Geophysical and Nonlinear Fluid Dynamics Seminar
AOPP, Oxford, 23 October 2012

University of Reading
NATURAL ENVIRONMENT RESEARCH COUNCIL

Diabatic processes and the structure of extratropical cyclones

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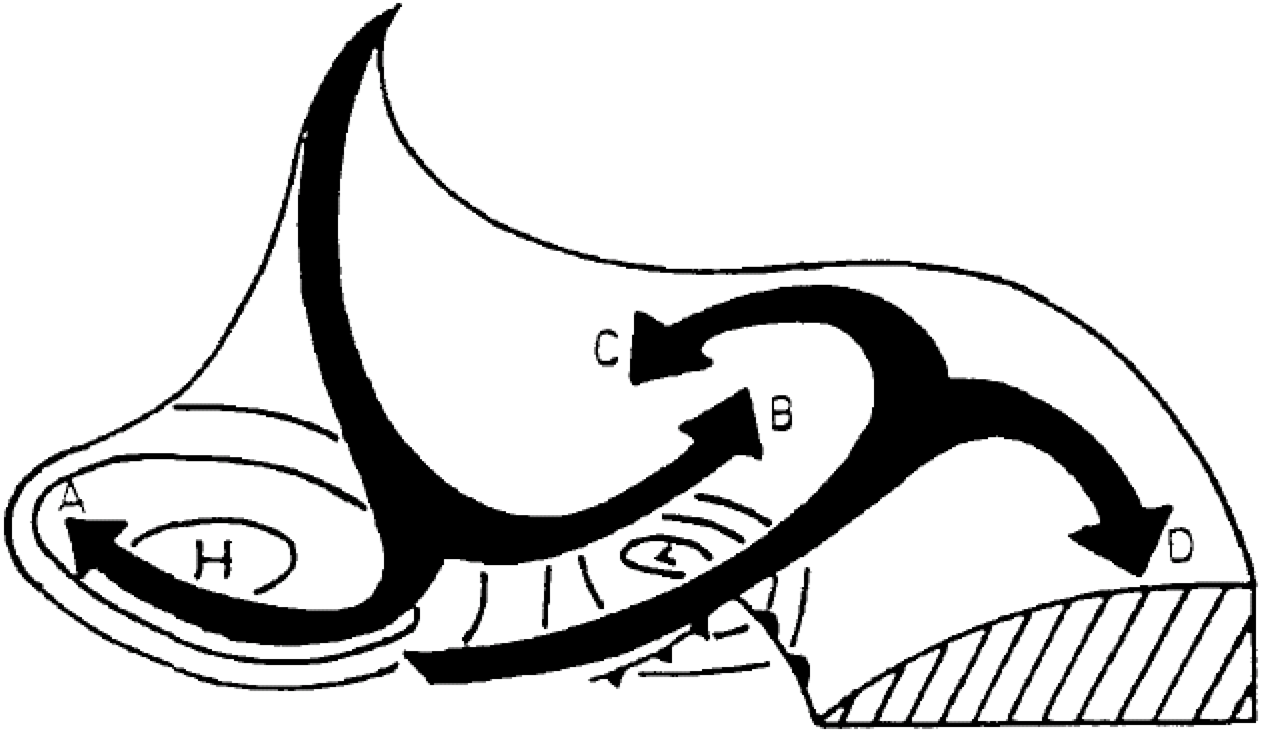
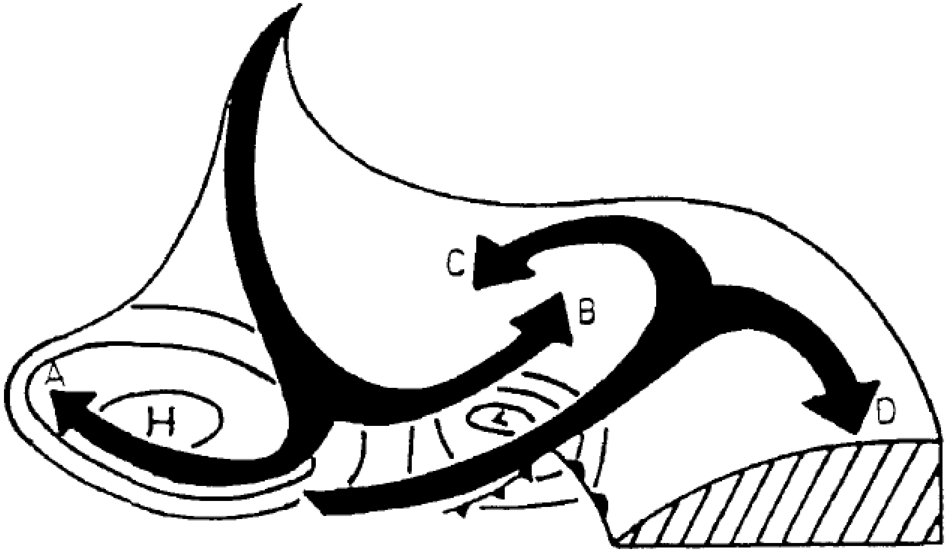
Isentropic flows in baroclinic waves

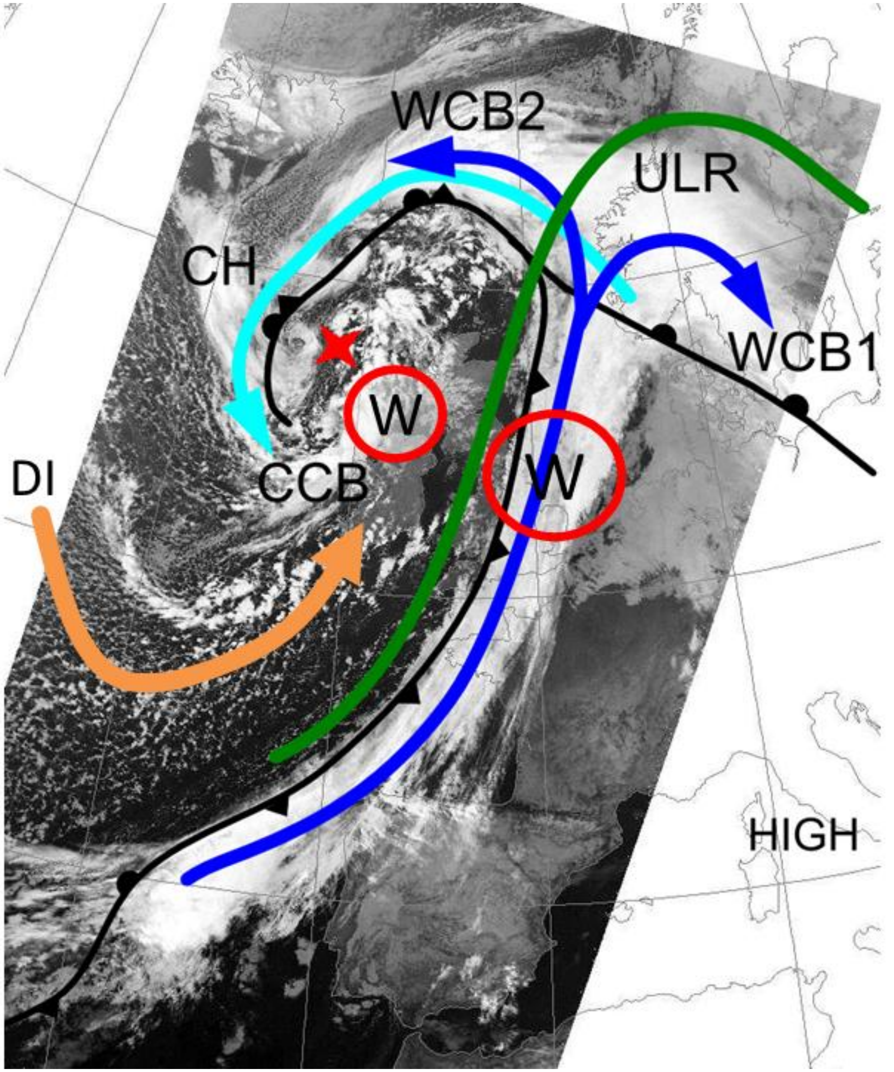


Thorncroft *et al*., (1993)

Isentropic flows in baroclinic waves



Thorncroft *et al*., (1993)



Why study diabatic processes in extratropical cyclones?

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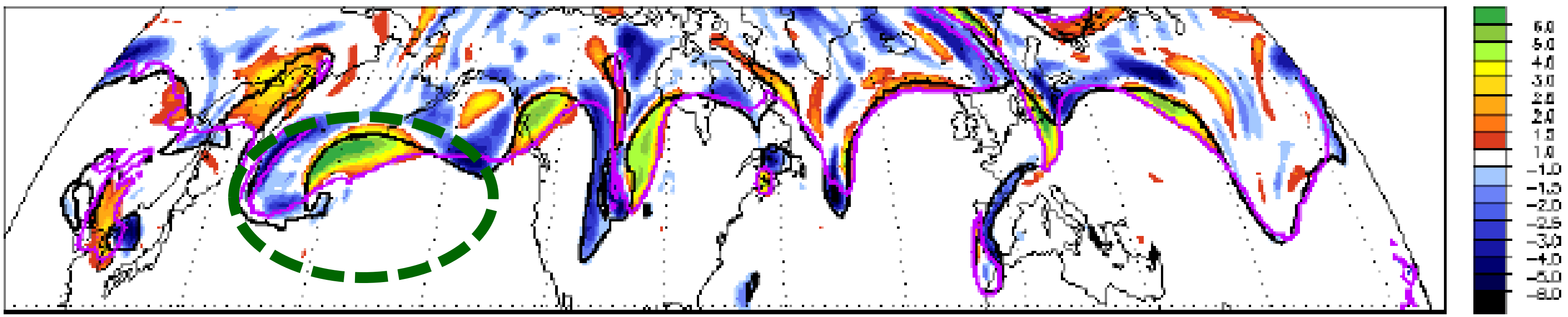
- Diabatic processes are fundamental to clouds and precipitation (i.e. weather)
- In NWP models these processes are parameterized
- The nonlinear feedback between the cloud scale and larger-scale dynamics has implications for:
  - Forecasts of heavy precipitation and high wind events
  - Assimilation of high resolution data (e.g., radar)
  - Linking forecast error to model representation of processes
  - Diabatic (heating) effects on medium-range forecasts
  - Design of perturbed physics ensembles

Diabatic PV near the tropopause



PV distribution "Forecast-Analysis" field at 320 K for a 72 h forecast to 10 October 2001, based on the ECMWF Integrated Forecast System (from Marco Didone, PhD thesis ETH Zürich).

Systematic error (PV overestimated) in medium-range weather forecasts on the downstream side of troughs.

Climatological importance

(Dunning, Gray, Methven, Chagnon, Masato)

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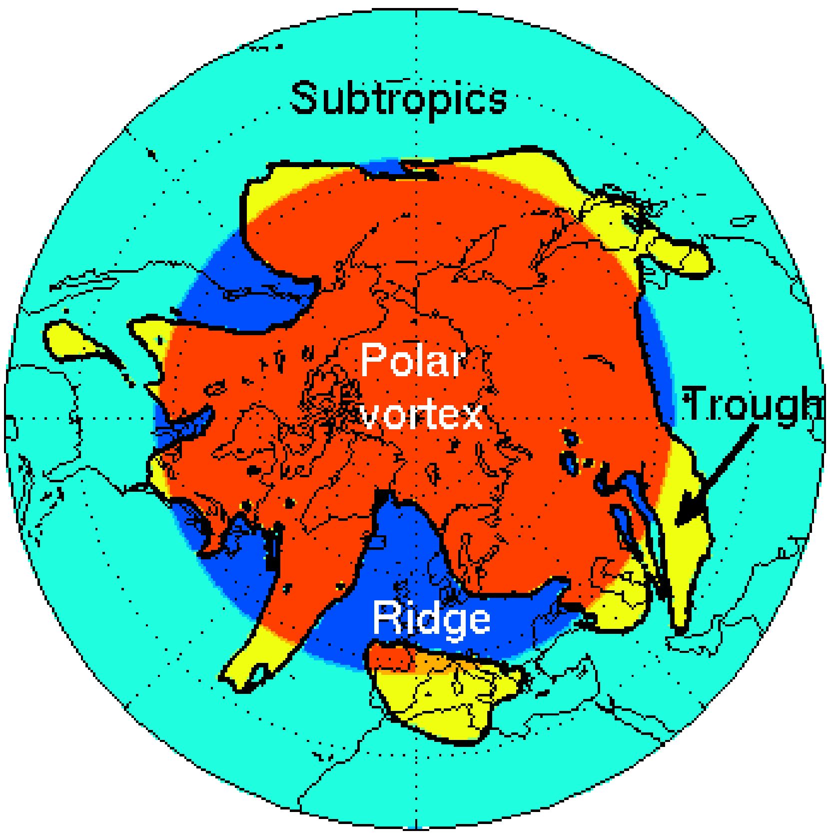
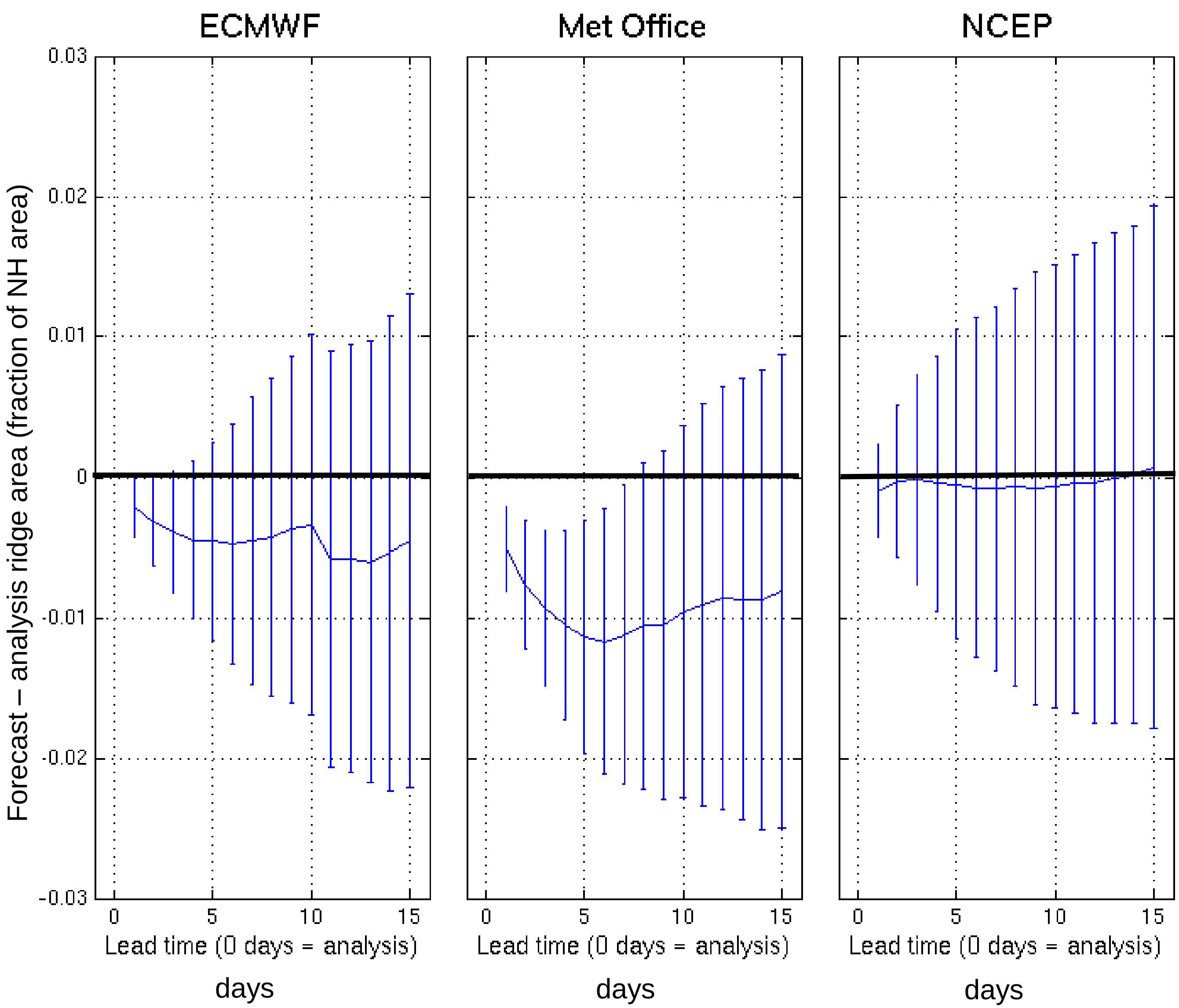
- TIGGE data: DJF 2006-2012
- PV on 320K isentrope
- Three operational centres: ECMWF, Met Office, NCEP
- Four categories defined using equivalent latitudes



Forecast error in ridge area



Tropopause defined as PV=2.2 PVU.

ECMWF and Met Office systematically under-predict ridge areas.

DIAMET

DIAbatic influences on Mesoscale structures in ExTratropical storms

- Consortium led by Geraint Vaughan (NCAS-weather director) with Methven, Parker and Renfrew as other lead PIs + Met Office partners. Response to NERC Natural Hazards theme action call.
- Overarching theme is the role of diabatic processes in generating mesoscale PV and moisture anomalies in cyclones, and the consequences of those anomalies for weather forecasts.
- Three-pronged approach:

a) Determining influence of diabatic processes on mesoscale structure (PV tracers partitioned by process)

b) Improving parameterisation of convection (in cyclone environment), air-sea fluxes and microphysics.

c) Using feature-tracking within the Met Office ensemble prediction system to quantify the predictability of mesoscale features and the dependence of the skill of weather forecasts (precipitation and winds) on mesoscale features.

FAAM research aircraft (BAe146)

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Objectives

- Evaluate the accuracy of numerical models in simulating atmospheric diabatic processes in extratropical cyclones
- What diabatic processes are important?
- What effect do these processes have on the cyclone's development?
- What are the consequences for the subsequent development of the upper-level atmospheric structure?

Methods

- Tracers tracking changes in potential vorticity (PV) and potential temperature (θ)
- Trajectory analysis - computation of Lagrangian trajectories following air parcels subject to the model-resolved velocity field

Tracers (I)

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- The variables of interest (PV, θ) are decomposed as

$$\varphi(x,t) = \varphi_0(x,t) + \sum_{i=\mathrm{proc}} \Delta\varphi_i(x,t)$$

$$\mathrm{proc} = \{\text{parameterised processes}\}$$

  where φ_0 represents a conserved field (redistribution by advection of the initial field) and $\Delta\varphi_i$ represents the accumulated tendency of φ due to a parameterised process.

- Parameterised processes:
  - short- and long-wave radiation
  - large-scale cloud formation
  - convection
  - boundary layer

Tracers (II)

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- Thus, there are evolution equations for φ_0 and for each $\Delta\varphi_i$

$$\frac{D\varphi_0}{Dt} = \frac{\partial \varphi_0}{\partial t} + \mathbf{v}\cdot\nabla\varphi_0 = 0$$

The conserved field is affected by advection only

$$\frac{D\Delta\varphi_i}{Dt} = \frac{\partial \Delta\varphi_i}{\partial t} + \mathbf{v}\cdot\nabla\Delta\varphi_i = S_{\varphi_i}$$

Each accumulated tendency is affected by advection and by a particular source of φ given by S_{φ_i}

- The evolution equation for the relevant variables can then be written as

$$\frac{\partial \varphi}{\partial t} = -\mathbf{v}\cdot\nabla\varphi_0 - \mathbf{v}\cdot\nabla \sum_{i=\mathrm{proc}} \Delta\varphi_i + \sum_{i=\mathrm{proc}} S_{\varphi_i}$$

Total rate of change

Advection of conserved field

Advection of accumulated tendencies

Sources

Consistency between tracers and trajectories

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- Theoretically, θ_0 is conserved along trajectories. In practice, this is not true mainly because we simply cannot expect a perfect match between the advection in the model and the offline computation of trajectories.
- We select those trajectories that do not depart too much from their initial θ_0 value.
- The trajectories that are rejected largely correspond to trajectories that end up in the far right-end of the theta distribution in a long trailing tail beyond the value of θ = 340 K.

Case-Study I:
An extratropical cyclone on 30 September 2011

Case-Study I:
30 September 2011

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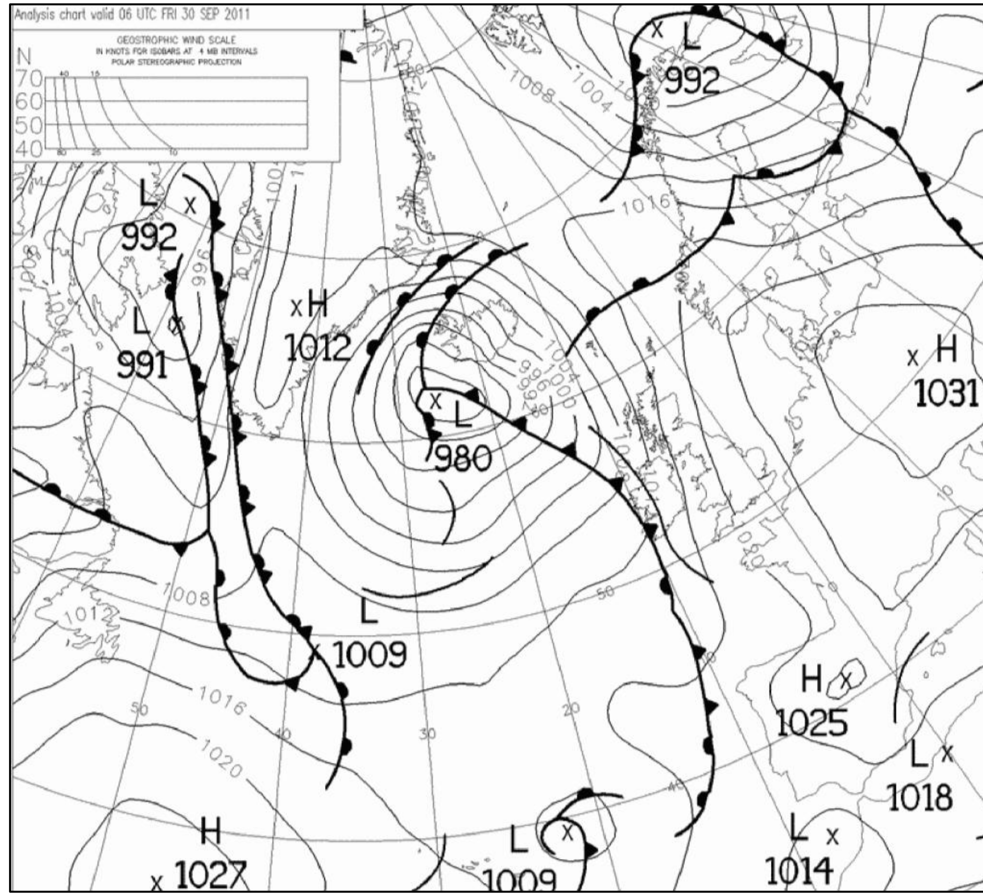
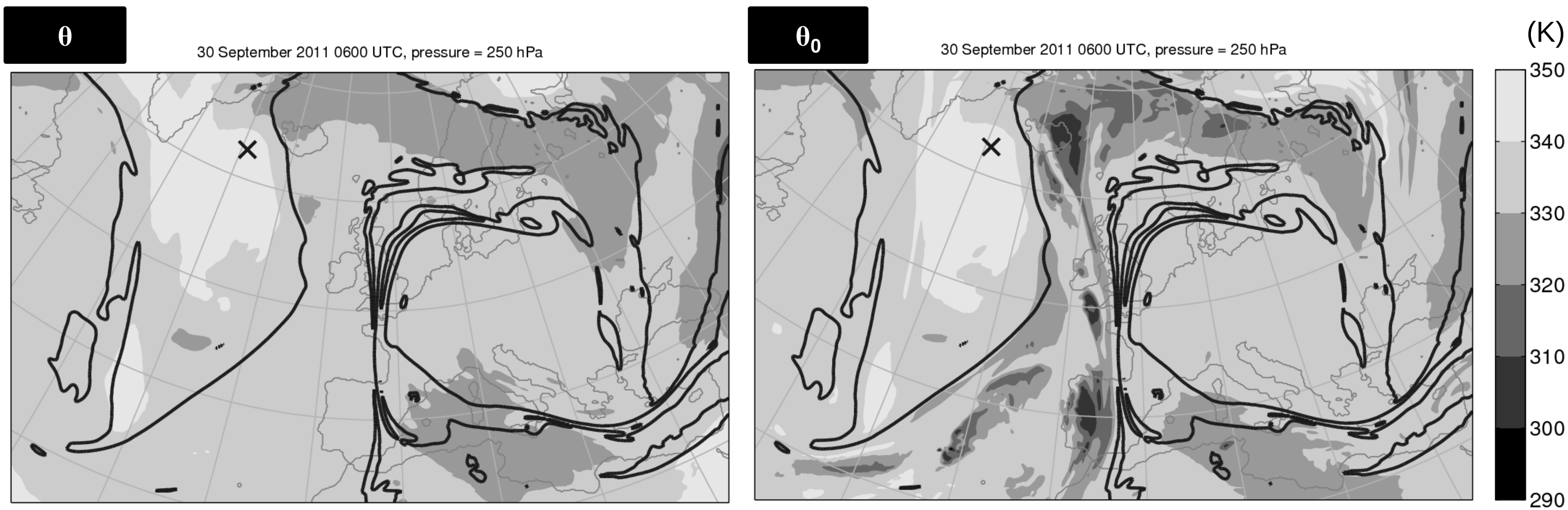
- Low-pressure system centred to the southwest of Iceland with a long-trailing cold front.
- Development began 0600 UTC 28 September 2011 at 43°N 28°W.
- From there it travelled northwards to be located around 62°N 25°W at 1200 UTC 30 September 2011, deepening from 997 hPa to 973 hPa in 54 hours.
- Precipitation over the United Kingdom on 30 September 2011.



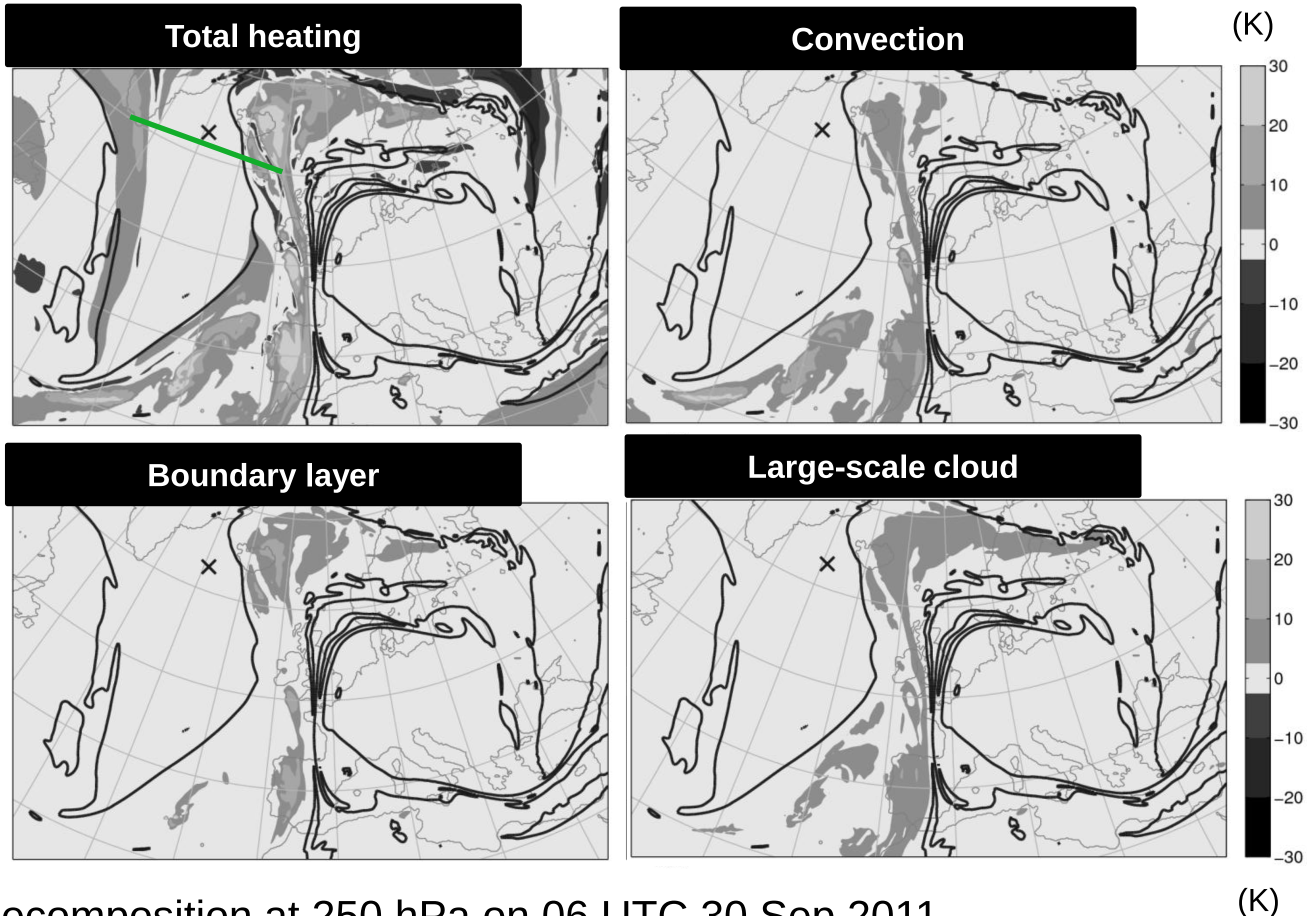
Met Office operational analysis chart at 06 UTC 30 Sep 2011
(archived by http://www.wetter3.de/fax)

Diabatic potential temperature at 250 hPa



- θ decomposition at 250 hPa on 06 UTC 30 Sep 2011.
- **Bold black lines** represent the 2-PVU contour.
- Black crosses (**X**) indicate the position of the mean sea-level low-pressure centre.

Diabatic potential temperature at 250 hPa



- θ decomposition at 250 hPa on 06 UTC 30 Sep 2011.
- **Bold black lines** represent the 2-PVU contour.
- Black crosses (**X**) indicate the position of the mean sea-level low-pressure centre.
- The green line represents the position of the section in the next frames.

Diabatic potential temperature (Vertical structure)

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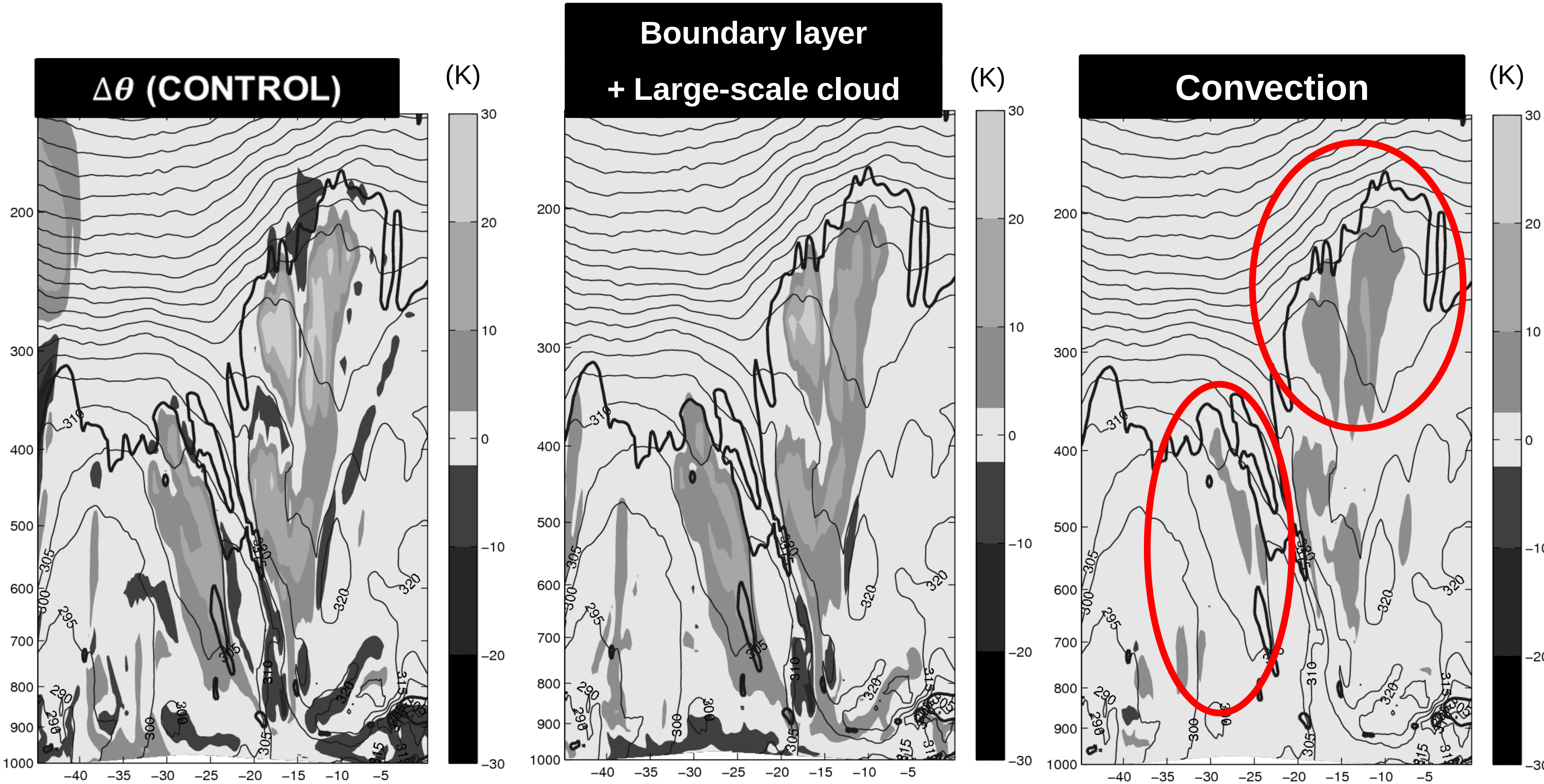
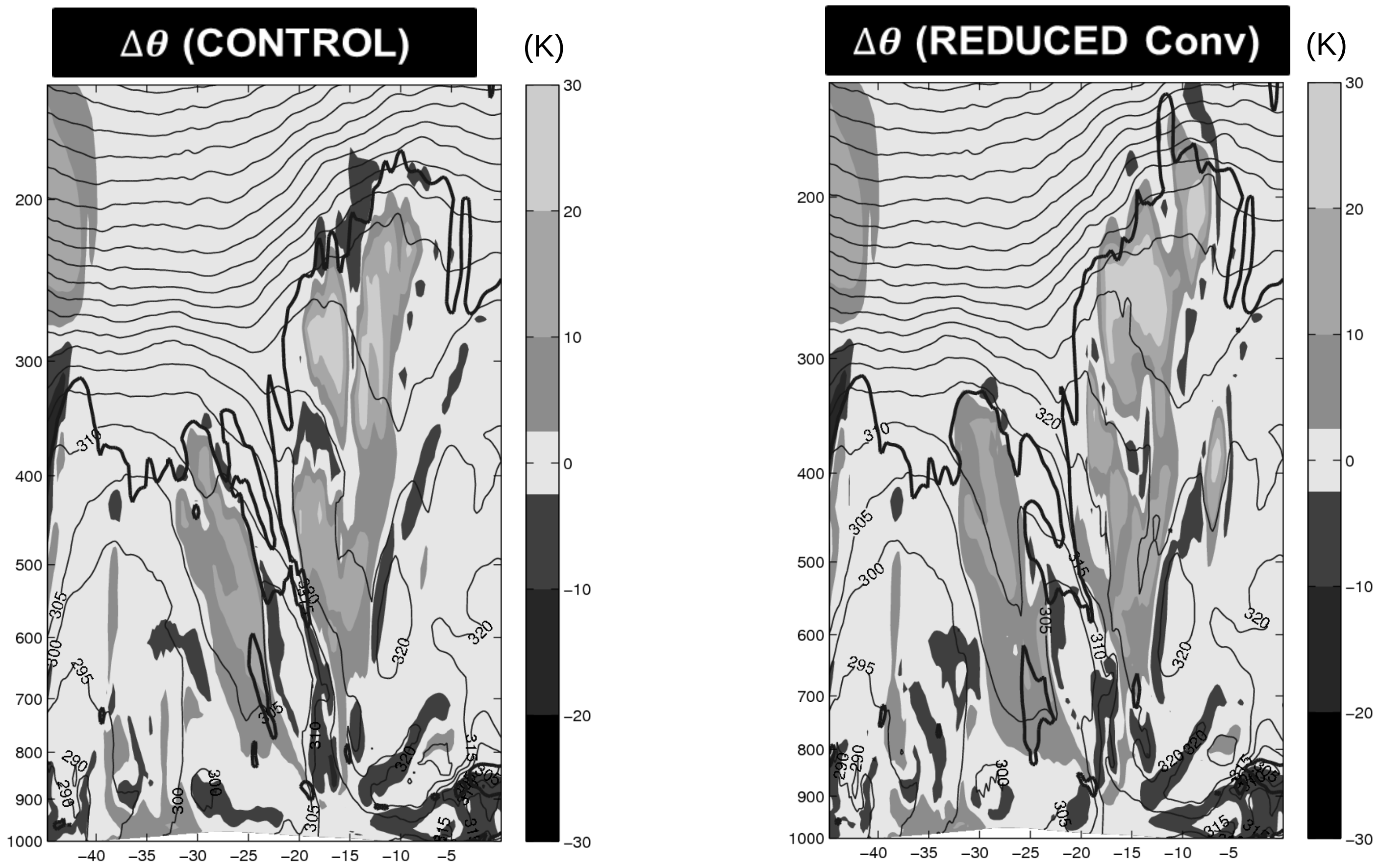


- **Bold black** lines represent the 2-PVU contour.
- Thin black lines represent equivalent potential temperature contours with a 5-K separation.

Diabatic potential temperature (Vertical structure)



- **Bold black** lines represent the 2-PVU contour.
- Thin black lines represent equivalent potential temperature contours with a 5-K separation.

Trajectory analysis

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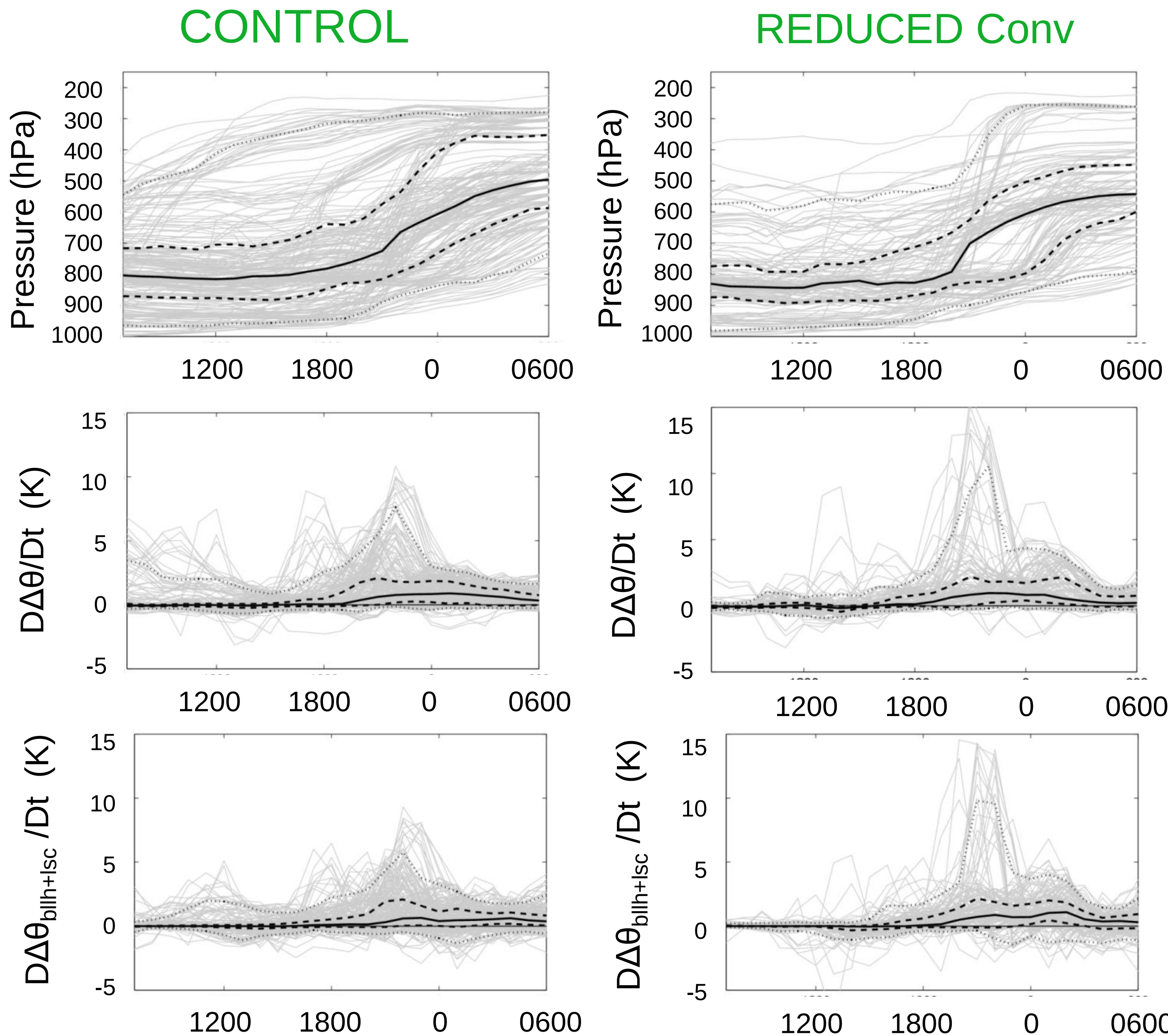
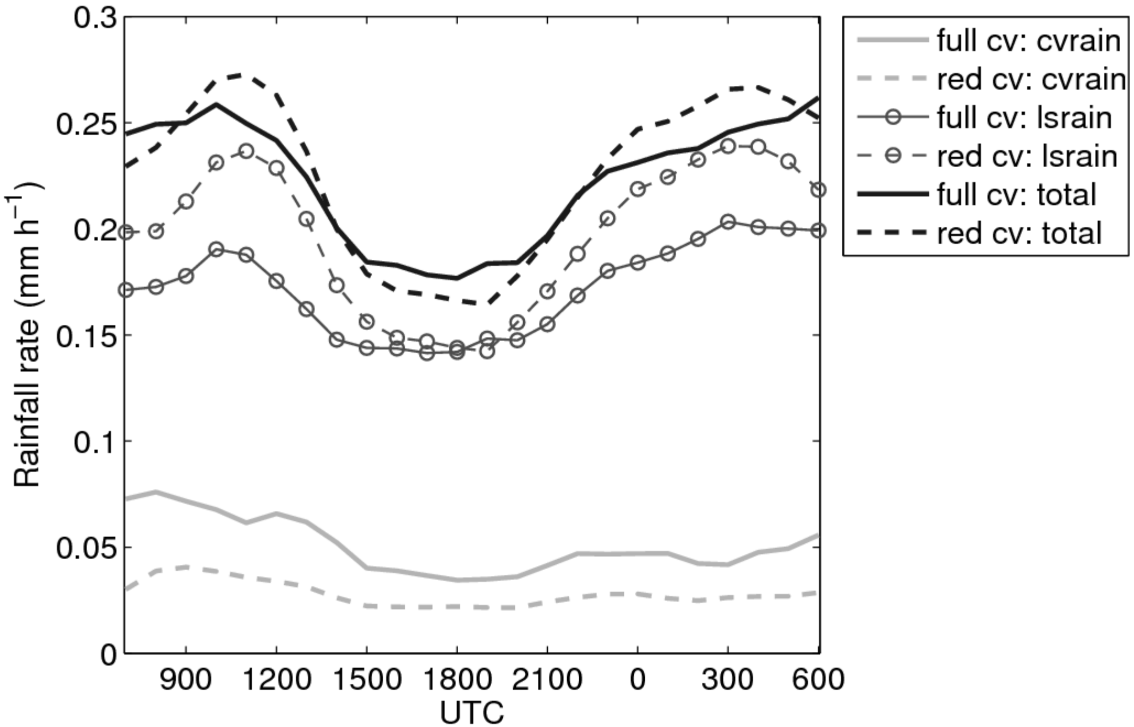
- Evolution along trajectories that have strong accumulated heating.
- Solid lines represent the median
- Dashed lines represent the 25th and 75th percentiles
- Dotted lines represent the 5th and 95th percentiles of the trajectory ensemble
- Grey lines represent individual trajectories.



Convective–large-scale precipitation split

Rain rate averaged over an area of 1500-km radius centred on the low pressure centre, showing the contributions from convective (cvrain) and large-scale rain (lsrain) to the total precipitation (total) for CONTROL and REDUCED Conv.



Summary and conclusions from Case-Study I

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- The convection and large-scale cloud parameterisations were the most active numerical diabatic sources in this case
- Two simulations, one with standard parameterised convection and one with reduced parameterised convection were contrasted
- The upper-level PV structure was sensitive to the details of the parameterisation schemes and their interaction
- Although, the convective – large-scale precipitation split was different, both simulations produced a similar amount of total precipitation
- The most important diabatic modifications to potential temperature appeared along the warm conveyor belt

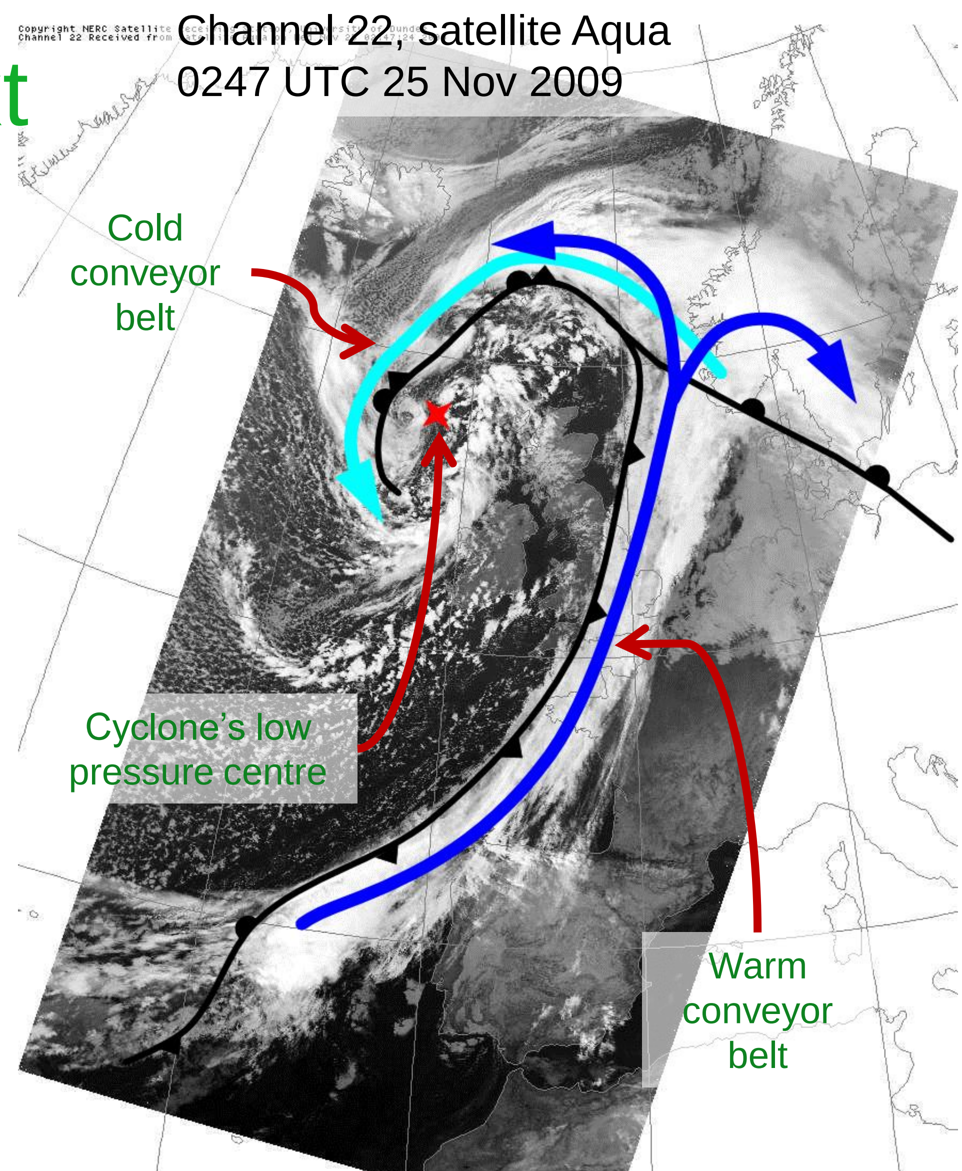
Case-Study II:
An extratropical cyclone on 25 November 2009 (T-NAWDEX III)

Work in collaboration with Dr Hanna Joos and Dr Maxi Böttcher

ETH Zürich

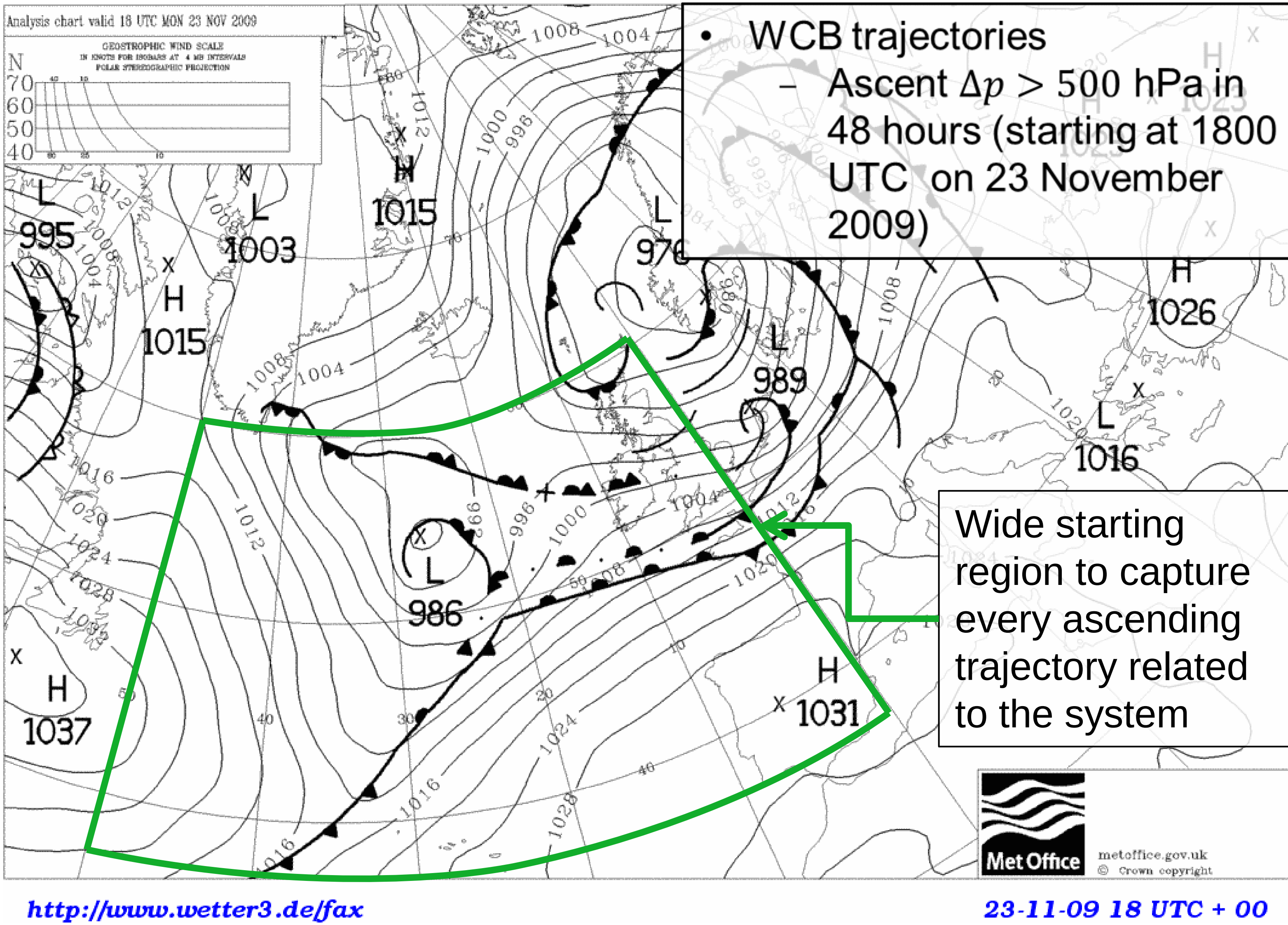
Case-Study II: Synoptic-scale context

- The surface low formed in the North Atlantic on 23 November 2009 along an east-west oriented baroclinic zone
- The low deepened from 0000 UTC 23 November to 0000 UTC 25 November 2009 and moved eastward.
- By 0000 UTC 25 November, the system was occluded and had undergone “frontal fracture”.
- Precipitation was heavy and continuous along the length of the cold front during the period 23-25 November 2009. As such, this is an ideal case for examining diabatic heating in a WCB.
- The upper-level trough associated with the primary low amplified in concert with the surface low.
- The downstream ridge and downstream trough also amplified during this period.



Satellite image courtesy of NERC Satellite Receiving Station, Dundee University, Scotland http://www.sat.dundee.ac.uk
Surface fronts based on the Met Office analysis at 00 UTC 25 Nov 2009 (archived by http://www.wetter3.de/fax)

Trajectory selection



- WCB trajectories
  - Ascent $\Delta p > 500$ hPa in 48 hours (starting at 1800 UTC on 23 November 2009)

Wide starting region to capture every ascending trajectory related to the system

Upper-level structure (I)

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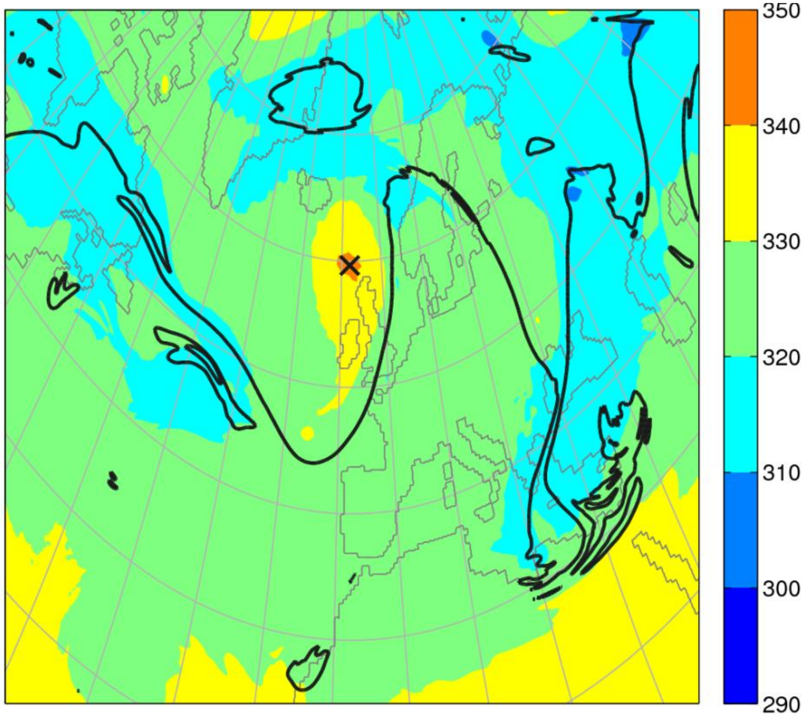
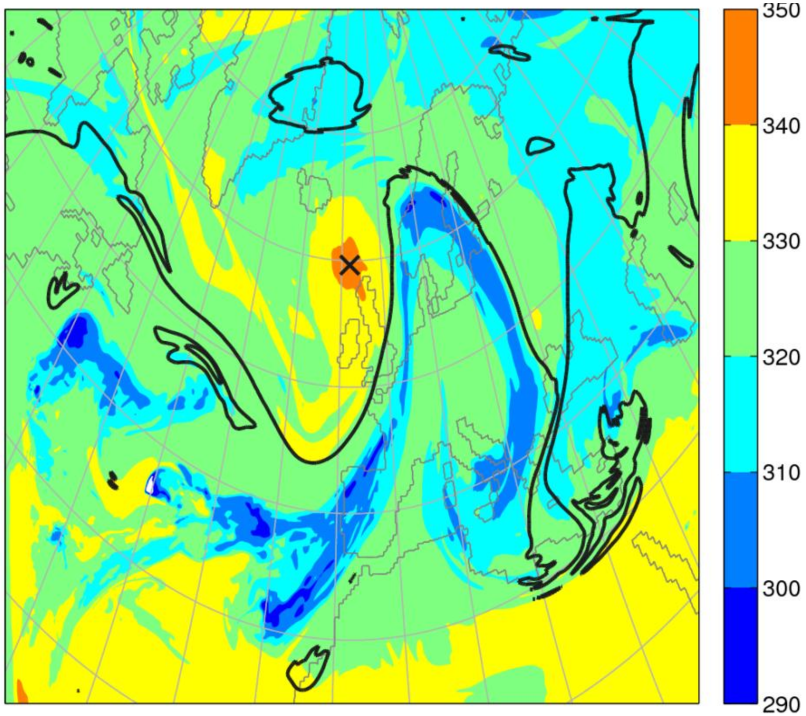
Potential temperature (K)



Potential temperature conserved component (K)



Model level at 9.68 km

Upper-level structure (II)

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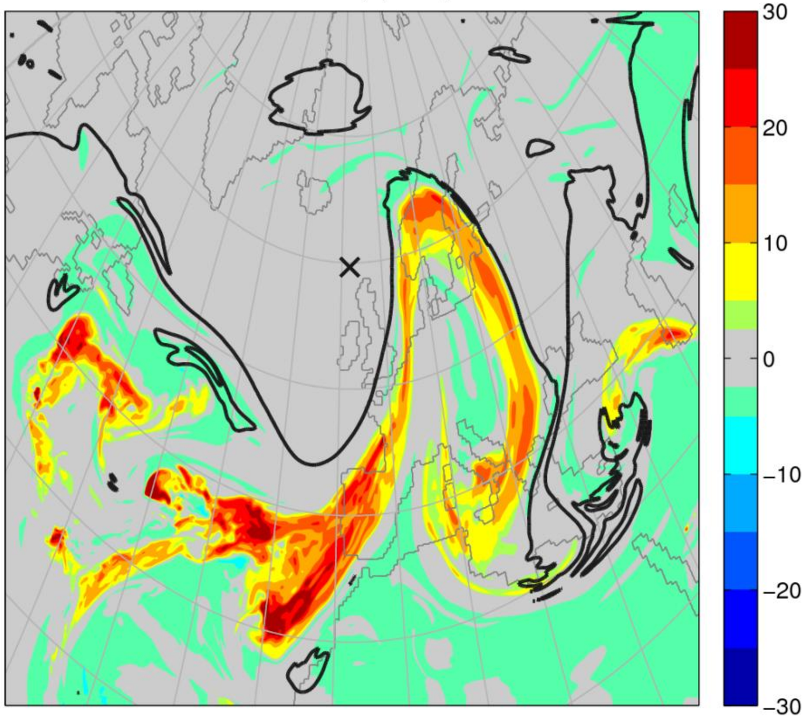
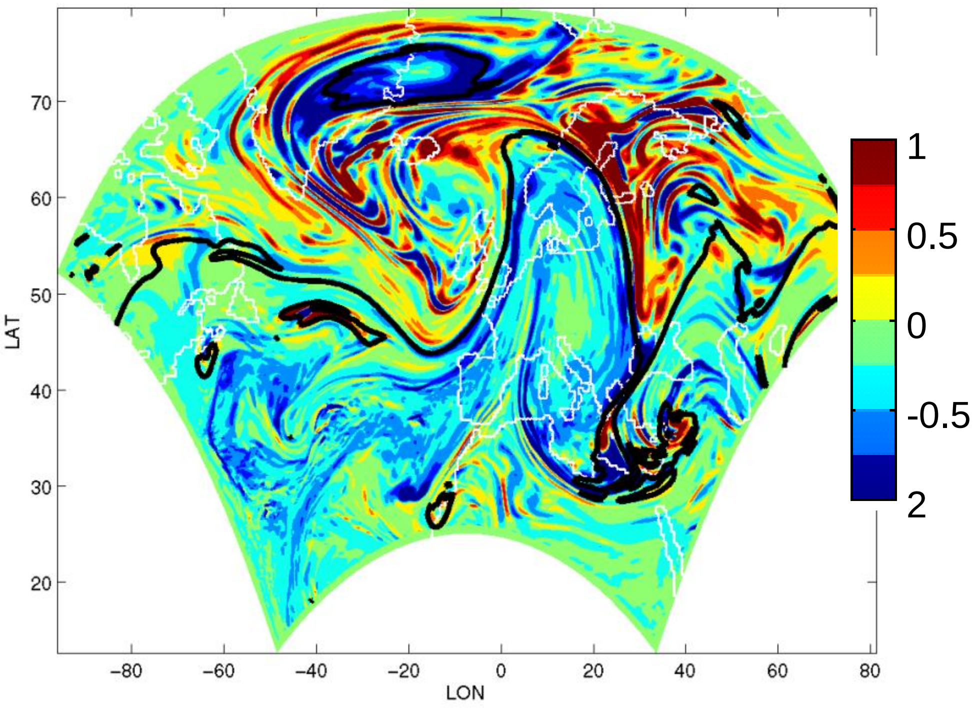
Diabatic potential temperature (K)

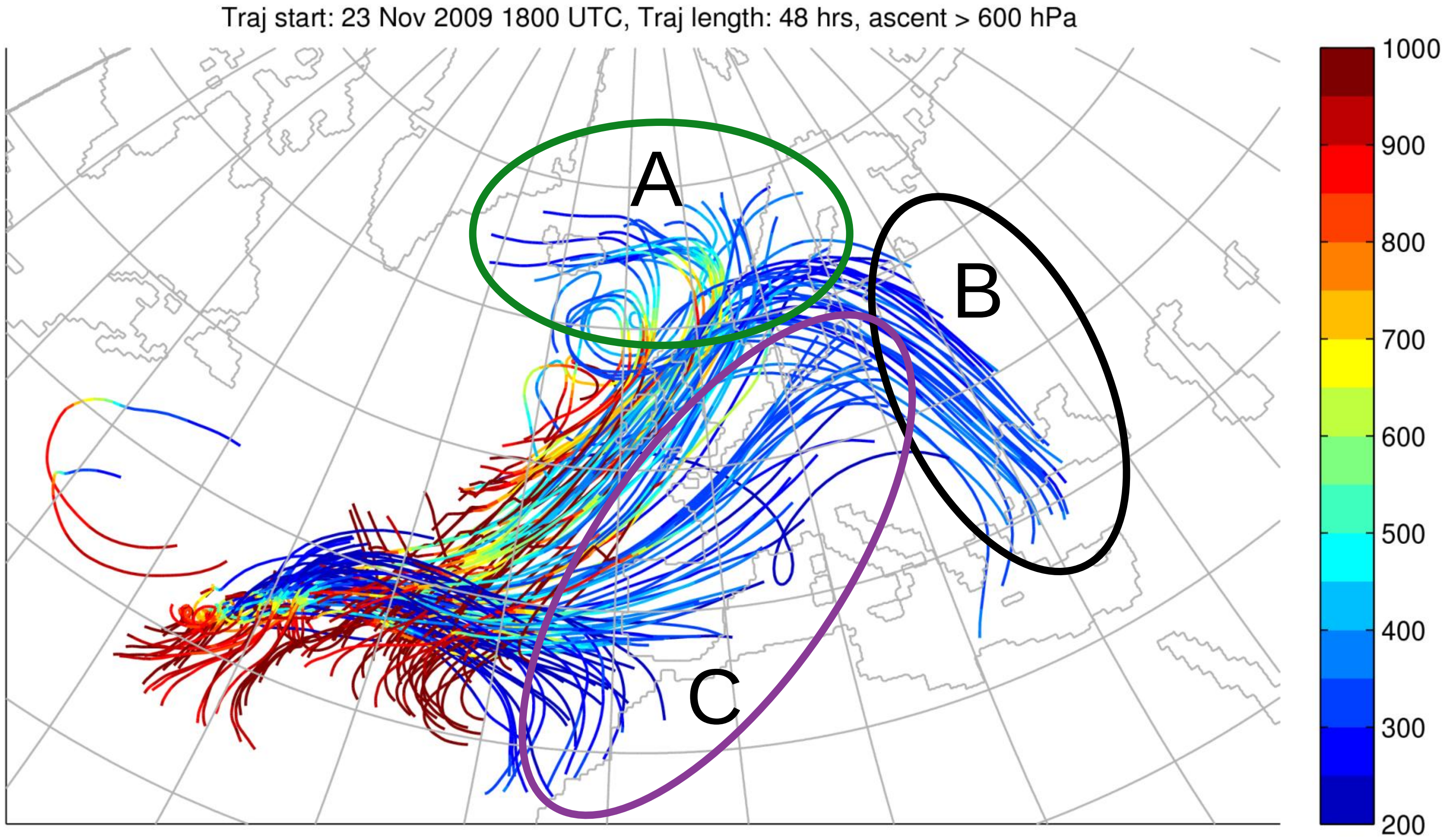


Diabatic potential vorticity (PVU)

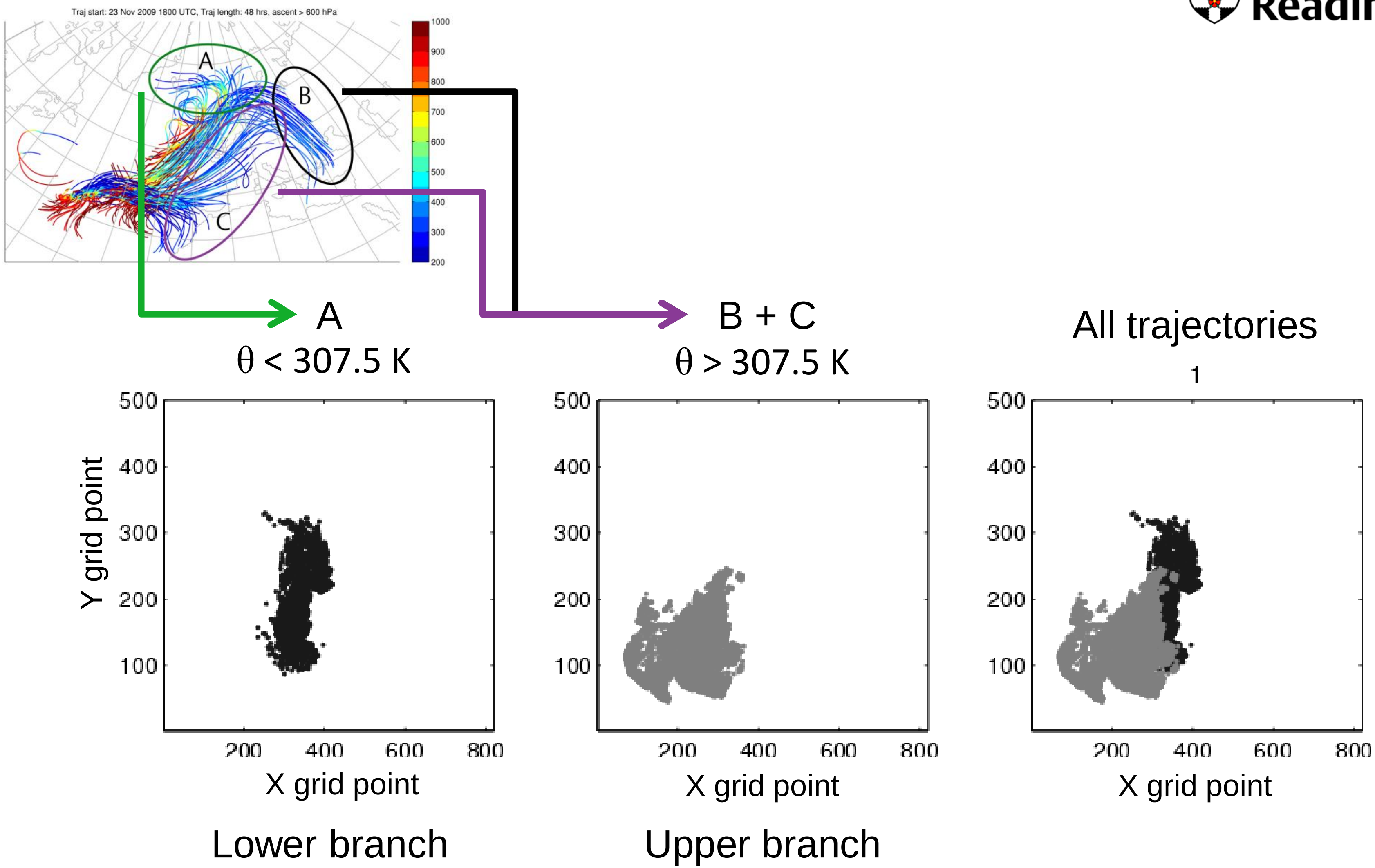


Model level at 9.68 km

Trajectory bundle

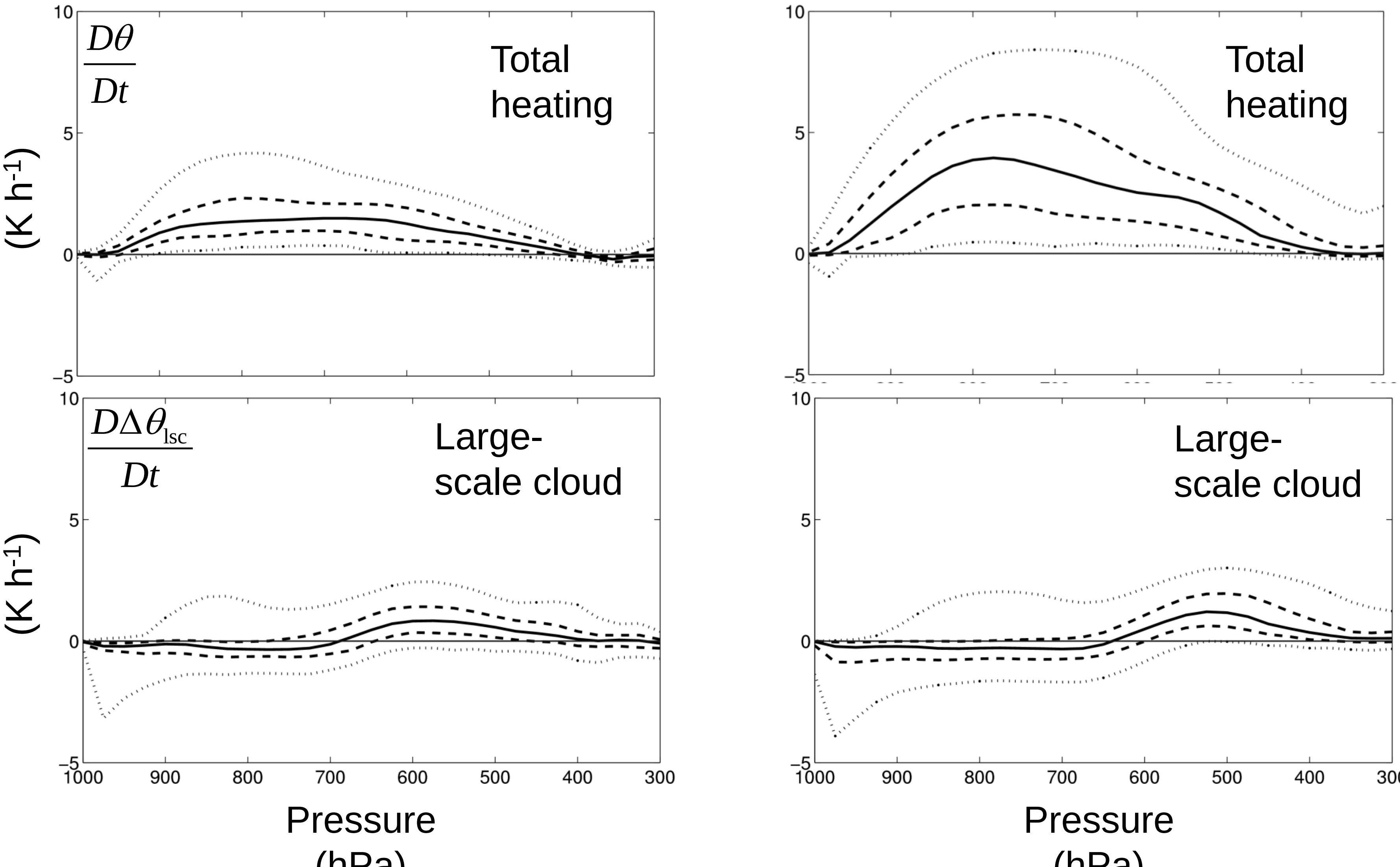


Identification of sub-streams



Heating rates – MetUM (I)

A   B + C



Heating rates – MetUM (II)

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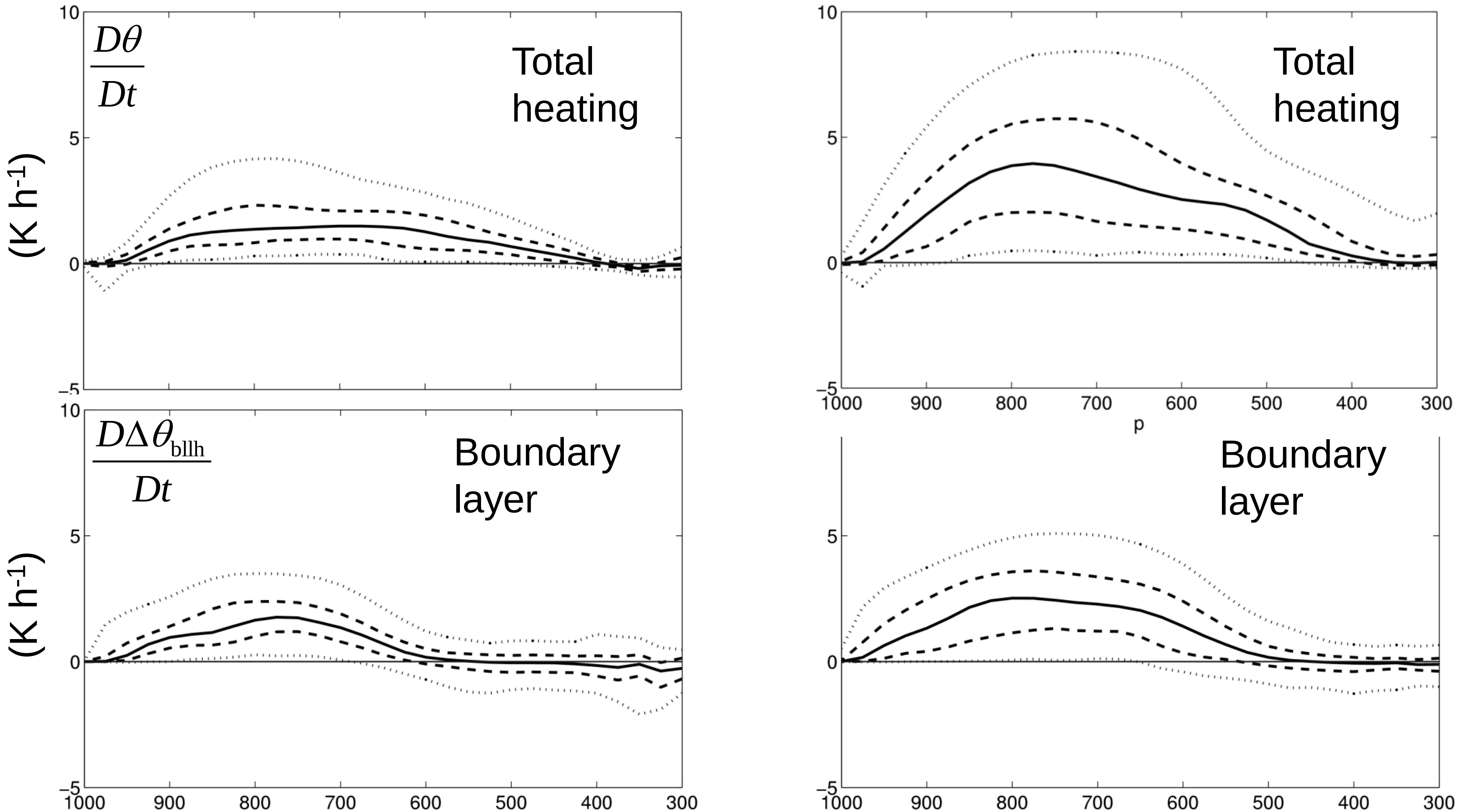
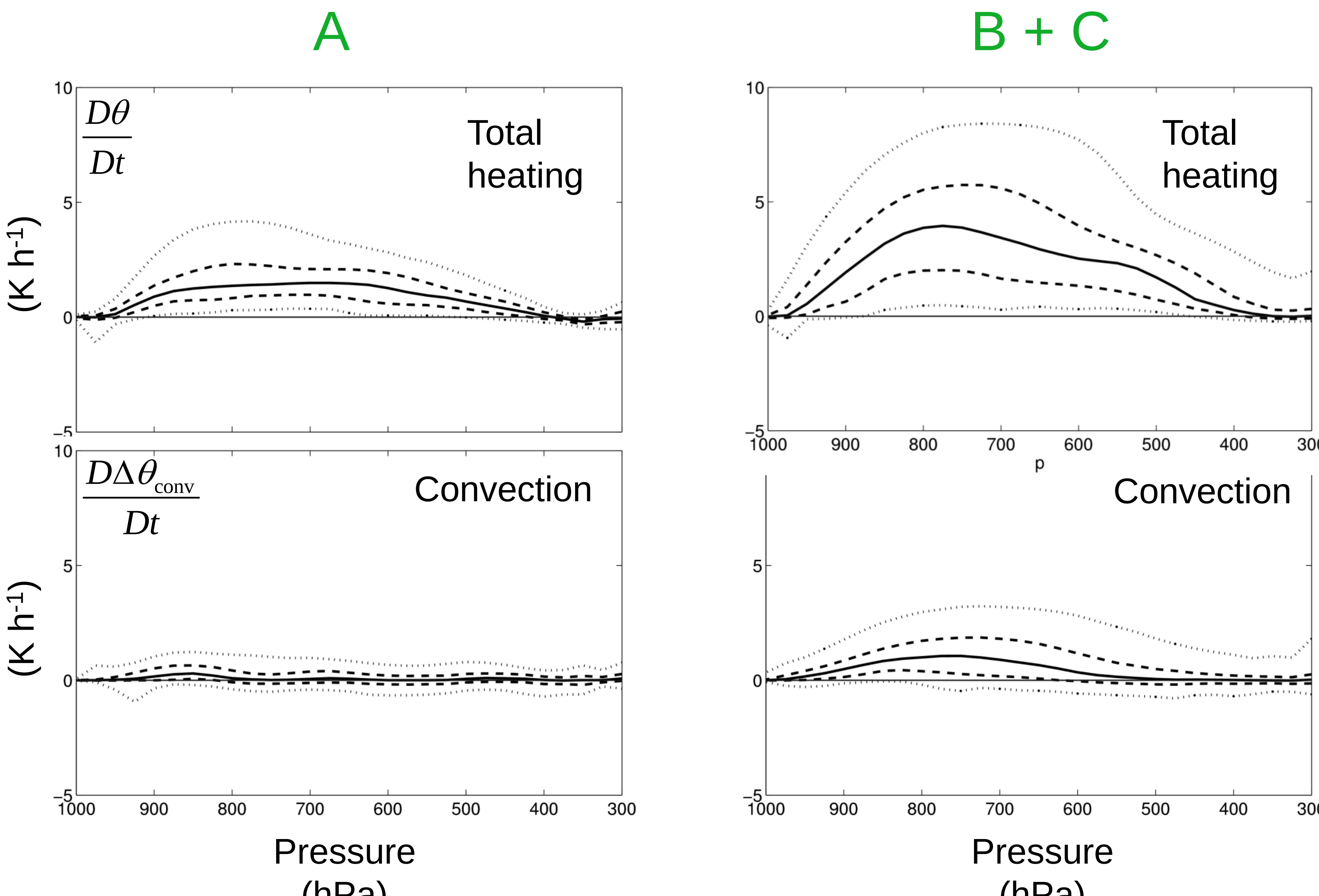
A B + C



Pressure (hPa)

Pressure (hPa)

Heating rates – MetUM (III)



Conclusions

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- The upper-level PV structure reflects the WCB split and is affected by it
- The action of diabatic processes is different for each branch
- The upper-level PV structure is modified by these diabatic processes (through the WCB split)
- The modifications to the upper-level PV structure depend on the details of the parameterisation of sub-grid scale processes and the interaction between parameterisation schemes

Conclusions

- Are these modifications important for the subsequent evolution of the cyclone?
- If they are then the details of the treatment of sub-grid scale processes is crucial for free-running simulations (climate projections)
  - Reanalyses benefit from data assimilation which maintains the model evolution close to reality
  - Climate projections are unable to benefit from these techniques

Future work

- Complete a systematic comparison between two models
  - Met Office Unified Model (MetUM) at Reading
  - COnsortuim for Small-scale MOdelling (COSMO) model at Zürich
  - Two complementary diabatic decomposition techniques
- Perform high-resolution (convection-permitting) simulations of parts of the WCB
- Systematic comparison against observations (and reanalyses)