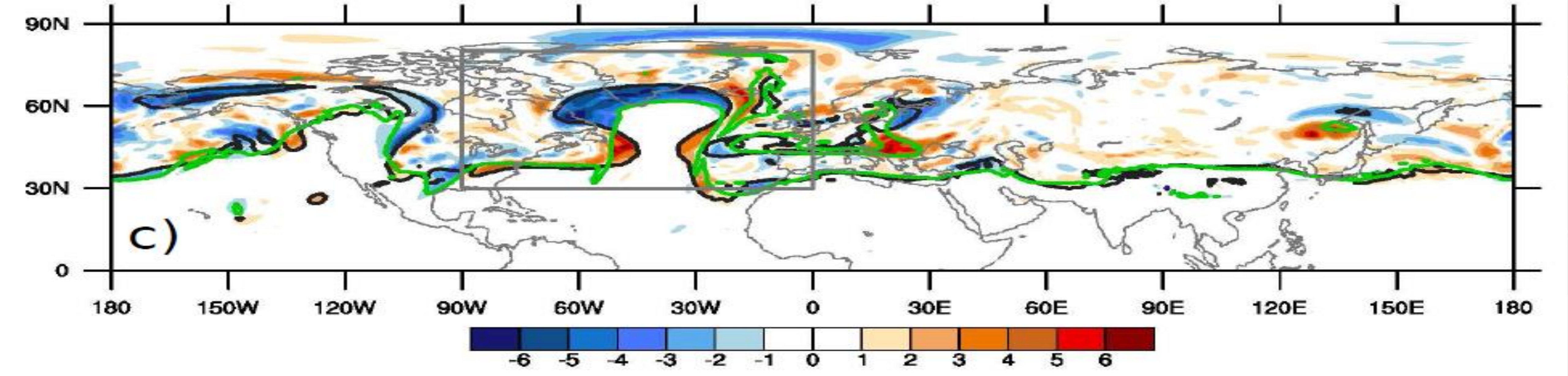
Department of Meteorology

University of Reading

Dynamic, diabatic and orographic processes in extratropical cyclones:



Suzanne Gray

Potential vorticity
A brief introduction

Potential vorticity

$$PV = \frac{(f + \boldsymbol{\xi}) \cdot \nabla\theta}{\rho}$$

$$\approx \frac{(f + \xi_z)}{\rho} \frac{\partial \theta}{\partial z}$$

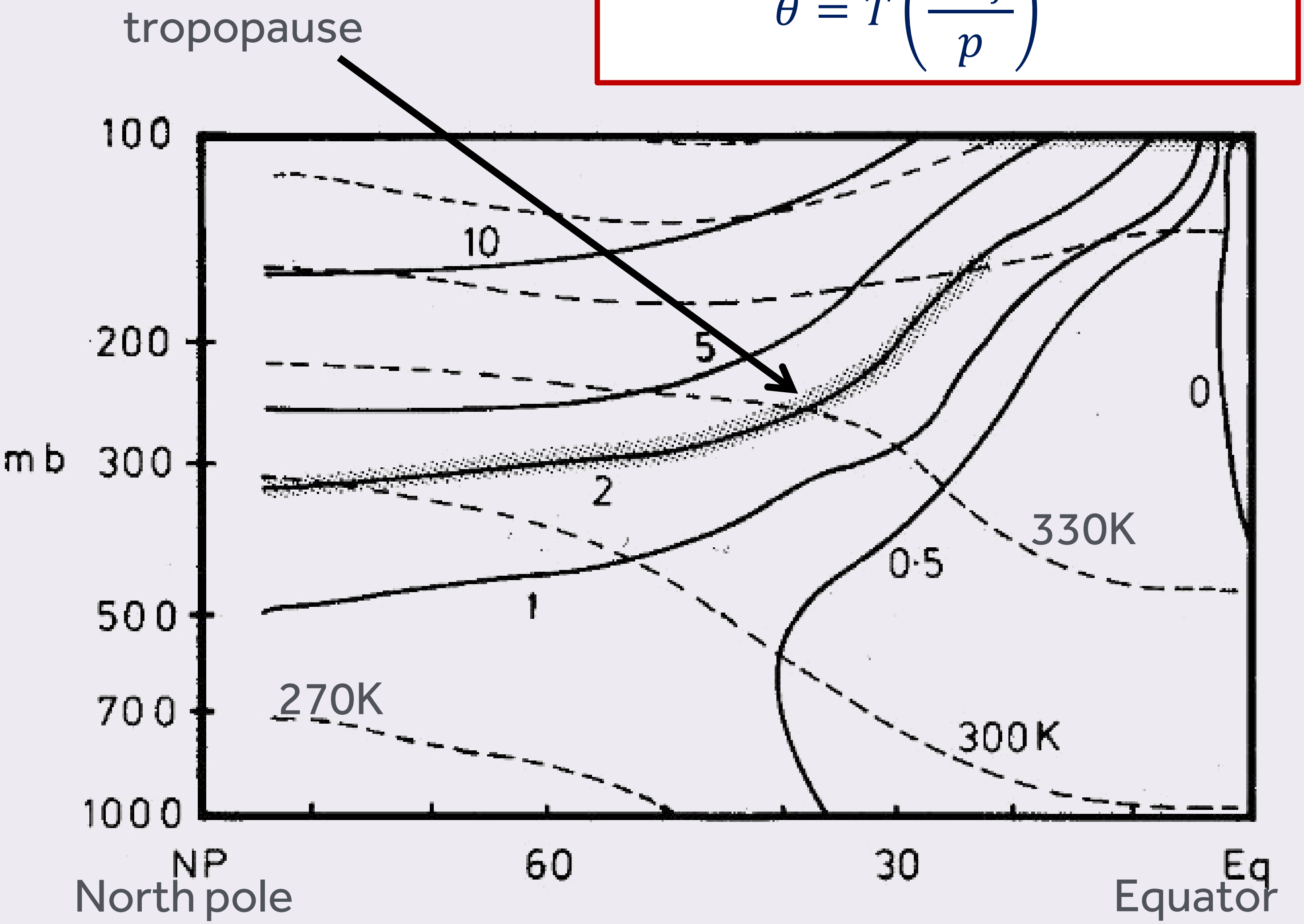
where ρ is air density and ξ is vector relative vorticity

Potential vorticity is conserved following fluid parcels for adiabatic frictionless flow.

This makes it a good tracer for upper-tropospheric air over several days.

Recall potential temperature:

$$\theta = T \left(\frac{p_{ref}}{p}\right)^{R/c_p}$$



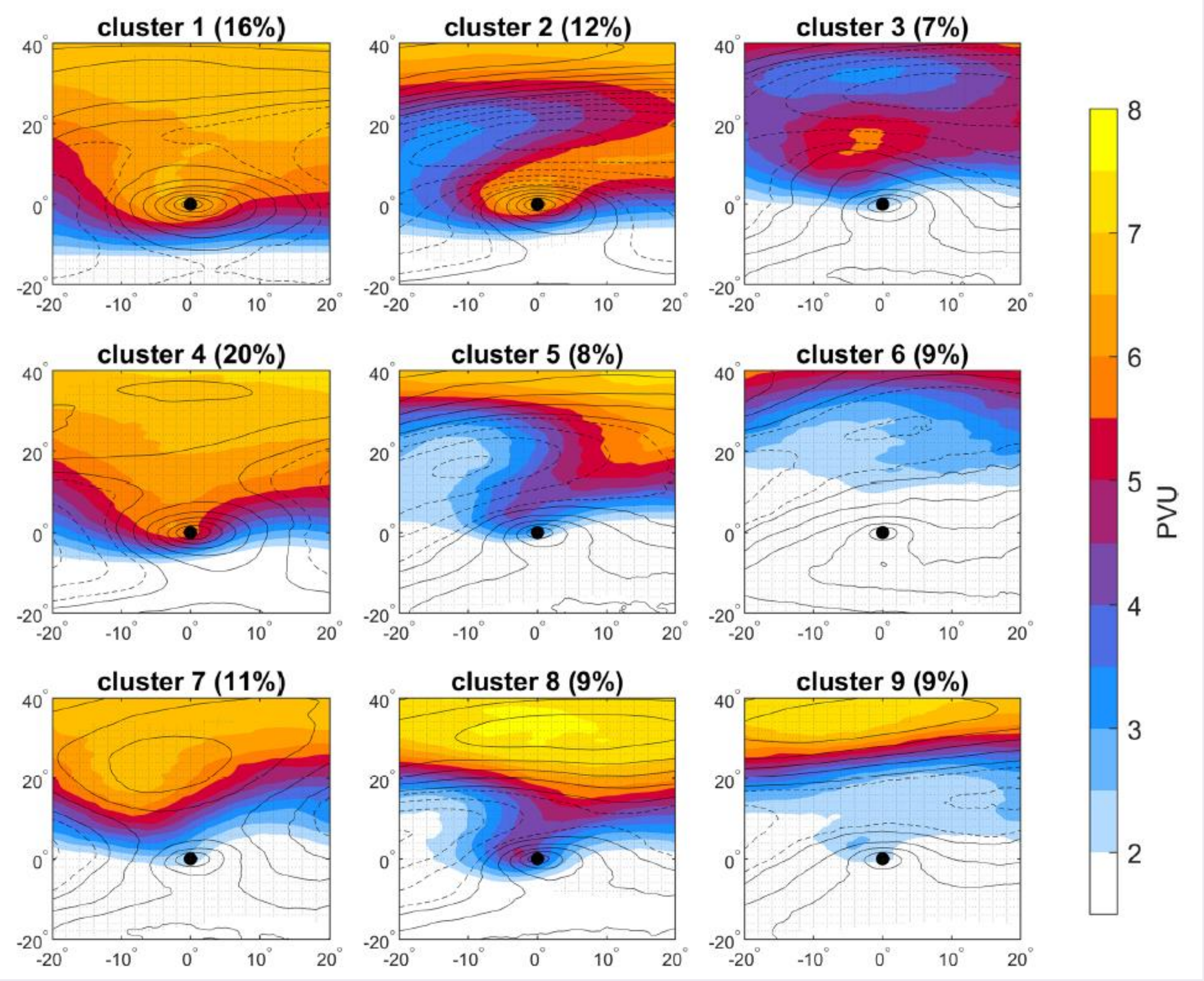
Climatology of PV (in PVU, solid) and θ (dashed) in N. Hemisphere winter (Hoskins, 1990)

PV in Mediterranean cyclones

- Cyclones can have different upper-level PV structures

Cyclone-centred composites of PV (shaded) and sea-level pressure (contours) from self-organising map analysis of >3000 cyclones

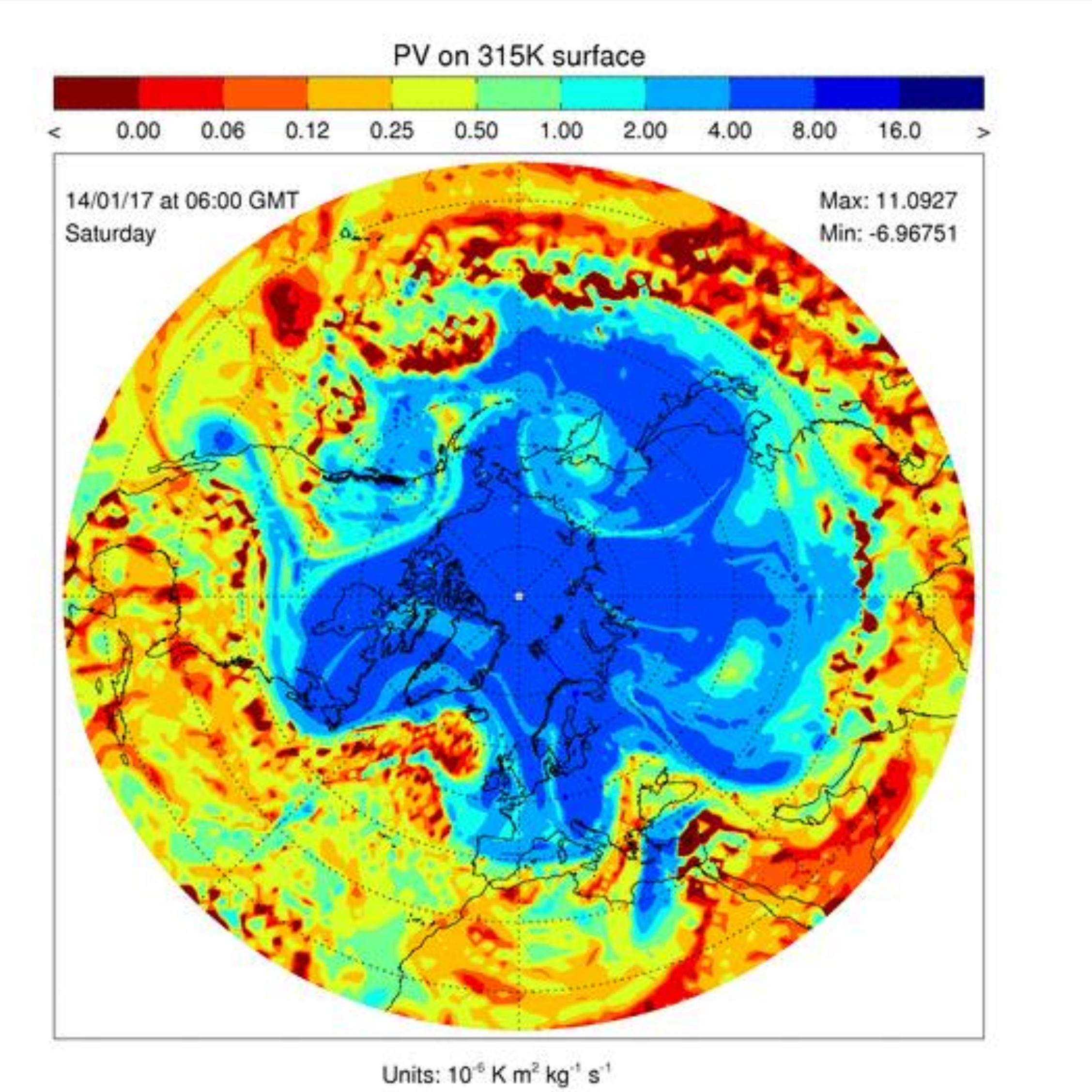
Although clustered by PV, clusters have different 3D structures, life-cycles and hazards



Givon et al. (2024)

Planetary Rossby waves

- Large amplitude waves are always present in the atmosphere.
- Dispersive waves propagating westwards relative to the mean flow.
- They conserve potential vorticity
- Exhibit stirring, stretching and folding properties including vortex roll up.

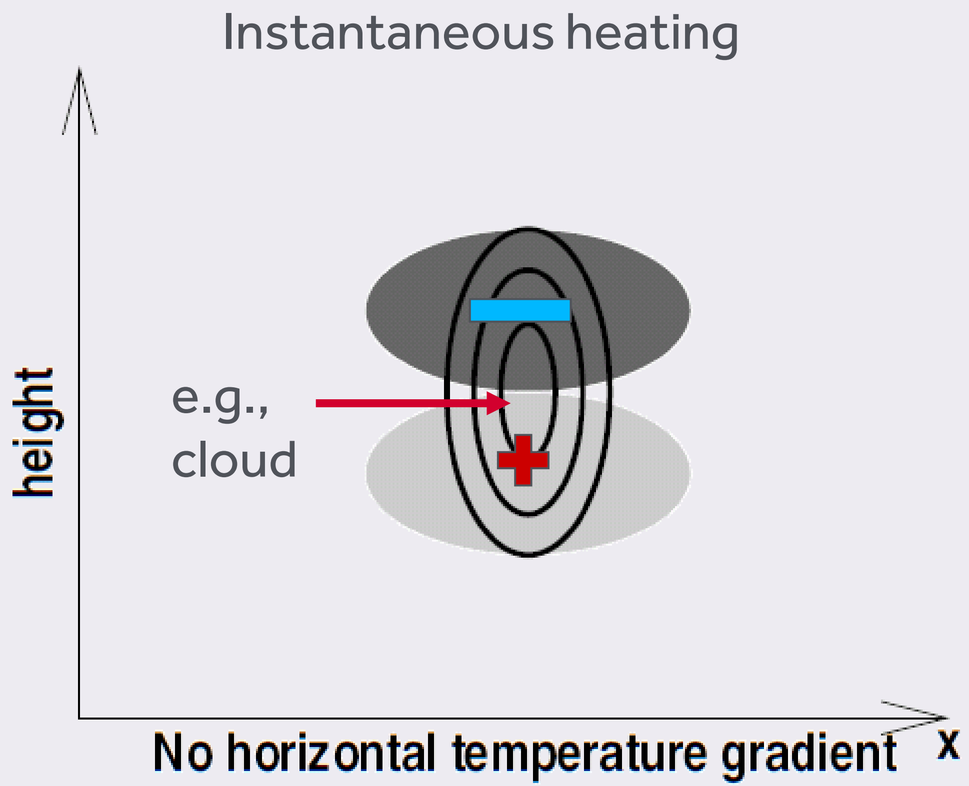


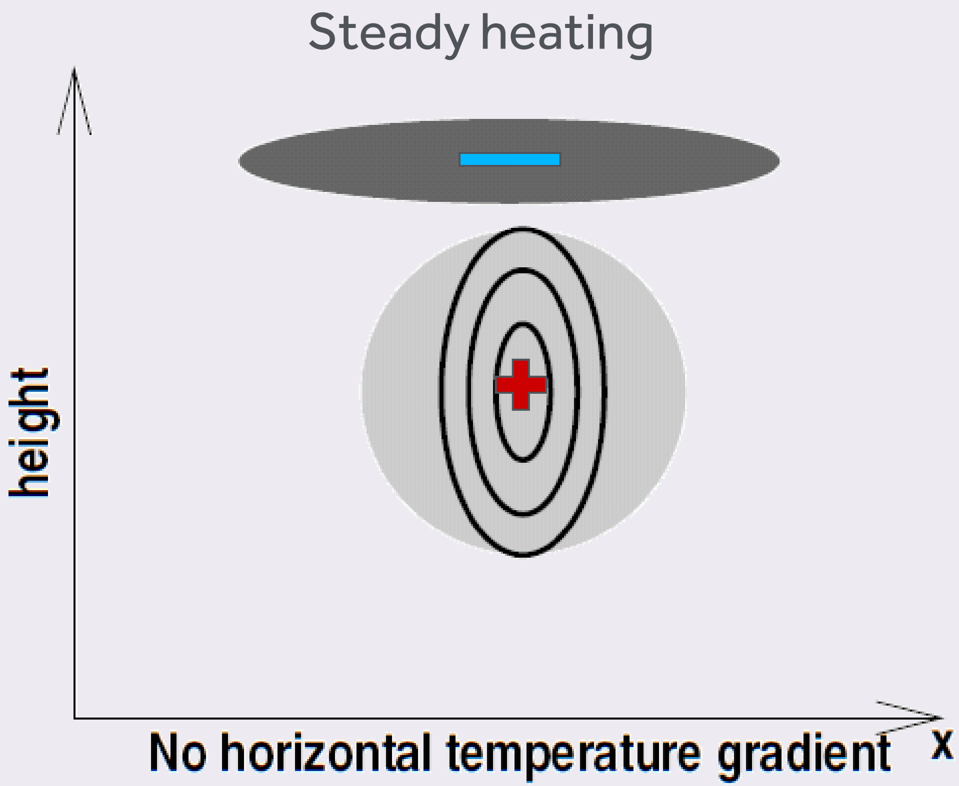
ECMWF PV on 315 K isentrope animation

Diabatic PV modification

$$\frac{DPV}{Dt} \cong \frac{1}{\rho}(f + \xi)\frac{\partial \dot{\theta}}{\partial z}$$

where $\dot{\theta}$ is the heating rate





PV dipole arising from heating applied in a barotropic environment

Dry dynamical processes

Baroclinic instability

Eric Eady (1915-1966)

The development of extratropical cyclones through baroclinic instability has been known about for more than 70 years (Eady, 1949, Charney, 1948).

Jule Charney (1917-1981)

Eady model

Eady model of baroclinic instability (1949)

- maximum growth rate

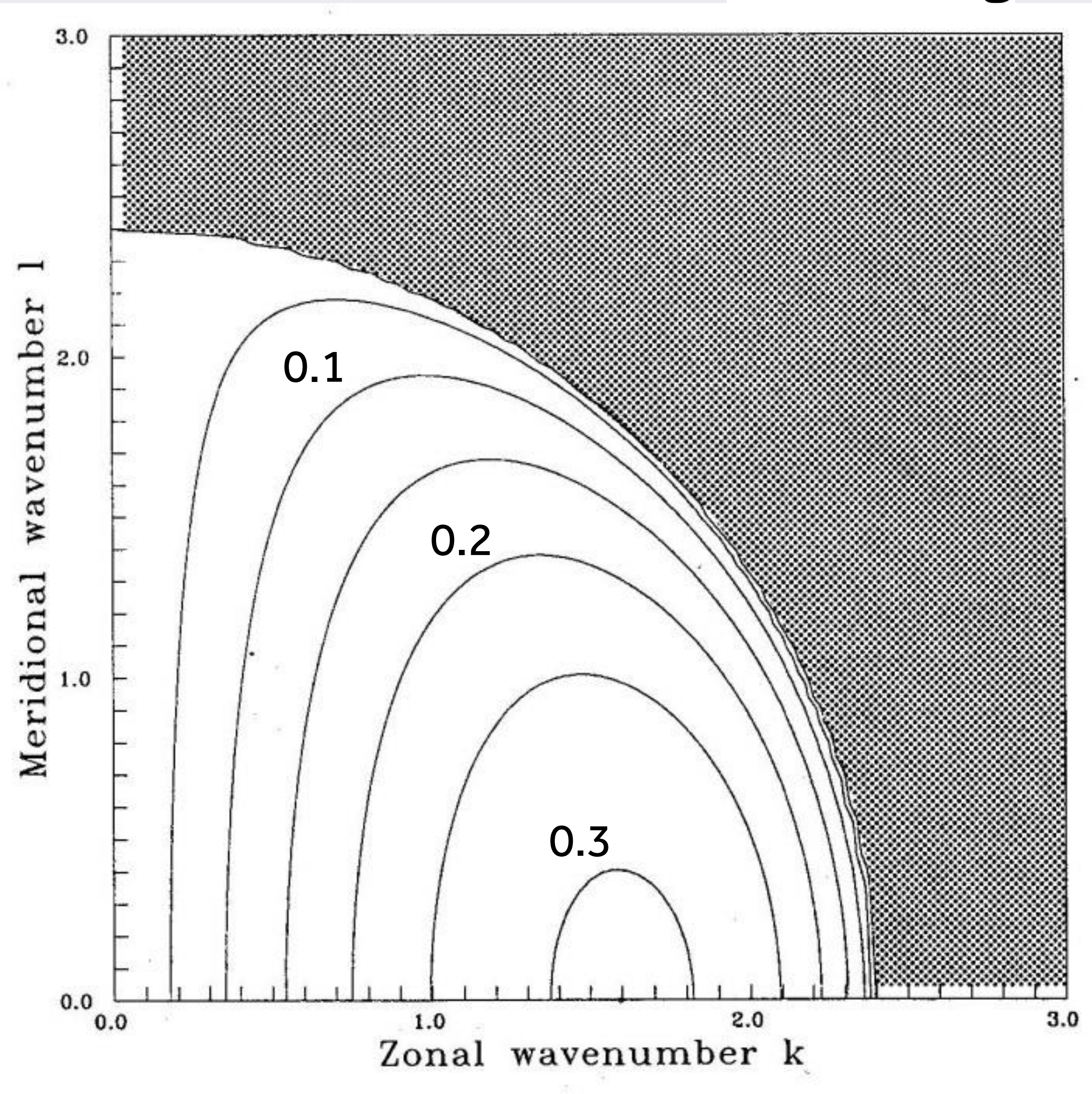
$$\sigma = \frac{0.31f}{N}\frac{\partial \bar{u}}{\partial z}$$

- at wavenumber

$$k = \frac{1.6f}{NH}$$

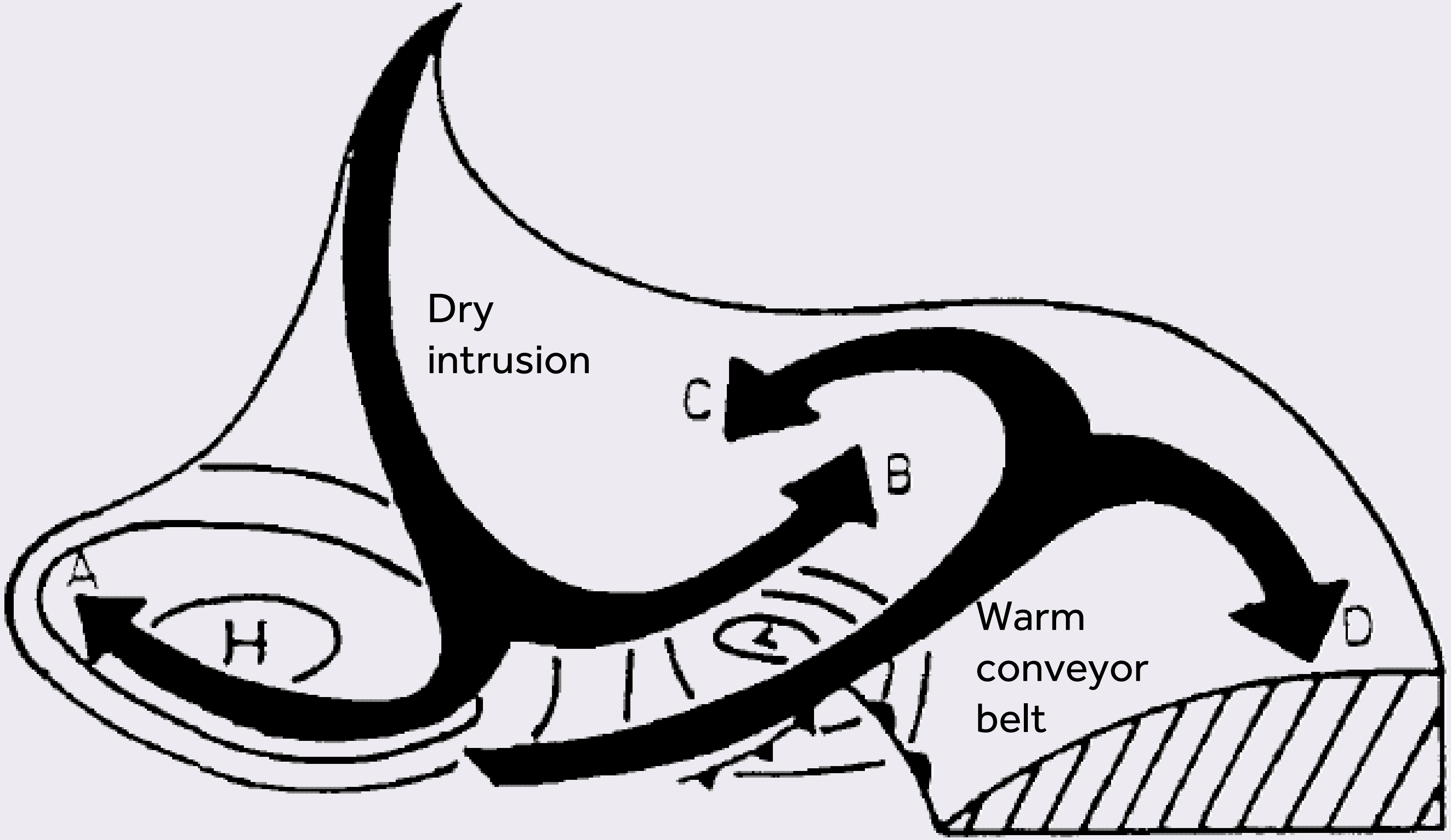
For moist cyclones consider

$$N \rightarrow N_{effective}$$



James (1994)

Idealised, dry baroclinic lifecycles



Isentropic relative flow in a baroclinic wave

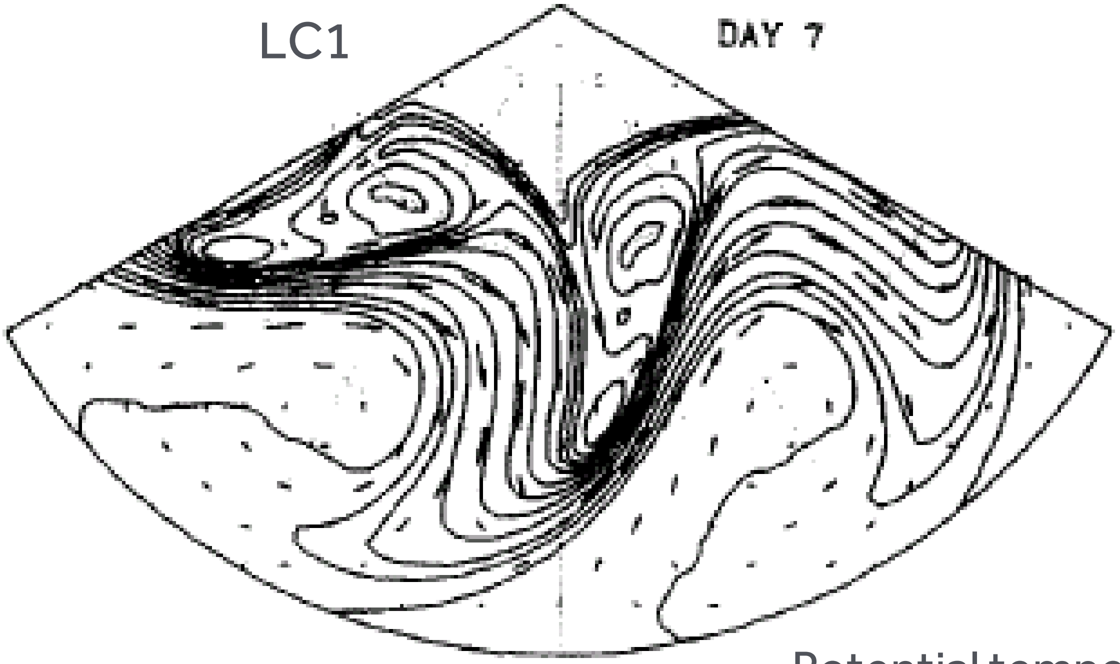
Thorncroft *et al.*, (1993)

Idealised, dry baroclinic lifecycles (LC1,2)

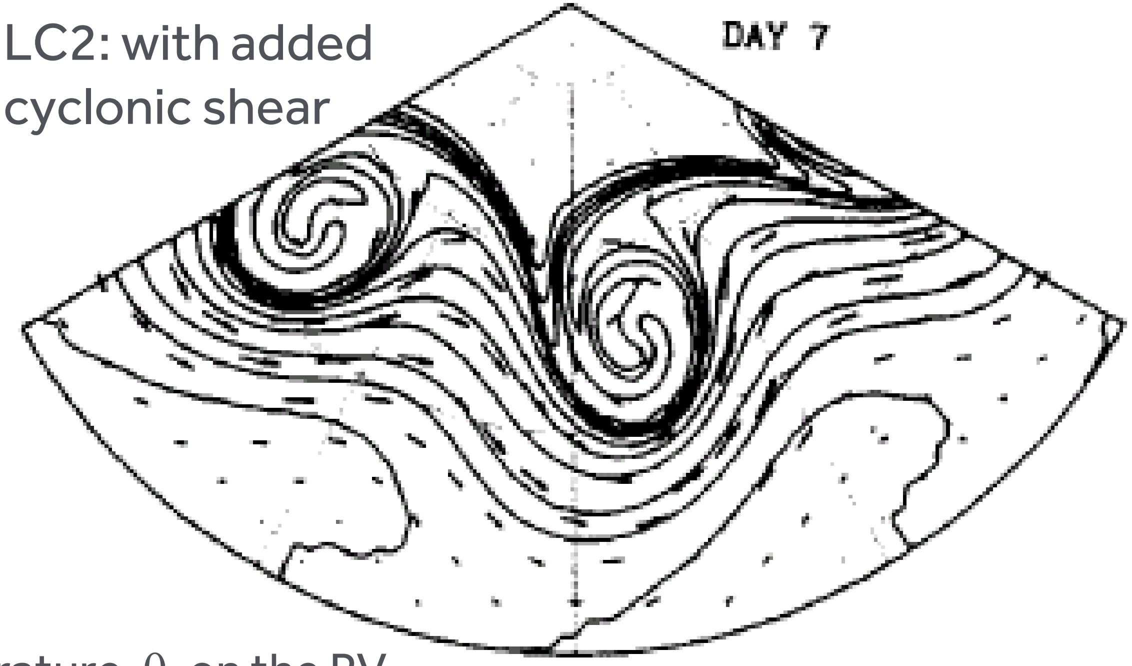
backward-tilted, thinning troughs being advected anticyclonically and equatorward

forward-tilted, broadening troughs wrapping themselves up cyclonically and poleward

LC1



LC2: with added cyclonic shear



Potential temperature, θ, on the PV = 2PVU surface (tropopause)

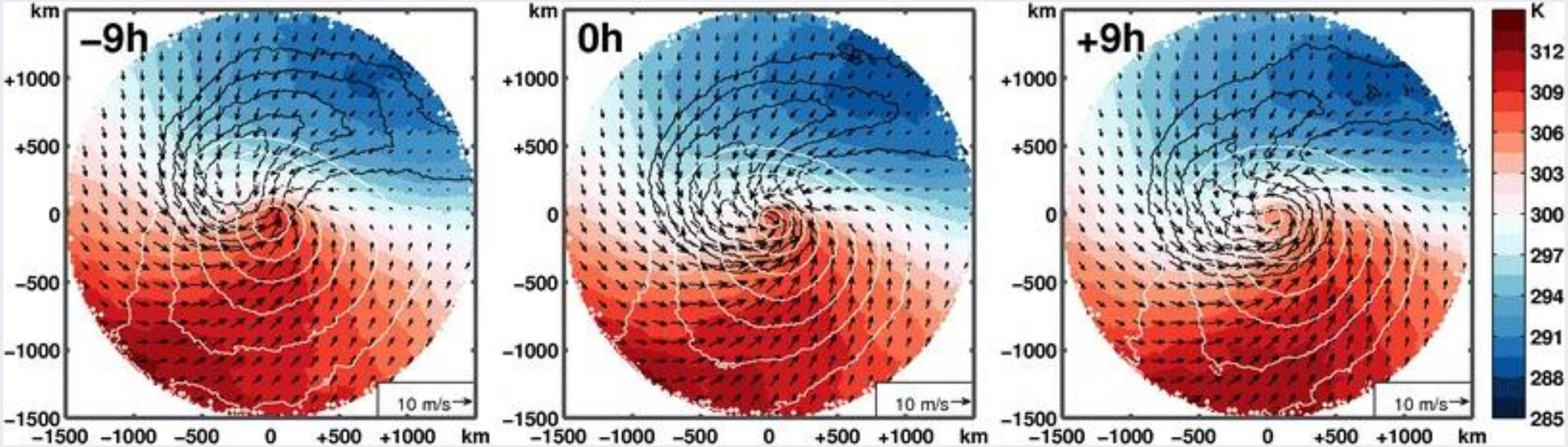
Rossby wave breaking

Produces major cut-offs in high latitudes

Thorncroft *et al.*, (1993)

Mediterranean cyclones

A potential vorticity streamer or cut-off low system is commonly present close to intense Mediterranean cyclones implying baroclinic forcing

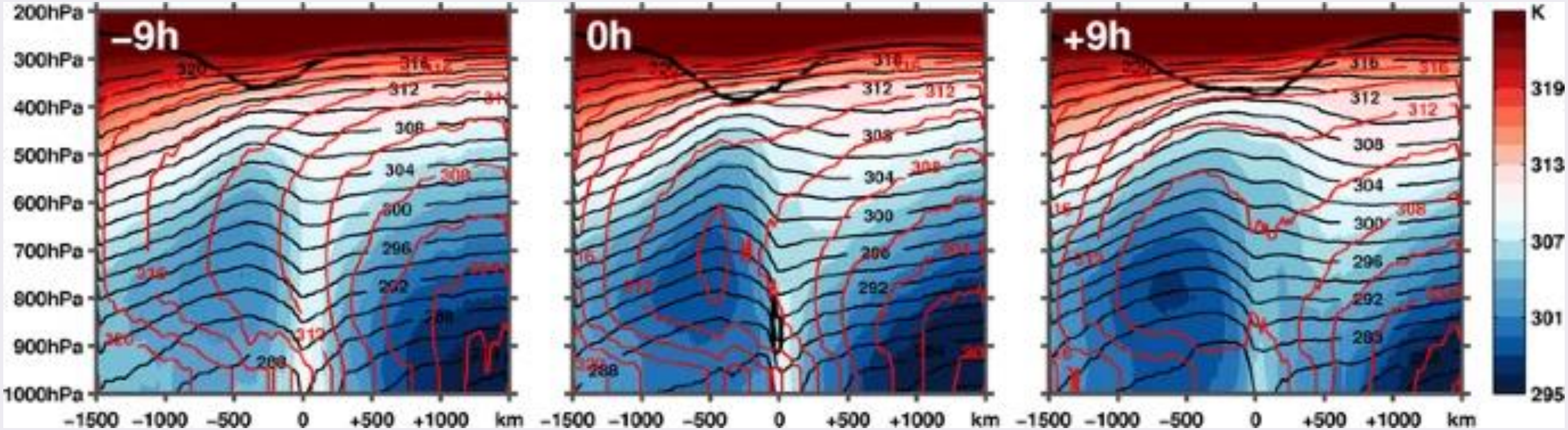


Composite cyclone structure of θ_e and wind at 850 hPa, sea level pressure (white contours) and pressure of the 2-PVU tropopause (black contours)

Dynamical tropopause tends to wrap cyclonically around the cyclone centre, reflecting a PV streamer, which gradually intrudes deeper into the troposphere.

From Flaounas *et al.*, 2015

Mediterranean cyclones



Composite cyclone vertical cross sections of θ_e (colour), θ (black contours), θ_{es} (red contours) and the 2-PVU tropopause (thick black contour)

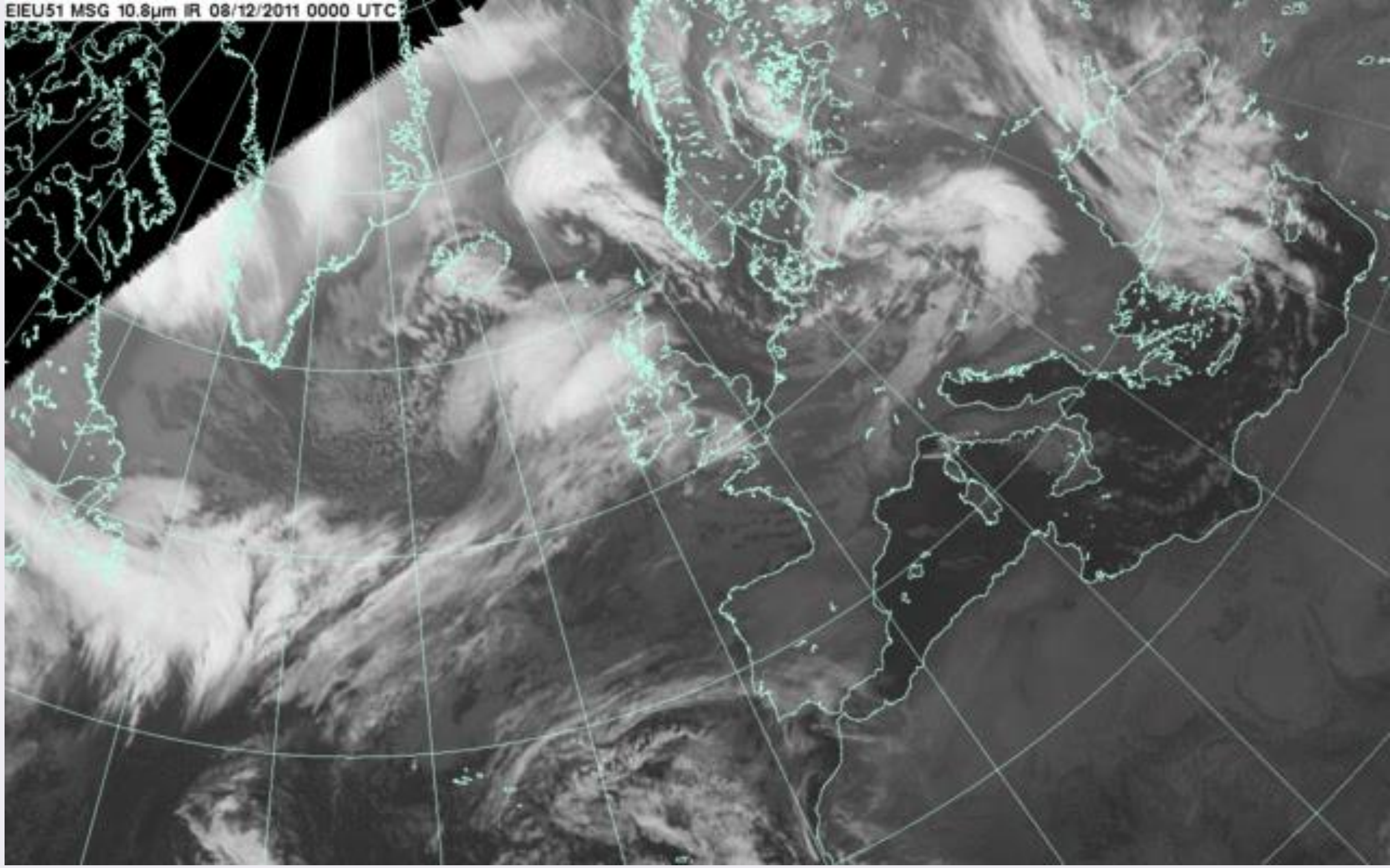
-9h: PV streamer is to the west of the cyclone centre
0h: PV streamer descends to 400 hPa
+9h: PV streamer is over cyclone centre and wider

From Flaounas *et al.*, 2015

Diabatic processes

Importance

Understanding and accurately modelling the effect of cloud-scale processes on grid-scale dynamics remains a challenge.



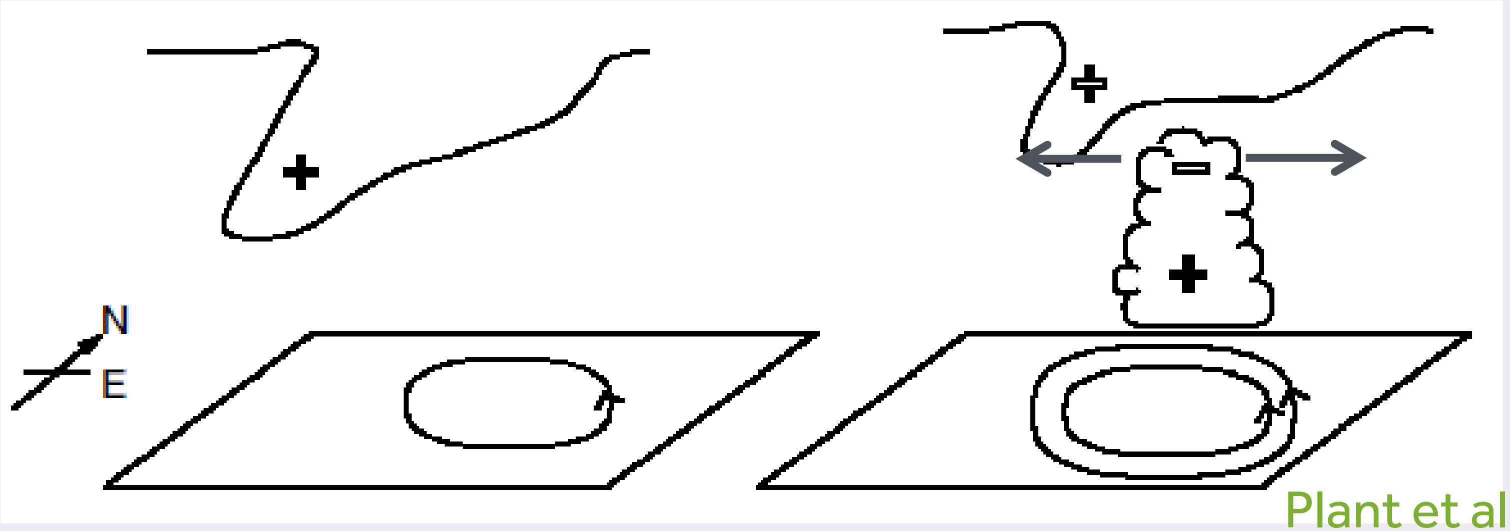
The link between the cloud scale and larger-scale dynamics has implications for

- Forecasts of heavy precipitation and high wind events,
- Possible downstream propagation of errors,
- Possible biases in climatological structure of cyclones, troughs, and ridges,
- Design of perturbed physics ensembles.

Diabatic effects on cyclones

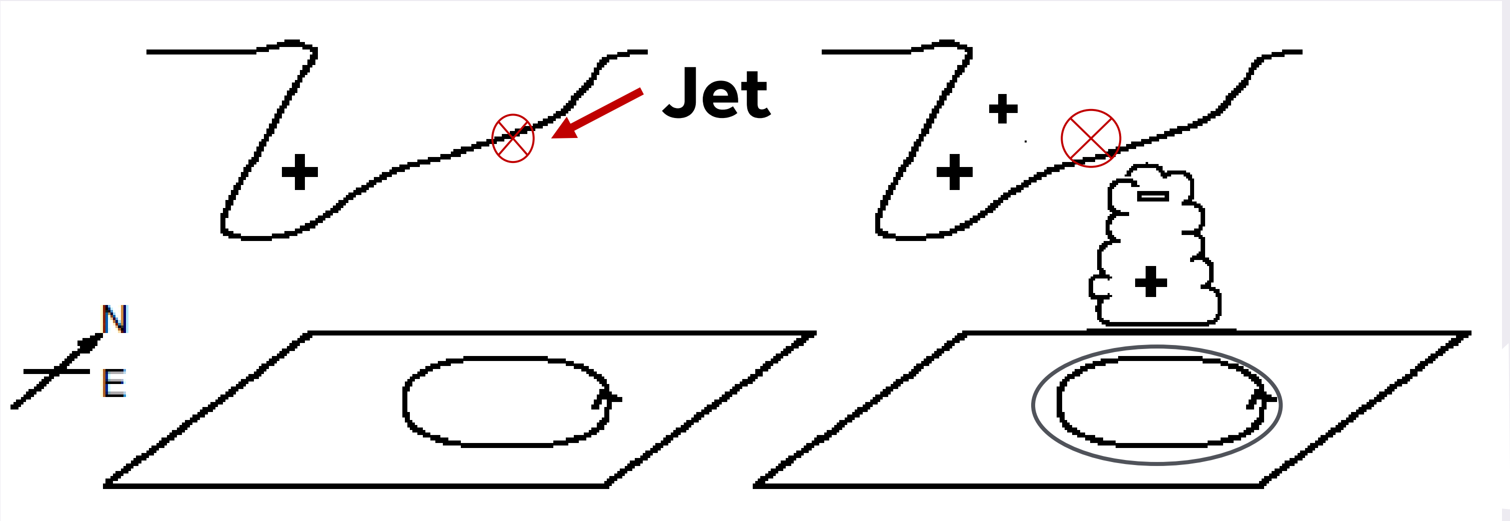
Direct effect
Tropopause erosion and/or upper-level divergence.

Associated with 'type C' cyclogenesis



Plant et al. (2003)

Indirect effect
Jet enhancement leading to modified Rossby wave propagation



Extratropical vs. Mediterranean cyclones

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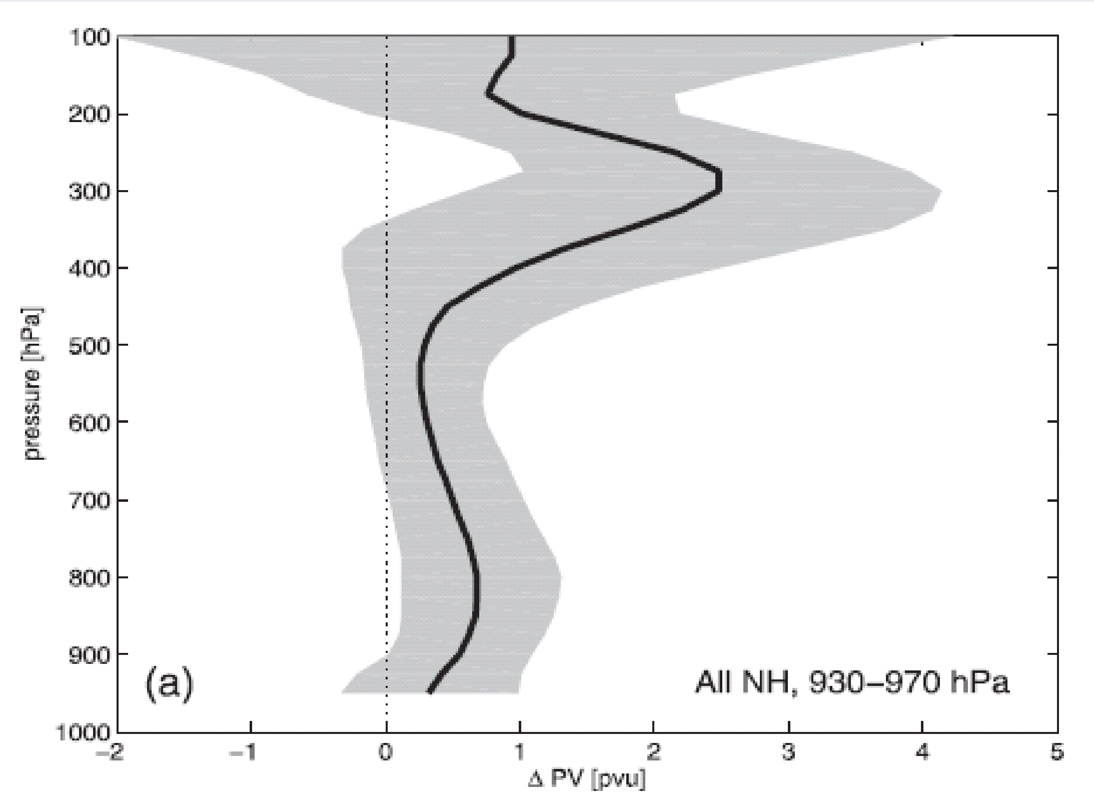
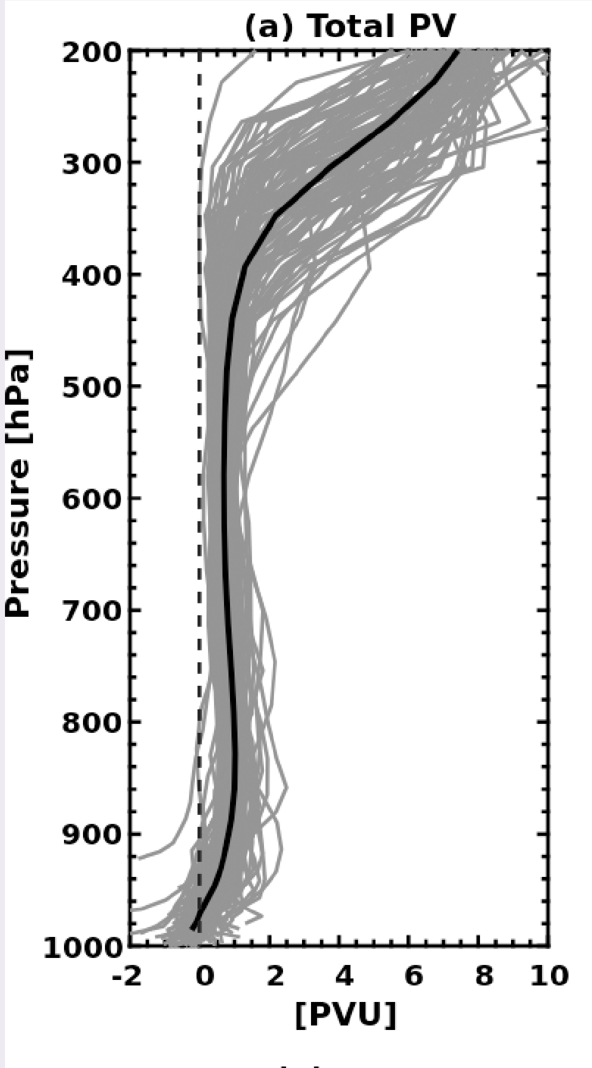
PV anomaly composite (200 km radius) NH DJF intense cyclones



Similar profiles: high PV values in the upper troposphere due to troughs or tropopause folds, or PV streamers; local maximum of PV at lower levels is related to diabatic heating.

Total PV composite (100 km radius)
100 intense Mediterranean cyclones



Čampa and Wernli (2012)

Flaounas *et al.* (2021)

Tools for diagnosing diabatic processes

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Traditional model sensitivity experiments to determine how model processes affect development

Passive “diabatic” (PV, moisture, θ) tracers

PV tendency diagnostics with Lagrangian trajectories

...to attribute PV anomalies to diabatic processes

Piecewise PV inversion (of diabatically generated PV anomalies) to determine the strength of associated circulation

Surface pressure tendency equation to determine diabatic contribution to surface pressure change

Ensemble sensitivity analysis (a form of lagged linear regression

Model Adjoint methods

...to determine how initial condition perturbations affect forecast metrics

Semi-geotriptic (=semi-geostrophic outside boundary layer) balance tool to determine ageostrophic flow response to diabatic heating

Tools: piecewise PV inversion

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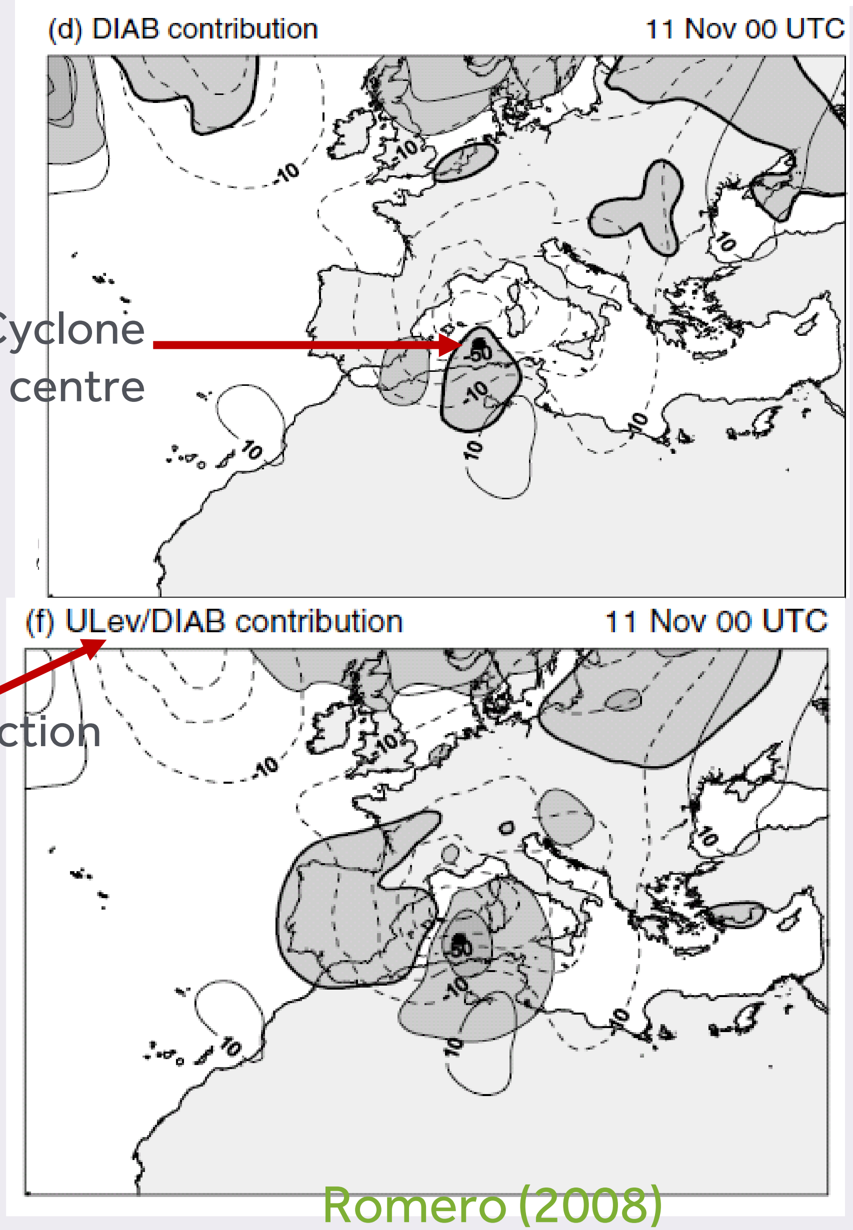
- Identify PV anomalies using thresholds for pressure, relative humidity etc. Typically consider upper-level, surface thermal anomaly. and diabatically generated.
- Apply PV inversion to each anomaly using a balance assumption such as Charney (1955) nonlinear balance to determine the contributions to the instantaneous cyclone intensity. Pioneered by Davis and Emanuel (1991).
- Other work has gone beyond this to diagnose the contributions from interactions between the different PV anomalies using a factor separation approach (Romero, 2008).



Cyclone centre

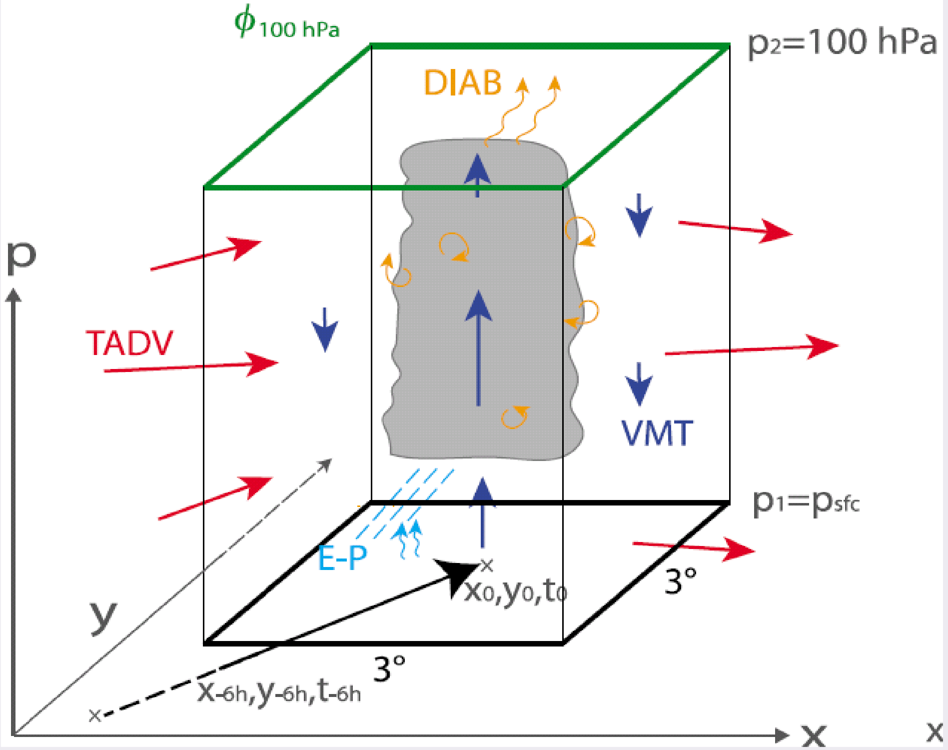
Interaction term

Contours: total Z_{925} tendency; shading contributions from terms

Romero (2008)

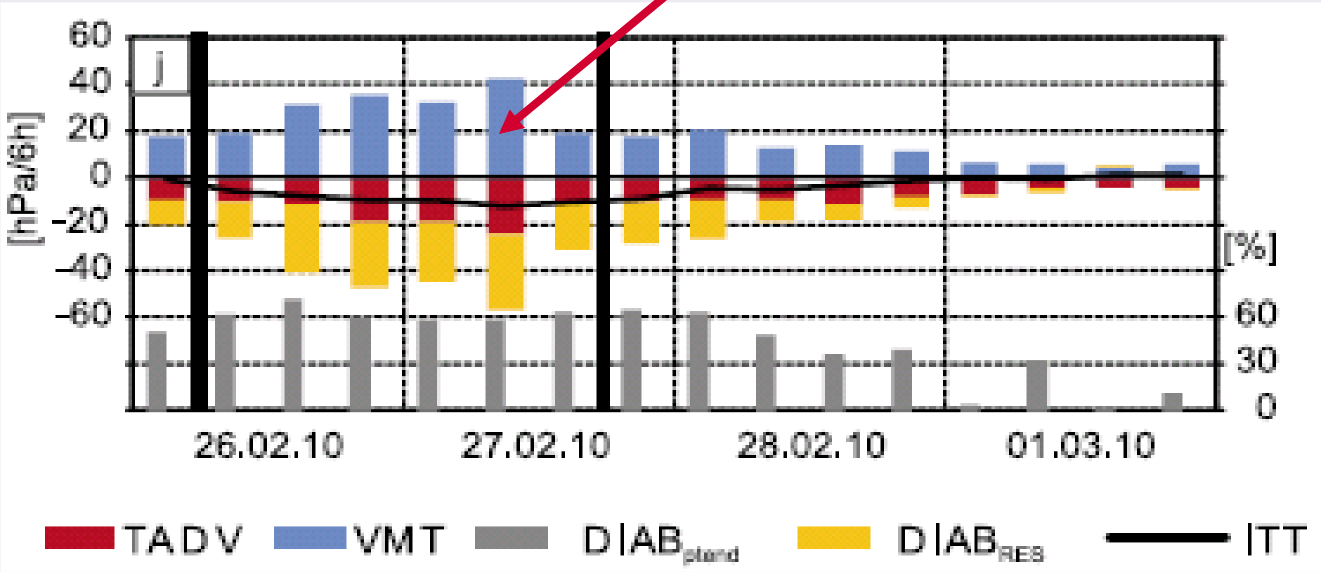
Tools: pressure tendency equation

Diagnose terms in a vertical column that moves with the storm



Fink et al. (2013)

Intensification period



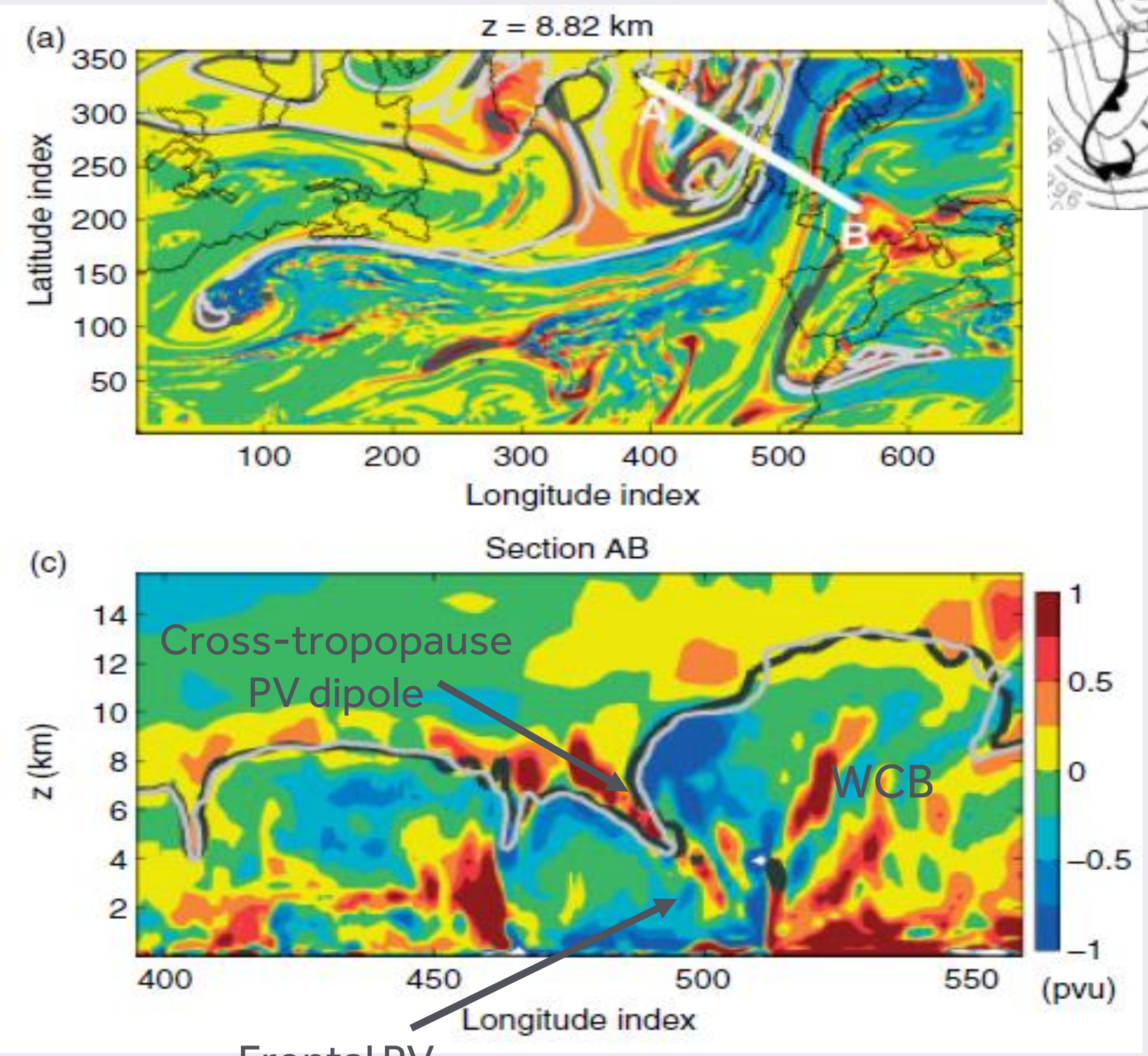
Windstorm Xynthia (Feb. 2010)

ITT – vertically integrated virtual temperature tendency split into........
TADV – horizontal temperature advection
VMT – vertical motions
DIAB – diabatic processes inc. radiation, LH due to phase changes, dissipation and diffusion
E-P – evaporation - precipitation

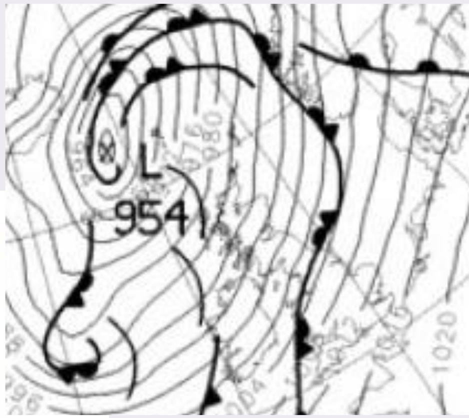
Tools: PV tracers

- Diagnosis of diabatically generated PV, its attribution to modelled physical processes and influence on forecast evolution.
- **Diabatic tracers** are tracers of changes in potential temperature and PV due to diabatic processes. PV tracers enable identification of modifications to the circulation and stability and the diabatic processes responsible for such modifications.

Diabatically generated PV



Frontal PV tripole



Chagnon et al. (2013)

Tools: PV tracers

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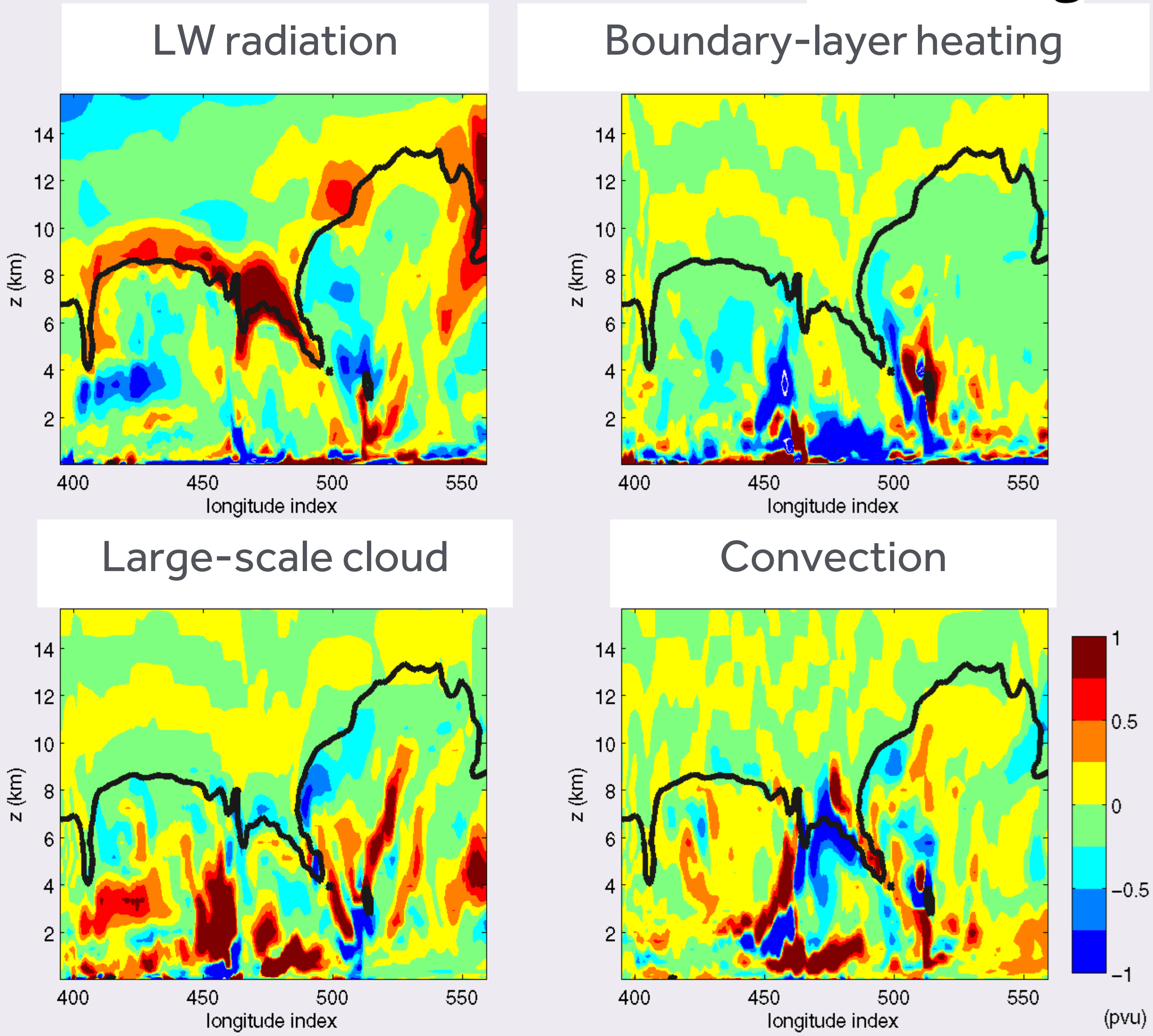


Chagnon et al. (2013)

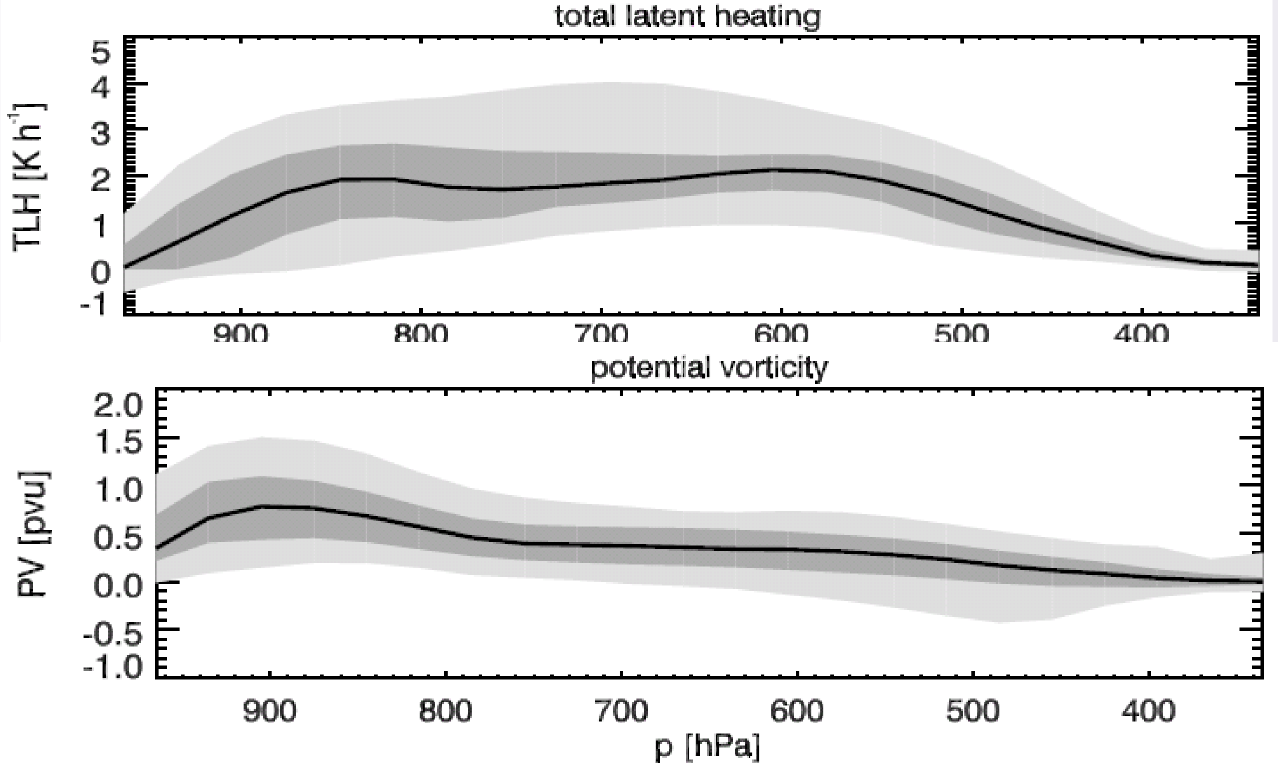
Tools: trajectories

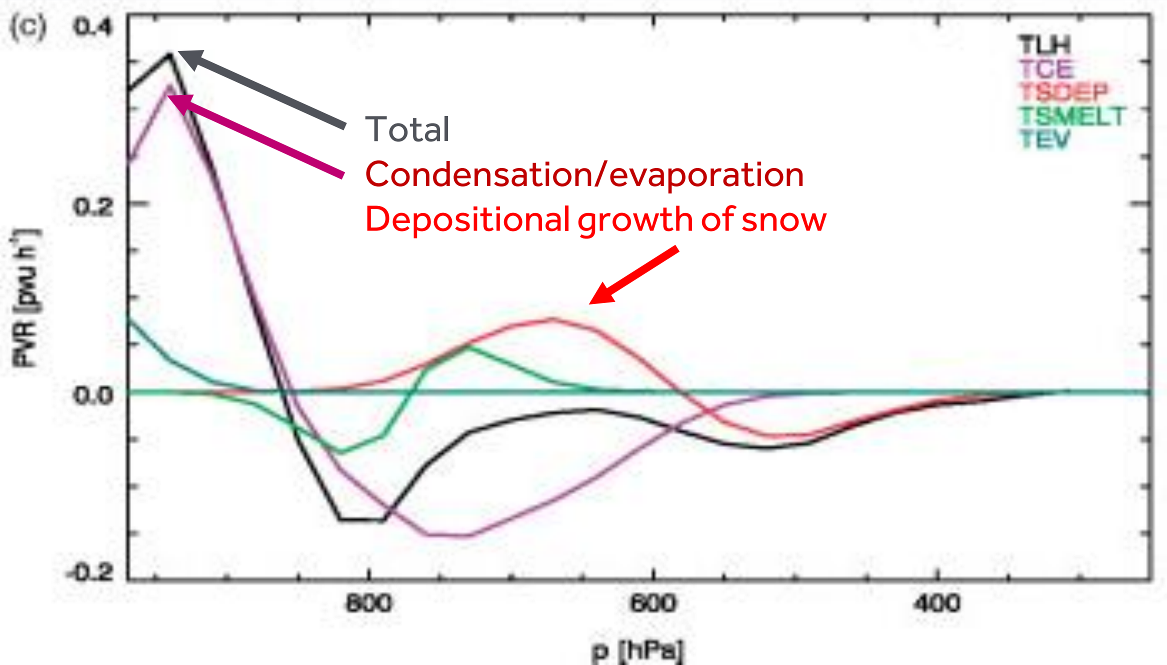
- Heating rates associated with different diabatic processes diagnosed along trajectories.
- Associated diabatically generated PV calculated using

$$DPVR = \frac{DPV}{Dt} = \frac{1}{\rho}\boldsymbol{\eta}\cdot\nabla(DHR)$$
$$\approx \frac{1}{\rho}\eta_z\frac{\partial}{\partial z}(DHR)$$

where $\boldsymbol{\eta}$ is absolute vorticity = $f + \xi$

- Diabatic heating contributions from different microphysical processes strongly modulated by local vorticity to yield contributions to PV.



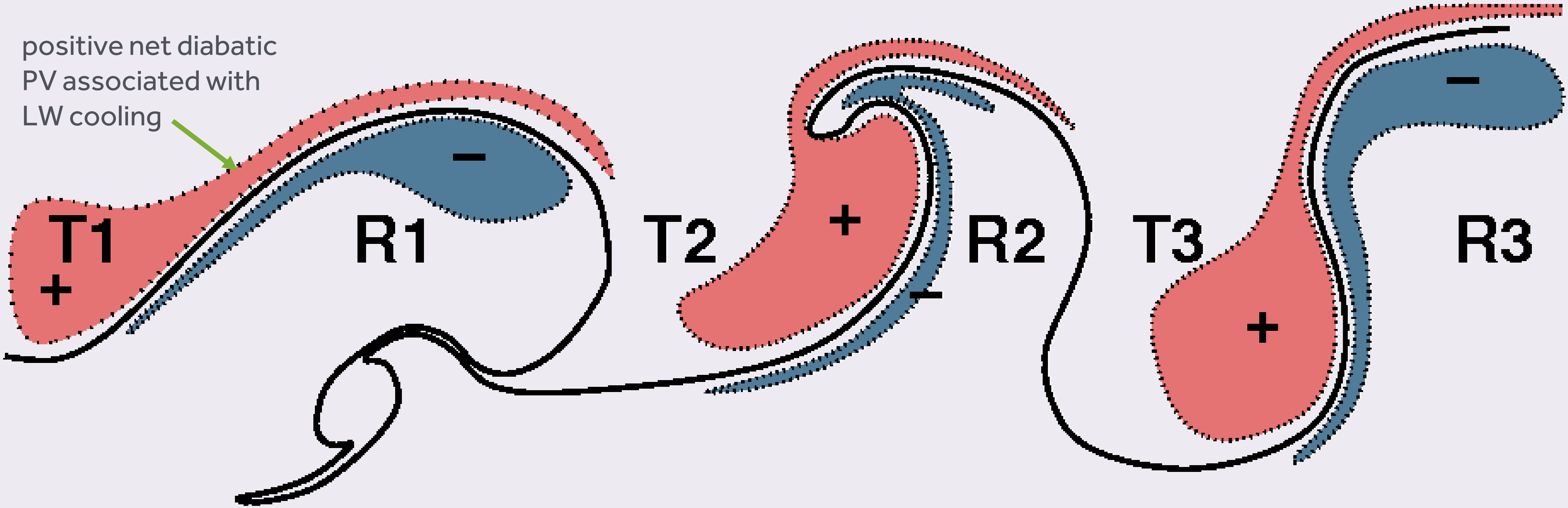


Joos and Wernli (2012)

Downstream impact

The main effect of diabatic PV is to enhance the anomalies associated with meridional displacements (from a zonal background flow): the diabatic PV and dry PV anomalies are in phase.

positive net diabatic PV associated with LW cooling



Schematic illustration of the diabatic PV dipole relative to the tropopause in an evolving wave

Chagnon et al. (2013)

Dynamic vs. diabatic contributions

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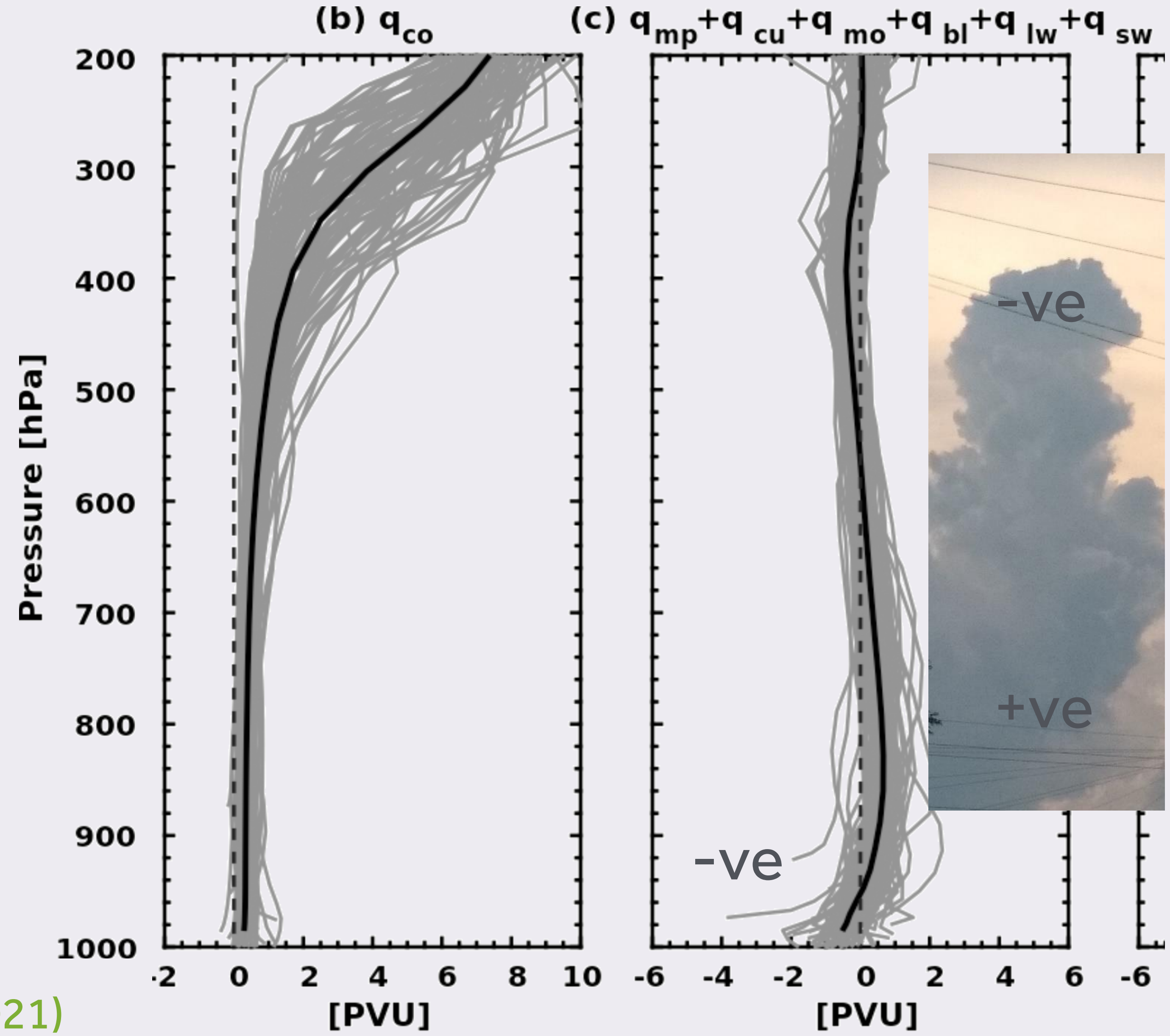
100 intense Mediterranean cyclones

Left: conserved PV – from advection of PV streamer into domain.

Possible role of mountains as PV sources at low levels in several cases (PV anomalies generated in wake of mountains due to internal dissipation of the airflow)

Right: non-conserved PV. Vertical profile consistent with diabatic processes.



Flaounas et al (2021)

Dynamic vs. diabatic contributions

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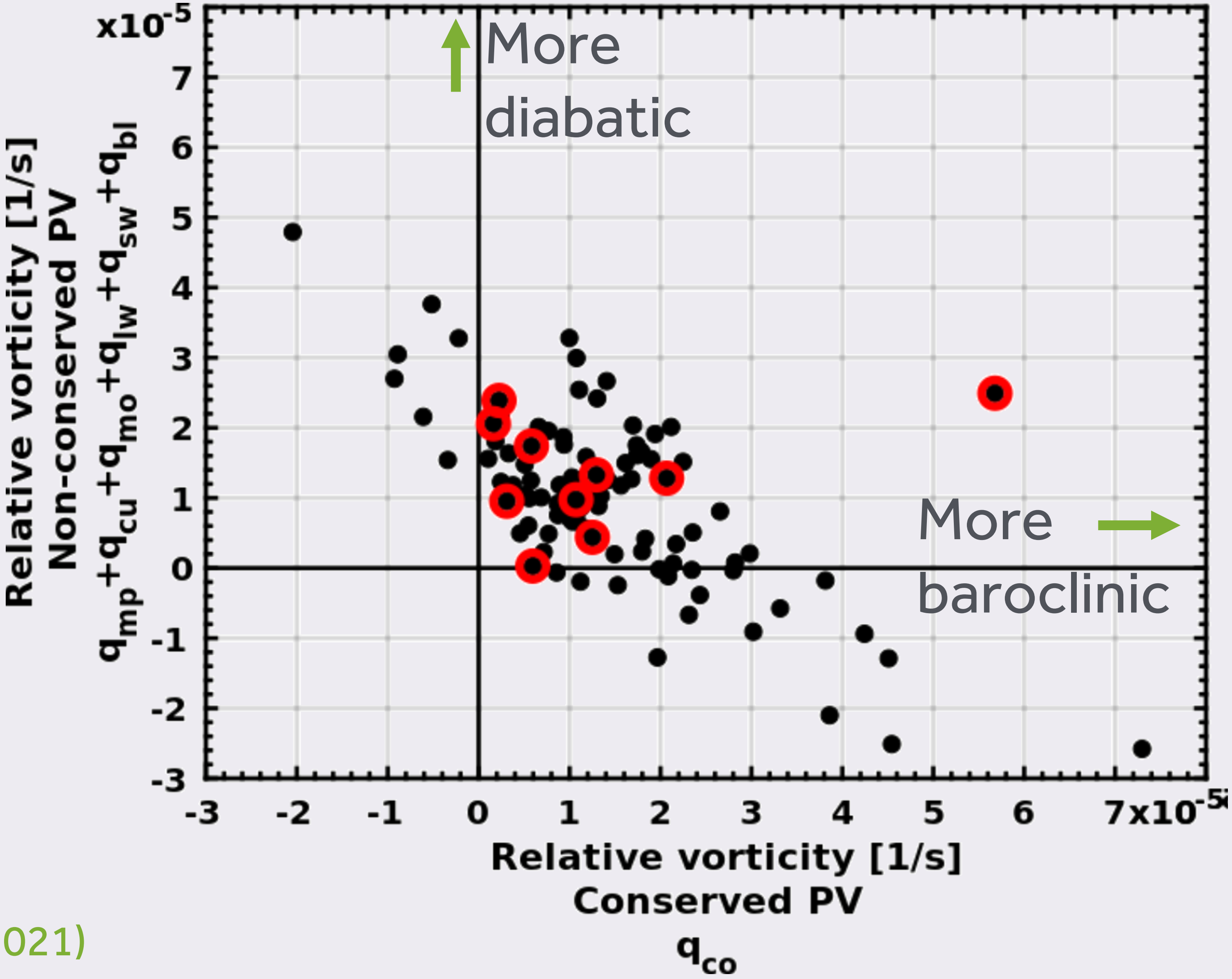
Balanced 850 hPa relative vorticity due to conserved (dynamic) and non-conserved (diabatic) PV.

Average values within 300 km radius of centre.

Medicanes are in red.

Inverse relationship

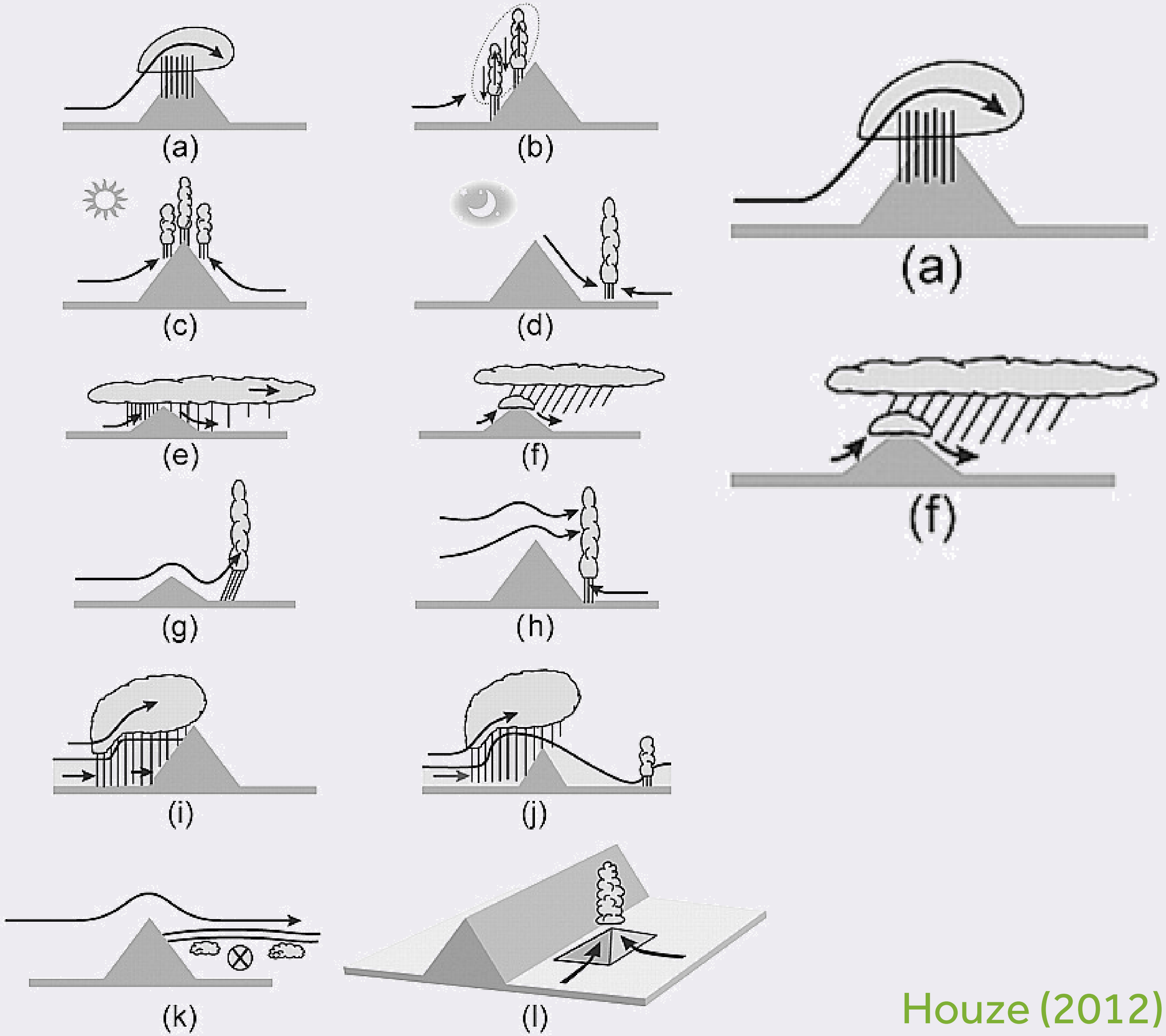


Flaounas et al (2021)

Orographic processes

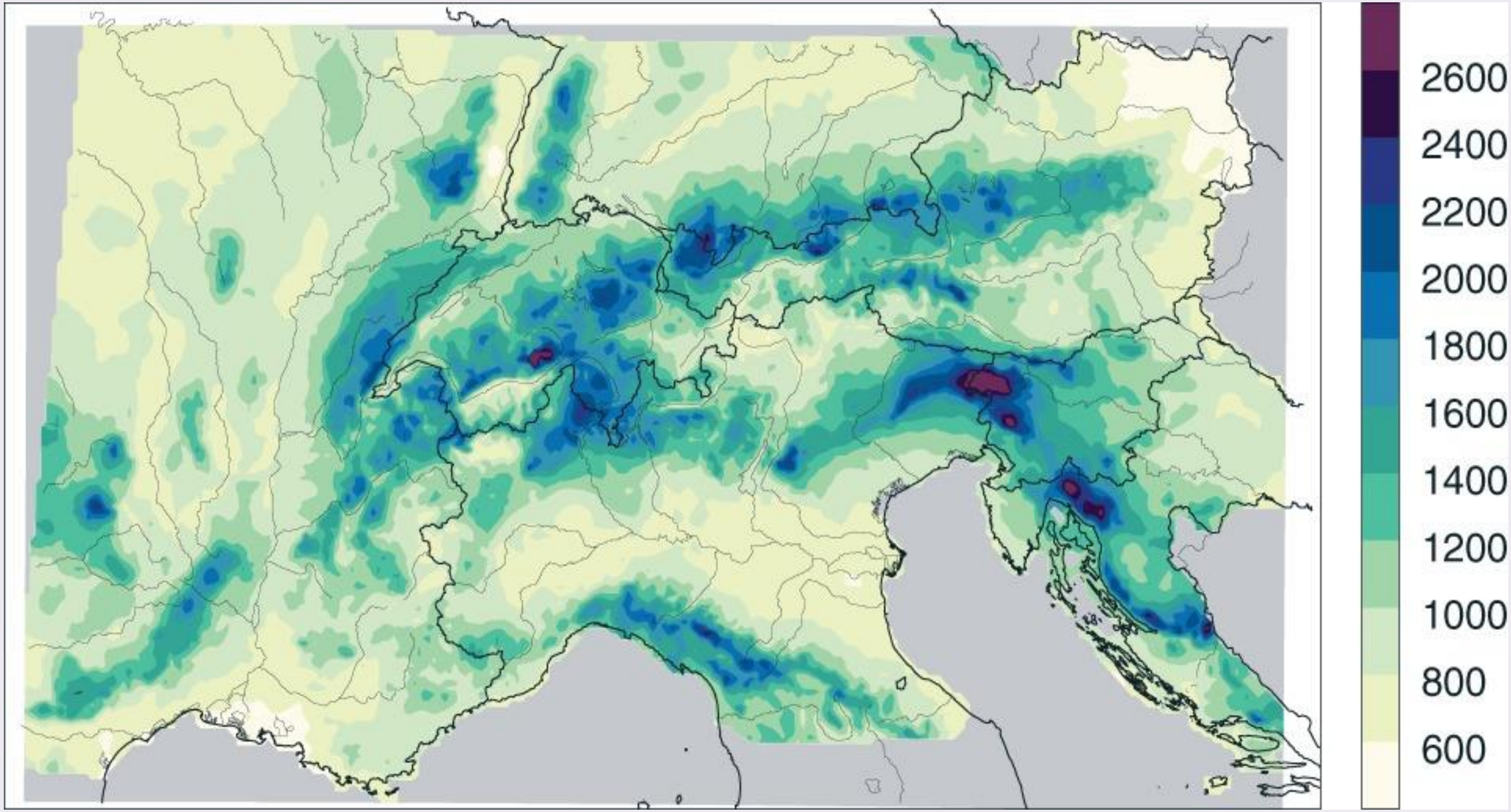
Orographic precipitation enhancement

(a) Laminar upslope flow
(b) Overturning upslope flow
(c) Diurnal forcing – solar heating
(d) Diurnal forcing – nighttime cooling
(e) Pre-existing cloud layer enhancement over small hill (no lee-side evaporation)
(f) Seeder-feeder: pre-existing cloud (seeder) + shallow orographic cloud (feeder)
(g) Lee waves
(h) Lee wave interaction with cloud fed by low-level moist flow
(i) Flow blocking
(j) Partial flow blocking with lee side super-critical flow and hydraulic jump
(k) Downslope flow on lee of major mountains leading to capping inversion and PI.
(l) Instability release by mountain foothills.



Houze (2012)

Example: the Alps

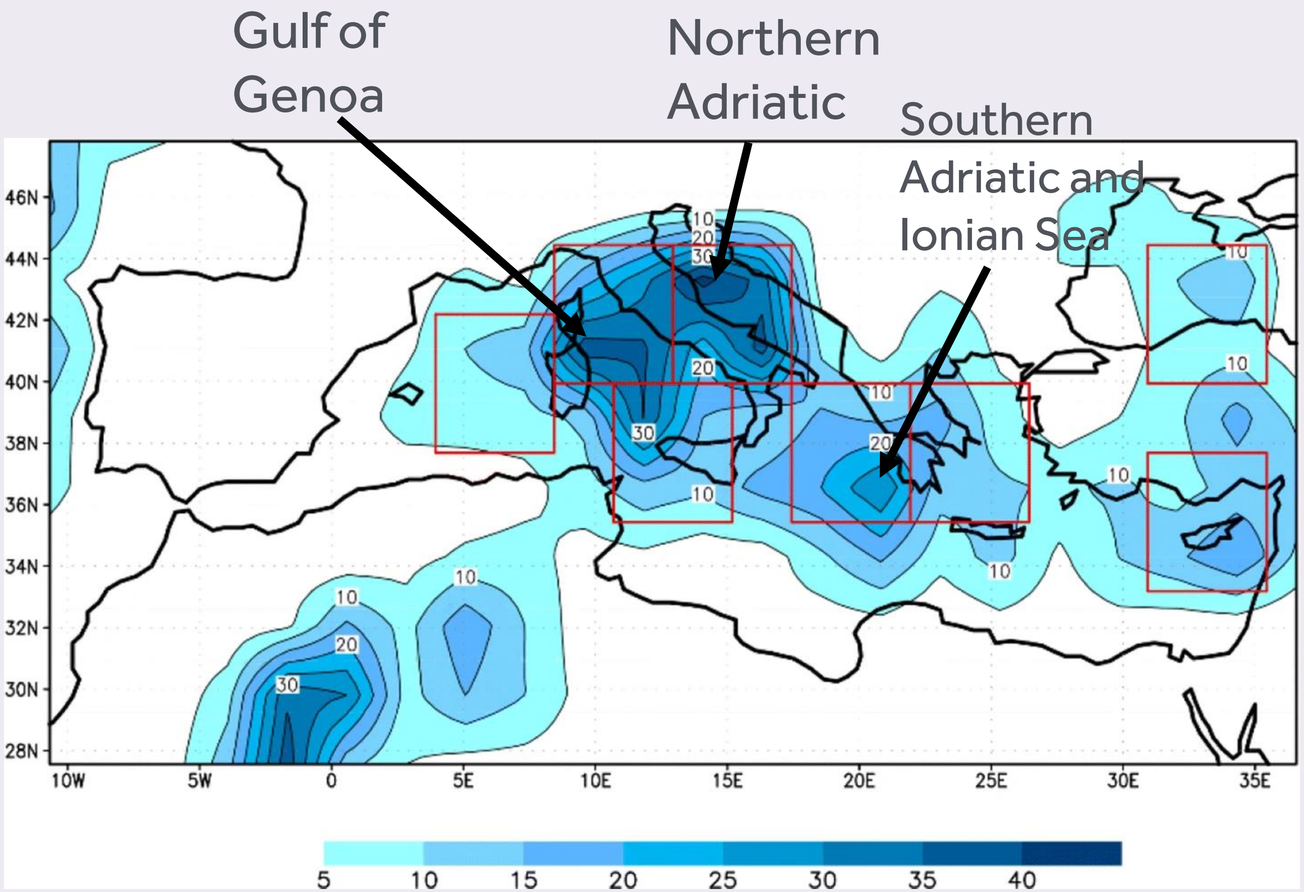


Mean annual precipitation (mm per year) for the period 1971–2008.

Isotta et al. (2013)

Lee cyclogenesis

Mediterranean cyclogenesis frequently occurs in the lee of mountains



Number of intense cyclones that achieve max. circulation in grid box over 45-year period

Homar et al. (2006)

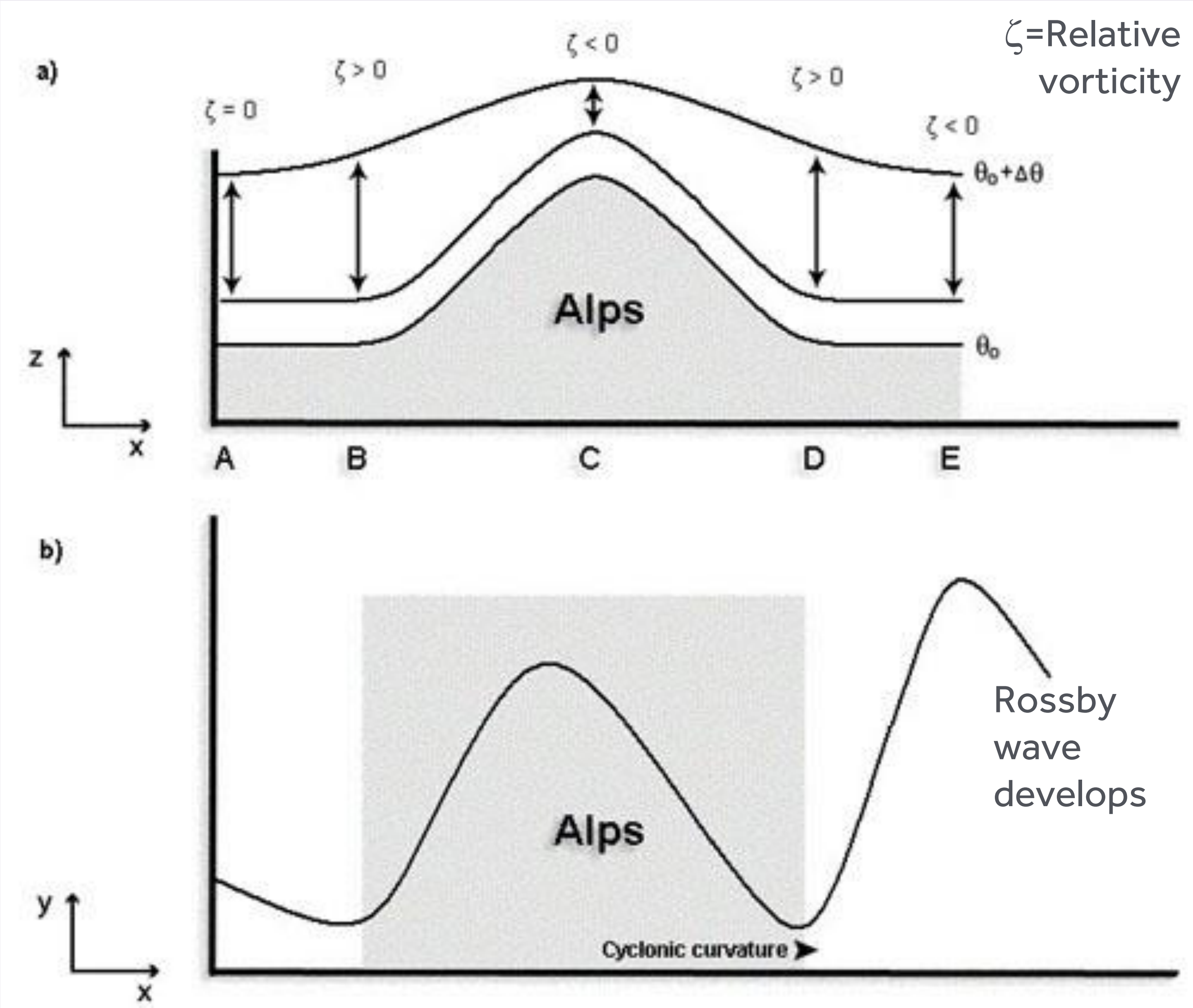
Lee cyclogenesis

lee cyclogenesis (AMS glossary)

- (*Also called* orographic cyclogenesis.) The synoptic-scale development of an atmospheric cyclonic circulation on the downwind side of a mountain range.

- Weak development giving rise to a lee trough can occur due to a redistribution of uniform vorticity as large-scale flow passes over a mountain barrier (conservation of PV implies that an increase in $|\partial\theta/\partial p|$ leads to a decrease of relative vorticity and vice versa).

Note: *f* also changes as flow moves meridionally so modifying vorticity changes



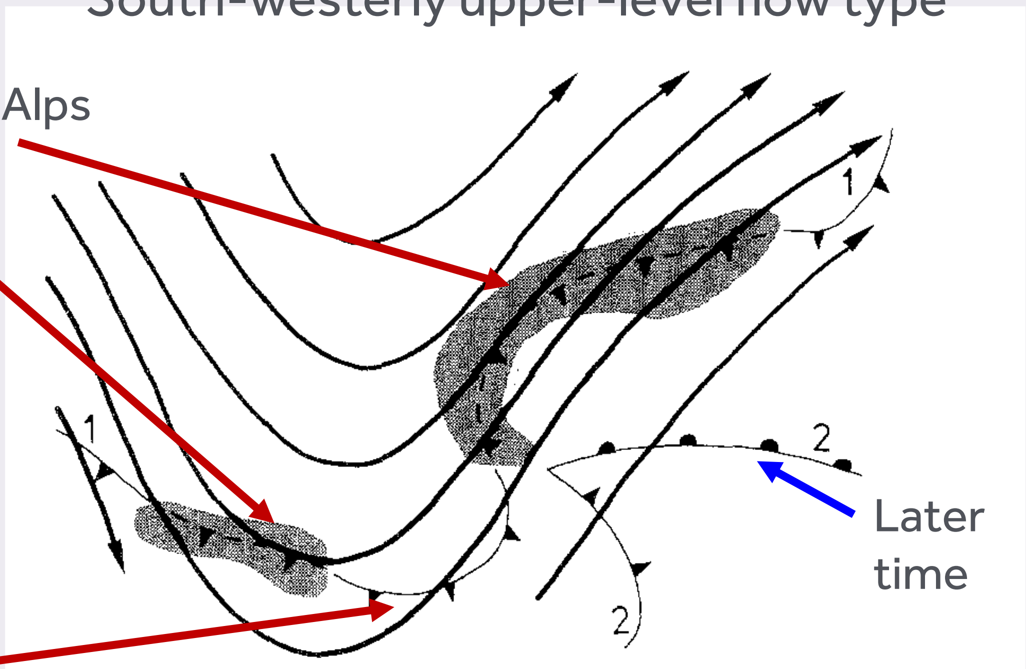
From EUMetrain

Lee cyclogenesis

- Stronger development occurs when the mountain range interacts with a developing baroclinic wave. In this instance the mountain acts to position the cyclone or generate a secondary cyclone in the lee.

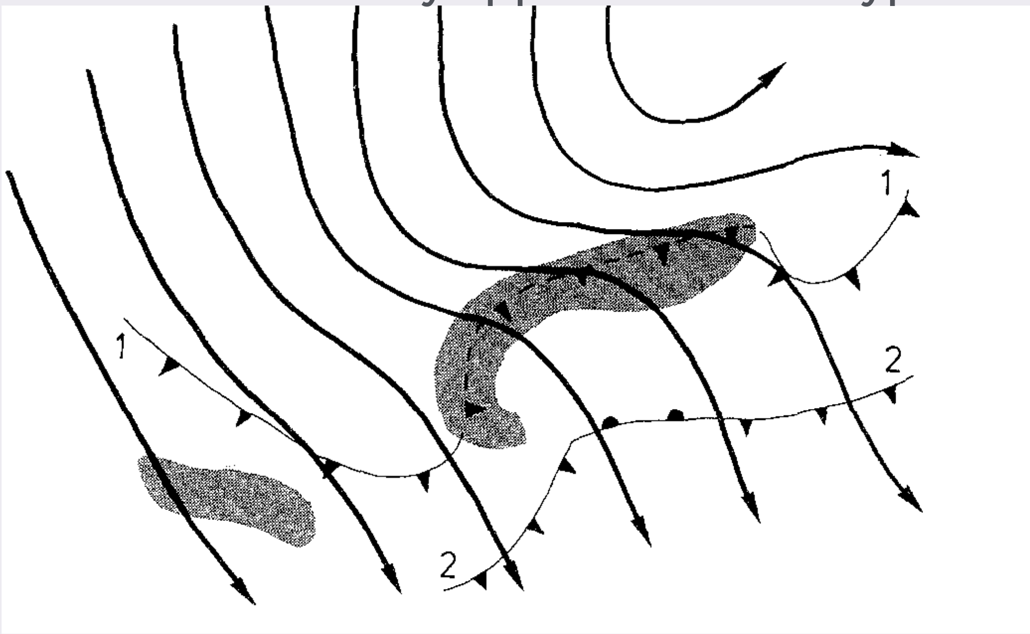
South-westerly upper-level flow type

Pyrenees and Alps



Wave in cold front corresponding to upper-level trough

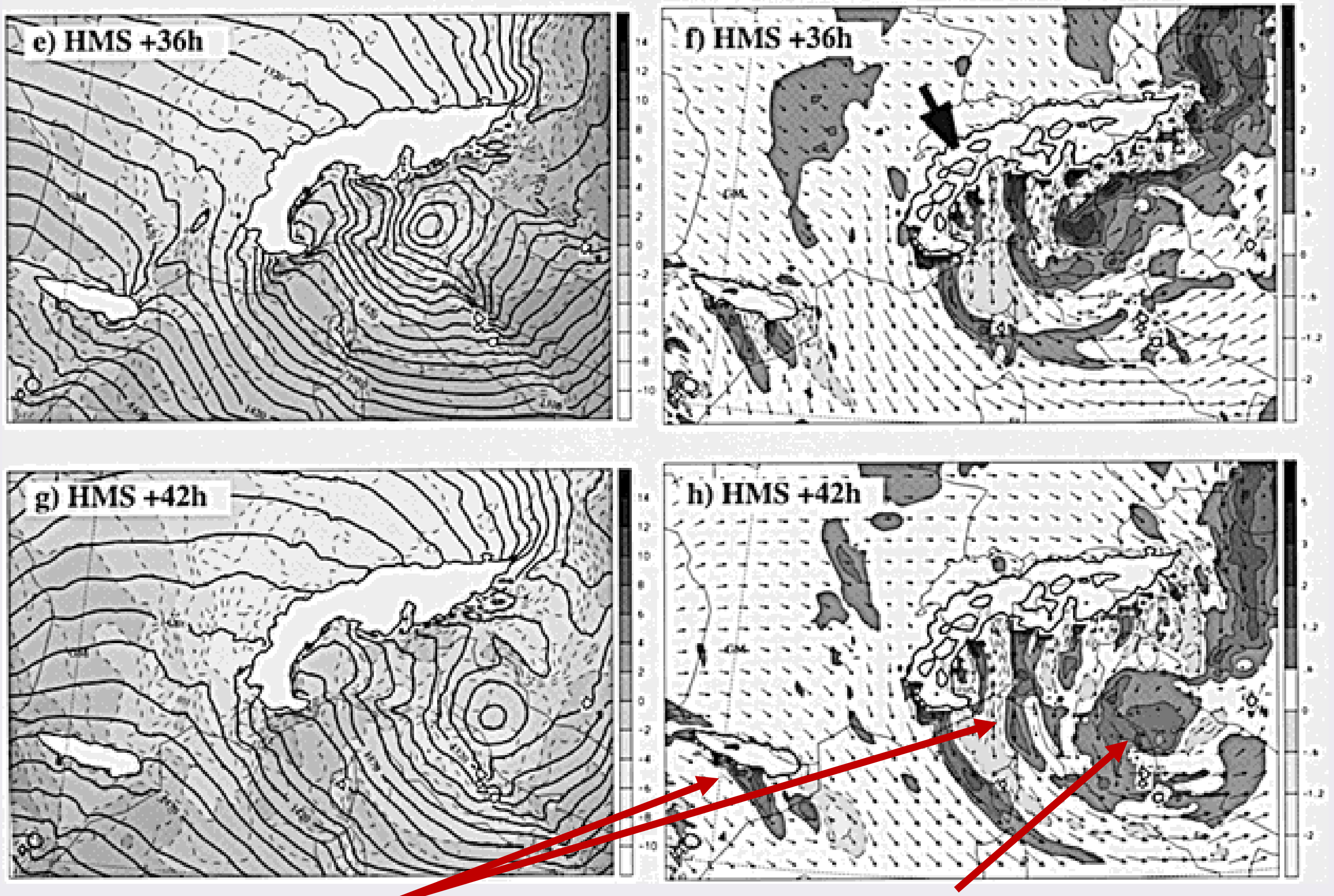
North-westerly upper-level flow type



Pichler and Steinacker (1985)

Potential vorticity banners

- Low-level elongated bands of PV can form downstream of high orography such as the Alps.
- Individual pairs of banners with anomalously +ve and –ve PV are due to flow splitting.
- Primary banners – splitting on scale of the whole Alps.
- Secondary banners – splitting on scale of individual peaks.
- Width 50-150 km; length up to 1500 km; extend from surface up to ~500 hPa.
- Banners can wrap up and contribute to low-level PV anomaly in a developing lee cyclone.



PV banners due to flow splitting

Diabatically generated PV

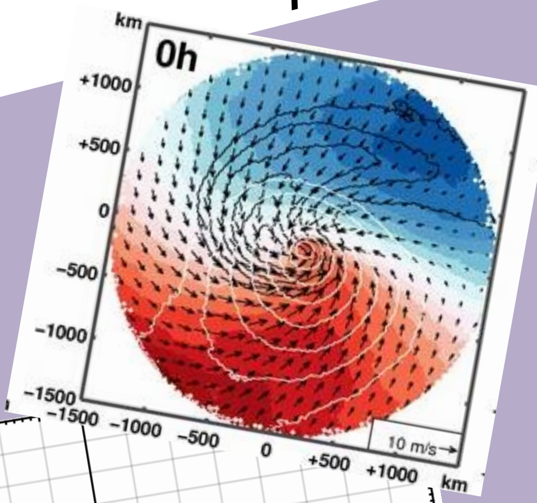
Left: 850-hPa geopotential and temperature.
Right: 850-hPa PV and wind vectors

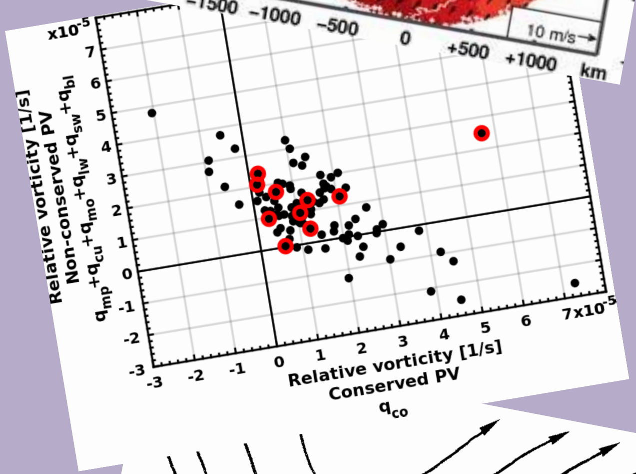
From Aebischer and Schär (1998)

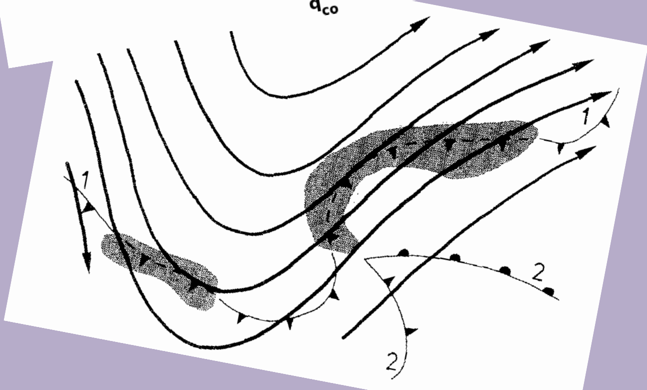
Summary

- Potential vorticity is a very useful diagnostic – conserved in adiabatic frictionless flow.
- Extratropical cyclones can develop through baroclinic instability in a dry environment but diabatic processes can modify the intensity and structure of cyclones and, in the Mediterranean, be important for cyclogenesis.
- A potential vorticity streamer or cut-off low system is commonly present close to intense Mediterranean cyclones implying baroclinic forcing.
- Baroclinic and diabatic processes are both important for intense Mediterranean cyclones (and the relative importance of these processes are inversely related).
- The complex orography surrounding the Mediterranean can be important for development and genesis of cyclones, as well as affecting the precipitation structure.

$$PV = \frac{(f + \xi) \cdot \nabla\theta}{\rho}$$







Balance: thermal wind balance

Combining geostrophic and hydrostatic balance gives **thermal wind balance**: horizontal gradients in buoyancy, *b* (which is related to potential temperature) are related to vertical wind shear.

$$\frac{\partial p}{\partial z} = -\rho g$$

Hydrostatic balance

low *p*

positive (cyclonic) relative vorticity

For $f > 0$
i.e., N. hemisphere

high *p*

Negative (anticyclonic) relative vorticity

cold

vorticity increases with height

$$\boxed{\frac{\partial \xi}{\partial z} \propto -b'}$$

Buoyancy anomaly (+ve for warm air)

warm

vorticity decreases with height

See textbook by Hoskins and James, section 12.2, for the derivation