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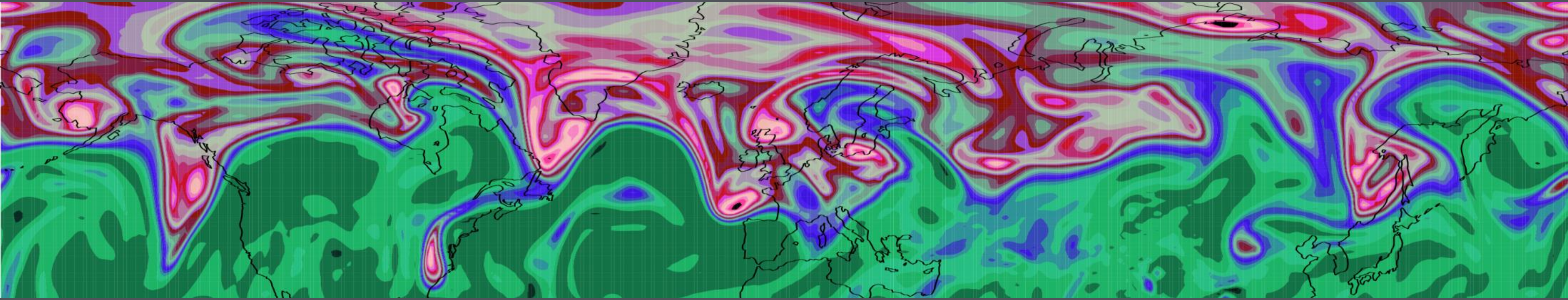
Effects of Diabatic Heating in WCBs on Jet Stream Perturbations and Predictability



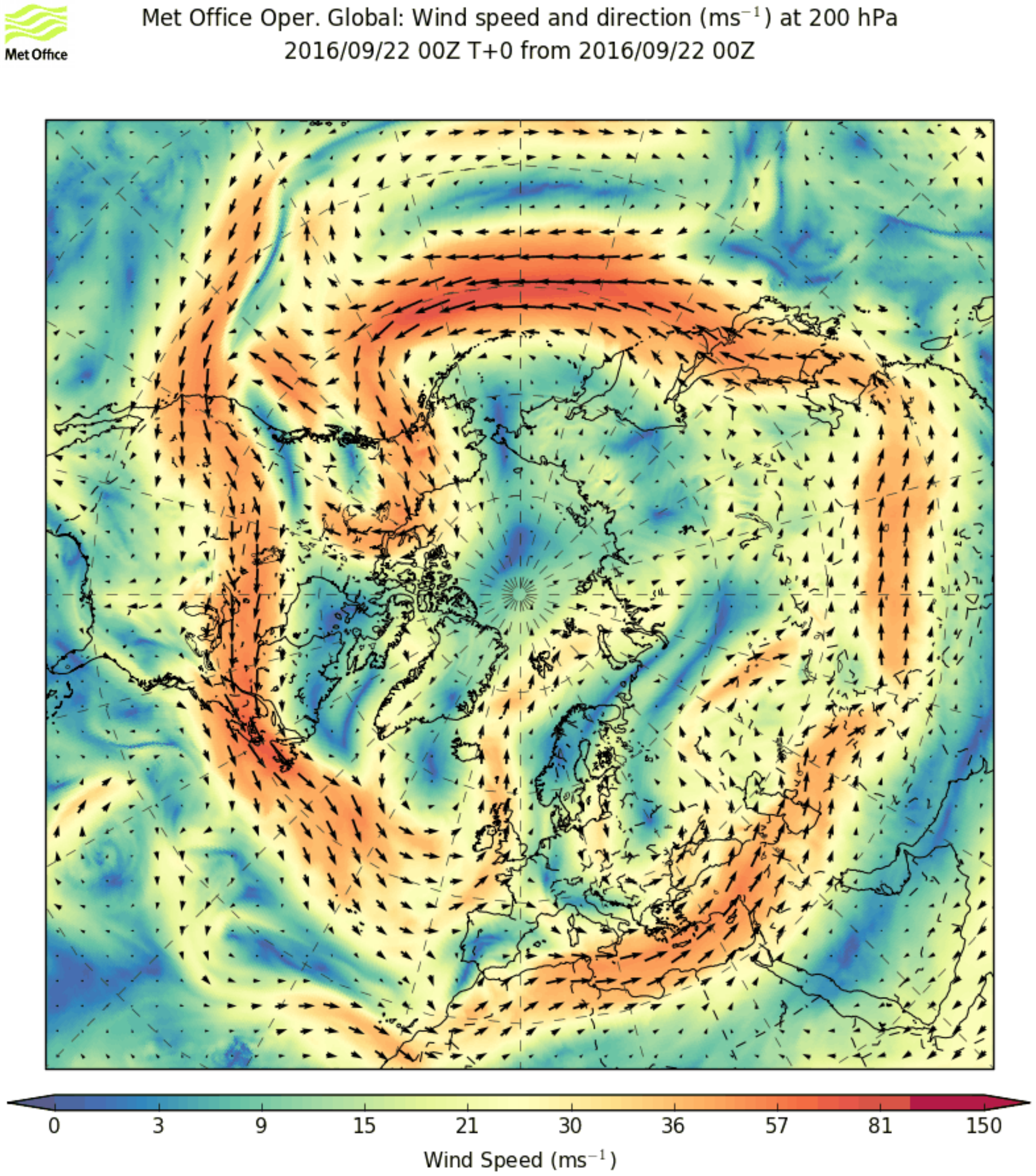
John Methven, University of Reading

Thanks to Ben Harvey (NCAS), Leo Saffin (Leeds/Reading), Jake Bland (Reading), Suzanne Gray (Reading), Andreas Schaefler (DLR), Claudio Sanchez (Met Office) & Mike Cullen (Met Office)

Jet Stream Dynamics and Predictability

1. Quasi-stationary Rossby waves and persistent weather regimes
2. Observations of the jet stream and North Atlantic weather systems:
   North Atlantic Waveguide and Downstream Impacts Experiment (NAWDEX)
3. Waveguide disturbances: trigger, propagation and downstream impact on predictability
4. Diabatic processes: influence on jet stream and predictability of weather downstream
5. Conclusions

Jet stream evolution over one week of NAWDEX campaign


Met Office Oper. Global: Wind speed and direction (ms^{-1}) at 200 hPa
2016/09/22 00Z T+0 from 2016/09/22 00Z

Movie of winds at 200 hPa (short-range Met Office forecasts)

Frame interval = 1 hour

SUMMER 2007 FLOODS

High impact persistent weather

Dominated by flooding

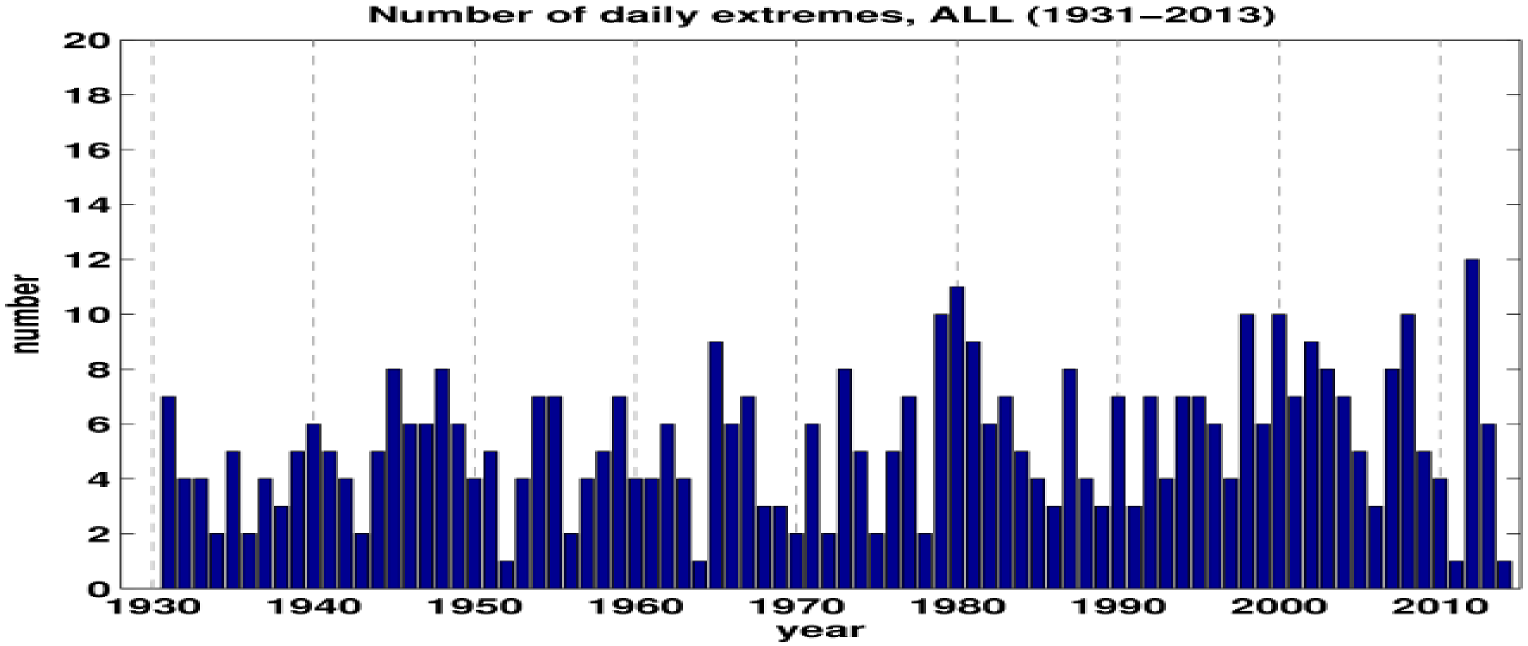
48,000 households flooded

350,000 people without fresh water supplies (Gloucestershire)

42,000 acres of agricultural land flooded

Total cost to UK economy ~ £3.2 billion (Environment Agency, Jan 2010)

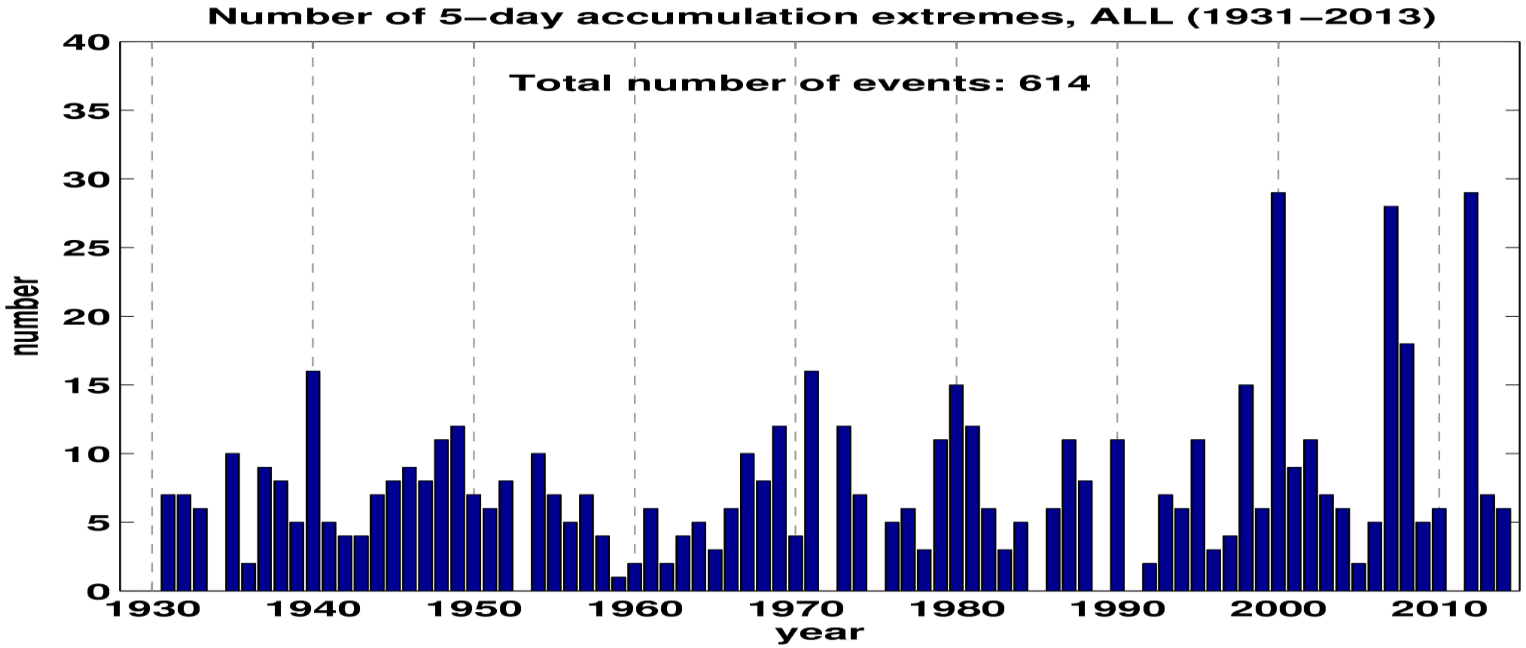
Number of days per year with extreme England-Wales precipitation (EWP) *daily* total



Extremes here defined as wettest 2% of days on record.

Derived from EWP index – based on rain gauge network.

Number of extreme *5-day rainfall* accumulation events per year

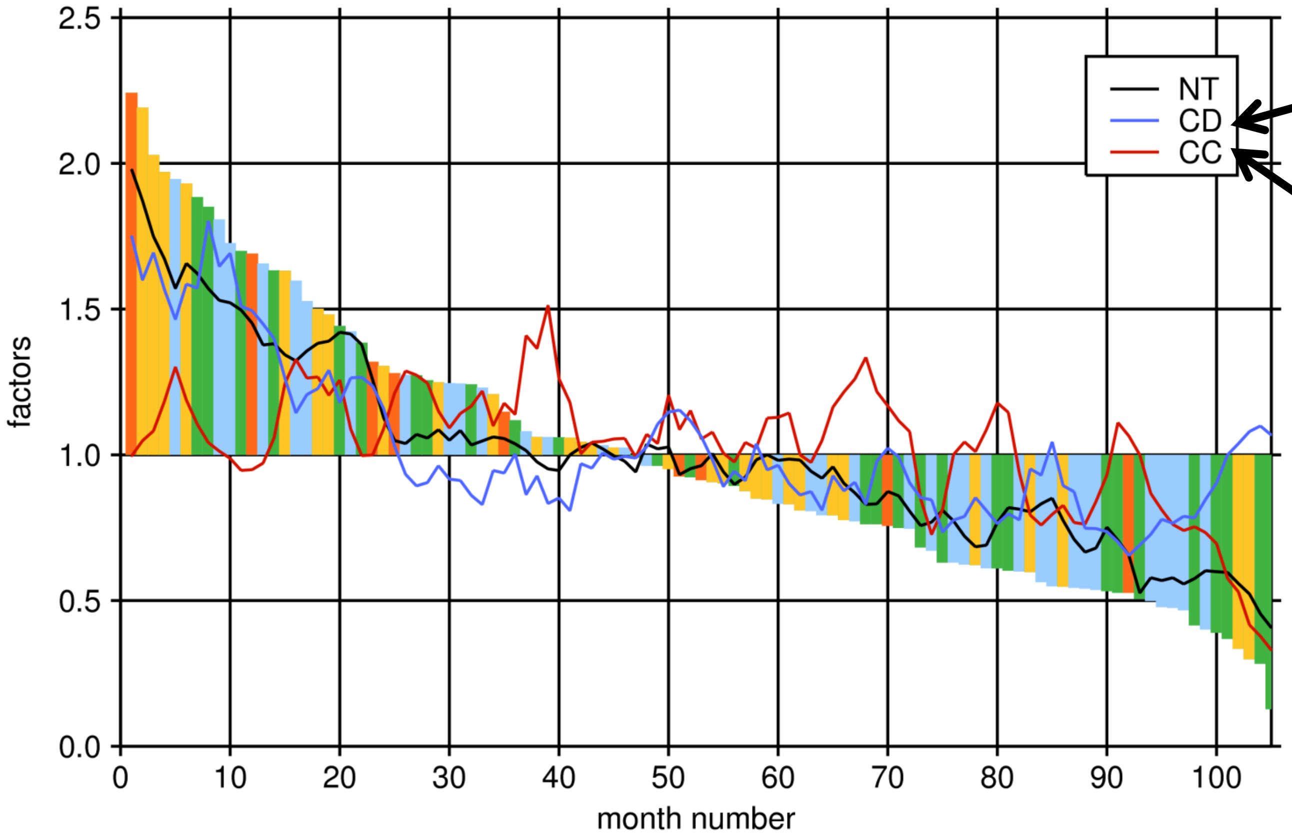


- ❑ Indicates that **persistence** has been unusual in two decades
- ❑ **Autumn 2000, summer 2007 & 2008, summer+Dec 2012!**

(De Leeuw, Methven & Blackburn, *Int. J. Clim.*, 2015)

Ranked monthly precipitation (summer only)

blue 1980s, green 1990s, yellow 2000s, orange 2010s



cyclone duration

cyclone count (relative to average)

- ❑ **Wettest summer months related to duration of cyclone rainfall events**
- ❑ **SSTs anomalously cold at airmass origins in wettest months**

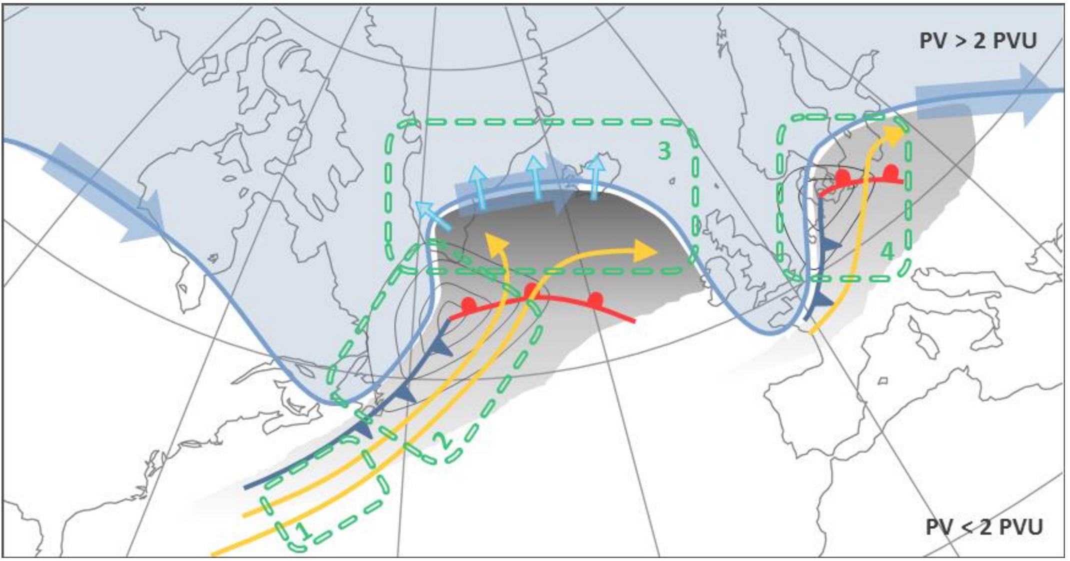
(De Leeuw, Methven & Blackburn, *J. Climate*, 2017)

North Atlantic Waveguide & Downstream Impacts Experiment

NAWDEX Aim: 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

Period 15 Sep to 22 Oct 2016

See Schäfler et al. (*BAMS, 2018*)



[Top]: Sketch of NAWDEX main goals: Observation of diabatic process in WCB (1,2), ridge formation (3) and downstream effects (4)

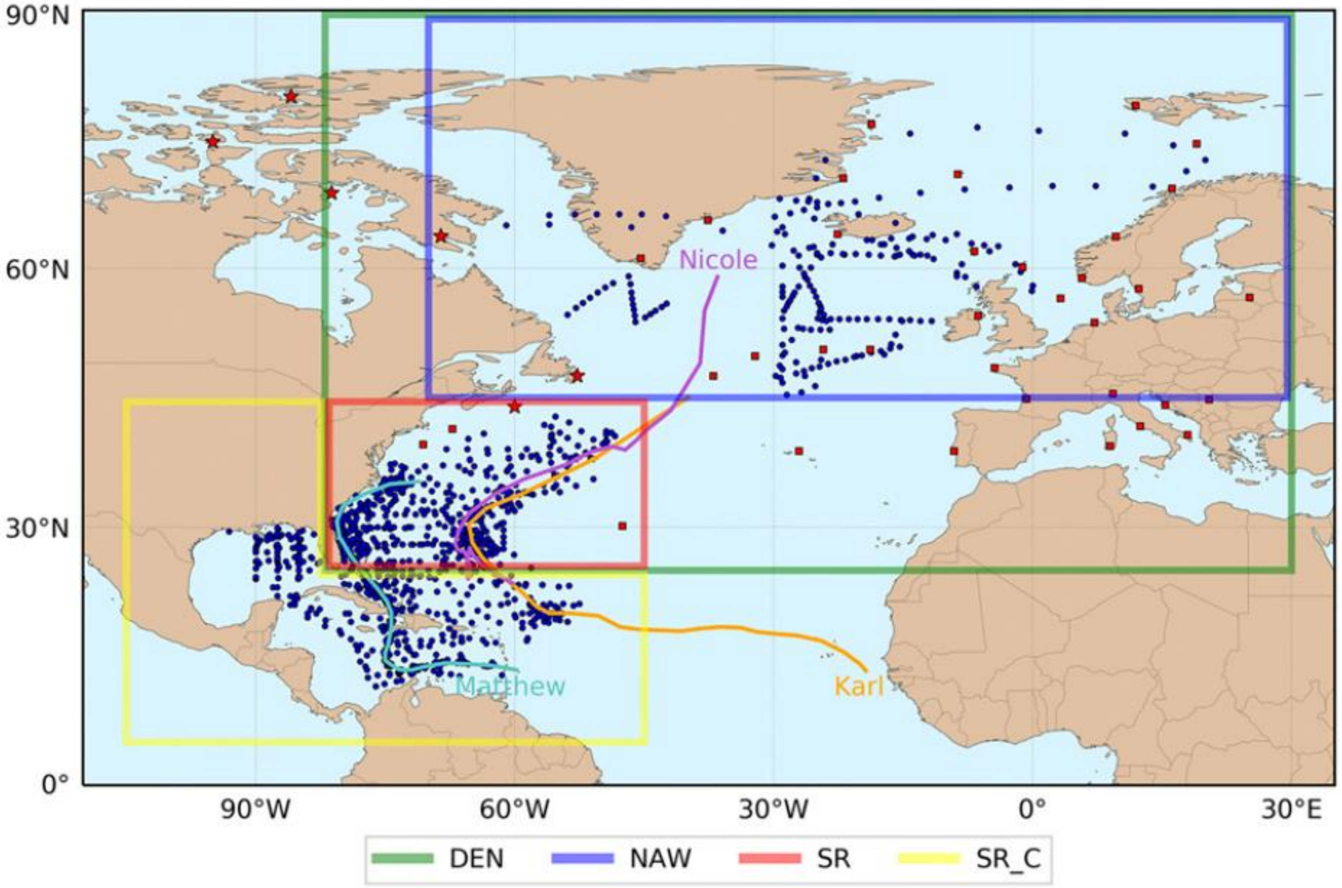
DLR HALO

DLR Falcon

SAFIRE Falcon

FAAM BAe146

Data denial experiments using ECMWF IFS cycling over NAWDEX+SHOUT campaign month



Schindler, Weissmann *et al, MWR* (2020)

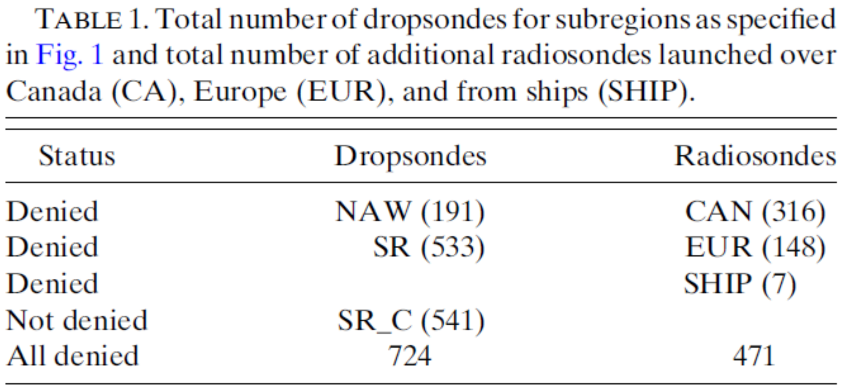


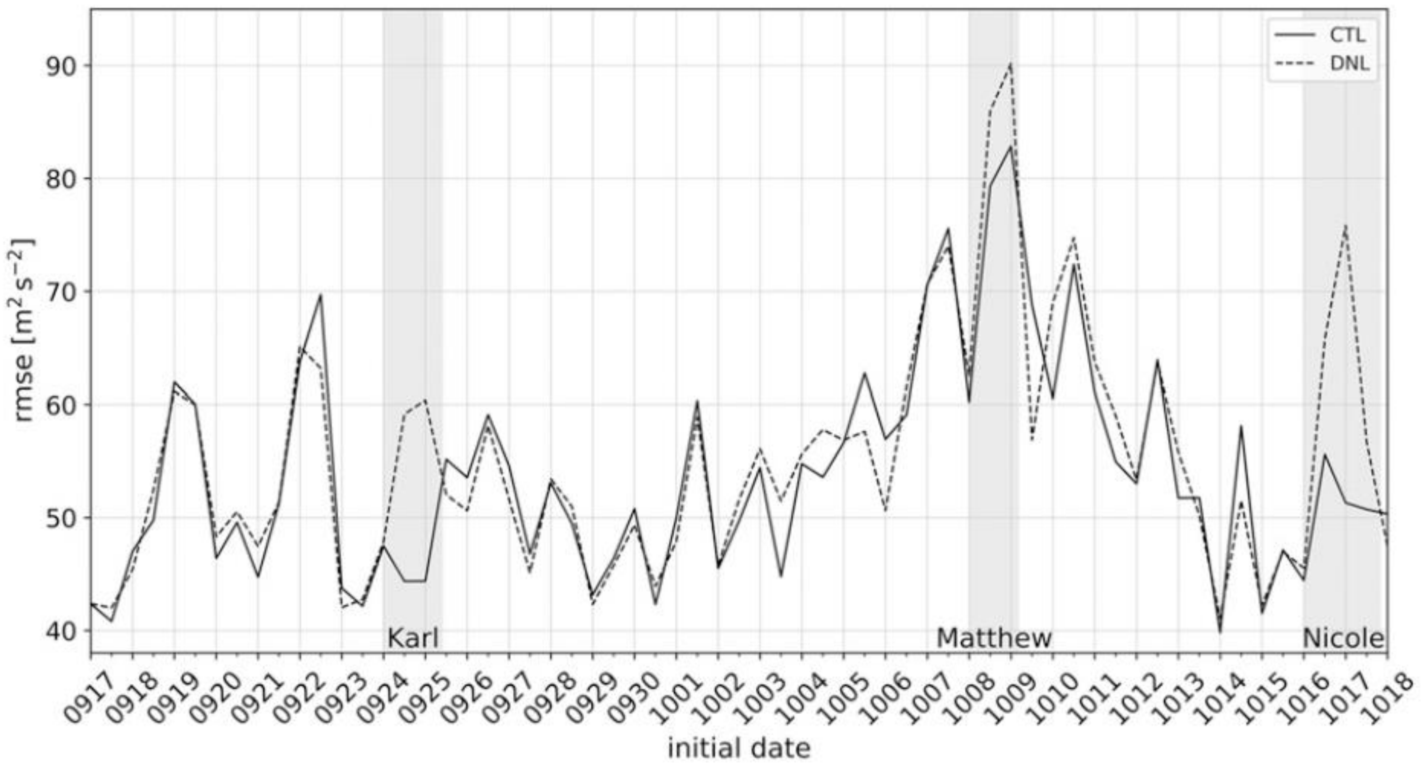
TABLE 1. Total number of dropsondes for subregions as specified in Fig. 1 and total number of additional radiosondes launched over Canada (CA), Europe (EUR), and from ships (SHIP).

Status	Dropsondes	Radiosondes
Denied	NAW (191)	CAN (316)
Denied	SR (533)	EUR (148)
Denied		SHIP (7)
Not denied	SR_C (541)	
All denied	724	471

- Mean forecast error in Z500 (T+48) reduced by 1-3% on average
- Typical for other campaigns during THORPEX including T-PARC (2008)
- cf 10-20% a decade earlier in FASTEX (1997)
  - Review of observation targeting: **Majumdar, *BAMS* (2016)**

Data denial experiments using ECMWF IFS cycling over NAWDEX+SHOUT campaign month

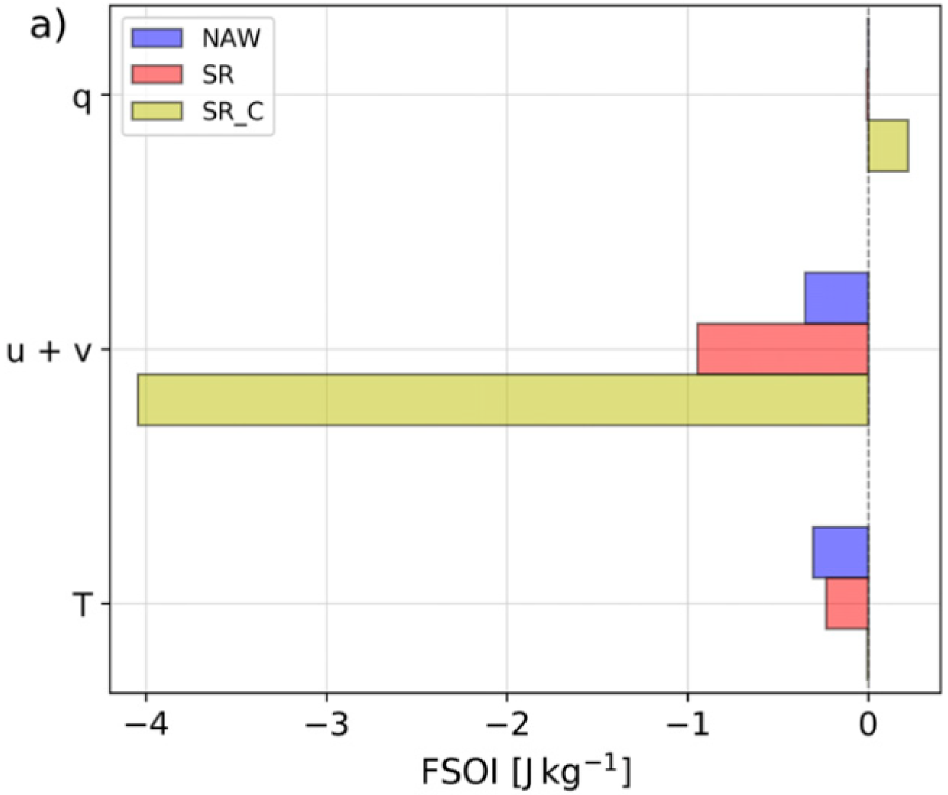
Schindler, Weissmann *et al, MWR* (2020)

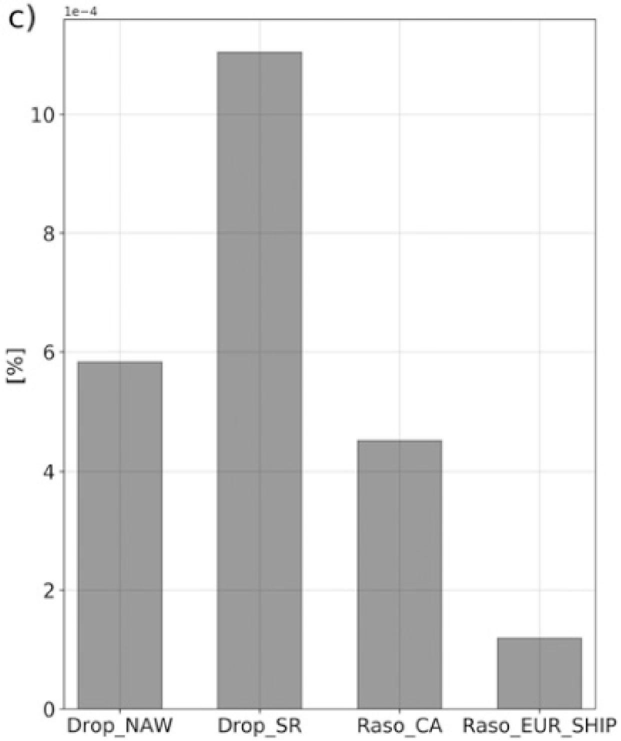


RMSE for Z500 comparing CTRL and Denial expts

- Reduction of forecast error (northern North Atlantic & Europe) is much greater (up to 30%) in events with observations of cyclones undergoing extratropical transition
- Using 4D-VAR with Ensemble of DA to *estimate analysis error* and flow dependent background covariance
- Impact greatest at T+48 hr

Quantifying impact of observations



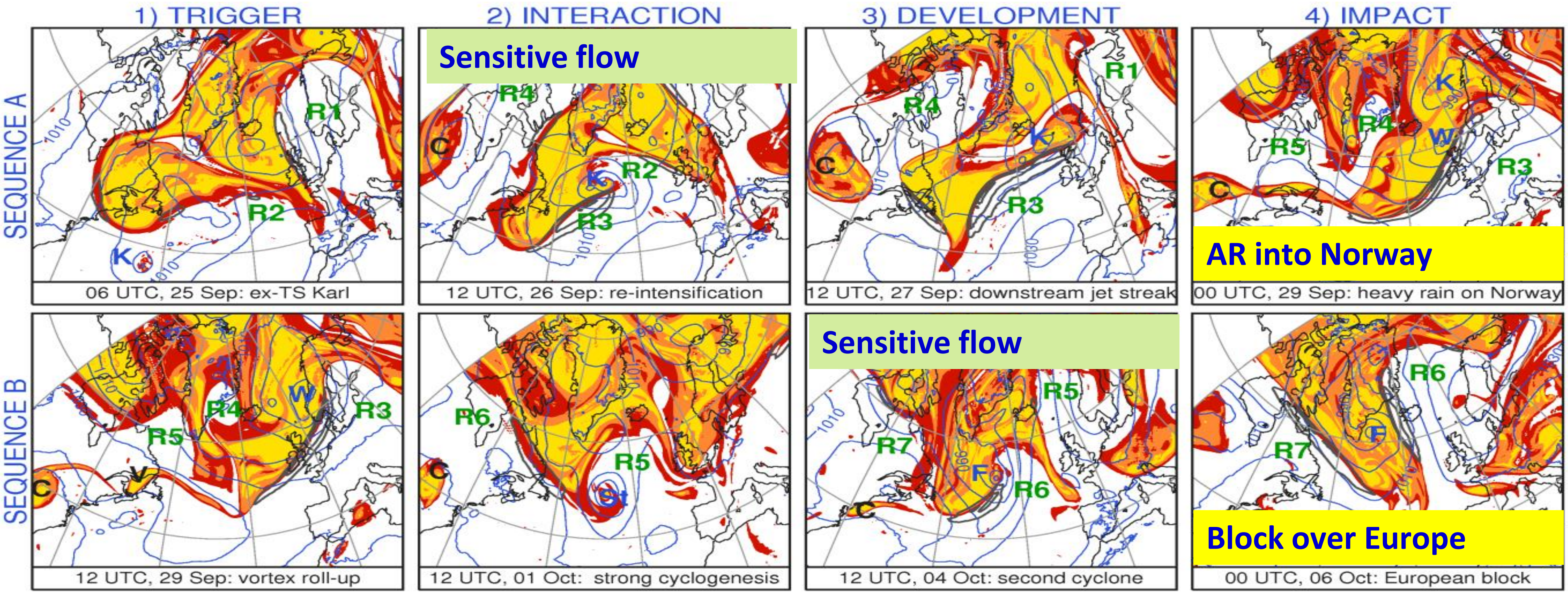


- FSOI = Forecast Sensitivity to Observation Impact
- Measure is total perturbation energy
- Extra wind obs (in subtropics) dominate impact

- Relative impact per observation
- Greatest from SHOUT dropsondes (Ex-TC)
- Remote profiles over Canada and North Atlantic have similar impact

The NAWDEX Storyline

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



1) TRIGGER

2) INTERACTION

3) DEVELOPMENT

4) IMPACT

SEQUENCE A

06 UTC, 25 Sep: ex-TS Karl

Sensitive flow

12 UTC, 26 Sep: re-intensification

12 UTC, 27 Sep: downstream jet streak

AR into Norway

00 UTC, 29 Sep: heavy rain on Norway

SEQUENCE B

12 UTC, 29 Sep: vortex roll-up

12 UTC, 01 Oct: strong cyclogenesis

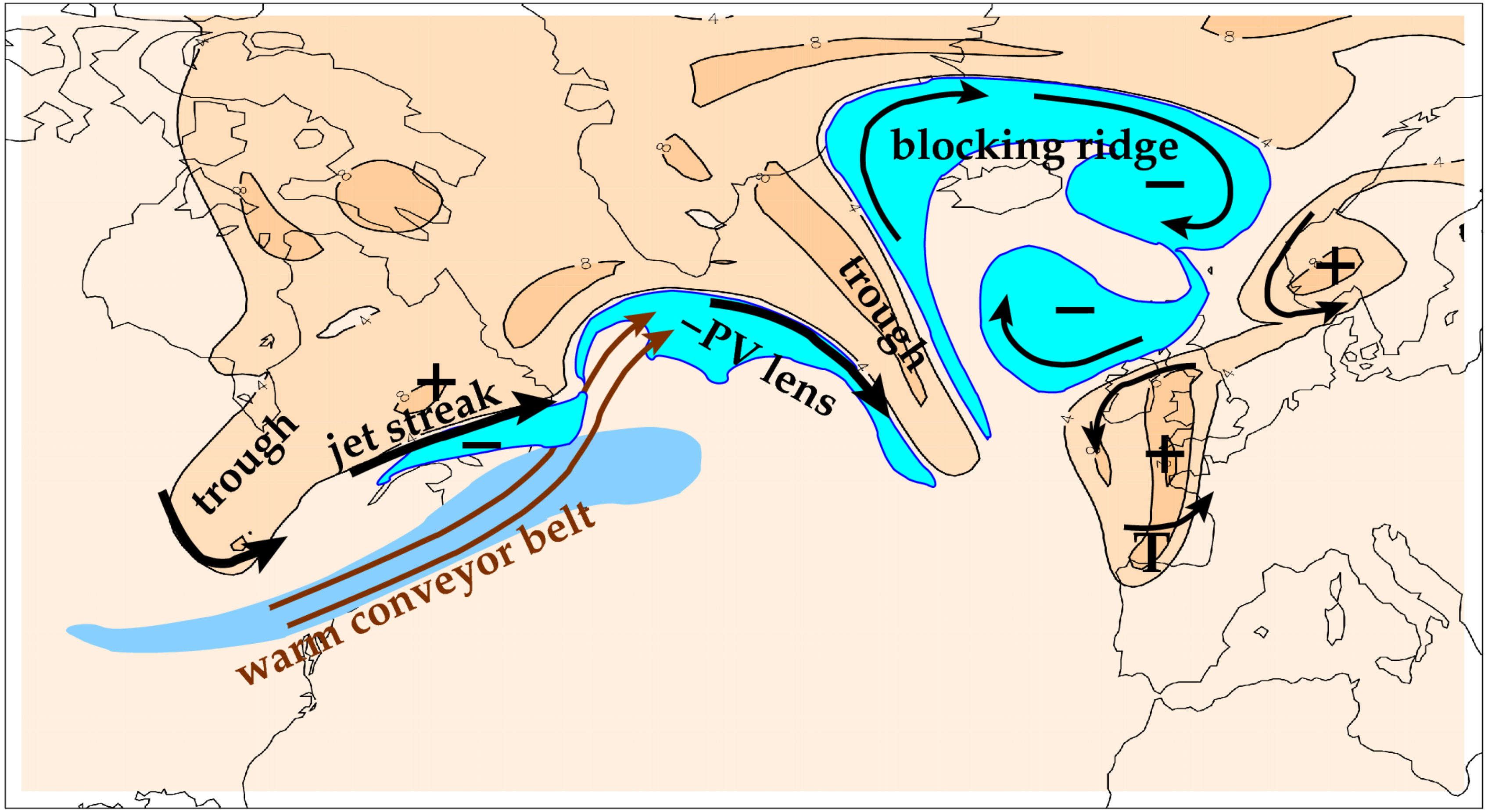
Sensitive flow

12 UTC, 04 Oct: second cyclone

Block over Europe

00 UTC, 06 Oct: European block

WCB outflow and diabatic mass transport into ridges



Features related to the meandering tropopause and jet stream
(orange is stratospheric air; cyan marks upper tropospheric PV anomalies)

PV modification along air parcel trajectories

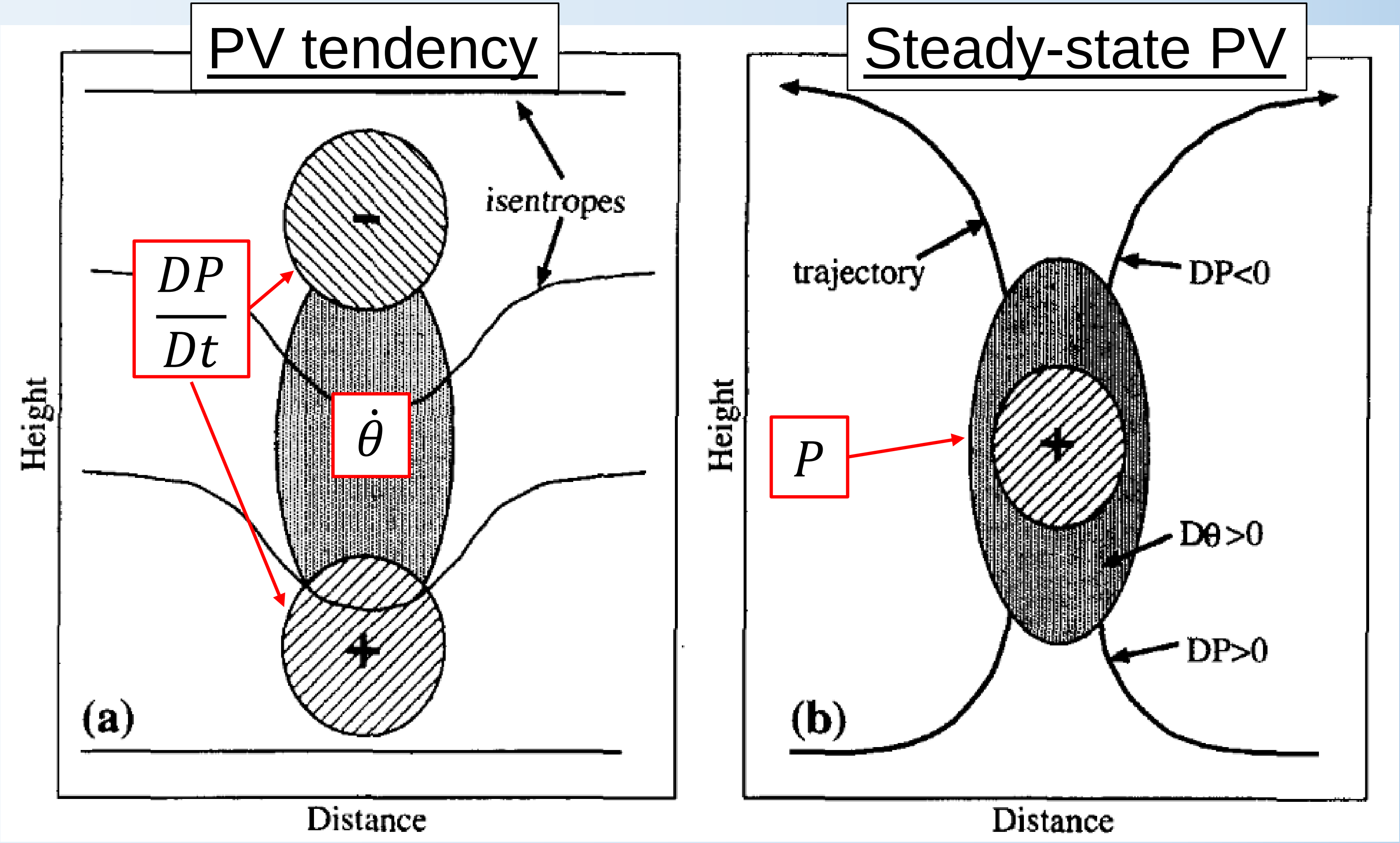
Lagrangian PV equation:

PV

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

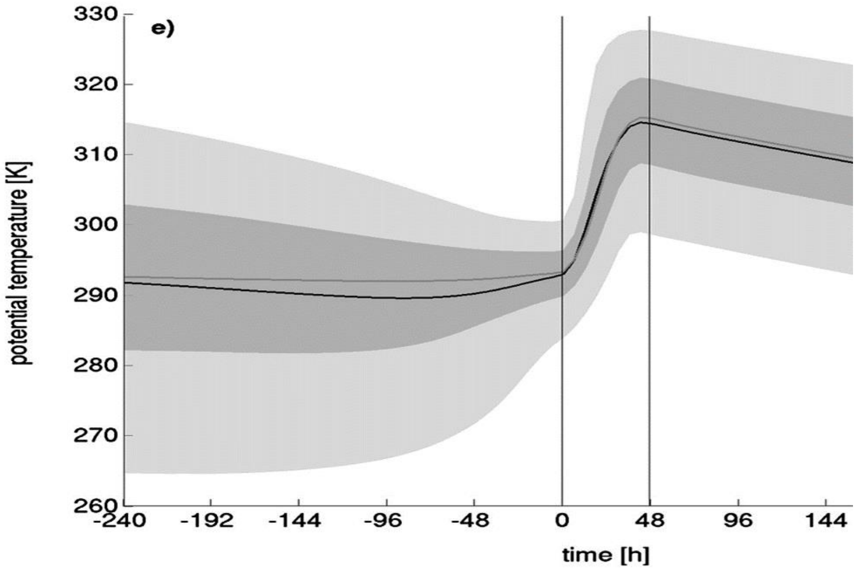
Absolute vorticity

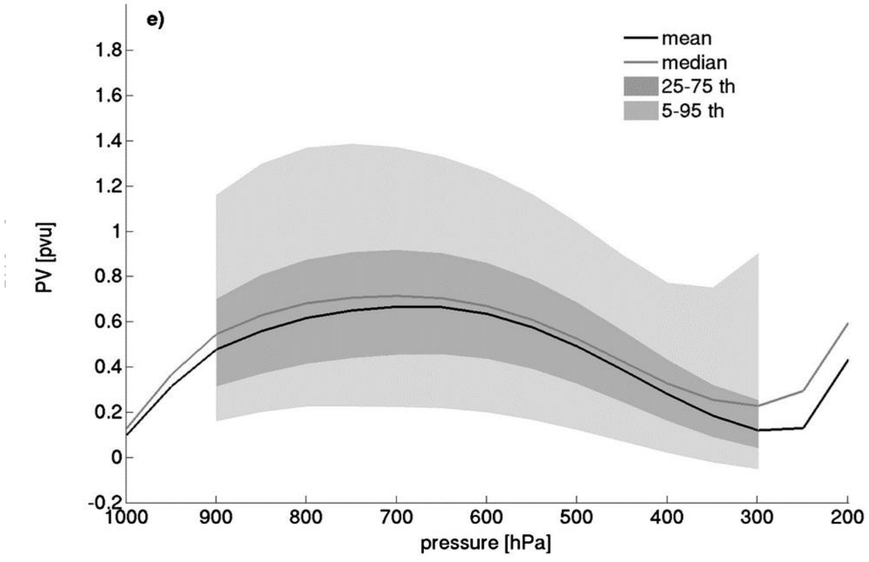
Diabatic heating ($\frac{D\theta}{Dt} = \dot{\theta}$)



Wernli and Davies (*QJRMS*, 1997)

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

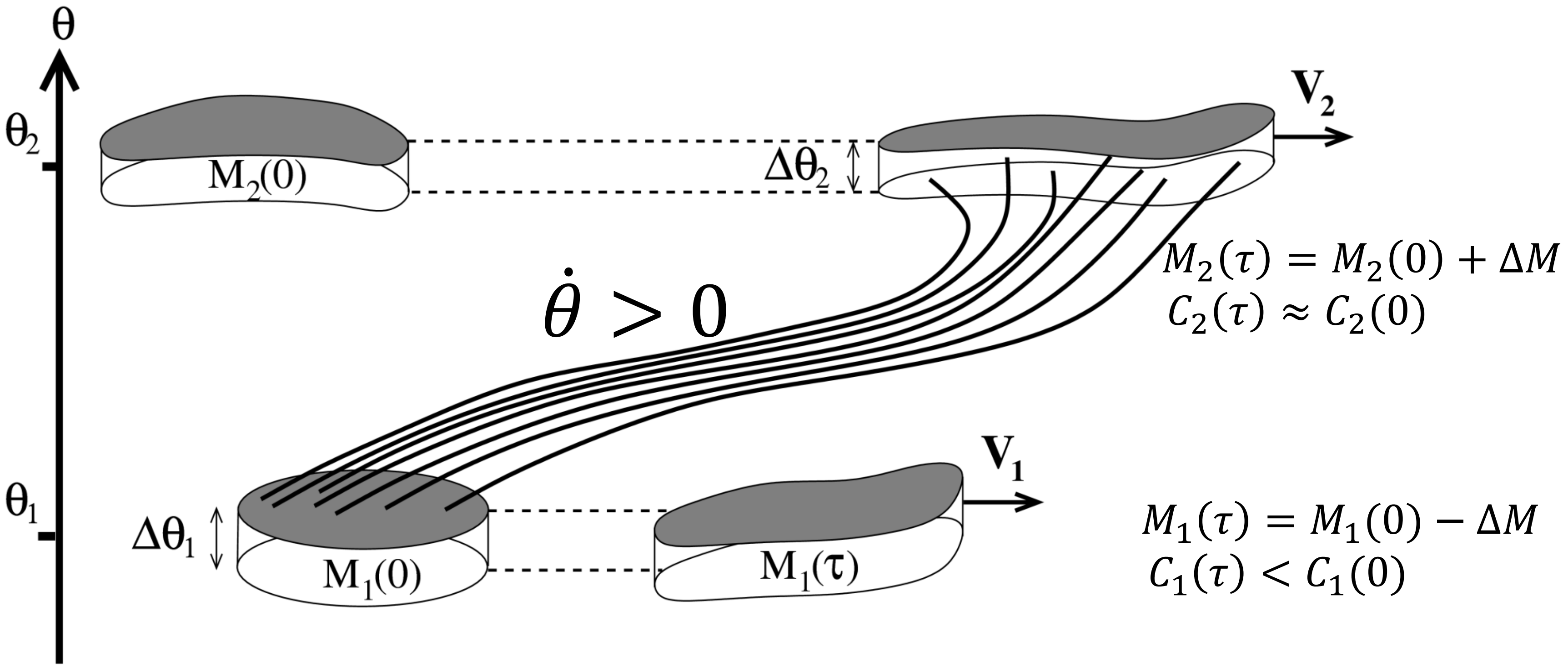
- Why is PV constrained in this way?
- Implications for role of heating?

PV in warm conveyor belts

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

Heating ⇒ **diabatic mass transport** from lower to upper volume

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



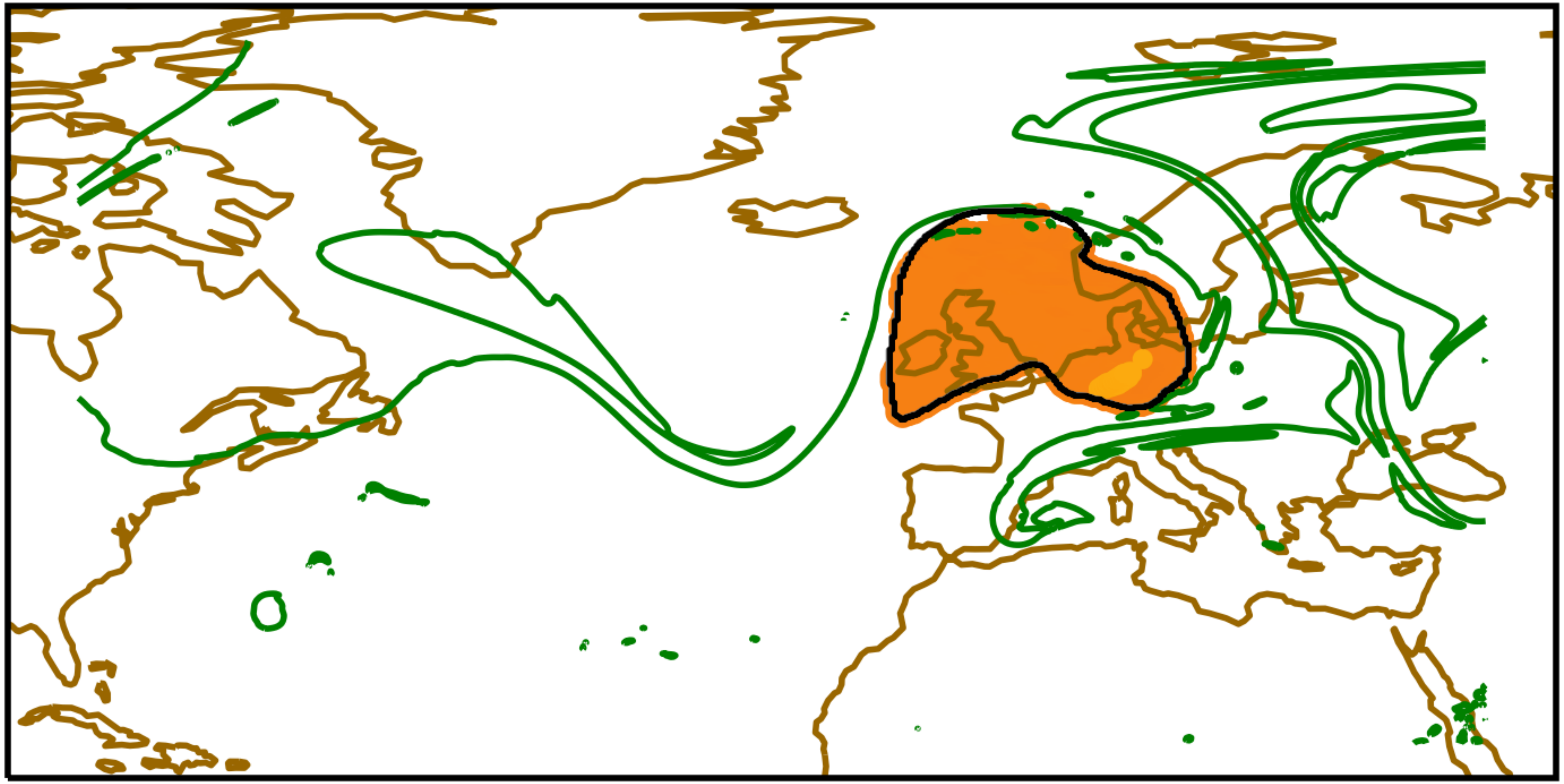
$$M_2(\tau) = M_2(0) + \Delta M$$
$$C_2(\tau) \approx C_2(0)$$

$$M_1(\tau) = M_1(0) - \Delta M$$
$$C_1(\tau) < C_1(0)$$

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

Outflow volume at outflow time

University of Reading

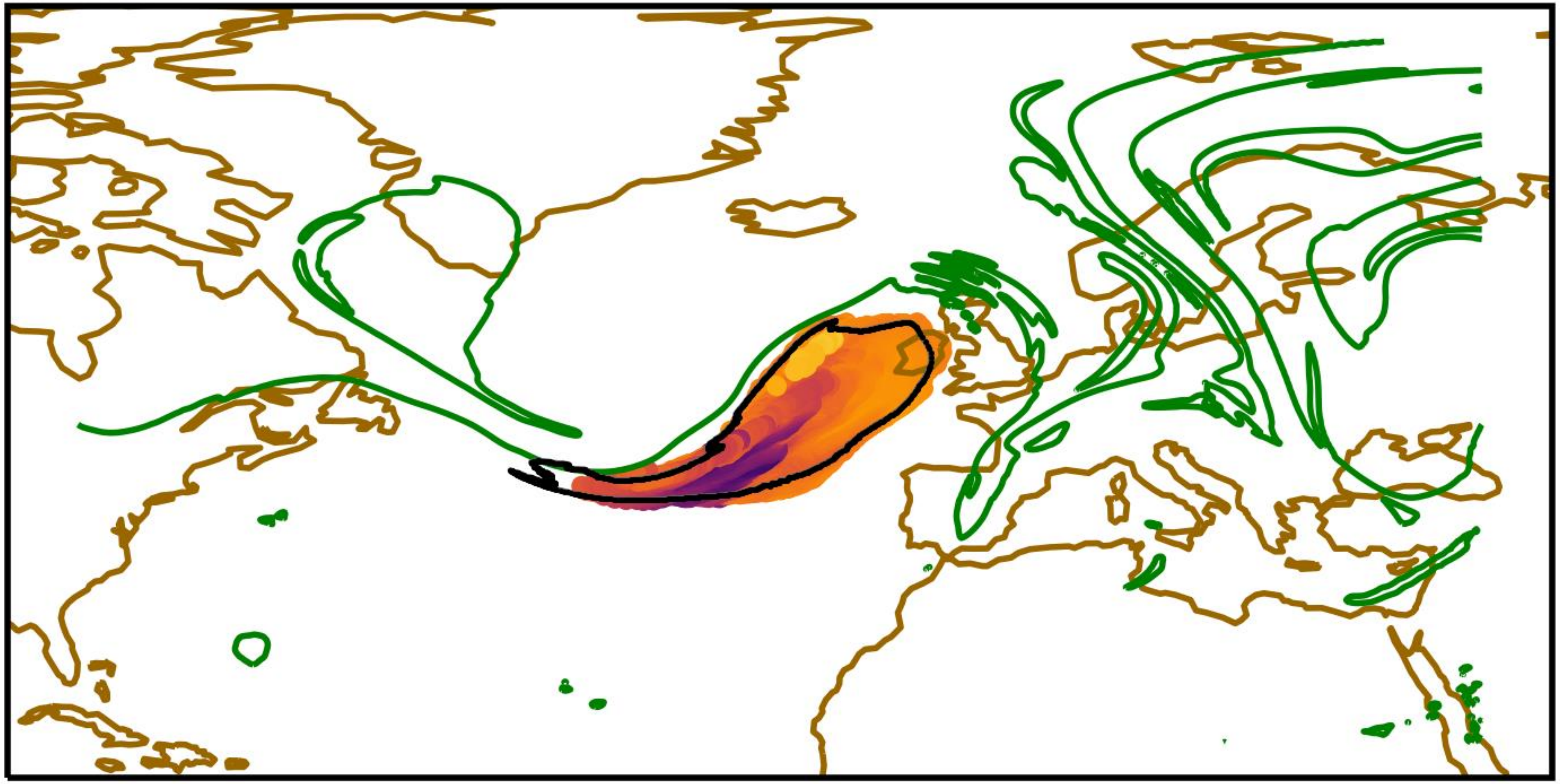


Black contour = lateral boundary of "outflow volume" on 325K surface

Yellow = release locations of 3D back trajectories from outflow volume

Green contour = tropopause on 325K

Following backwards (T-18)

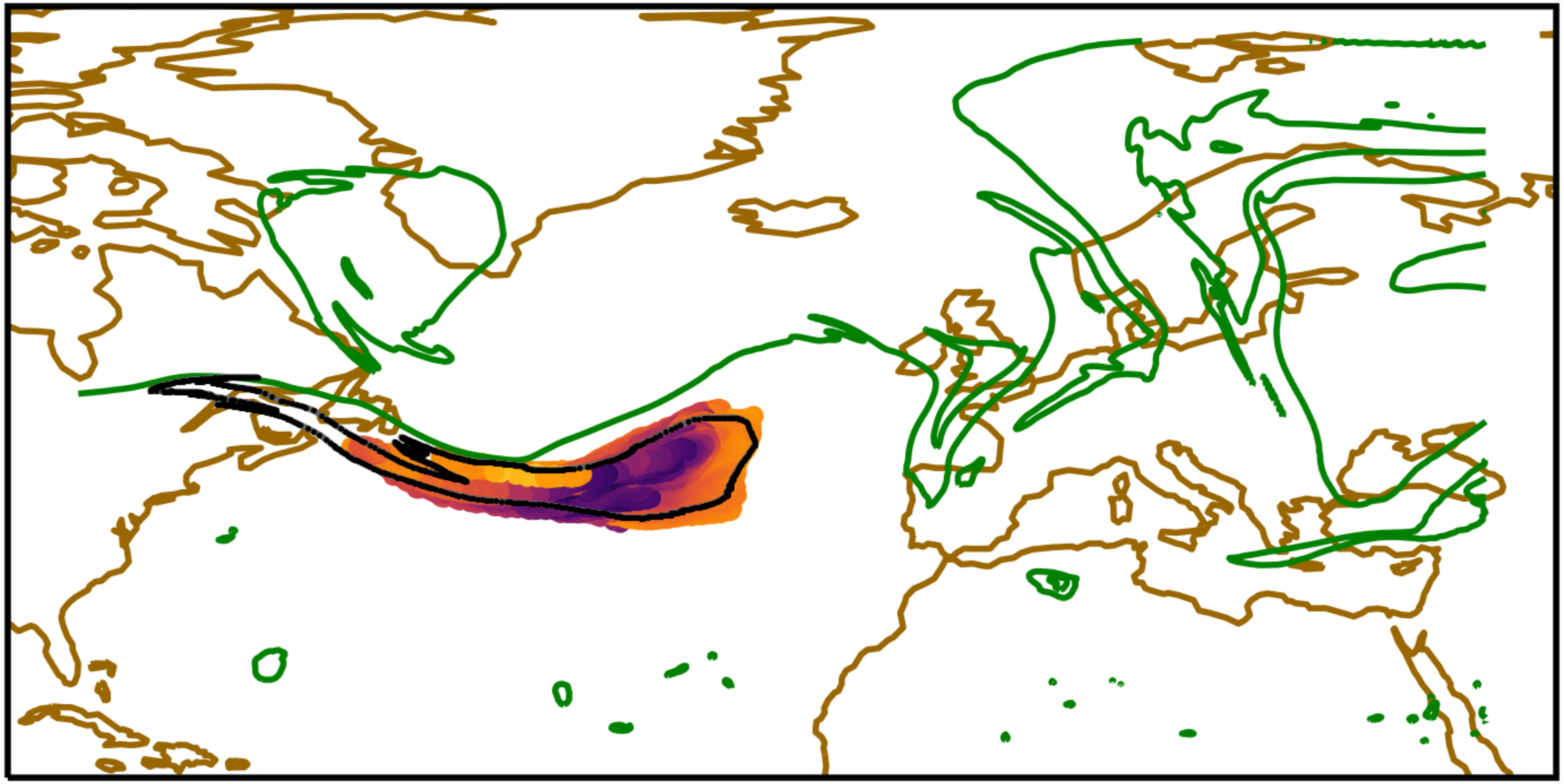


Contour = lateral boundary of “outflow volume” on 325K surface

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

Green contour = tropopause on 325K

Following backwards (T-30)

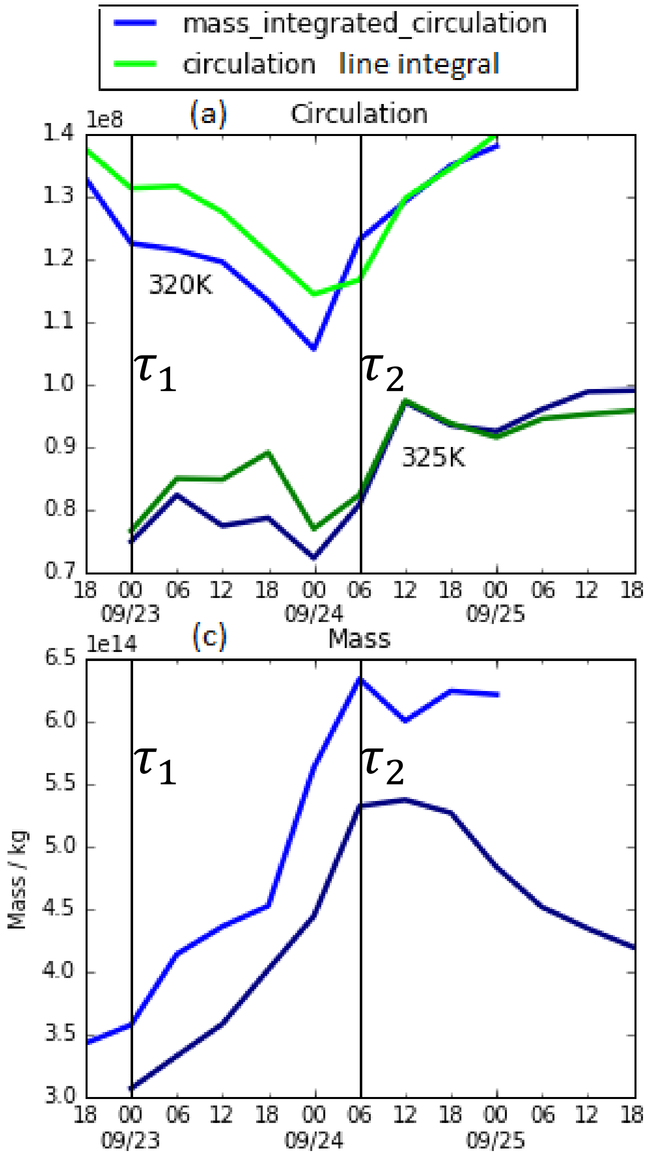


Contour = lateral boundary of “outflow volume” on 325K surface

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

Green contour = tropopause on 325K

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.

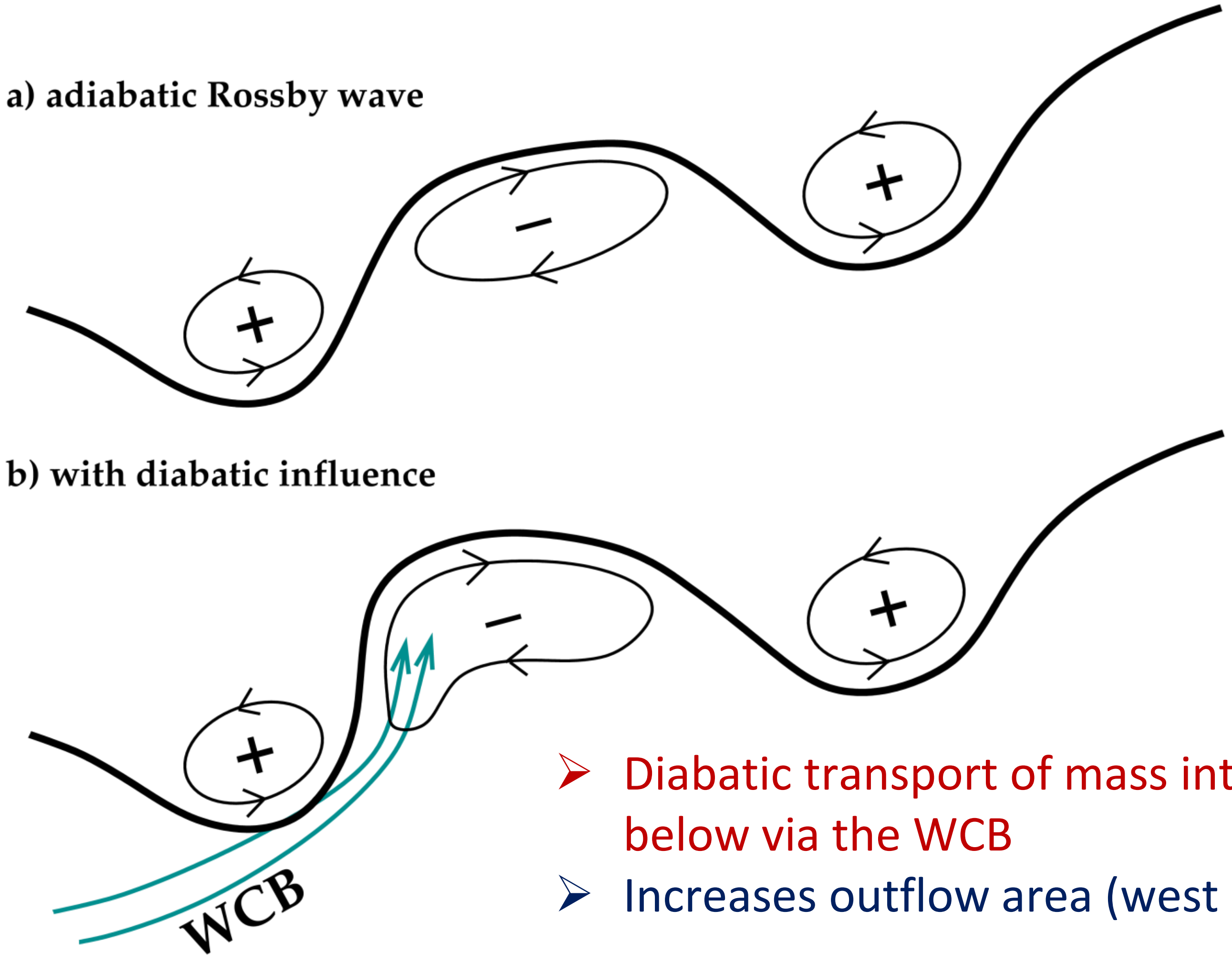
Then, why is outflow size important to block formation?

$$C = \int_{\partial S} \underline{u}.d\underline{l} = \iint_{S} (\nabla \times \underline{u}).d\underline{S} = < f + \xi > S$$

As area increases, anticyclonic relative flow (ξ < 0) is stronger around the boundary.

Saffin *et al.* (*QJRMS, 2021*)

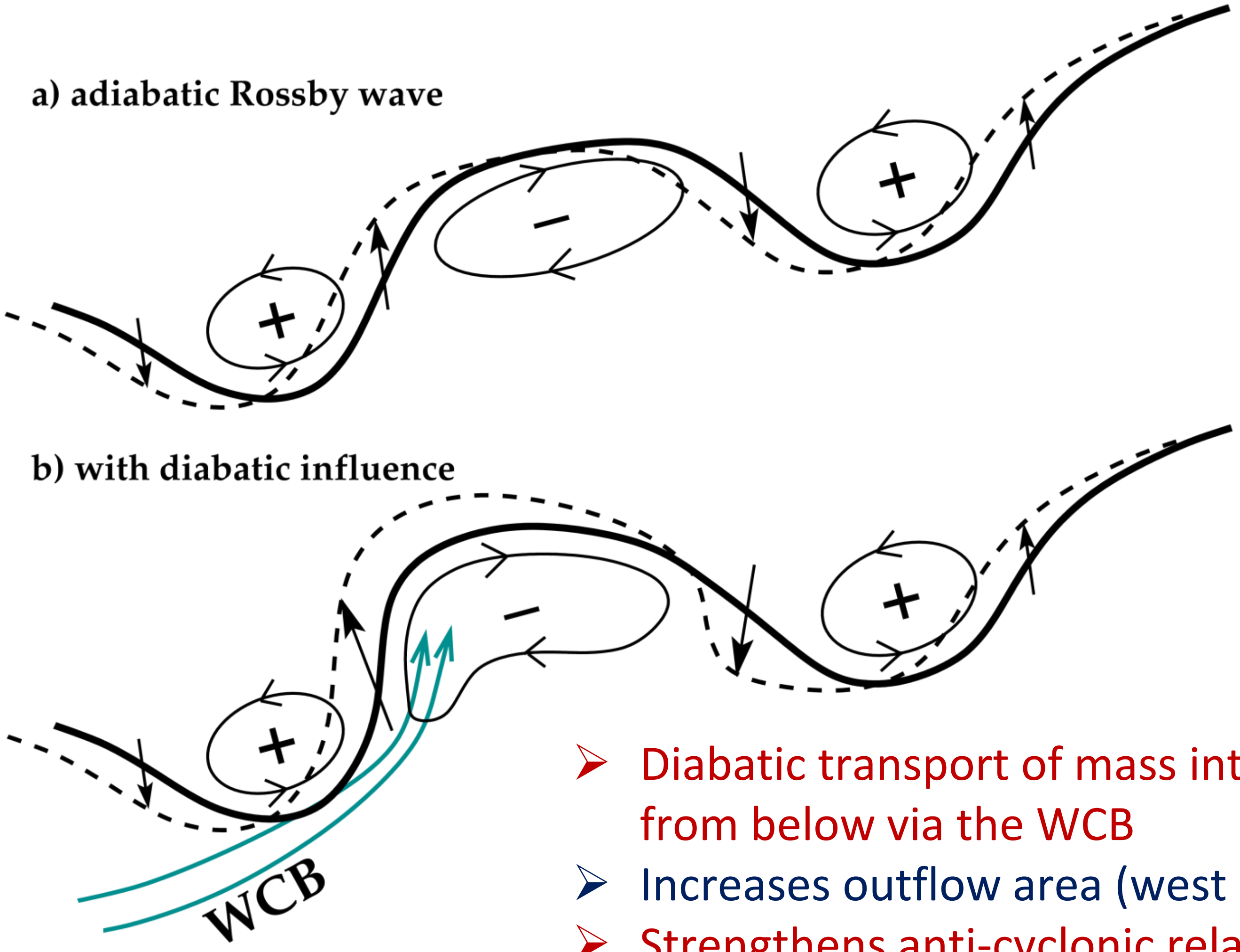
Diabatic influence on the waveguide



- Diabatic transport of mass into isentropic layer from below via the WCB
- Increases outflow area (west and north flanks)

As described in case study of “forecast bust” by Grams, Magnusson & Madonna (2018), *QJRMetS*

Diabatic influence on the waveguide

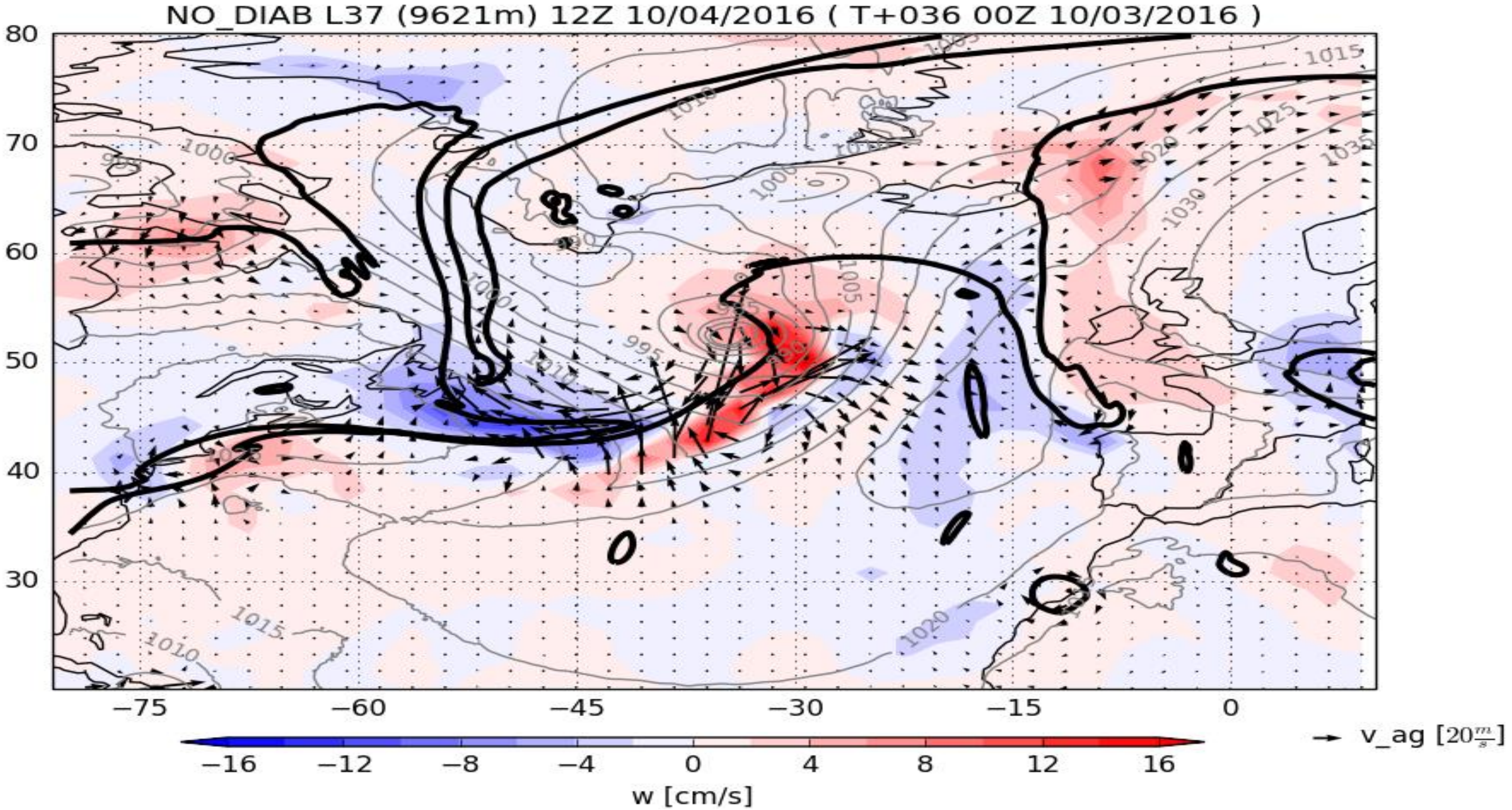


- Diabatic transport of mass into isentropic layer from below via the WCB
- Increases outflow area (west and north flanks)
- Strengthens anti-cyclonic relative flow
- Distorts Rossby wave by advection

Amplification of ageostrophic flow by heating

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

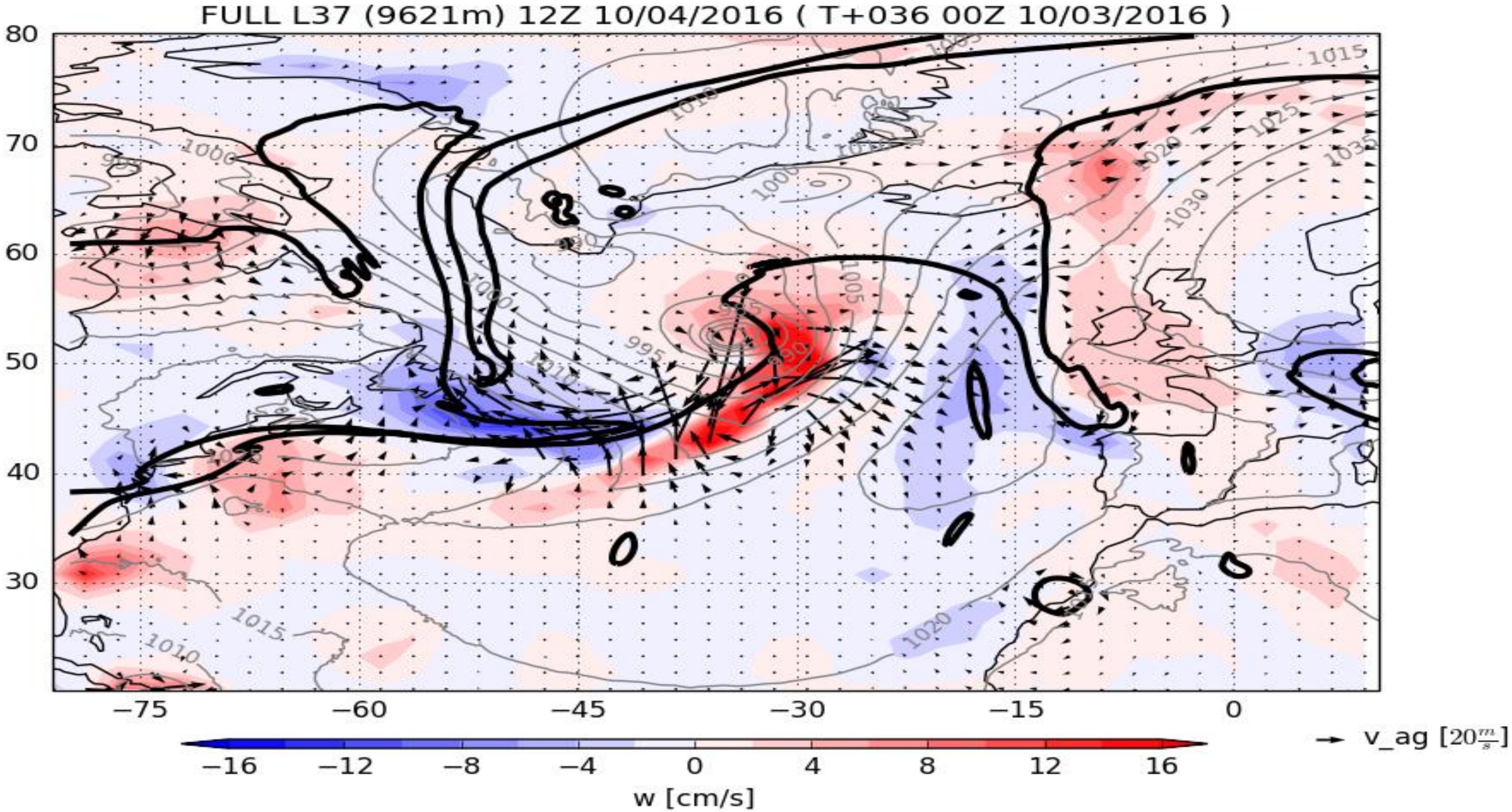
***Without* forcing from heating**



Amplification of ageostrophic flow by heating

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

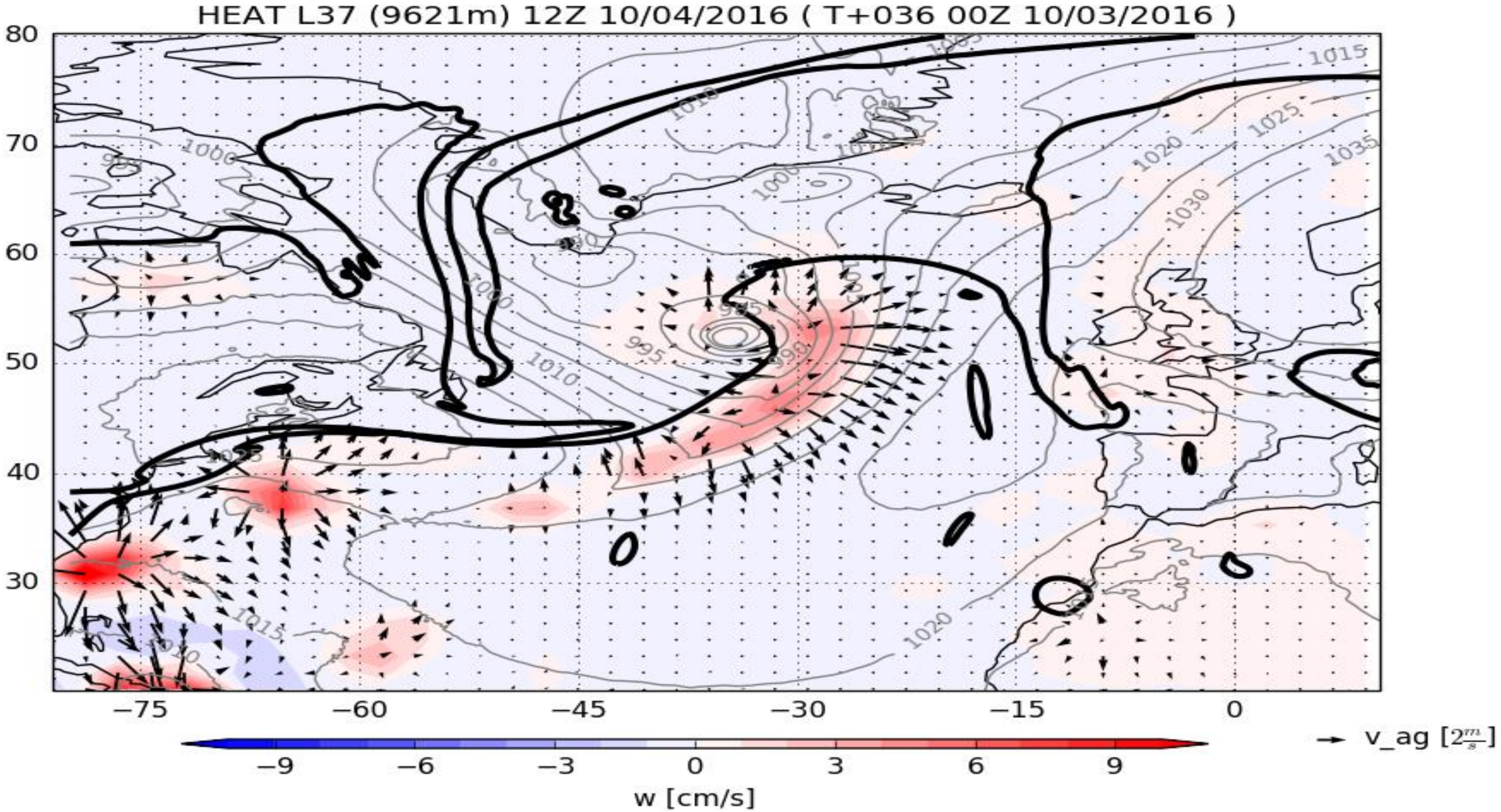
With forcing from full parametrized heating from MetUM



Amplification of ageostrophic flow by heating

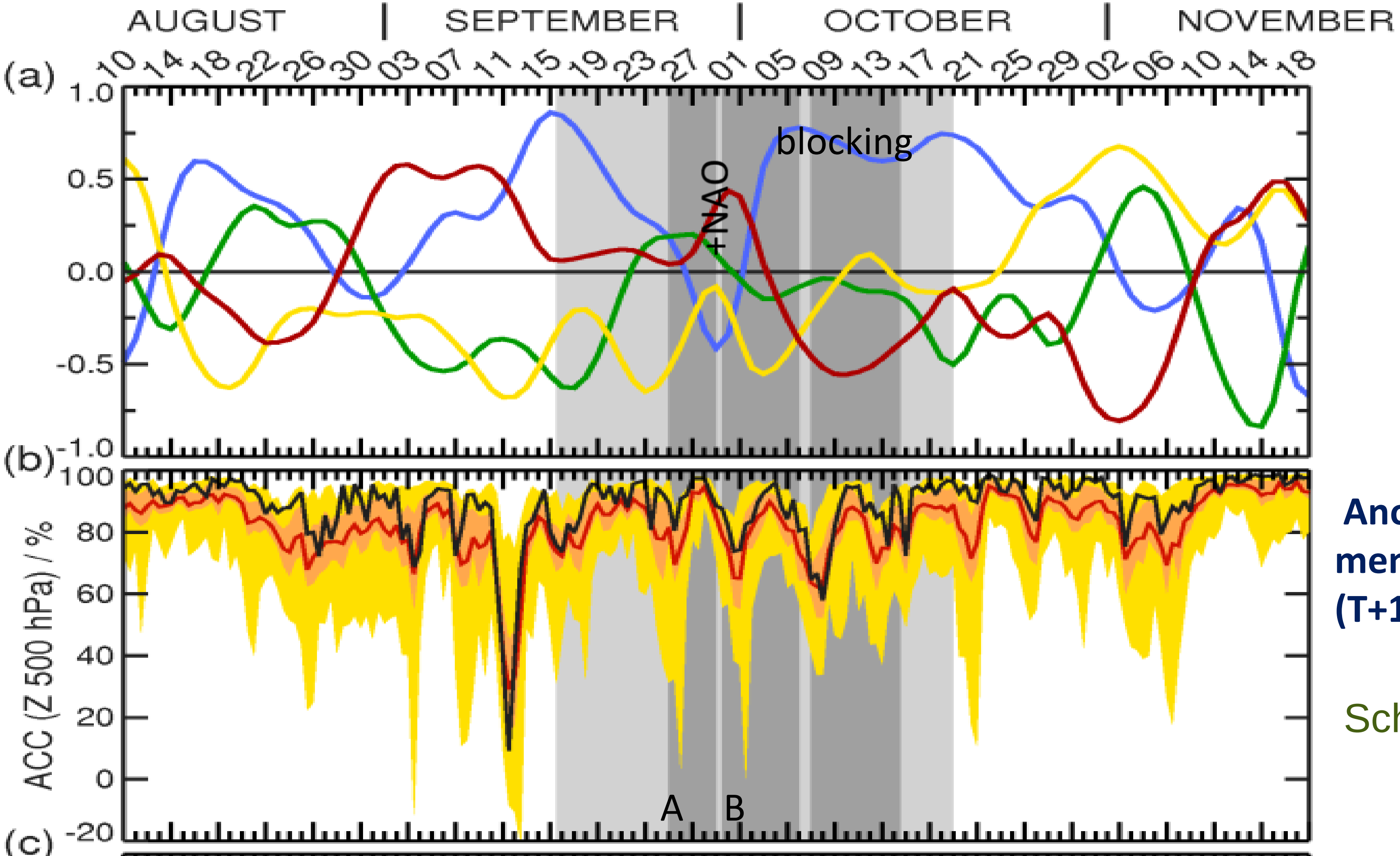
Balanced ageostropic flow and w from S-G “omega” equation.

Only forcing from heating **(no geostrophic forcing)**



Lowest predictability associated with large-scale regime transitions?

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

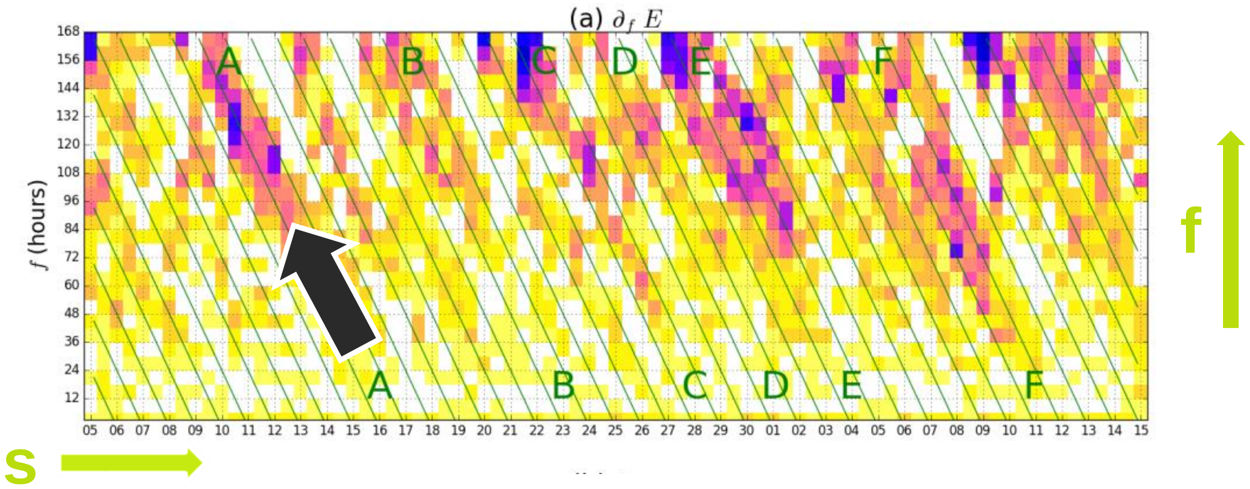


Anomaly correlations between members of forecast ensemble (T+120) and verifying analyses

Schäfler *et al.* (*BAMS, 2018*)

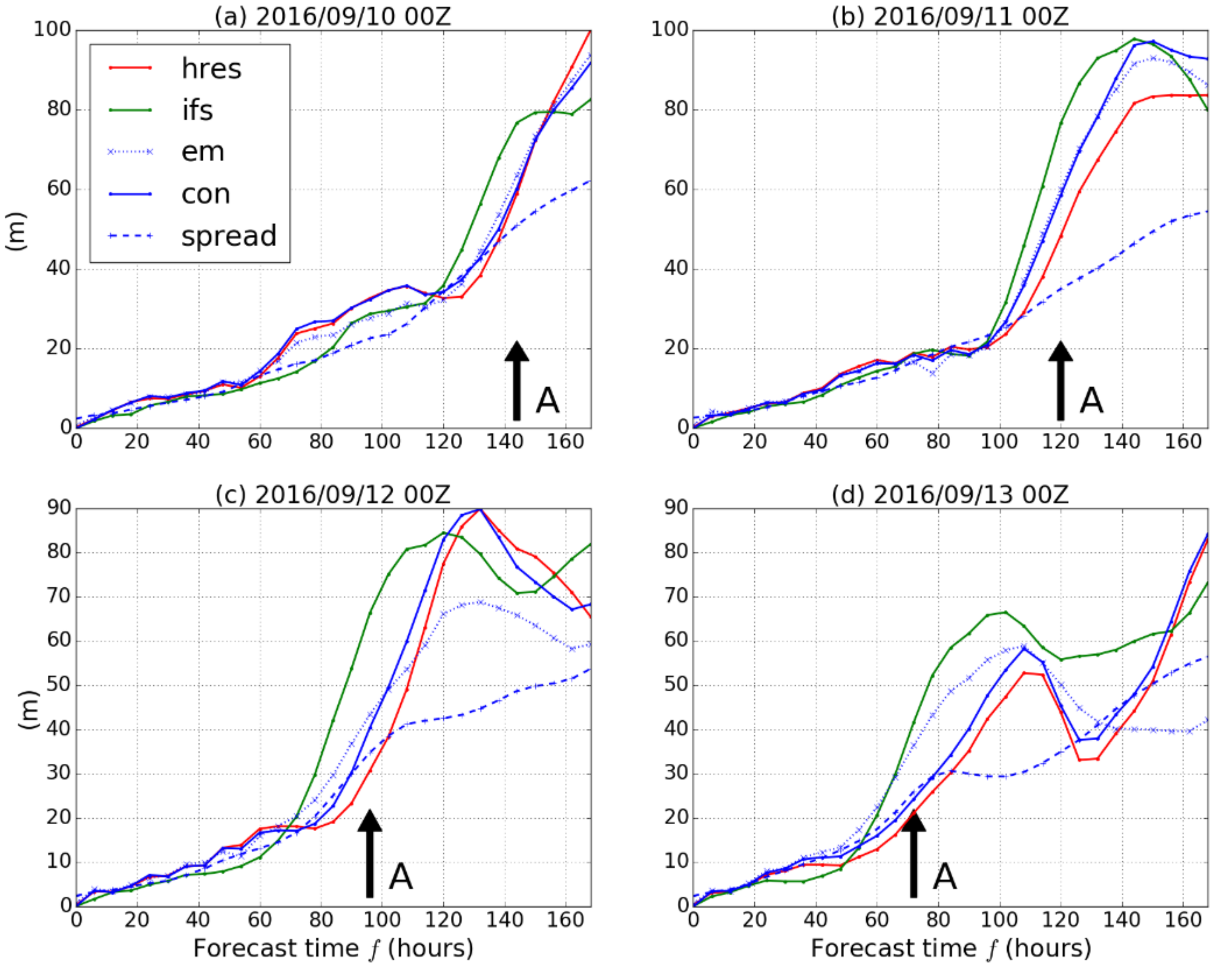
Met Office

Predictability barriers (1)



Rate of change of RMSE in Z500 (∂E / ∂f) with **forecast lead time, *f*,** for all **forecast start dates, *s*,** *over* NAWDEX Period (15/9 to 15/10). **Validation time *t*** is constant along diagonals.

These are events where error grows rapidly (UM & IFS), occurring at the same ***t***



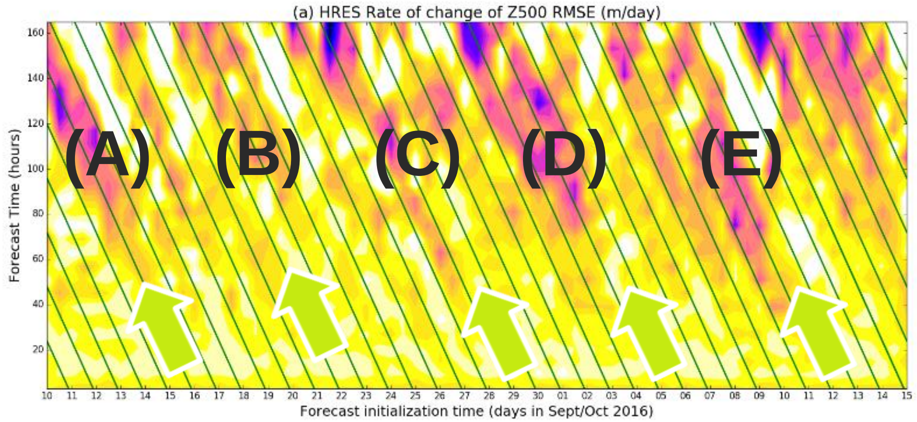
Rate of increase in MOGREPS ensemble spread (Z500) is not as marked

Semi-geostrophic diagnostics link heating to PBs

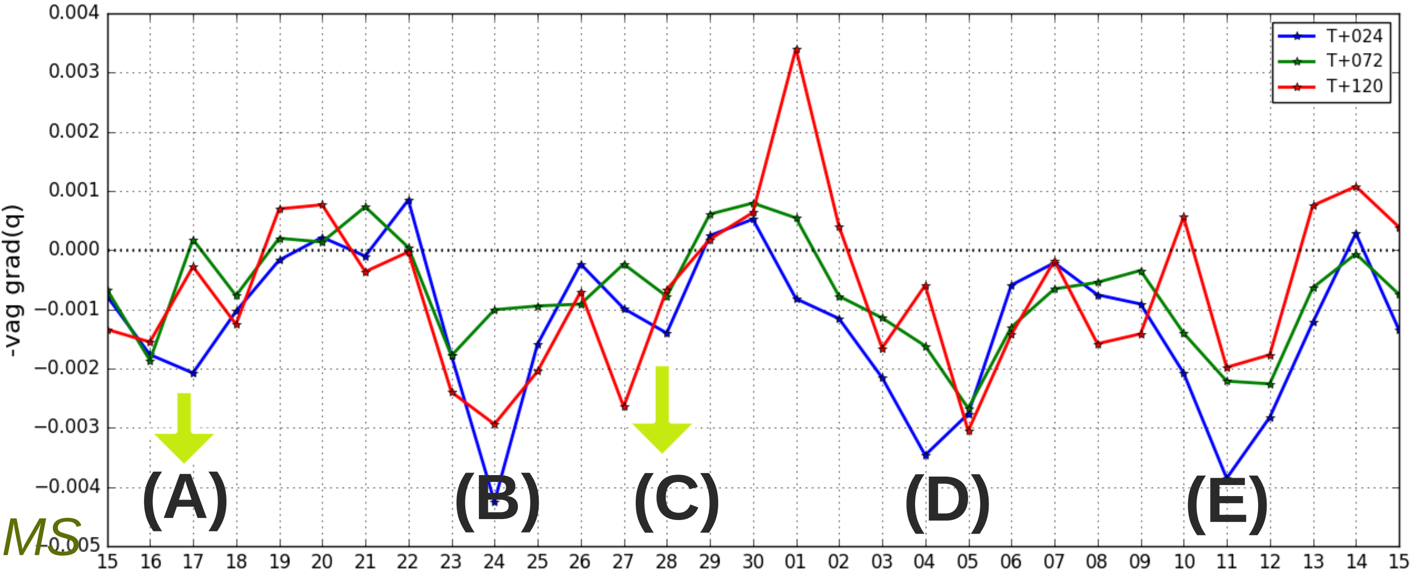
SG diagnostics within MetUM
(Cullen, *Fluids,* 2018).

Calculate advection of PV by the ageostrophic wind attributable to diabatic heating

$$-v_{ag}(diab) \cdot \nabla q$$



Diagnostic shows areas where there is advection of the tropopause gradient.
Negative for ridge-building

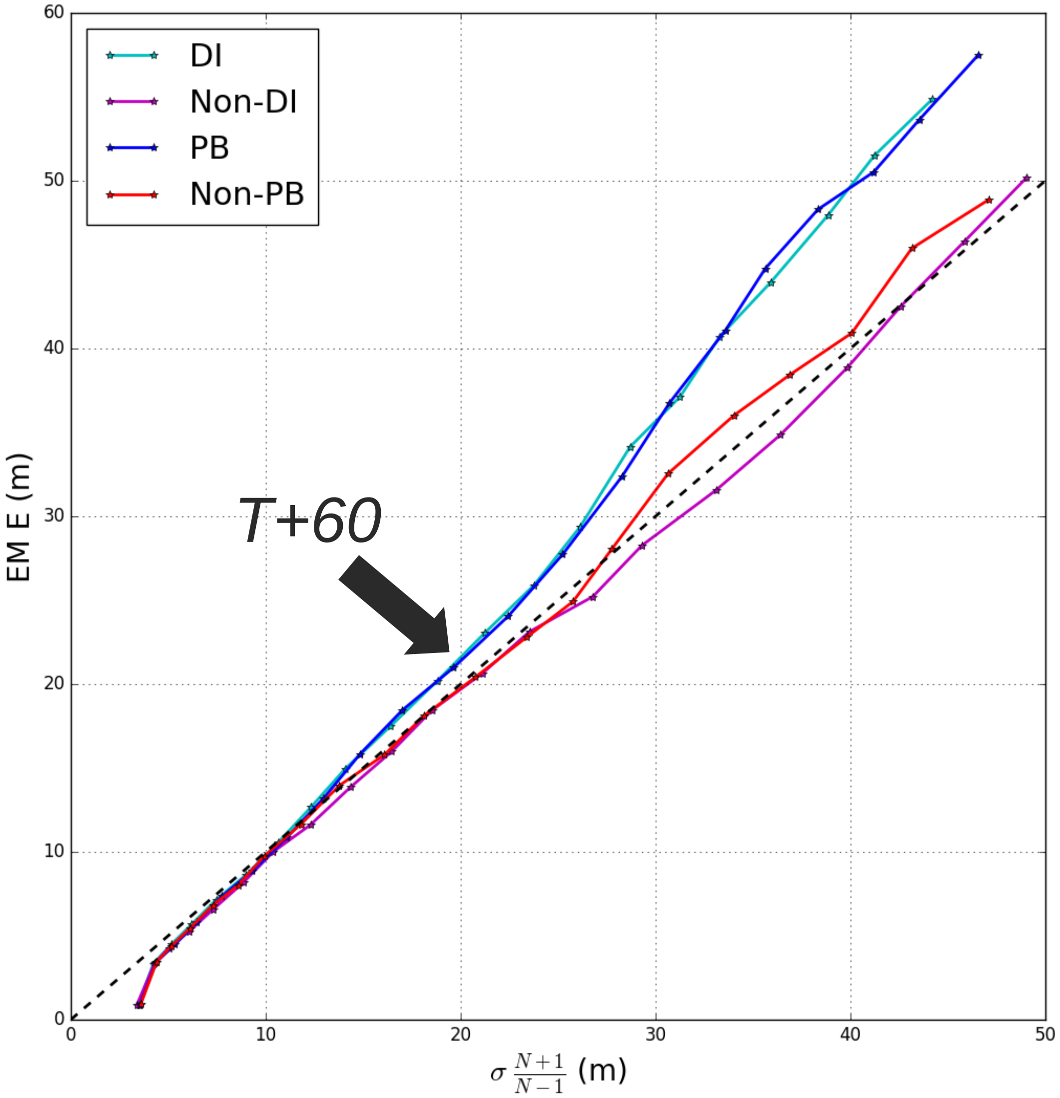


Sanchez, Methven, Cullen & Gray (2020), *QJRMS*

[Top]: v_ag (diab) grad(q) averaged over the predictability barrier domain (60-0E, 30-70N). *Dims: PVU/hr*

Heating and predictability barriers (PBs)

- Ensemble forecasts on days NOT associated with PBs are well calibrated.
- But, for PB events error grows faster than spread
- Same results obtained by compositing days with strong diabatic influence (DI) on tropopause advection
- **Conclude** – predictability is lower when diabatic processes influence tropopause
- *Model error - diabatic influence is too weak in medium-range forecasts*

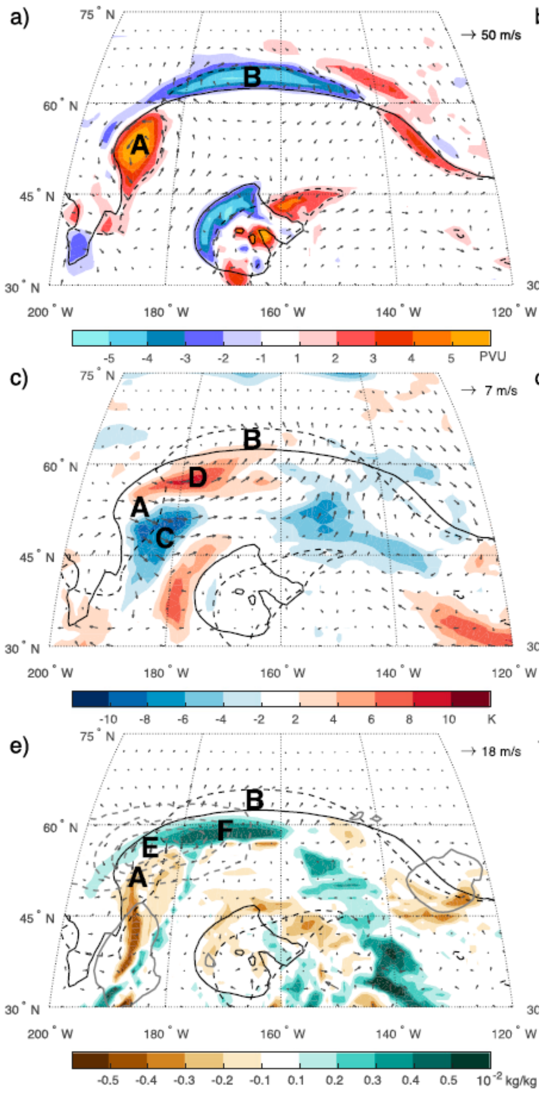


RMSE (*E*) vs spread (*σ*) on event-days and the complement. Event defined as upper threshold in PB or DI timeseries.

Sanchez, Methven, Cullen & Gray (2020), *QJRMS*

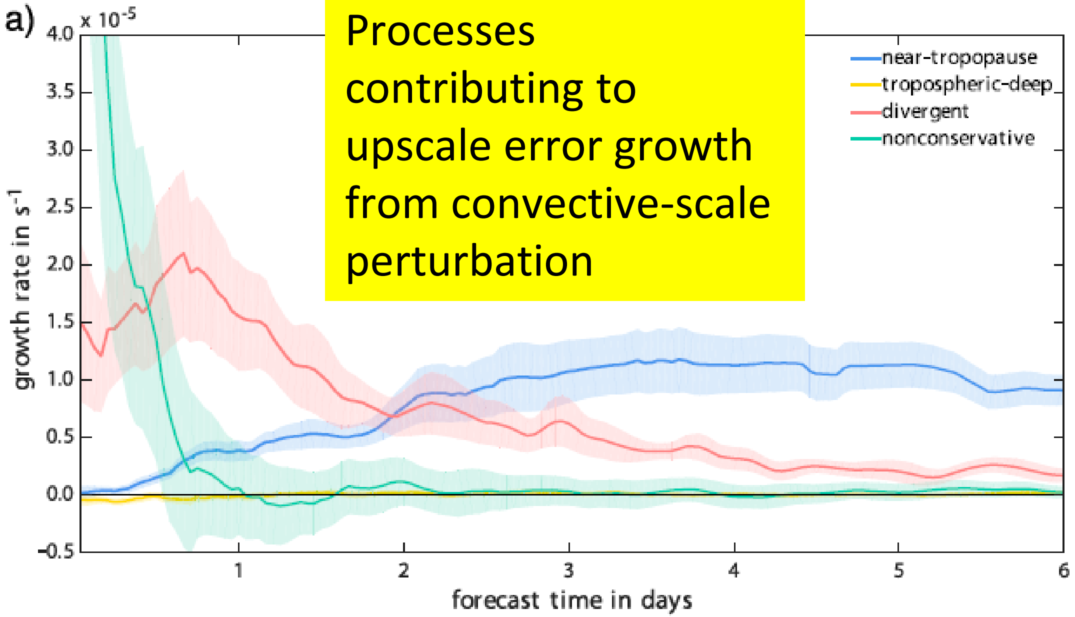
Processes dominating forecast error growth

Baumgart, Riemer *et al, MWR* (2018, 2019)



Example of forecast error over Pacific at **T+ 4.5 day**

- A, B = Potential vorticity (PV) errors associated with tropopause
- C, D = Errors in temperature @875 hPa
- E = Error in surface pressure of cyclone
- F = Error in humidity of WCB @700 hPa (associated with cyclone)



Processes contributing to upscale error growth from convective-scale perturbation

Conclusions

1. **Persistent high impact weather often connected with Rossby waves on jet stream**
   - e.g., precipitation extremes with quasi-stationary Rossby waves
   - transitions between large-scale weather regimes

2. **Effects of heating in WCBs and outflow near the tropopause in ridges**

   ⇒ Vertical motion, divergent outflow and baroclinic growth are amplified

   ⇒ Expansion of outflow volume (and ridge) by advection of tropopause

   ⇒ **Greater anticyclonic circulation in ridge affects large-scale evolution**

3. **Predictability barriers (T+5 day) all associated with diabatic influence on ascent within cyclone, tropopause advection by outflow and its consequences**

   ⇒ Impact of extra obs is mainly from wind. Error growth on convective scale is short-lived – need to affect baroclinic waves (ground to tropopause coupling)

   ⇒ When diabatic influence at tropopause level is large, ensemble spread grows faster, *but not as fast as large-scale error growth*. **Why? Model error?**

Conservation for 3D isentropic layers

Consider control volume enclosed above and below by isentropic surfaces and laterally *by a PV contour (q=Q)*.

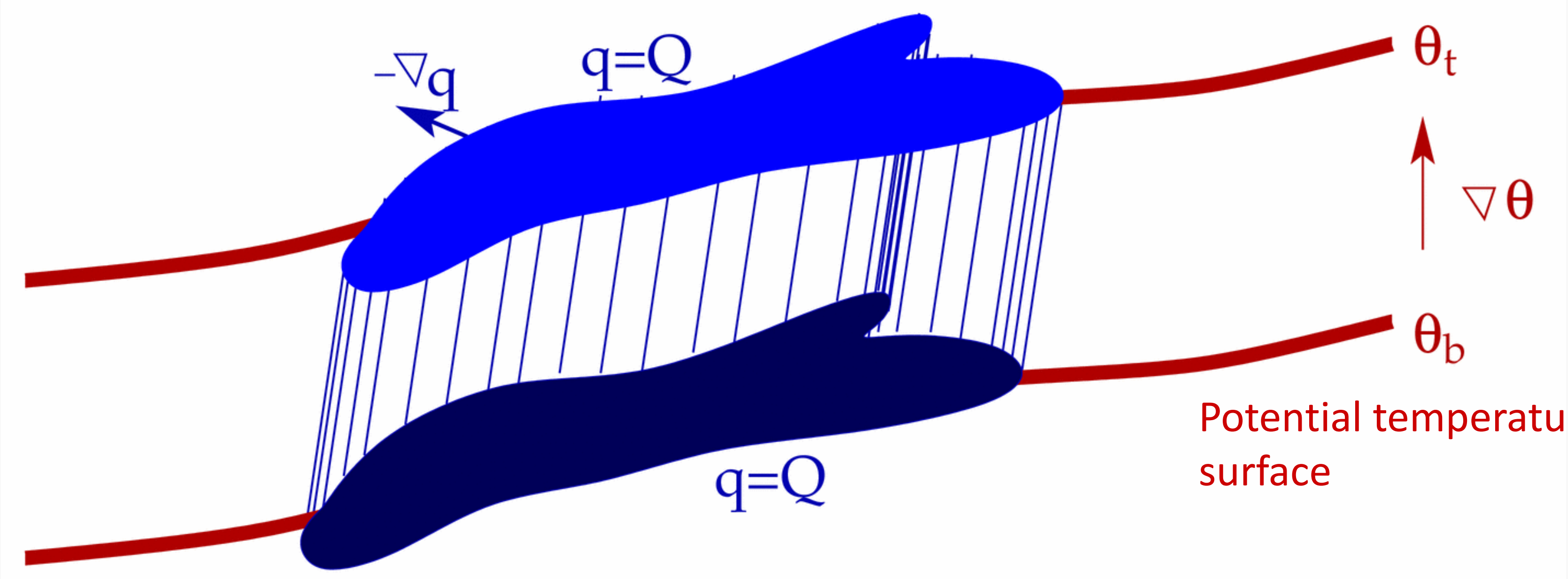
If flow is adiabatic and frictionless, the mass and circulation of the volume must be conserved.

(e.g., Bühler and Haynes, 1999

Thuburn and Lagneau, 1999)

$$\mathrm{M} = \iiint\limits_{q \geq Q} \sigma dS d\theta$$

$$C = \iiint\limits_{q \geq Q} \zeta_\theta dS d\theta = \iiint\limits_{q \geq Q} \overset{\text{density}}{\sigma}\,\overset{\text{PV}}{q} dS d\theta$$



Potential temperature surface

Integral PV conservation (circulation)

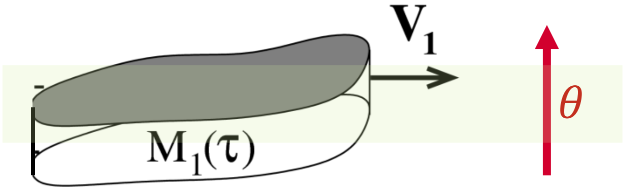
Integrate **PV equation** over control volume (lateral boundary velocity $\mathbf{V}_b$)

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

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

Conservation of circulation, *C*
(if $V_b=V$ & J-integral = 0)

Integrate **mass continuity** over control volume



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

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

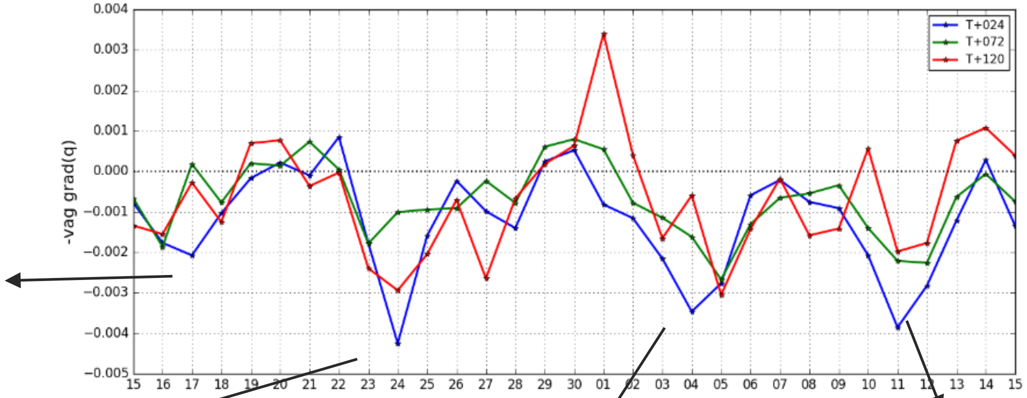
$$\frac{dM}{dt} \quad = \quad -D_{top}+D_{bot}$$

Diabatic mass flux convergence "dilutes" average PV

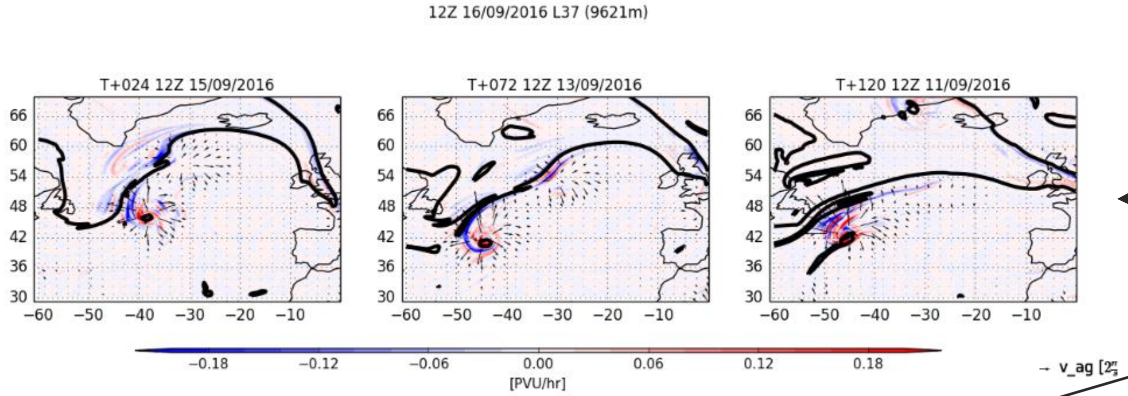
Mass-weighted average PV or *amount of PV substance* divided by mass (Haynes & McIntyre, 1990)

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

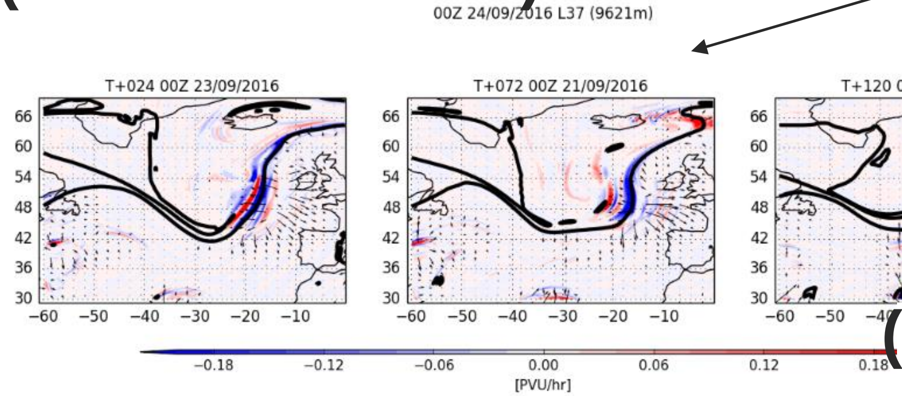
Events associated with lower predictability



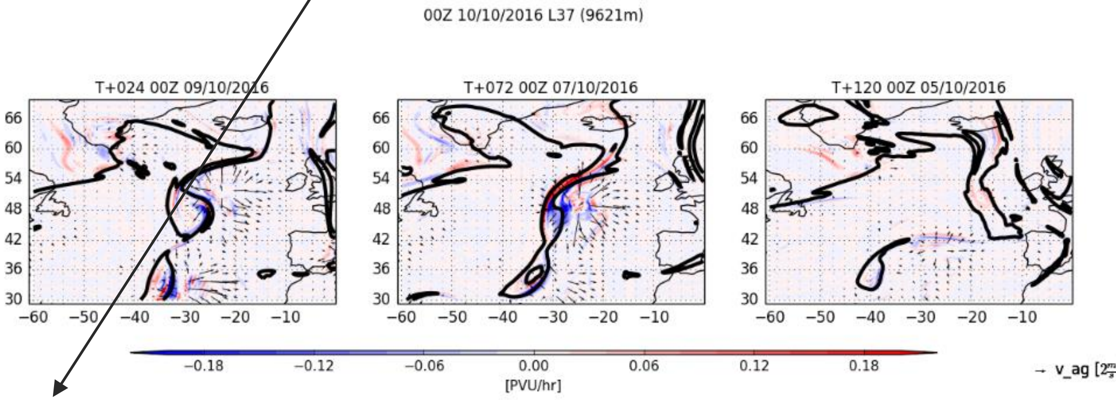
(Ian: 16 12Z)



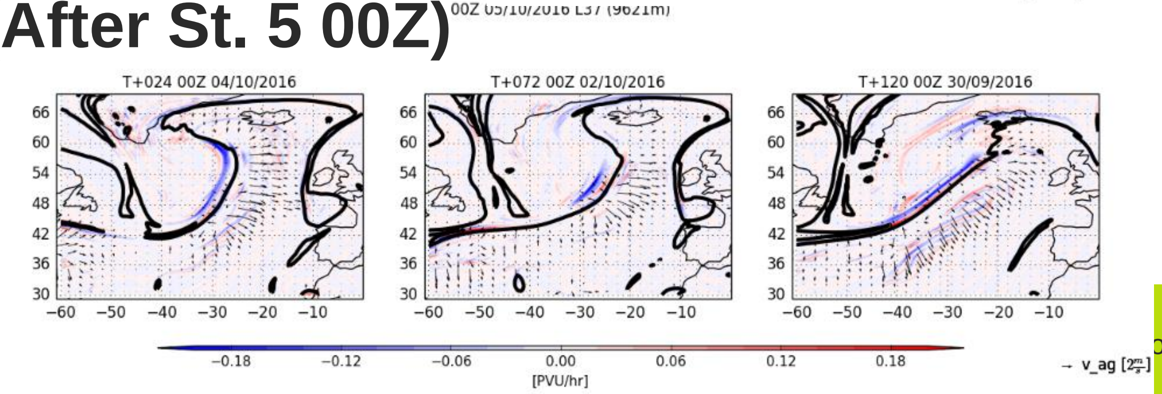
(Vladiana: 24 00Z)



(Sanchez. 10 00Z)



(After St. 5 00Z)

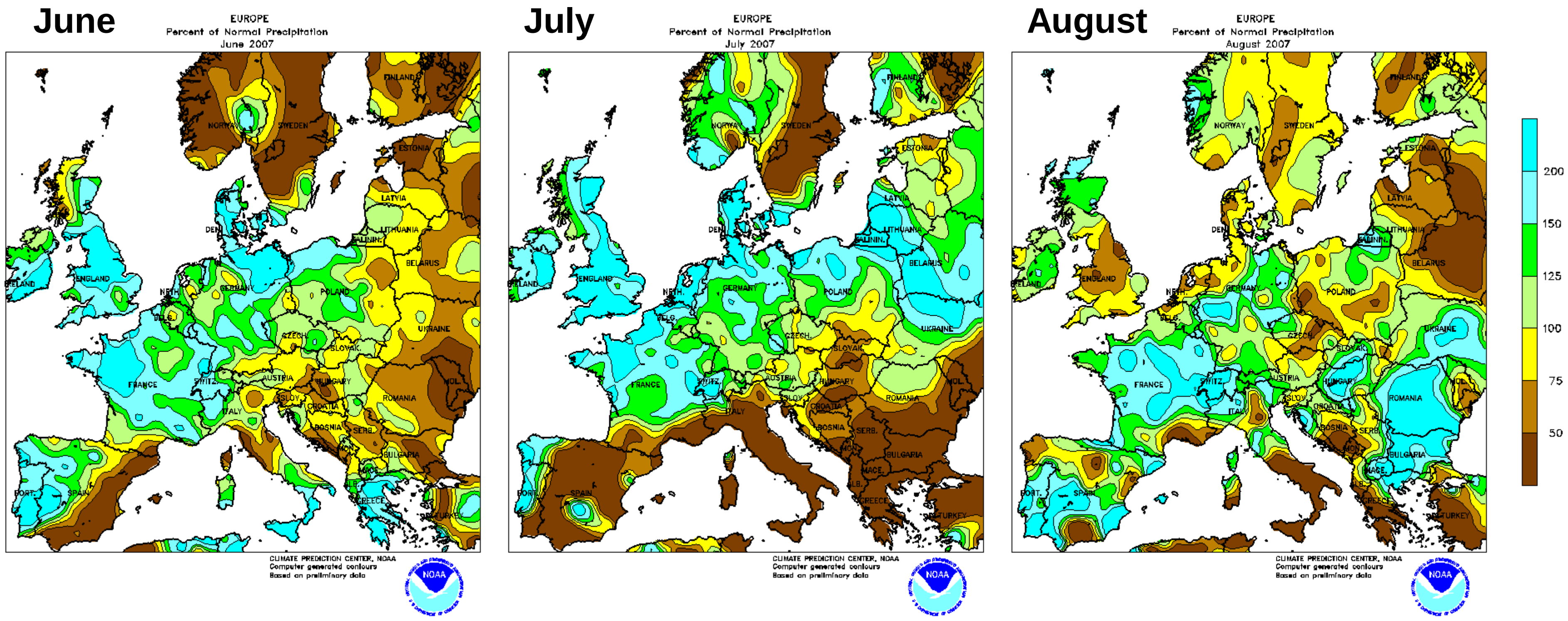


Summer 2007

European precipitation anomalies (% of 1961-1990 average)

Floods in NW Europe, wildfires in SE Europe

Both linked to stationary wave pattern on the jet stream



Blackburn, Methven and Roberts (2008), *Weather*