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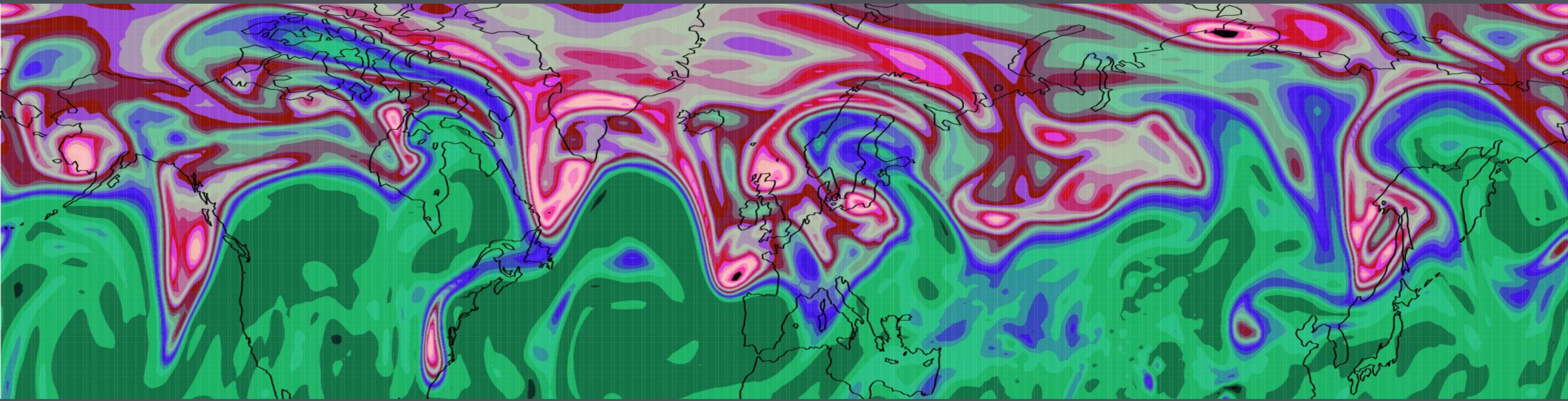
Mechanisms for Diabatic Influence on the Jet Stream and Block Onset



John Methven, Ben Harvey, Leo Saffin, Jake Bland
Department of Meteorology, University of Reading

Claudio Sanchez, Met Office

Influences of latent heat release on development of weather systems

1. Diabatic heating intensifies ascent, vortex stretching and baroclinic growth rate

2. Majority of ascent occurs in "*warm conveyor belt*" (WCB) of cyclones (poleward moving, warm, moist air)

3. Heating enables ascent across surfaces of constant potential temperature (θ) - *diabatic mass transport*

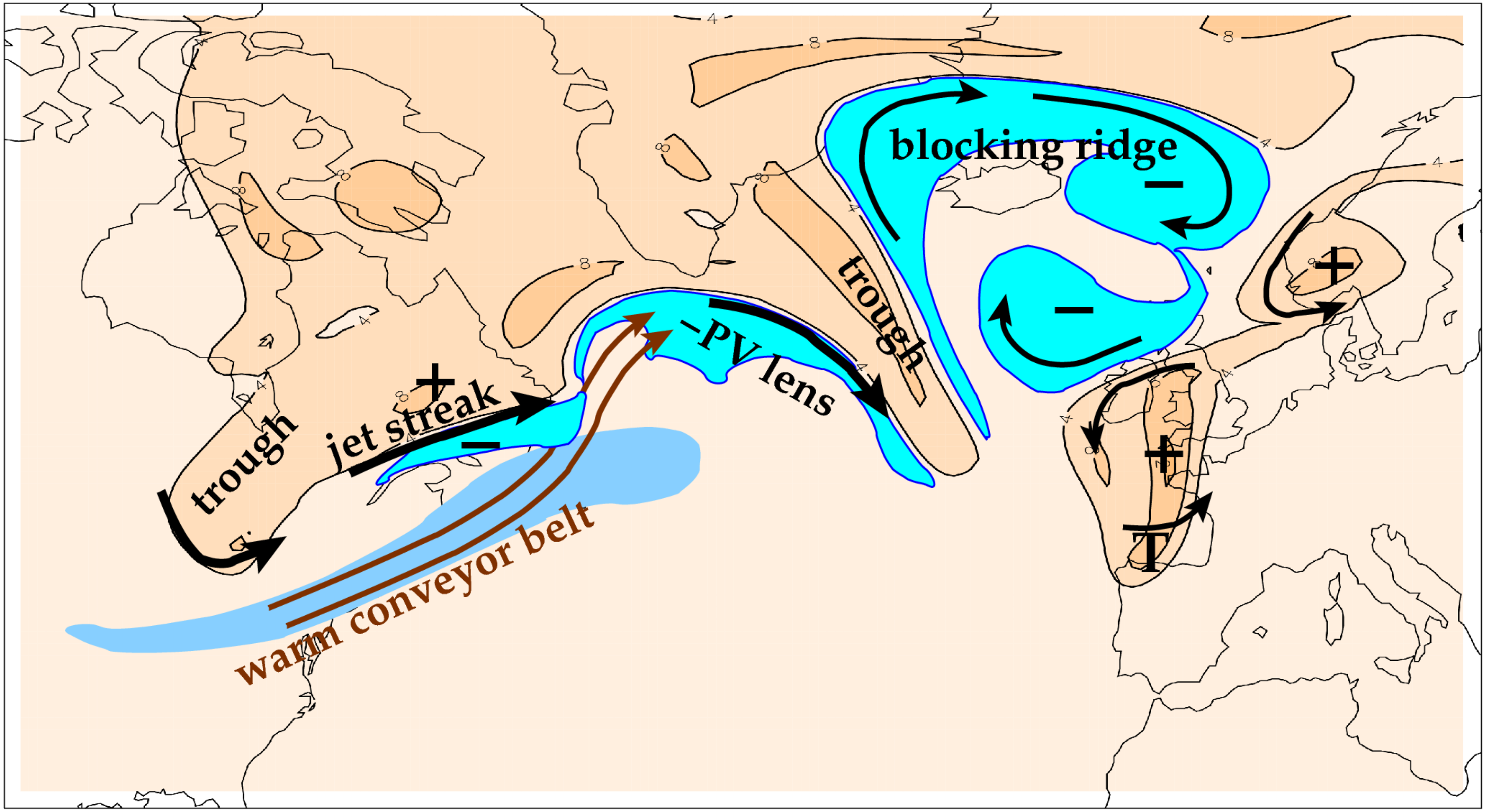
4. Mass outflow of WCBs into the upper troposphere in the *ridges of meandering jet stream*

Q.1 What fraction of mass in a ridge arrives by diabatic transport?

Q.2 What influence does it have on Rossby wave behaviour?

***Overarching scientific aim of NAWDEX*:**

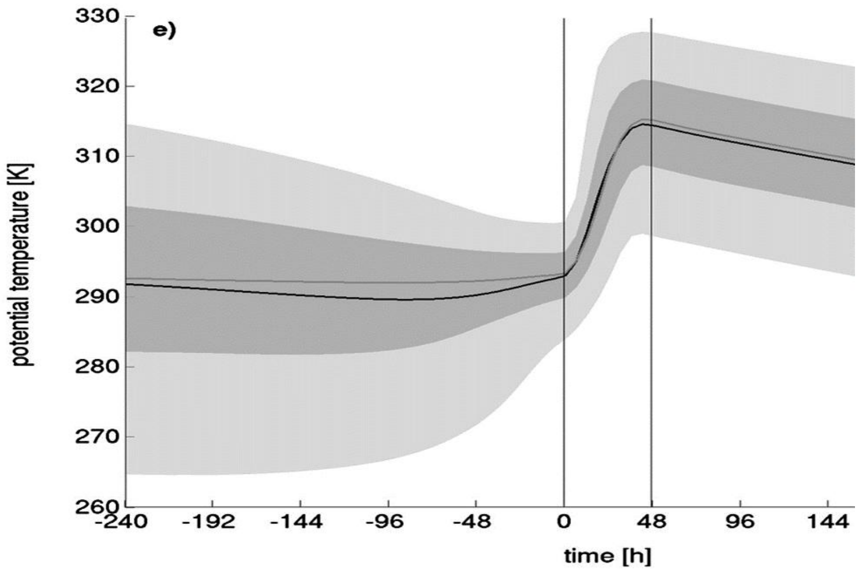
to quantify the effects of diabatic processes on disturbances to the jet stream near North America, their influence on downstream propagation across the North Atlantic, and consequences for high-impact weather in Europe.

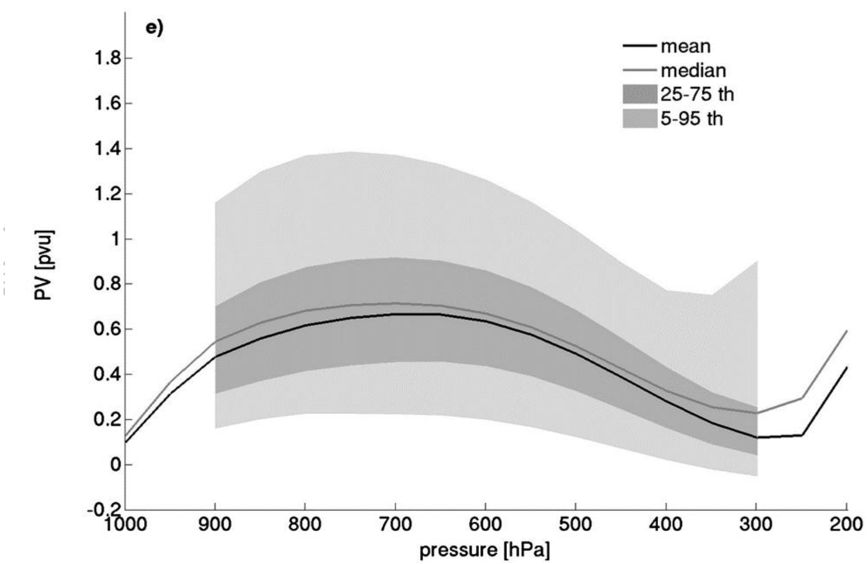


Features related to the meandering tropopause and jet stream

(orange is stratospheric air; cyan marks upper tropospheric PV anomalies).

Air mass changes following WCB





- WCB frequently defined as a *coherent ensemble of trajectories* (following the resolved flow)
- Climatology from

  Madonna et al, 2014, J. Climate

A. θ increases by greater than isentropic spread of the inflow or outflow layer of the CET

B. Although PV increases below heating maximum, it decreases again above.
   PV of outflow ≈ PV of inflow

- Why is PV constrained in this way?
- Implications for role of heating?

PV evolution equation (I)

Lagrangian form of Ertel PV equation:

$$\rho \frac{DP}{Dt} = \boldsymbol{\zeta} \cdot \nabla \dot{\theta} + \nabla \times \boldsymbol{F} \cdot \nabla\theta$$

PV increases below heating maximum (and decreases above it).

However, there is not an obvious constraint on PV values.

Now consider flux (or local conservation) form of PV equation:

$$\frac{\partial}{\partial t}(\rho P) + \nabla \cdot (\rho P \boldsymbol{u}) = \nabla \cdot \left(\boldsymbol{\zeta}\dot{\theta} + \boldsymbol{F} \times \nabla\theta\right)$$

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$\Rightarrow$ J = *"non-advective PV flux"* arising from non-conservative processes

(Haynes & McIntyre, 1987, JAS)

PV evolution equation (II)

Impermeability theorem

First, define the local normal vector to local isentropic surfaces as

$$\boldsymbol{n} = \nabla\theta / |\nabla\theta|$$

and split the absolute vorticity into components that are normal and parallel to the local isentropic surface:

$$\boldsymbol{\zeta} = (\boldsymbol{\zeta} \cdot \boldsymbol{n})\boldsymbol{n} + \boldsymbol{\zeta}_{//}$$

We can write the flux form PV equation as:

$$\frac{\partial}{\partial t}(\rho P) + \nabla \cdot (\rho P \tilde{\boldsymbol{u}}) = \nabla \cdot \left(\boldsymbol{\zeta}_{//}\dot{\theta} + \boldsymbol{F} \times \nabla\theta\right) = -\nabla . J'$$

Using $\rho P = (\boldsymbol{\zeta} \cdot \boldsymbol{n})|\nabla\theta|$ and partitioning velocity into cross-isentropic and along-isentropic components:

$$\boldsymbol{u}_J = \frac{\dot{\theta}}{|\nabla\theta|}\boldsymbol{n} \qquad \tilde{\boldsymbol{u}} = \boldsymbol{u} - \boldsymbol{u}_J$$

$\Rightarrow$ ***PV impermeability theorem*** *(Haynes & McIntyre, 1990, JAS)*

$(\rho P\tilde{u} + J').n = 0$ **There can be no PV flux across isentropic surfaces**

Integral PV conservation (circulation)

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Integrate PV equation over control volume (lateral boundary velocity $\mathbf{V}_b$)

$$\frac{\mathrm{d}}{\mathrm{d}t}\iiint rq\,\mathrm{d}A\,\mathrm{d}\theta + \int\oint \left\{rq\left(\mathbf{V}-\mathbf{V}_\mathrm{b}\right)+\mathbf{J}\right\}.\mathbf{n}\,\mathrm{d}l\,\mathrm{d}\theta = 0,$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(C\Delta\theta) = \Delta\theta\frac{\mathrm{d}C}{\mathrm{d}t} = 0$$

Circulation conservation (if V_b=V & J′-integral=0)

Integrate mass continuity over control volume

$$\frac{d}{dt}\iiint r\,dA\,d\theta \quad + \quad \int\oint r\left(\mathbf{V}-\mathbf{V}_b\right).\mathbf{n}\,dl\,d\theta$$

$$+\iint \left[r\dot{\theta}\right]_{bot}^{top} dA \quad = \quad 0$$

$$\frac{dM}{dt} \quad = \quad -D_{top}+D_{bot}$$

Diabatic mass flux convergence "dilutes" average PV

Mass-weighted average PV or *amount of PV substance* divided by mass (Haynes & McIntyre, 1990)

$$\langle q\rangle = \frac{\iiint rq\,dA\,d\theta}{\iiint r\,dA\,d\theta} = \frac{C\Delta\theta}{M}$$

PV in warm conveyor belts

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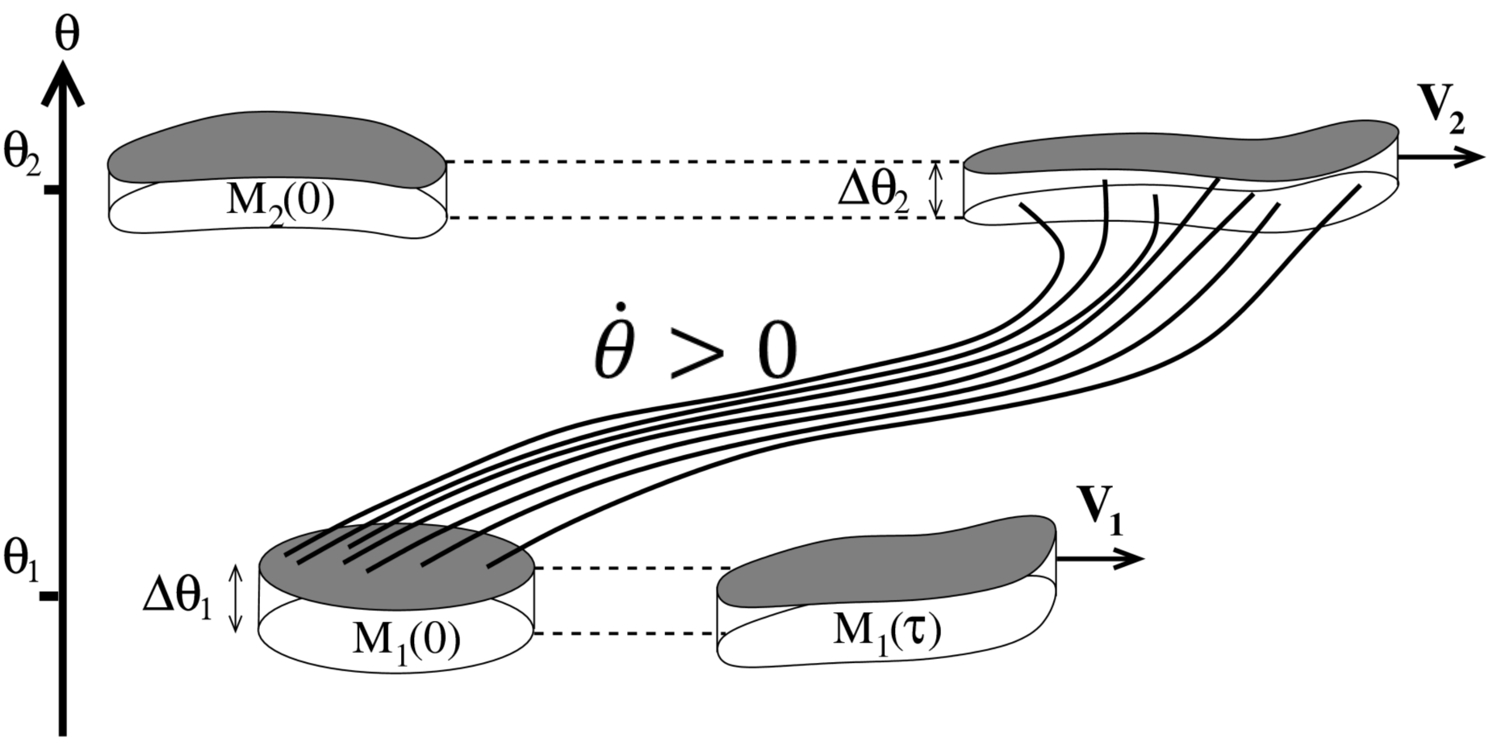
Consider two volumes, in isentropic layers representing the inflow and outflow of a warm conveyor belt.

Heating $\Rightarrow$ **diabatic mass transport** from lower to upper volume

Concentrates PV substance of "inflow volume" and dilutes outflow PVS



Methven, *Q. J. Royal Met. Soc. (2015)*

Is this conceptual picture realised?

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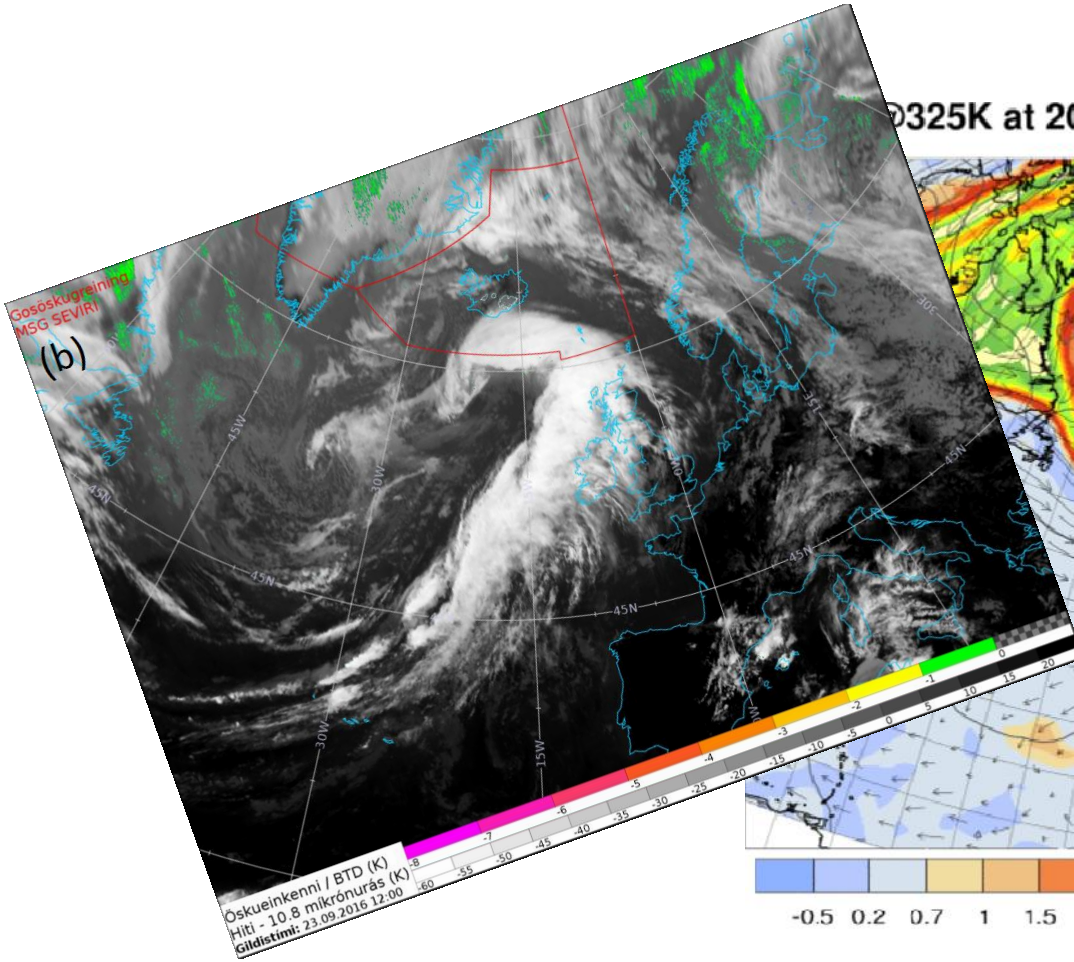
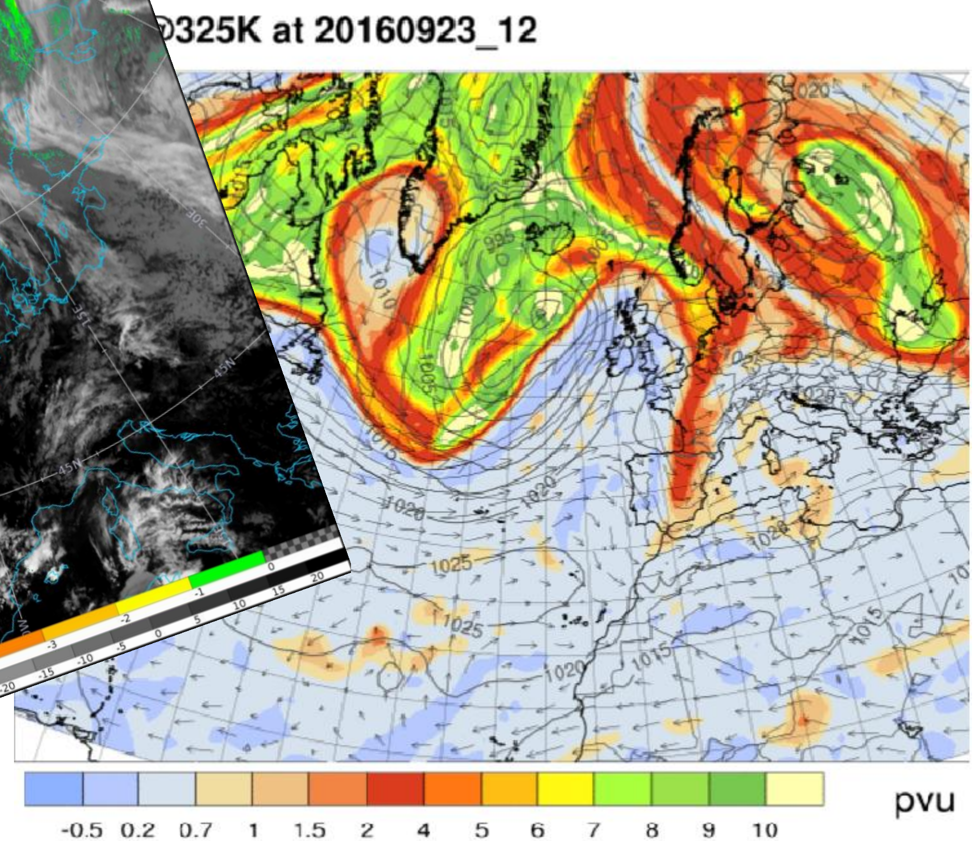
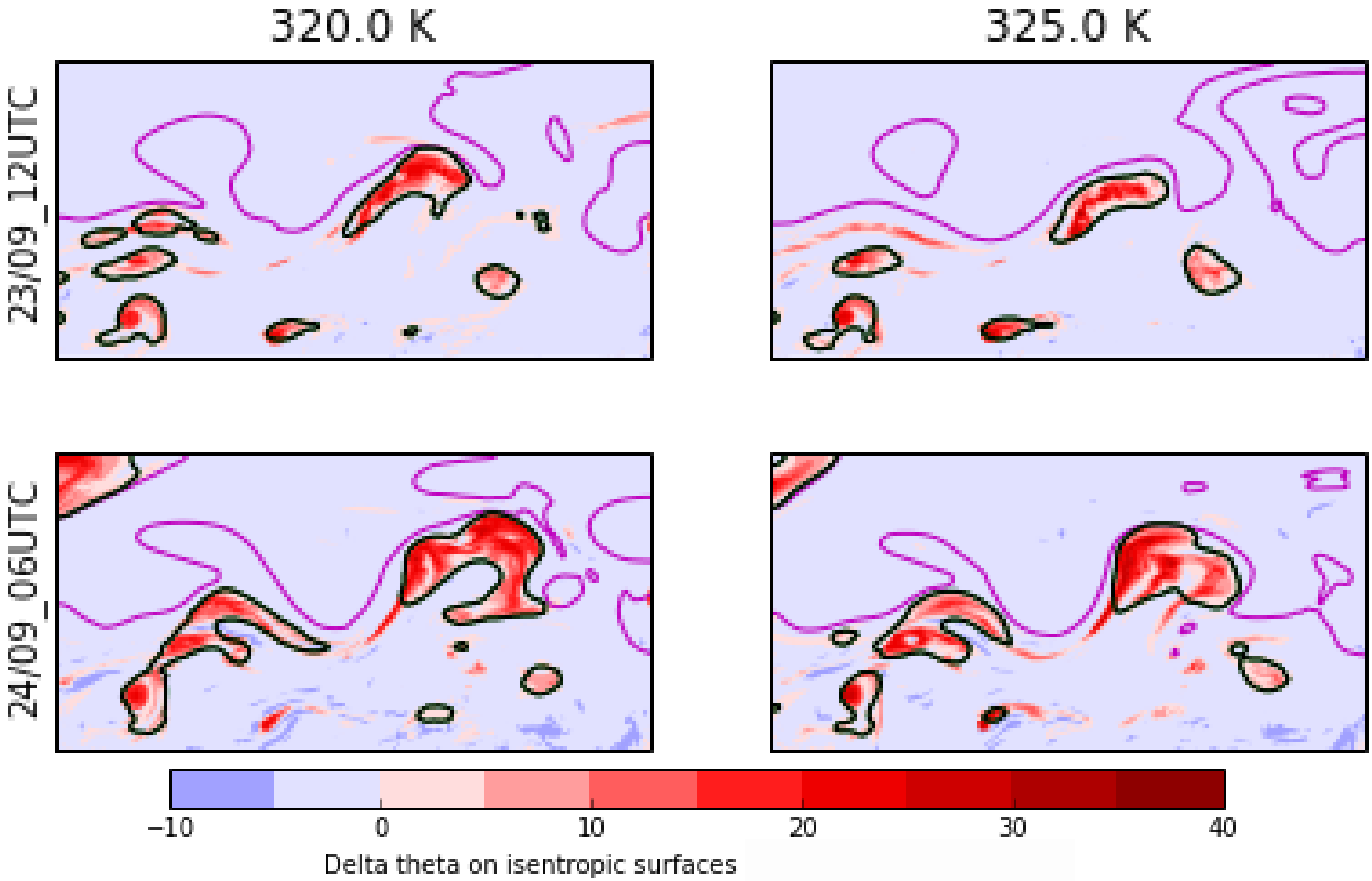




Examine NAWDEX case 3 (Jake Bland, MSc)

IR satellite image and corresponding PV map: 12UT 23/9/2016

Defining outflow volume using net heating



Black contour = lateral boundary of “outflow volume” on θ-surface

Outflow volume at outflow time

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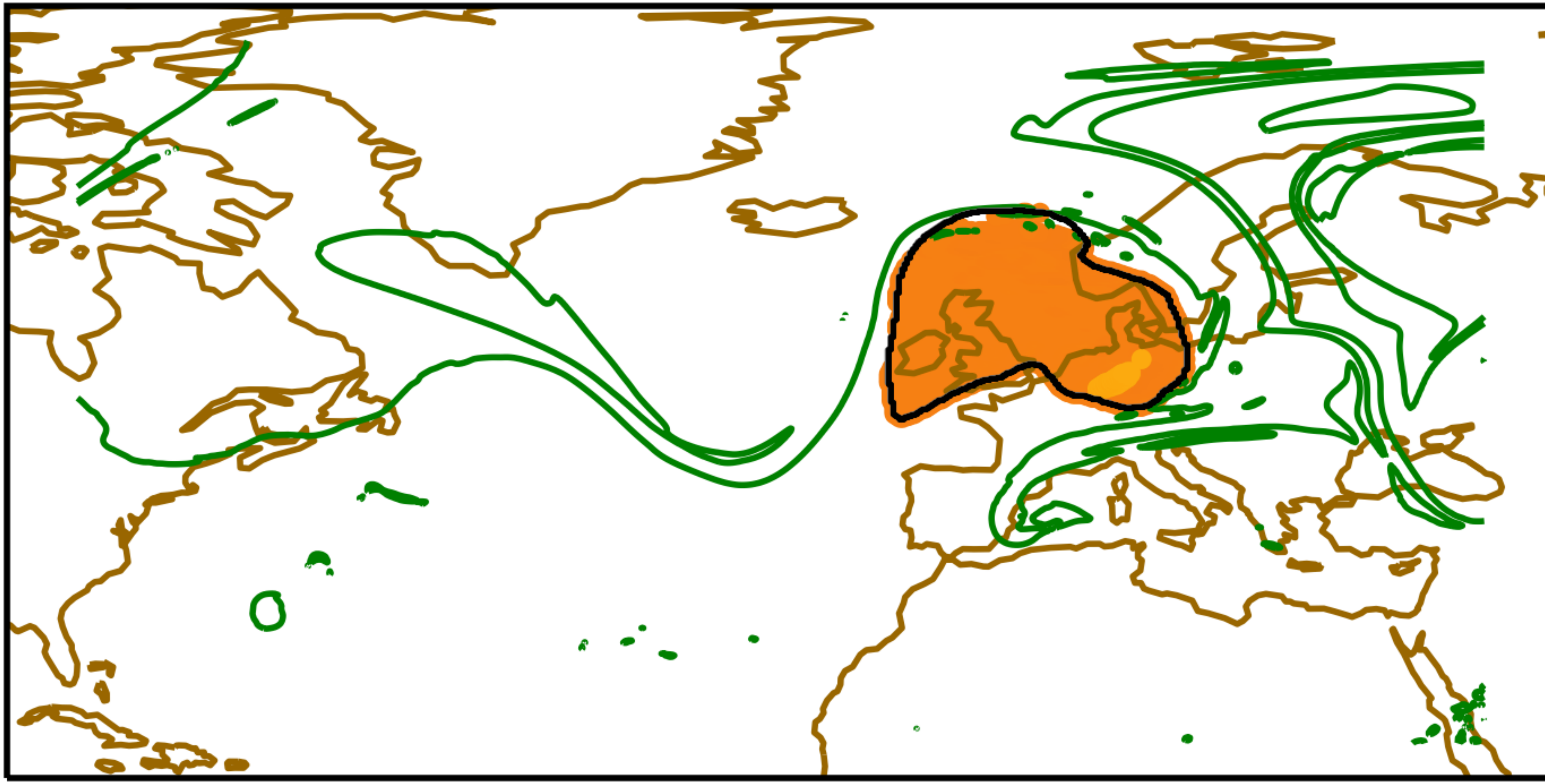
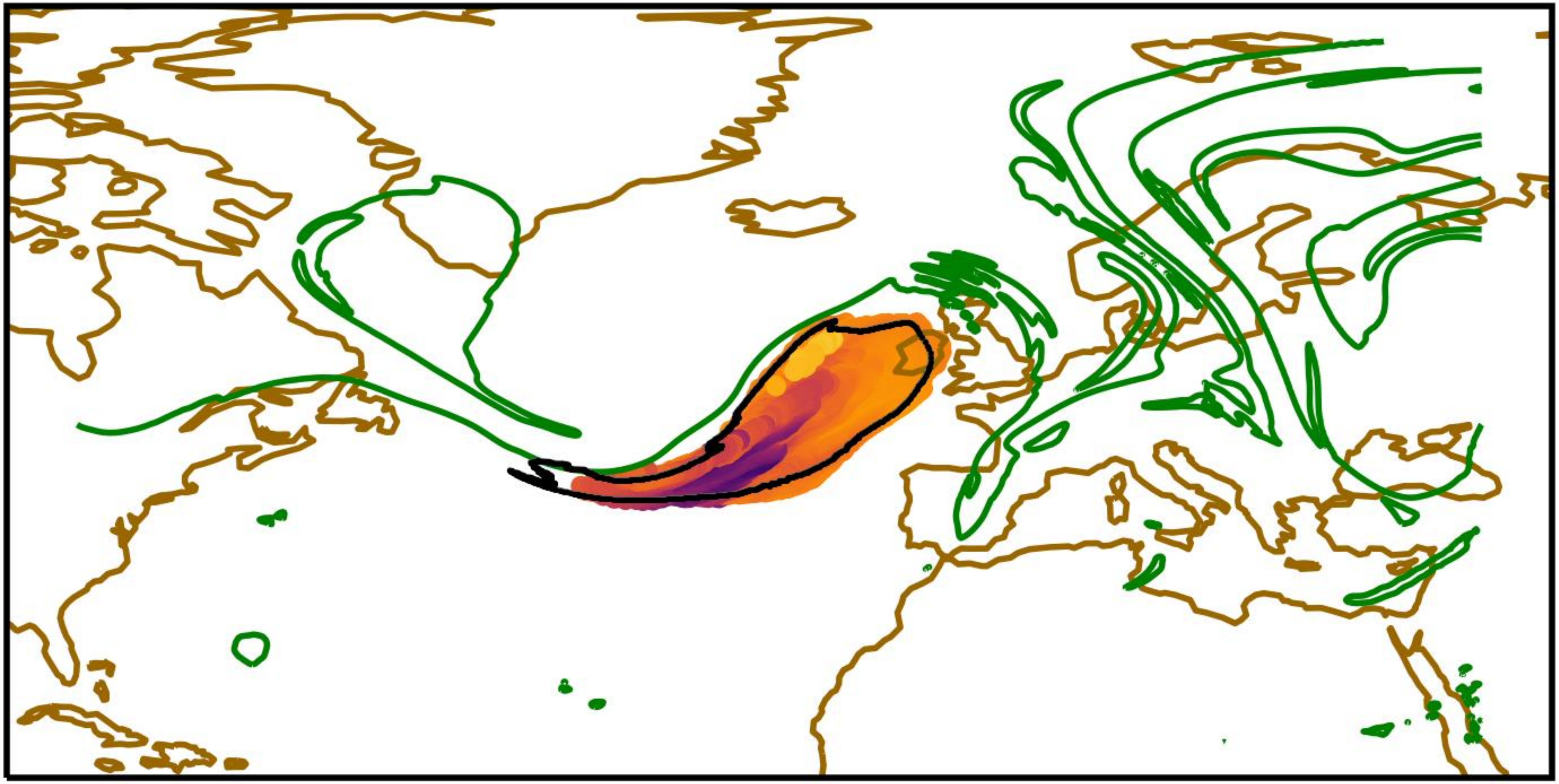


Black contour = lateral boundary of “outflow volume” on 325K surface
Yellow = release locations of 3D back trajectories from outflow volume
Green contour = tropopause on 325K

Following backwards (T-18)

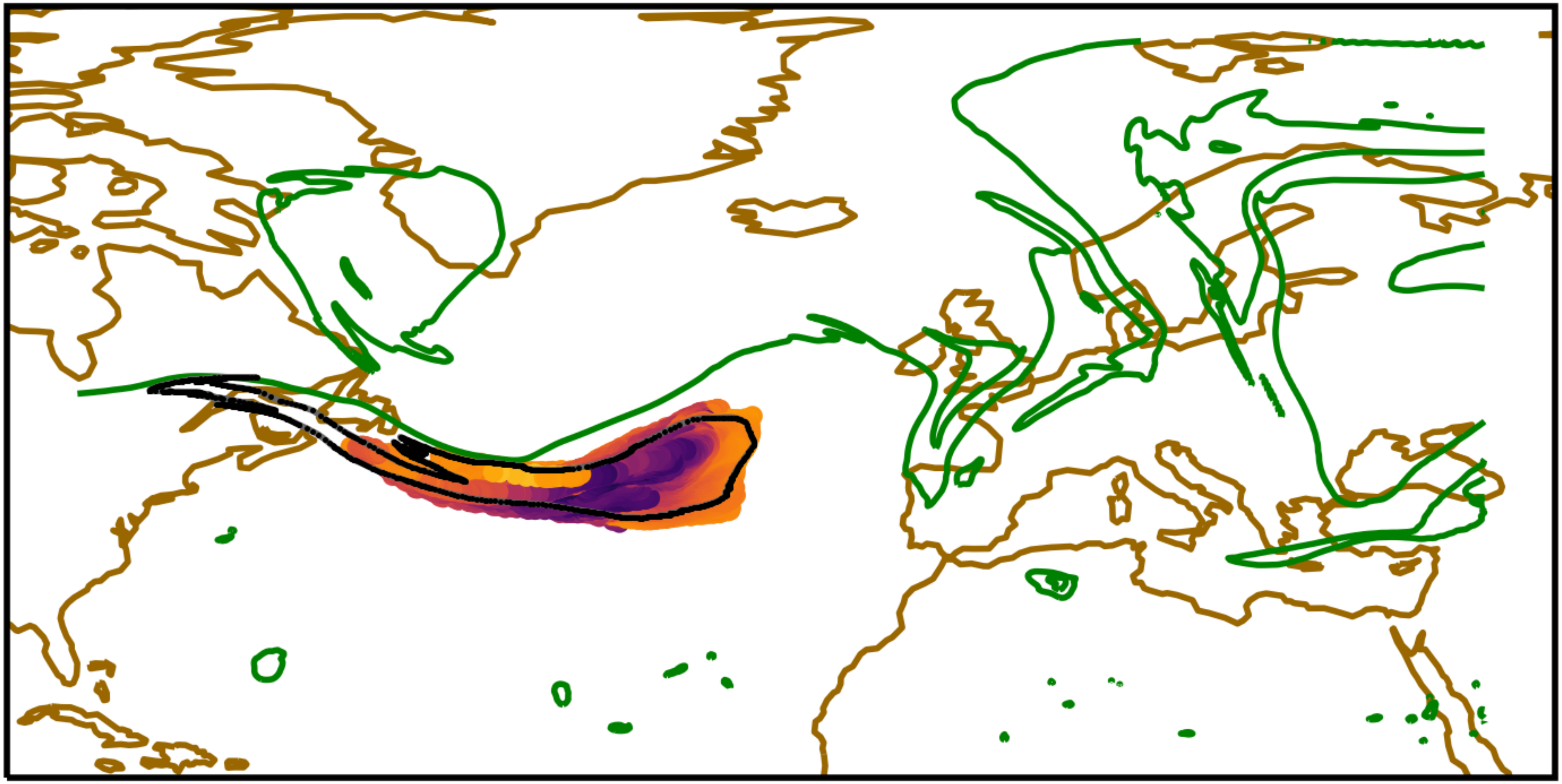


Contour = lateral boundary of “outflow volume” on 325K surface

Colour dots = θ at locations of 3D back trajectories from outflow volume

Green contour = tropopause on 325K

Following backwards (T-30)



Contour = lateral boundary of “outflow volume” on 325K surface

Colour dots = θ at locations of 3D back trajectories from outflow volume

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PV in warm conveyor belts

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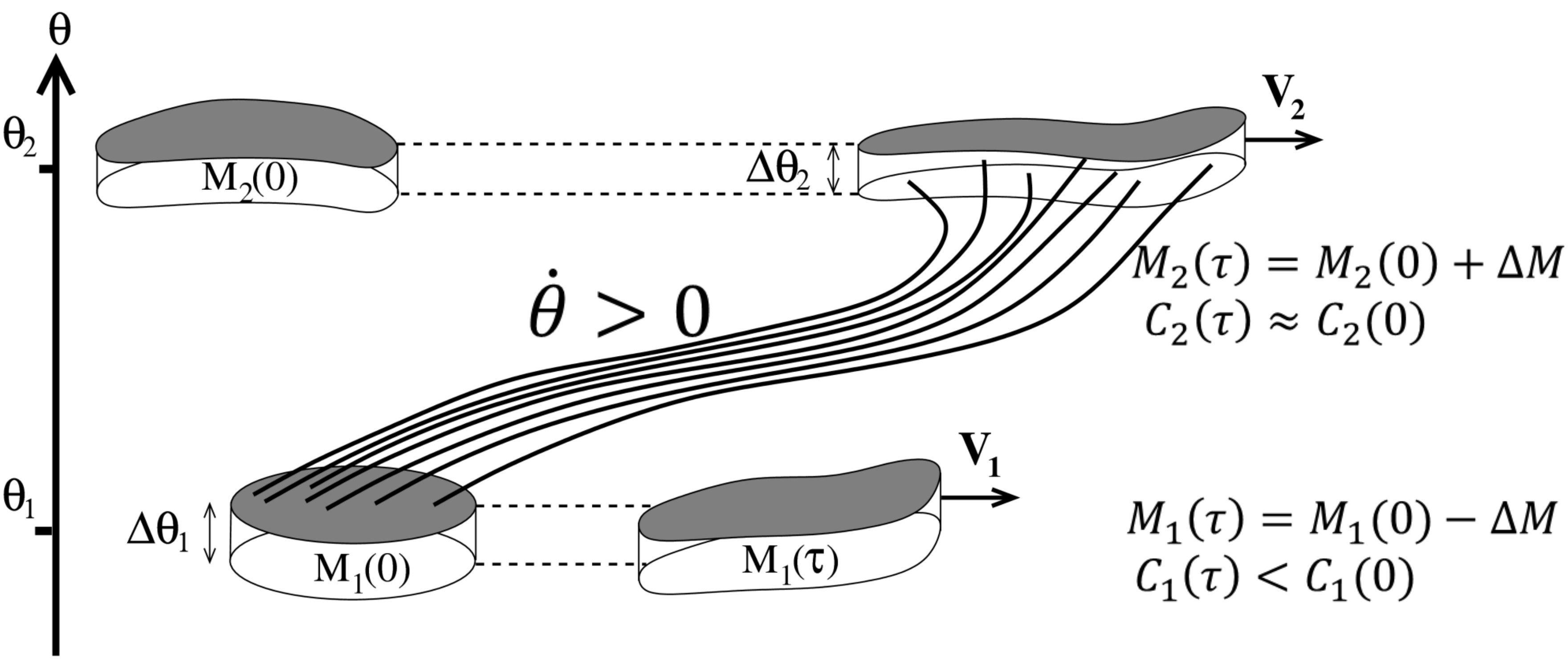
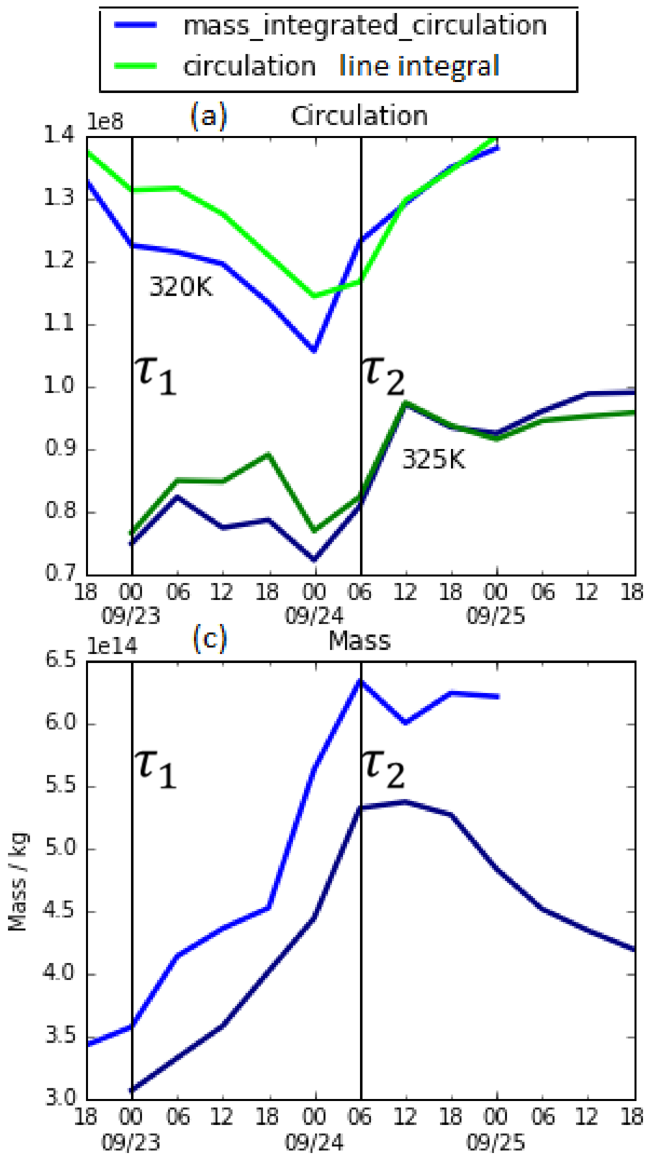
Concentrates PV substance of "inflow volume" and dilutes outflow PVS



Methven, *Q. J. Royal Met. Soc. (2015)*

Circulation and mass of outflow



Fractional variation in circulation of outflow volume is small

Verifying that circulation is conserved even though diabatic processes are strong within WCB

Large increase in mass of outflow volume (x2) by diabatic mass transport from below

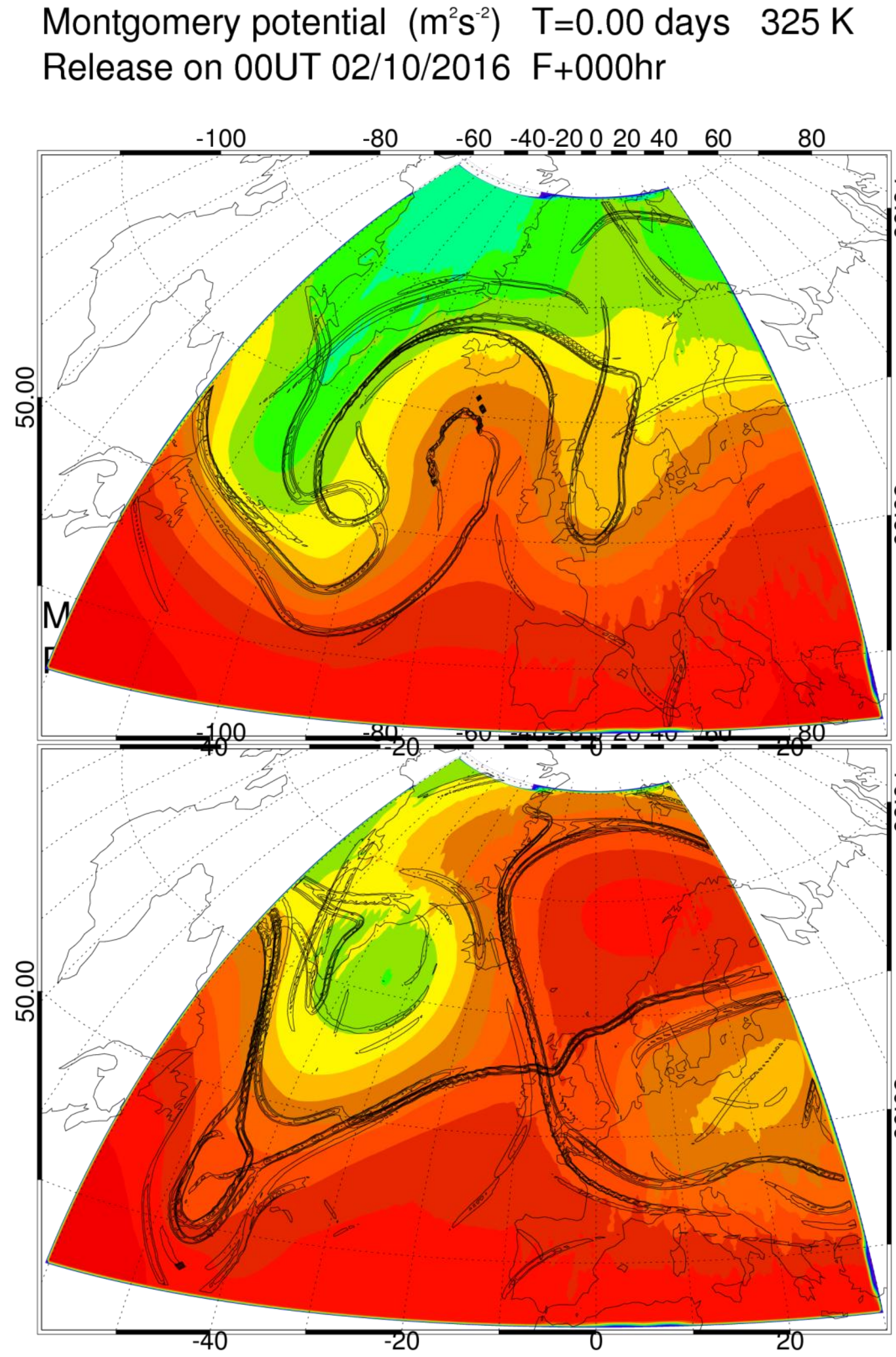
$$\frac{\Delta M}{M_2(\tau)} = 0.44 \pm 0.02$$

Transition from wave to block?

Block onset- transition from a large amplitude wave into dipole structure

Pfahl et al (2015).
Air masses in ridges making transition into block experience greater heating

How do diabatic processes influence this topological transition?

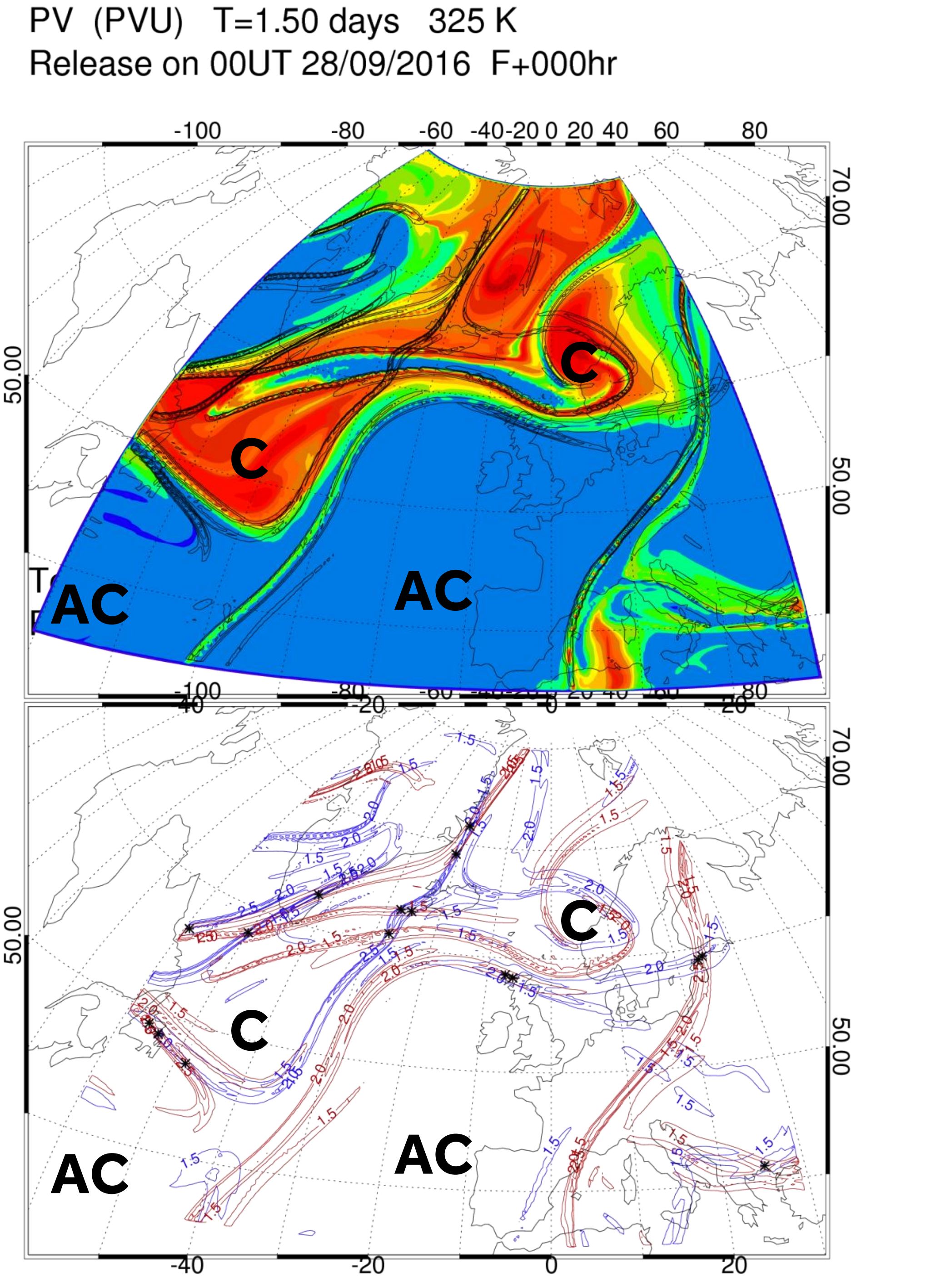


Lagrangian coherent structures

Example of large amplitude Rossby wave.

***Unstable (+ stable) manifolds*. Locations from which neighbouring forward (+ backward) trajectories separate rapidly.**

Generalisation of "cat's eyes" for unsteady (aperiodic) flows.

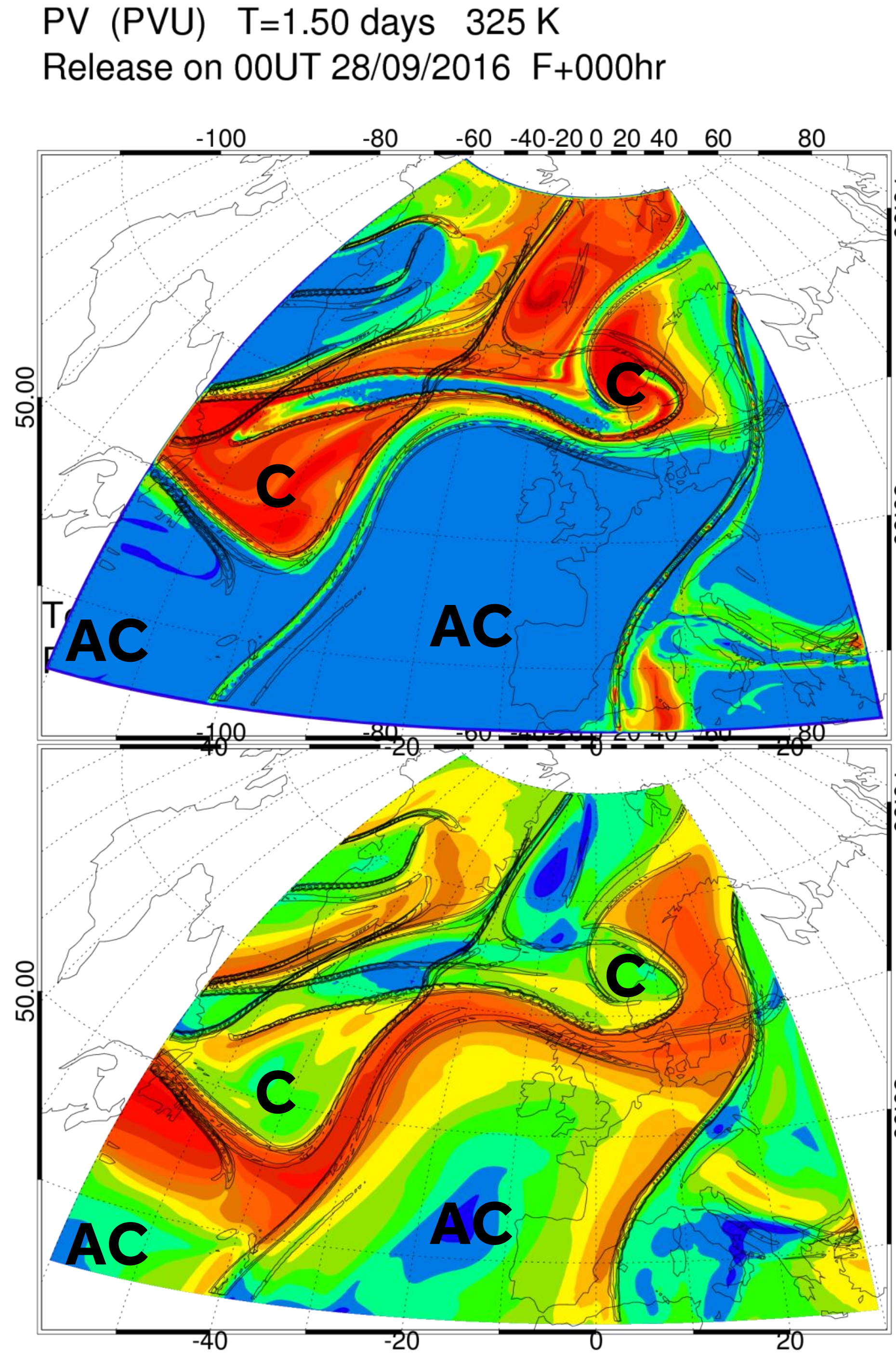


Lagrangian coherent structures

Example of large amplitude Rossby wave.

Black = *unstable (+ stable) manifolds*. Locations from which forward (+ backward) trajectories separate rapidly.

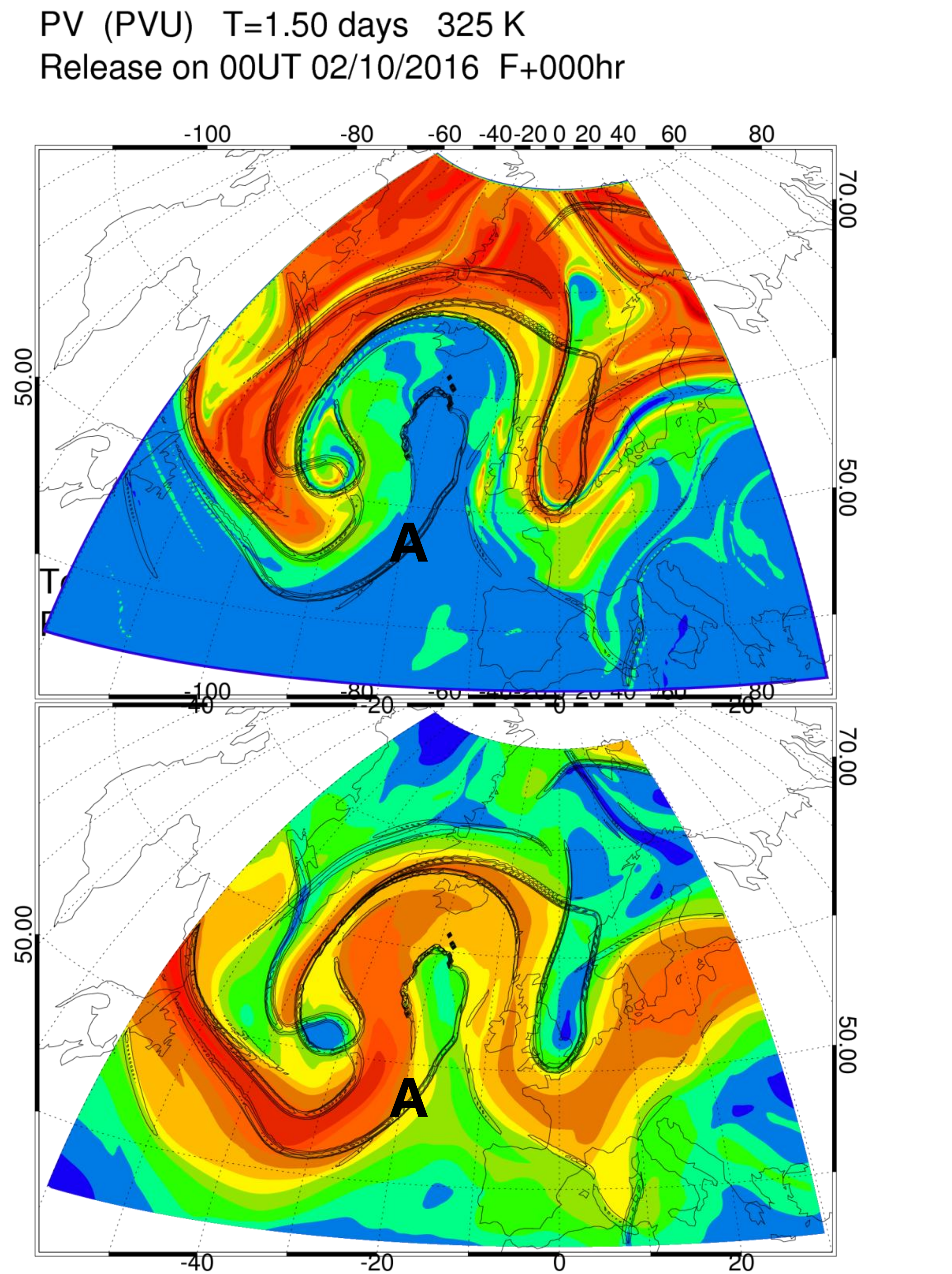
Colour indicates sum of back and forward trajectory length from each point.
Highlights jet stream and eddy regions



Formation of “omega block”

Rossby wave reaches large amplitude.
Vortex roll-up forms new hyperbolic point, A, and A/C cut-off.

Colour indicates sum of back and forward trajectory length from each point.

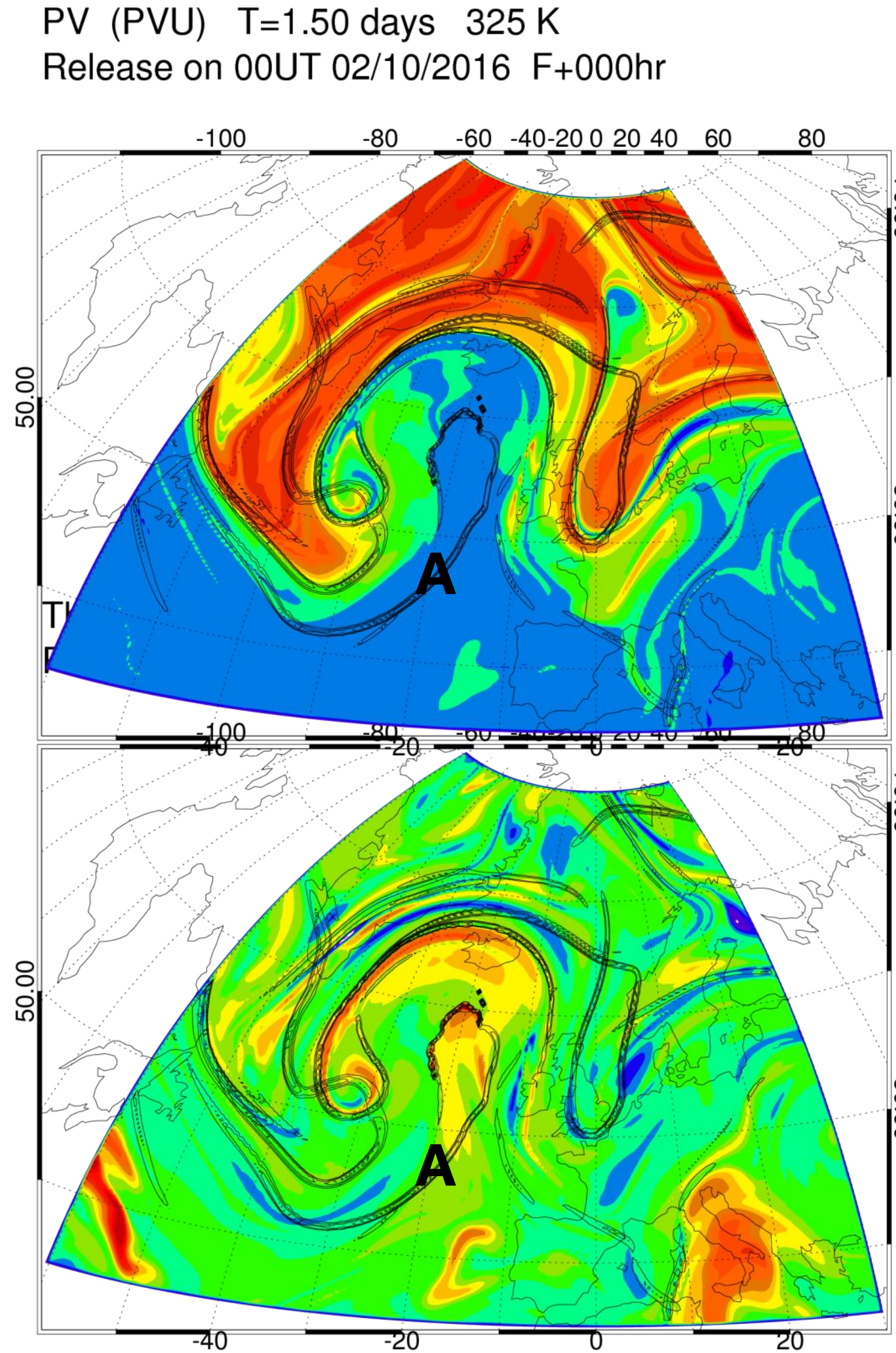


Diabatic mass transport into A/C cut-off volumes

Latent heating enables diabatic mass transport into cut-off volume.

Adiabatic flow would be constrained to isentropic surfaces and could not cross into cut-off, once formed.

Field is *net heating* along trajectories over 1.5 days

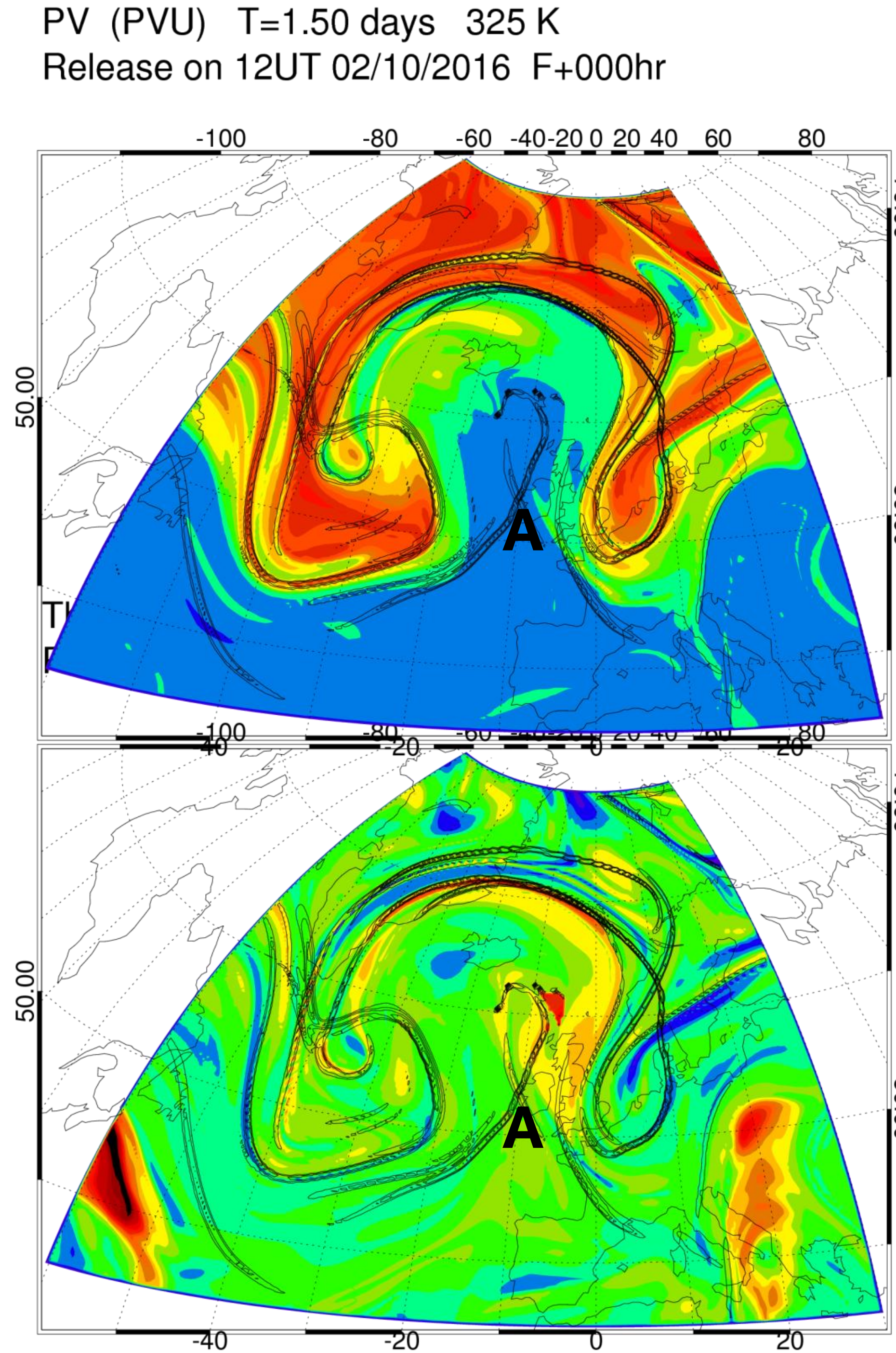


Diabatic mass transport into A/C cut-off volumes

Once hyperbolic point, A, is formed, it can only be destroyed by non-conservative processes.

It moves with the flow. Path of A = "hyperbolic trajectory"

Field is *net heating* along trajectories over 1.5 days



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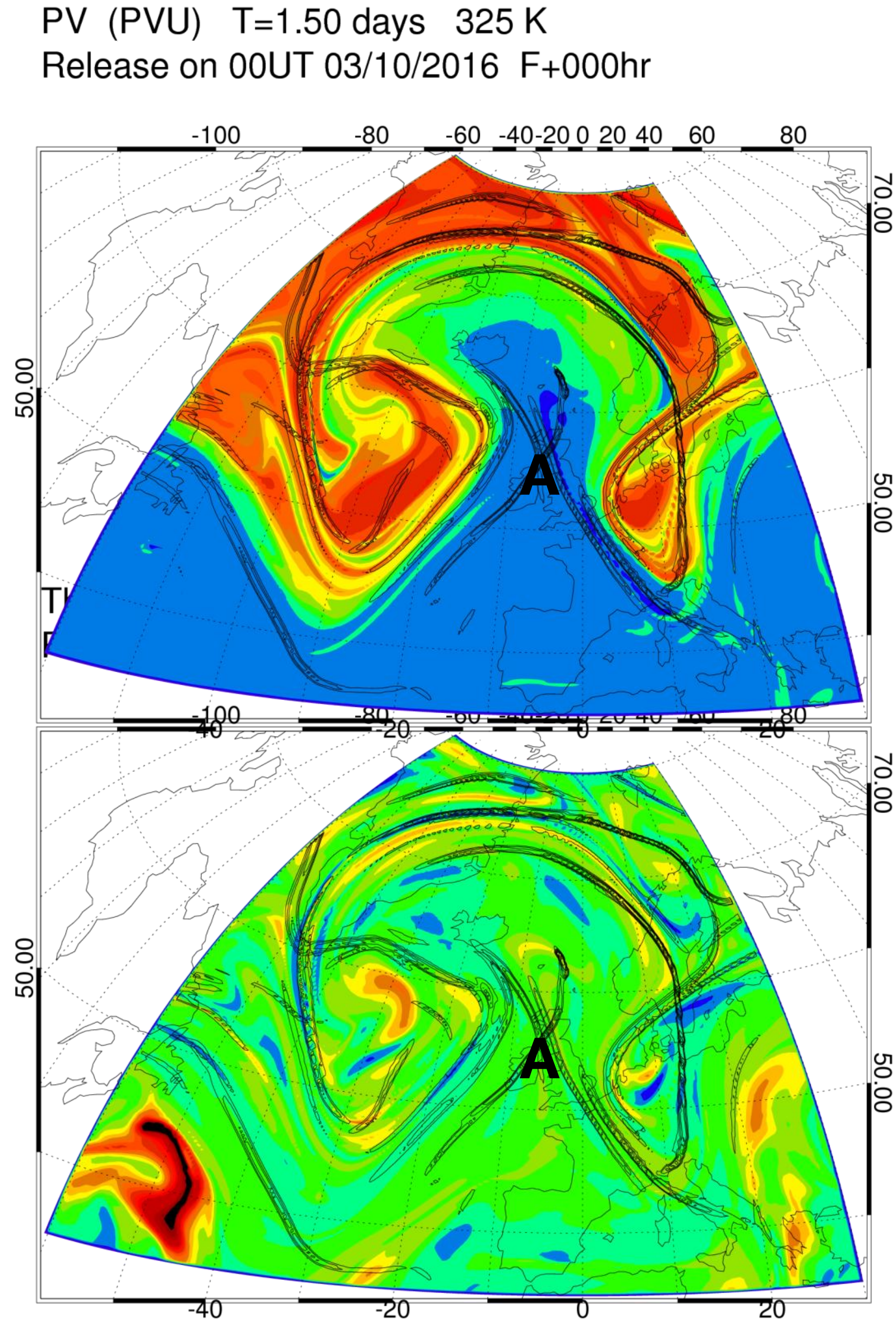
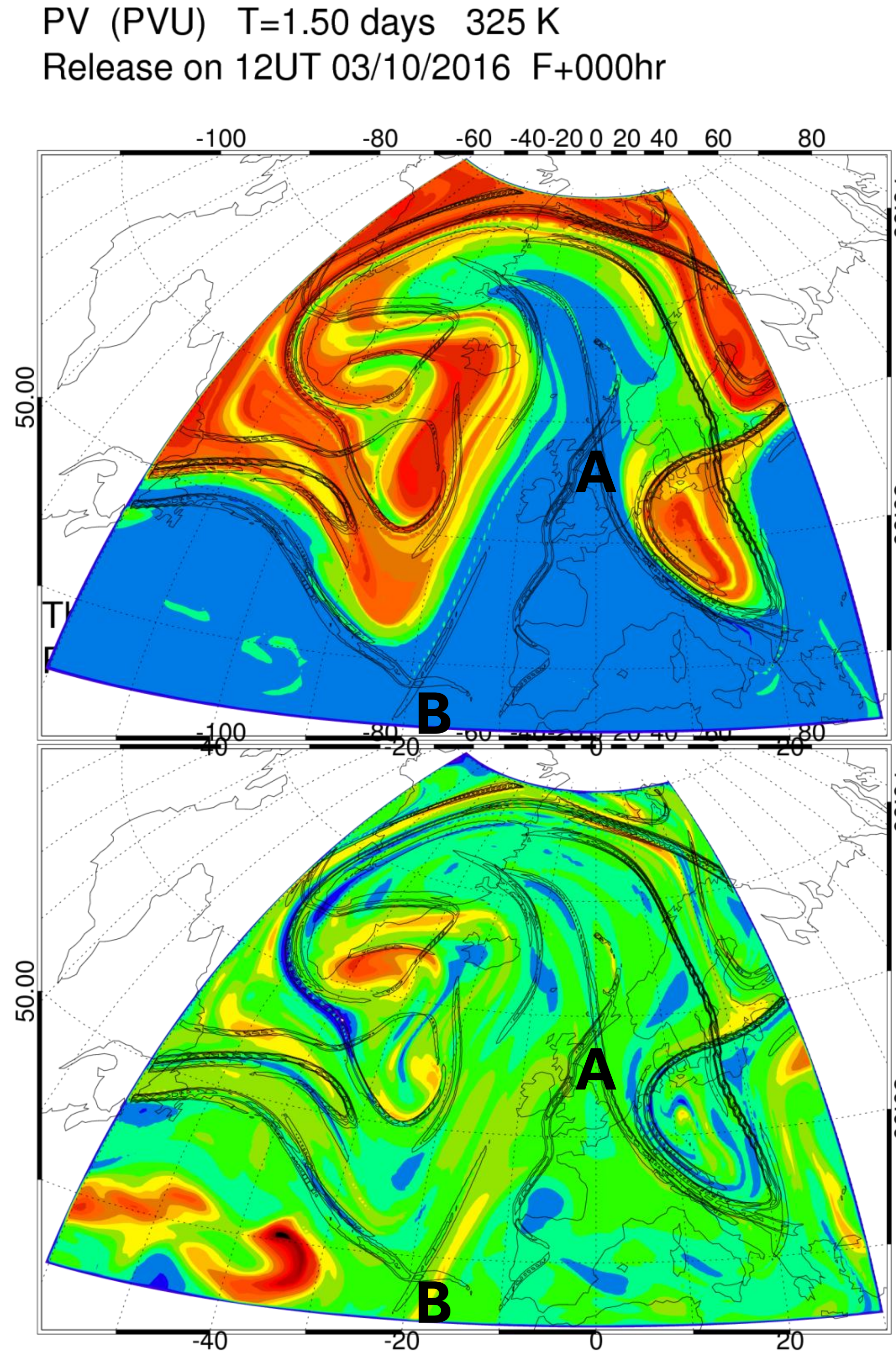


Diabatic mass transport into A/C cut-off volumes

Hyperbolic point B forms near tip of extended trough



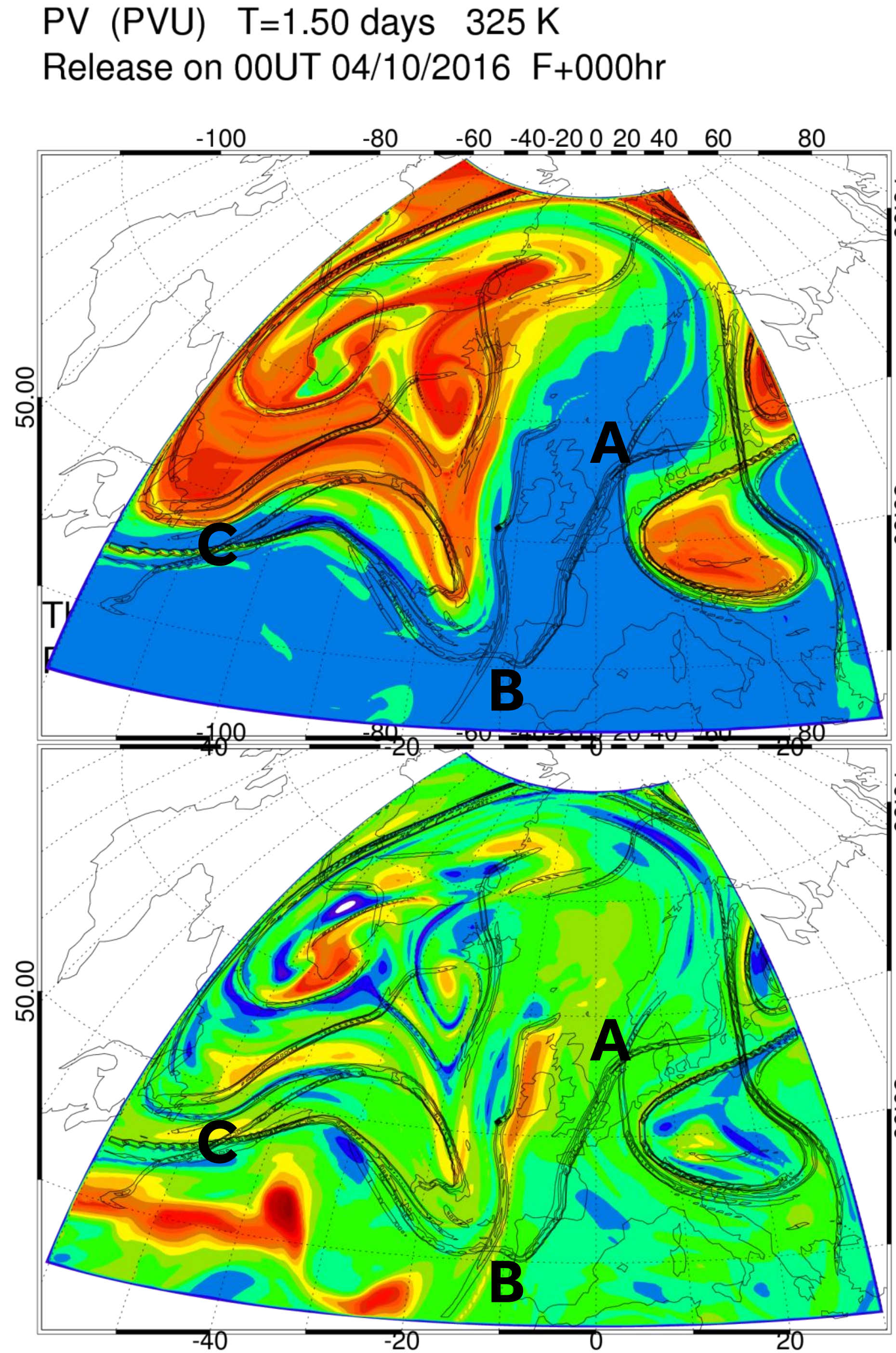
Field is *net heating* along trajectories over 1.5 days

Diabatic mass transport into A/C cut-off volumes

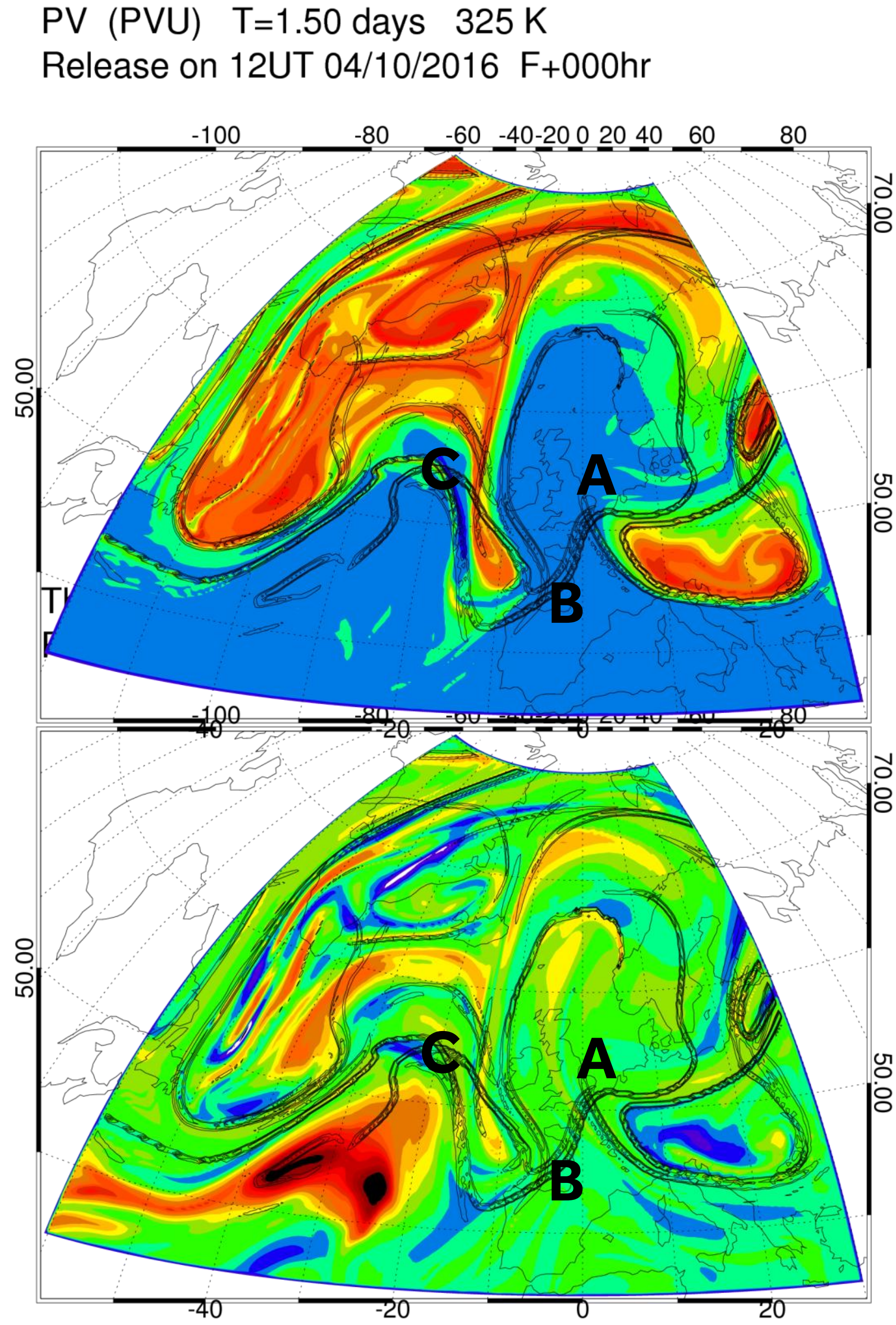
Hyperbolic point C forms near tip of next trough

Diabatic mass transport into volume north of B

Field is *net heating* along trajectories over 1.5 days



Diabatic mass transport into A/C cut-off volumes



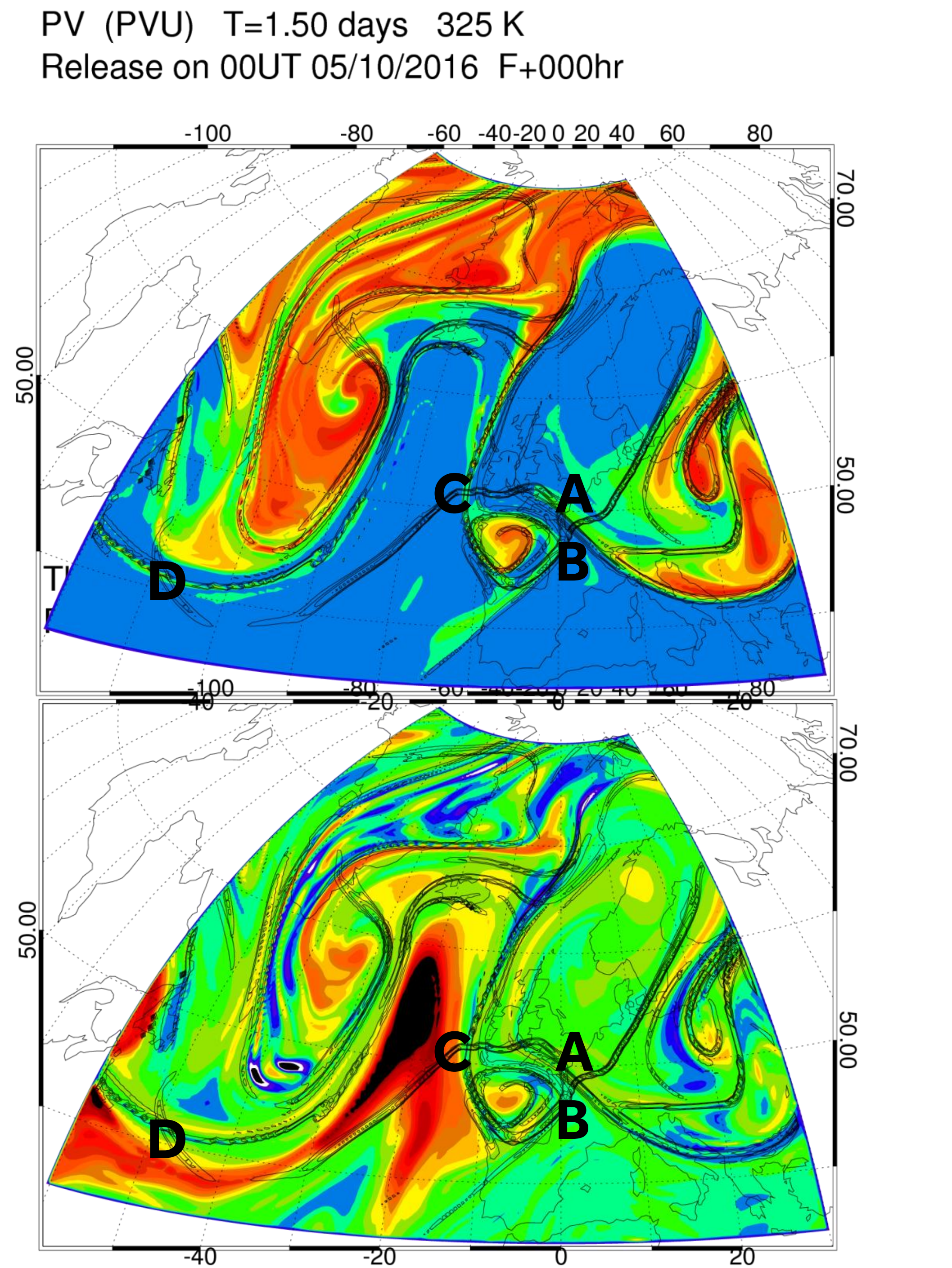
Field is *net heating* along trajectories over 1.5 days

Diabatic mass transport into A/C cut-off volumes

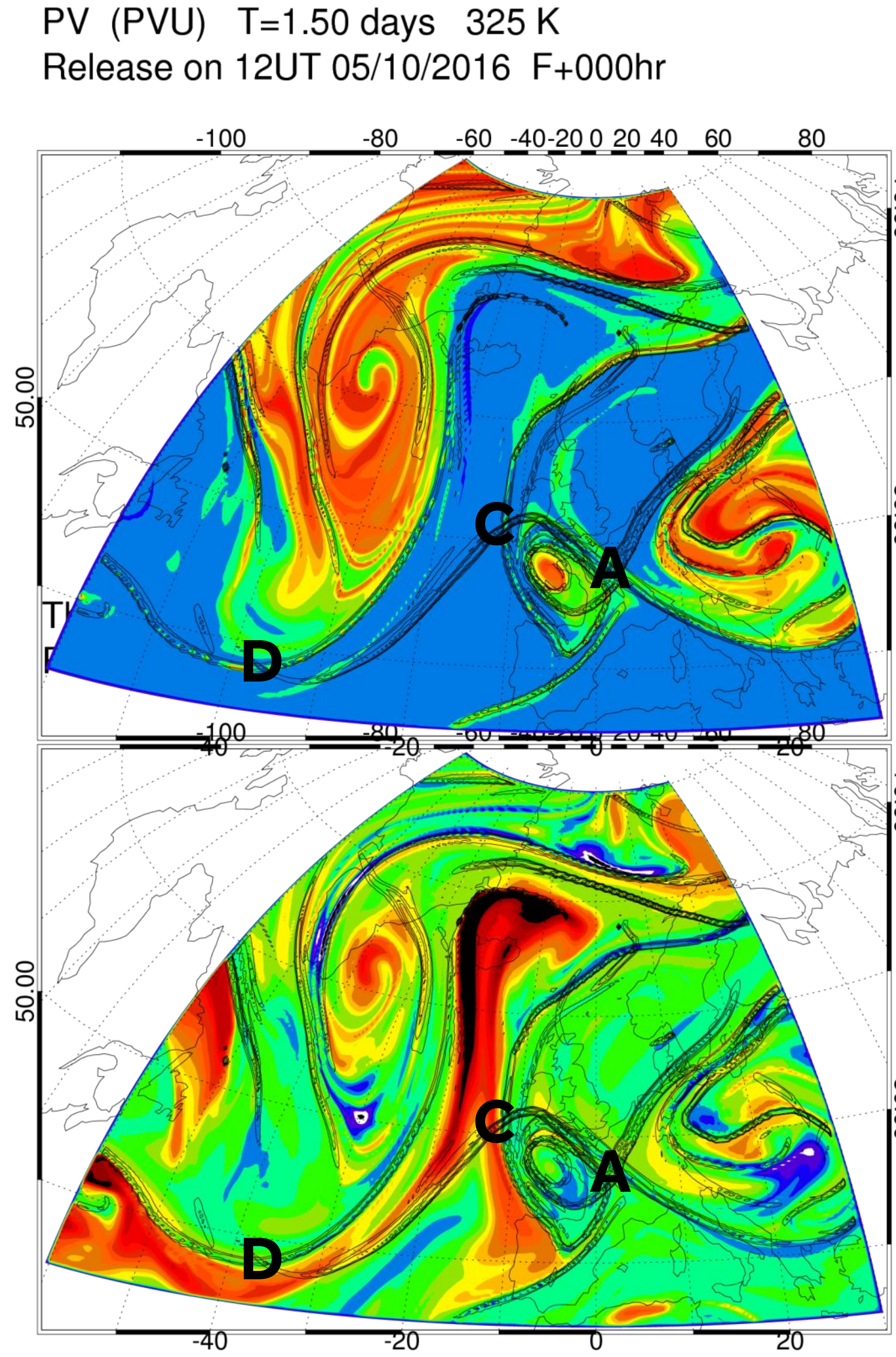
Hyperbolic point D forms near tip of next trough

Large diabatic mass transport into WCB outflow volume, northwest of C

Field is *net heating* along trajectories over 1.5 days

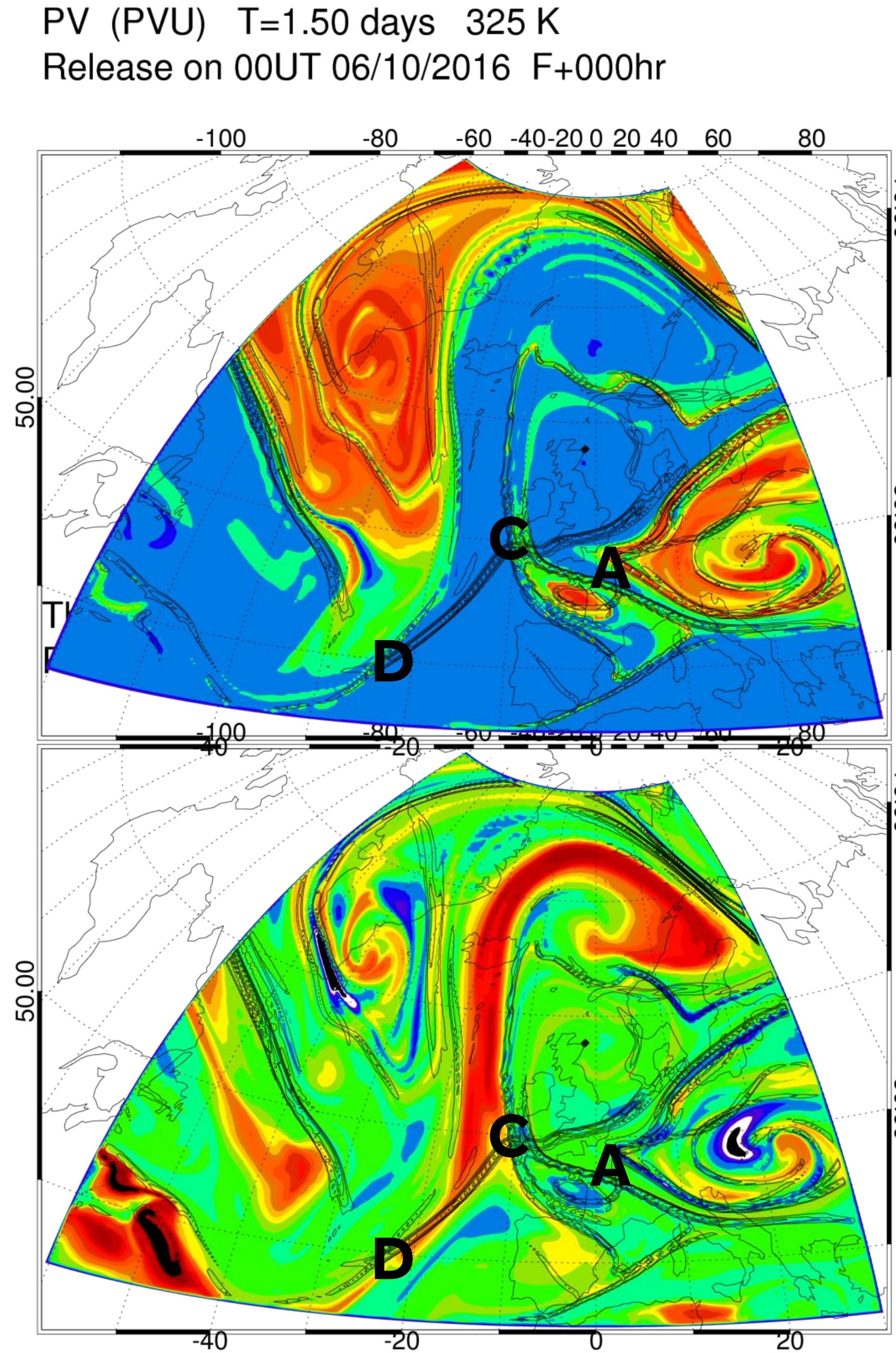


Diabatic mass transport into A/C cut-off volumes



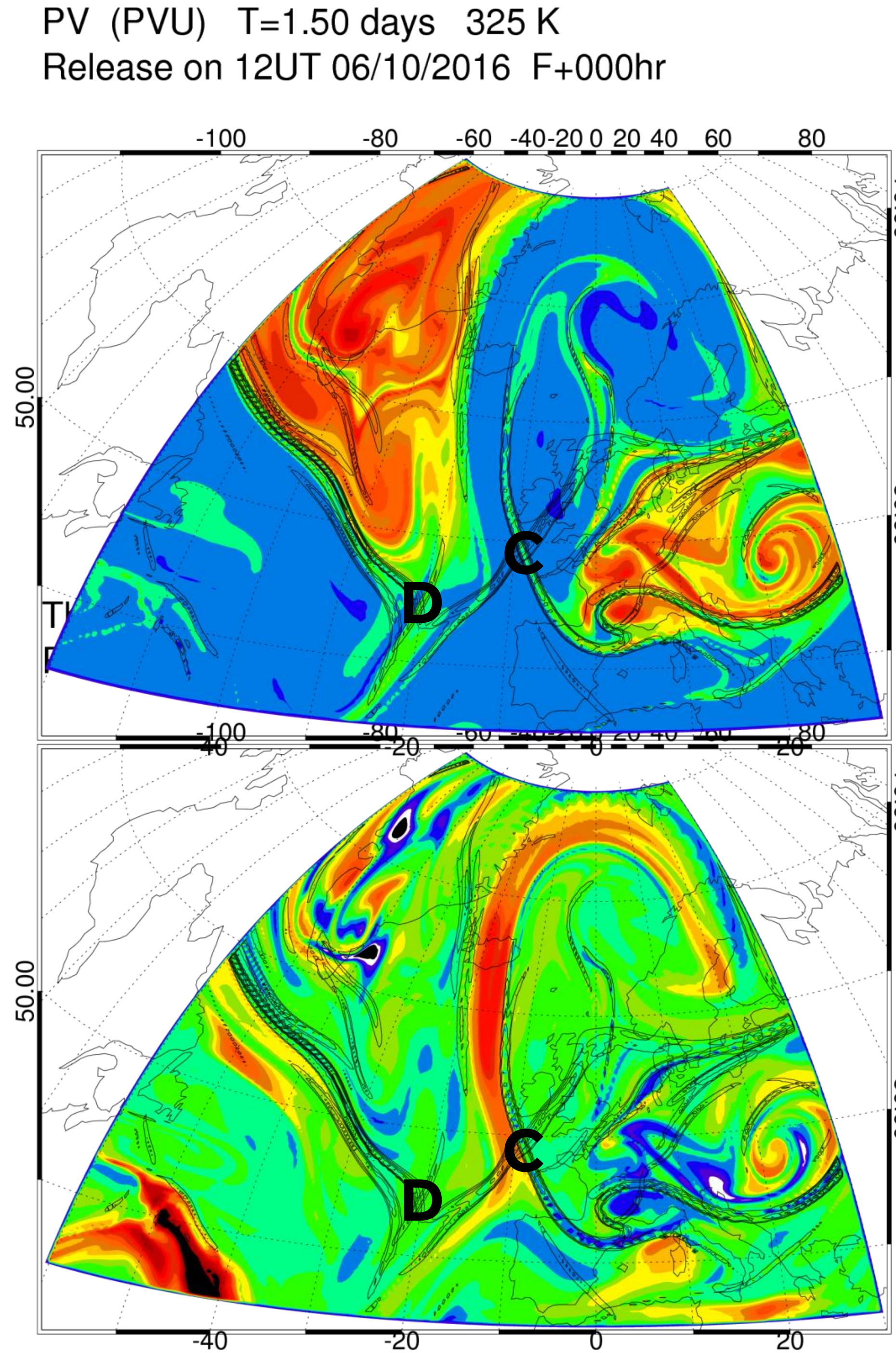
Field is *net heating* along trajectories over 1.5 days

Diabatic mass transport into A/C cut-off volumes



Field is *net heating* along trajectories over 1.5 days

Diabatic mass transport into A/C cut-off volumes



Field is *net heating* along trajectories over 1.5 days

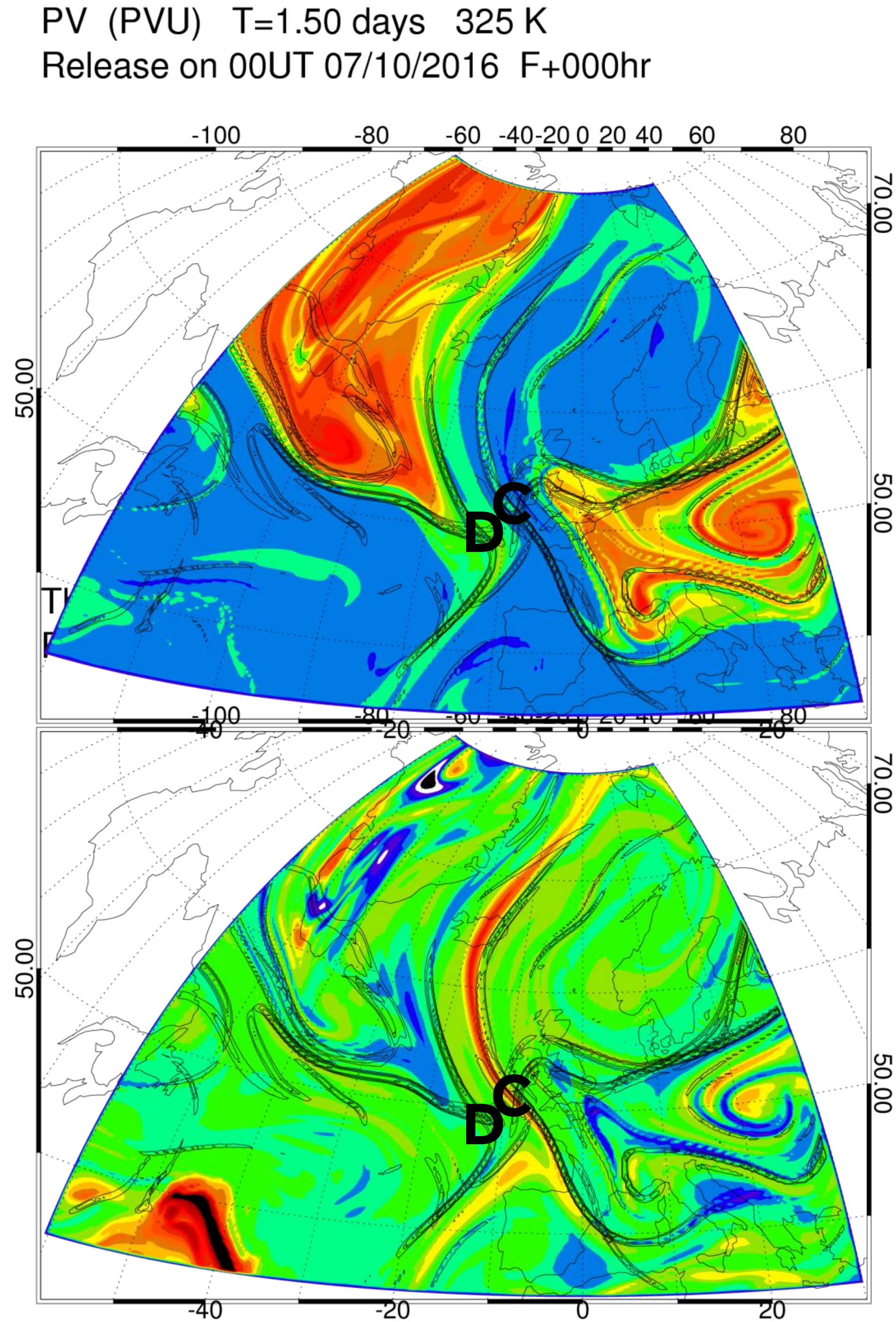
Diabatic mass transport into A/C cut-off volumes

C and D converge to form strengthen hyperbolic point in front of *dipole block.*

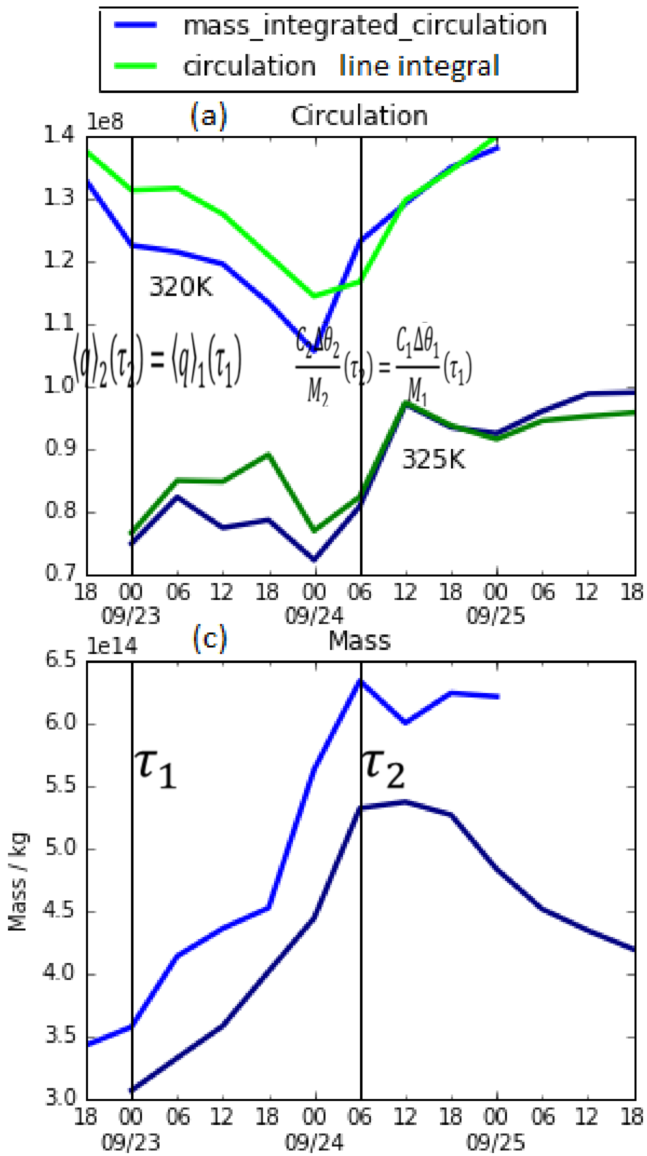
Vortex roll-up ⇒ emergence of new hyperbolic trajectories

Latent heating can *double* mass in A/C cut-off regions.

Crucial to blocking onset?



Circulation and mass of outflow



Large **increase in mass of outflow volume** (x2) by diabatic mass transport from below.

But, variation in circulation is small.

Consequence of **PV impermeability theorem**, Haynes and McIntyre (1987, 1990). Circulation cannot be changed through diabatic mass flux.

Then, why is outflow size important to block?

$$C = \int_{\partial S} \underline{u}.d\underline{l} = \iint_S (\nabla \times \underline{u}).d\underline{S} = \langle f + \xi \rangle S$$

As area, *S*, increases, anticyclonic relative flow is stronger around the boundary.

Conclusions

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1. Key ingredients to a WCB *(even with embedded convection):*
   a. Net heating ($\Delta\theta$) is large cf range of θ in "inflow" and "outflow"
   b. Horizontal advection on each isentropic surface is dominated by the "balanced flow" (including ageostrophic motion)

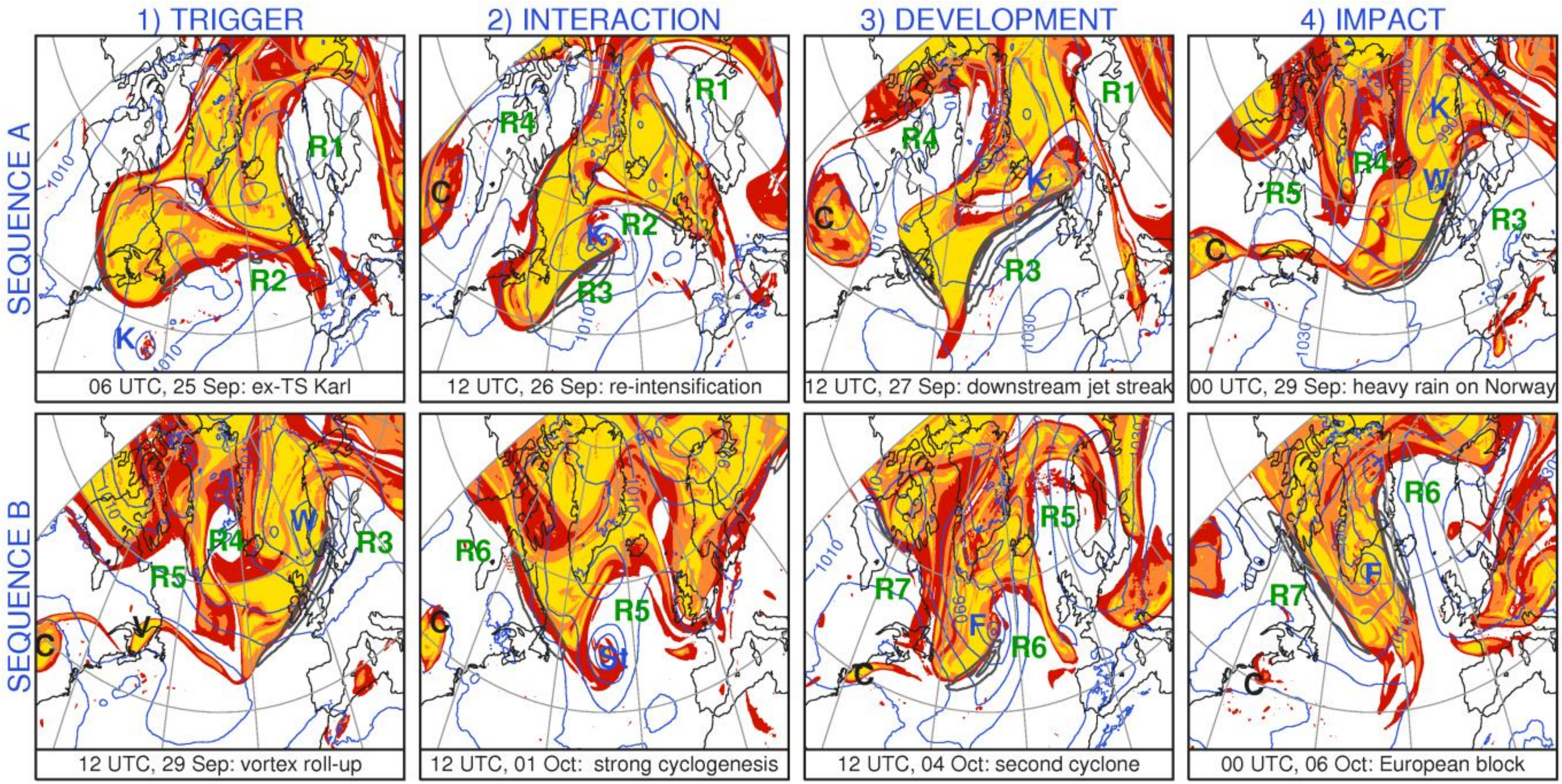
2. **Influence of latent heating** on level and mass of WCB outflow
   - Circulation in outflow layer is unchanged (by direct diabatic effects)
   - Average PV of outflow = PV of the inflow *(from PV impermeability)*

3. **Diabatic mass transport expands anti-cyclonic cut-offs**
   - Can double mass of outflow volume **(prohibited for adiabatic flow)**
   - Fractional mass increase , $\frac{\Delta M}{M_0} \approx \frac{\Delta A}{A_0} + \frac{\Delta r}{r_0}$
   - Integrated anticyclonic vorticity = -(f- circulation/area)

Thankyou for your attention

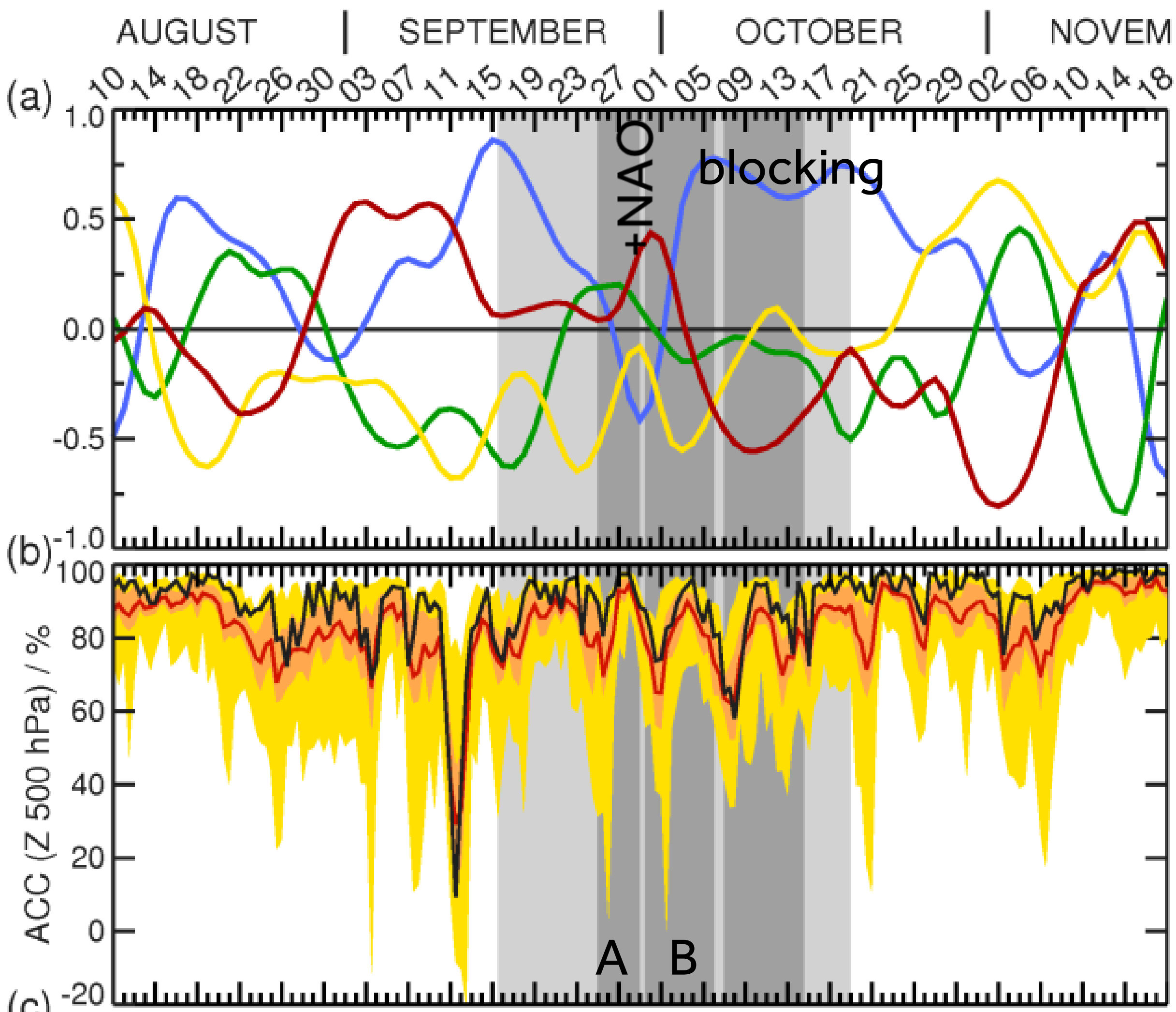
The NAWDEX Storyline

Mesoscale triggers interact with the jet stream, modifying development and high impact weather downstream



Lowest predictability following trigger - a precursor to a regime transition?

Time series of Z500 data projected onto 4 large-scale patterns of variability



Anomaly correlations between members of forecast ensemble (T+120) and verifying analyses

Semi-geostrophic theory in 3-D (Hoskins, 1975)

- Makes *geostrophic momentum approximation (GMA)*
  - **Advection by full flow** including w and *ageostrophic wind*

Q. How is Rossby wave propagation affected compared with basic QG theory?

Amazingly, using the S-G coordinate transformation:

$$X = x + \frac{v_g}{f}\ , \qquad Y = y - \frac{u_g}{f}\ , \qquad Z = z\ , \qquad T = t$$

the S-G evolution in (X, Y, Z) is similar to Q-G evolution in (x, y, z)

Transformed into physical coords, +ve vorticity regions contract

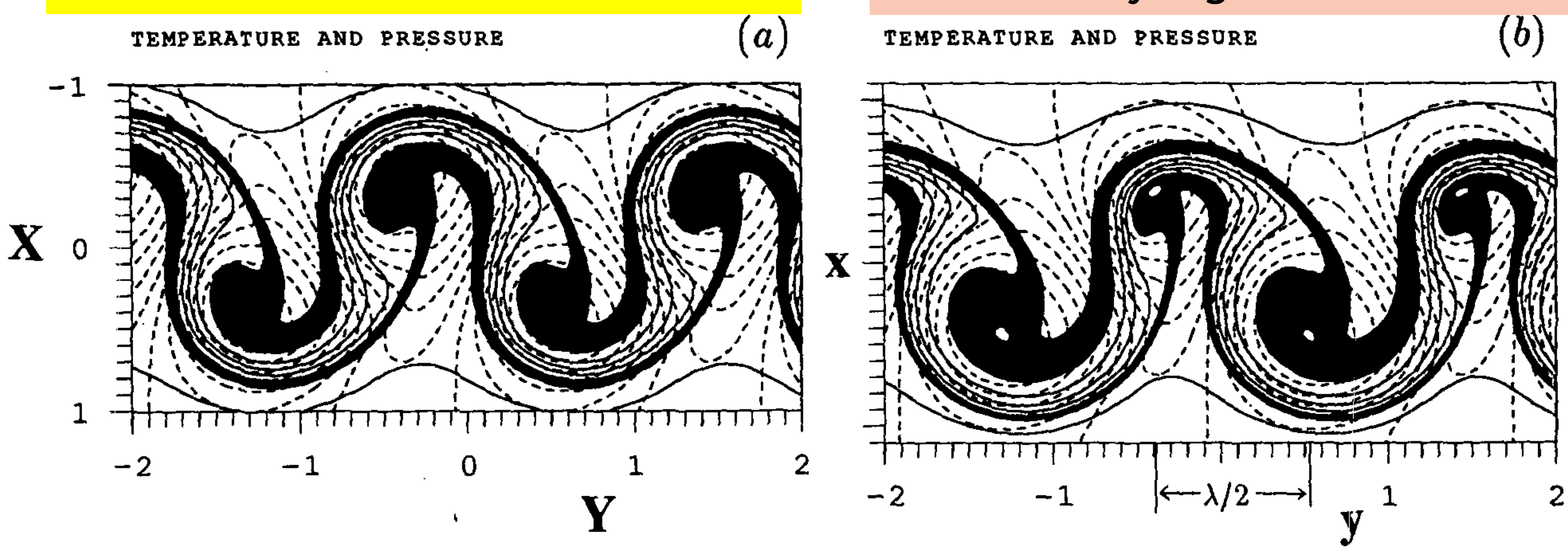


Figure: Davies, Schar and Wernli, *J. Atmos. Sci.*, 1991

C. Effects of heating on Rossby waves

Vertical velocity can be deduced using the S-G omega equation.

Its form in momentum coordinates (Hoskins & Draghici, 1977) is:

$$\nabla_X^2 \left(\frac{g\rho_r}{\theta_0 f_0} q_g w^* \right) + f_0^2 \frac{\partial^2 w*}{\partial Z^2} = \boxed{2\nabla_X . \mathbf{Q}} + \boxed{\nabla_X^2 H}$$

Geostrophic forcing

Diabatic forcing (H=heating)

"Large-scale rain" parametrization of heating: $H = \alpha w^*$, $\hat{Z} = \frac{N_0}{f_0} Z$

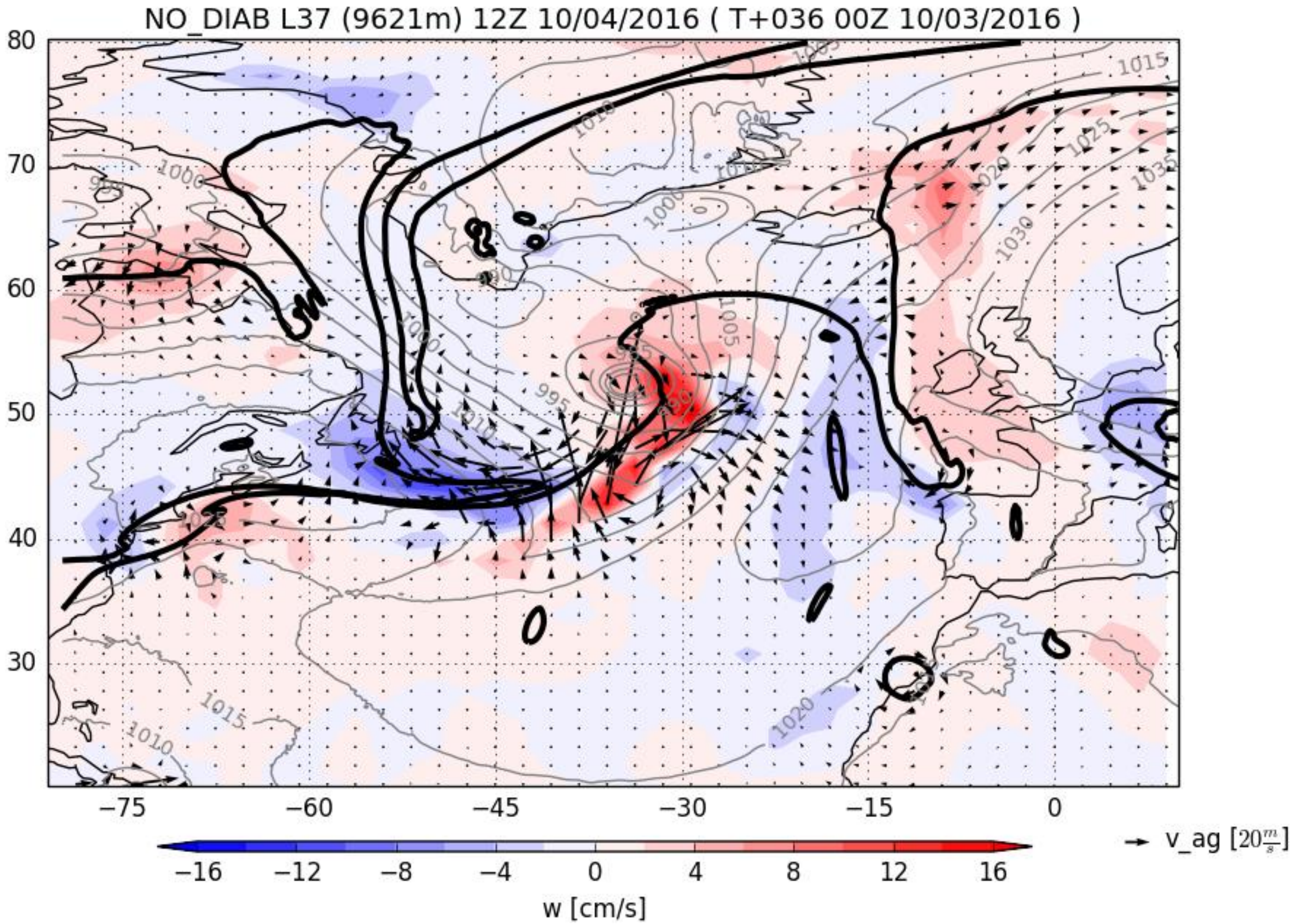
$\Rightarrow$ Response of moist equations using effective static stability, N_{eff}

$$\nabla_X^2 \left(\frac{N_{eff}^2}{N_0^2} w^* \right) + \frac{\partial^2 w*}{\partial \hat{Z}^2} = 2\nabla_X . \mathbf{Q}$$

Amplification of ageostrophic flow by heating

Balanced ageostropic flow and w from S-G "omega" equation.

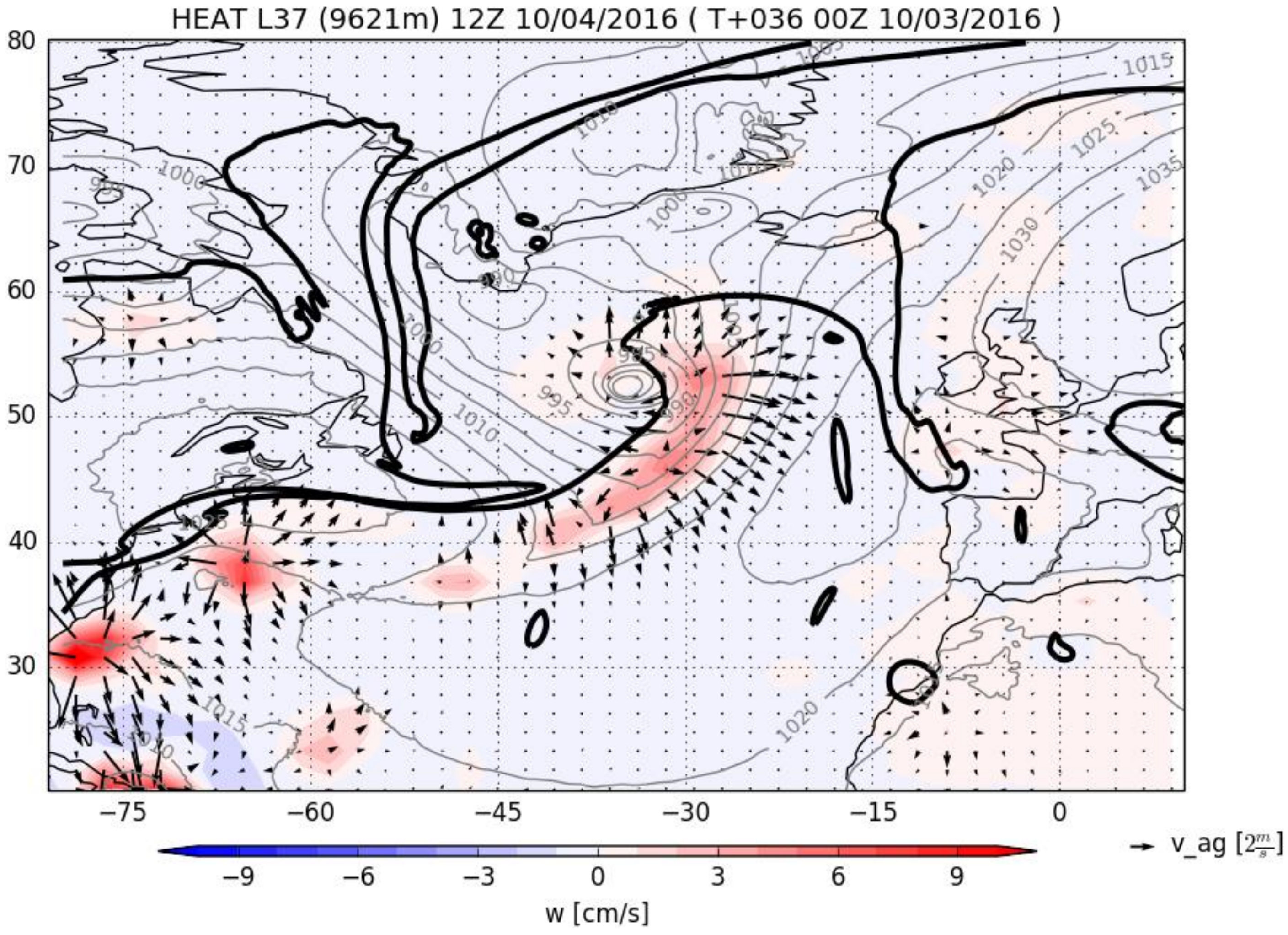
Without* forcing from heating.** ***Mike Cullen & Claudio Sanchez.



Amplification of ageostrophic flow by heating

Balanced ageostropic flow and w from S-G "omega" equation.

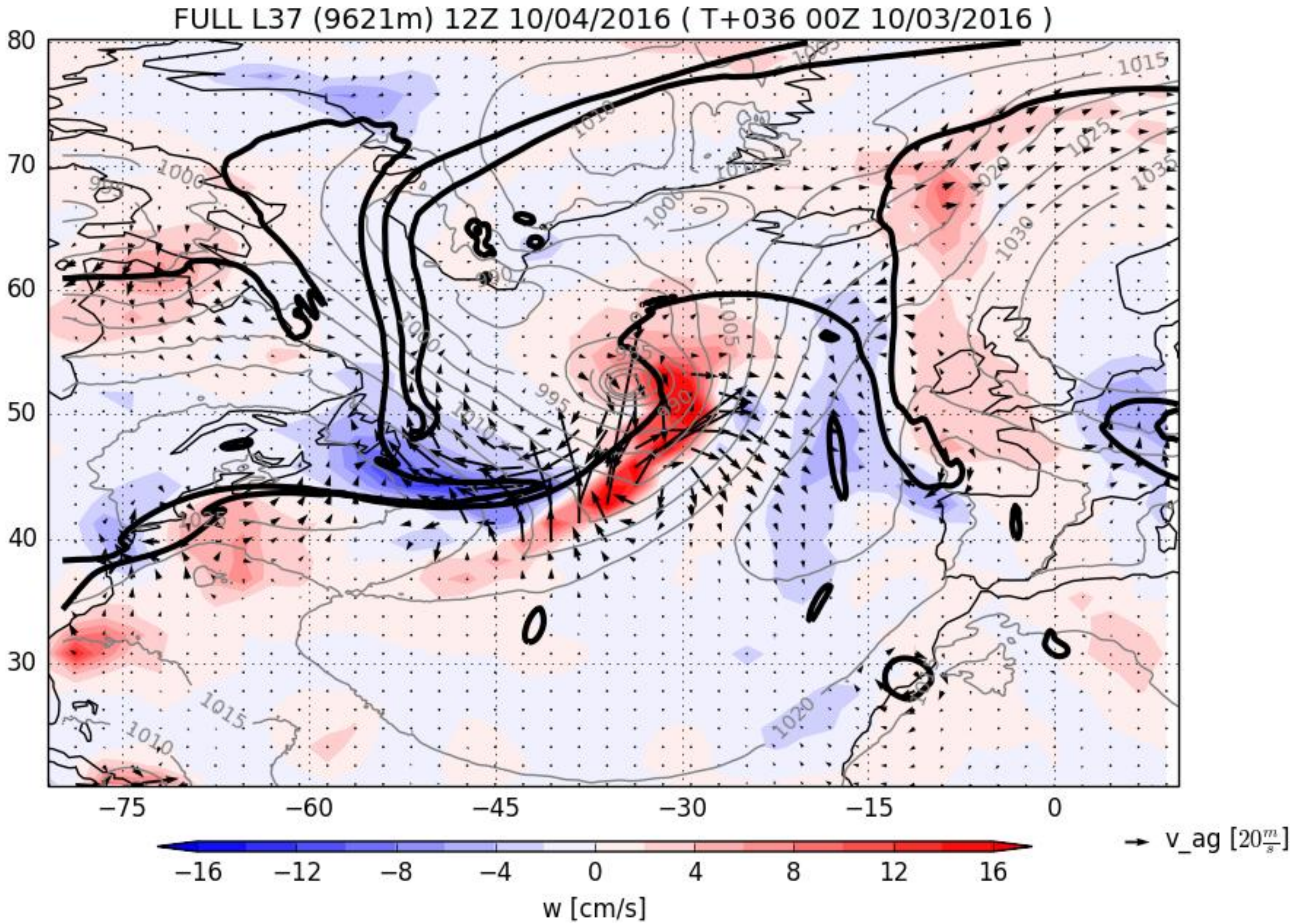
In response to **heating from physical parametrizations.**



Amplification of ageostrophic flow by heating

Balanced ageostropic flow and w from S-G “omega” equation.

With forcing from full parametrized heating from MetUM.



Amplification of ageostrophic flow by heating

Balanced ageostropic flow and w from S-G "omega" equation.

Heating proportional to vertical velocity ("large-scale rain").