Revisiting the isentropic view of PV modification in warm conveyor belts

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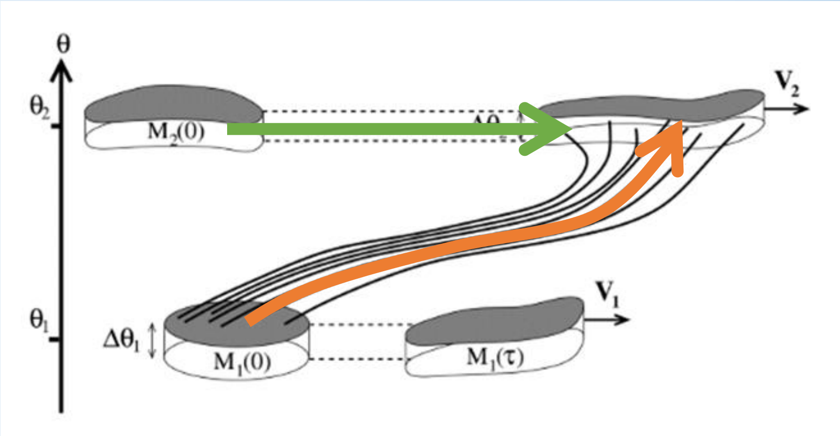
Outline

- There are two (equally-valid?) frameworks for interpreting diabatic PV changes
  - Air parcel trajectories
  - Isentropic trajectories
- Why might isentropic trajectories be useful?
- An illustration: Cyclone Vladiana



Methven (2015)

PV modification along air parcel trajectories

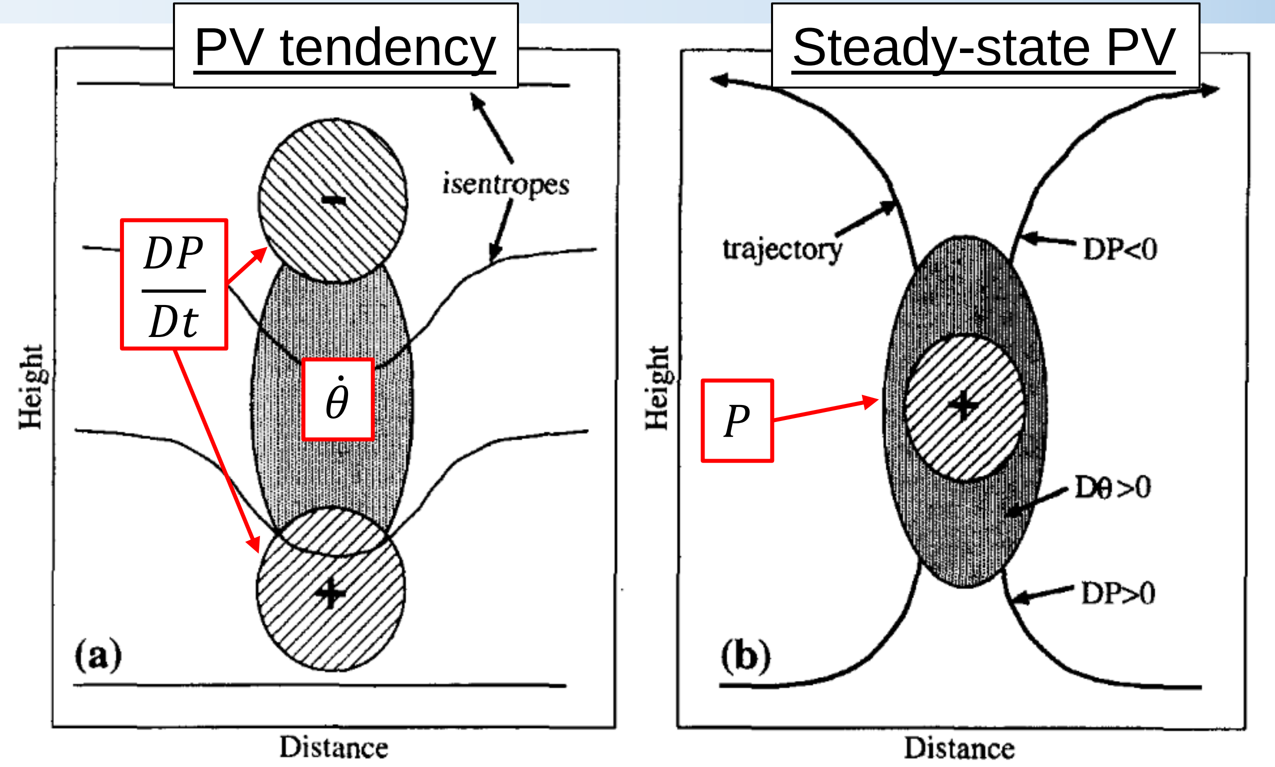
Lagrangian PV equation:

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

PV

Absolute vorticity

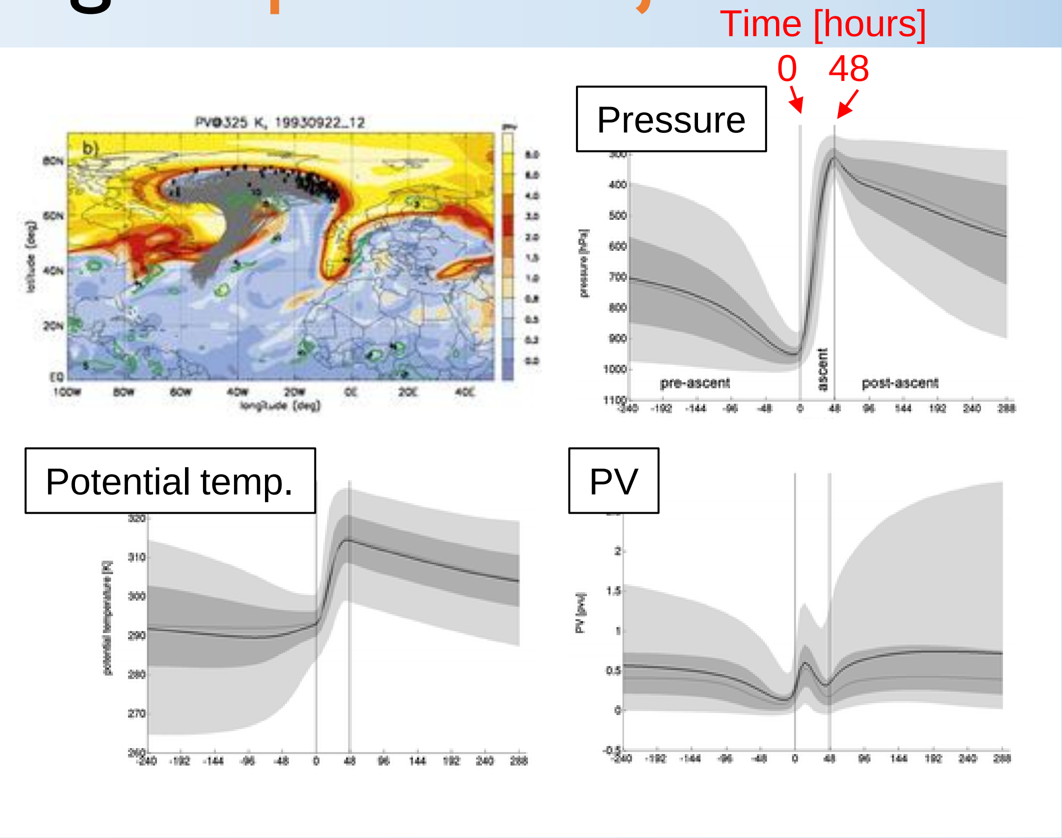
Diabatic heating ($\frac{D\theta}{Dt} = \dot{\theta}$)



Wernli and Davies (*QJRMS*, 1997)

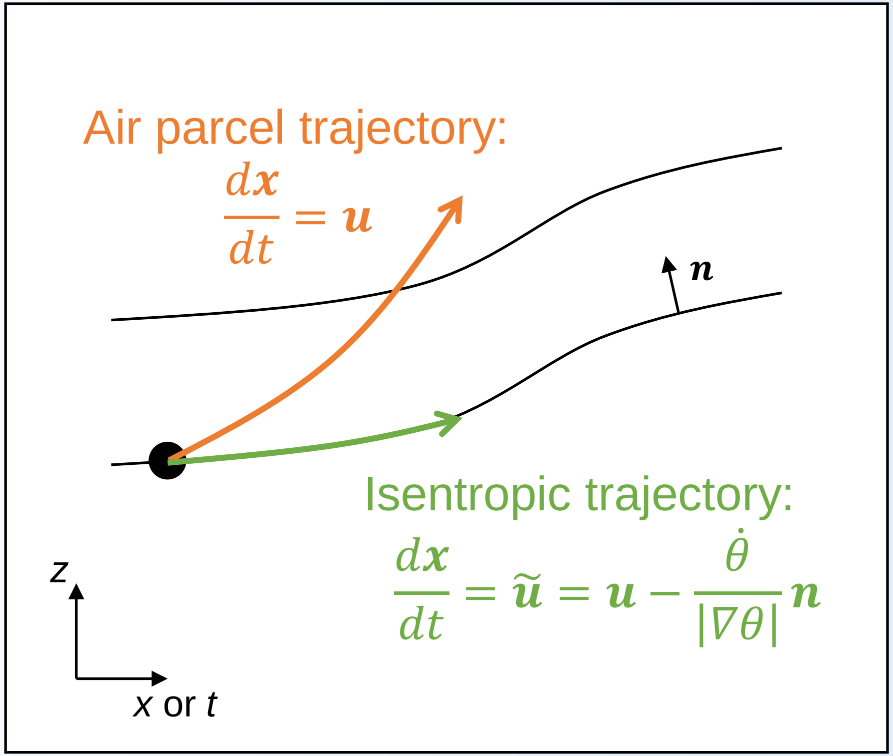
PV modification along air parcel trajectories

- WCB trajectories: ascend by 600 hPa in 48 hours
- Composite evolution from ERA-Interim (North Atlantic, DJF)
- All trajectories warm (mean change = +20K)
- PV evolution is more complex: maximum value occurs mid-ascent



Madonna et al (*JAS*, 2014)

Air parcel vs isentropic trajectories



- Air parcel trajectories follow the (resolved) wind
- Isentropic trajectories follow the flow along isentropic surfaces
- These are identical unless there is diabatic heating
- Note: isentropic framework fails if statically unstable

PV modification along isentropic trajectories

Key Idea: Instead of thinking of PV as being **attached to fluid parcels**, think of it as being **attached to isentropic surfaces**:

$$\frac{\widetilde{D}}{Dt} = \partial_t + \widetilde{\boldsymbol{u}} \cdot \nabla \quad \text{with} \quad \widetilde{\boldsymbol{u}} = \boldsymbol{u} - \frac{\dot{\theta}}{|\nabla\theta|}\boldsymbol{n}$$

The PV equation becomes:

$$\rho \frac{\widetilde{D}P}{Dt} = P \frac{\partial}{\partial z}\left(\frac{\rho\dot{\theta}}{\theta_z}\right) - \theta_z \boldsymbol{k} \cdot \nabla_\theta \times \left(\boldsymbol{V}_z \frac{\dot{\theta}}{\theta_z}\right)$$

E.g. Haynes and McIntyre (1987)

Can we learn anything from isentropic trajectories that we don't already know from air parcel trajectories?

Suggest 3 **potential benefits** of using isentropic trajectories:

1. More natural **physical interpretation**
   → retain circulation / mass ideas from adiabatic dynamics
2. More **monotonic evolution** of PV following trajectories
   → a cleaner attribution of physical processes?
3. Less variation of **trajectory positions** with resolution
   → a fairer comparison across models?
   → a simpler evaluation of convection schemes?

PV modification along isentropic trajectories

PV represents the mass-weighted circulation on an isentropic surface:

$$\langle P \rangle = \frac{\mathcal{C}\ \delta\theta}{\mathcal{M}}$$

→An exact, bulk formula

If adiabatic:

- Mass is conserved because we're following a material volume
- Circulation is conserved due to Kelvin's circulation theorem

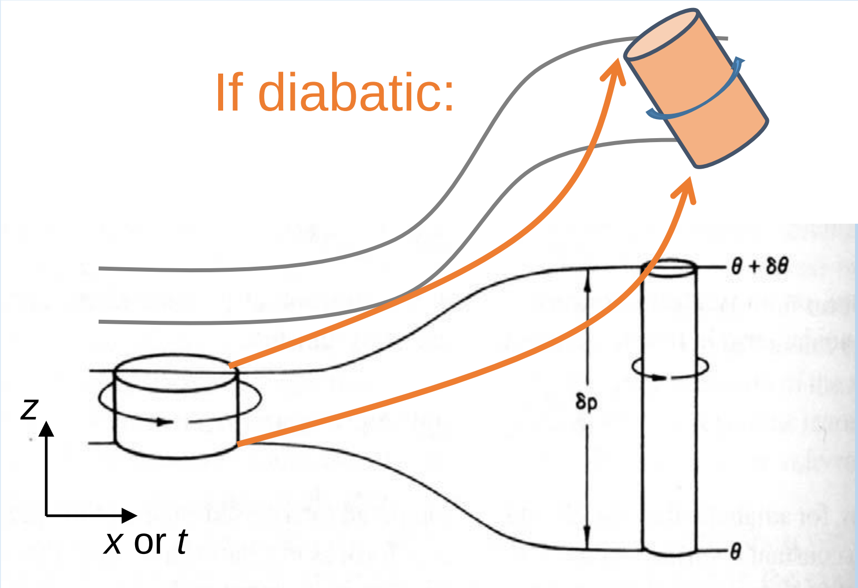


Fig. 4.7 A cylindrical column of air moving adiabatically, conserving potential vorticity.

Holton (2004)

PV modification along isentropic trajectories

If instead we follow isentropic trajectories:

- Circuit remains aligned with isentropes (by definition)
- Relationship between $\langle P \rangle$ and $\mathcal{C}$ remains (+physical interpretation)

But…No longer following air parcels. Two issues:

- Mass (and circulation) are not conserved
- Conceptually more difficult?

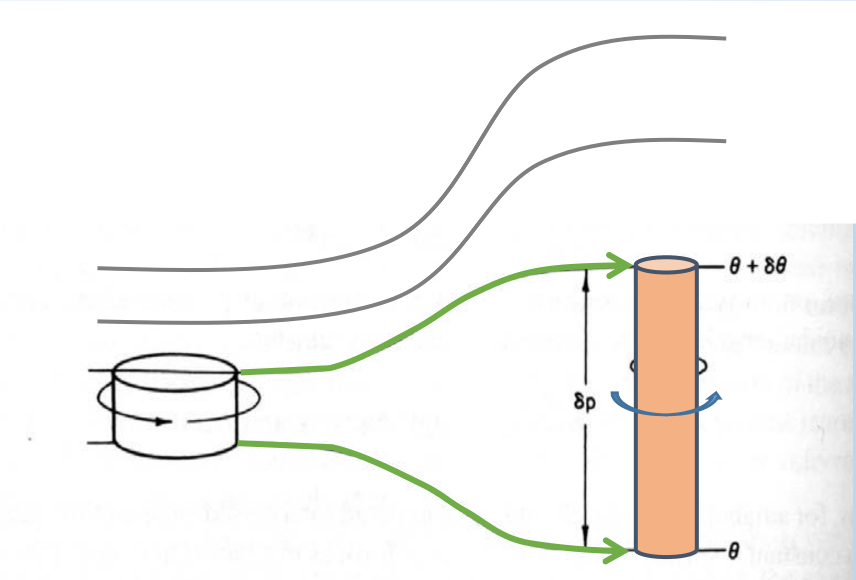


Fig. 4.7 A cylindrical column of air moving adiabatically, conserving potential vorticity.

Holton (2004)

PV modification along isentropic trajectories

$$\langle P \rangle = \frac{\mathcal{C}\,\delta\theta}{\mathcal{M}} \quad \rightarrow \quad \mathcal{M}\frac{d\langle P \rangle}{dt} = -\langle P \rangle \frac{d\mathcal{M}}{dt} + \delta\theta \frac{d\mathcal{C}}{dt}$$

[recall isentropic PV equation: $\rho \frac{\tilde{D}P}{Dt} = P \frac{\partial}{\partial z}\left(\frac{\rho\dot{\theta}}{\theta_z}\right) - \theta_z \boldsymbol{k} \cdot \nabla_\theta \times \left(\boldsymbol{V}_z \frac{\dot{\theta}}{\theta_z}\right)$]

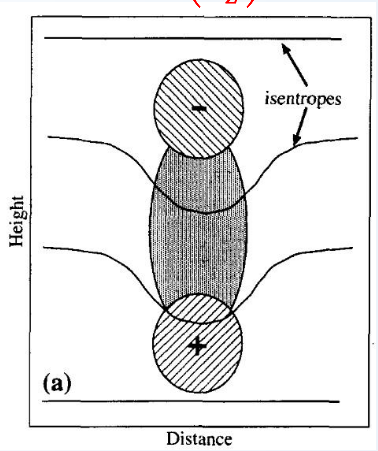
Two distinct physical mechanisms modifying PV:

1. PV concentration/dilution [diabatic mass flux convergence]
2. Diabatic circulation source/sink [Kelvin's circulation theorem]

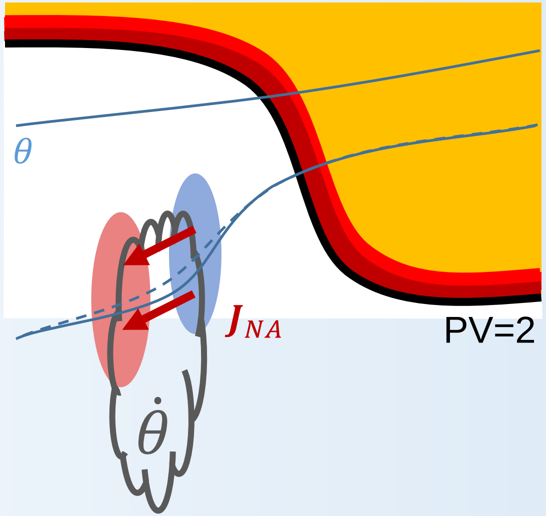
PV dilution/concentration

- A vertical dipole: concentration below heating, dilution above
- Proportional to P so can't turn the PV negative

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



$$-\theta_z \boldsymbol{k}\cdot\nabla_\theta\times\left(\boldsymbol{V}_z\frac{\dot{\theta}}{\theta_z}\right)$$



Diabatic circulation source/sink

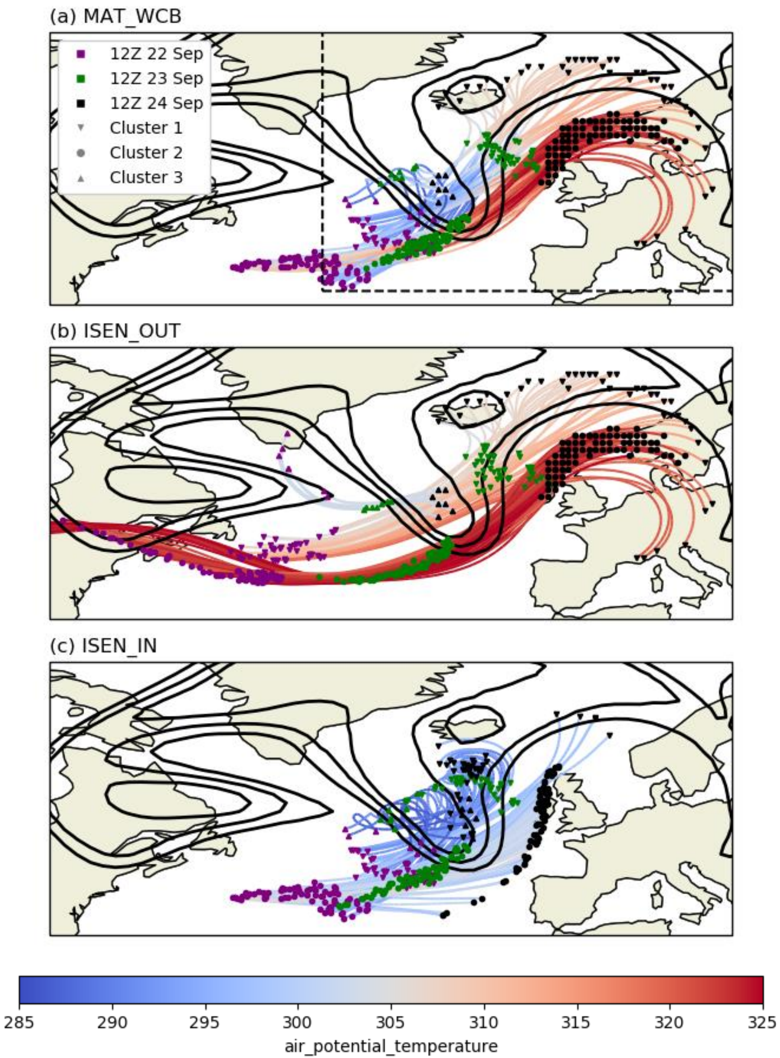
- Requires heating in the presence of vertical wind shear
- *Can* act to turn the PV negative
- Can be written as $\nabla\cdot\boldsymbol{J}$ (the "non-advective PV flux")
- $\boldsymbol{J}$ is always directed 'down the isentropic slope'
- On an isentropic surface, there is an exact dipole: large-scale PV field does not 'feel' this term
- Scaling: importance grows at small scales – dominates on convective scale

Illustration: Cyclone Vladiana (Sep 2016; NAWDEX IOP3)

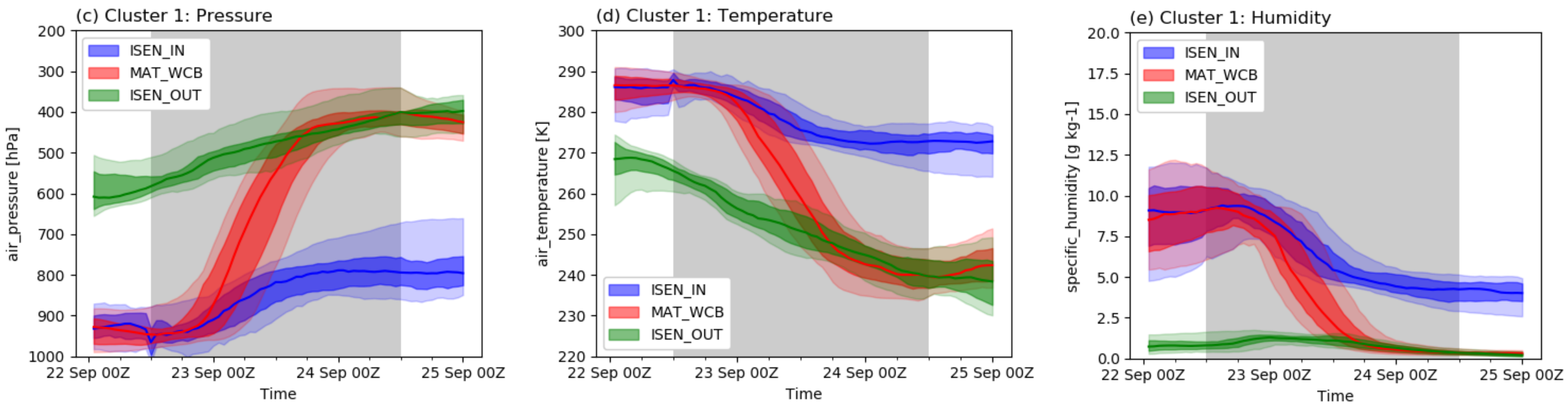
- N96 MetUM simulation of a ‘fairly typical’ cyclone (≈150 km grid spacing)
- Store hourly model output including all diabatic and frictional tendencies

Method:

1. Identify WCB trajectories in the standard way (ascend 500 hPa in 48 hours): *MAT_WCB*
2. Compute isentropic trajectories backwards from the outflow region: *ISEN_OUT*
3. Compute isentropic trajectories forwards from the inflow region: *ISEN_IN*

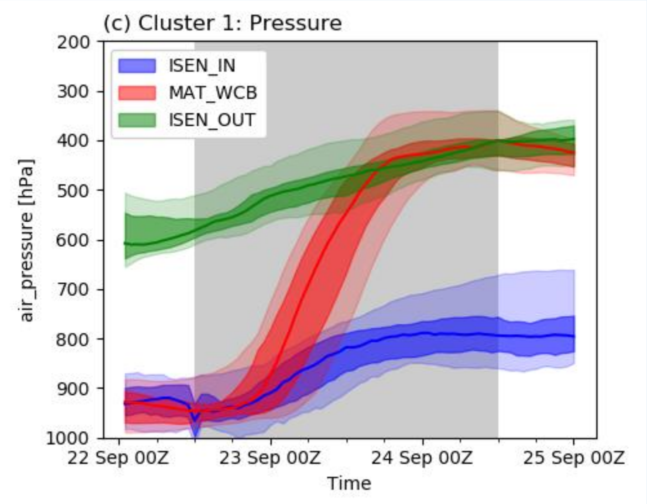


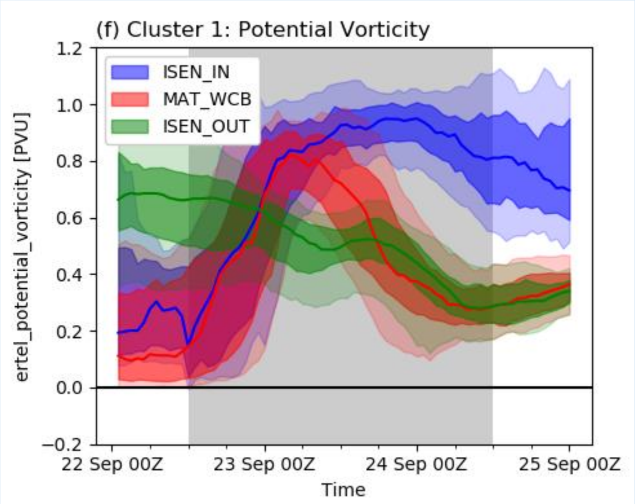
Evolution of physical properties along trajectories



- Strong ascent and drying along *MAT_WCB* trajectories (net heating=20K)
- Both *ISEN_IN* and *ISEN_OUT* trajectories still ascend (cf dry baroclinic wave) but by 200hPa instead of 600hPa

Evolution of PV along trajectories

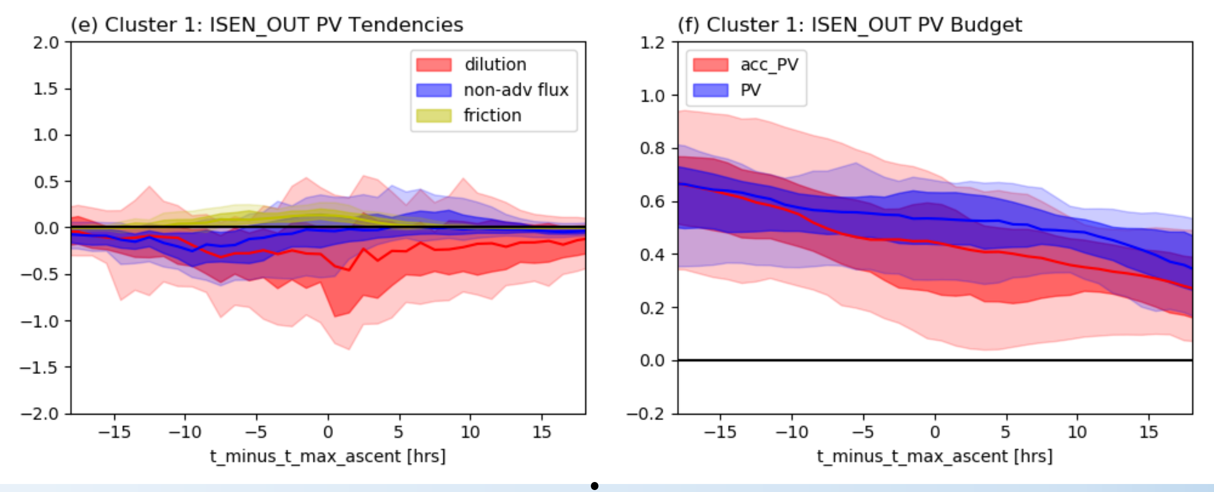




- Typical WCB PV evolution along *MAT_WCB*:
  Increase whilst below 600 hPa, followed by decrease above
- Monotonic PV evolution along isentropic trajectories:
  Gradual decrease along *ISEN_OUT*, increase along *ISEN_IN*

PV budget along isentropic trajectories

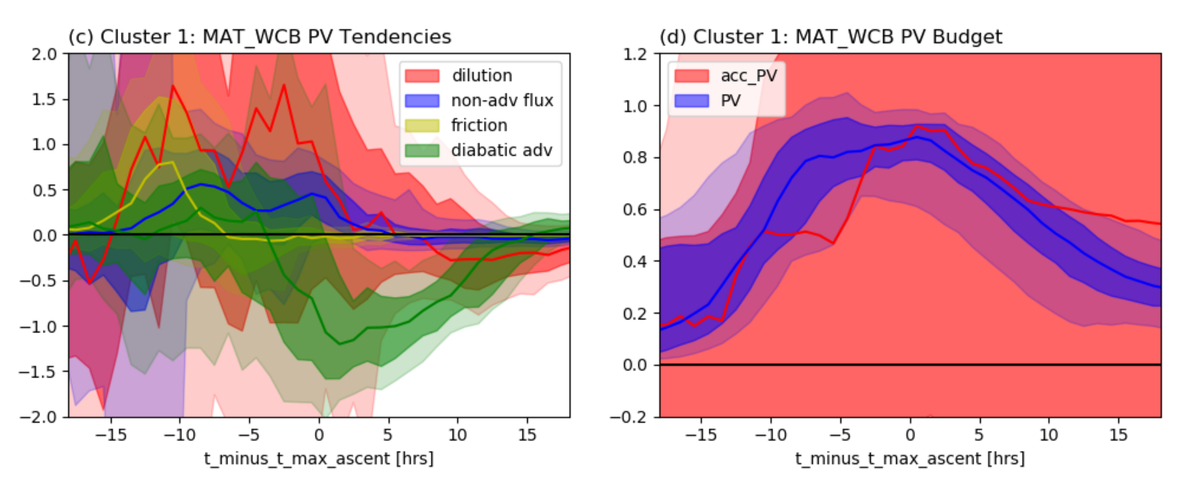
$$\rho \frac{\widetilde{D}P}{Dt} = P \frac{\partial}{\partial z}\left(\frac{\rho\dot{\theta}}{\theta_z}\right) - \theta_z \boldsymbol{k} \cdot \nabla_\theta \times \left(\boldsymbol{V}_z \frac{\dot{\theta}}{\theta_z}\right)$$



- Compute 2 source terms using total $\dot{\theta}$ (sum of all processes – but dominated by convective param here)
- PV decrease along *ISEN_OUT* is dominated by dilution term
- Budget closes very well for 36 hour trajectories

PV budget along air parcel trajectories

$$\rho \frac{DP}{Dt} = P \frac{\partial}{\partial z}\left(\frac{\rho \dot{\theta}}{\theta_z}\right) - \theta_z \boldsymbol{k} \cdot \nabla_\theta \times \left(\boldsymbol{V}_z \frac{\dot{\theta}}{\theta_z}\right) + \frac{\rho \dot{\theta}}{\theta_z} \frac{\partial P}{\partial z}$$

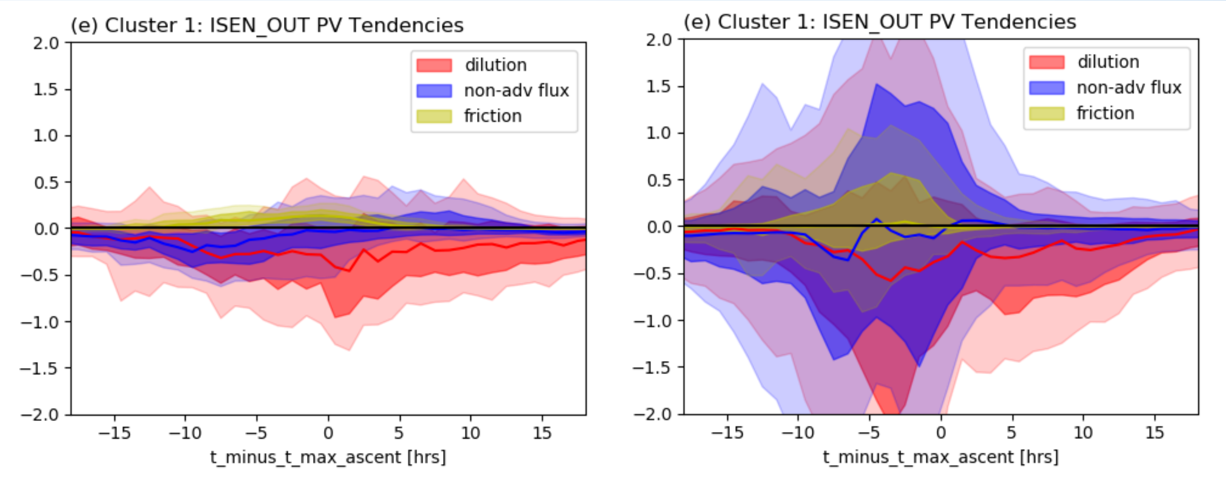


- PV evolution for *MAT_WCB* more complex:
  - Initial increase due to PV concentration + circulation changes + friction
  - Later decrease dominated by advection across PV gradient
- Traj mean budget closes well, but huge spread whilst at low levels

Impact of model resolution

$$\rho \frac{\widetilde{D}P}{Dt} = P\frac{\partial}{\partial z}\left(\frac{\rho\dot{\theta}}{\theta_z}\right) - \theta_z \boldsymbol{k}\cdot\nabla_\theta \times \left(\boldsymbol{V}_z \frac{\dot{\theta}}{\theta_z}\right)$$

N96 (≈150 km grid) N320 (≈50 km grid)



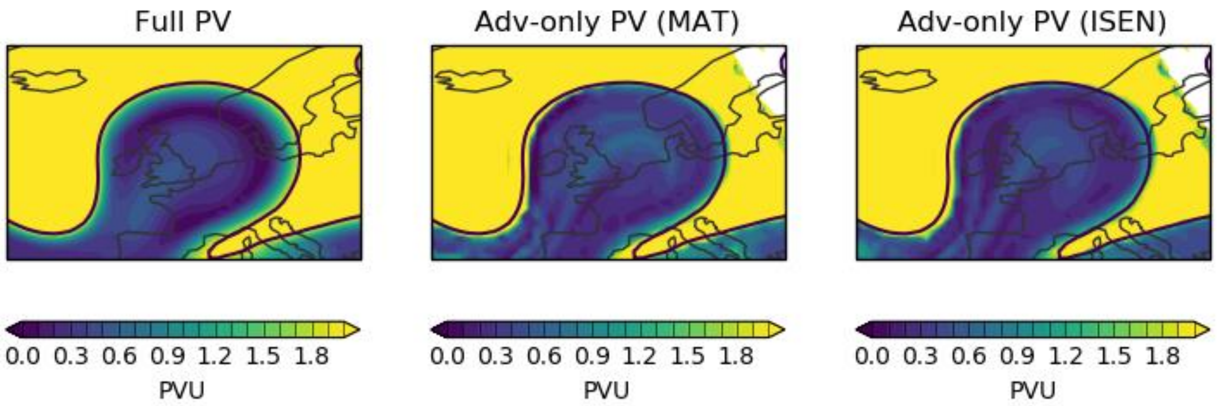
- Much larger spread in circulation tendencies at N320 than N96 [→strong horizontal PV dipoles emerging]
- But the mean changes from all 3 terms are almost identical

Aside: What is diabatic PV?

Typically think of it as:

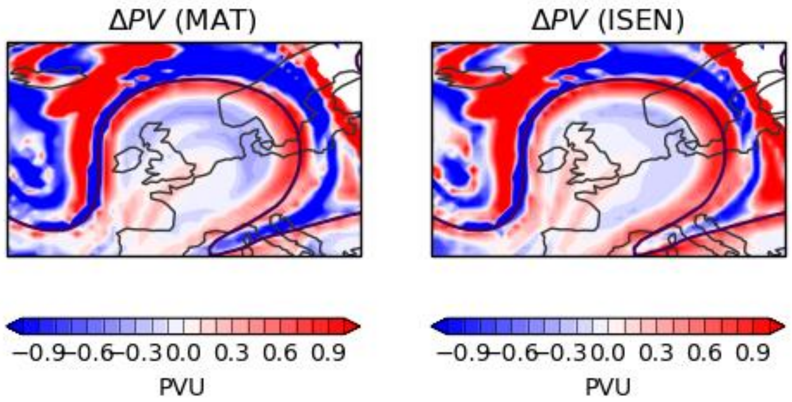
the part of the PV field generated by diabatic processes during a certain time period

But this depends on the framework used:
The PV generated by diabatic processes is different if you follow air parcel trajectories or isentropic trajectories



Reverse domain-filling trajectories released at 12Z on 24 Sep

All panels show 325K



Summary

- There are two (equally valid?) frameworks for understanding diabatic modification of PV
  - The air parcel view is used a lot in the literature
  - Can we learn anything extra from the isentropic view?
- Identified 3 potential benefits of the isentropic view
  1. A more natural physical interpretation
  2. Expect more monotonic changes in PV
     → allowing a cleaner attribution of physical processes?
  3. Expect isentropic trajectory positions to vary less with resolution
     → providing a fairer comparison across models?
     and/or evaluation of convection parametrisation schemes?