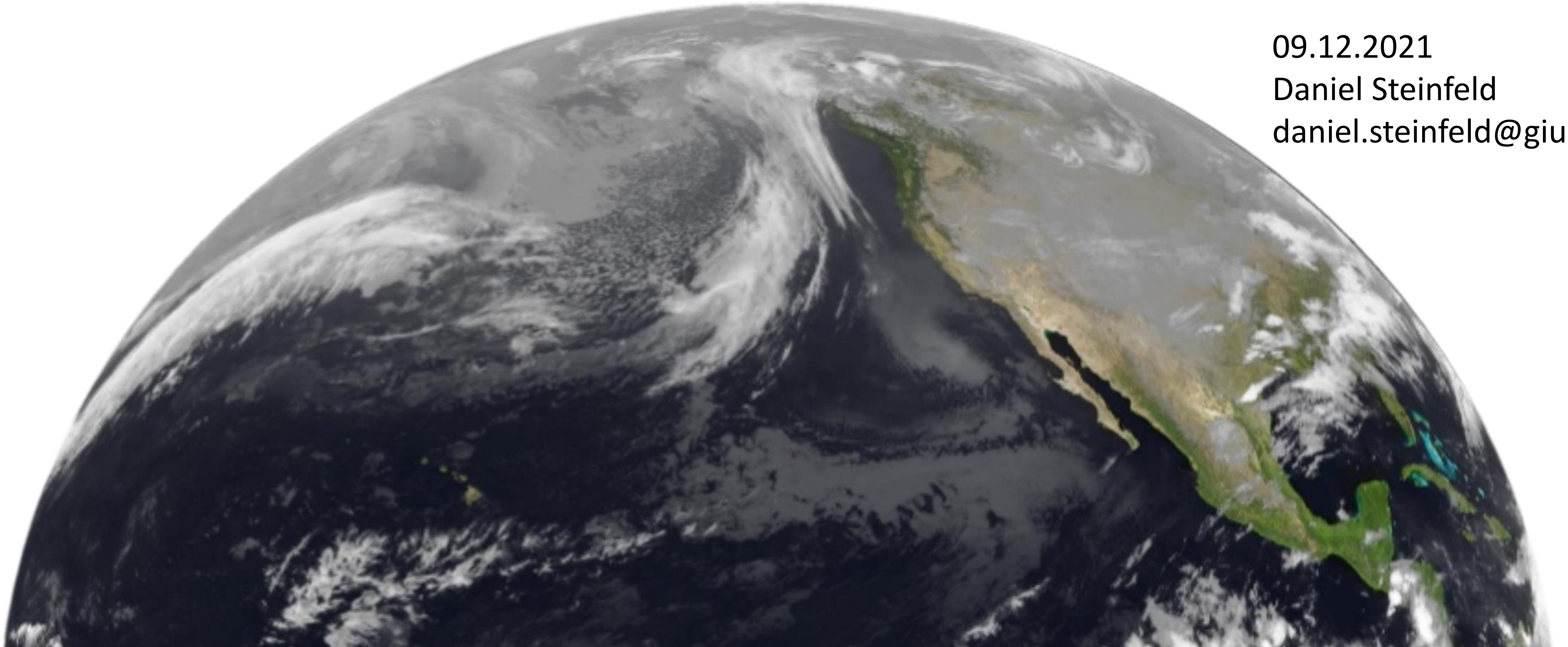
# Meteorology 3 – week 12

The Non-Conservation of Potential Vorticity
Atmospheric Blocking

UNIVERSITÄT BERN
OESCHGER CENTRE
CLIMATE CHANGE RESEARCH



09.12.2021
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# Today's Outline | Overview

Basics of Ertel PV

- Repetition (week 7/8)
- Identification of weather features on isentropic PV charts

Non-conservation of PV: the PV tendency equation

- Diabatic processes and warm conveyor belts
- Role of latent heating for large-scale atmospheric flow

Atmospheric blocking

# Ertel PV | Definition

repetition from week 7/8

**Ertel PV:**
Full Navier – Stokes eq.

$$PV = \frac{1}{\rho} \boldsymbol{\eta} \cdot \nabla\theta$$

Absolute Vorticity:
A measure of the rotation of an air mass

$$\boldsymbol{\eta} = \nabla \times \mathrm{u} + 2\Omega$$

Gradient of potential temperature:
stability of the atmosphere

$$\nabla\theta = \left(\frac{\partial\theta}{\partial x}, \frac{\partial\theta}{\partial y}, \frac{\partial\theta}{\partial z}\right)$$

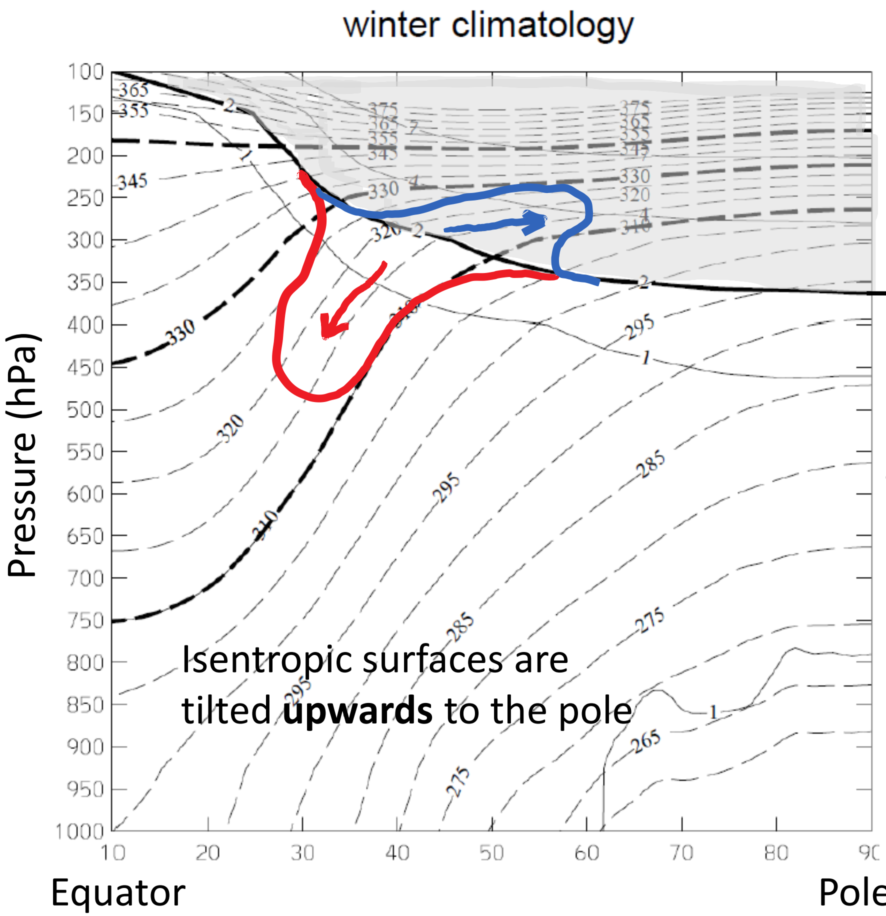
conserved along flow:
holds only for frictionless
& adiabatic flow!

$$\frac{D}{Dt} PV = 0$$

- contains information about the wind and temperature field (invertibility principle)
- very insightful maps of PV for weather diagnosis and forecast
- dynamics of weather systems (cyclones, blocking) can be understood as formation and interactions of PV anomalies

# Ertel PV | vertical distribution of PV and θ

repetition from week 7/8




**Stratosphere**:
High stability, high PV ( > 2 pvu)

**Tropopause**:
2 pvu isoline

**Troposphere**:
Low stability, low PV ( < 2 pvu)

**Ertel PV:** $PV = \frac{1}{\rho}\boldsymbol{\eta} \cdot \nabla\theta$

**Unit:** 1 pvu = $10^{-6}$ $m^2$ $s^{-1}$ K $kg^{-1}$

For adiabatic flow, wind follows the isentropic surfaces

Positive PV anomaly:
cyclonic wind field

Negative PV anomaly:
anticyclonic wind field

from Large Scale Dynamics lecture at ETH, by H. Wernli & L. Papritz

# Ertel PV | Isentropic PV maps

Vol. 111 OCTOBER 1985 No. 470

Quart. J. R. Met. Soc. (1985), 111, pp. 877–946 551.509.3:551.511.2:551.511.32

On the use and significance of isentropic potential vorticity maps

By B. J. HOSKINS[1], M. E. McINTYRE[2] and A. W. ROBERTSON[3]

[1] Department of Meteorology, University of Reading
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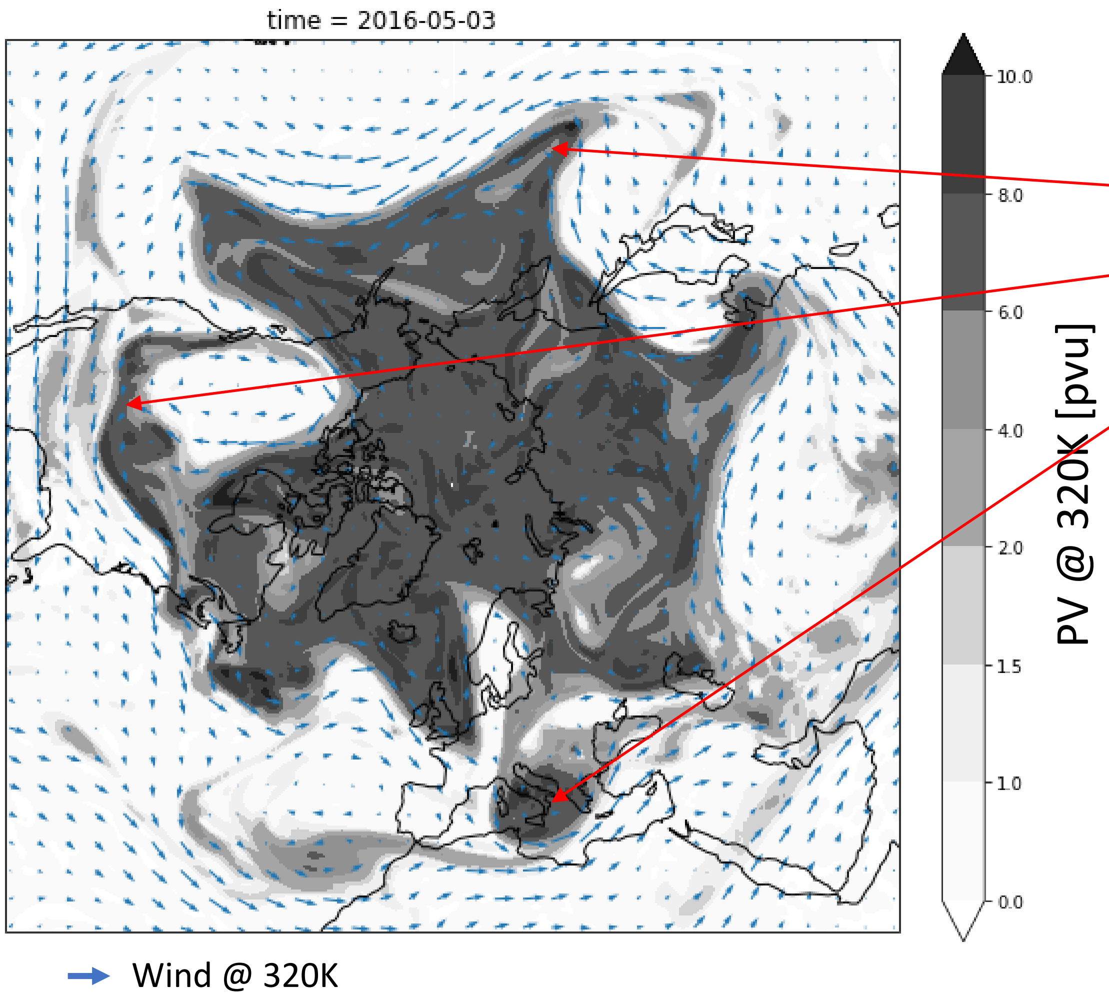


**Positive PV anomalies**:
equatorward extension of high-PV air

- troughs
- PV streamer
- stratospheric cut-off

**Negative PV anomalies:**
poleward extension of low-PV air

- ridges
- atmospheric blocking

**Formation:**

- meridional advection of PV in Rossby waves (undulations of the jet stream)
- Rossby wave breaking
  see week 8/9 about atmospheric waves

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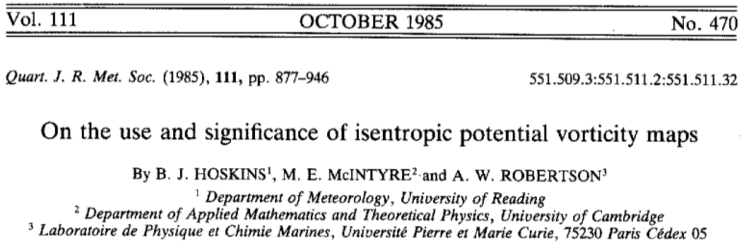

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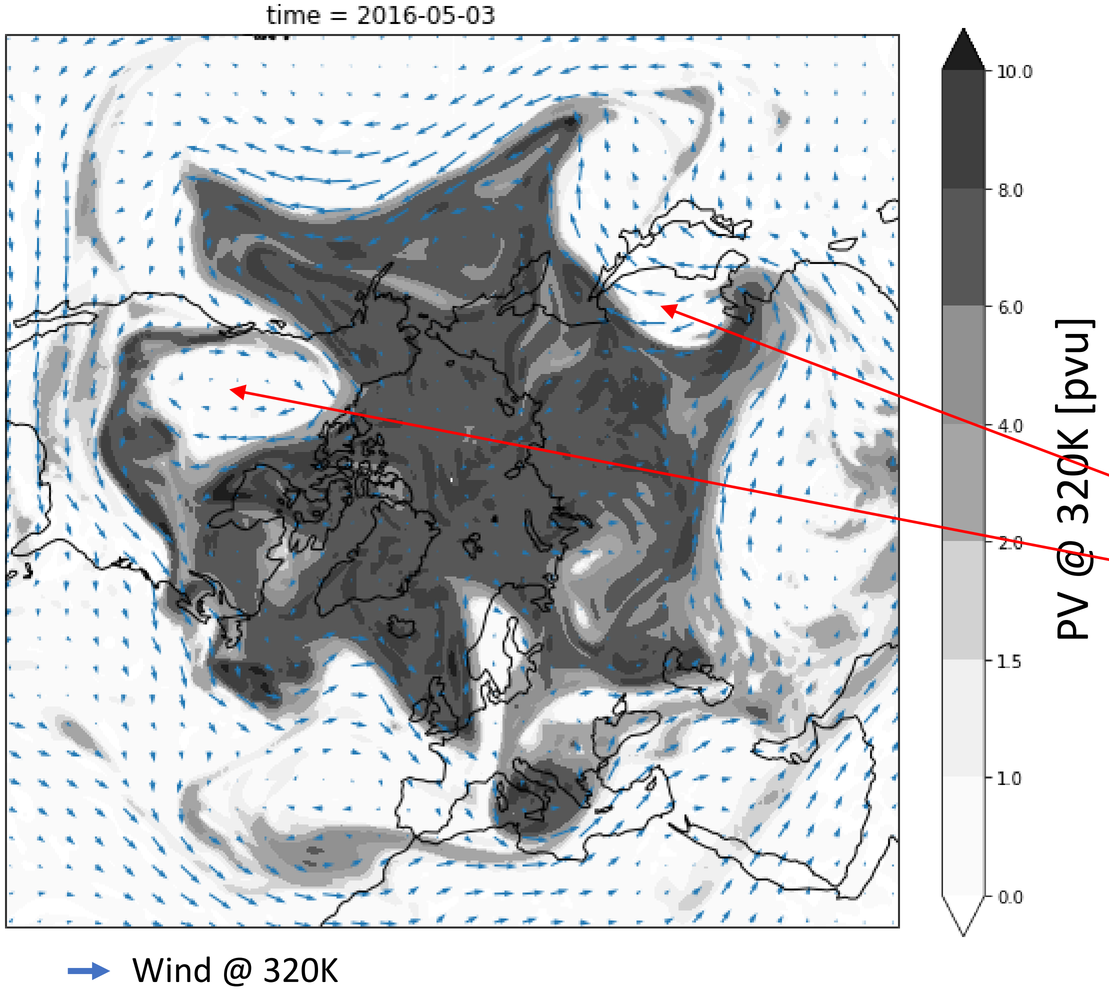


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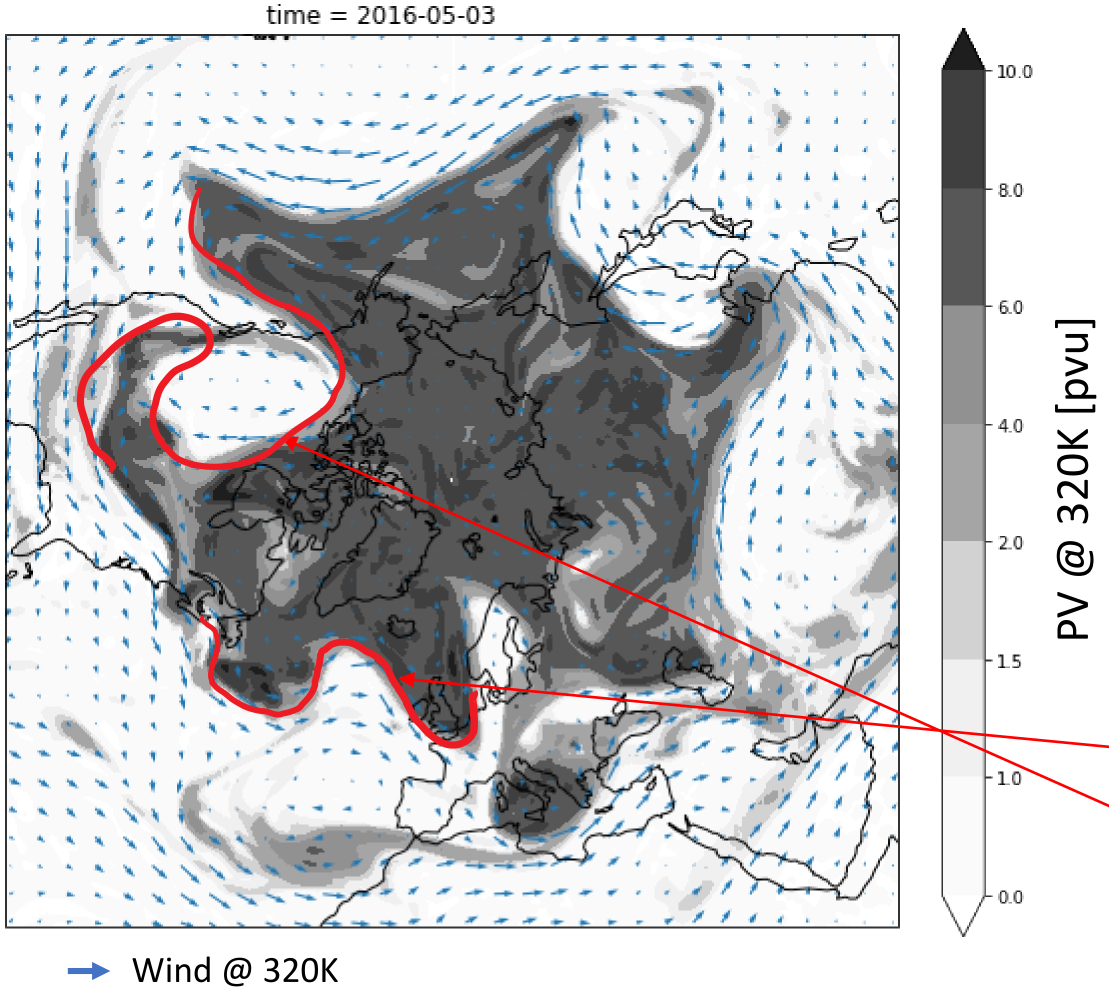


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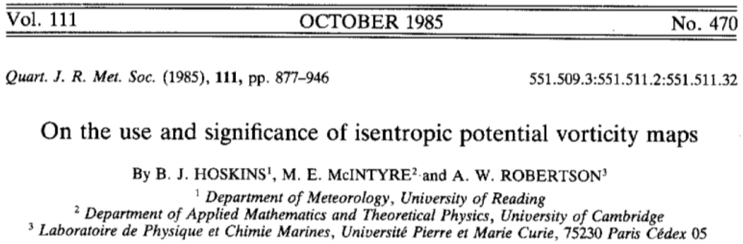
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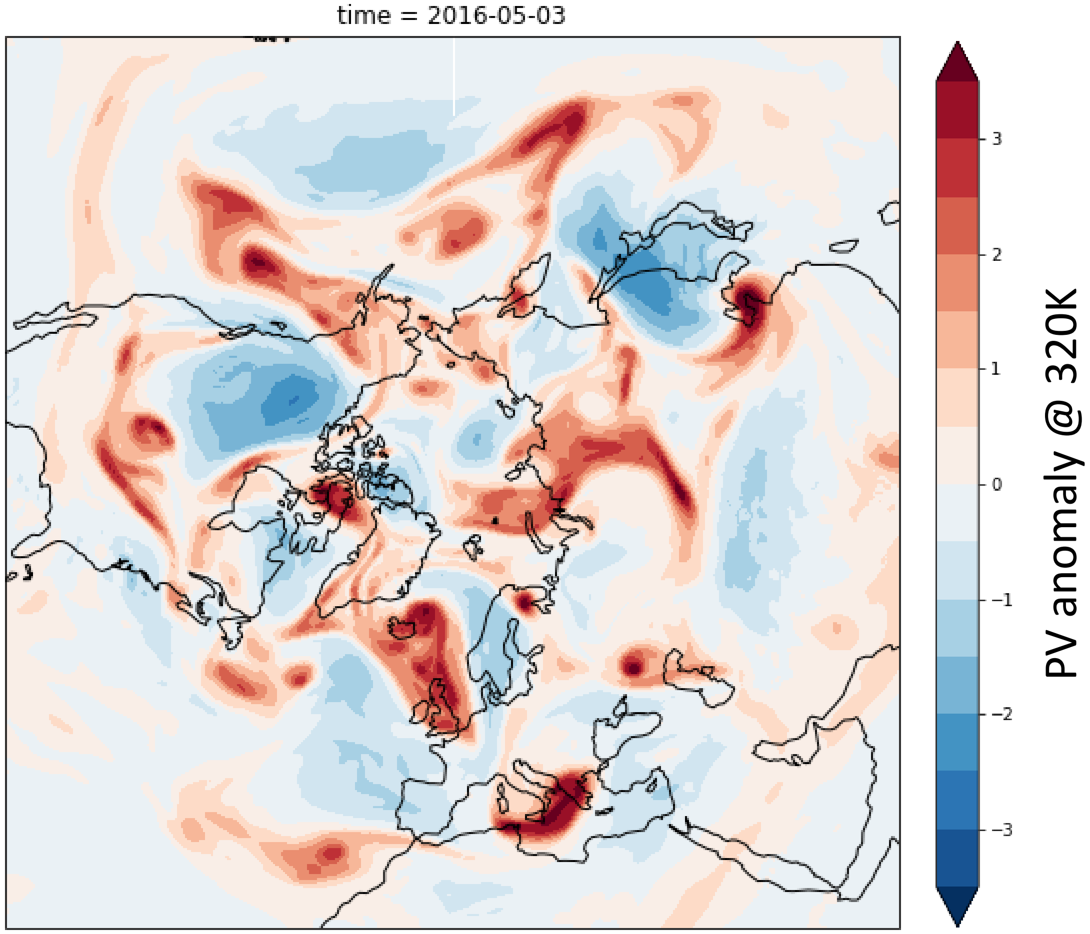


anomaly with respect to climatological mean

**Positive PV anomalies**:
equatorward extension of high-PV air
- troughs
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poleward extension of low-PV air
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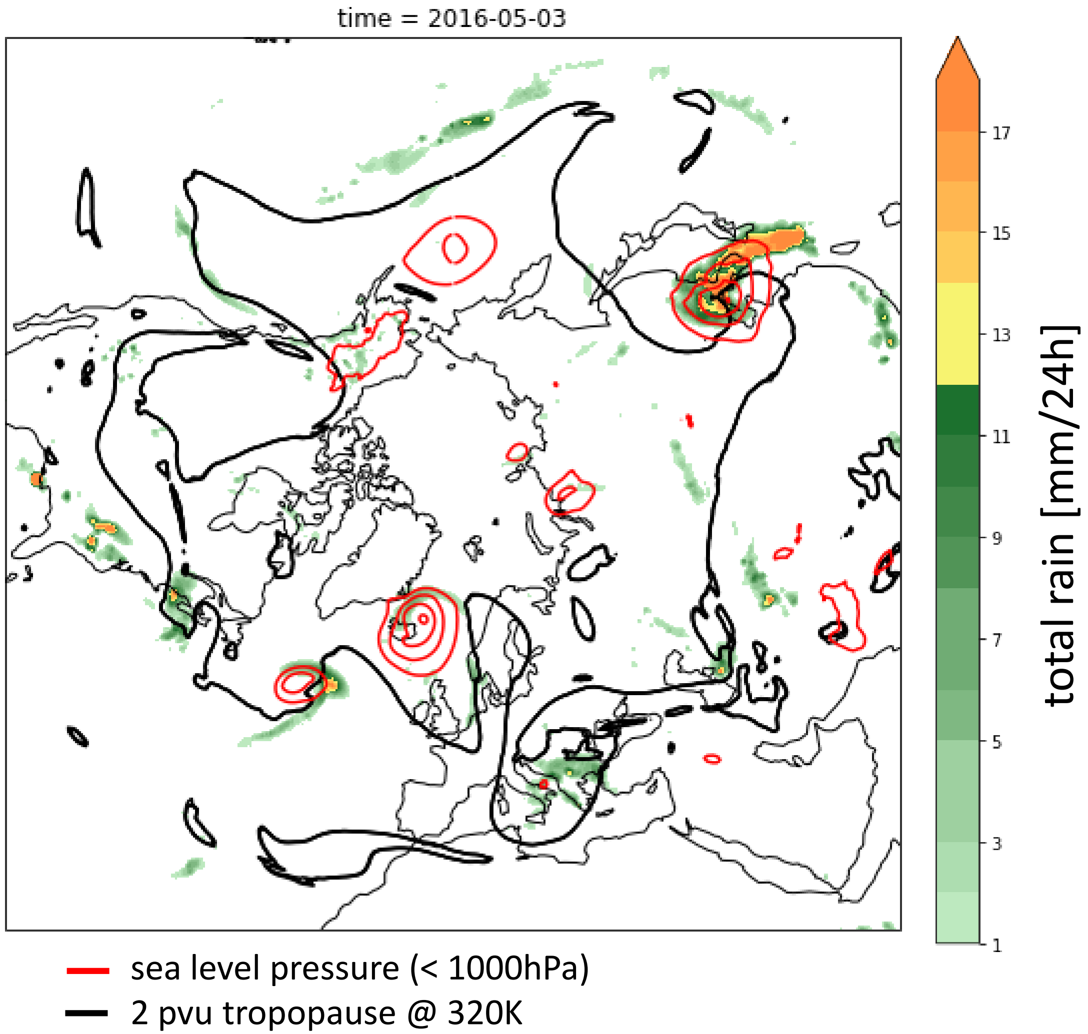
# Ertel PV | Isentropic PV maps




**Impact on surface weather**:

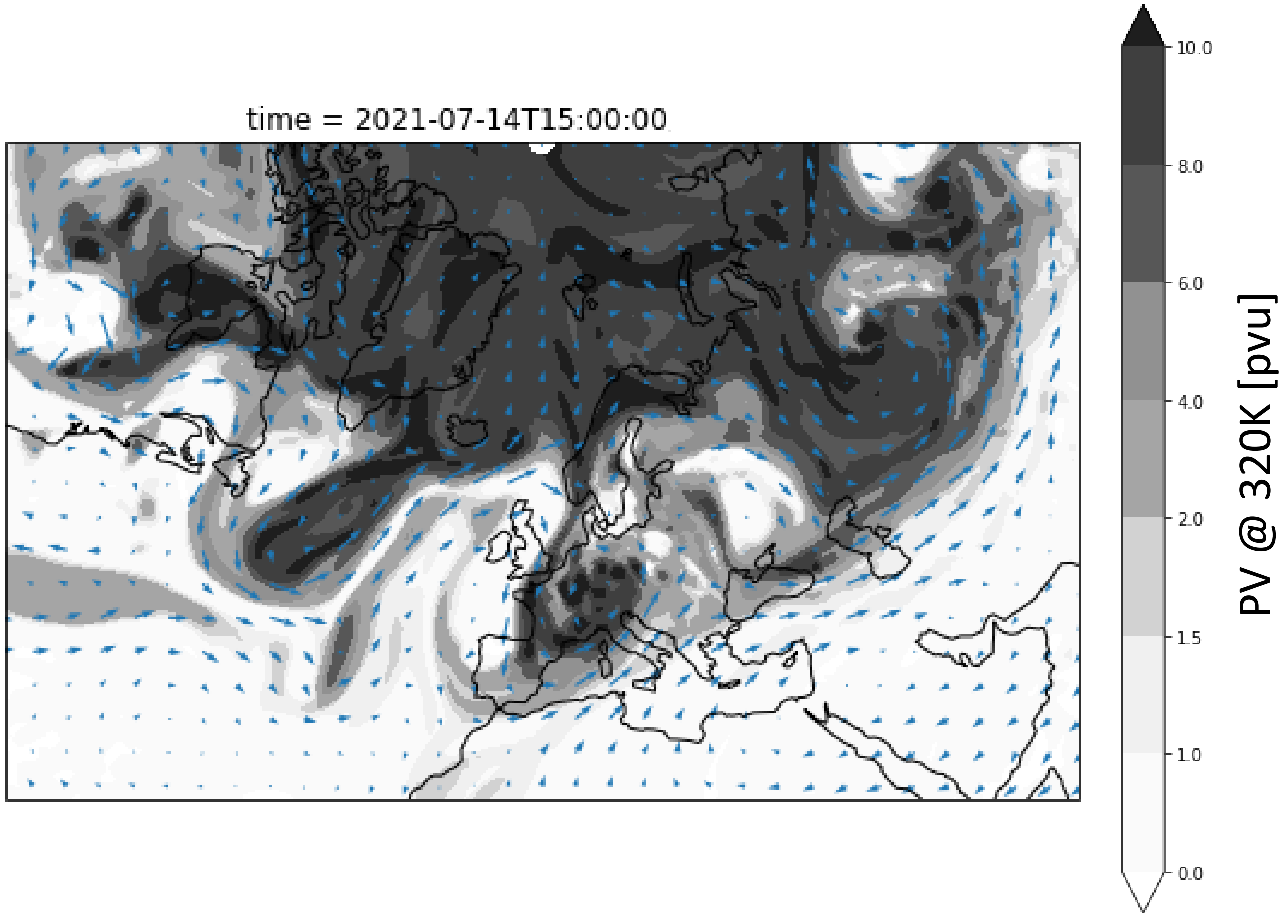
**Positive PV anomalies**:

- extratropical cyclone can form and intensify ahead of upper-level positive PV anomalies (see week 11)
- poleward advection of warm and moist air on eastern side
- cold air advection on western side
- decreased stability below cut-off

**Negative PV anomalies:**

- high-pressure system / anticyclone
- subsidence: dry and warm weather
- atmospheric blocking: prolonged stagnation of air can lead to temperature extremes (heat waves in summer and cold spells in winter)

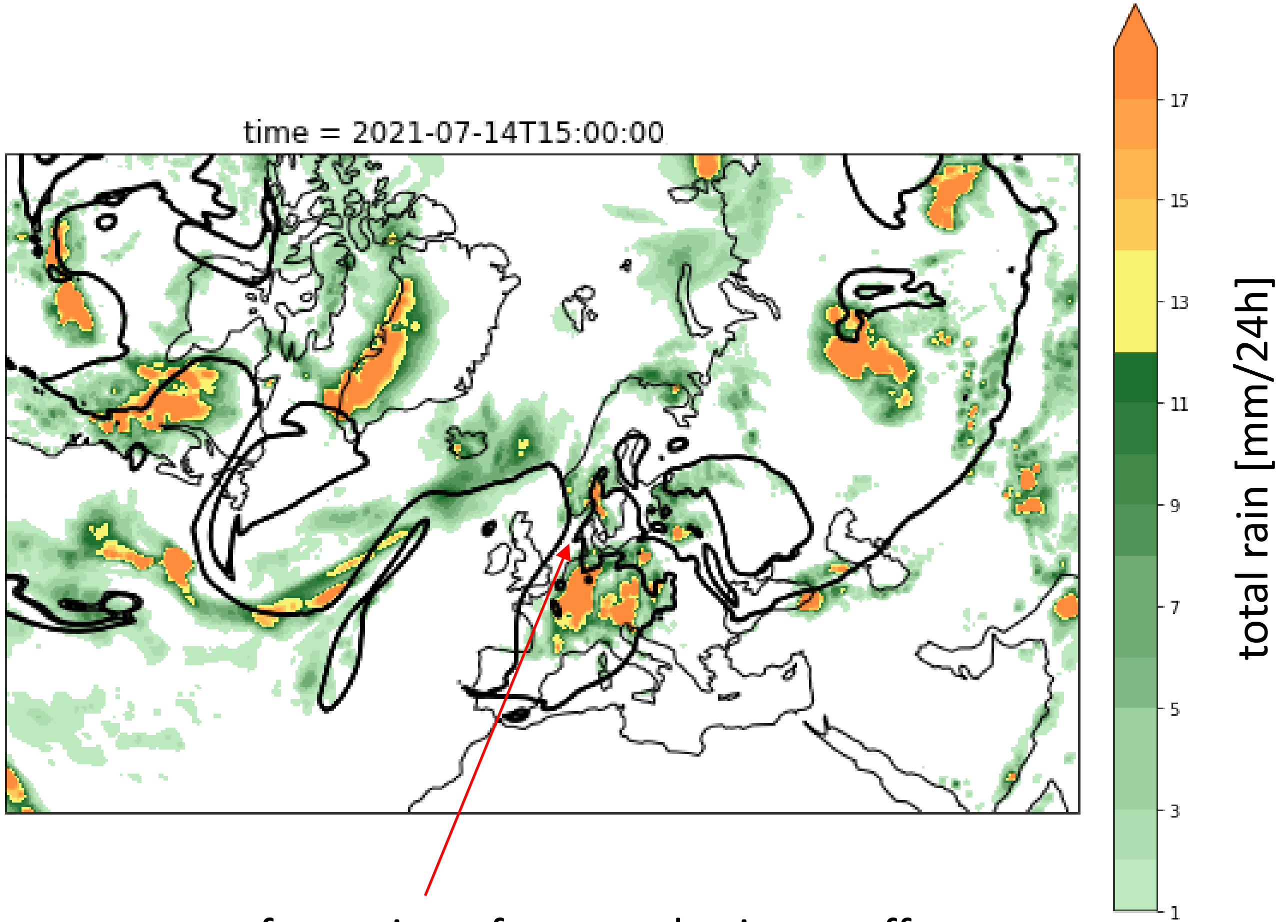
# Ertel PV | Isentropic PV maps - Exercise




**Try yourself**:

1. Highlight major upper-level PV features!
2. Where to you expect strong precipitation?

# Ertel PV | Isentropic PV maps - Exercise




formation of stratospheric cut-off

**2021 Summer European floods**

https://public.wmo.int/en/media/news/summer-of-extremes-floods-heat-and-fire

# Ertel PV | Some useful resources

**Forecasts**:

- https://apps.ecmwf.int/webapps/opencharts/products/medium-pv
- https://www.atmos.washington.edu/~hakim/tropo/310_pv.html

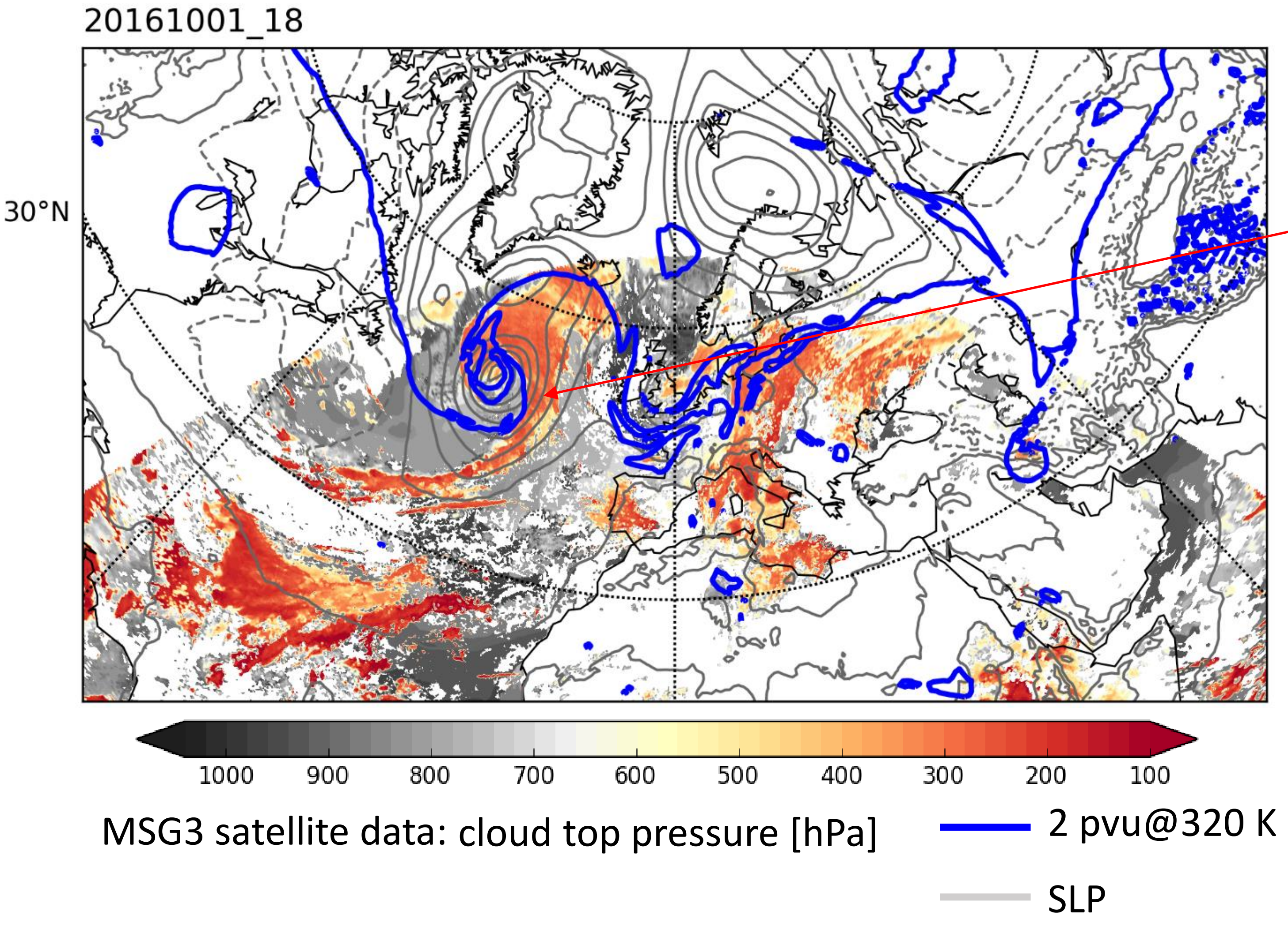
**Download ERA5 reanalysis dataset:**

- https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview

**Calculate PV yourself with MetPy in Python:**

- https://github.com/steidani/weather/blob/master/forecast/gfs_forecast_pv.ipynb

# Is the assumption of adiabatic flow a good one?




- stronlgy intensifying cyclone and amplyfing upper-levl ridge
- elongated band of high-reaching clouds

- Precipitation and clouds in cyclones = **latent heat release**
  - potential temperature is not conserved
  - fow is not adiabatic anymore

The assumption of adiabatic flow is **not** always satisfied!

**Diabatic effects** (e.g. latent heat release) modify PV and play an important role for the evolution of large-scale weather systems (as we will see now)

# PV non-conservation | Deriviation

We are looking for an evolution equation:

$$\frac{D}{Dt}PV = \frac{D}{Dt}\left(\frac{1}{\rho}\boldsymbol{\eta}\cdot\nabla\theta\right) = \ \dots$$

see week 1 for $\frac{D}{Dt}$

Plug in vorticity and thermodynamic energy equation:

Vorticity equation:

$$\frac{D}{Dt}\left(\frac{\boldsymbol{\eta}}{\rho}\right) = \left(\frac{\boldsymbol{\eta}}{\rho}\cdot\nabla\right)\boldsymbol{u} + \frac{1}{\rho^3}\cdot\nabla\rho\times\nabla\rho + \frac{1}{\rho}\nabla\times\mathbf{F}$$

frictional forces

see week 4 (only vertical component)

Thermodynamic energy equation:

$$\frac{D}{Dt}\theta = \dot{\theta} = \left(\frac{\theta}{c_p T}\cdot\nabla\right)H$$

latent heat release

see week 2

… such that the material rate of change of PV is given by:

$$\frac{D}{Dt}PV = \frac{\boldsymbol{\eta}}{\rho}\cdot\nabla\dot{\theta} + \frac{1}{\rho}\nabla\theta\cdot\nabla\times\mathbf{F}$$

diabatic changes — frictional changes

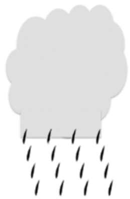
# PV non-conservation | Diabatic modification of PV

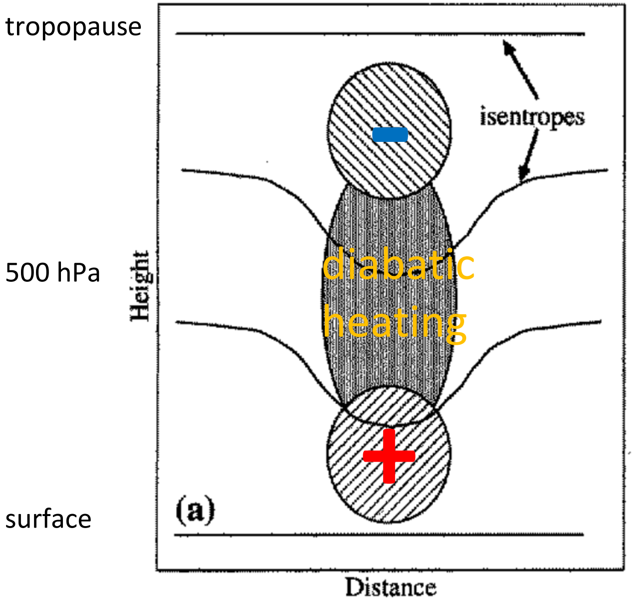
Material rate of change of PV (approx. for large scale) :

$$\frac{D}{Dt}PV = \frac{\boldsymbol{\eta}}{\rho}\cdot\nabla\dot{\theta} + \frac{1}{\rho}\nabla\theta\cdot\nabla\times\mathbf{F} \cong \boxed{\frac{1}{\rho}(\zeta + f)\cdot\frac{\partial\dot{\theta}}{\partial z}}$$

Vertical absolute vorticity

Vertical gradient of the diabatic heating rate





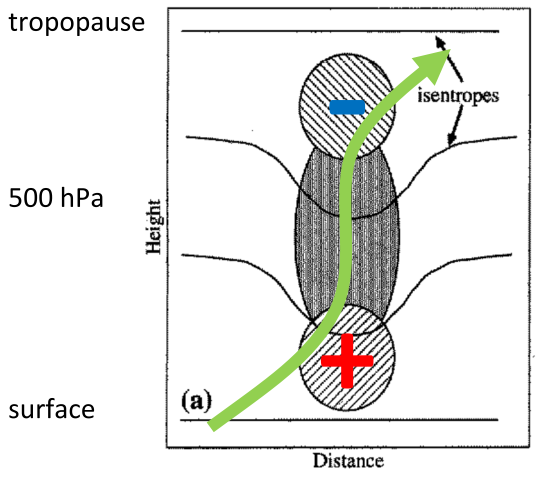

Wernli and Davies, 1997

$\frac{\partial\dot{\theta}}{\partial z} < 0$: PV destruction → generation of negative PV anomaly in upper troposphere

$\frac{\partial\dot{\theta}}{\partial z} > 0$: PV production → generation of positive PV anomaly in lower troposphere

see week 11: cyclone intensification

# PV non-conservation | Diabatic modification of PV in WCB




$\frac{\partial \dot{\theta}}{\partial z} < 0$: PV destruction

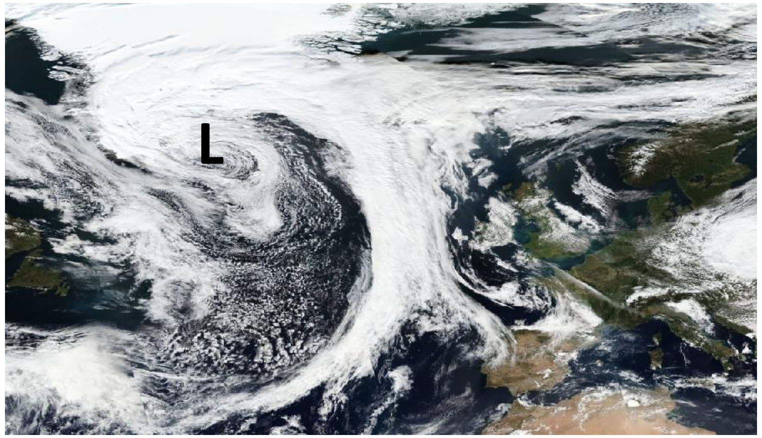
diabatic heating

$\frac{\partial \dot{\theta}}{\partial z} > 0$: PV production

**WCB** = warm conveyor belt (see week 11)

- ascent of > 600 hPa in 2 days
- latent heating > 20 K

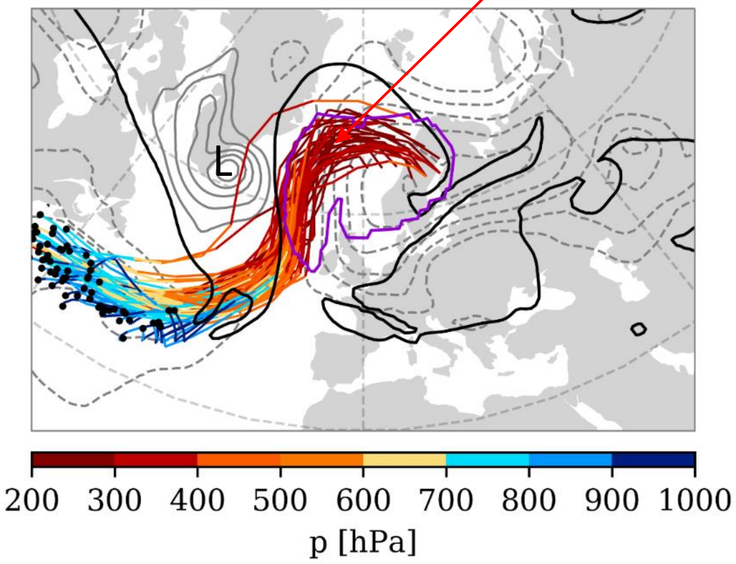
Madonna et al., 2014
Joos and Wernli, 2012
Binder et al., 2016

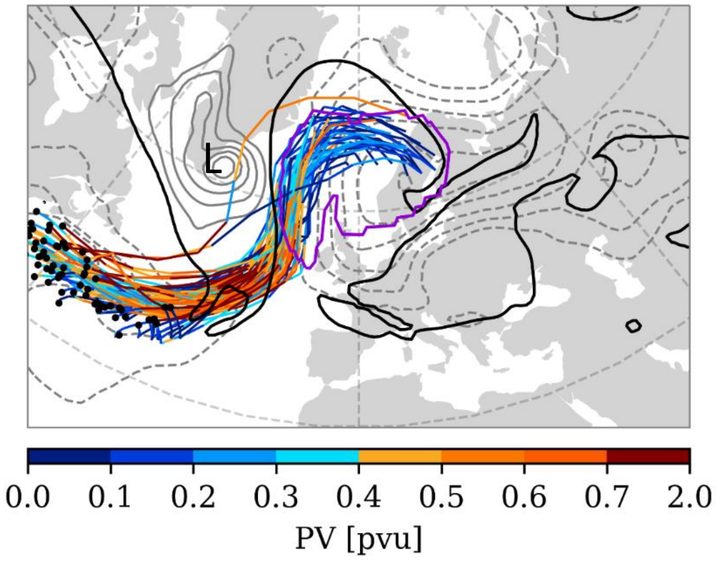



https://worldview.earthdata.nasa.gov/

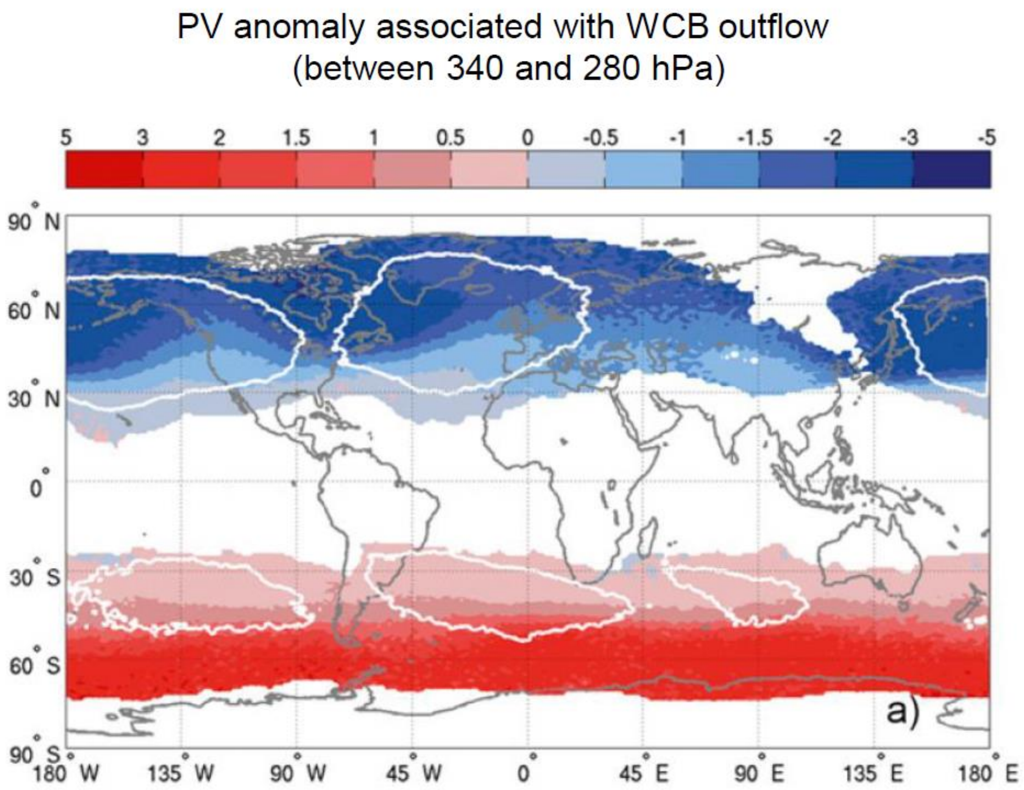
2 pvu @ 320 K
SLP
negative PV anomaly

air parcel trajectories

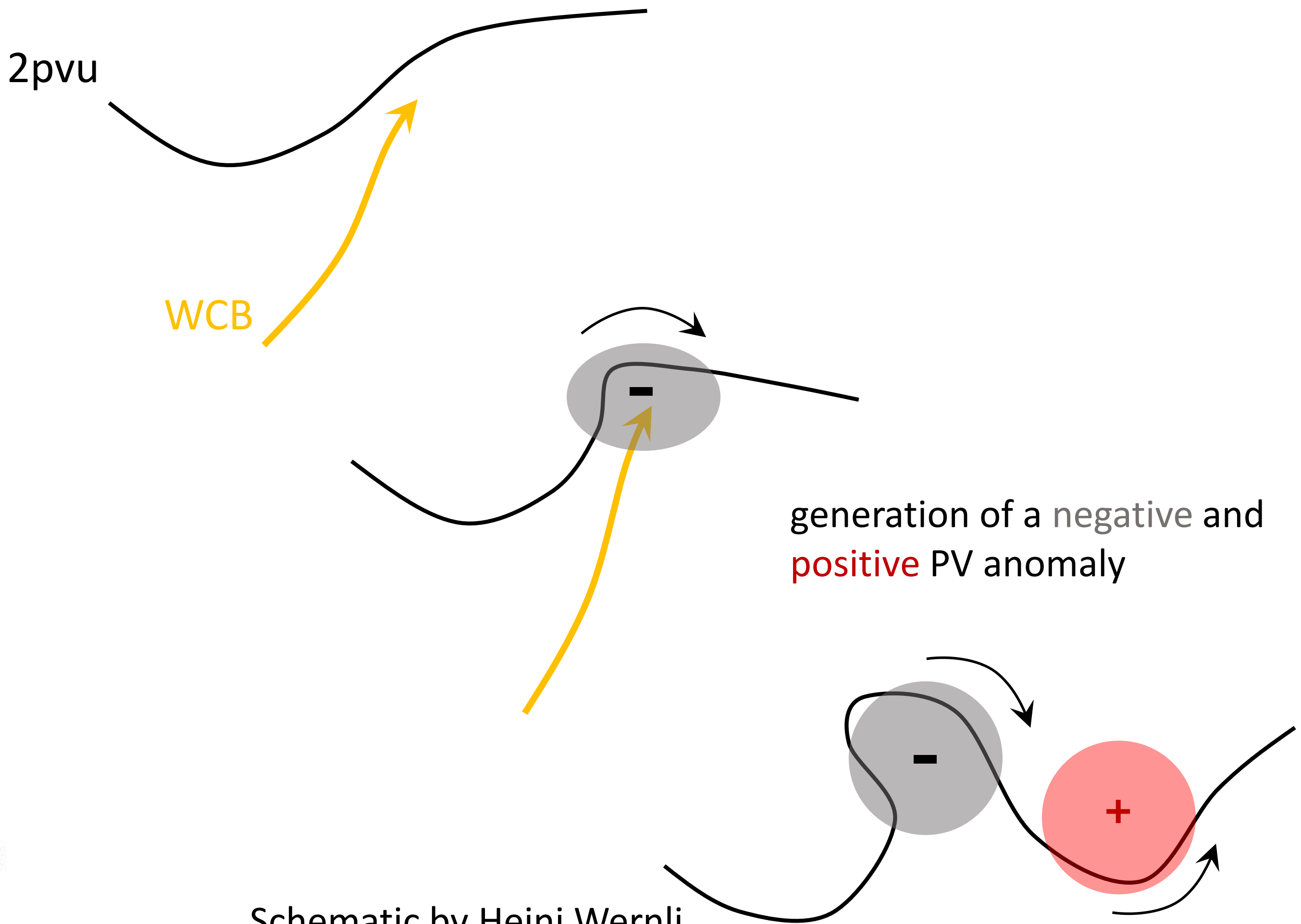


# PV non-conservation| Ridge amplification due to low PV in WCB outflow

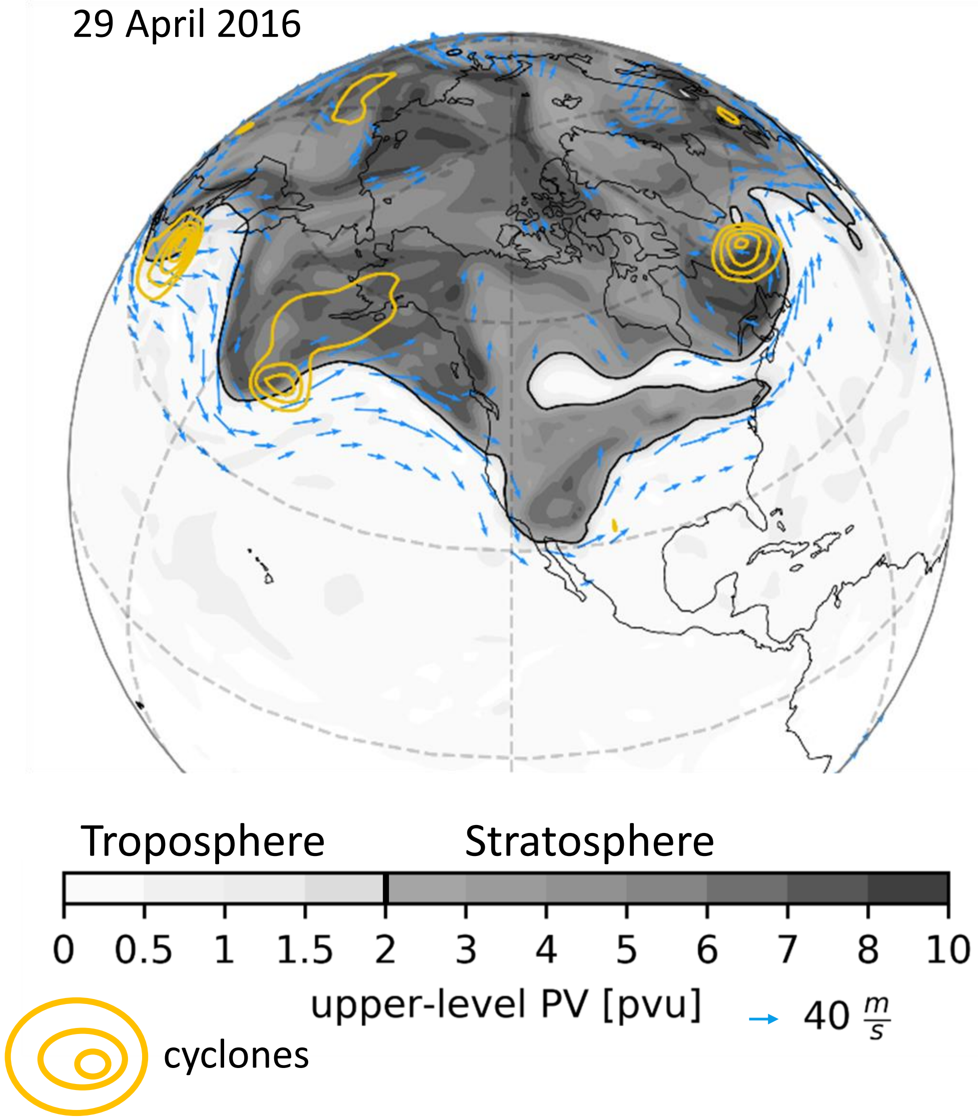



Madonna et al., 2014




Schematic by Heini Wernli

# Atmospheric blocking| Definition



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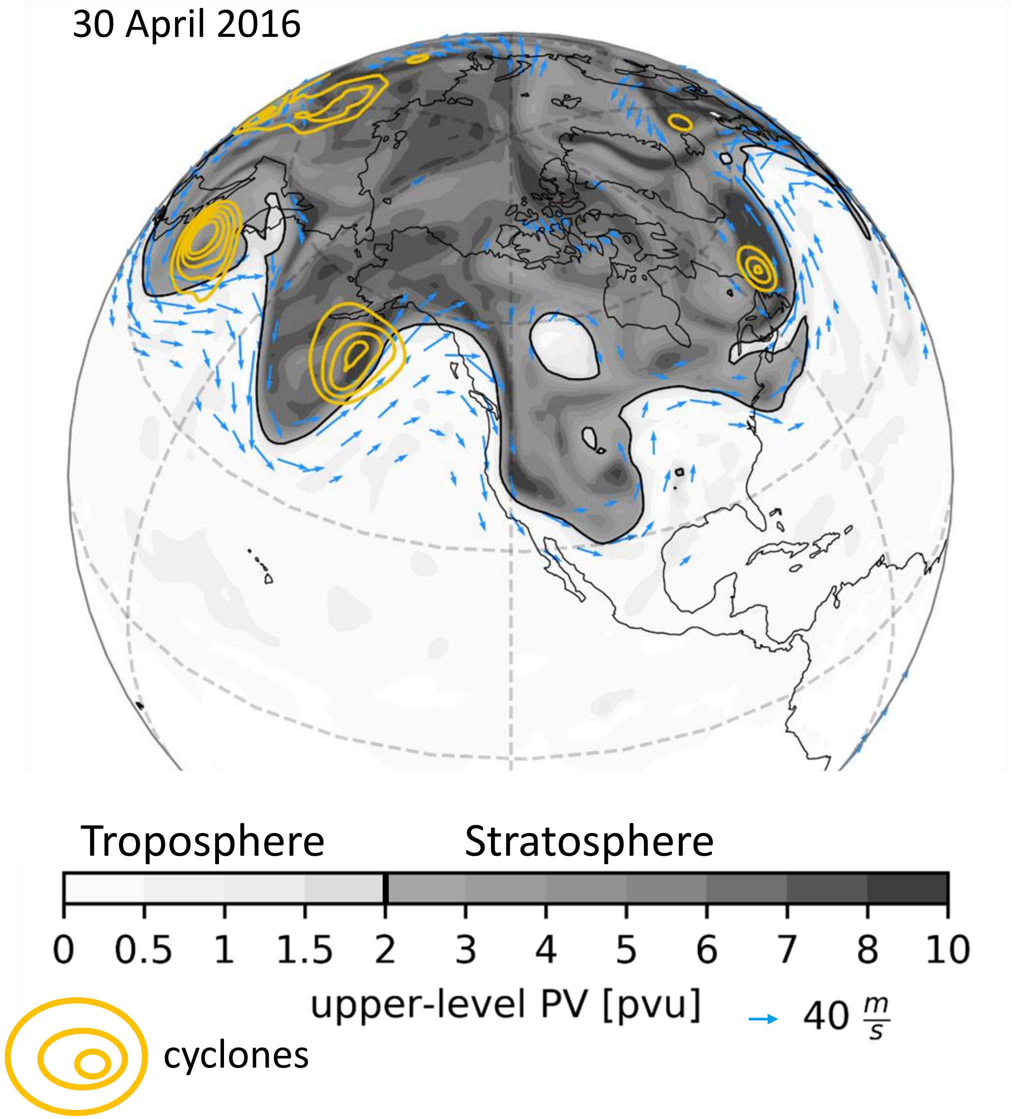

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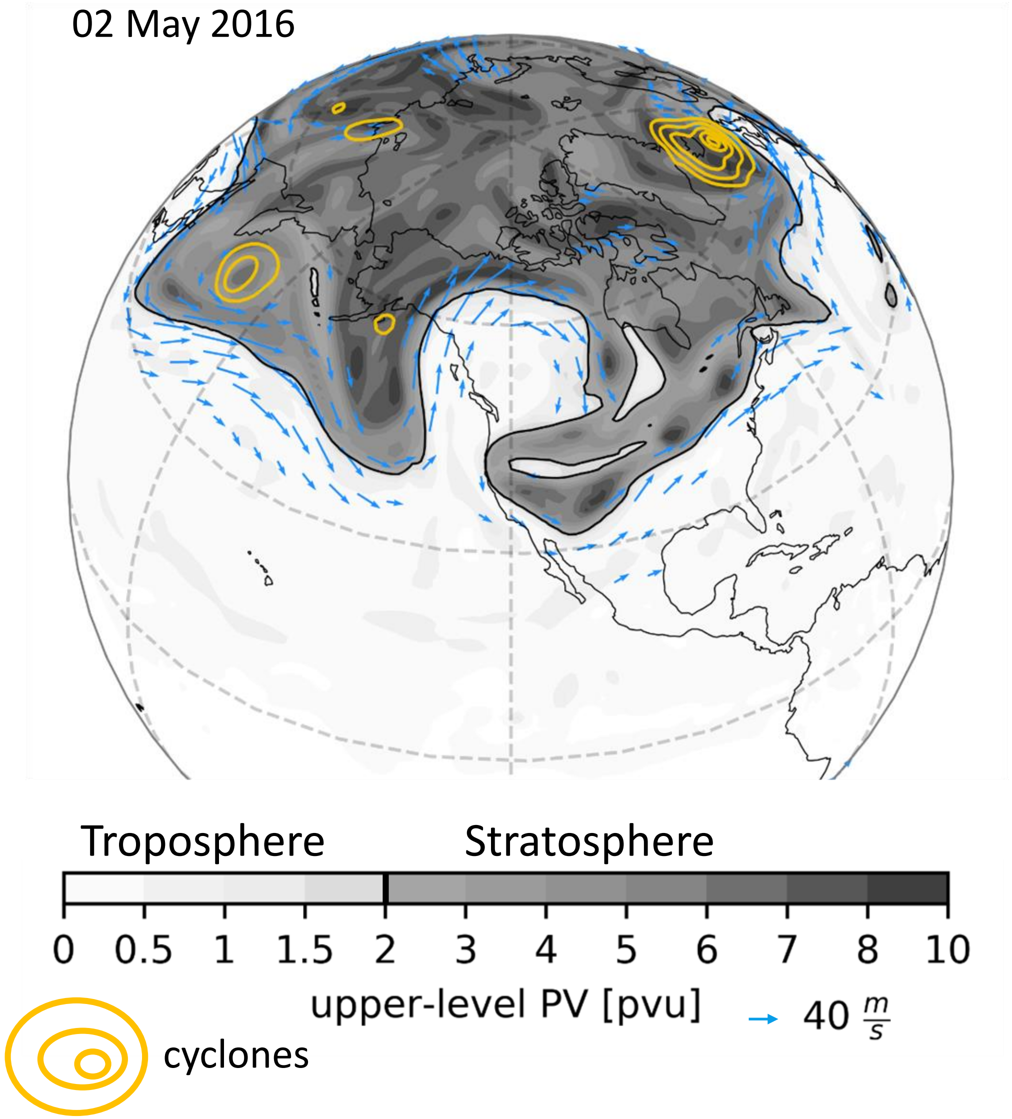
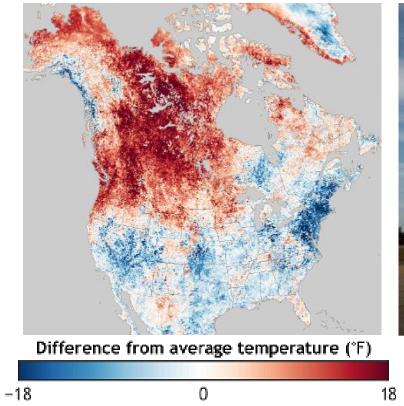



- Persistent and quasi-stationary anticyclonic circulation (negative PV) anomalies that disrupt the normal westerly flow («flow reversal»)
- The normal eastward progression of synoptic weather systems is obstructed («blocked»)
- Once established, blocks persist for longer than synoptic timescale, often leading to extreme weather conditions




Fort McMurray Wildfires May 2016

# Atmospheric blocking | Simple PV framework

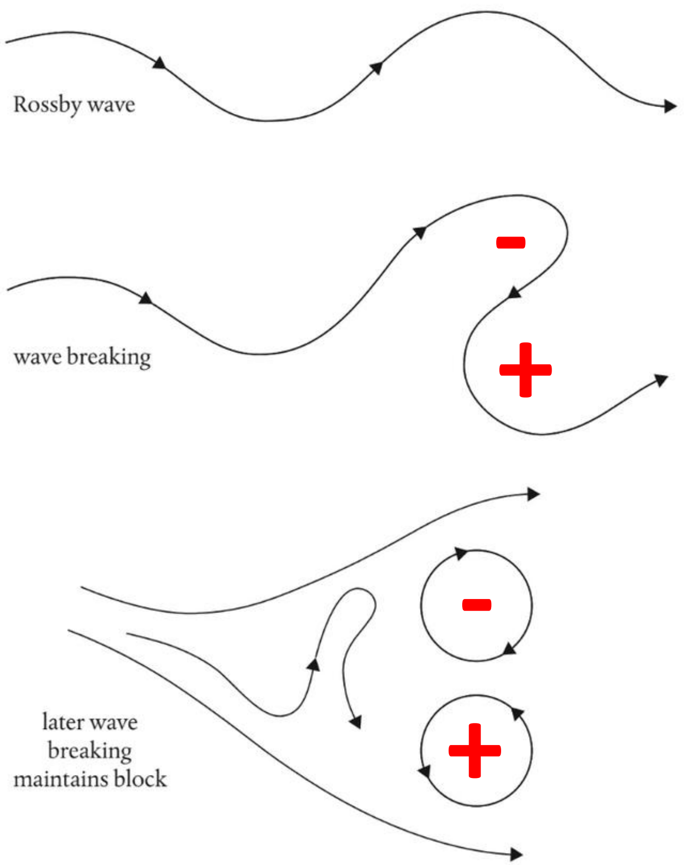
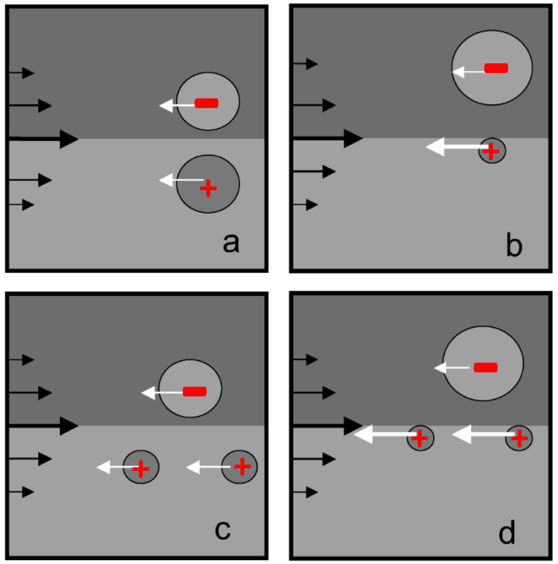



Fig. 14.3. Rossby wave breaking and its role in blocking.

from Jet Stream: A Journey Through Our Changing Climate by Tim Woollings

- Blocking can be considered as a non-linear development (amplification) of upper-level PV anomalies and Rossby wave breaking (similar to wave that arrives at the beach and breaks)
- Once established, the block supports the amplification and breaking of later Rossby waves → **persistence** (from week up to a month)

- The negative PV anomaly is flanked with positive PV anomalies, configurations resulting from the wave breaking
- PV anomalies keep each other in place against background westerlies → **quasi-stationary**

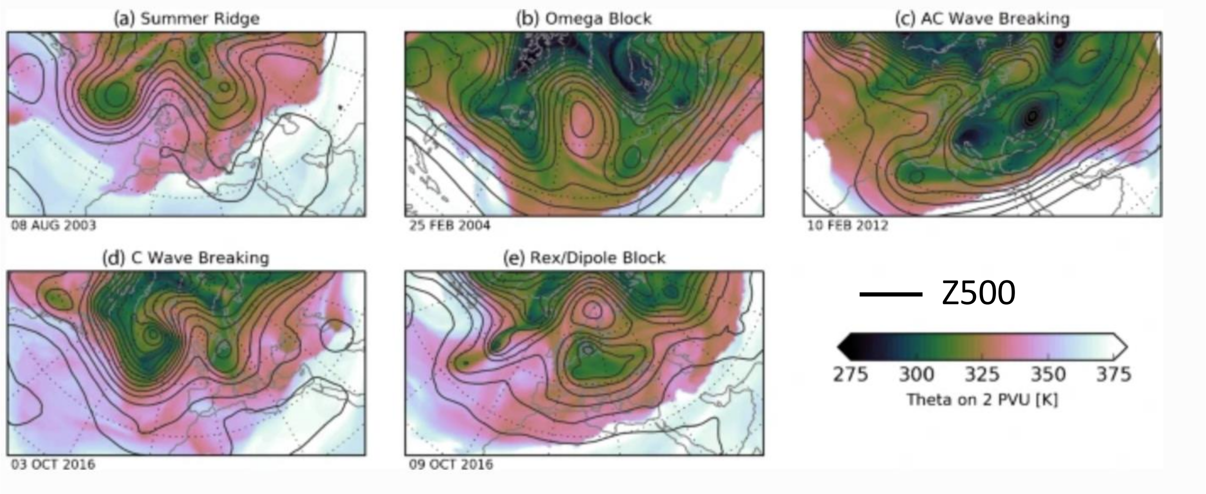



Dark (light) corresponds to high (low) PV anomalies. Black arrows indicate the background mean flow. White arrows indicate the flow acting on the PV anomaly induced by the other PV anomalies

Altenhoff et al. 2008

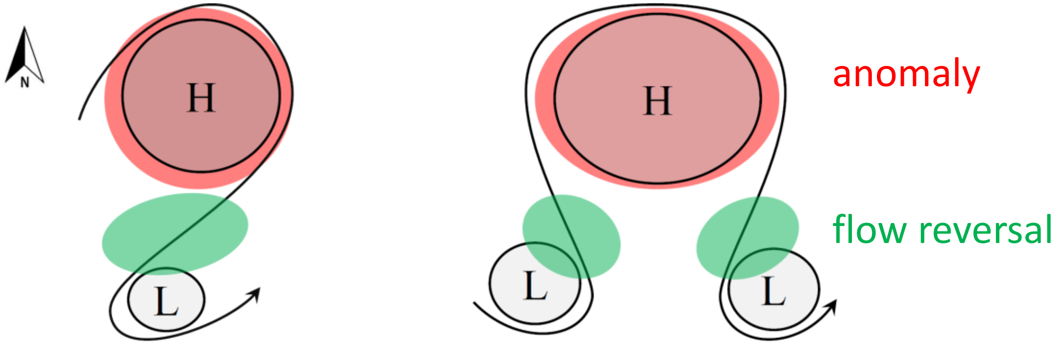
# Atmospheric blocking| Types and circulation patterns

**Circulation patterns during blocking**




Woollings et al., 2018

**Blocking types**




Dipole «Rex» block

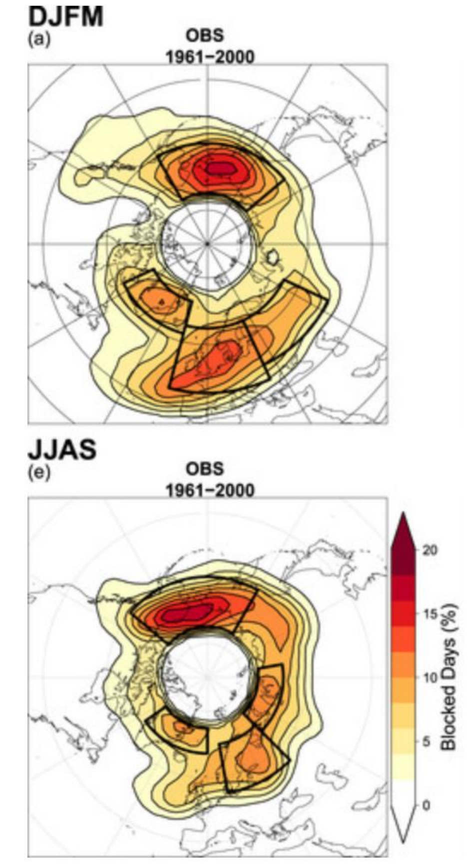
Omega «Ω» block

adapted from Bluestein, 1993

# Atmospheric blocking| Indices and climatology

classical *blocking index:* ***reversal*** *of flow*

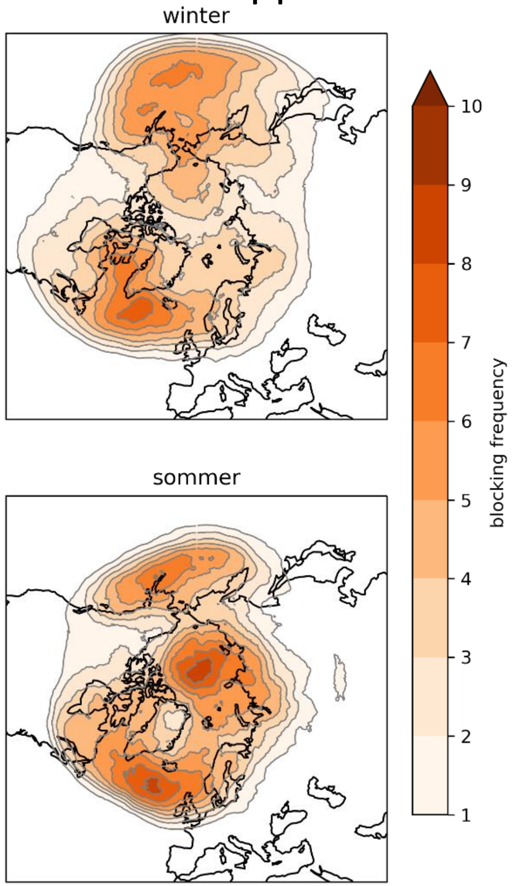
based on Z500 geopotential height




Davini and D'Andrea, 2020

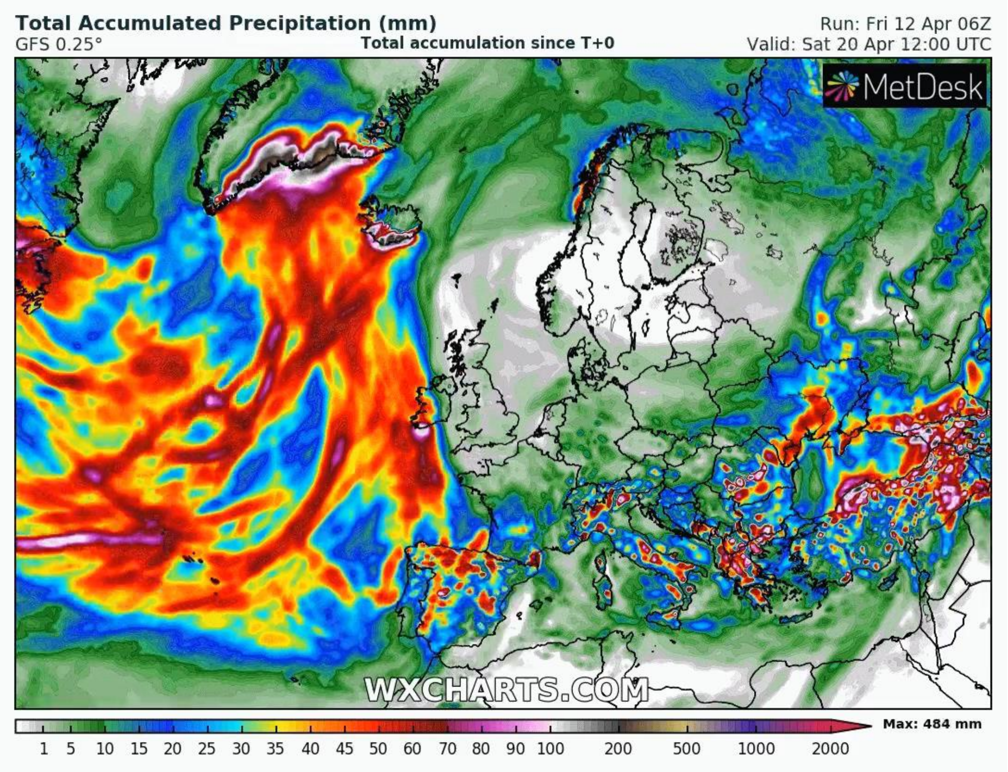
***anomalous*** *index*

based on upper-level PV

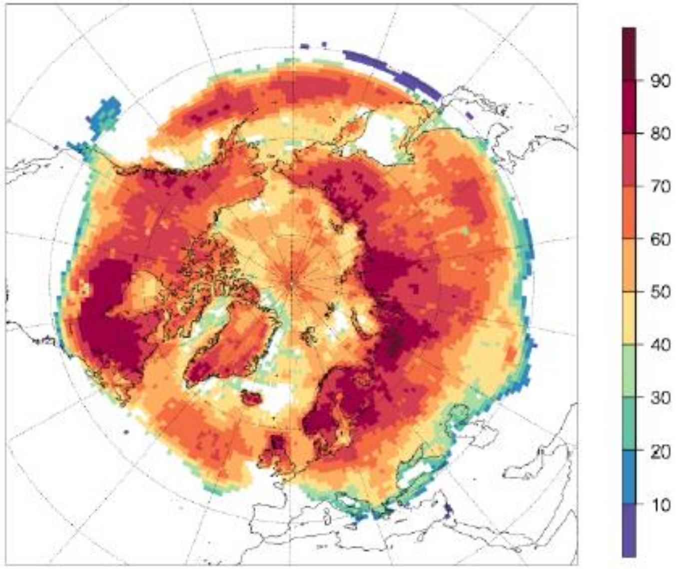



adapted from Schwierz et al., 2004

# Atmospheric blocking| Impact and extreme weather




Summer hot extremes co-located with blocking

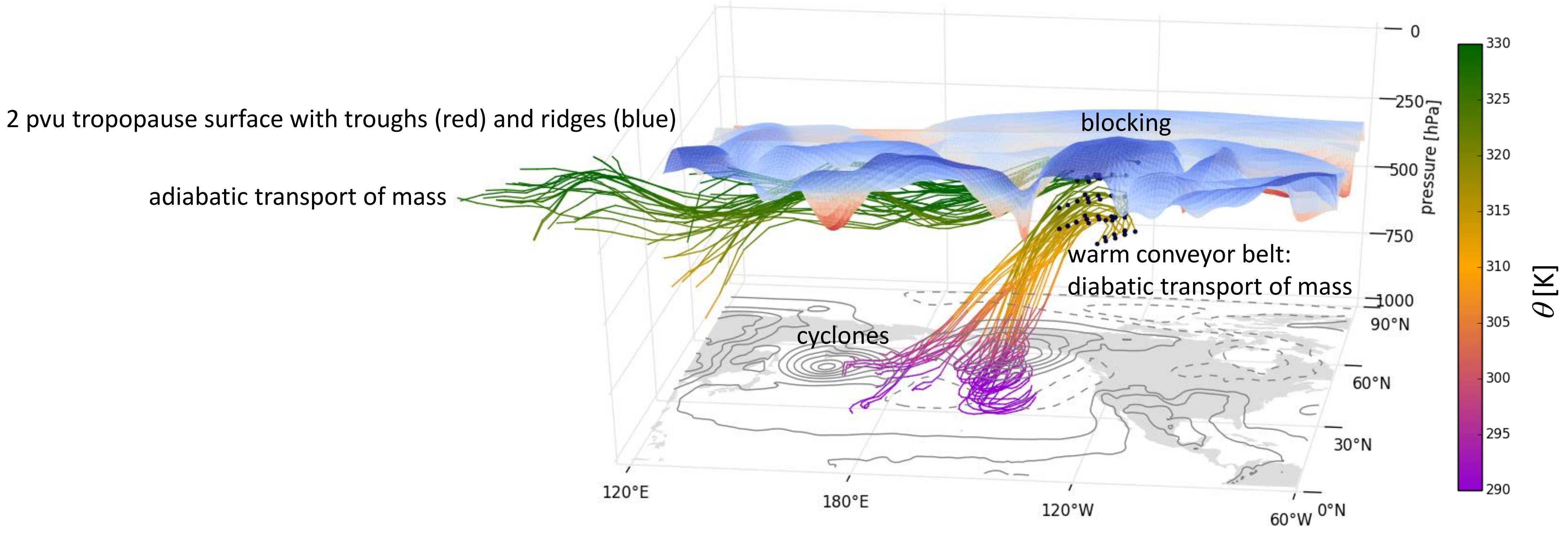



Percentage of hot temperature extremes co-occurring with atmospheric blocking at the same location.

Pfahl and Wernli, *Geophys. Res. Lett.*, 2012

# Atmospheric blocking | Role of cyclones and diabatic heating

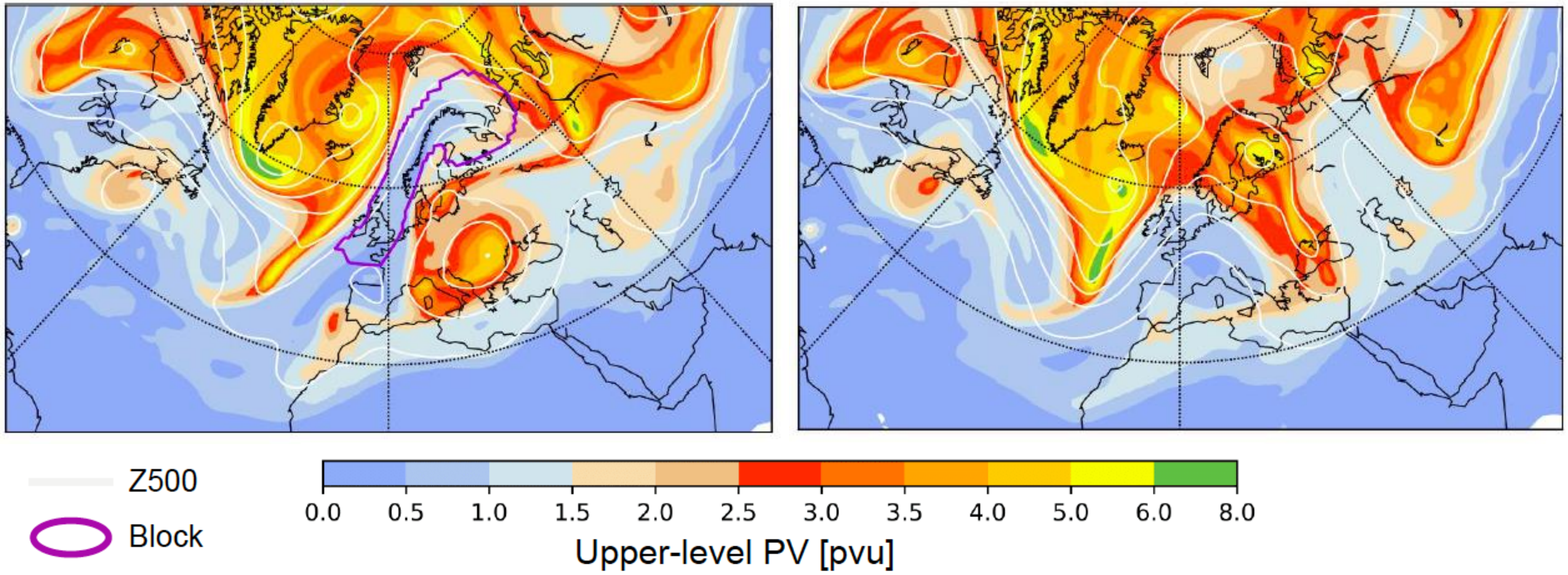
- Classic theories assume blocking to be driven by «dry dynamics»
  → **adiabatic** transport of air mass near the tropopause
- Pfahl et al., 2015 show that almost **50%** of all negative PV anomalies in blocks are generated by diabatic heating
  → **diabatic** transport of air mass in WCB ahead of extratropical cyclones



# Atmospheric blocking| Sensitivity experiments

reference simulation

no latent heating / no WCB



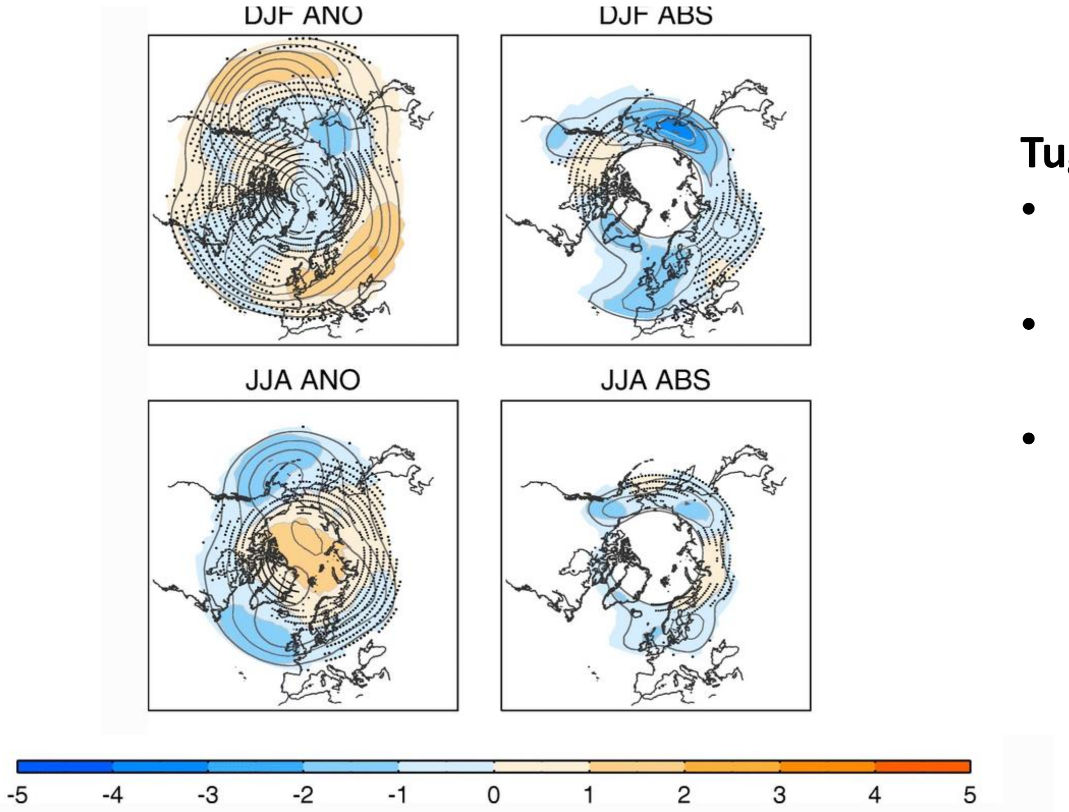

Scandinavian blocking in October 2016 from a reference simulation with the ECMWF IFS model.

Sensitivity simulation in which the diabatic heating in the upstream cyclone has been switched off over the North Atlantic.

# Atmospheric blocking| Response to climate change

anomaly index

reversal index



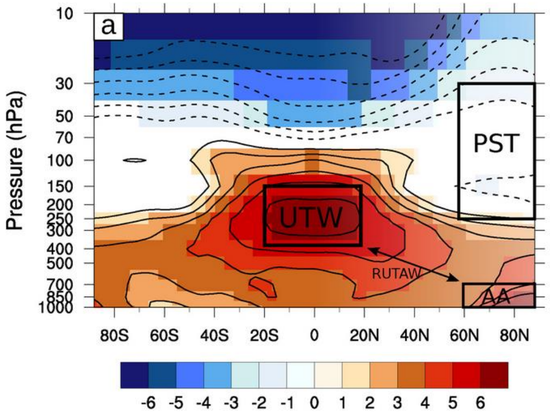

Multi-model mean blocking frequency changes
(2061 – 2090 minus 1961 - 1990)

Woollings et al., 2018

- projected changes in blocking occurrence are small
- climate models do not agree on regional sign of changes (dots = model disagreement)

**Tug-of-war** between competing effects of the Arctic and Tropics:

- Arctic Amplification (AA) → reduced baroclinicity → weaker and wavier jet stream?
- Upper-tropospheric warming in the tropics (UTW) → increased barcolinicity → stronger and more zonal jet?
- More atmospheric moisture:
    - increased stability
    - increased latent heating → more diabatic PV modification?




Multi-model mean temperature changes

Peings et al., 2018

# Summary| PV non-conservation and atmospheric blocking

After this lecture you should

- be able to identify weather systems in isentropic PV maps:
  troughs, ridges, PV streamer, PV cut-off, blocks, jet stream
- know how diabatic processes modify PV:
  example with warm conveyor belts
- understand why diabatic processes are important for the development of large-scale weather systems:
  - positive PV anomalies: cyclone intensification (week 11)
  - negative PV anomalies: upper-level ridges and atmospheric blocking (today)
- know how atmospheric blocking can be described in a simple PV framework:
  interaction of negative and positive PV anomalies (“omega” and “dipole” configuration) in the upper troposphere for persistence and quasi-stationary