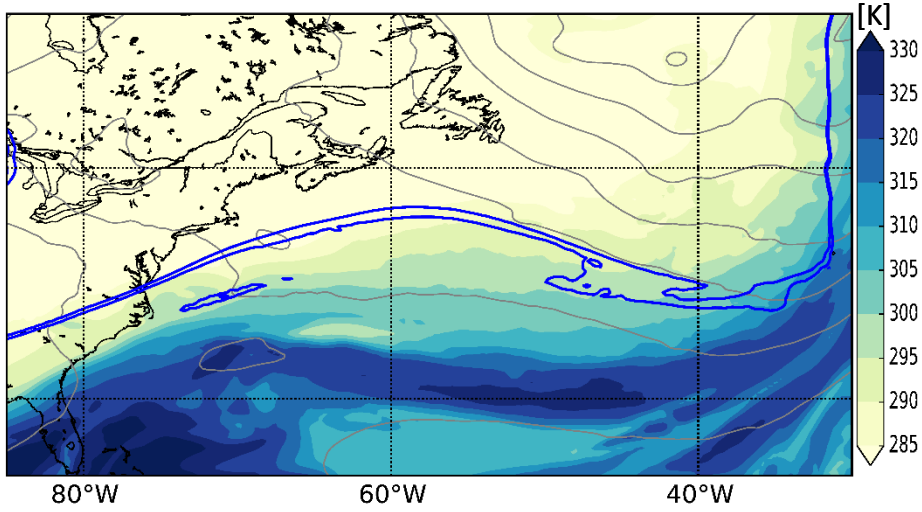
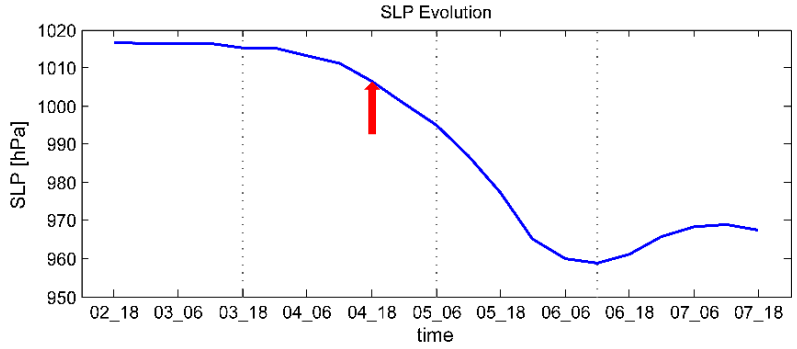
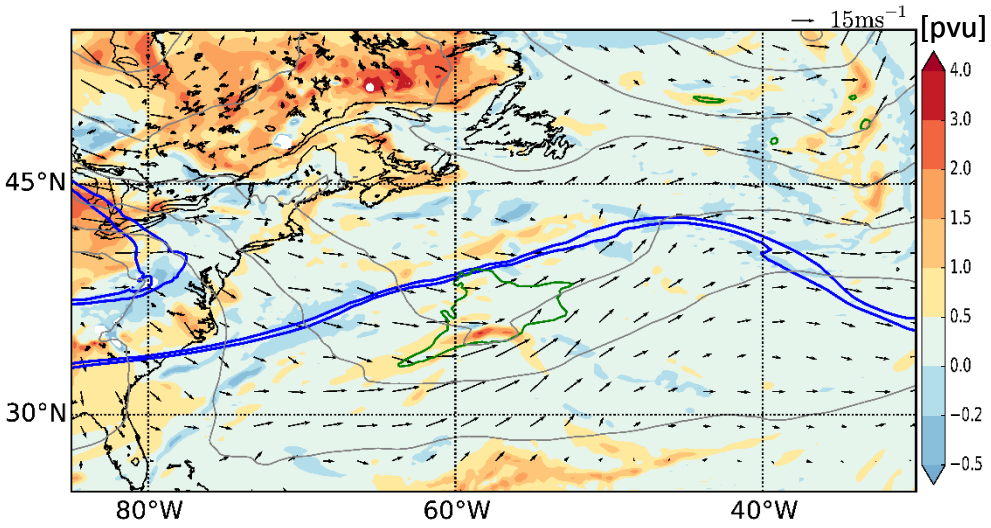


θ_e at 900 hPa

Case study synoptic overview and general characteristics of the DRW

04 Jan 2013 16 UTC
propagation phase (DRW)





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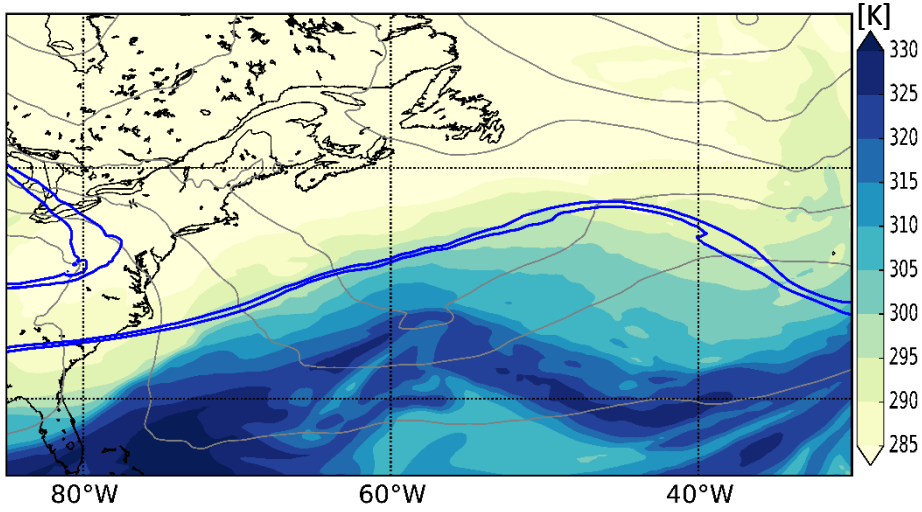
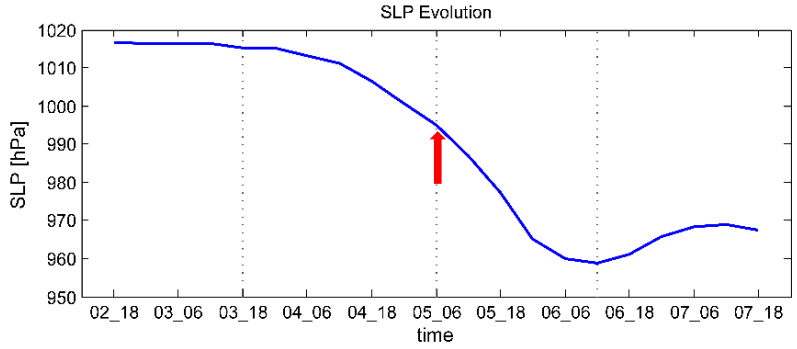
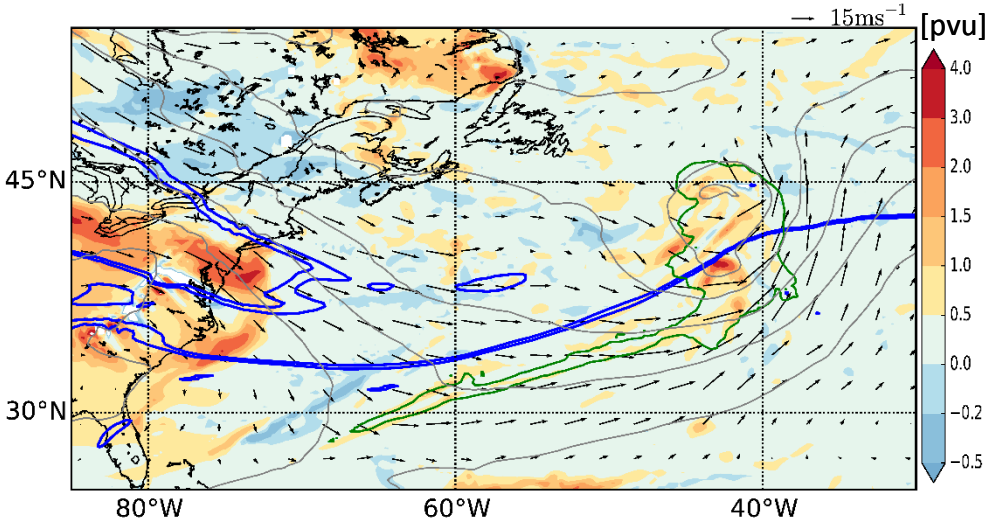


θ_e at 900 hPa

Case study synoptic overview and general characteristics of the DRW

05 Jan 2013 06 UTC
intensification phase





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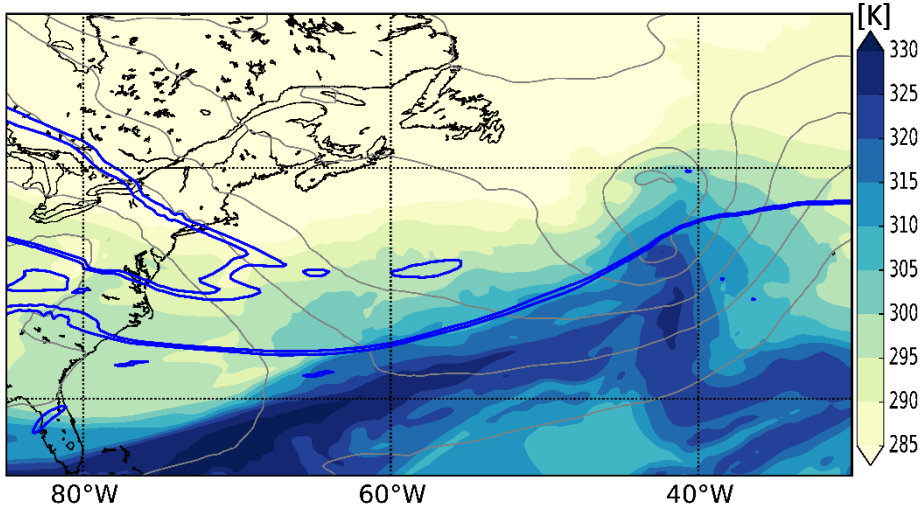
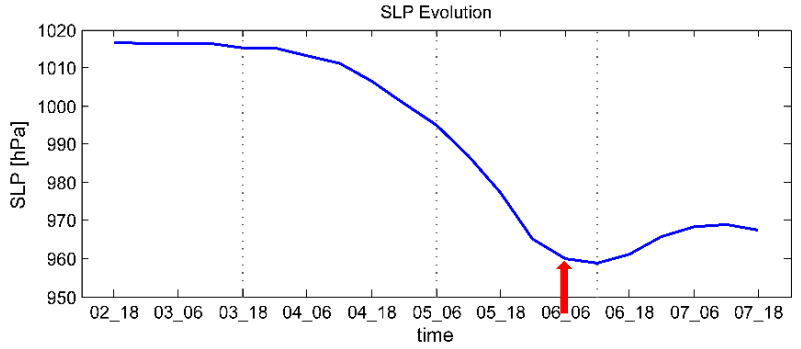
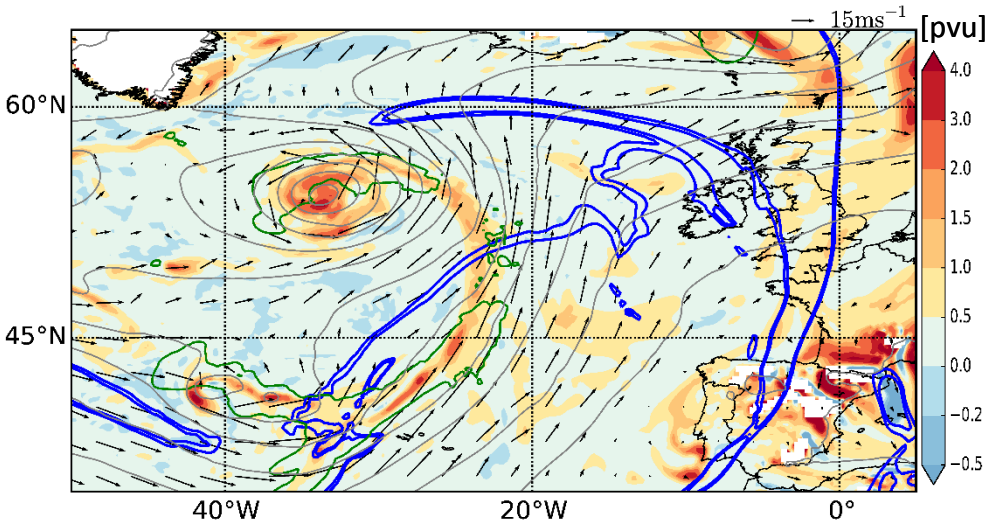


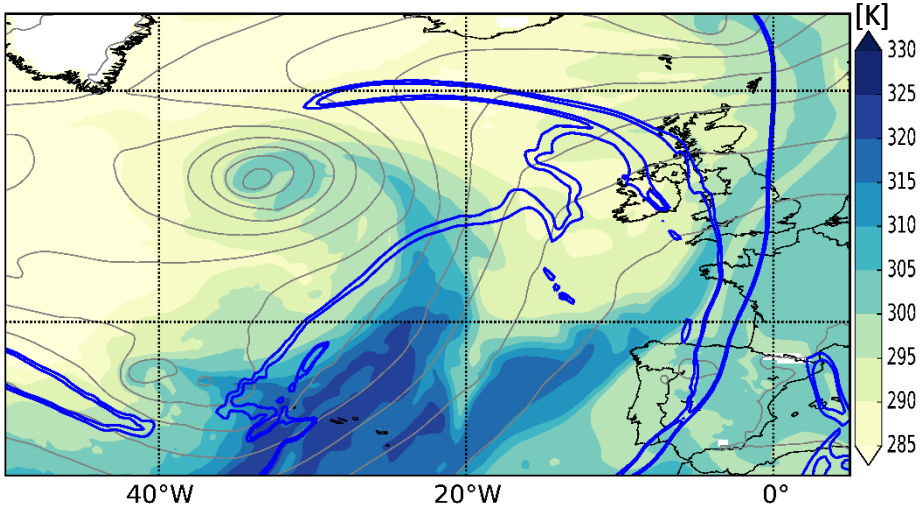
θ_e at 900 hPa

Case study synoptic overview and general characteristics of the DRW

06 Jan 2013 06 UTC
mature ET-cyclone phase







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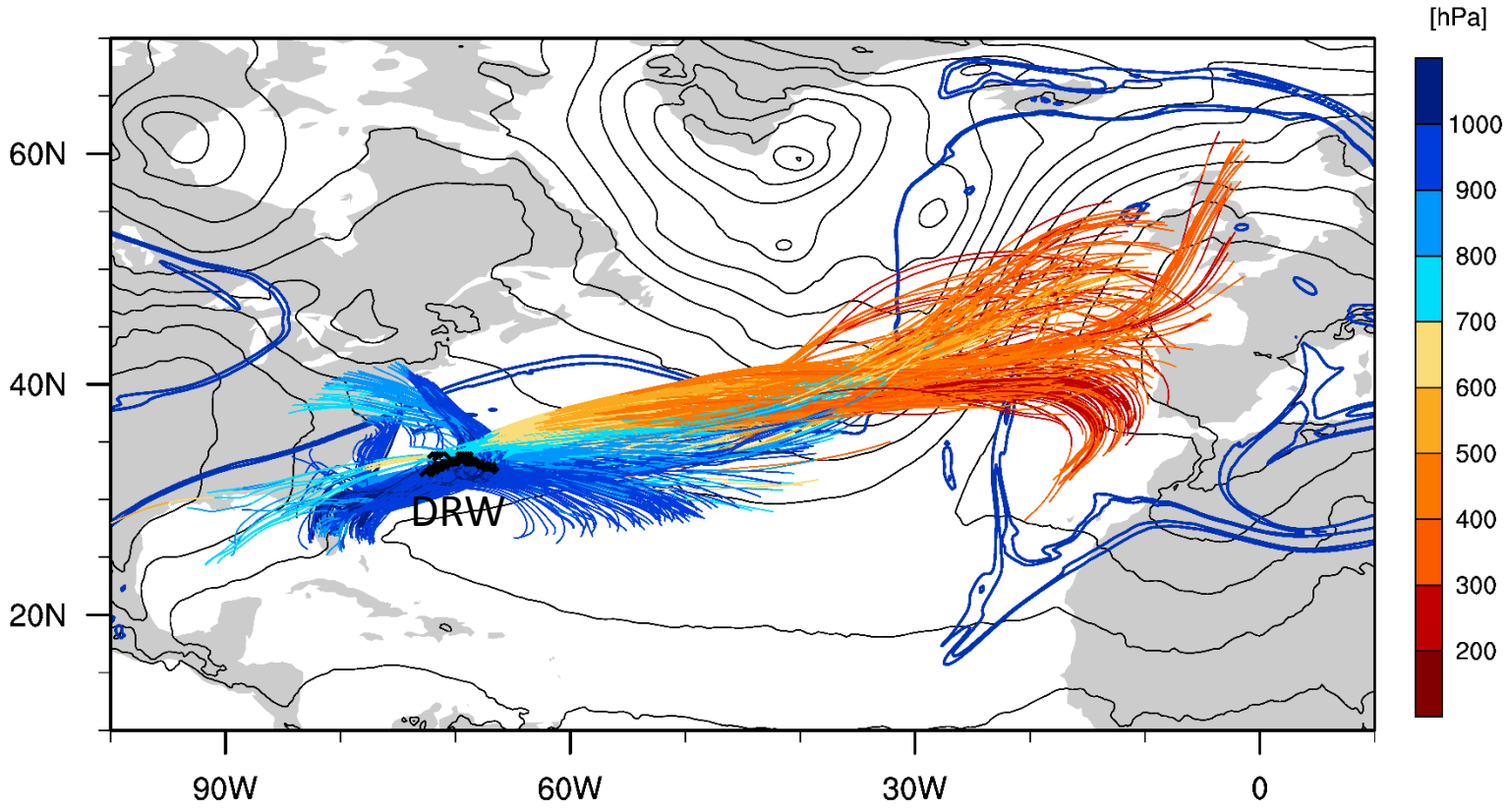
Results

trajectories and air streams

- started on 04 Jan 2013 04 UTC (propagation phase)
- colored according to pressure level



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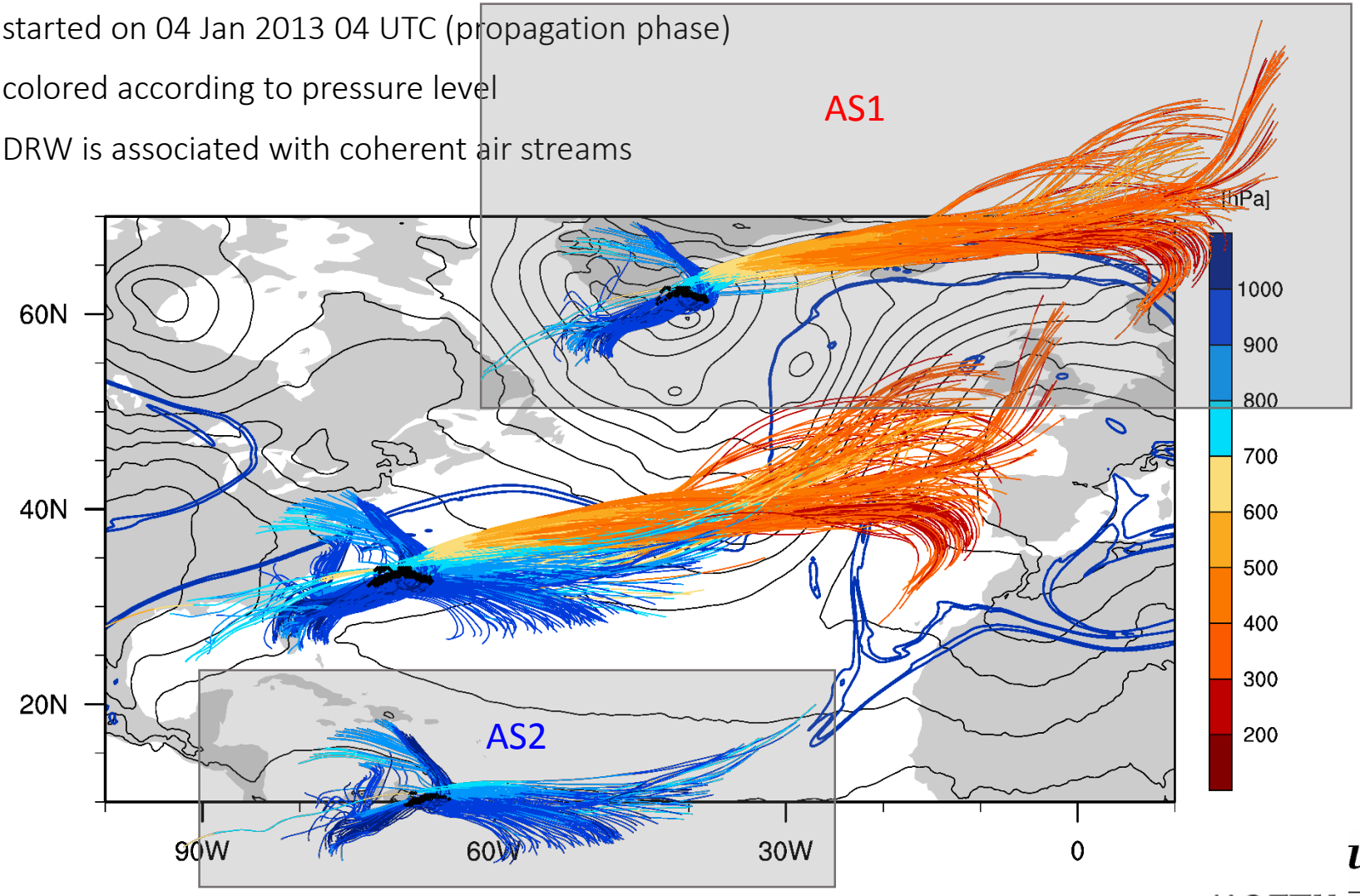
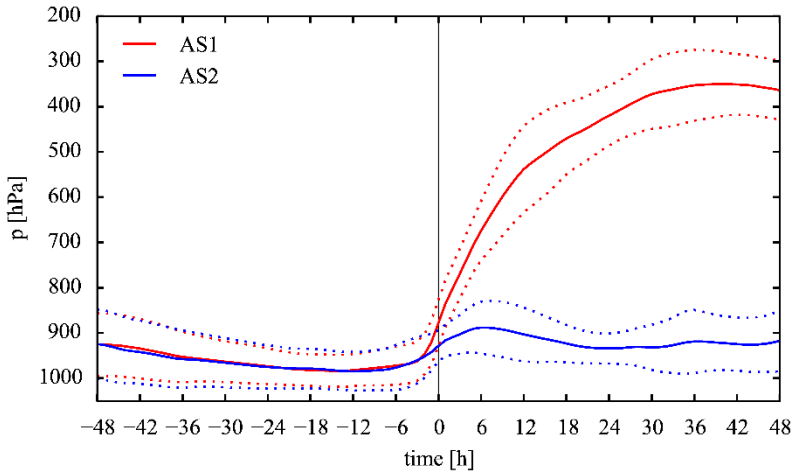
- DRW is associated with coherent air streams



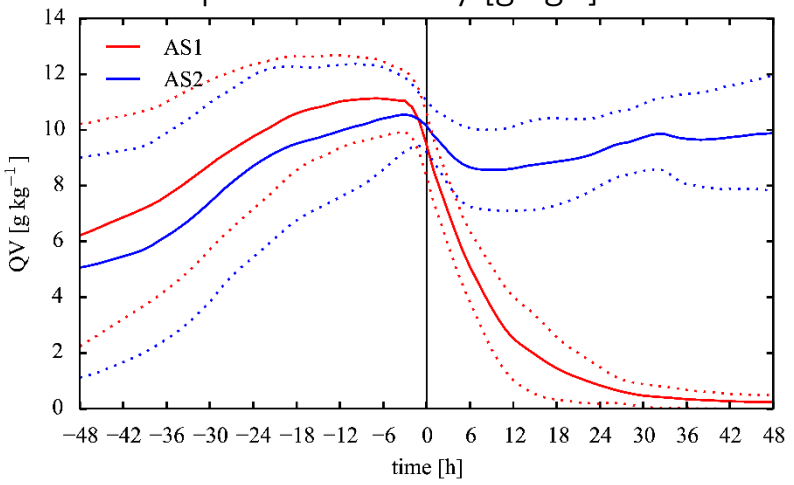
Results

air stream characteristics

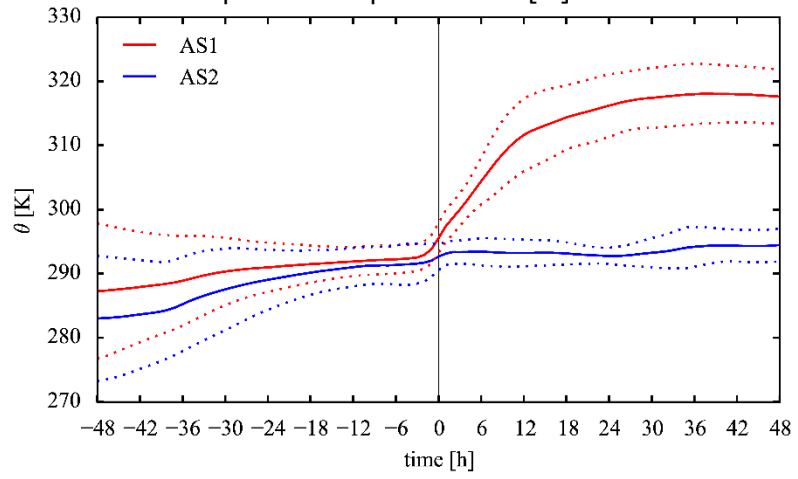
pressure [hPa]



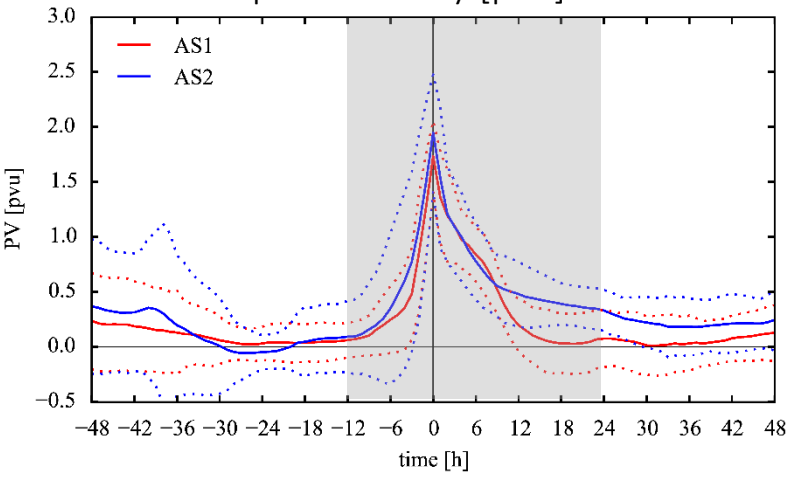
specific humidity [g kg^{-1}]



pot. temperature [K]

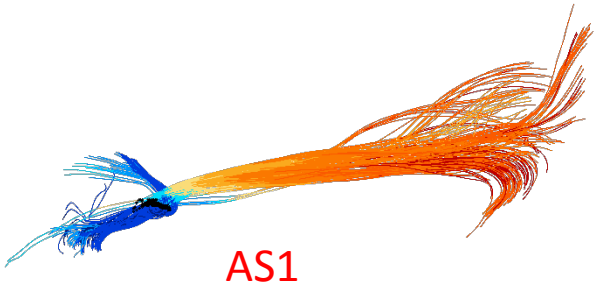


pot. vorticity [pvu]

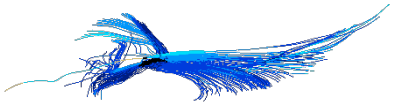


Results

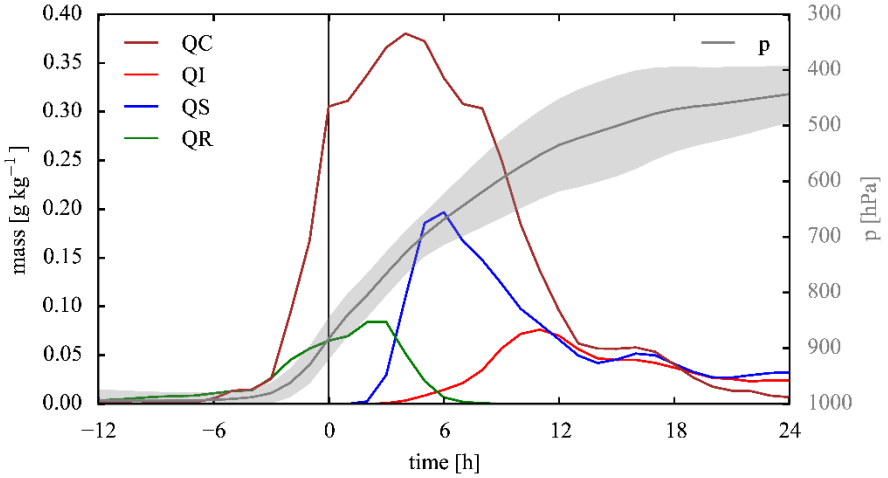
hydrometeor mass

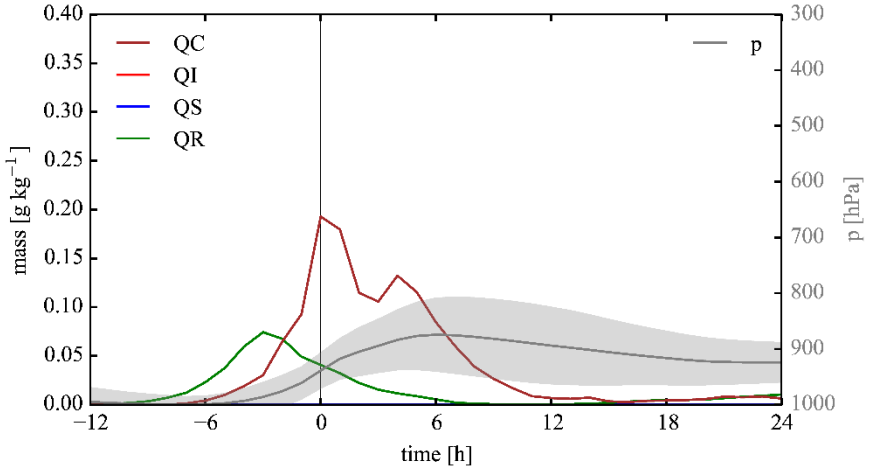


AS1



AS2

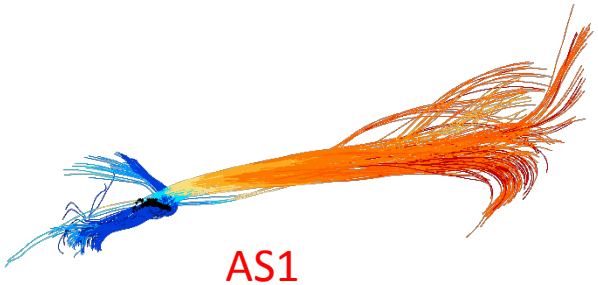




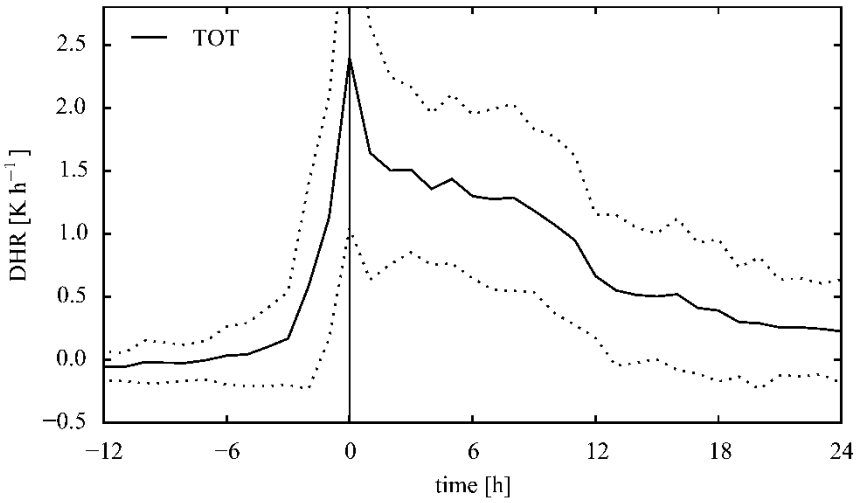
cloud liquid
cloud ice
snow
rain

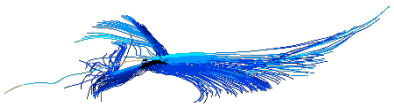
Results

diabatic heating rates [K h^{-1}]



AS1





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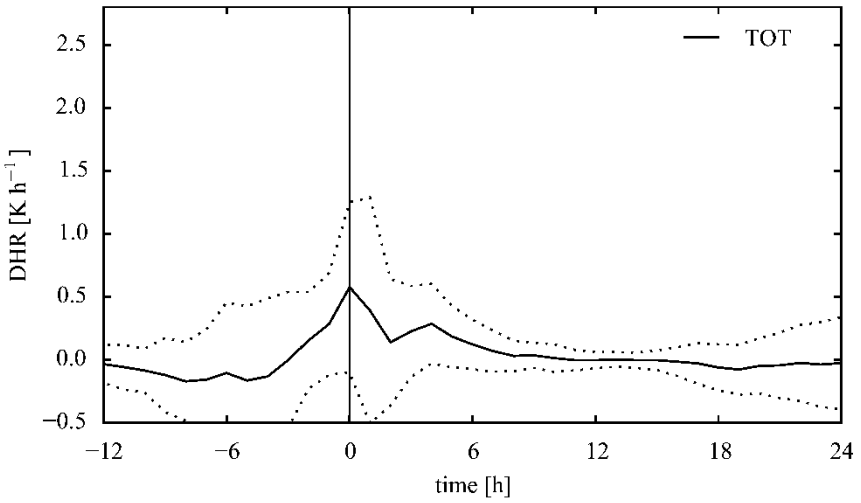
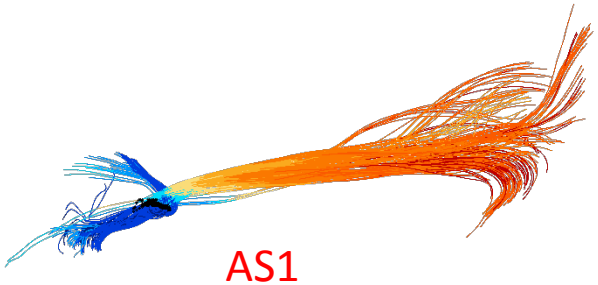


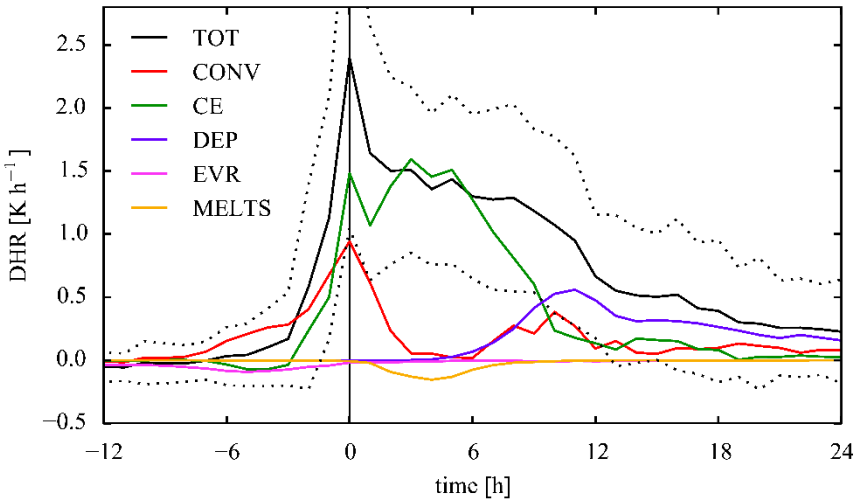
Total

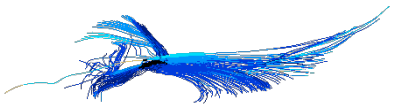
Results

diabatic heating rates [K h^{-1}]

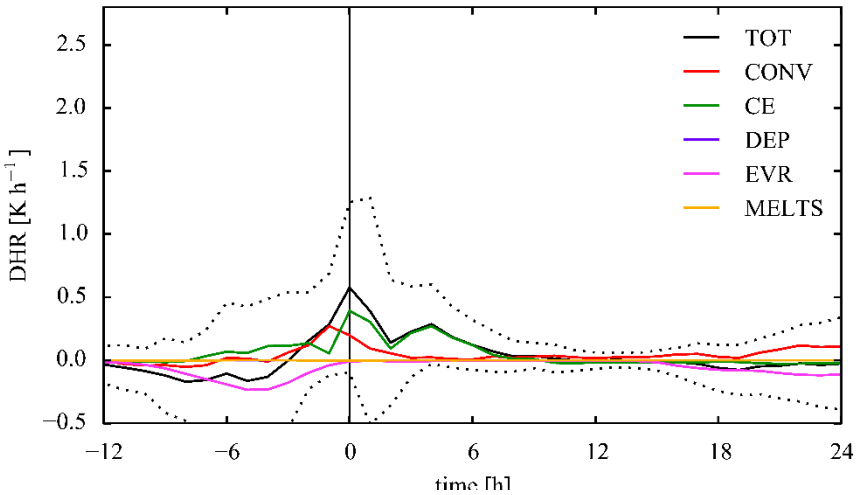


AS1





AS2



total

convection

condensation & evaporation

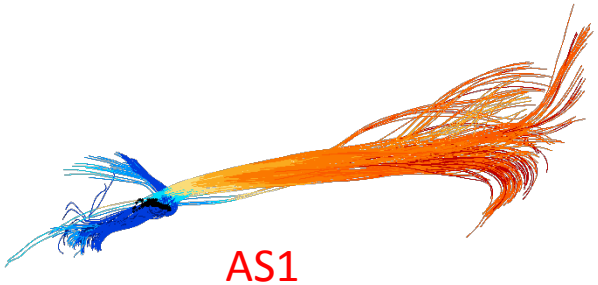
depositional growth of snow and ice

evaporation of rain

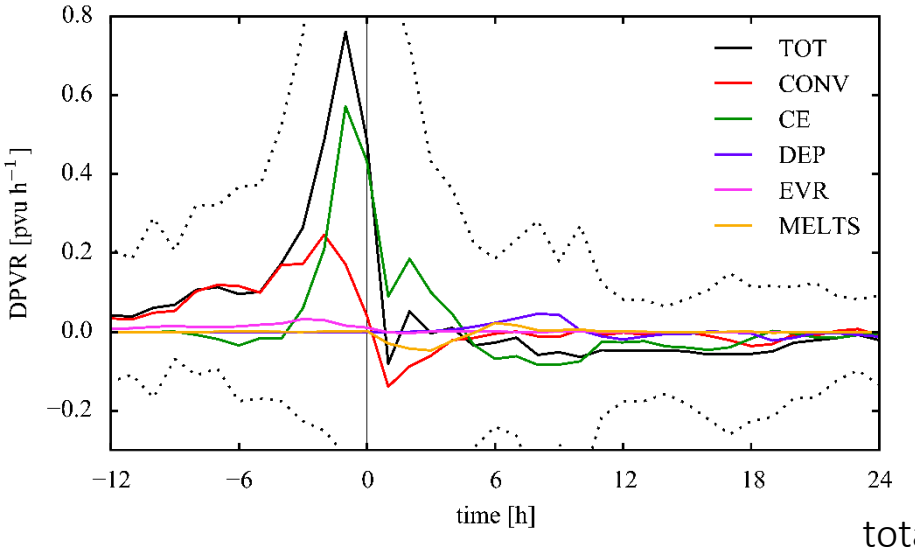
melting of snow

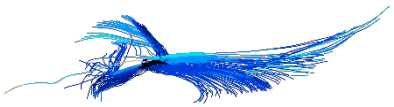
Results

Diabatic PV rates [pvu h^{-1}]

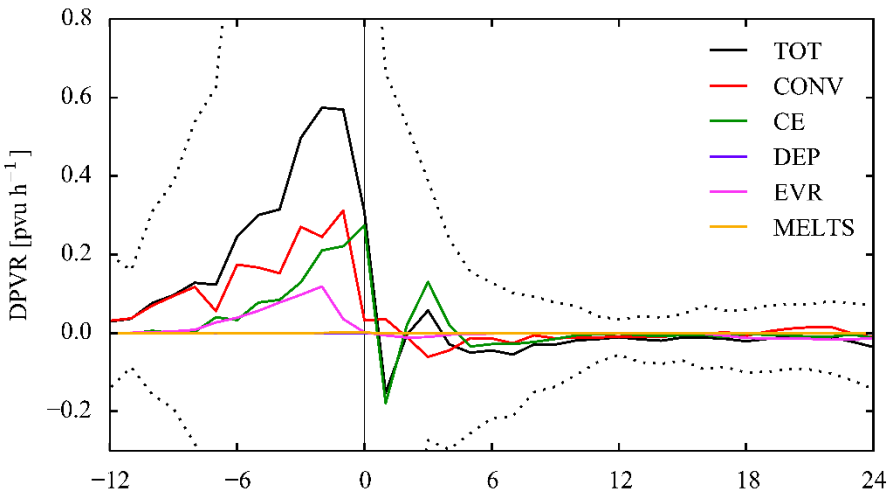


AS1





AS2



total

convection

condensation & evaporation

depositional growth of snow and ice

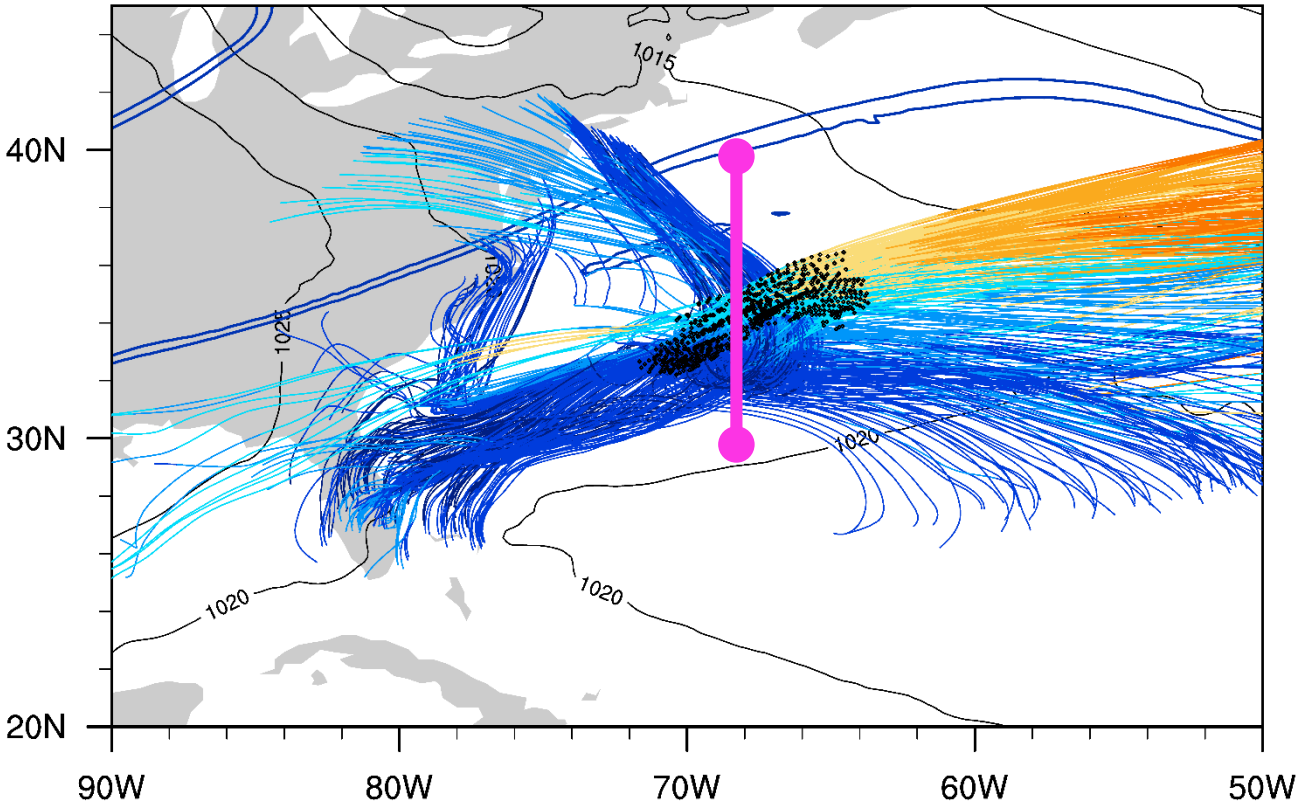
evaporation of rain

melting of snow

Results

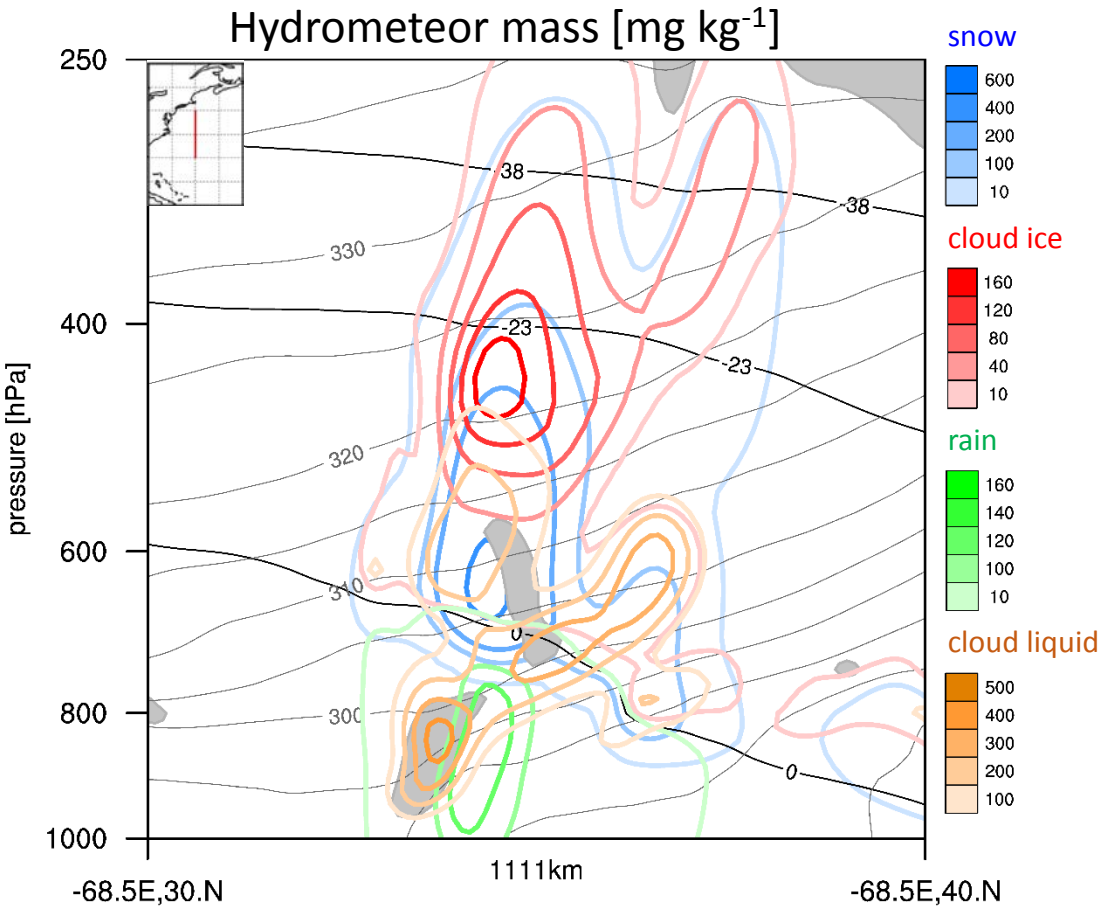
Structure of the DRW

- Combine Lagrangian with Eulerian framework
- vertical cross-section



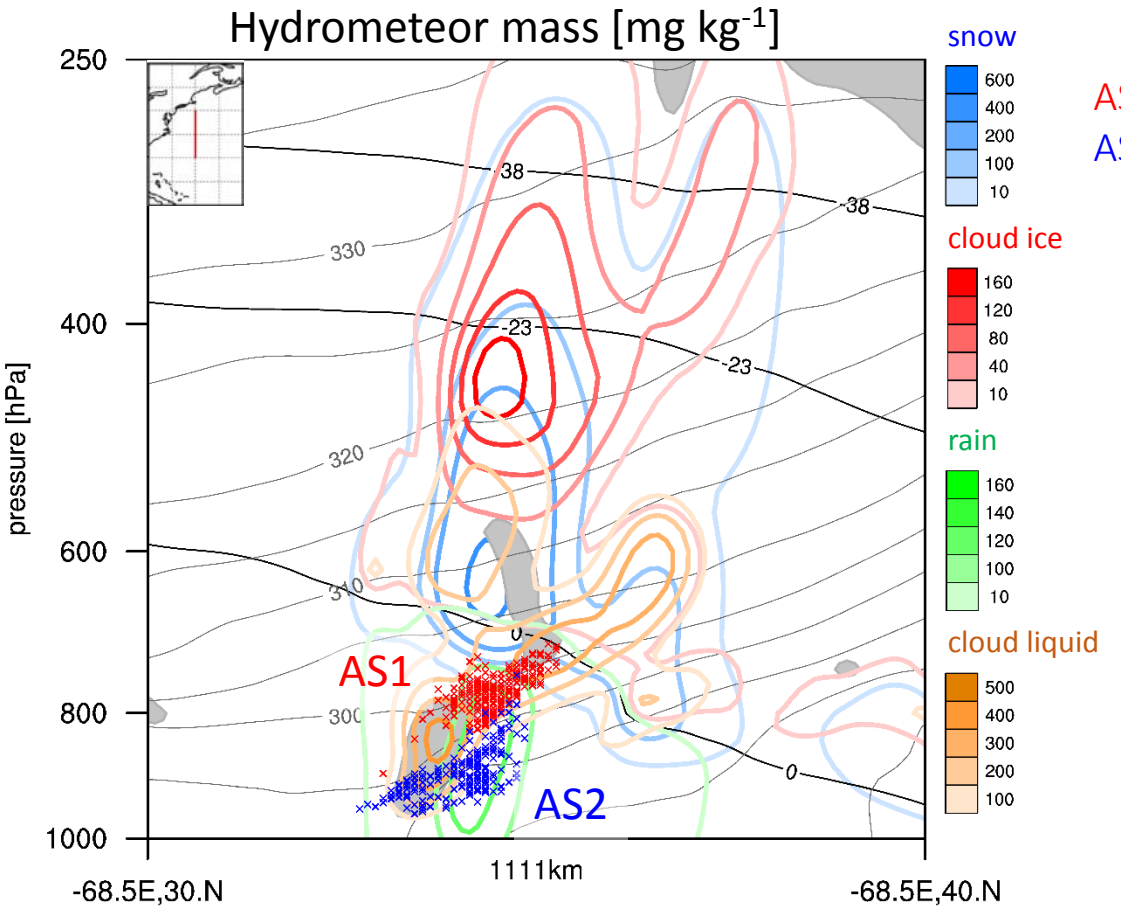
Results

Structure of the DRW



Results

Structure of the DRW and air parcel trajectories at t = 2 h

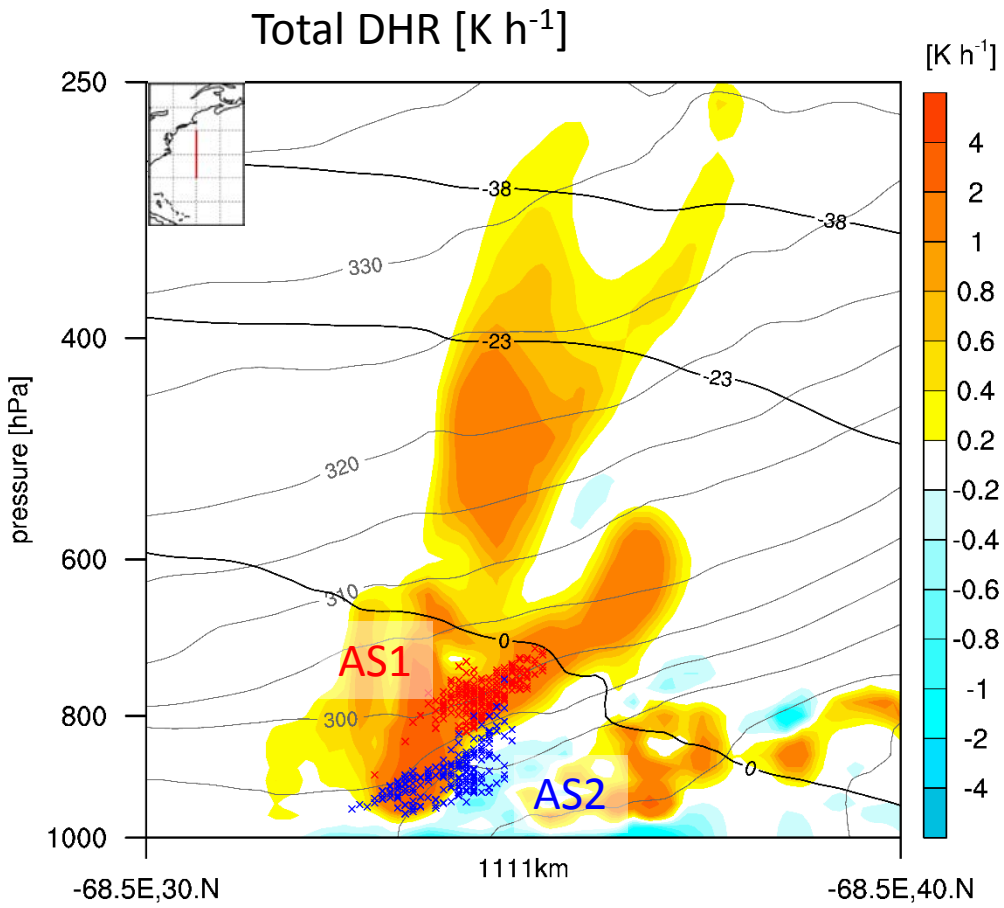


AS1 → mixed phase cloud

AS2 → below cloud: precipitation

Results

Structure of the DRW



AS1 → heating: CE, CONV, DEP

AS2 → cooling: EVR, CE

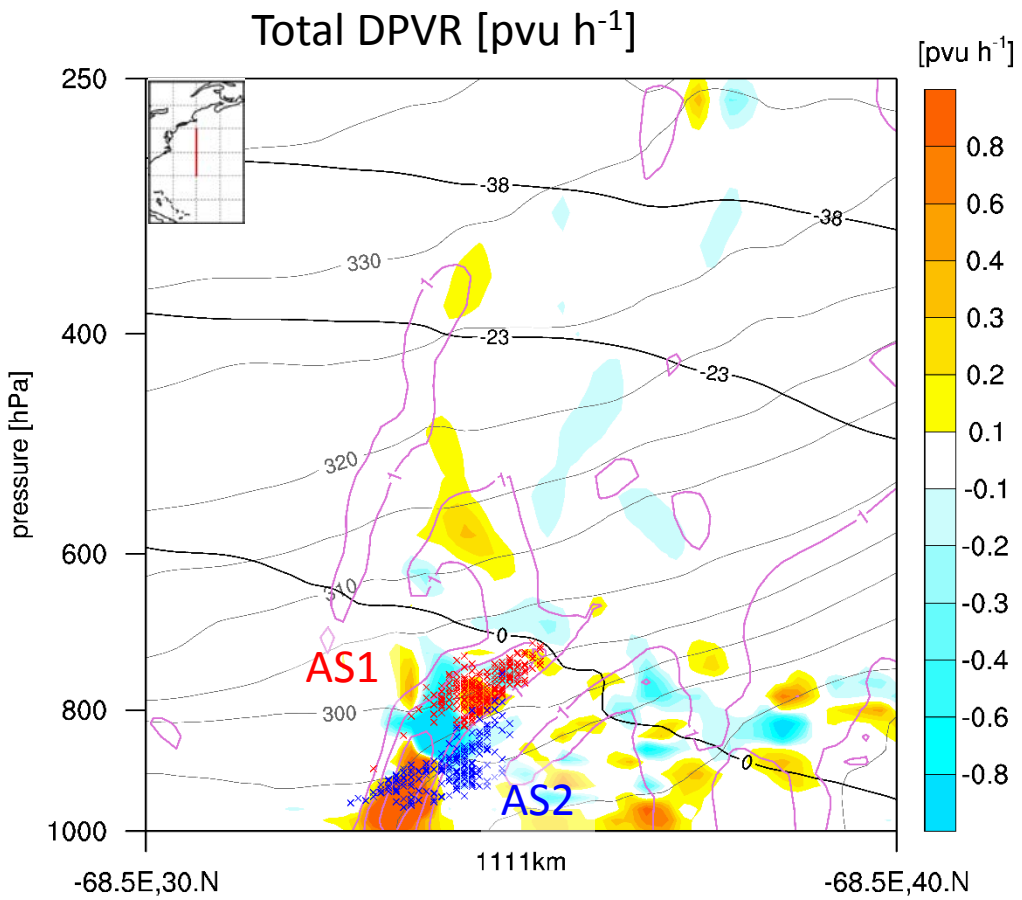
$\frac{\partial \dot{\theta}}{\partial z} < 0$: PV erosion

maximum of latent heating

$\frac{\partial \dot{\theta}}{\partial z} > 0$: PV production

Results

Structure of the DRW



AS1 → PV production: CE, CONV

AS2 → PV production: EVR, CE, CONV

Strong gradient of the DHR
+
high values of absolute vorticity
=
strength of PV modification

Limitations

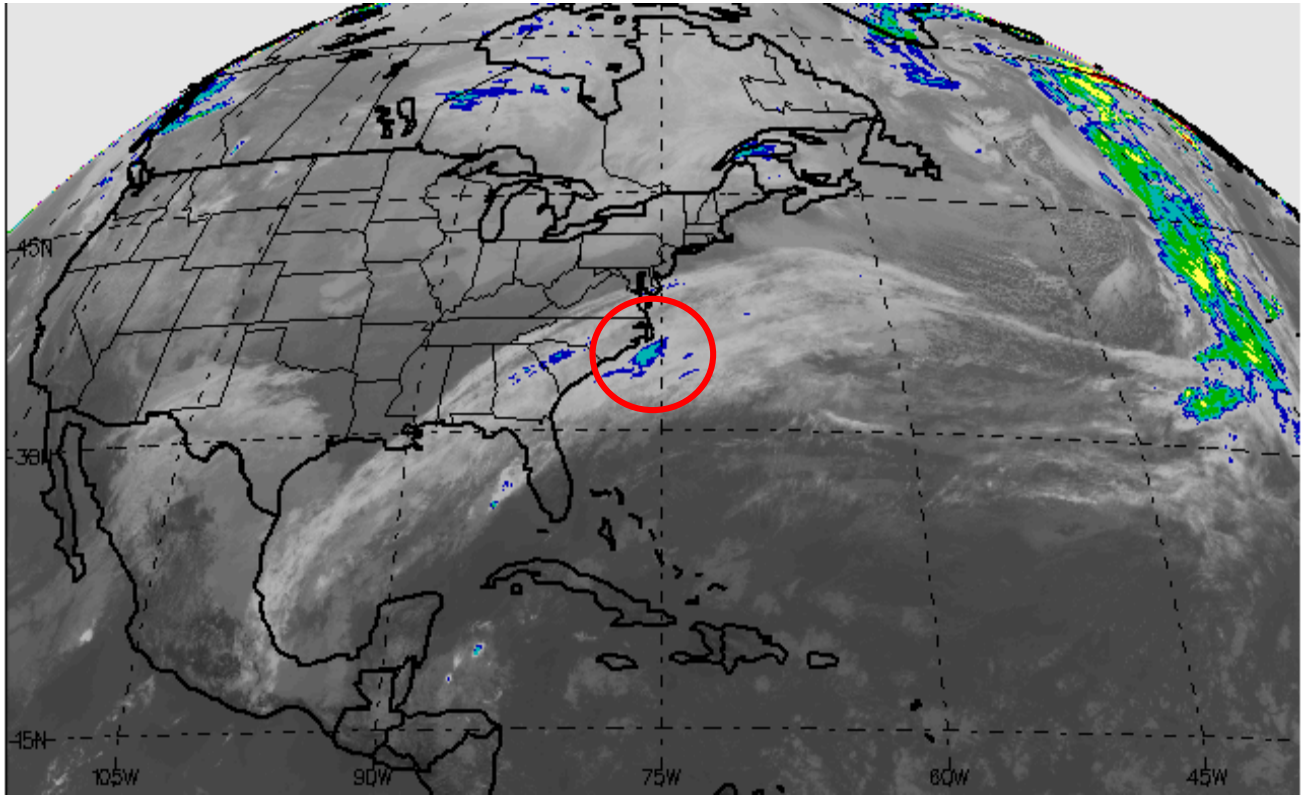
- Method does not account for frictional processes
- sub-grid scale processes: parameterization
- spatial and temporal resolution
- single case study

Conclusion

- distinct air streams are of critical importance for understanding the three dimensional clouds and PV structure of DRWs
- Condensation, convection and depositional growth of snow contribute significantly to heating in the DRW, while evaporation of cloud water and rain and melting of snow produces cooling.
- The interaction between coherent airstreams caused by the sedimentation of falling hydrometeors produces regions of heating and regions of cooling, thus a strong gradient of DHR.
- The strength of the PV modification depends on the gradient of the DHR as well as on the absolute vorticity occurring in the considered regions. Thus, strongest PVRs are close to the DRW center.

Thank you!

19 UTC 03 Jan 2013



IR satellite image GEOS East

References

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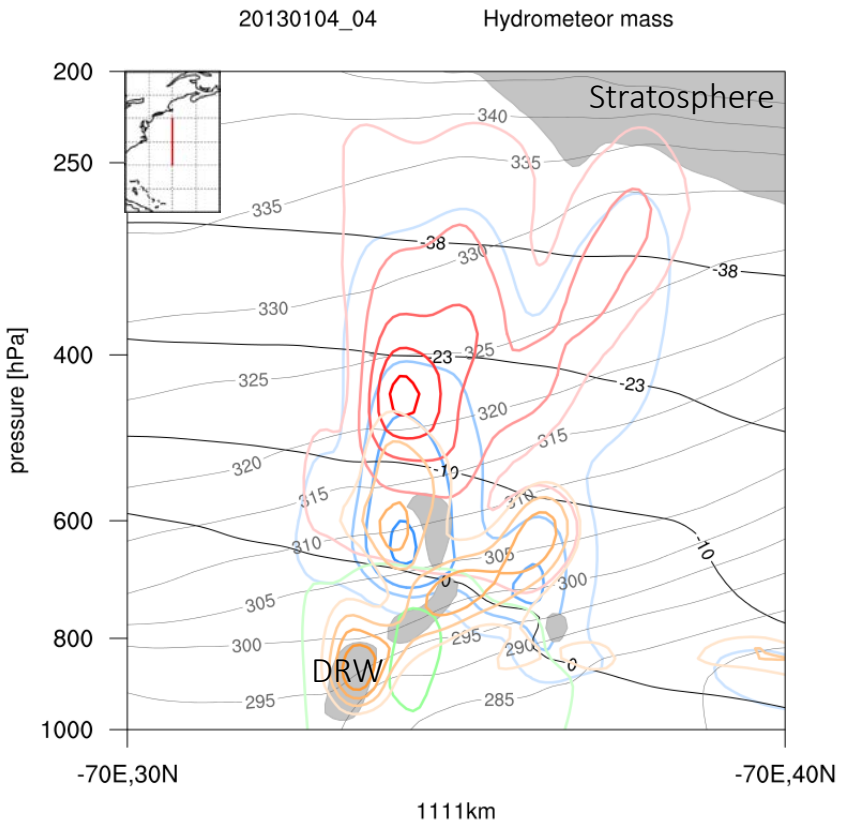
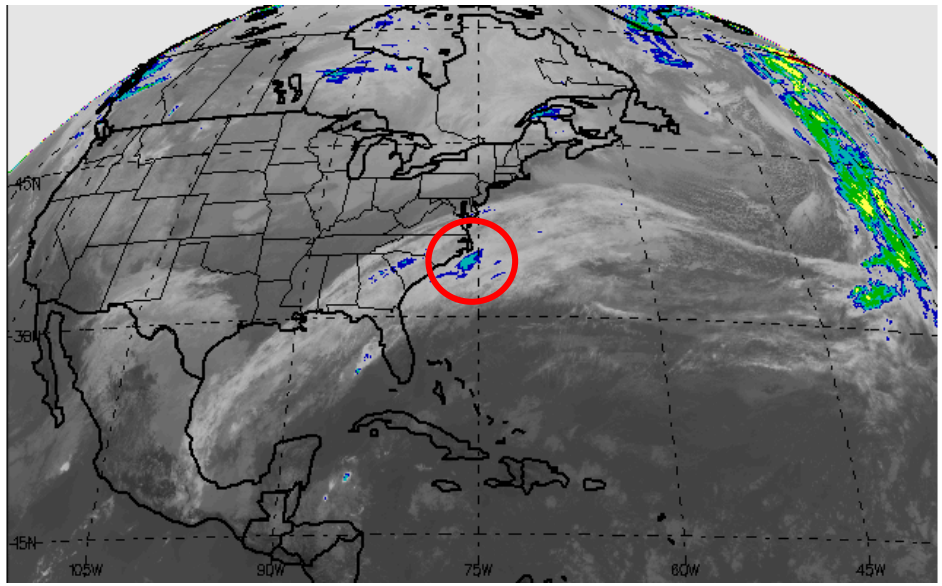
- Joos, H., Wernli, H. 2012. Influence of microphysical processes on the potential vorticity development in a warm conveyor belt: a case-study with the limited-area model COSMO. Quarterly Journal of the Royal Meteorological Society, 138, 407-418.
- Parker, D.J., Thorpe, A.J. 1995. Conditional Convective heating in a Baroclinic Atmopshere: A Model of Convective Frontogenesis. Journal of the Atmospheric Sciences, 52, 1966-1711.
- Wernli, H., Davies, H.C. 1997. A lagrangian-based analysis of extratropical cyclones. I: The method and some application. Quarterly Journal of the Royal Meteorological Society, 123, 1677-1704.

Appendix

Case study vertical cross-section & satellite image

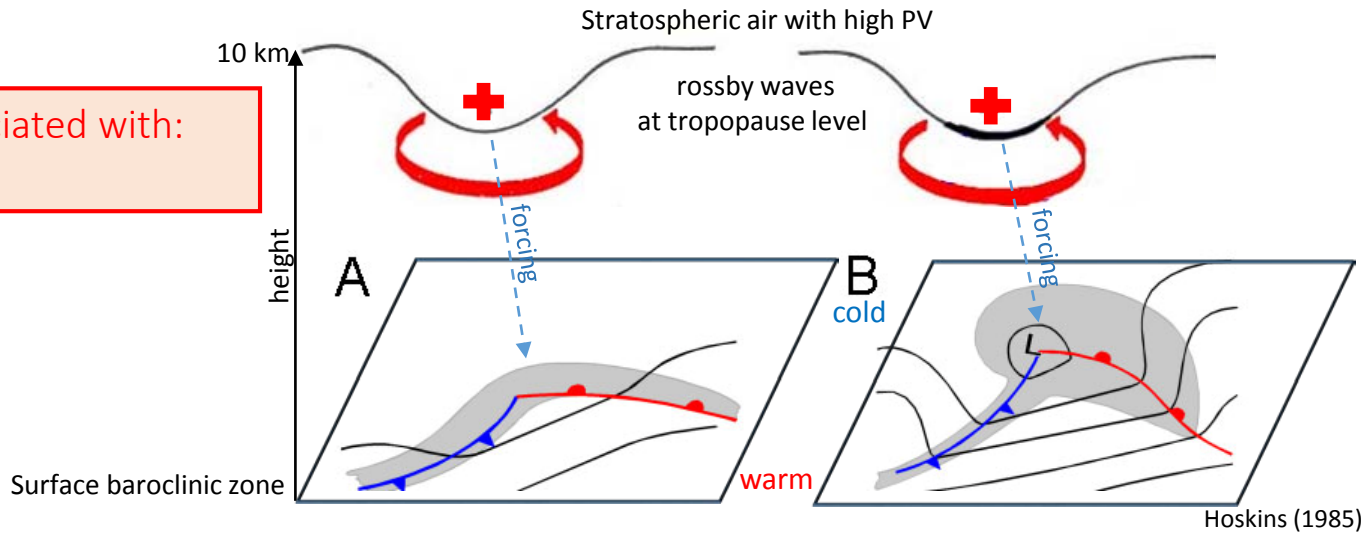




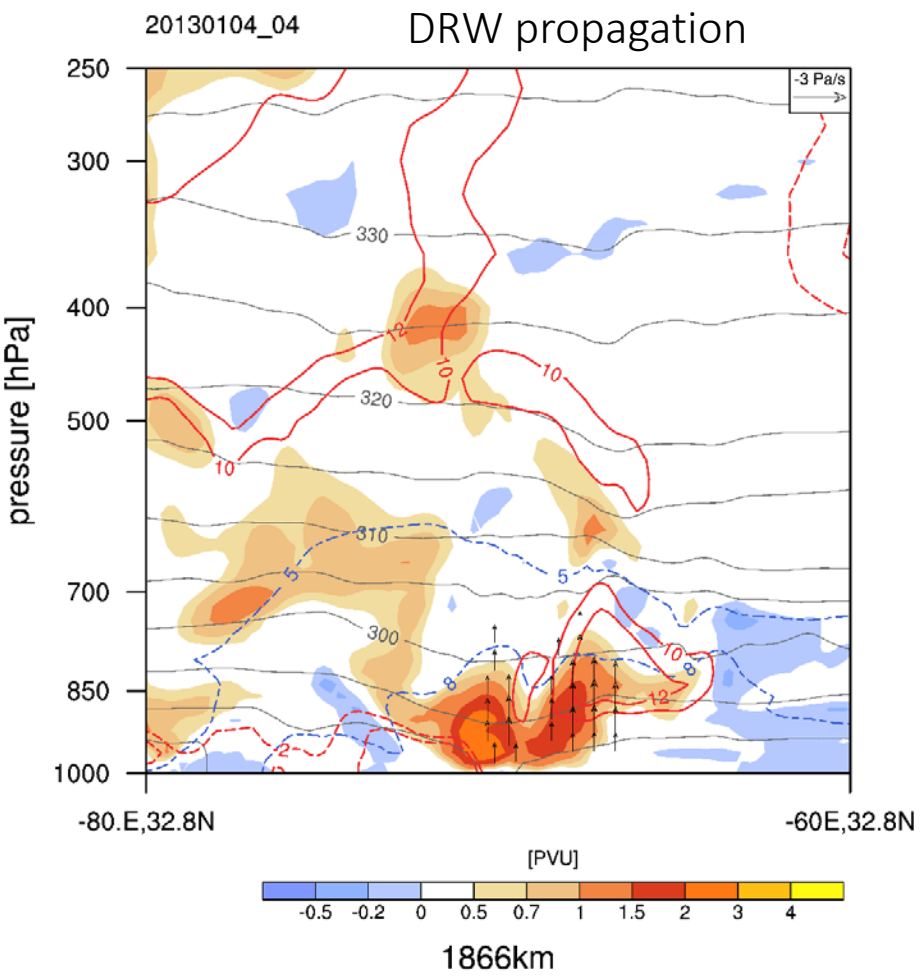
What is Potential Vorticity (PV)? cyclogenesis

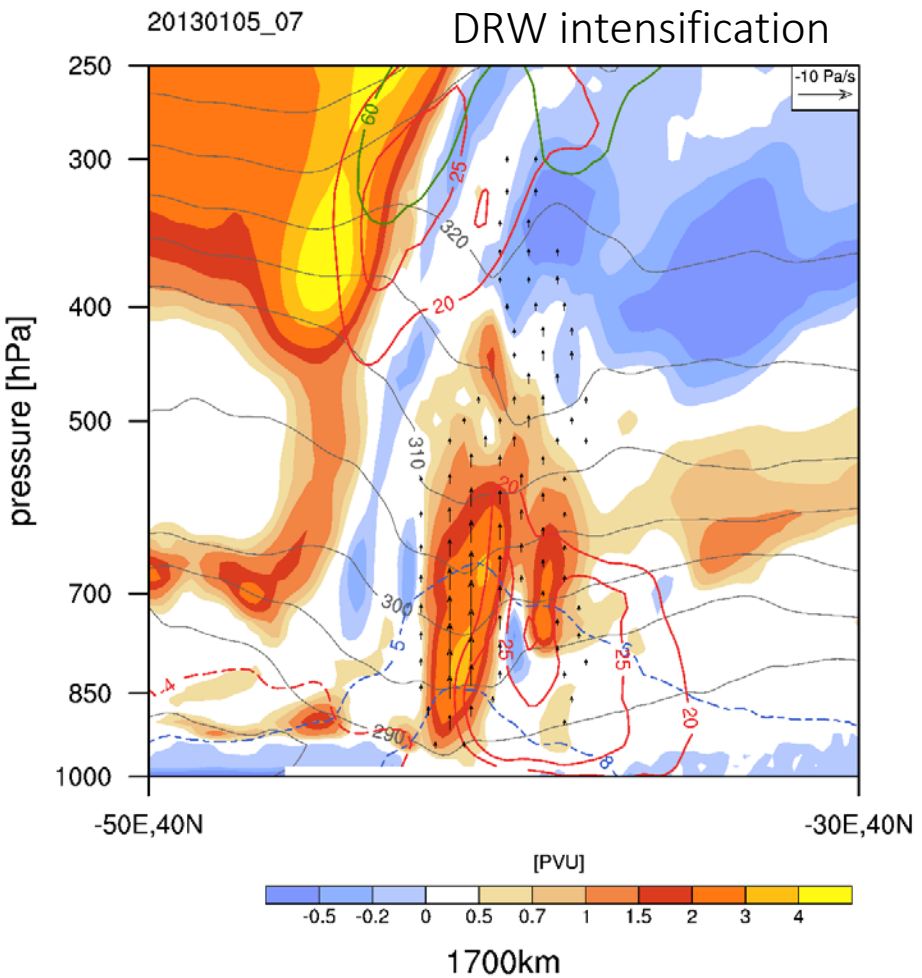
- Classic concept cyclogenesis: meridional advection of PV in a Rossby wave

Positive PV anomaly associated with:
- Cyclonic wind field



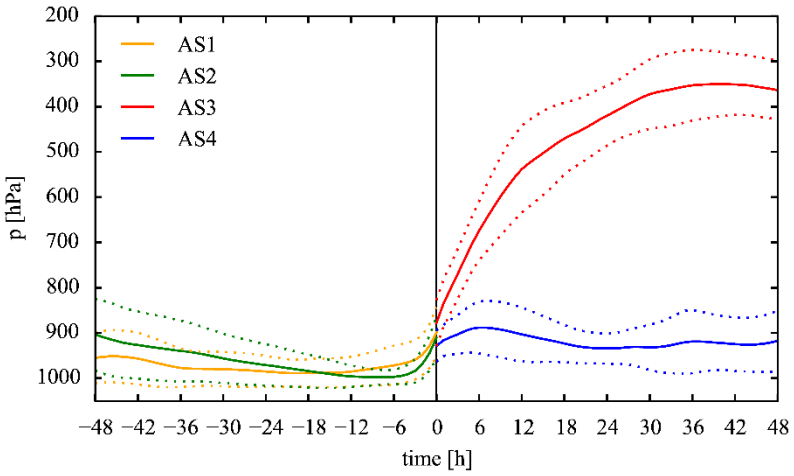
Case study vertical cross-section

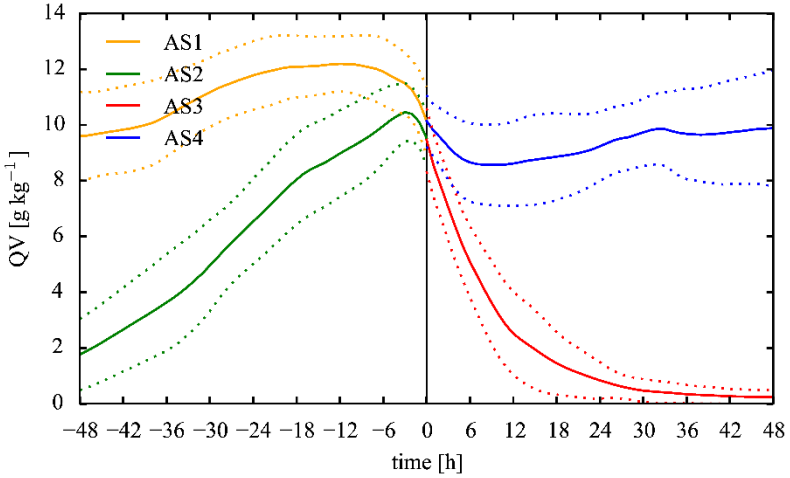


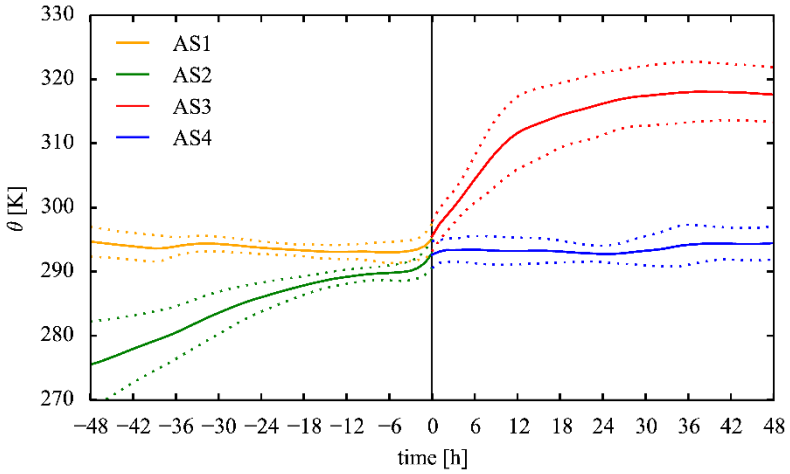


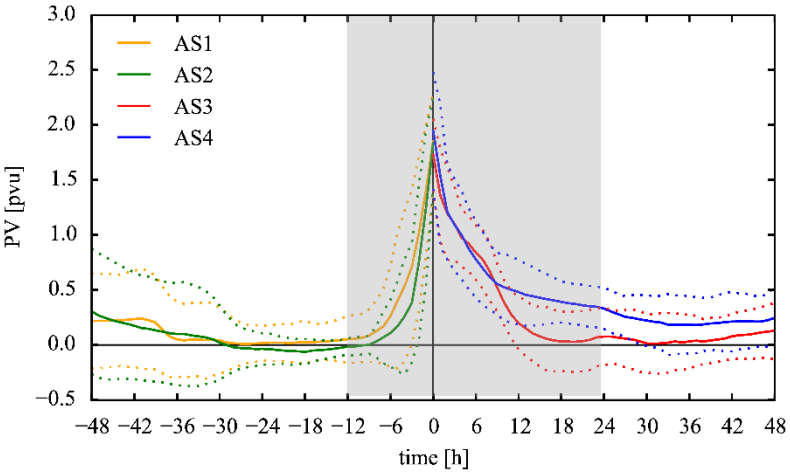
Results

air stream characteristics



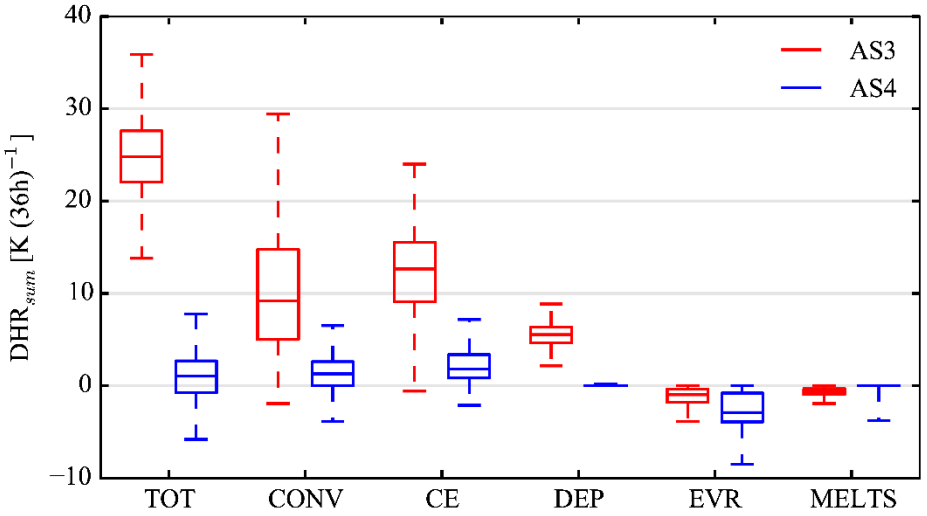


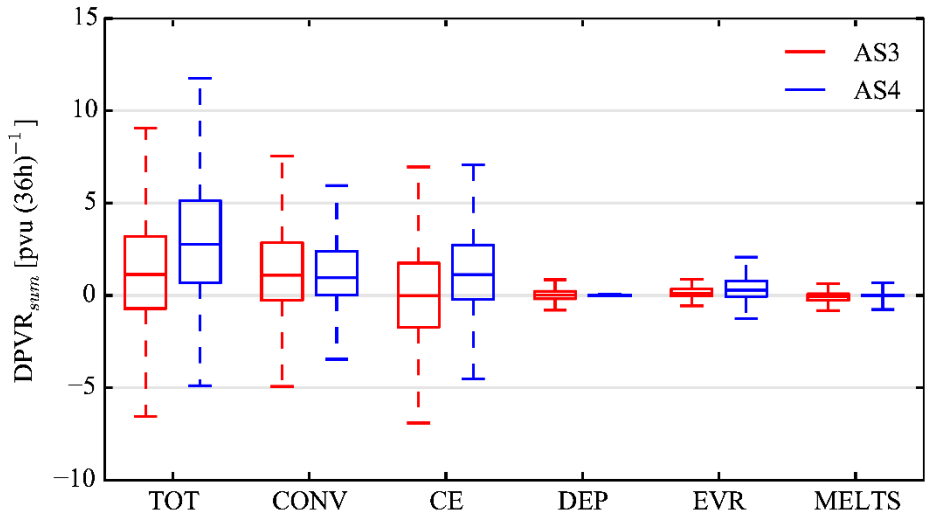




Results

integrated DHR and DPVR

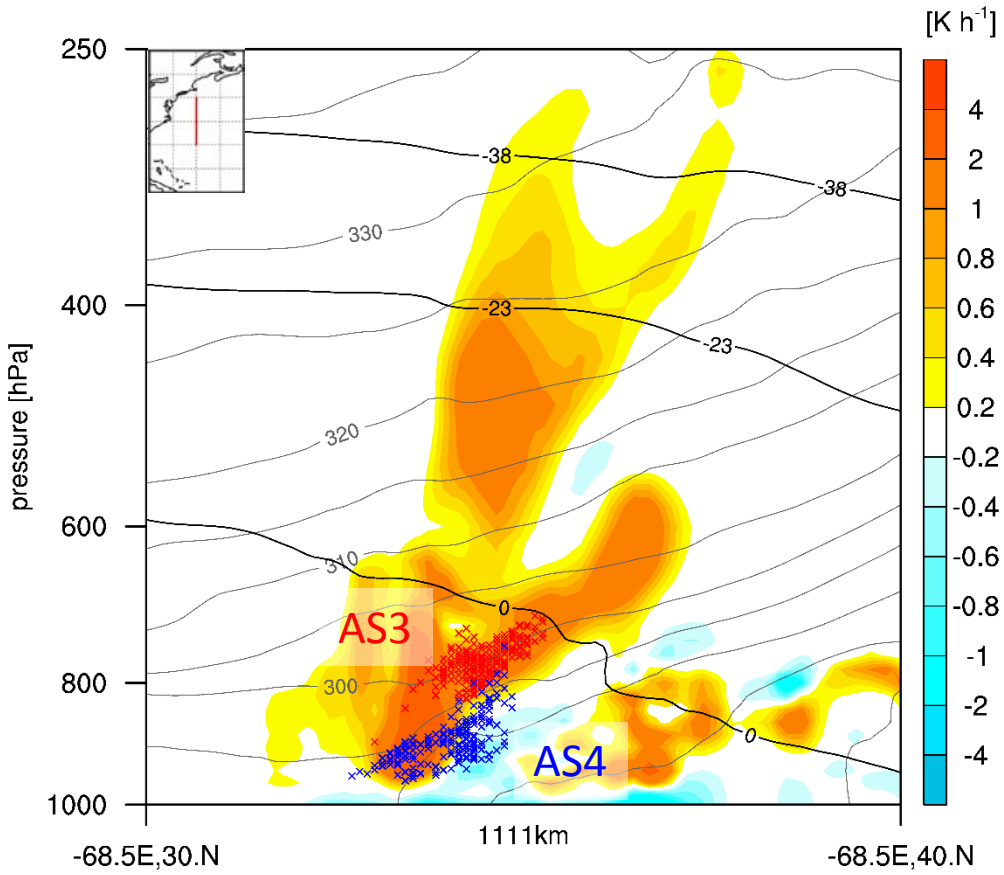


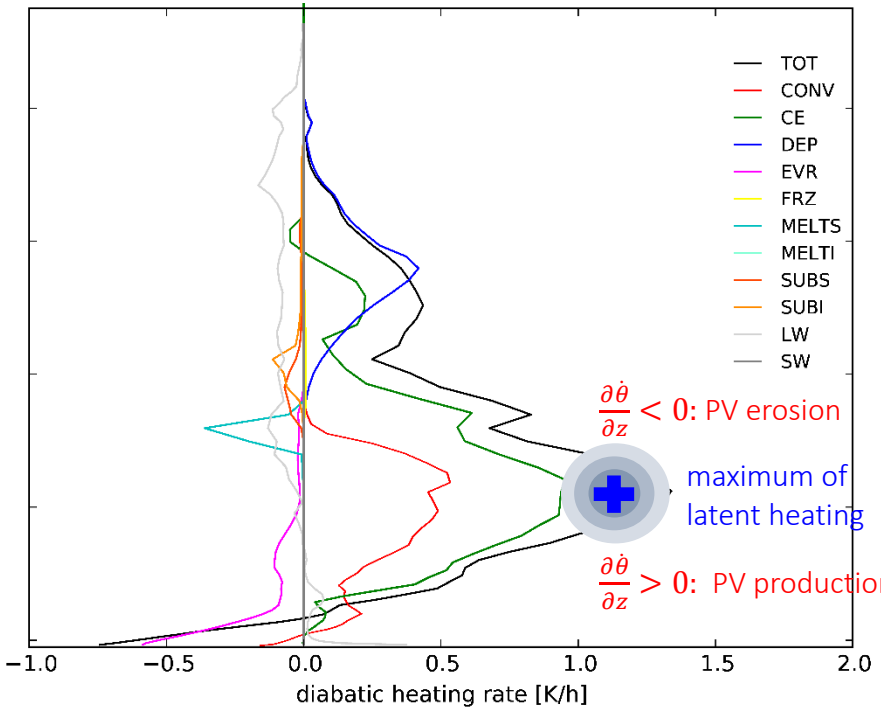


total
convection
condensation & evaporation
depositional growth of snow and ice
evaporation of rain
melting of snow

Results

Structure of the DRW



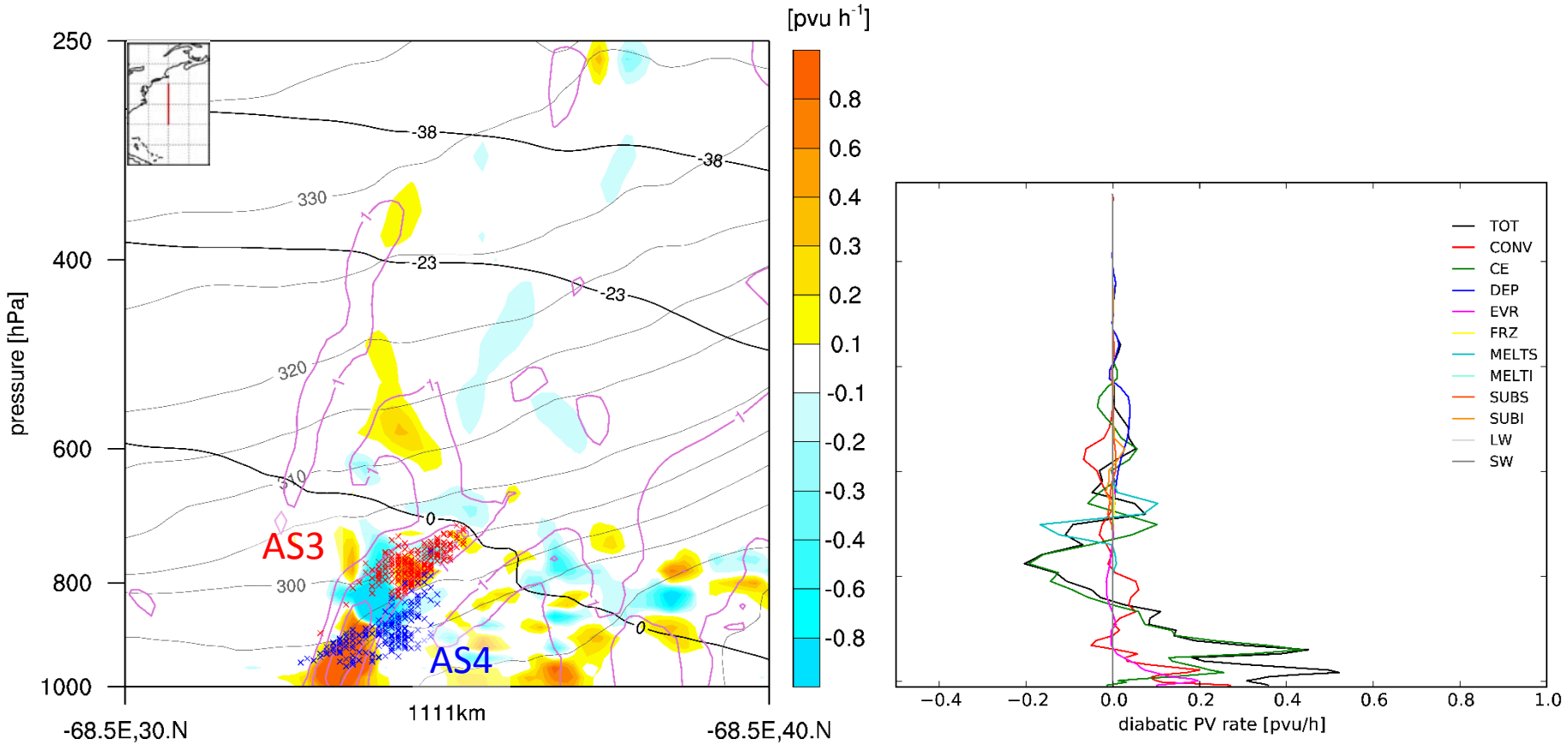


AS3 Heating: CE, CONV, DEP

AS4 Cooling: EVR, MELTS, CE

Results

Structure of the DRW



AS1 PV production: CE, CONV,
AS2 EVR