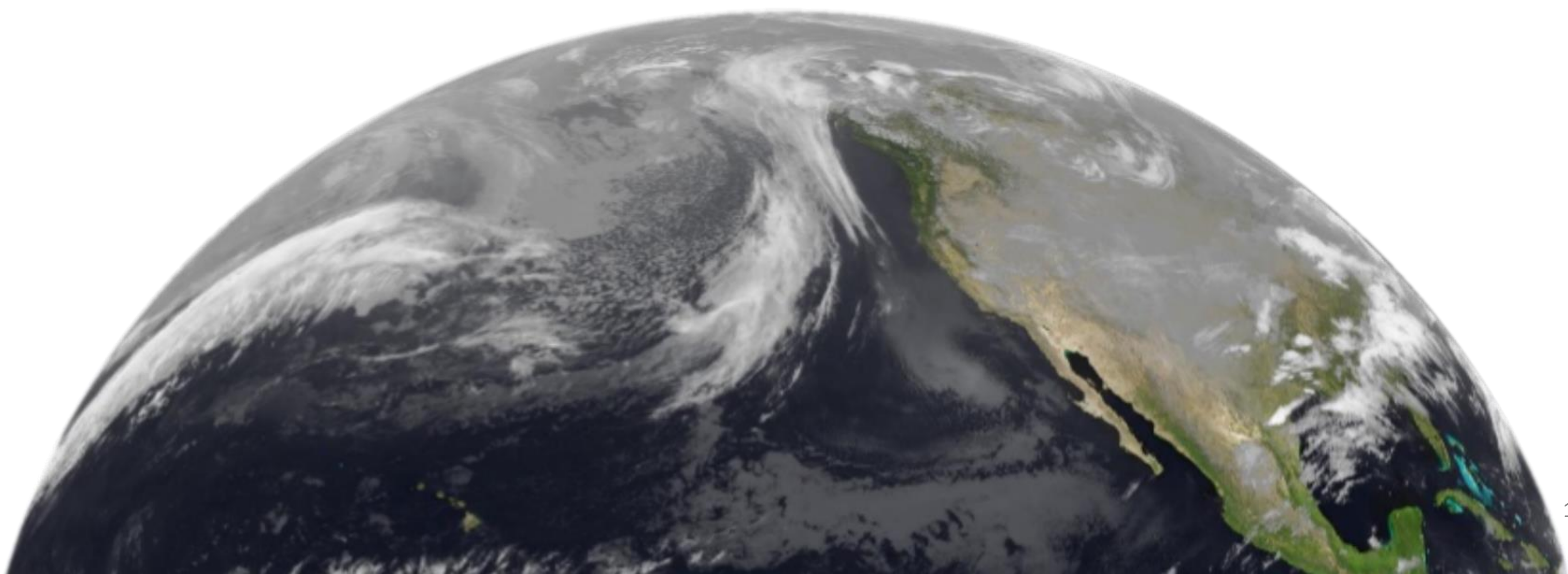
The role of latent heating in atmospheric blocking

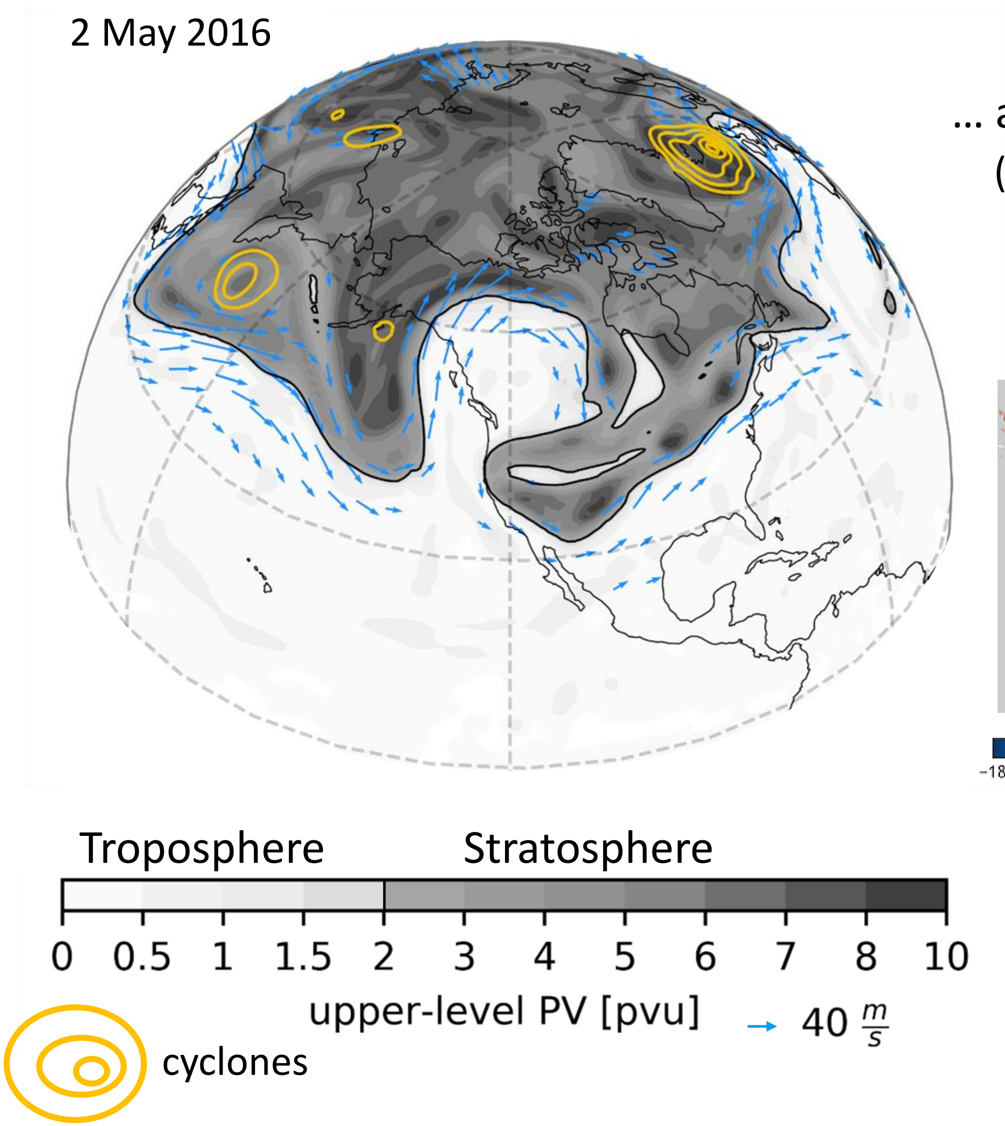
PhD Defense Daniel Steinfeld
15 May 2019

Committee:
Prof. Stephan Pfahl (FU Berlin)
Prof. Heini Wernli (ETHZ)
Prof. Tim Woollings (University of Oxford)

Chair:
Prof. David Bresch (ETHZ)



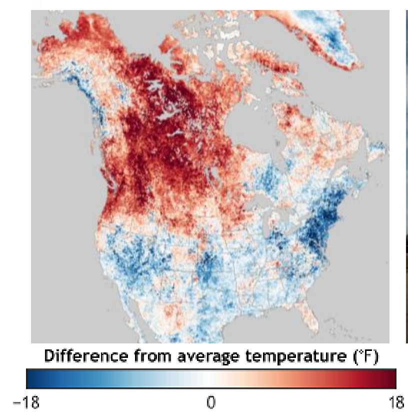
Introduction | Motivation



Atmospheric blocking

… anticyclonic circulation anomalies
(stationary high pressure systems)
Hoskins et al., 1985

… extreme surface weather
Pfahl and Wernli, 2012



Fort McMurray Wildfires May 2016

… increased forecast uncertainty
Rodwell et al., 2013
Woollings et al., 2018

Introduction | Blocking dynamics

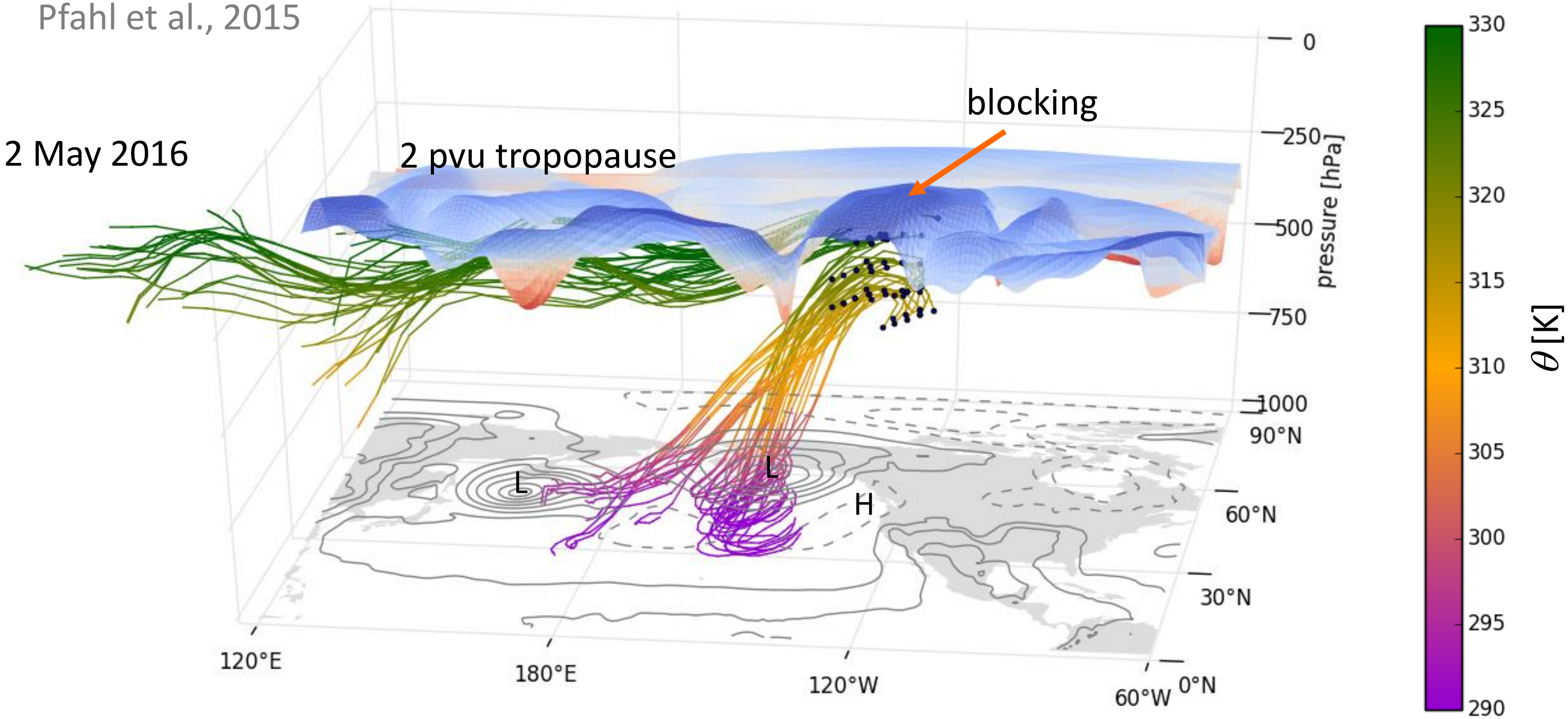
… still not fully understood

… classical blocking theories are based on dry (adiabatic) dynamics

Berggren et al., 1949; Charney & Devore, 1979; Shutts, 1983; Colucci, 1985; …and many more

… the role of moist (diabatic) processes

Pfahl et al., 2015



Introduction | Objectives

Improve understanding of atmospheric blocking, with a focus on the role of latent heating (LH)

Quantify the role of LH in atmospheric blocking

Global climatology

Era-Interim 1979 – 2016: 4270 blocking events and 30 mio trajectories

Causal relationship and sensitivity of blocking to changes in uptream LH

Numerical sensitivity experiments

Case studies with the global weather model IFS

Blocking and LH in a warmer and moister climate

Climate simulations

CESM large ensemble simulations for present-day and future climate

Method | Block tracking and latent heating

Atmospheric blocking:

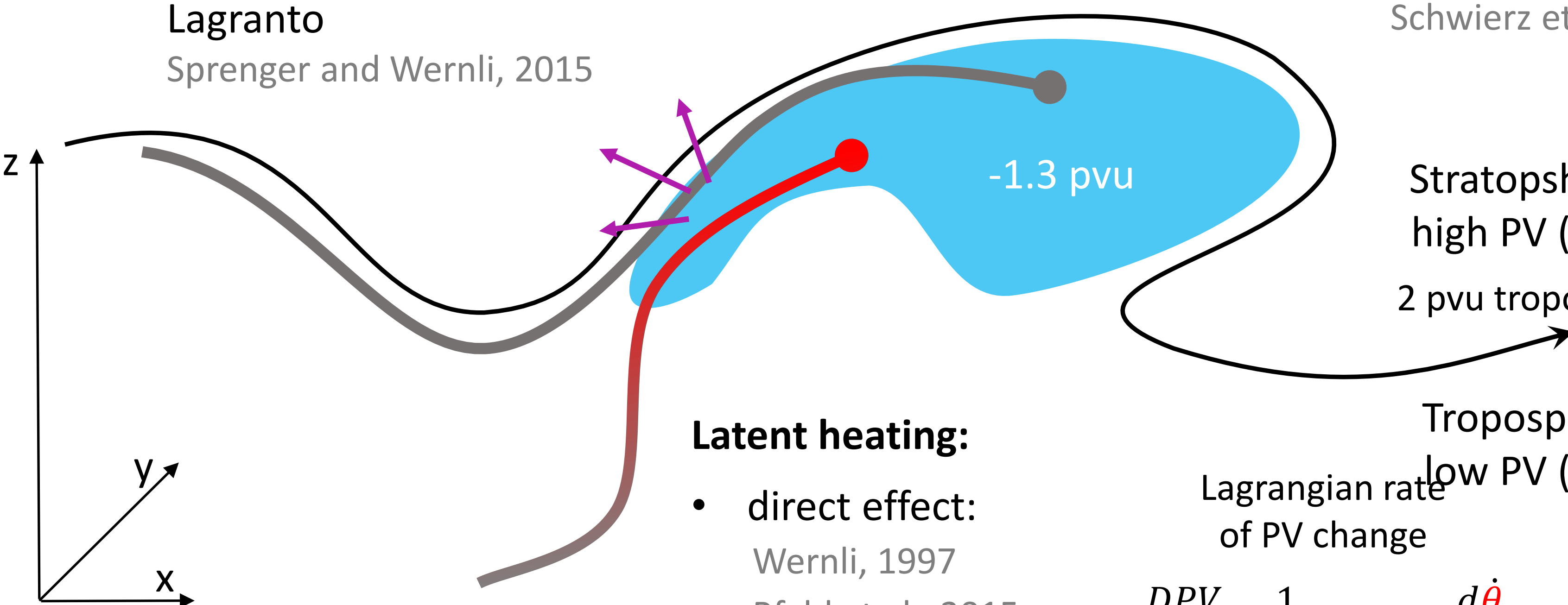
Persistent and quasi-stationary upper-level negative PV anomaly

Schwierz et al., 2004

Backward trajectories:

Lagranto

Sprenger and Wernli, 2015



Ertel Potential Vorticity

Ertel, 1942

Latent heating:

- direct effect:

  Wernli, 1997

  Pfahl et al., 2015

Lagrangian rate of PV change

$$\frac{DPV}{Dt} \simeq \frac{1}{\rho}(\zeta + f) \cdot \frac{d\dot{\theta}}{dz}$$

- indirect effect:

  Davis et al., 1993

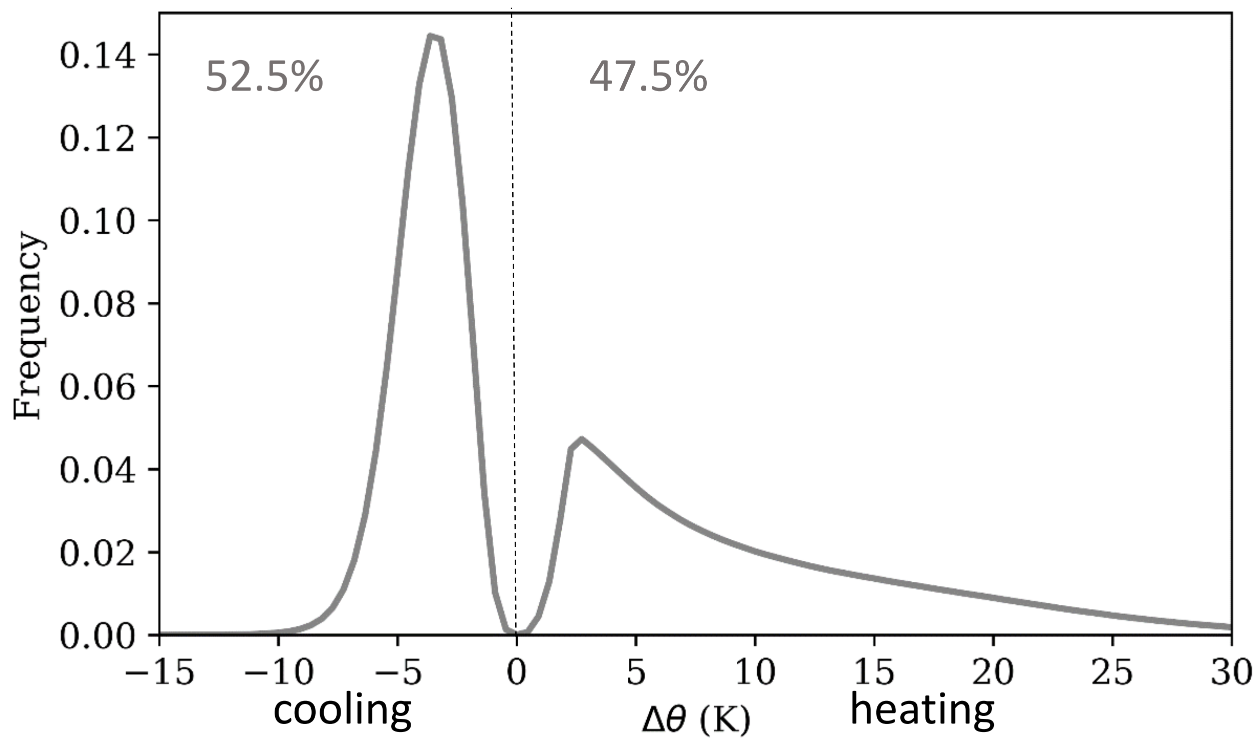
  Riemer and Jones, 2010

PV advection by divergent outflow

$$v_{\chi} \cdot \nabla PV$$

Climatology| Diabatic processes

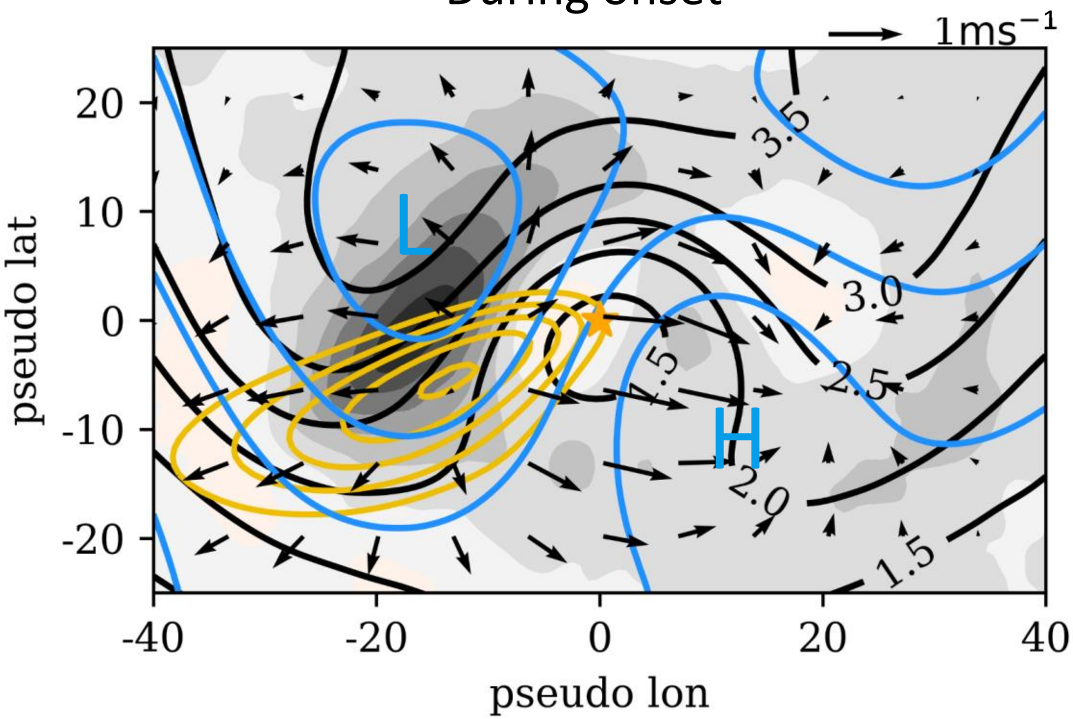
Air masses involved in blocking



Diabatic heating/cooling during **3** days before arriving in block

Climatology| Blocking-centered composites

During onset



upper-level PV [pvu]

SLP [hPa]

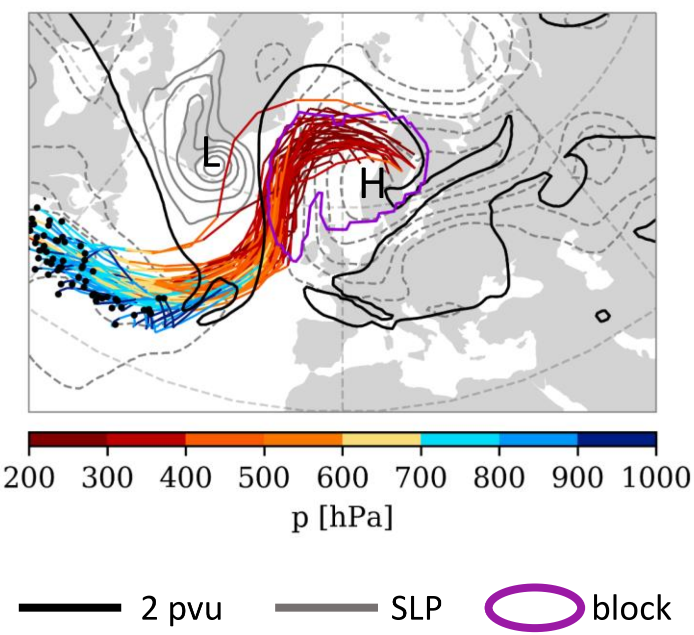
Density of trajectories at location of max. LH

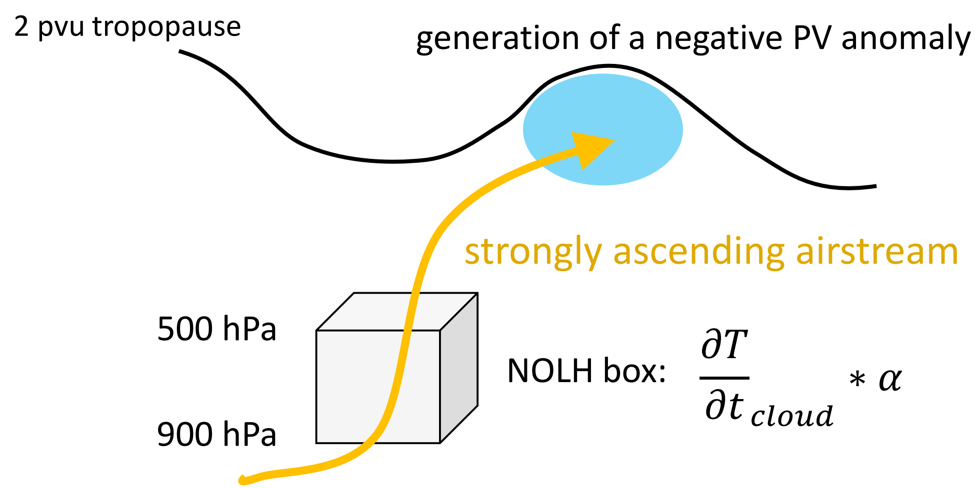
upper-level divergent wind

Sensitivity | Method

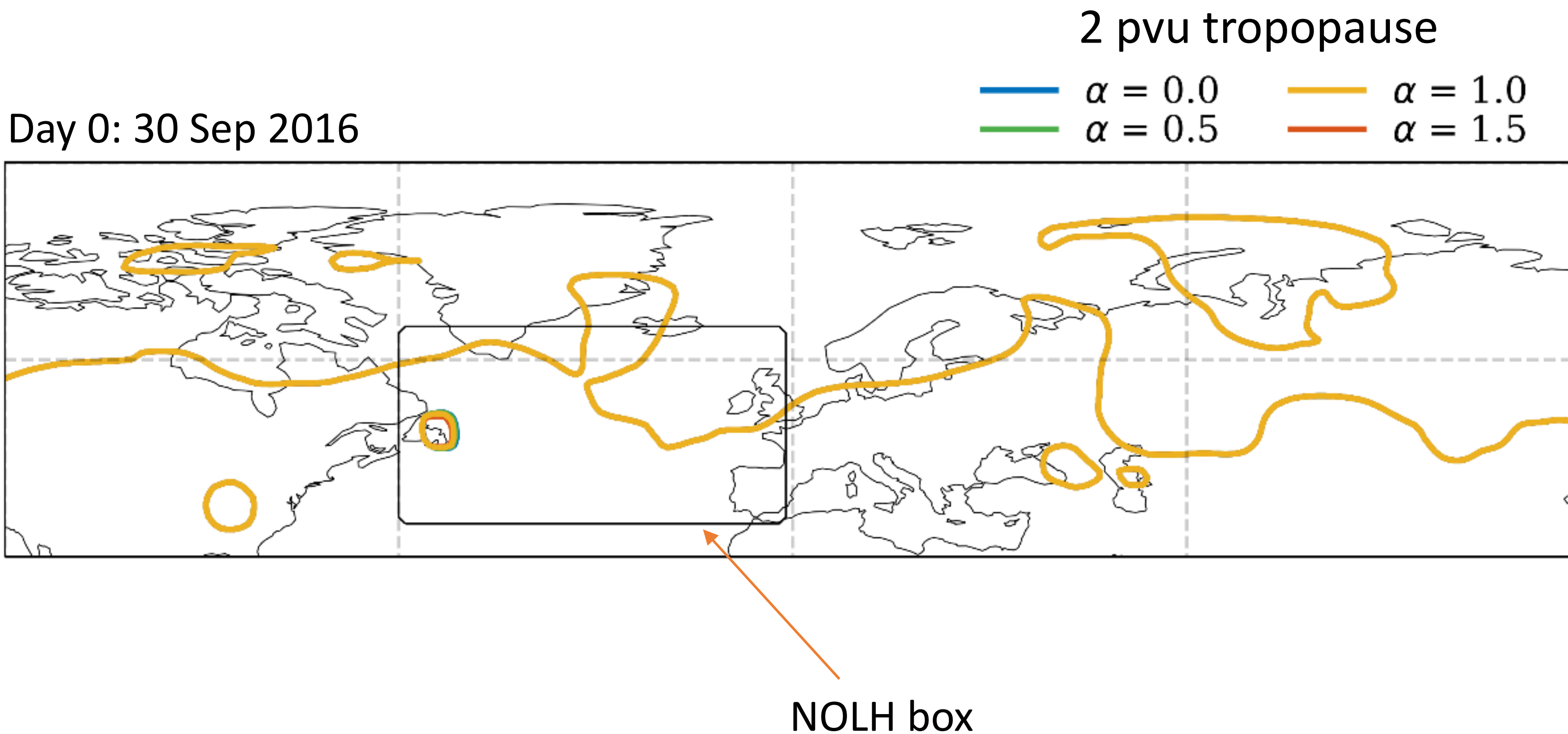
- Model: ECMWF global weather model IFS
- 10 day forecast simulations
  - CNTRL (full physics) with $\alpha = 1$
  - Sensitivity runs with modified LH in the LH region with $\alpha = 0.0, 0.5$ and 1.5

October 2016: Scandinavian block



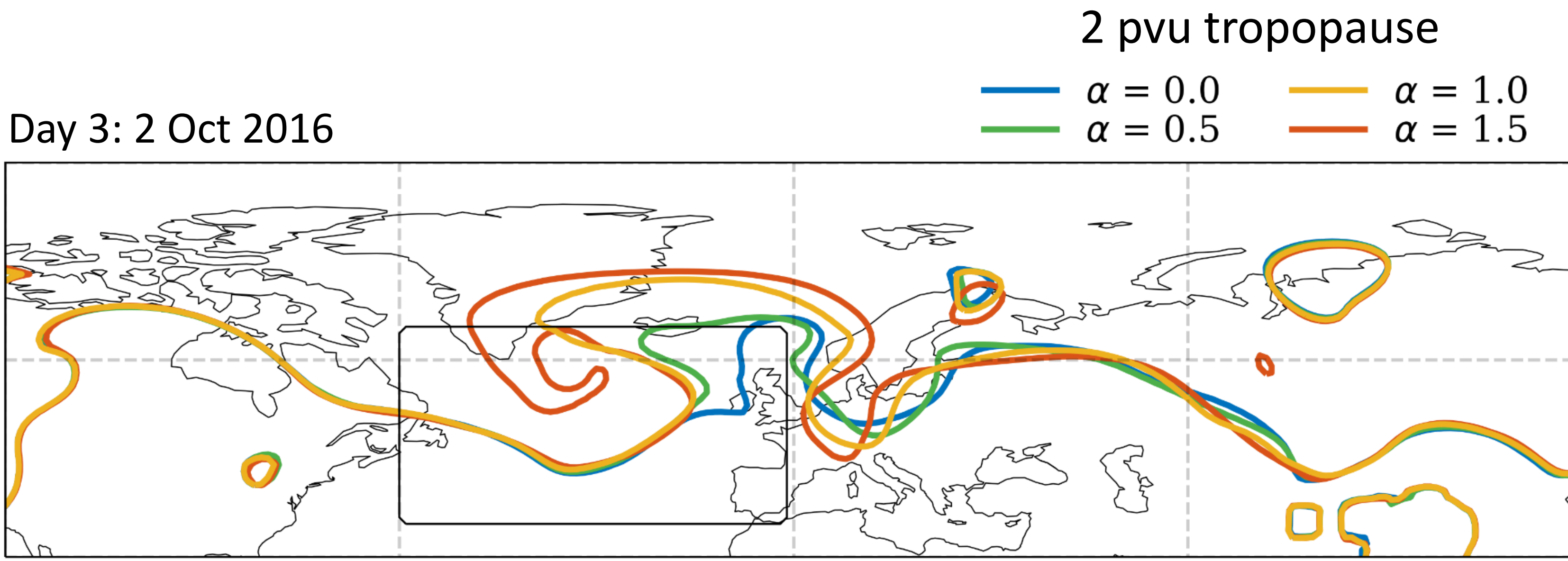


Sensitivity| Experiment

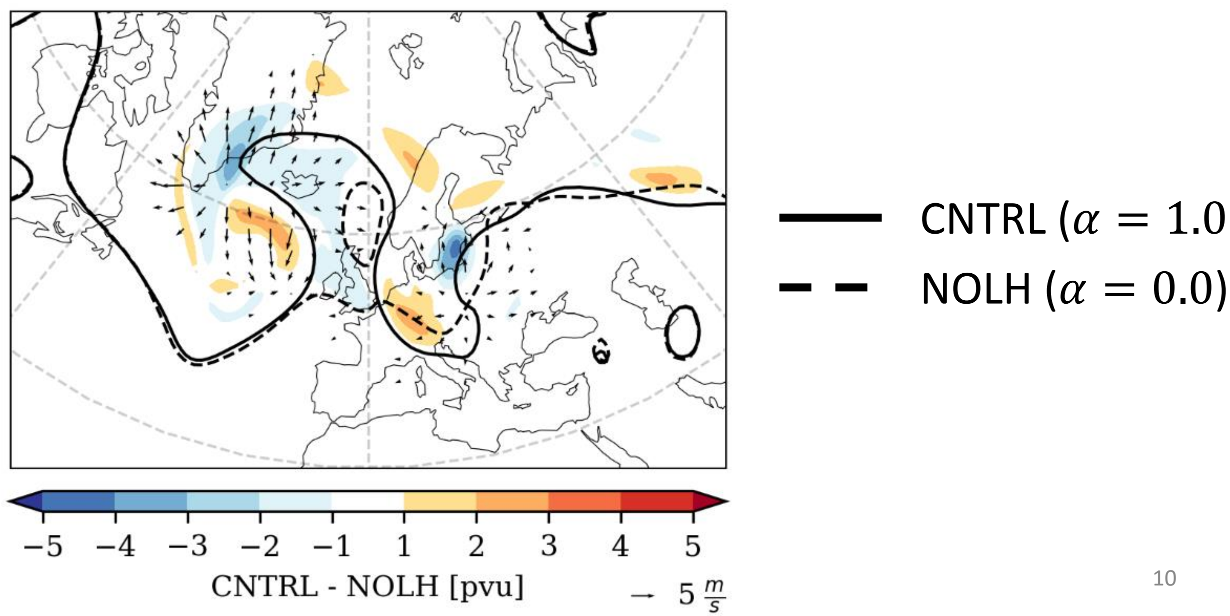


Sensitivity | Experiment

Day 3: 2 Oct 2016

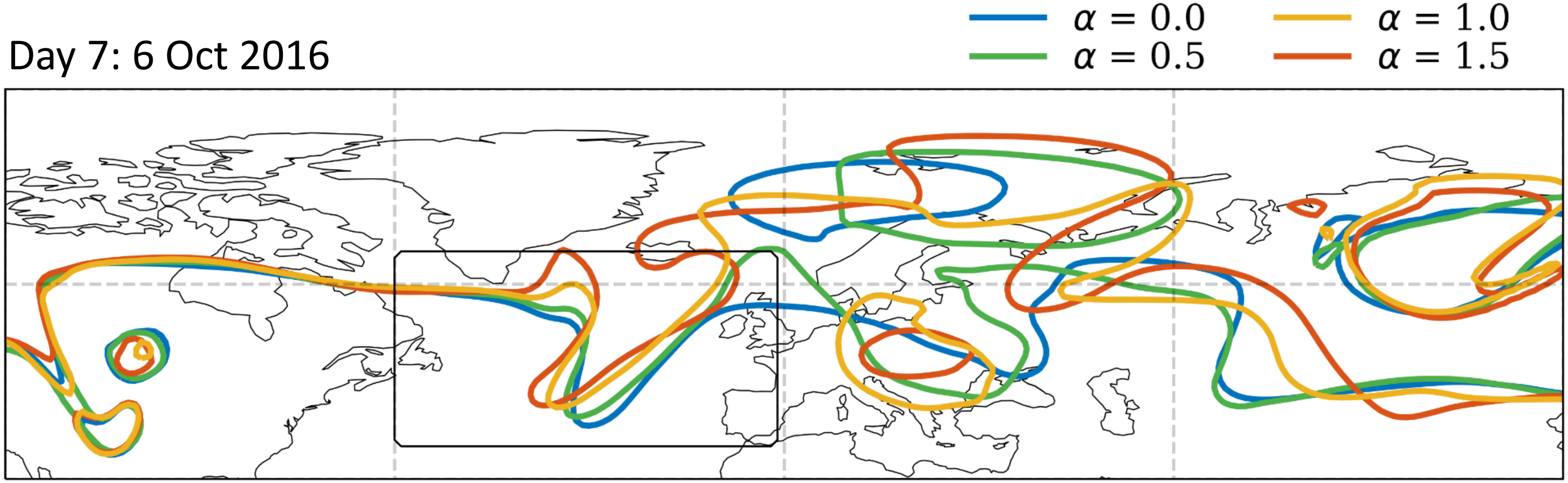


Difference in upper-level PV and divergent wind

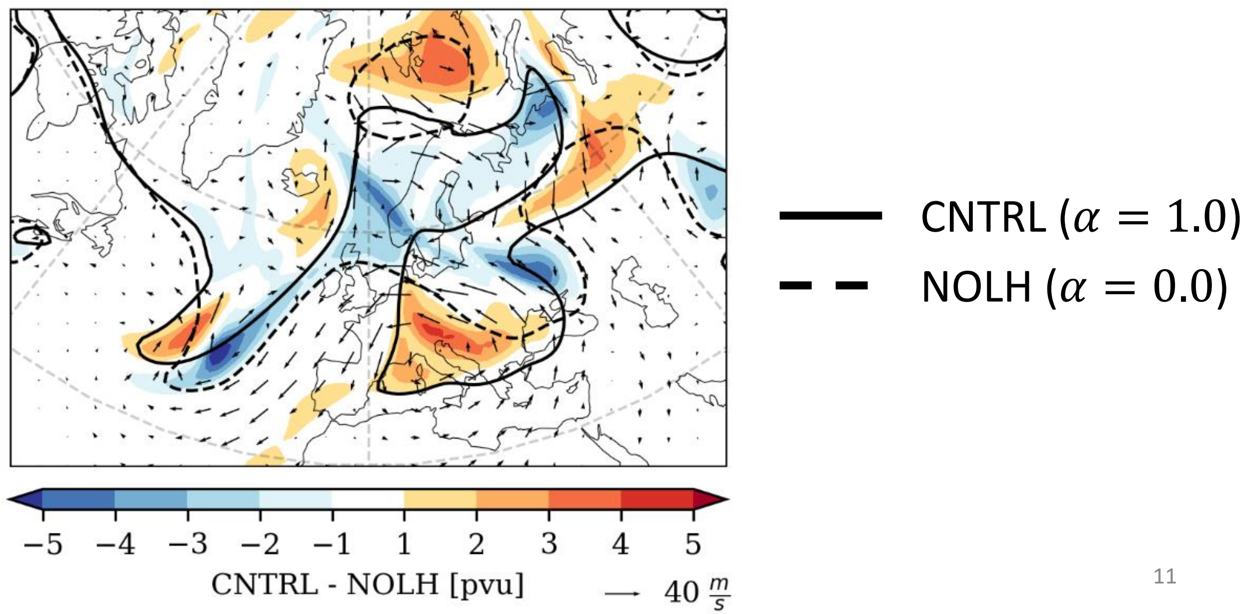


Sensitivity | Experiment

Day 7: 6 Oct 2016



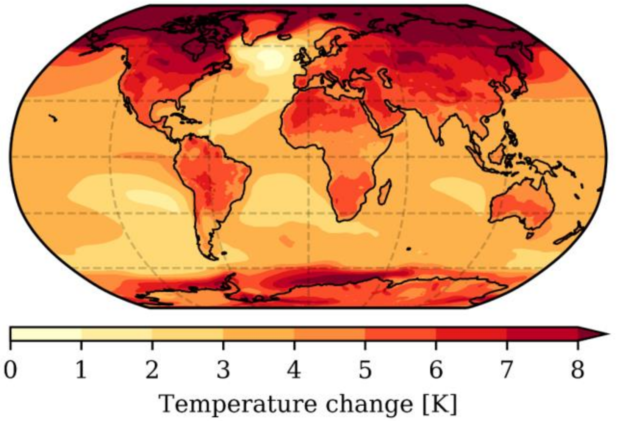
Difference in upper-level PV and rotational wind



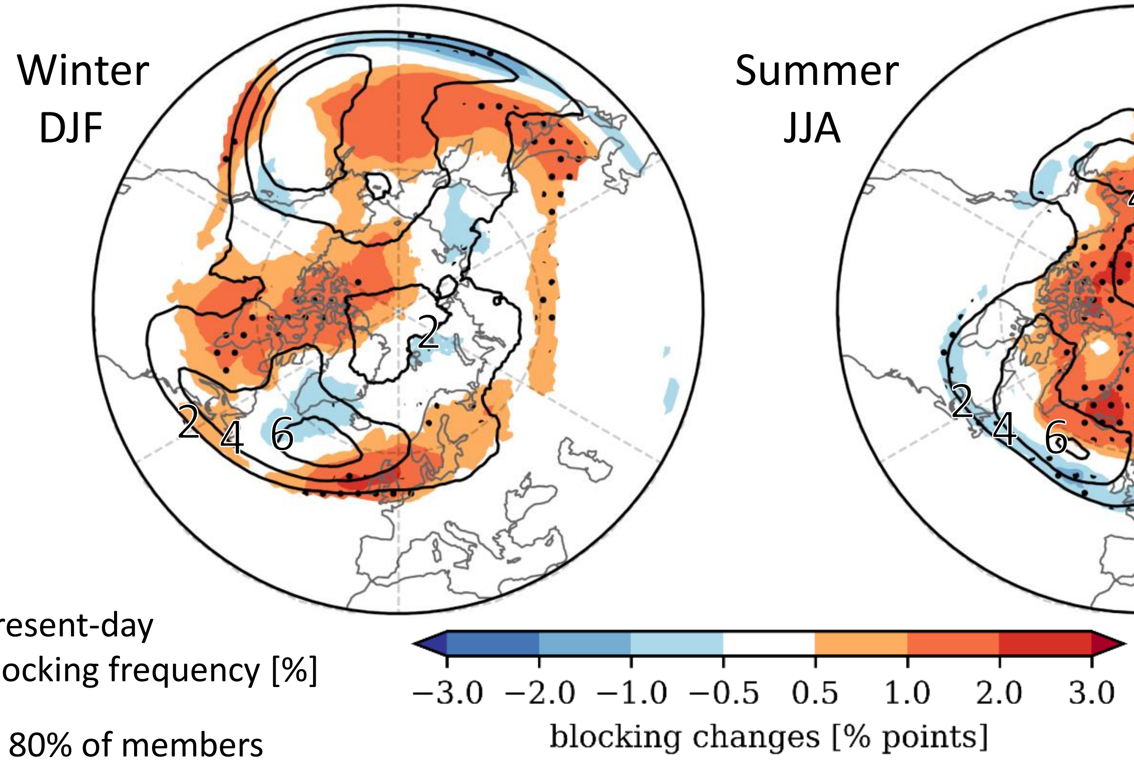
Future | Blocking occurence

CESM large ensemble (10 members) climate simulations:

- present-day climate: 1990 – 2000
- RCP8.5 future climate: 2091 – 2100



Change with global warming:

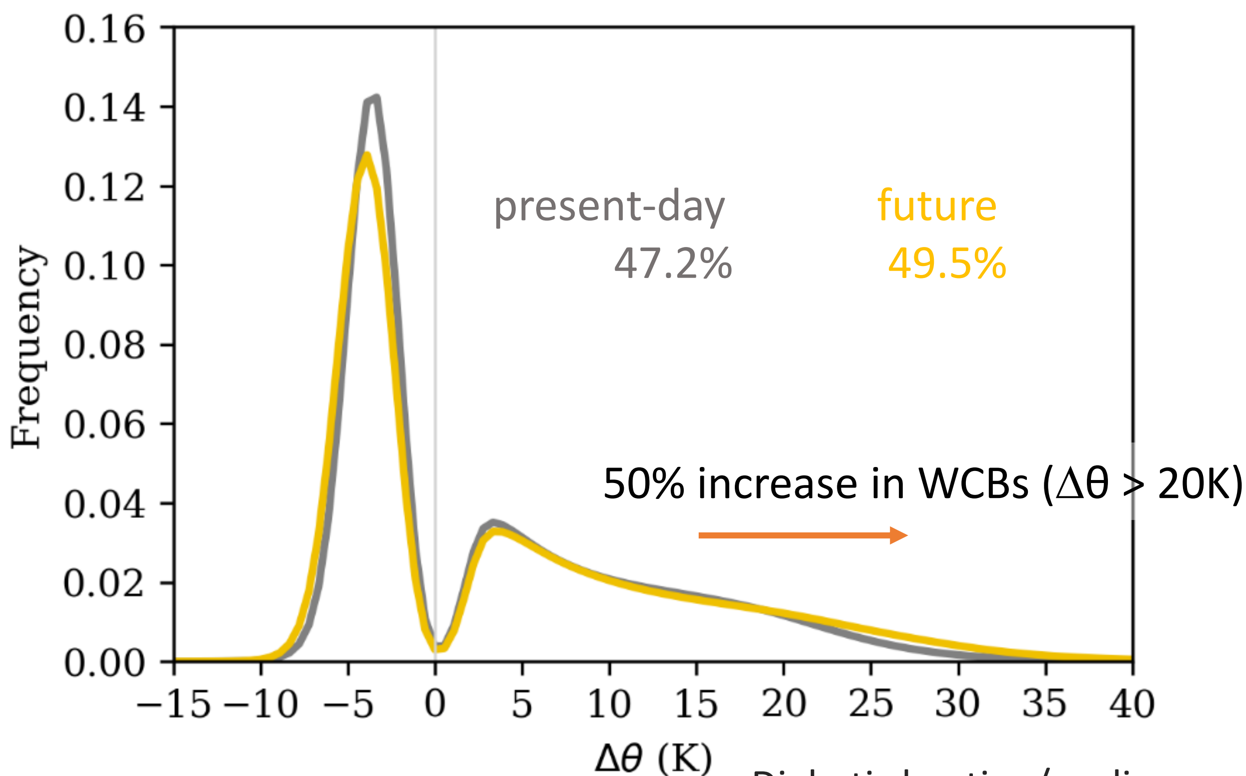


present-day blocking frequency [%]

> 80% of members agree on sign of change

Future | Diabatic processes

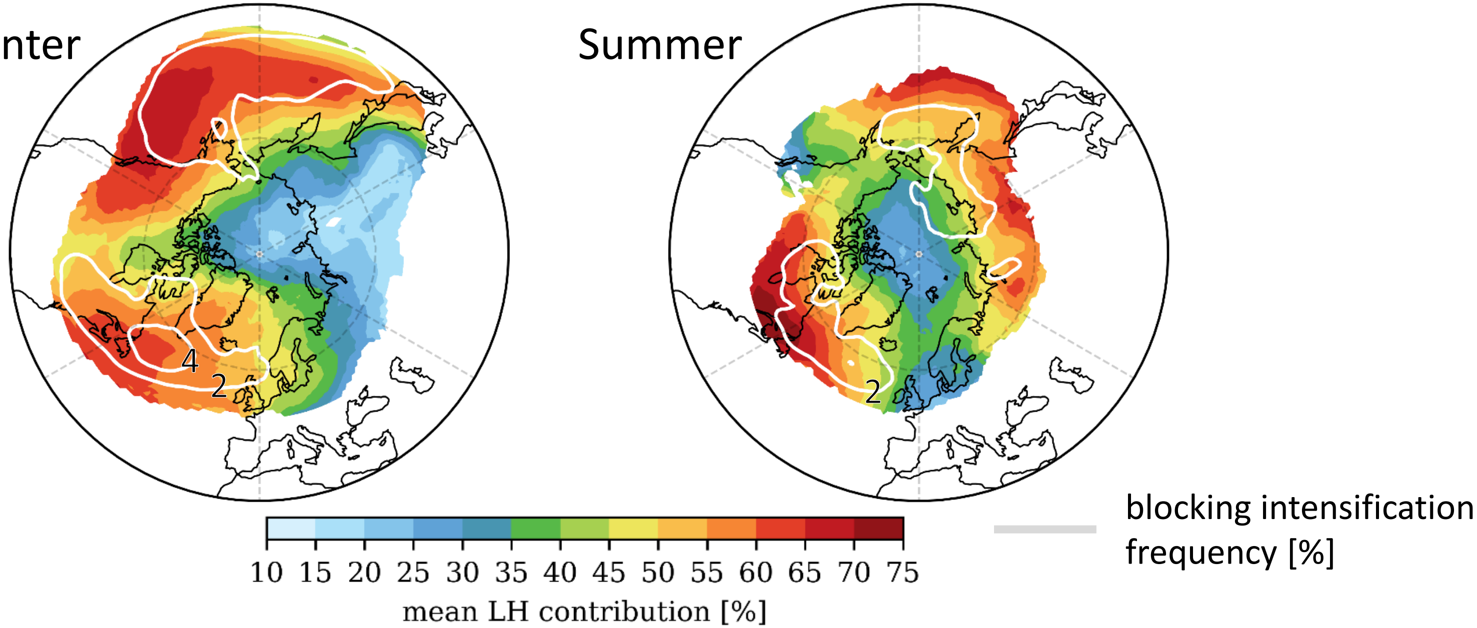
Air masses involved in blocking



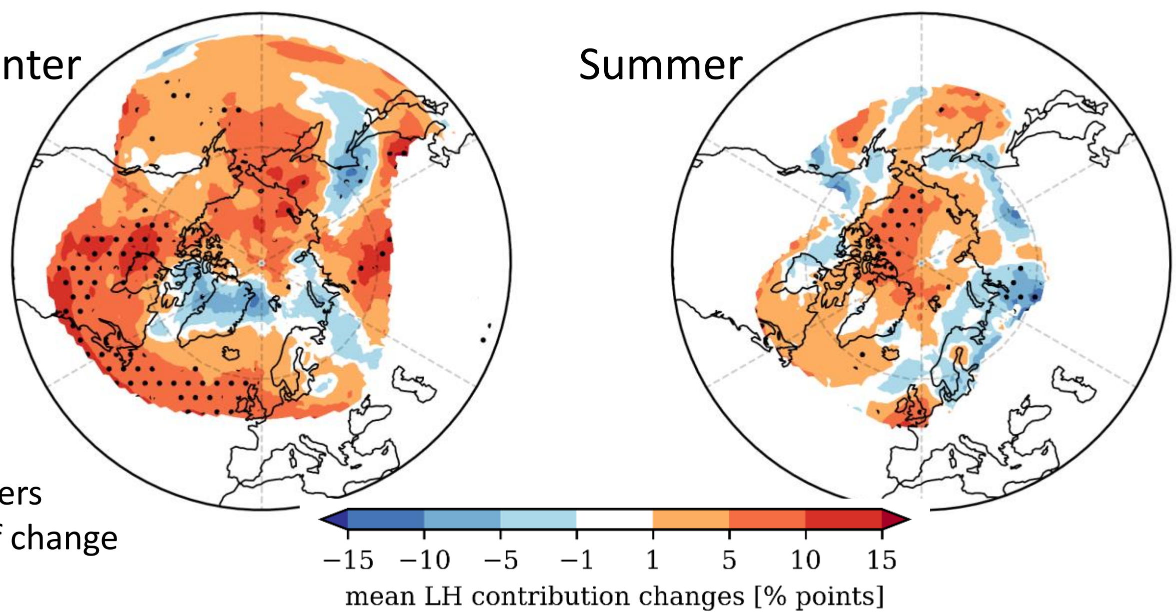
Diabatic heating/cooling during **3** days before arriving in block

Future | Diabatic processes

Present-day climate:



Change with global warming:

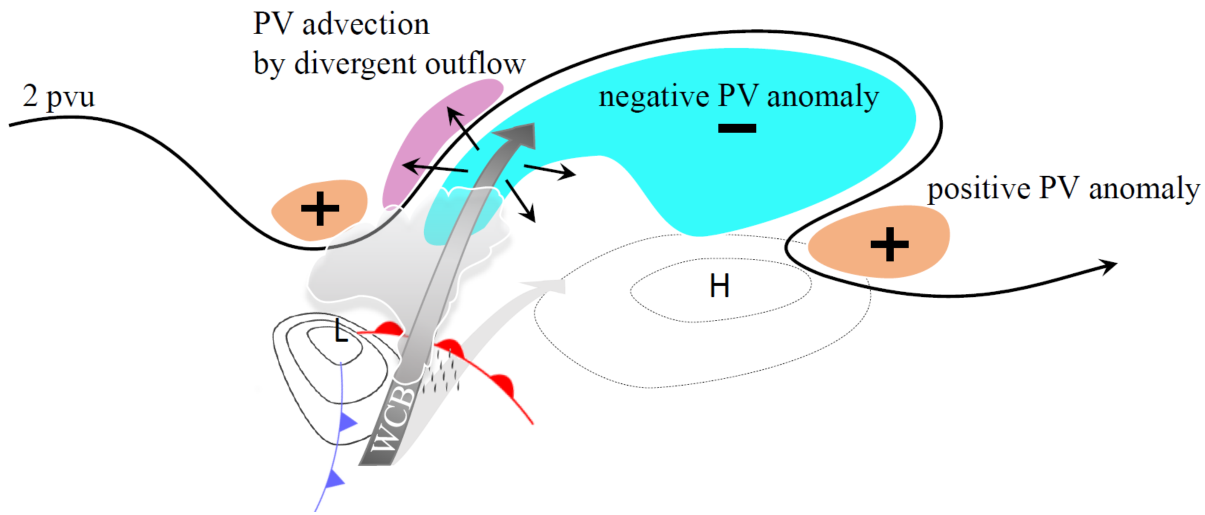


> 80% of members agree on sign of change

Conclusion | Synthesis

Climatology
- Around 50% of all blocking air masses ascend diabatically into the block

Effect of LH
- **direct**: cross-isentropic transport of low-PV air
- **indirect**: enhanced vertical motion and divergent outflow

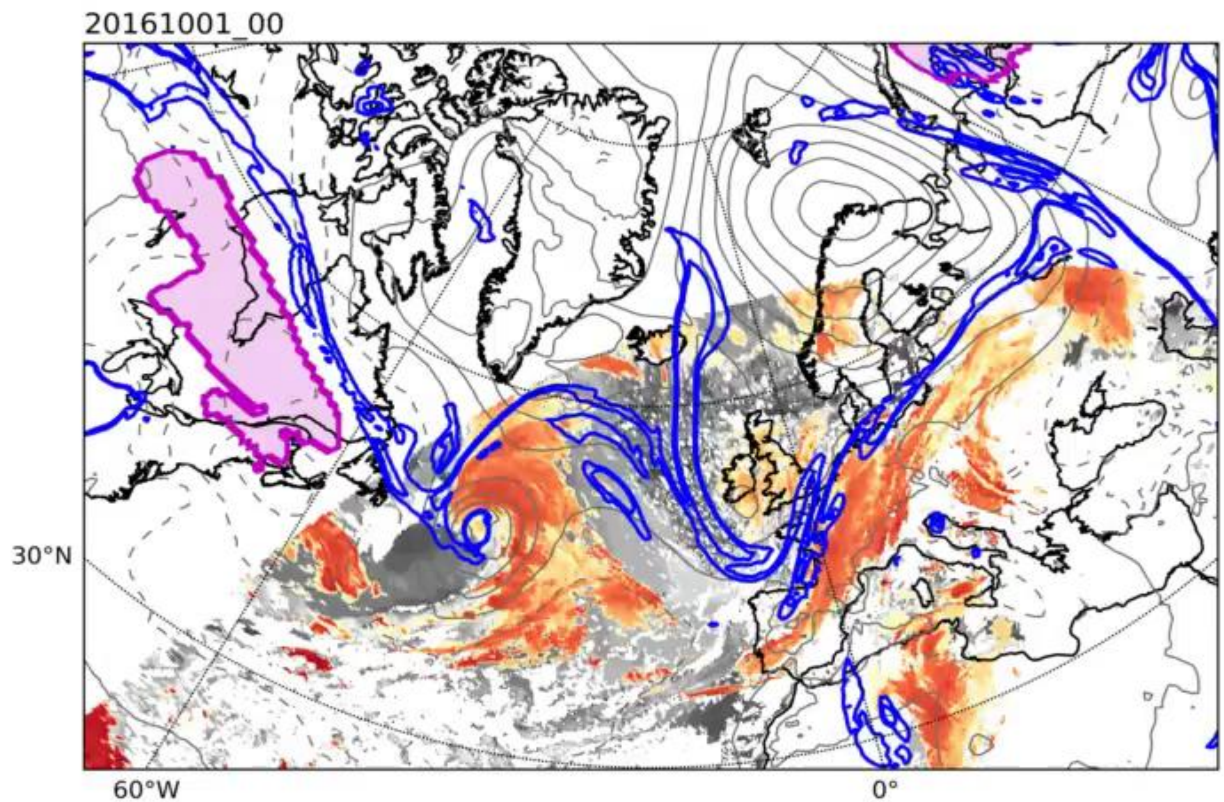


Sensitivity study
- changes in upstream LH lead to distinct differences in the blocking life cycle

Climate simulations
- weak and complex changes of blocking in a warmer and moister climate
- LH becomes slightly more important

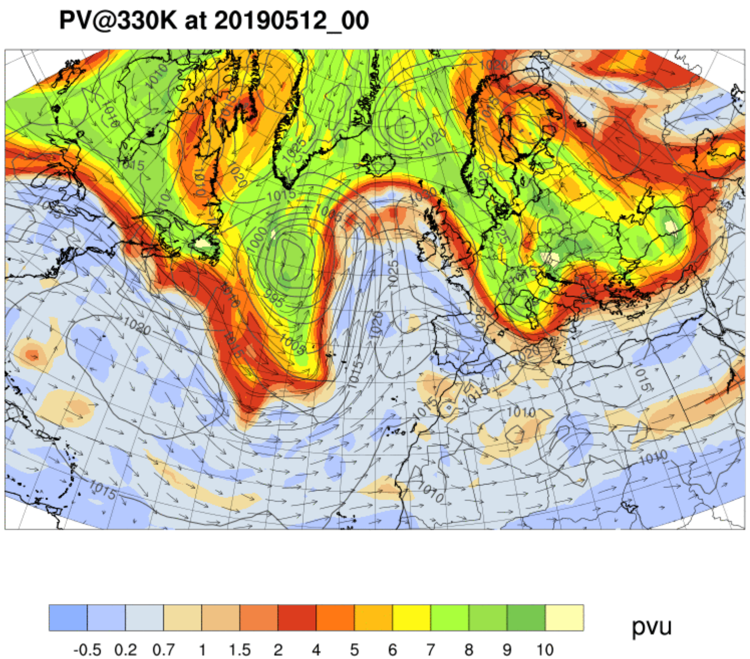
Thank you!

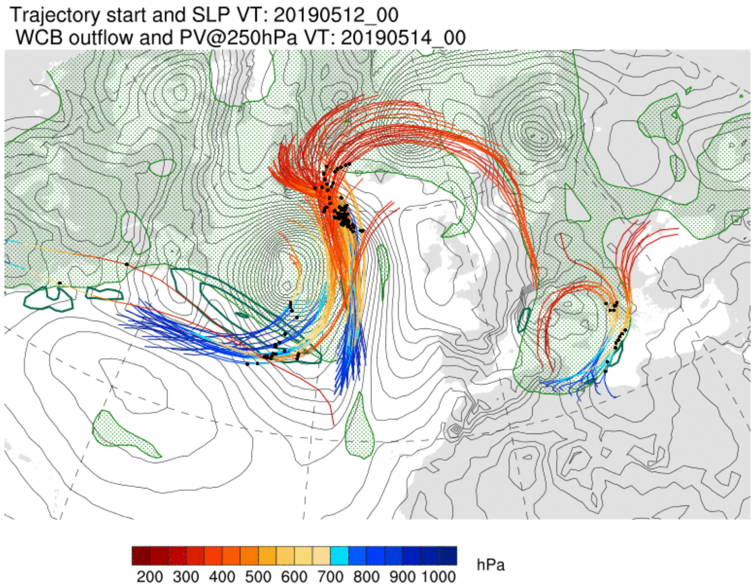
Special thanks to the Atmospheric Dynamics Group,
to Richard Forbes (ECMWF) for helping with the IFS and
to Urs Beyerle, the Climate Physics Group and NCAR for the CESM climate simulations

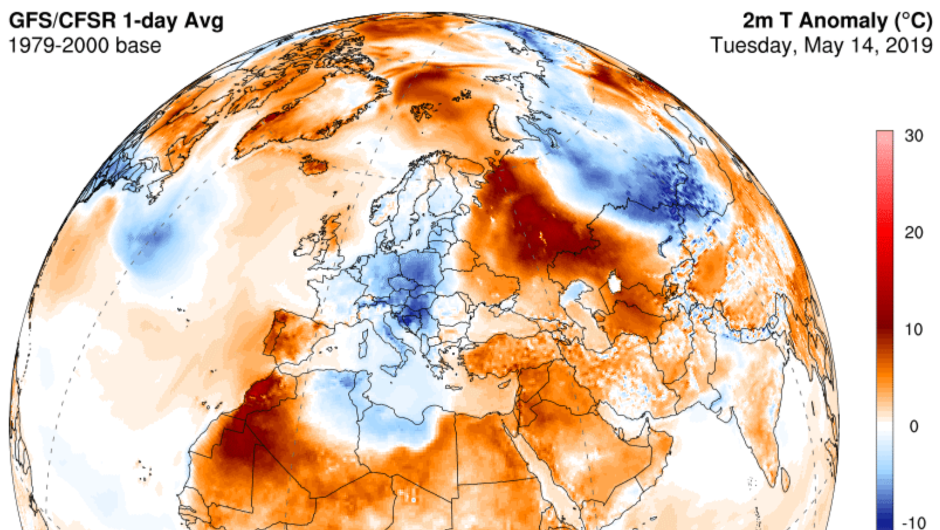


Appendix

Introduction| weather discussion



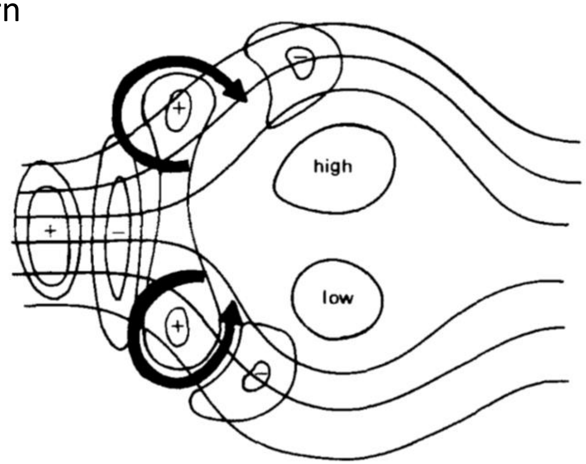




Introduction| Cyclones

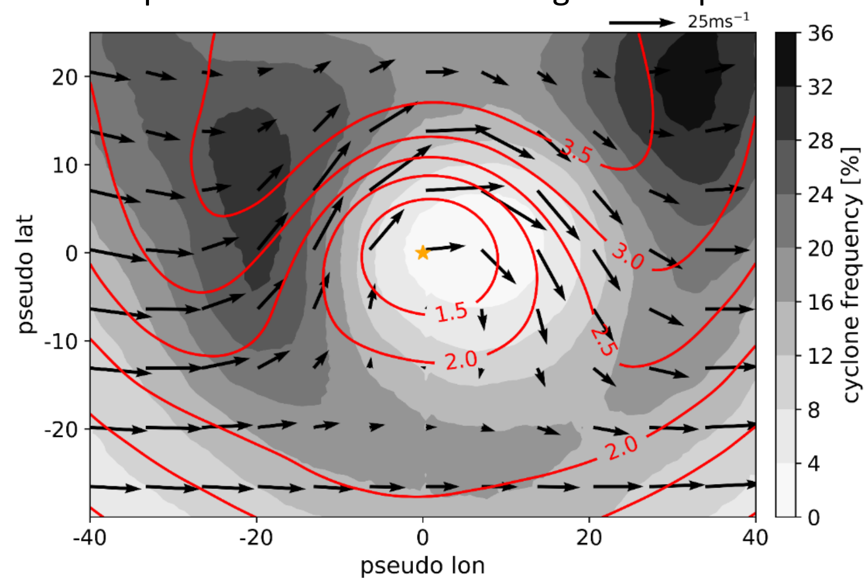
effect of synoptic-scale ‘transient’ eddies on time-mean flow

Shutts, 1983/1986: deformation of eddies propagating into a split jet stream with their associated vorticity forcing pattern



NEW: Yamazaki, 2013: Vortex-Vortex Interaction

Composite of 4270 blocks during mature phase

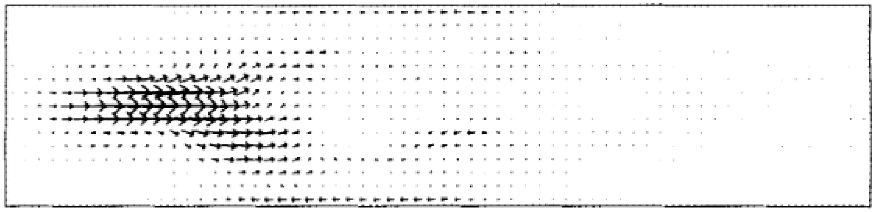


*up to 60% upstream cyclone frequency during onset

For example like the E-Vector (Hoskins, 1983):

$$\boldsymbol{E} = \left[\overline{v'^2 - u'^2}, -\overline{u'v'}\right]$$

$$\left(\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y}\right) \approx \boldsymbol{\nabla} \cdot \boldsymbol{E}$$



E-vector [m^2s^{-2}], Haines and Marshall, 1987

Method | Potential Vorticity

PV is not conserved under diabatic processes

Lagrangian rate of PV change

$$\frac{DPV}{Dt} \simeq \frac{1}{\rho}(\zeta + f) \cdot \underbrace{\frac{d\dot{\theta}}{dz}}$$

Vertical gradient of the diabatic heating rate

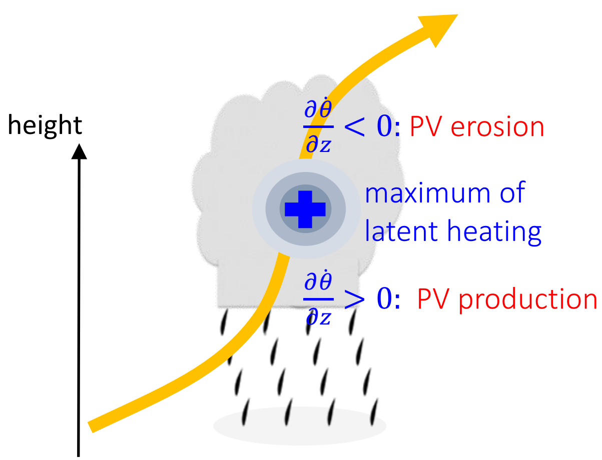
Hoskins et al., 1985
Wernli and Davies, 1997

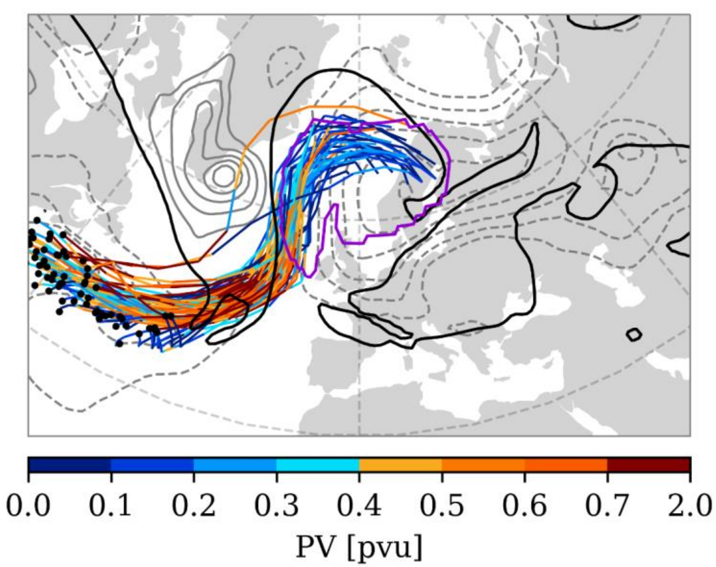
diabatic heating rate [K/s] = $\dot{\theta} = \frac{D\theta}{Dt}$

release and consume latent heat

Change of PV by **diabatic processes** (latent heating/cooling in clouds, radiation)

$\frac{d\dot{\theta}}{dz} > 0 \rightarrow$ **PV** $\uparrow$ $\quad$ $\frac{d\dot{\theta}}{dz} < 0 \rightarrow$ **PV** $\downarrow$





Method | Block identification

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

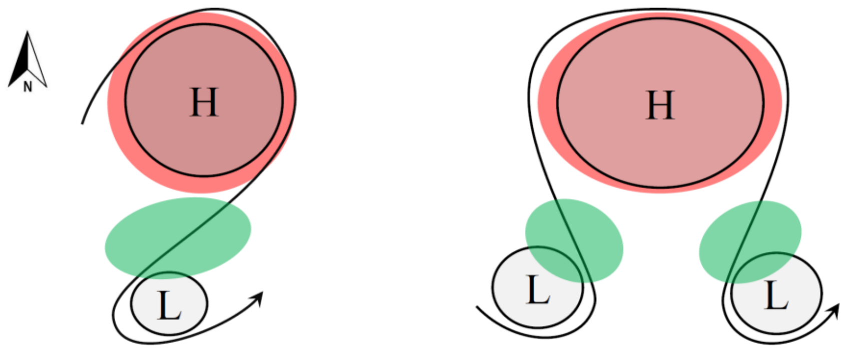
based on Z500 geopotential height

2D index from Scherrer et al., 2006
Tibaldi&Molteni

anomalous *index*

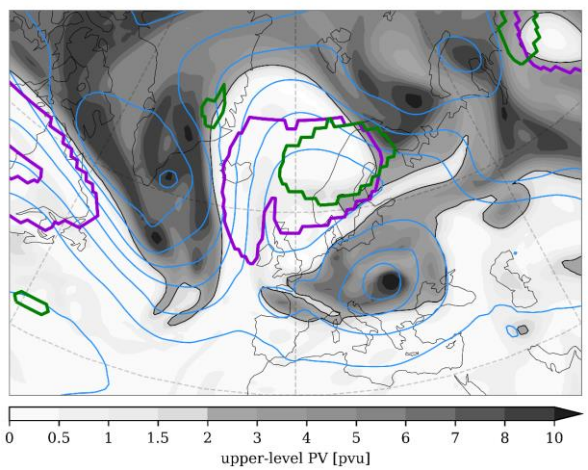
based on vertically-integrated PV

3D index from Schwierz et al., 2004



Dipole «Rex» block

Omega «Ω» block



Sensitivity| Case overview

October 2016: Scandinavian block