Diabatic Generation of Negative PV and its Impact on the Jet Stream

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Want to learn more? See Harvey et al (2020, QJRMS)

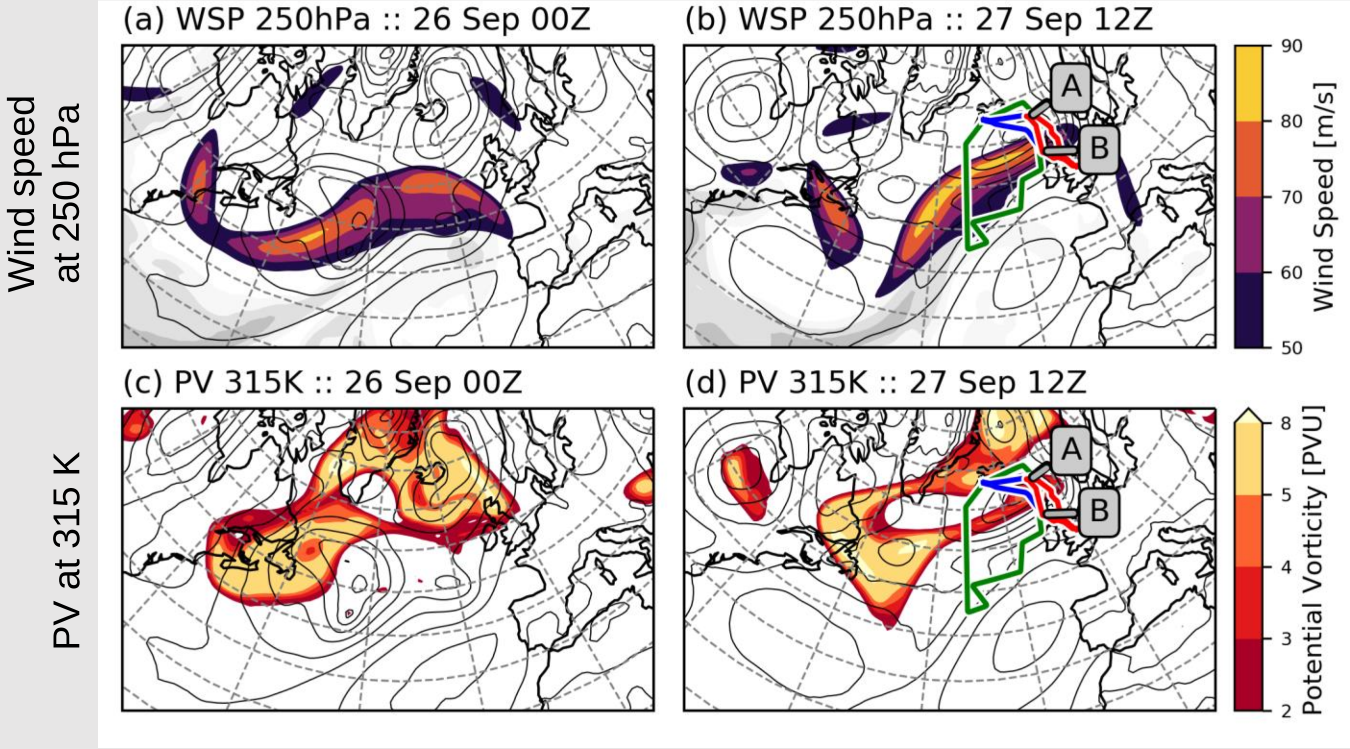
Introduction

- Localised regions of **negative potential vorticity** (PV) are frequently seen on the equatorward flank of the **upper-tropospheric jet streams** in analysis and forecast products
- Their positioning, on the anticyclonic side of the jet and often close to the jet core, suggest they are associated with an **enhancement of jet stream maximum winds**
- Given that PV is generally positive in the northern hemisphere and is conserved under adiabatic conditions, the presence of negative PV is **indicative of recent diabatic activity**
- However, little is understood on the mechanisms for its **generation and subsequent lifecycle**

Quick Summary

- We first use aircraft measurements from a recent field campaign to provide **direct observational evidence** for the presence of negative PV near the jet stream **– SLIDE 5**
- Theory is then developed to **understand the process** by which PV can turn negative and the **characteristic structure** of the resulting PV anomalies **– SLIDE 8**
- These ideas are illustrated with both a **simple idealised model** and an **operational forecast model** with online PV tracer diagnostics **– SLIDES 12 & 13**

Negative PV: Observations



[data = ERA-Interim]

Case study:
NAWDEX IOP4*

Ex-Tropical Storm Karl
- Progressed poleward on 25 Sep
- Interacted with mid-latitude jet stream on 26 Sep
- Generating a strong jet streak to the North of Scotland on 27 Sep

Multiple research flights on 27 Sep [coloured lines in (b) and (d)] – we focus on dropsondes released along section AB

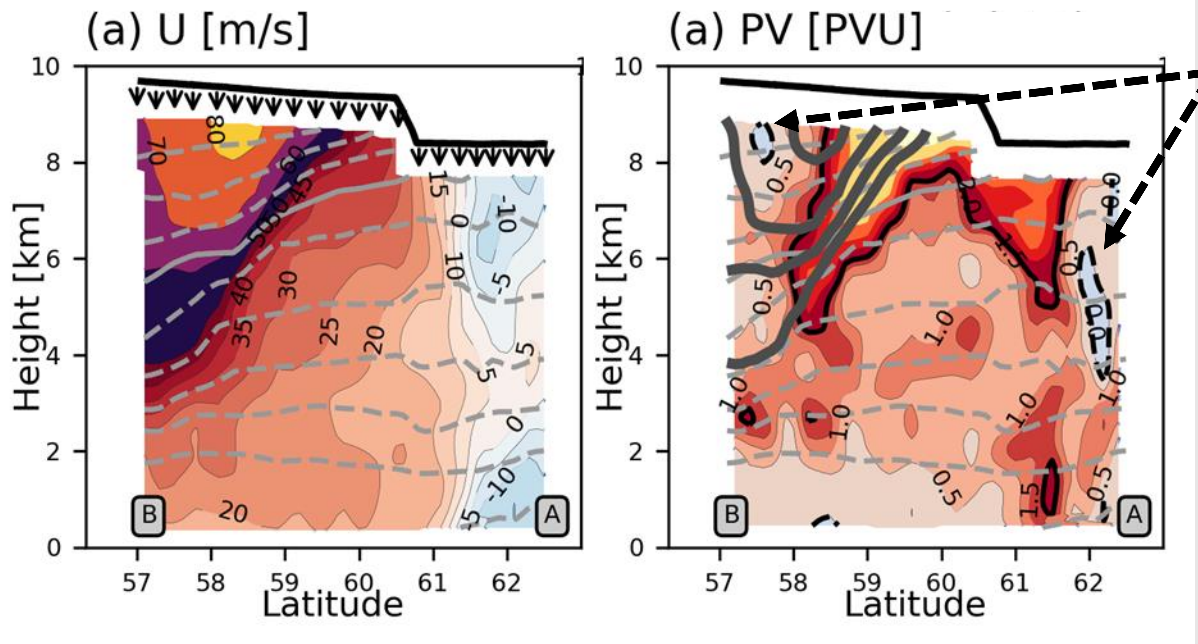
* NAWDEX = North Atlantic Waveguide and Downstream Impacts Expt. (Shäfler 2018, BAMS)

Negative PV: Observations

Dropsonde observations from section AB

22 sondes (average spacing 25 km)

from FAAM flight B981



Negative PV observed at 2 locations

Properties:

- Only weakly negative
- Small scale
- Located next to jet max

Computing PV from a dropsonde curtain:
Assume zonal symmetry, then Ertel PV is given by: $\rho P = \boldsymbol{\zeta} \cdot \nabla\theta = (f - u_y)\theta_z + u_z\theta_y$

Negative PV: Theory

Usual Lagrangian equation for PV (P) in the presence of diabatic heating ($\dot{\theta}$) – following air parcels:

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

INSTEAD, we consider the equivalent equation following isentropic trajectories - the isentropic PV equation:

$$\rho \frac{\tilde{D}P}{Dt} = P\nabla \cdot (\rho \boldsymbol{u}_D) + \nabla \cdot (\boldsymbol{\zeta}_{//}\dot{\theta})$$

See e.g. Haynes & McIntyre (1990)

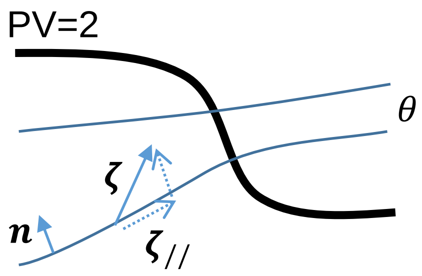
Notation

- Normal to θ surfaces: $\boldsymbol{n}$
- Projection of absolute vorticity onto isentropic surface: $\boldsymbol{\zeta} = (\boldsymbol{\zeta} \cdot \boldsymbol{n})\boldsymbol{n} + \boldsymbol{\zeta}_{//}$
- Diabatic mass flux:

$$\rho \boldsymbol{u}_D = \frac{\rho \dot{\theta}}{|\nabla \theta|}\boldsymbol{n}$$

- Isentropic advection:

$$\frac{\tilde{D}}{Dt} = \frac{\partial}{\partial t} + (\boldsymbol{u} - \boldsymbol{u}_D) \cdot \nabla$$



Negative PV: Theory

At first sight this looks more complex, but the source/sink terms have natural interpretations:

$$\rho \frac{\tilde{D} P}{Dt} = P\nabla \cdot (\rho \boldsymbol{u}_D) + \nabla \cdot (\boldsymbol{\zeta}_{//}\dot{\theta})$$

Dilution/concentration of PV:

$$\approx P \frac{\partial}{\partial z}\left(\frac{\rho\dot{\theta}}{\theta_z}\right)$$

- Proportional to P, so cannot change its sign

Isentropic flux term:

$$\approx \boldsymbol{k} \cdot \nabla_\theta \times (\boldsymbol{v}_z \dot{\theta})$$

- Requires heating in the presence of vertical wind shear
- From thermal wind balance: flux $\boldsymbol{\zeta}_{//}\dot{\theta}$ is ALWAYS directed *down the isentropic slope*

Notation

- Normal to θ surfaces: $\boldsymbol{n}$
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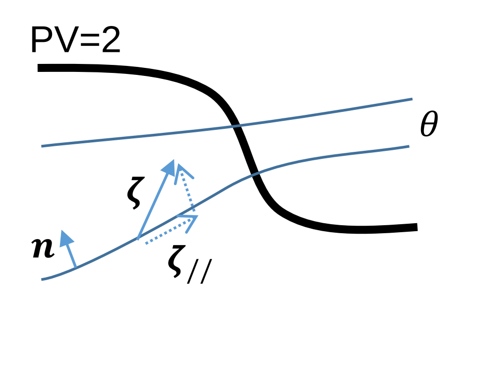
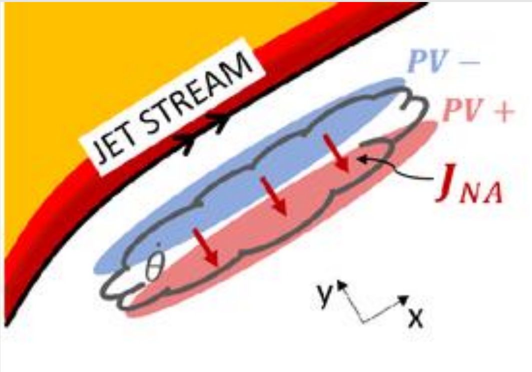
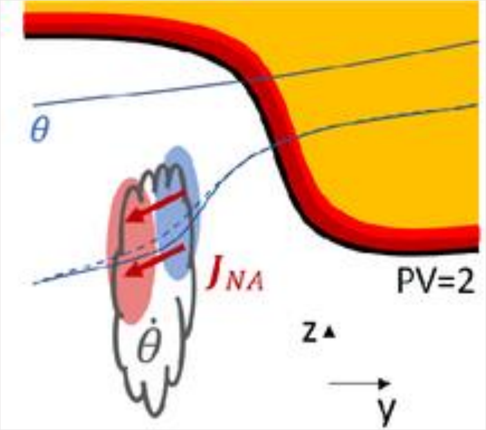


Negative PV: Theory

So what have we learnt?

- If negative PV occurs it must be generated by the **second term** (so requires **diabatic heating in the presence of vertical wind shear**)
- We can use this to **understand its structure**. For heating near the jet stream in a warm conveyor belt situation (see schematics):
    - Negative PV will appear on the **jet stream side** of the heating and **above the heating maximum**, i.e. strengthening and sharpening the jet
    - Any negative PV must accompanied by an equal positive PV anomaly further down the isentropic slope: the area-averaged PV cannot change sign





Negative PV: Idealised Model

Next up:

- Use the simplest relevant dynamical model to illustrate the structure of negative PV generated by heating:

2d semi-geostrophic model with heating:

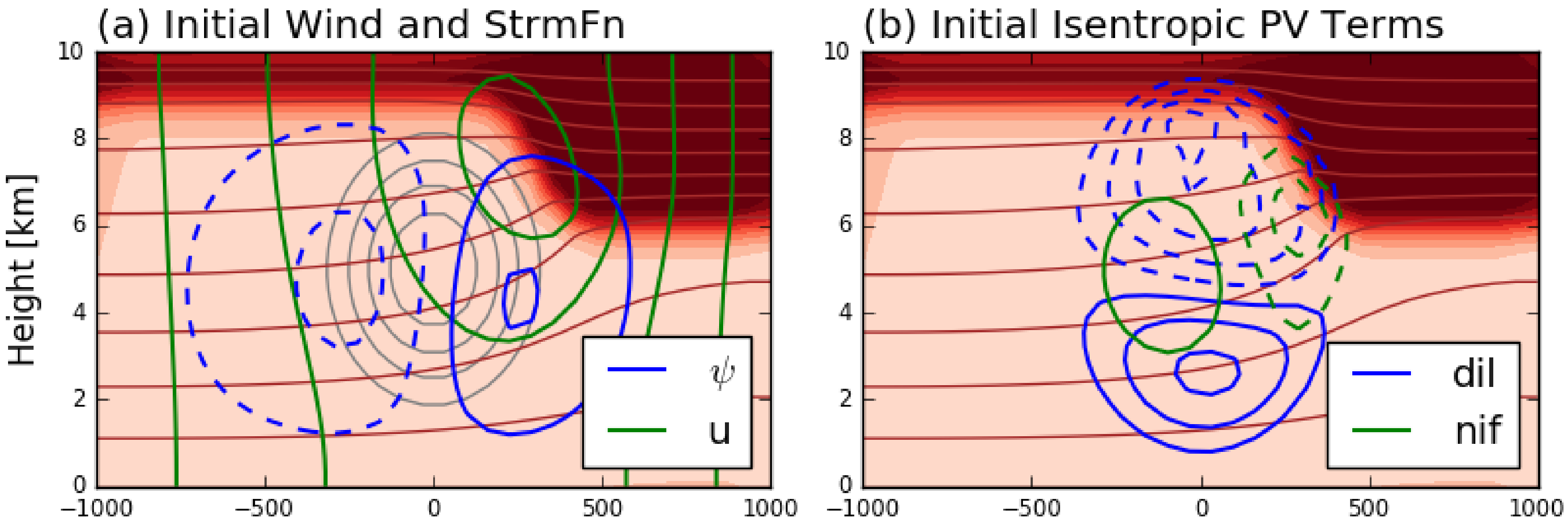
$$\frac{Du}{Dt} - fv = 0 \qquad \frac{D\theta}{Dt} = \dot{\theta}$$

Meridional flow is that which maintains TWB:

$$\psi_{yy}\theta_z + \psi_{yz}(u_z - \theta_y) + \psi_{zz}(f - u_y) = \dot{\theta}_y$$

- Use an initial state with a sloping tropopause and jet stream; add constant in time Gaussian heating region representing a WCB

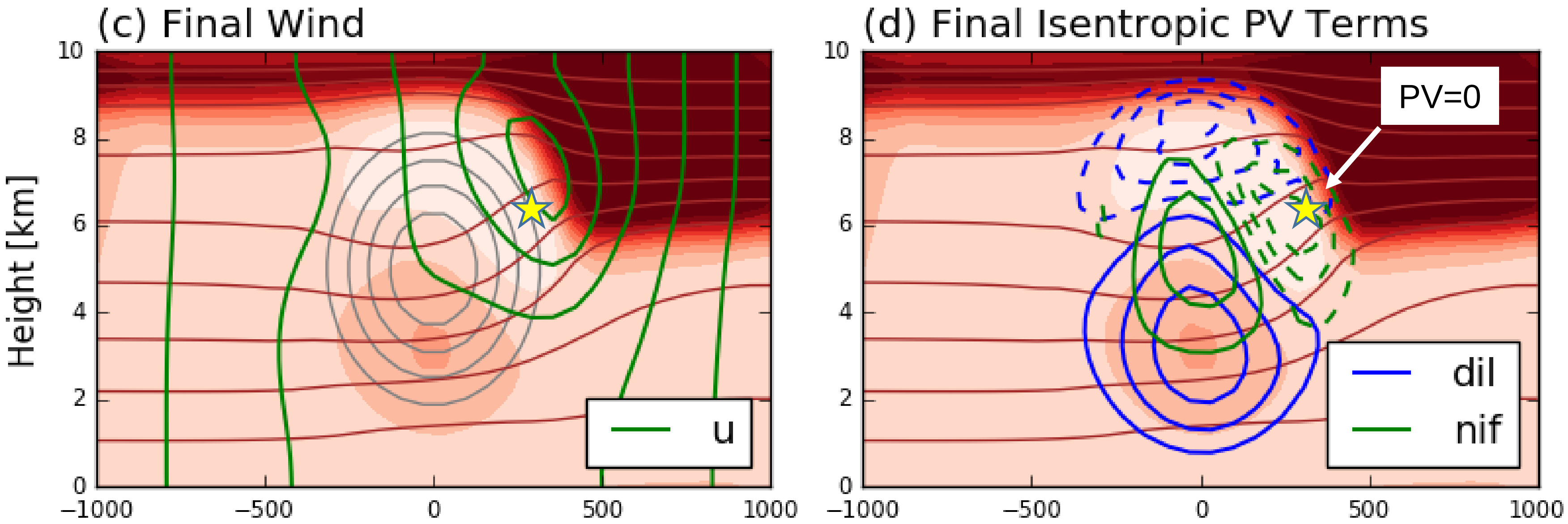
Negative PV: Idealised Model



Initial state: Localised jet stream winds (**green**), heating profile (**grey**) and induced meridional circulation (**blue**). **Shading** shows the PV.

Initial state PV tendency terms: Dilution/concentration (**blue**) and isentropic flux term (**green**)
Note: PV tendency is dominated by dilution/concentration, but the isentropic flux term is also present and transports PV down the isentropic slope [see SLIDE 7]

Negative PV: Idealised Model



Final state: The model runs until PV turns negative (at the star).
The jet has intensified. The PV change is dominated by the dilution/concentration term (-> vertical dipole), but the negative PV first appears on the **jet stream side** of the heating and **above the heating maximum** (very near the maximum of the isentropic flux term).

Negative PV: NWP Model

Finally: how did the forecast look in the case study we observed negative PV?

Use MetUM model with 'PV tracers' diagnostics. These allow the PV field to be split as

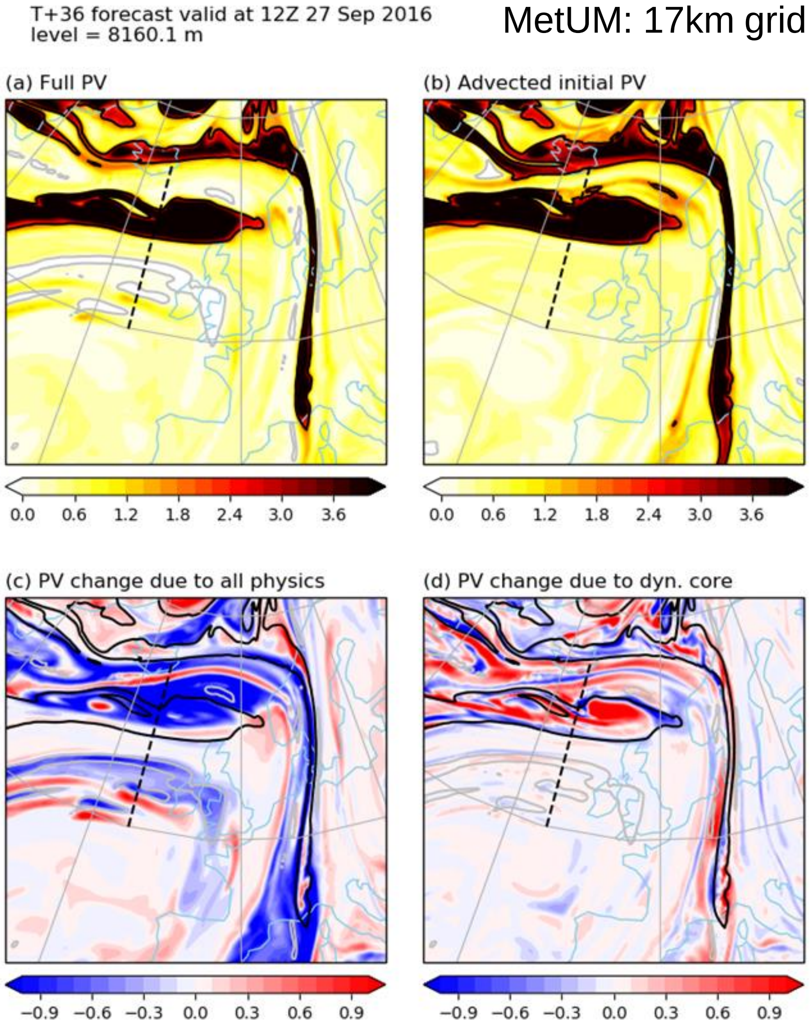
$$P = P_{adv} + \sum_n P_n$$

where P_n represents the accumulated PV during a forecast due to

- each physics parametrization
- an estimate of the non-conservation of PV by the dynamical core

NAWDEX IOP4:
Ex-Tropical Storm Karl

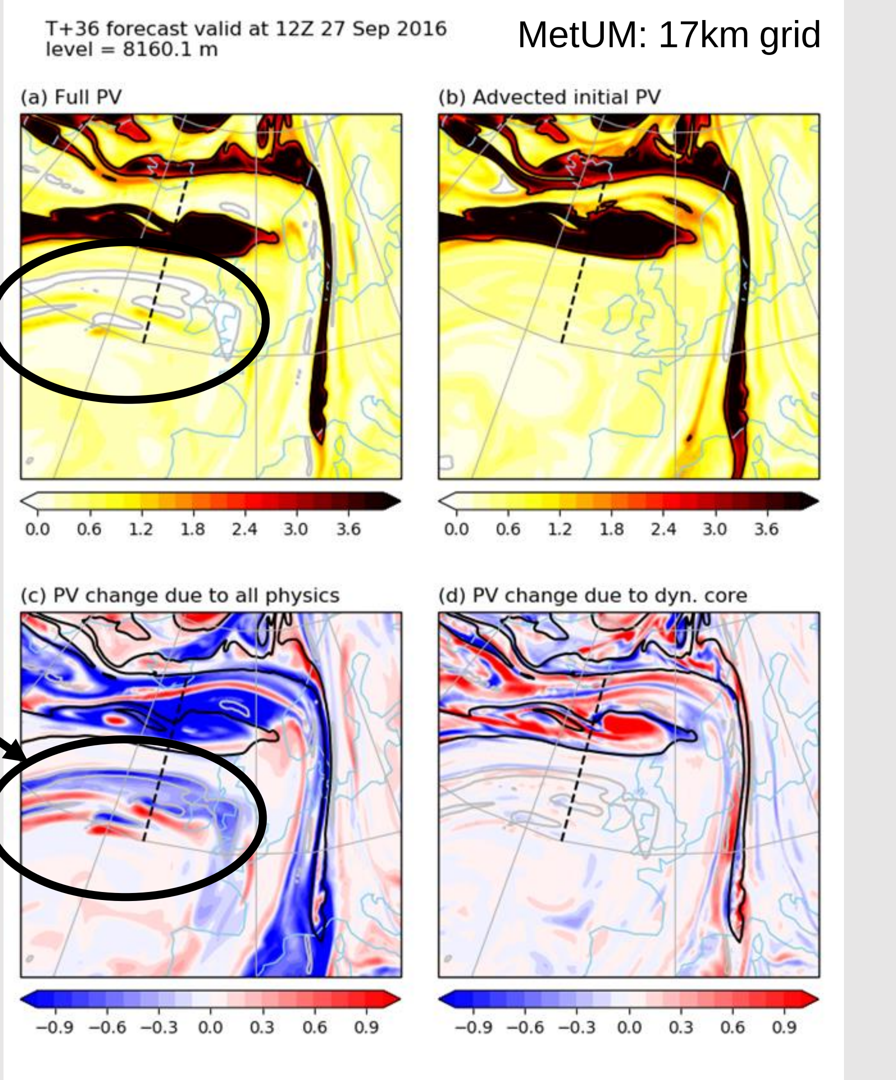
MetUM: 17km grid



Negative PV: NWP Model

Negative PV is present in quasi-horizontal bands in the region in which it was observed [grey contours show PV=0, black contours show PV=2PVU]

PV tracer diagnostics confirm the negative PV is produced by physics parametrisations in the model (here a combination of convection + large-scale rain schemes) (rather than being an artifact of numerical errors)



NAWDEX IOP4:
Ex-Tropical Storm Karl

Questions

- What is the fate of negative PV in the atmosphere?
  - How long does it last? How is it destroyed?
  - Can it be observed?
  - Is aggregation of convective-scale features important?
- Do models produce the negative PV realistically?
  - Does it survive for long enough?
  - Is it destroyed in the correct way?
  - Does it matter?!

Thanks for reading!