Young Investigator Group VH-NG-1243: "Sub-seasonal PREdictAbility: understanding the role of Diabatic OUTflow" (SPREADOUT)

Karlsruhe Institute of Technology

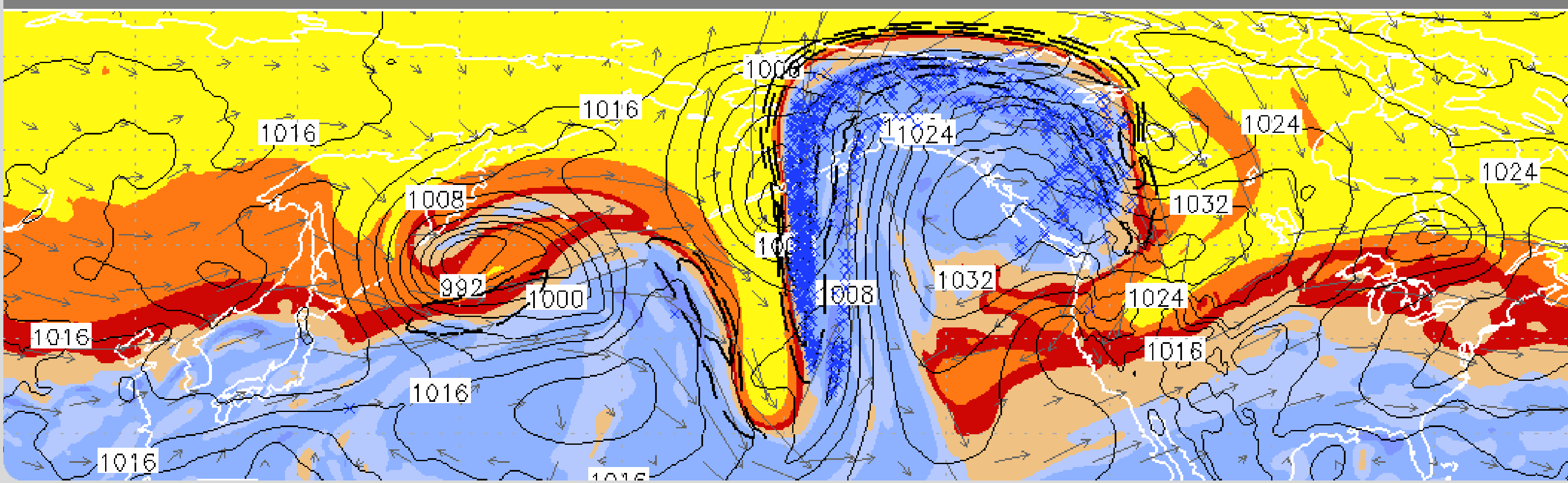
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ETH zürich

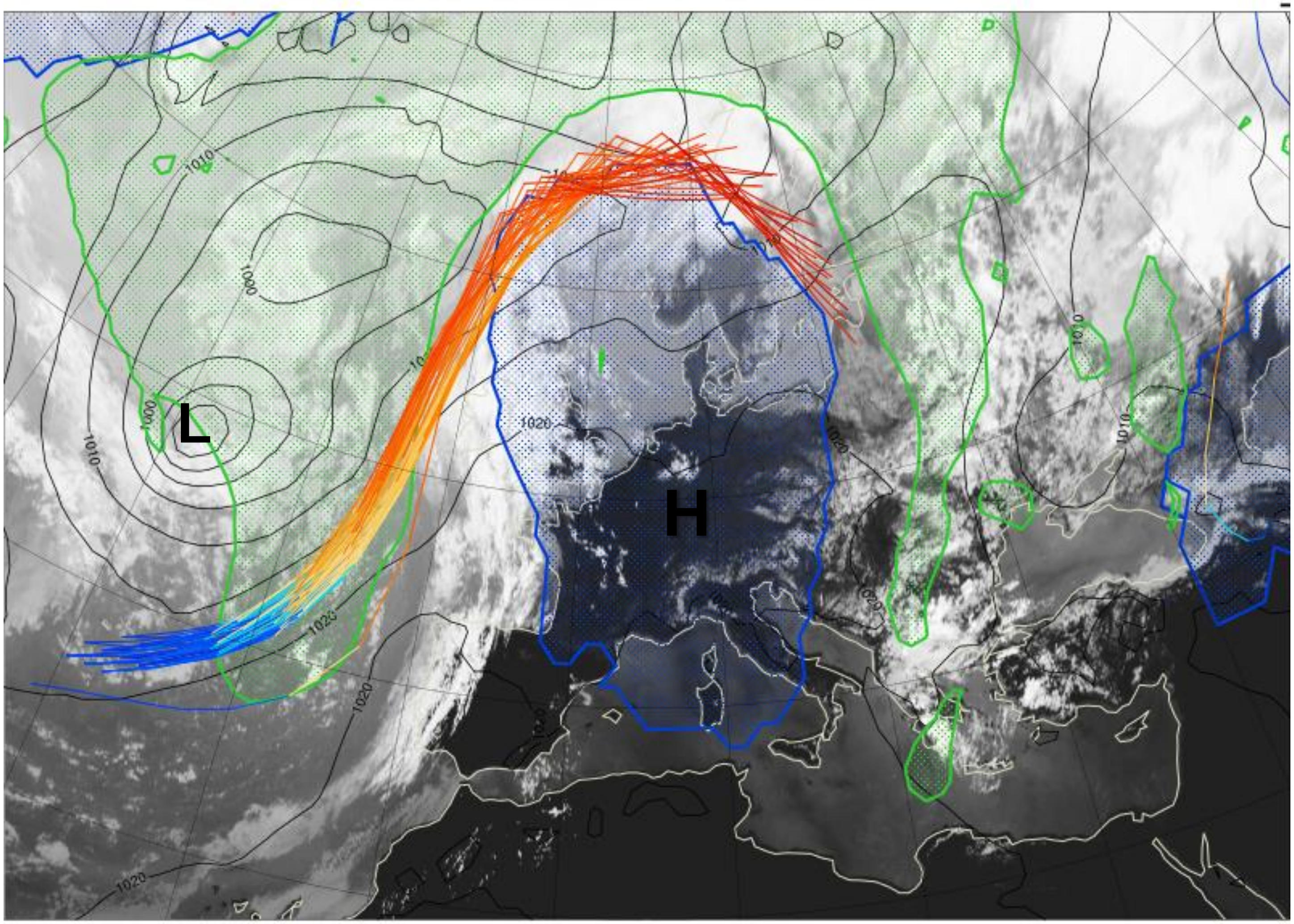
The impact of moist processes on the large-scale extratropical circulation

<u>Christian M. Grams</u> with contributions from: Heather Archambault, Marlene Baumgart, Maxi Böttcher, Yves Karrer, Erica Madonna, Linus Magnusson, Stephan Pfahl, Nicolas Piaget, Julian Quinting, Michael Riemer, Michael Sprenger, Daniel Steinfeld, Patrick Suter, Franziska Teubler, Heini Wernli, and others.

Institute of Meteorology and Climate Research – Department Troposphere Research



Heatwave Europe July 2015



MSG IR satellite 12 UTC 1 July 2015, jetstream (2PVU@325K), blocking
Strongly ascending and precipitating airstream – associated with North Atlantic cyclone - reaches into blocking region (MSLP 12 UTC 29 June 2015)

Outline

Moist processes & the large-scale circulation

1. Potential vorticity thinking
2. Diabatic influences on the large-scale circulation
3. Relevance for forecast error
4. Atlantic-European weather regime life cycles

Christian M. Grams grams@kit.edu Institute of Meteorology and Climate Research (IMK-TRO)

Potential vorticity

$$PV = \frac{1}{\rho}\vec{\eta}\cdot\nabla\Theta$$

$$PV = \frac{1}{\rho}\eta\frac{\partial\Theta}{\partial z}$$

unit: 1PVU = 10^{-6} K m^2 kg^{-1} s^{-1}

$$\eta = f + \vec{k}\cdot\nabla\times\vec{v}_h$$

Absolute vorticity / horizontal flow

Vertical stratification of the atmosphere/stability

$$\frac{dPV}{dt} = \frac{1}{\rho}\vec{\eta}\cdot\nabla\dot{\Theta} + \frac{1}{\rho}(\nabla\times\vec{F})\cdot\nabla\Theta$$

Total change in PV

diabatic PV modification

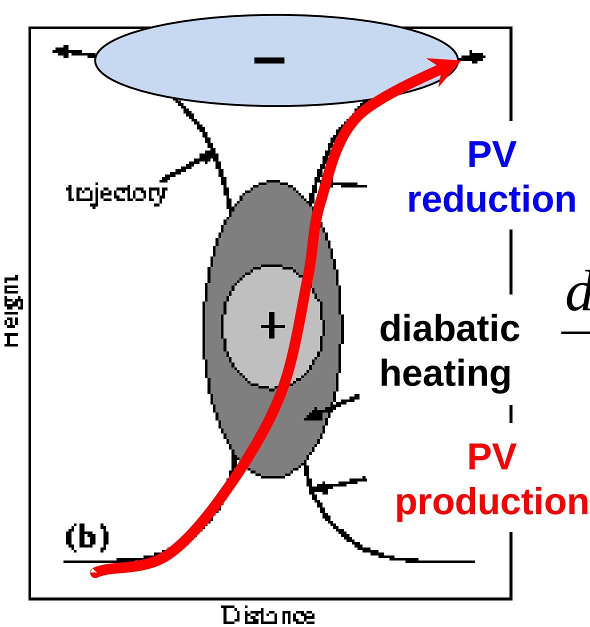
frictional processes

- PV is conserved under adiabatic frictionless flow (**conservation principle**)
- PV can be inverted given a balance condition and boundary conditions (**inversion principle**)

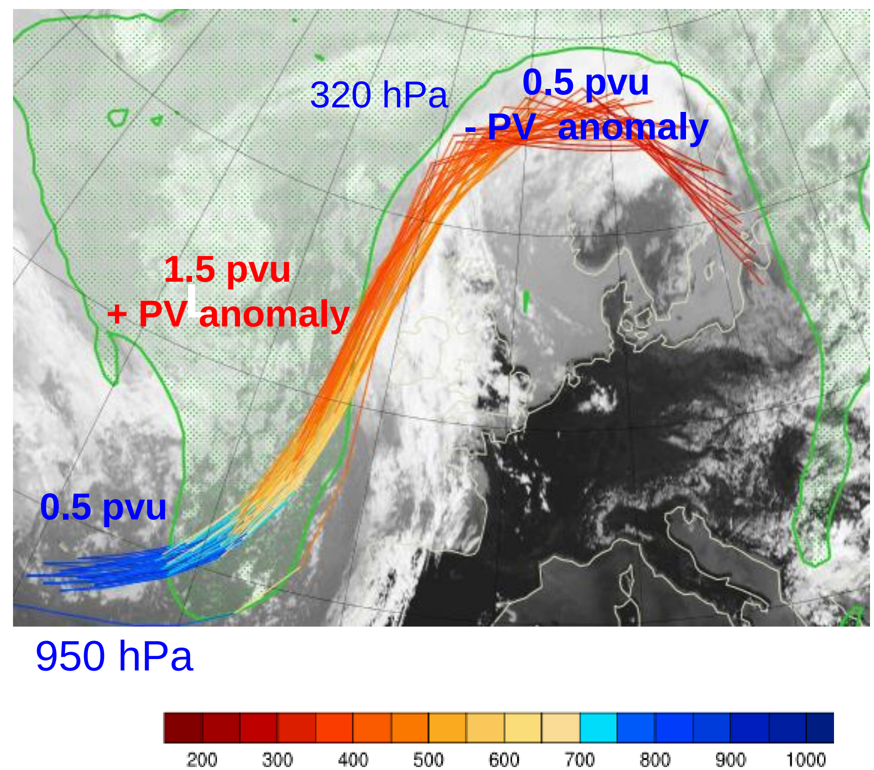
Warm conveyor belt

- rapidly ascending cross isentropic air flow (>600hPa/48h)
- diabatic heating of about 20K / 48h

see also WCB clim. by Madonna et al. (2014), *JCli,* http://dx.doi.org/10.1175/JCLI-D-12-00720.1



$$\frac{dPV}{dt} \mu \frac{d\dot{Q}}{dz}$$



Wernli and Davies (1997), *QJRMS*, http://dx.doi.org/10.1002/qj.49712353811

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Grams, C. M., et al., 2011: The key role of diabatic processes in modifying the upper-tropospheric wave guide. *Q.J.R. Meteorol. Soc.*, **137**, 2174–2193, doi:10.1002/qj.891.

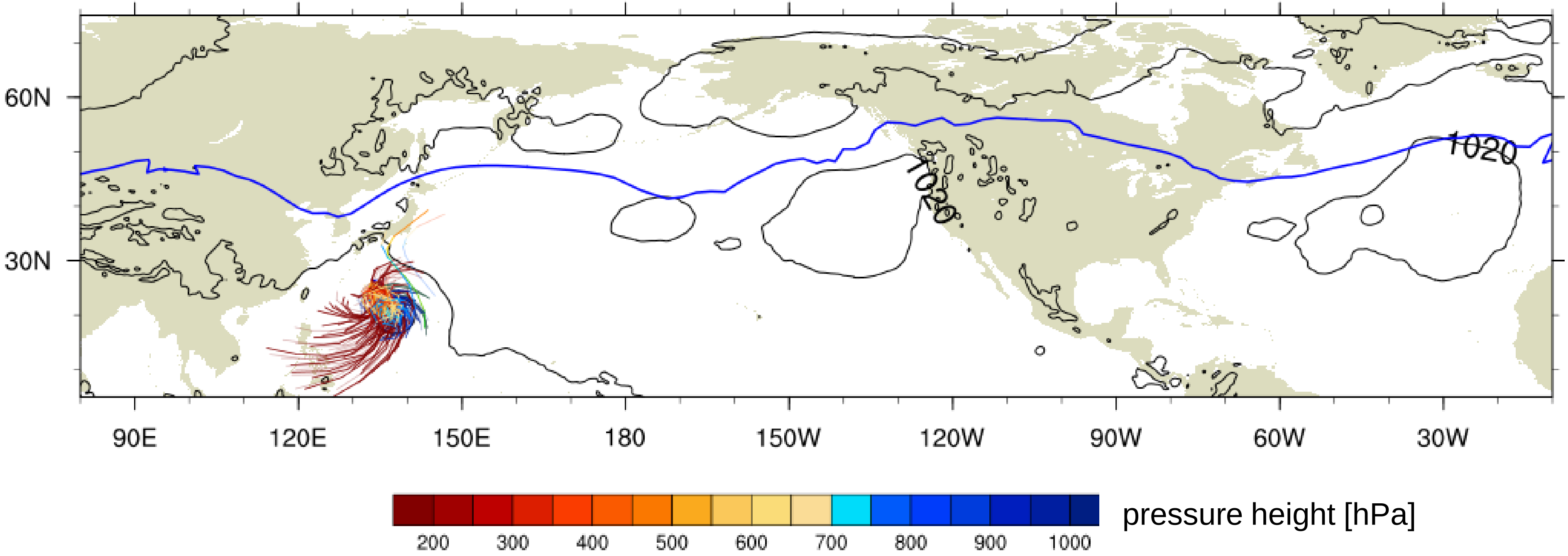
Grams, C. M., and H. M. Archambault, 2016: The key role of diabatic outflow in amplifying the midlatitude flow. *Mon. Wea. Rev.*, **144**, 3847–3869, doi:10.1175/MWR-D-15-0419.1.

Pfahl, S., et al., 2015: Importance of latent heat release in ascending air streams for atmospheric blocking. *Nature Geosci*, **8**, 610–614, doi:10.1038/ngeo2487.

Teubler, F., and M. Riemer, 2016: Dynamics of Rossby wave packets in a quantitative potential vorticity framework. *J. Atmos. Sci.*, **73**, 1063–1081, doi:10.1175/JAS-D-15-0162.1.

Diabatic outflow and upper-level flow

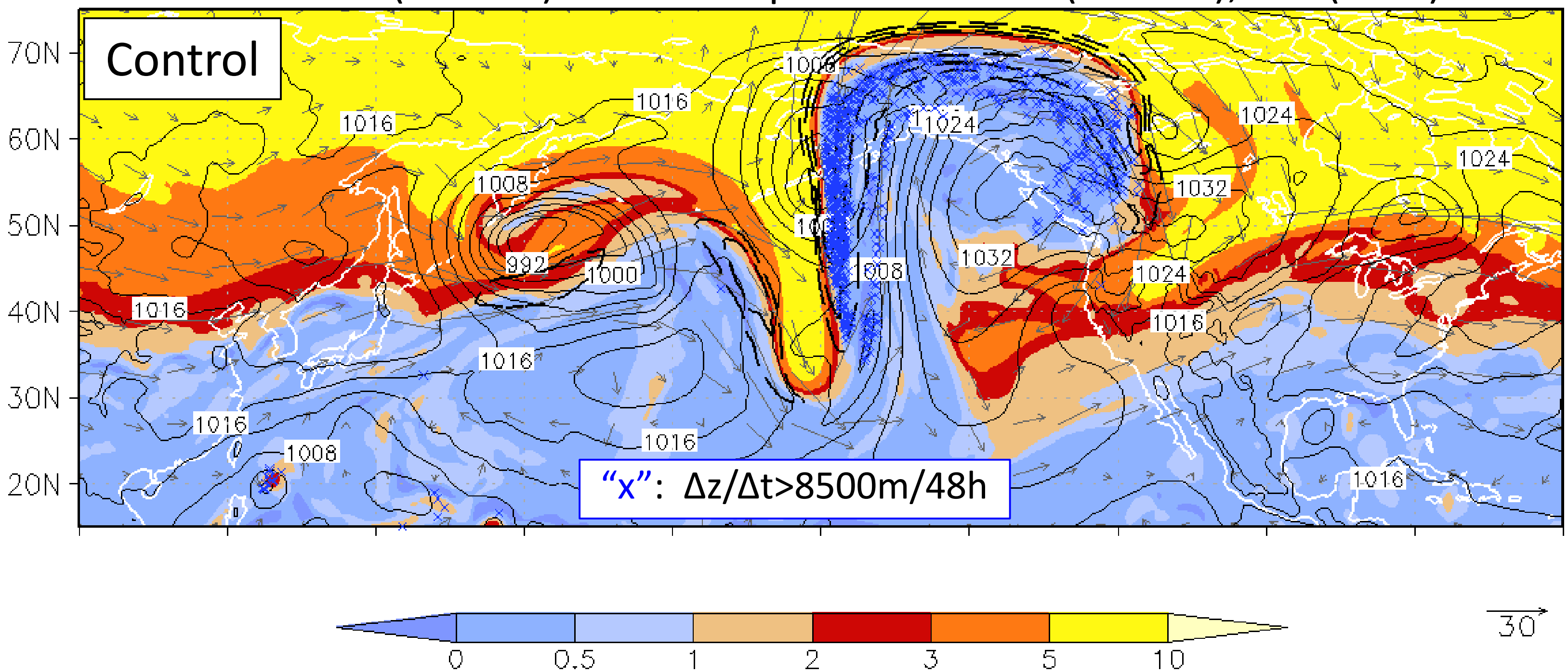
trajectories (Δz/Δt>8500m/48h), pmsl, 3PVU@335K



Grams and Archambault (2016), *MWR,* doi: 10.1175/MWR-D-15-0419.1

Diabatic outflow and upper-level flow

335-K PV (shaded) and wind speed >50 m s^{-1} (dashed); SLP (solid)

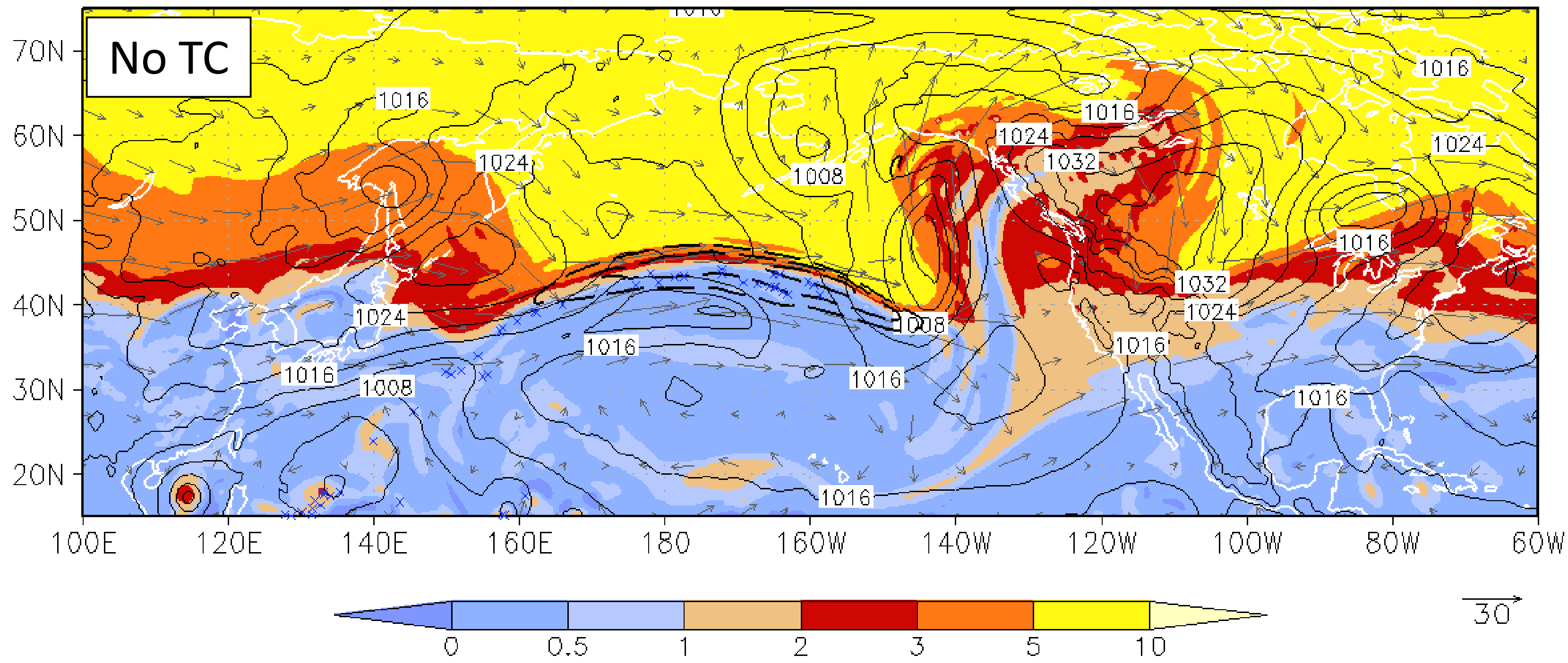


- downstream ridgebuilding by downstream WCB
- Strongly amplified upper-level flow and downstream blocking

Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1

Diabatic outflow and upper-level flow

335-K PV (shaded) and wind speed >50 m s^{-1} (dashed); SLP (solid)

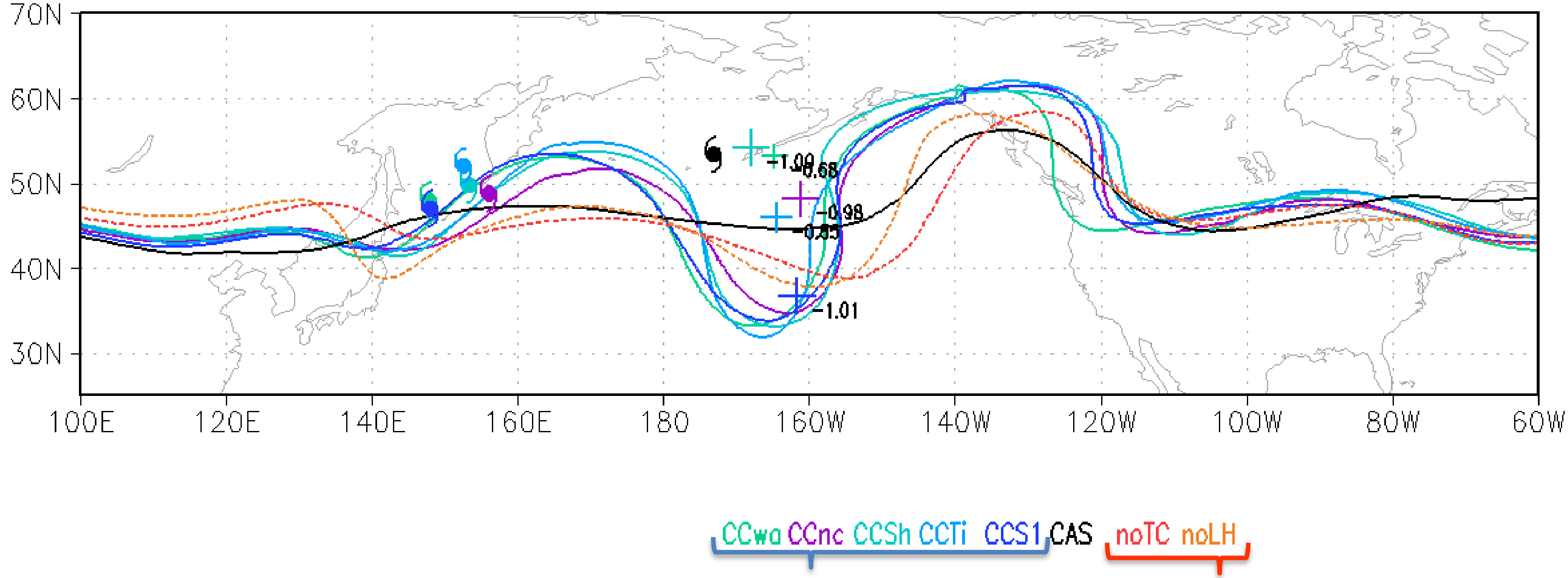


Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1

Diabatic outflow and upper-level flow

- diabatic outflow from different weather system categories jointly yield highly amplified midlatitude flow

Geopotential height 200hPa (1200 gpdm contour) **DS-WCB stage T+84h**



control ensemble

composite mean

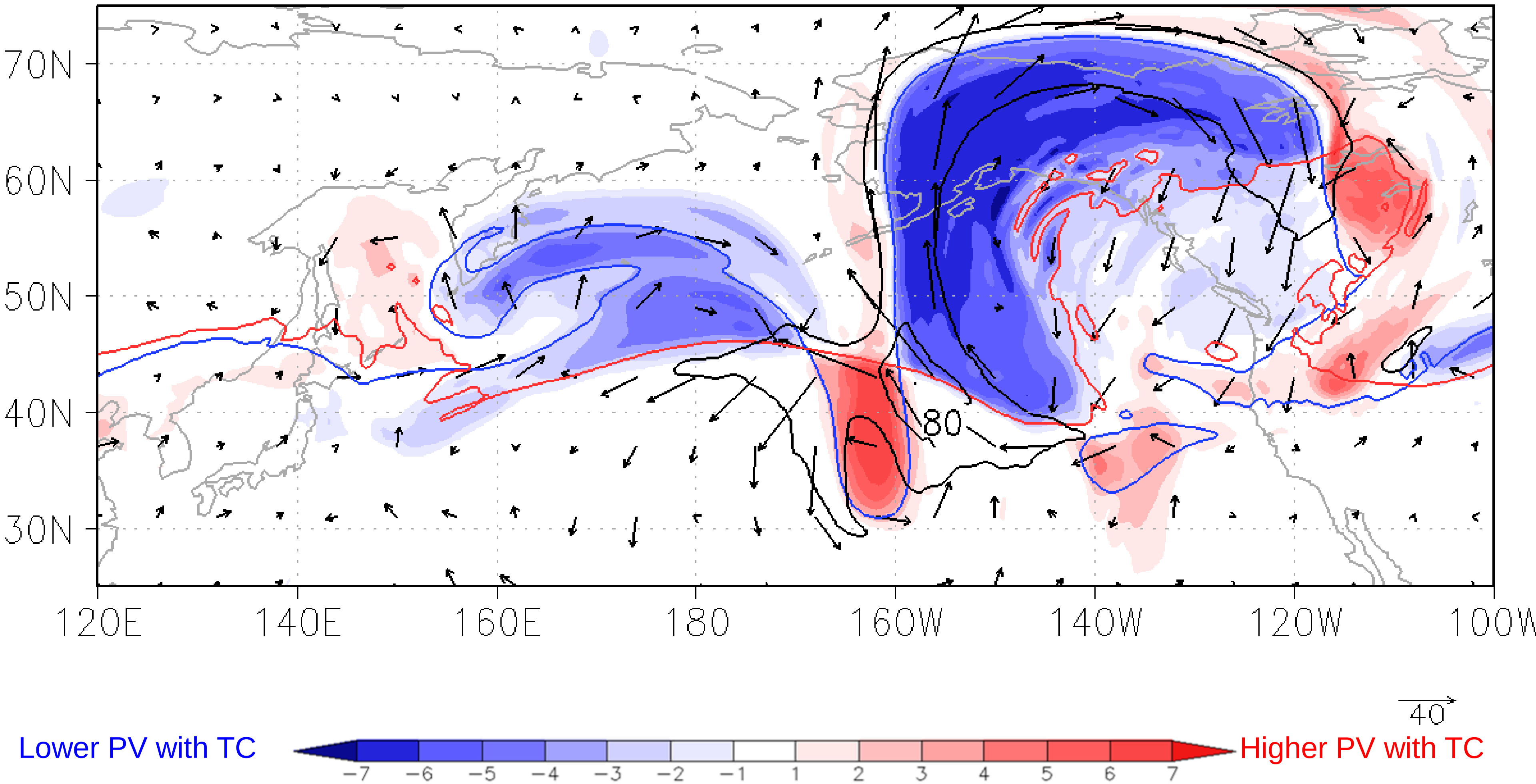
no TC/ no LHR (weak meridional moisture transport)

Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1

Downstream WCB outflow

T+108 h

335-K 2-PVU contours for Control and No TC,
and Control minus No TC PV and wind

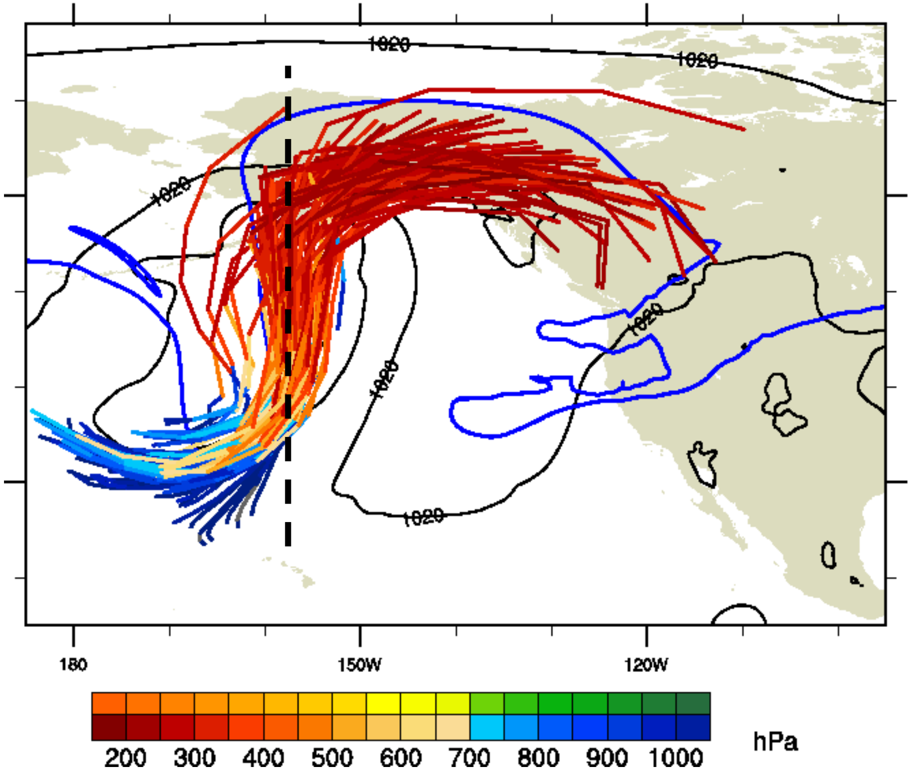


Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1

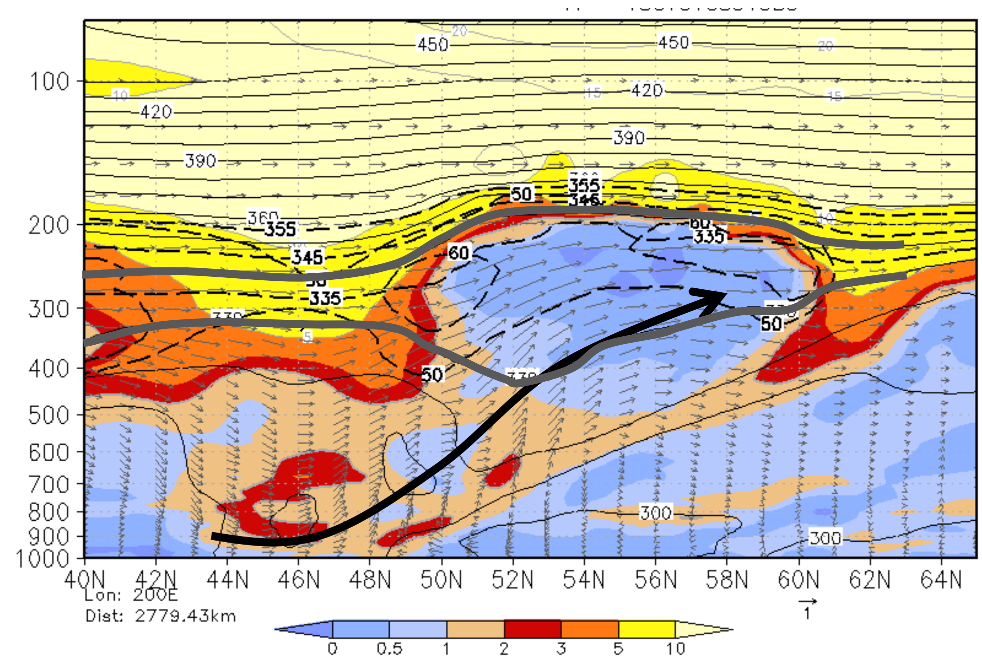
Diabatic outflow

Downstream WCB stage

trajectories (dz/dt>8500m/48h), pmsl, 3PVU@335K



PV [PVU], Θ (solid, in K), windspeed



Grams and Archambault (2016), *MWR,* doi: 10.1175/MWR-D-15-0419.1

Diabatic outflow

Downstream WCB stage

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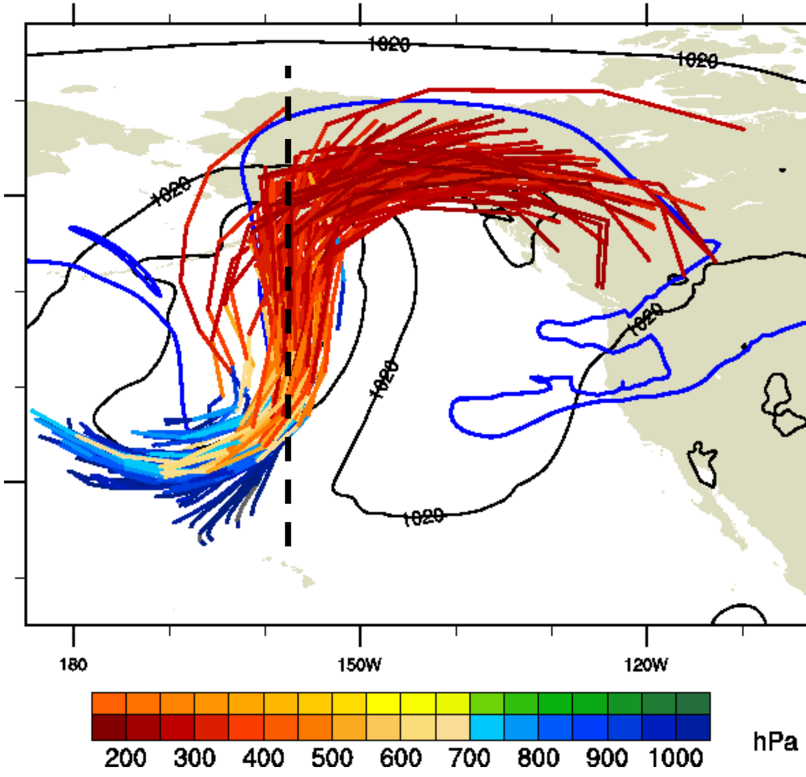
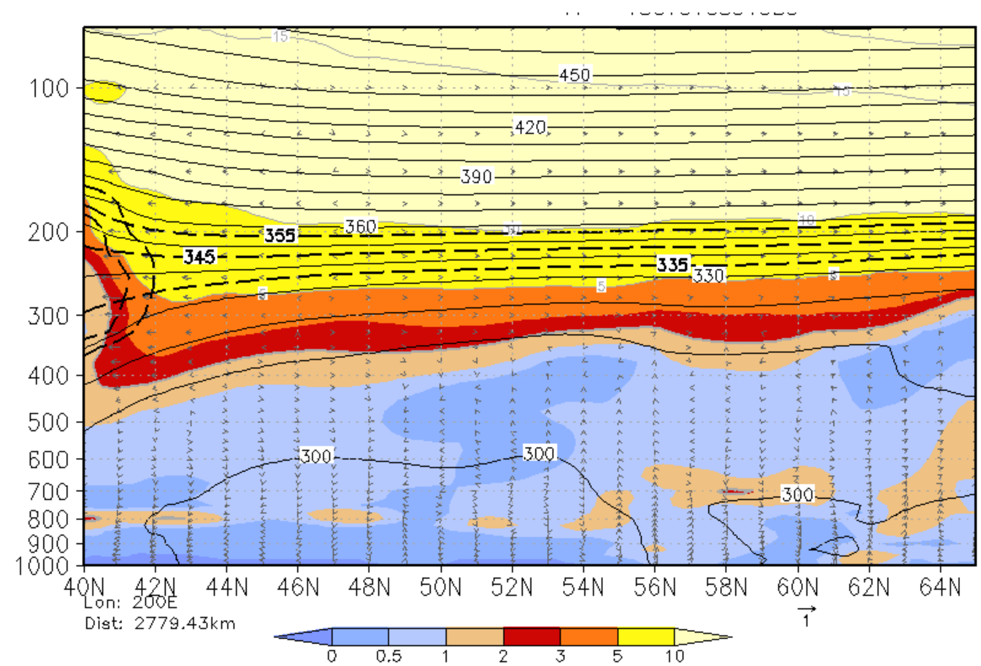
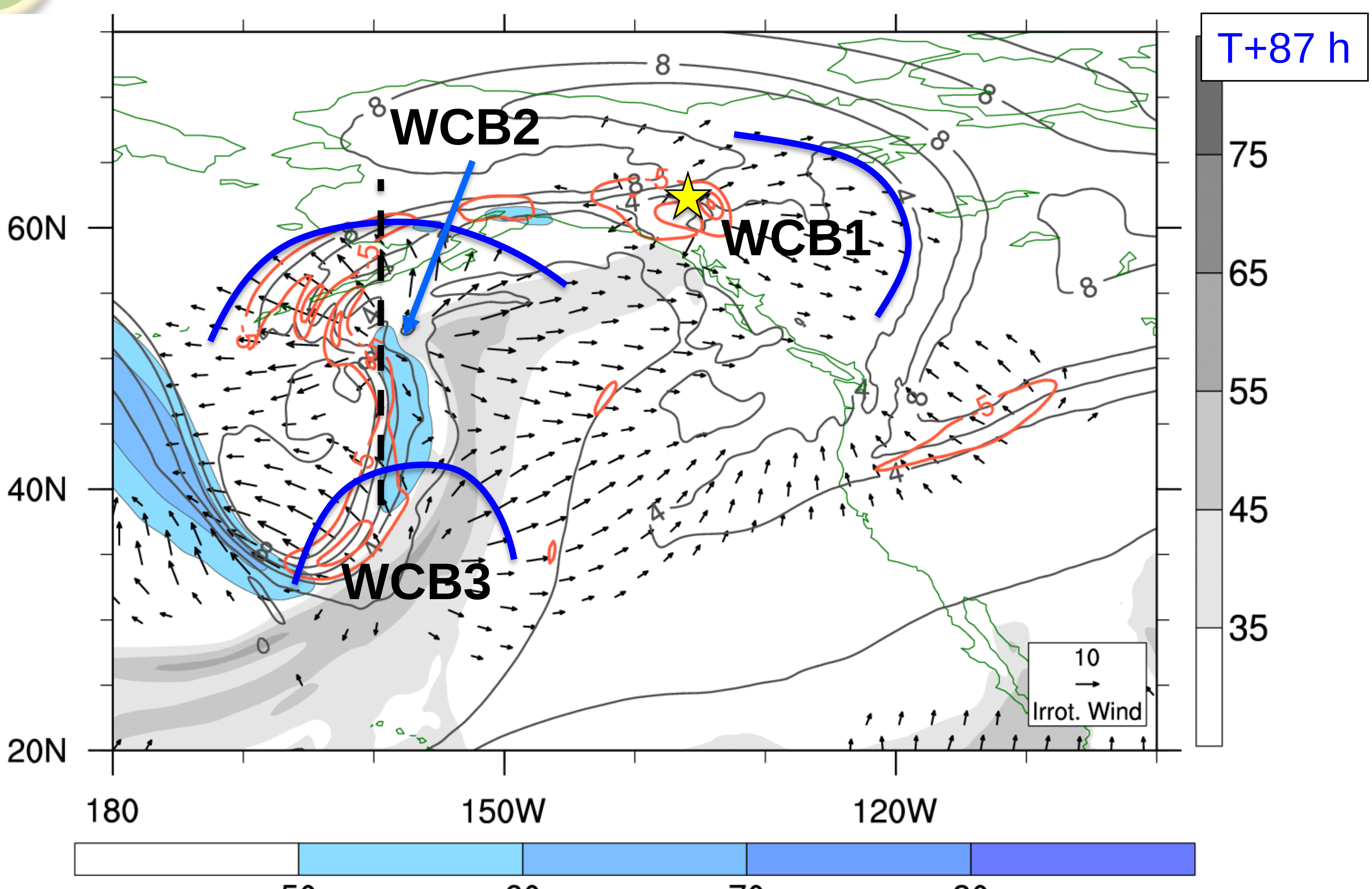


PV [PVU], ϴ (solid, in K), windspeed



Grams and Archambault (2016), *MWR*, doi: 10.1175/MWR-D-15-0419.1

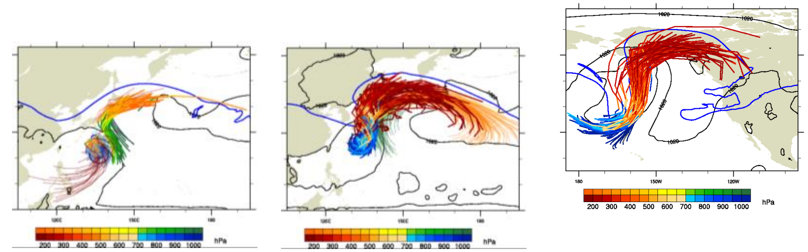
Downstream WCB outflow



250-150hPa **wind speed** (shading in m s^{-1}), **irrot. wind** (vectors), **neg. PV advection by irrot. wind** (red contours, PVU day^{-1}), **total precip. water** (gray shading, mm),

Outflow characteristics

- 3 stages of ET with diabatic outflow from different weather systems



(p, ϴ, PV: mean±stddev)	**PRE**	**ET/TC**	**DS WCB**
time of max. interaction	T+6h	T+45h	T+87h
$\max(-\vec{v}_{irr} \cdot \nabla PV)$ [PVU/h]	**1.27**	**2.03**	**1.09**
traj. ending at	T+12h	T+48h	T+108h
number of trajectories	1798	4727	4788
p[hPa] (outflow)	**234 ± 36**	**183 ± 38**	**256 ± 40**
ϴ[K] (outflow)	345 ± 5	355 ± 6	334 ± 3

recent review paper on downstream impact of tropical cyclones:

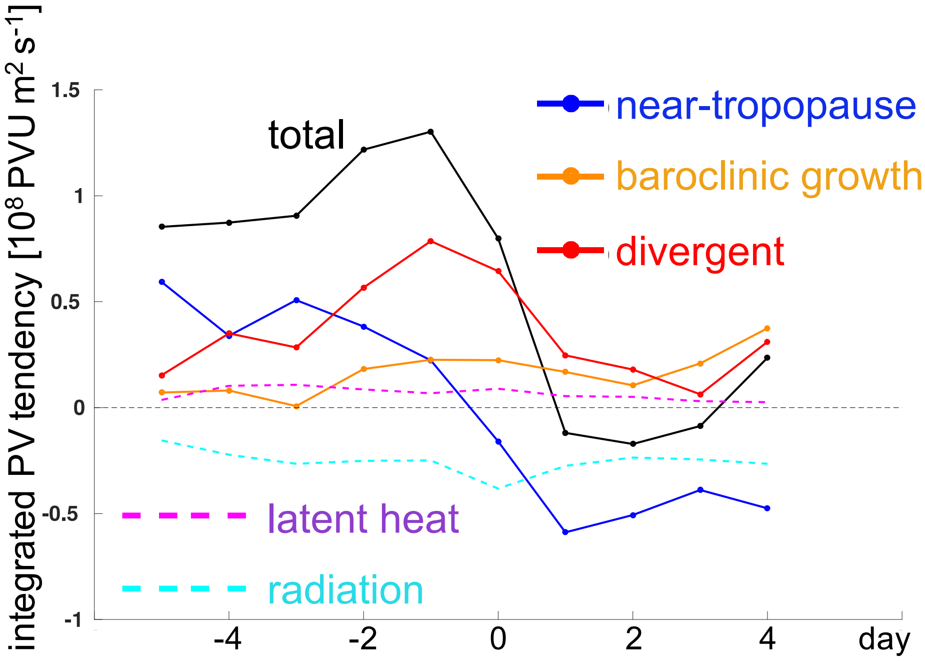
Keller, J. H., et al., 2019: The Extratropical Transition of Tropical Cyclones Part II: Interaction with the midlatitude flow, downstream impacts, and implications for predictability. ***Mon. Wea. Rev.*****,** doi:10.1175/MWR-D-17-0329.1.

Grams and Archambault (2016), *MWR,* doi: 10.1175/MWR-D-15-0419.1

advective PV tendencies

Ridge composite YOTC period

$$\left.\frac{\partial \mathrm{PV}'}{\partial t}\right|_\theta = -\mathbf{v}\cdot\nabla_\theta \mathrm{PV} + \mathrm{DIA}(\dot\theta, \mathrm{PV}, \mathbf{v}), \qquad (1)$$



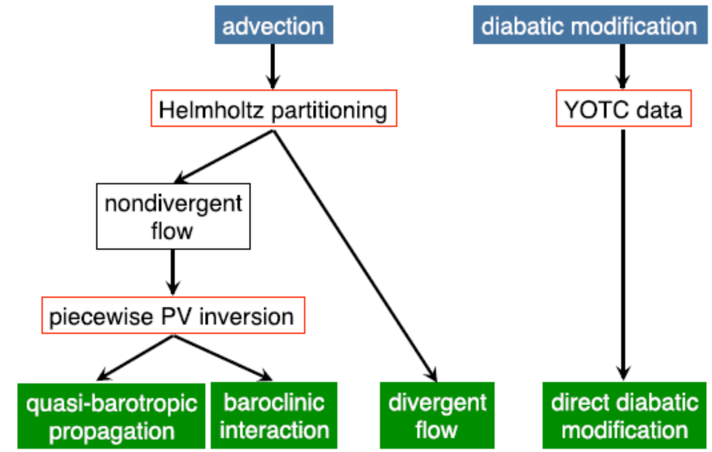


Figure 3 Teubler and Riemer, 2016, JAS

lifetime-integrated values [10^{13} PVU m^2]:

near-tropopause: -0.6

baroclinic growth: 1.4

divergent : 3.0

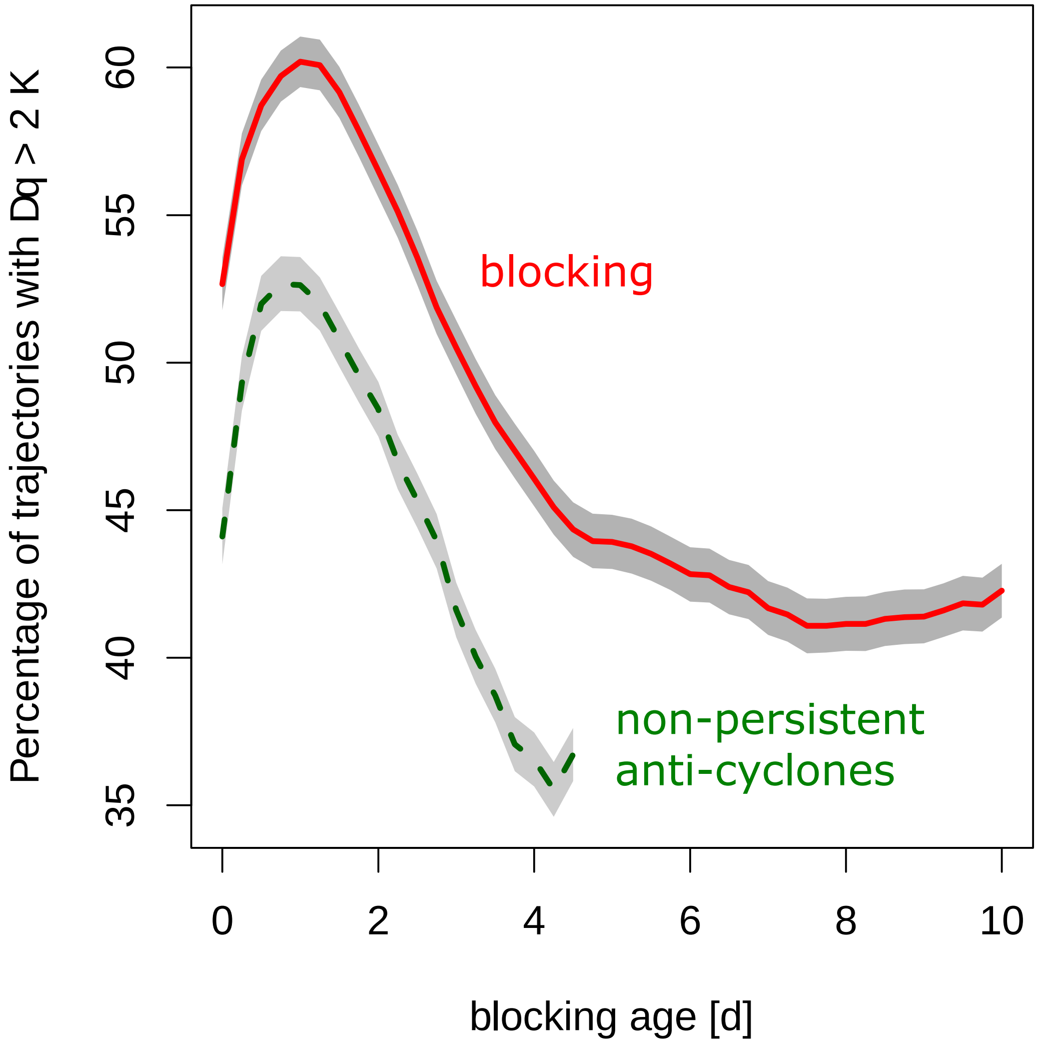
latent heat: 0.5

radiation: -2.1

Teubler, F., and M. Riemer, 2016: Dynamics of Rossby wave packets in a quantitative potential vorticity framework. *J. Atmos. Sci.*, **73**, 1063–1081, doi:10.1175/JAS-D-15-0162.1.

Teubler and Riemer YOTC composite in preparation **slide provided by Michael Riemer**

Diabatic influence on blocking



slides by Stephan Pfahl

Pfahl, S. et al. (2015), *Nature Geosci.*, [doi:10.1038/ngeo2487](https://doi.org/10.1038/ngeo2487)

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Grams, C. M., L. Magnusson, and E. Madonna, 2018: An atmospheric dynamics perspective on the amplification and propagation of forecast error in numerical weather prediction models: A case study. *Quart. J. Roy. Meteor. Soc.,* **144**, 2577–2591, doi:10.1002/qj.3353.

Baumgart, M., P. Ghinassi, V. Wirth, T. Selz, G. C. Craig, and M. Riemer, 2019: Quantitative View on the Processes Governing the Upscale Error Growth up to the Planetary Scale. *Mon. Wea. Rev.*, **147**, 1713–1731, doi:10.1175/MWR-D-18-0292.1.

RW characteristic of forecast error

- forecast error emerges along the midlatitude wave guide and propagates like RW

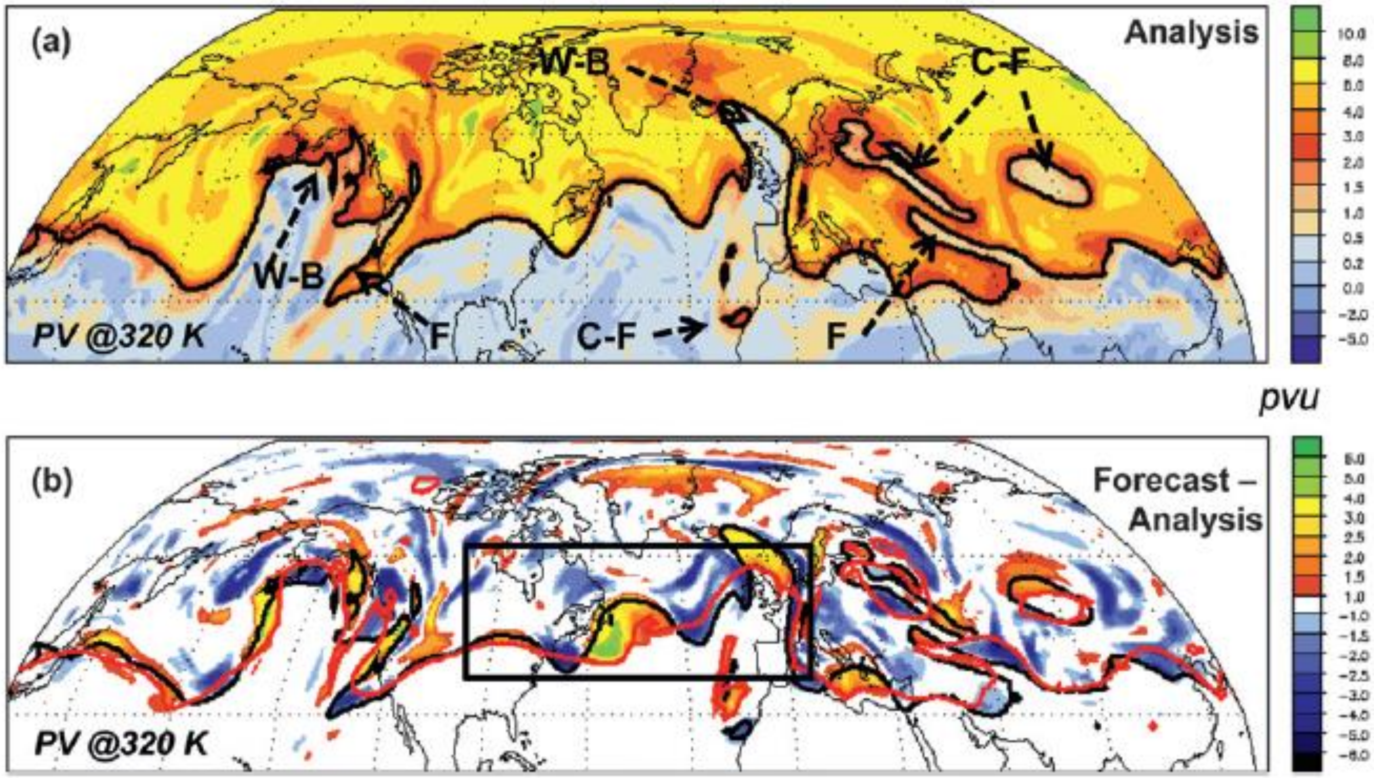
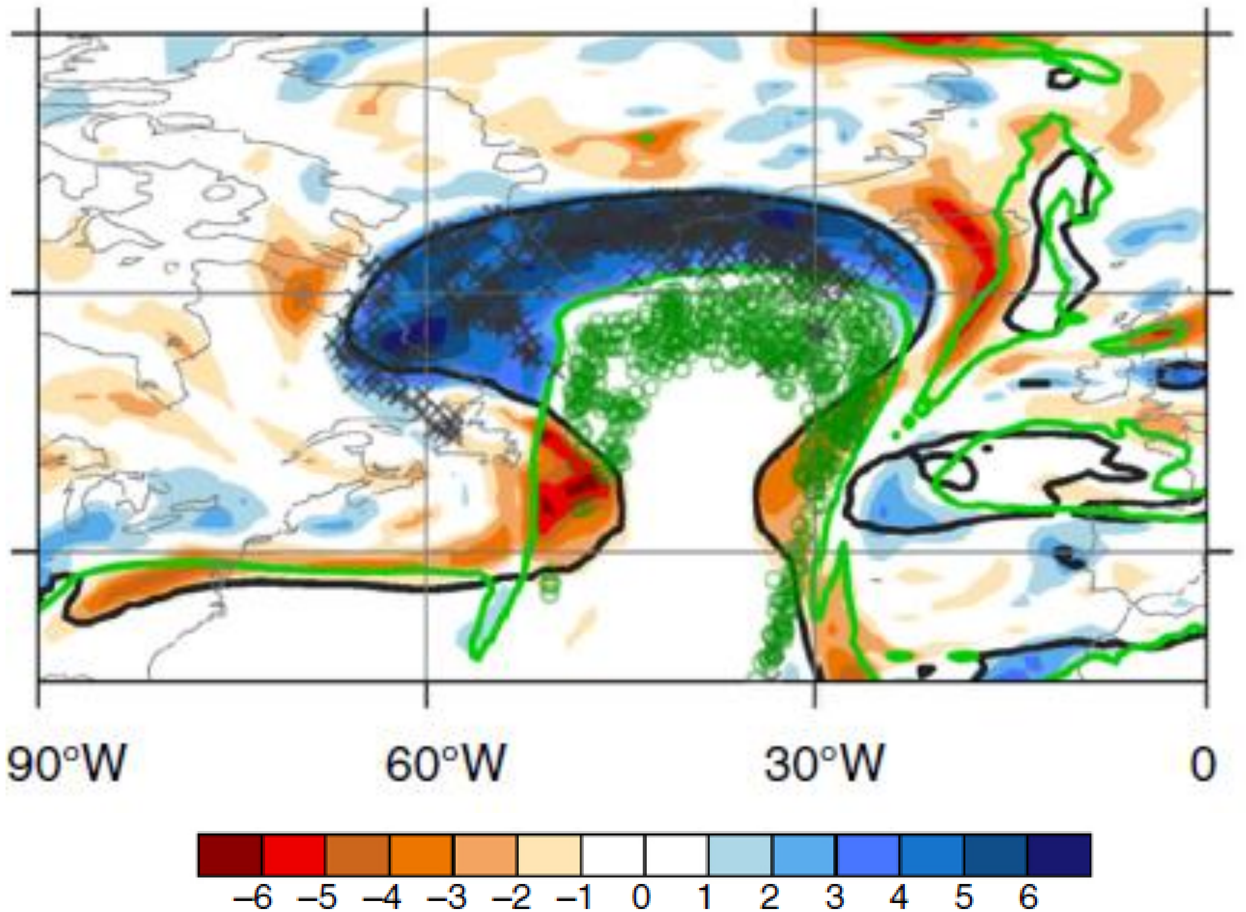


Figure 1 from Davies and Didone, 2013, *MWR*

Davies, H. C., and M. Didone, 2013: Diagnosis and Dynamics of Forecast Error Growth. *Mon. Wea. Rev.*, **141**, 2483–2501, doi:10.1175/MWR-D-12-00242.1.

WCB forecast error

- contribution of model error to misrepresentation of WCB results in error of the large-scale flow



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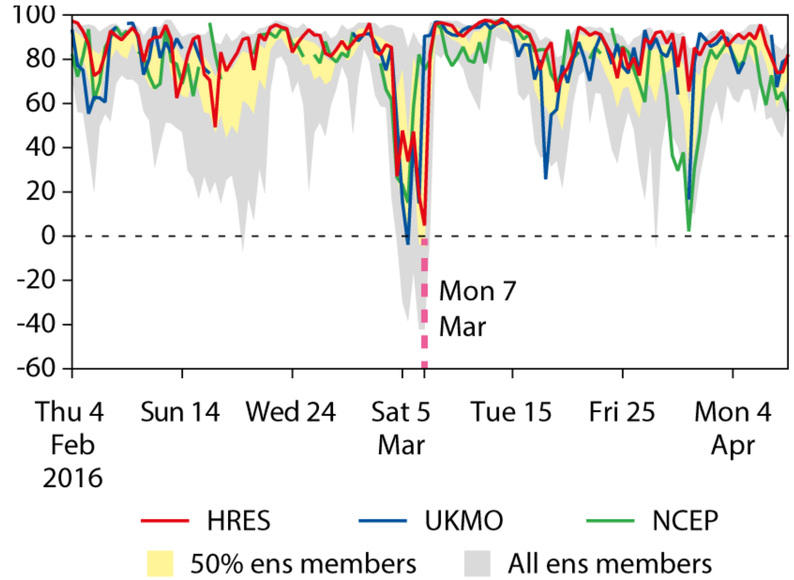
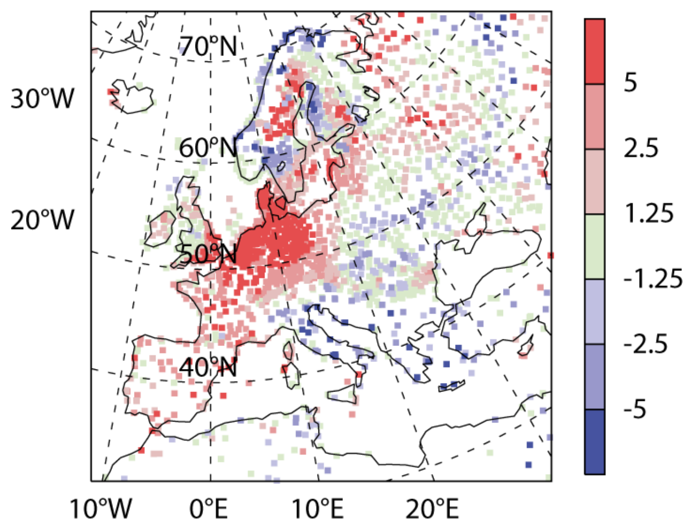
The March 2016 forecast bust

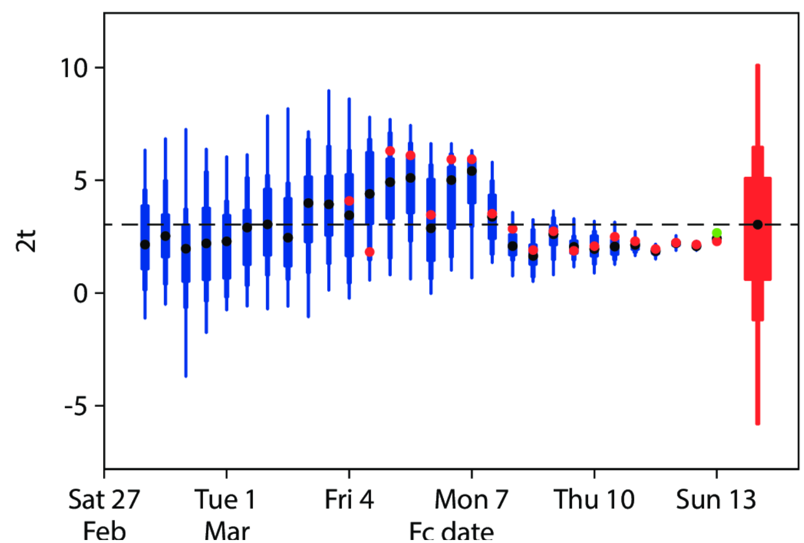


+144h Z500 ACC for HRES and ENS - Europe

forecast error 2m T



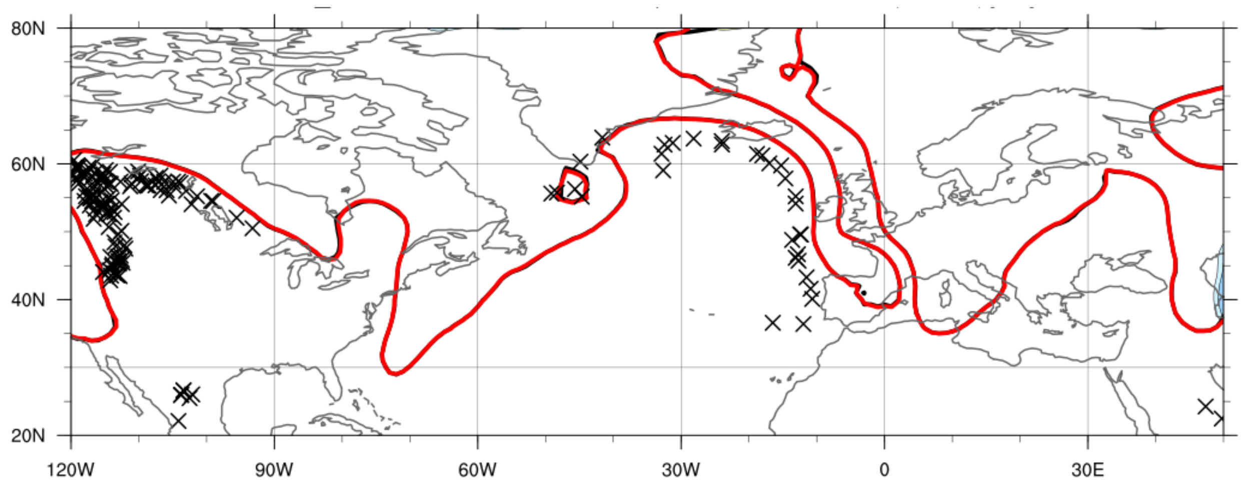
forecast of 2m T Germany at different init. times

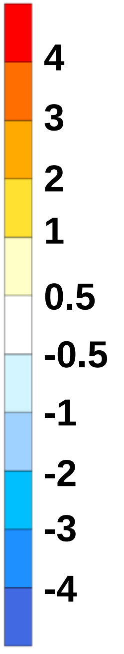


Grams, Magnusson, and Madonna (2018), *QJRMS*, doi: 10.1002/qj.3353

00UTC 7 March 2016 forecast bust

IFS **IPV315K** analysis – ensemble mean & WCB intersection points (analysis)





analysis
ensemble mean

PVU

x WCB ISP

Grams, Magnusson, and Madonna *(*2018), *QJRMS,* [doi: 10.1002/qj.3353](https://doi.org/10.1002/qj.3353)

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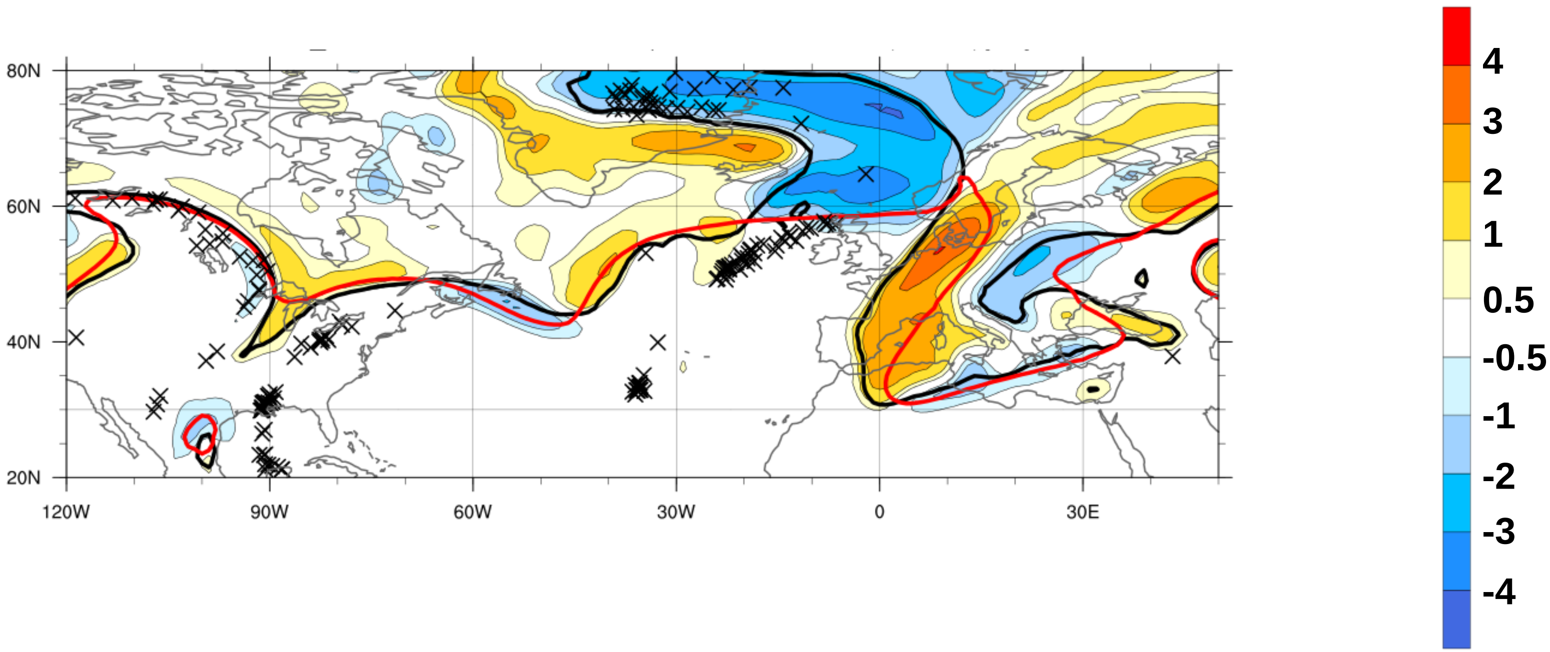

analysis

ensemble mean

PVU

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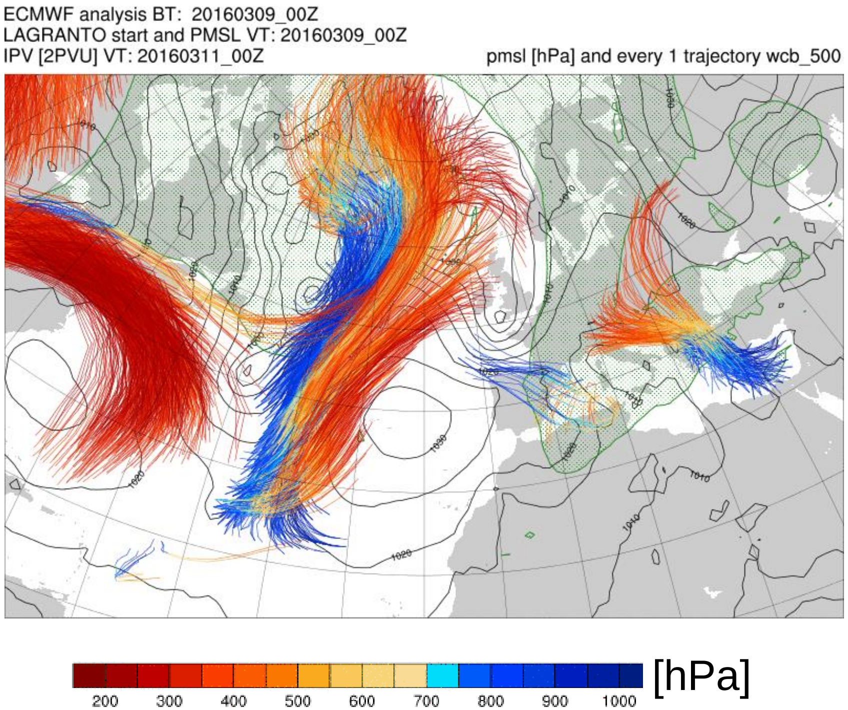
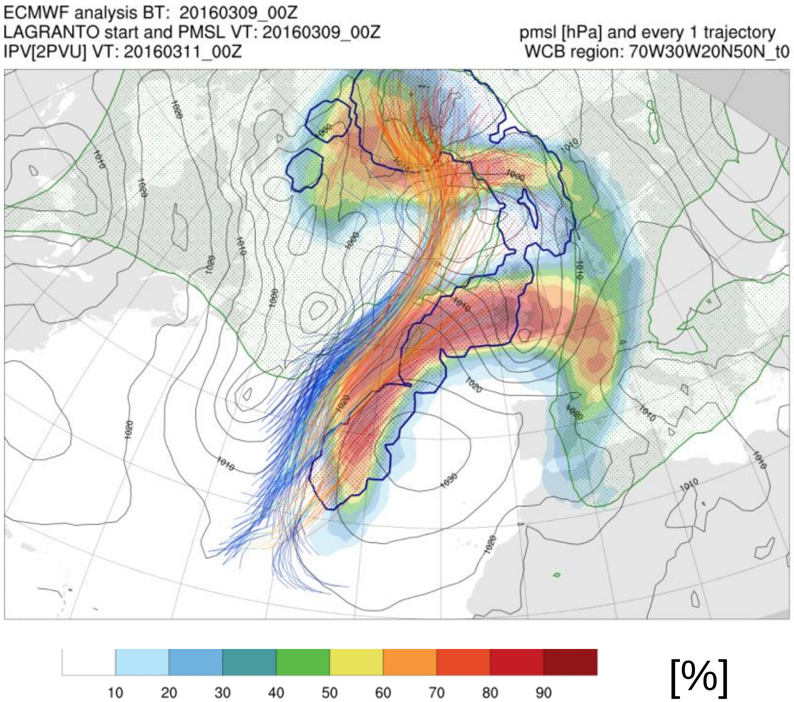
WCB activity during WR transition

ECMWF analysis





tra starting & pmsl 20160309_00

tra ending & 2PVU@315K &

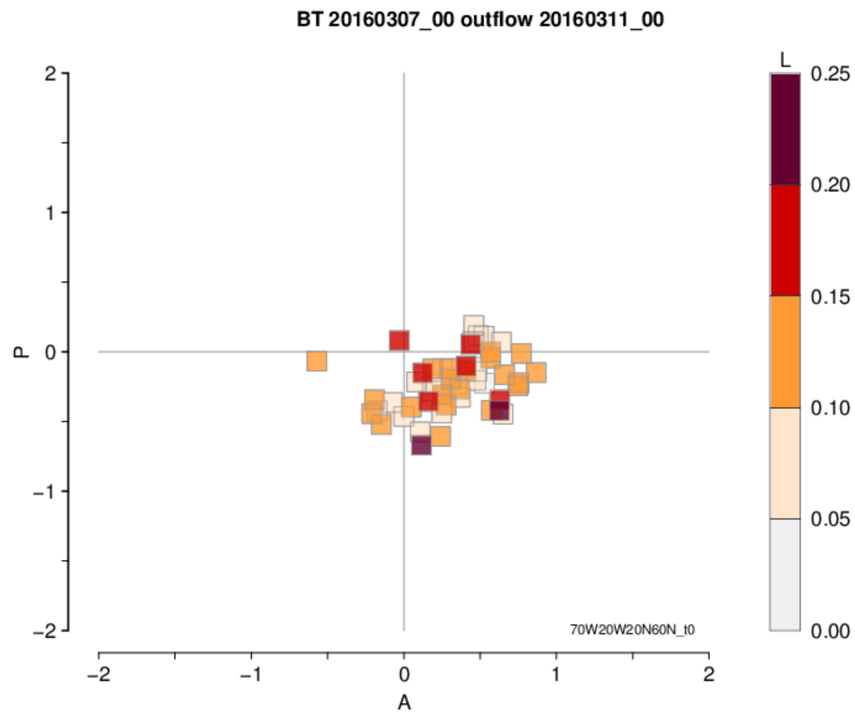
WCB outflow probabilities [%] 20160311_00

Grams, Magnusson, and Madonna (2018), *QJRMS,* doi: 10.1002/qj.3353

The PAL forecast metric

- Metric for quantifying the **P**V, **A**mplitude, and **L**ocation error of WCB outflow objects
- **P** term: <0, too weak / >0, too strong negative PV anomaly in outflow
- **A** term: <0, too few / >0 too many trajectories
- **L** term: 0 good; close to 2 → objects in opposite corners

PAL diagram illustrates the three components, for different forecast members



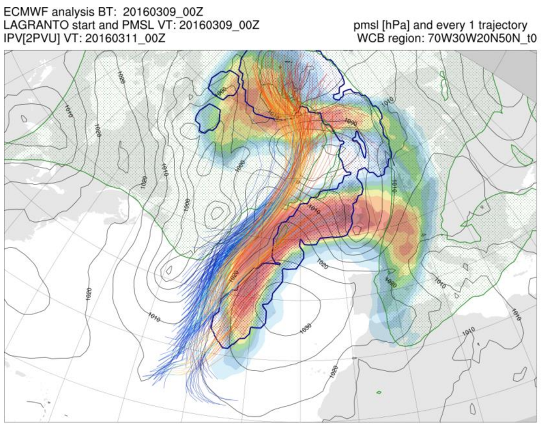
Madonna et al. (2015), *QJRMS*, [doi: 19.1002/qj.2442]

Role of WCB in forecast bust

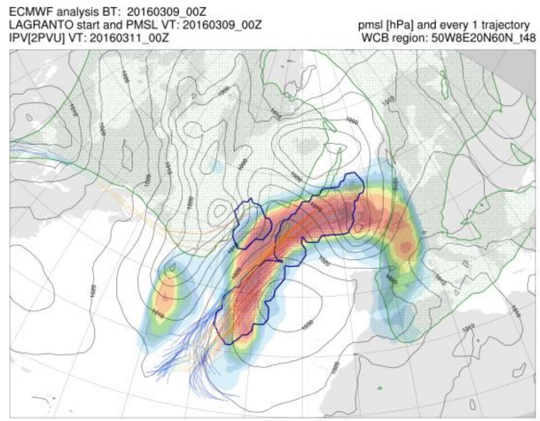
ECMWF ensemble initial time **20160307_00**

focus on WCB **starting 00 UTC 9 March (+48h) → ending 00 UTC 11 March (+96h)**

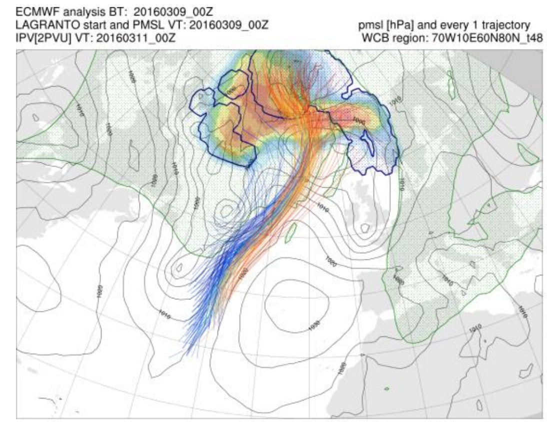
ALL

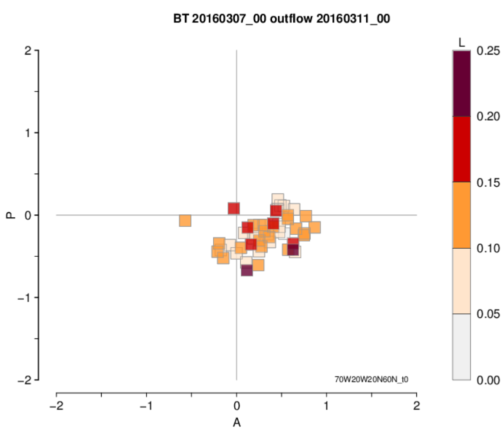


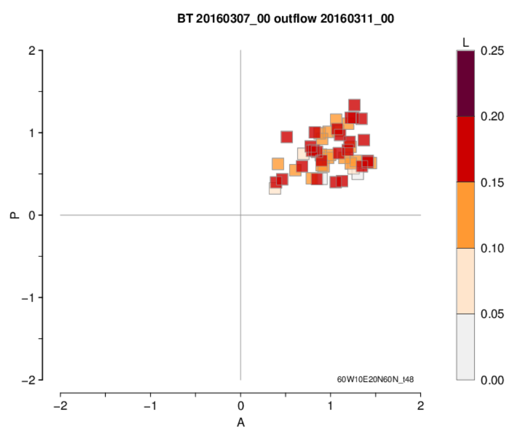
SOUTH

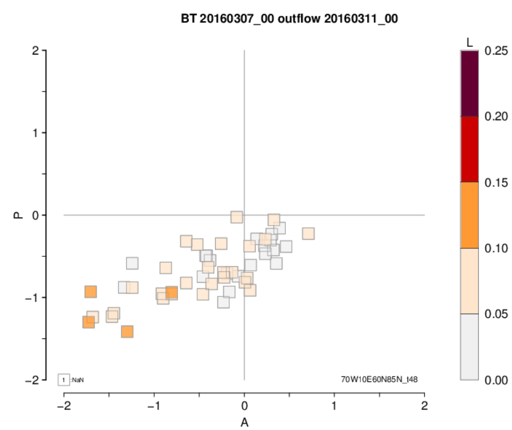


NORTH









Grams, Magnusson, and Madonna (2018), *QJRMS,* doi: 10.1002/qj.3353

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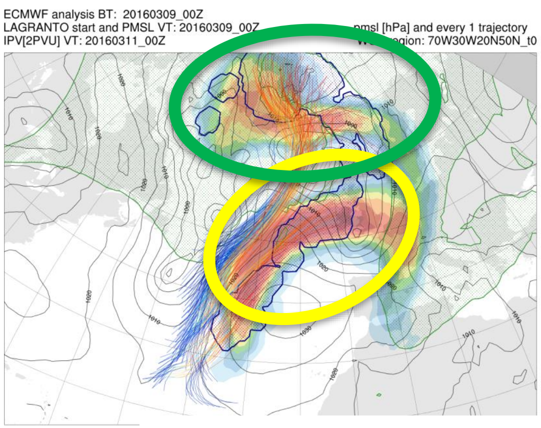
ALL



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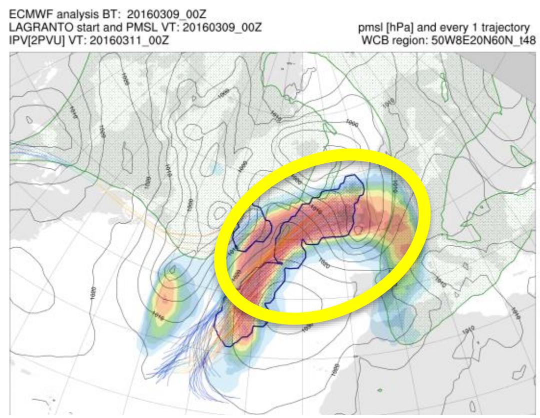
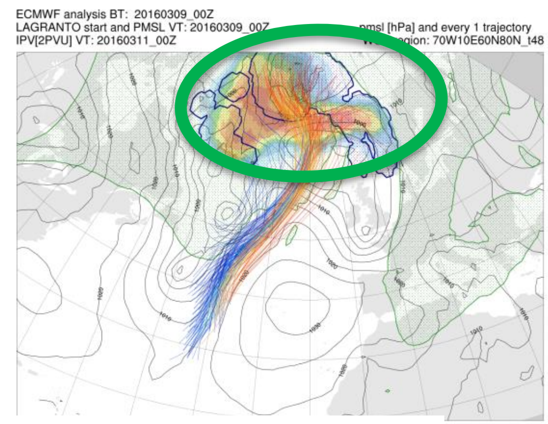
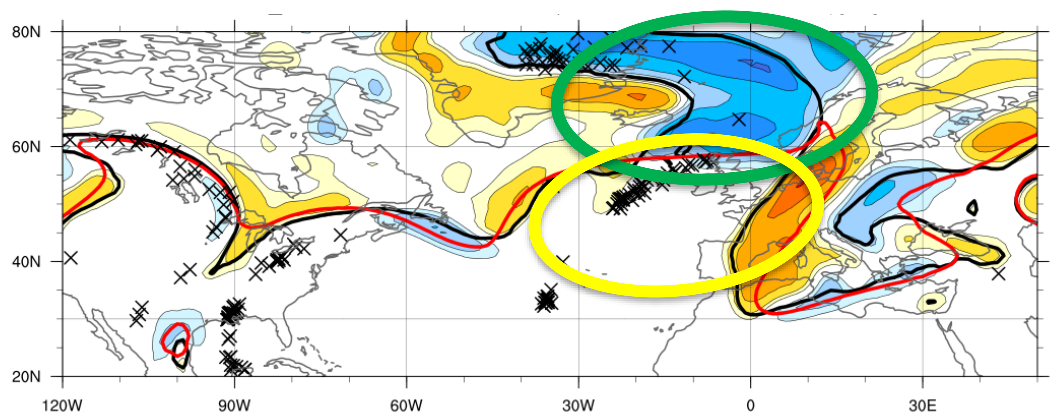


NORTH



- Southern branch too strong → maintained AR
- Northern branch too weak → missed BL onset

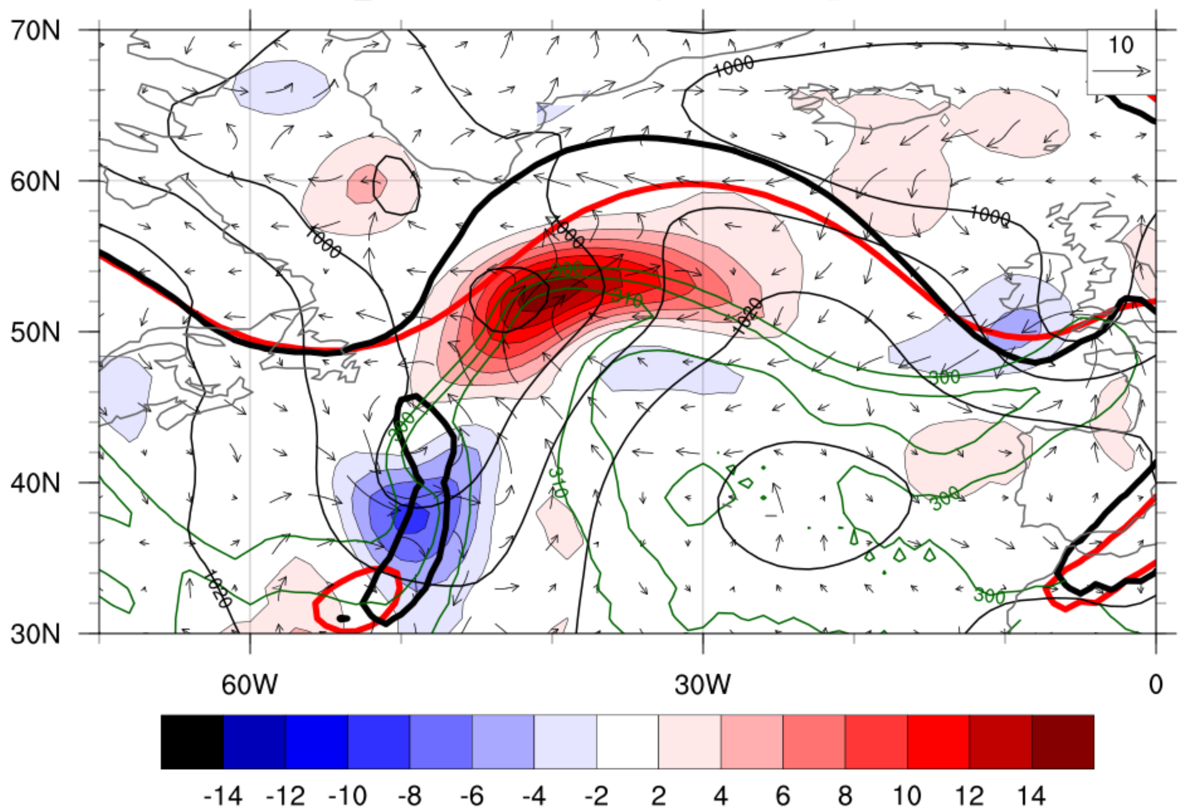


Grams, Magnusson, and Madonna (2018), *QJRMS*, doi: 10.1002/qj.3353

Initial condition error?

00 UTC 9 March

IPV@315K an/em, SLP ana, THE850 an-em,
wind850-500hPa an-em



- error in upper-level cut-off induces → cyclonic flow anomaly and ill-forecast SLP
- enhanced and tilted baroclinic zone missed → wrong WCB ascent

Initial condition error?

PV error tendencies

- 3 stage error growth model (Zhang et al. 2007) confirmed in PV framework

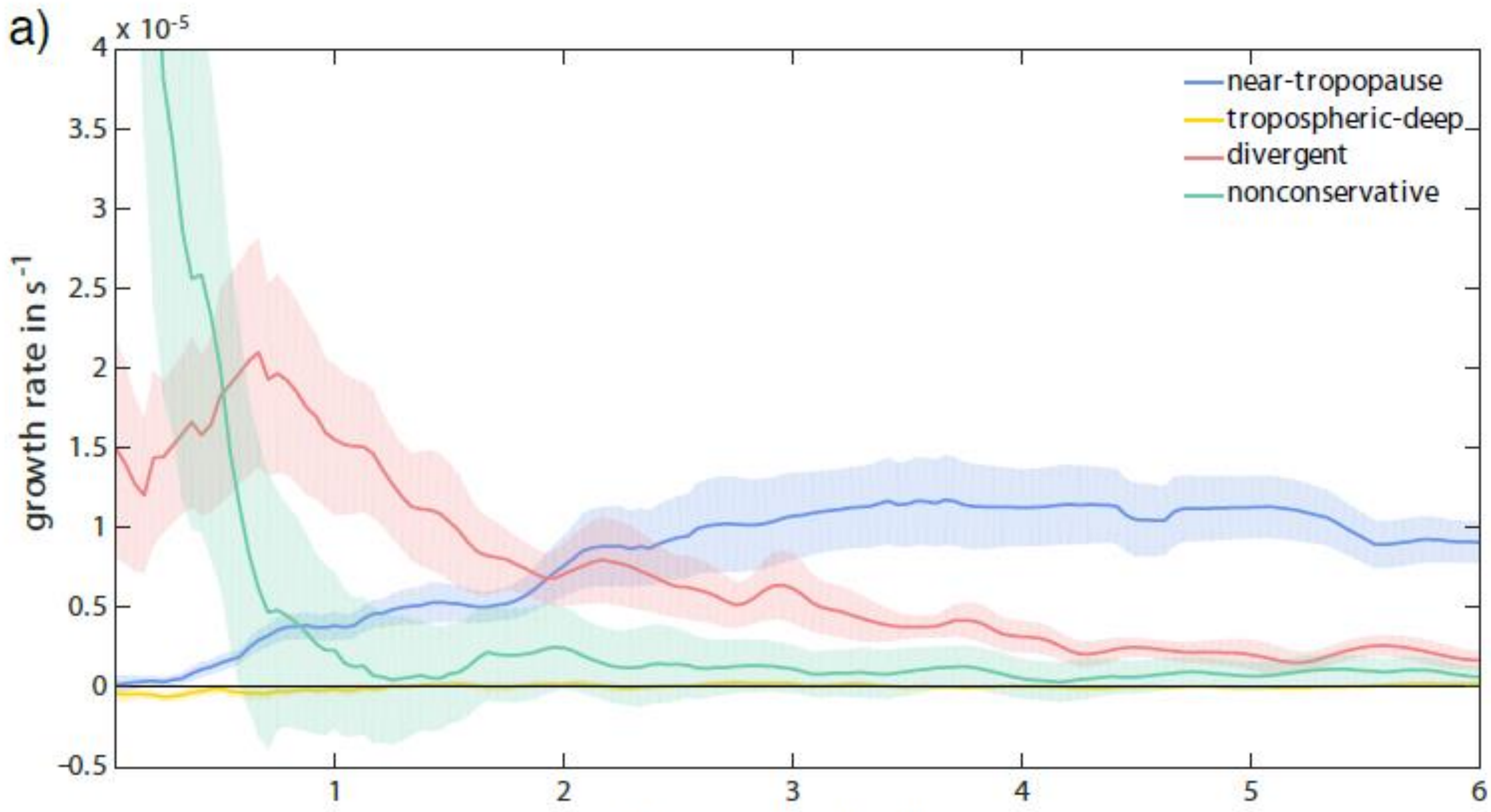


Figure 7 from Baumgart et al., 2019, *MWR*

Baumgart, M., P. Ghinassi, V. Wirth, T. Selz, G. C. Craig, and M. Riemer, 2019: Quantitative View on the Processes Governing the Upscale Error Growth up to the Planetary Scale. *Mon. Wea. Rev.*, **147**, 1713–1731, doi:10.1175/MWR-D-18-0292.1.

slide provided by Michael Riemer

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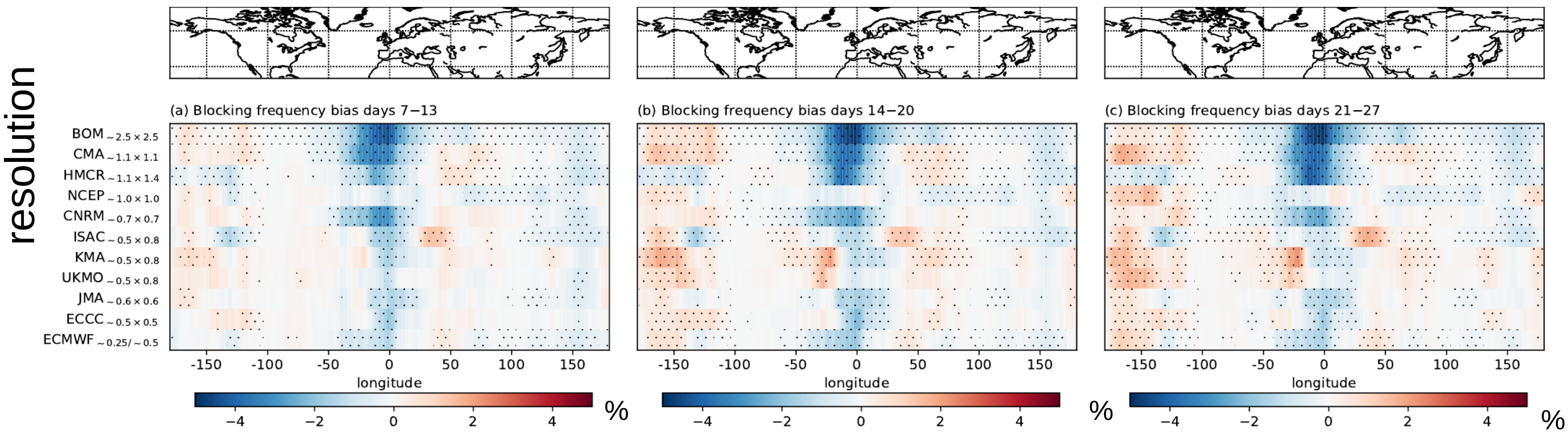
3. Relevance for forecast error
4. **Atlantic-European weather regime life cycles**

Grams, C. M., L. Magnusson, and E. Madonna, 2018: An atmospheric dynamics perspective on the amplification and propagation of forecast error in numerical weather prediction models: A case study. *Quart. J. Roy. Meteor. Soc.,* **144**, 2577–2591, doi:10.1002/qj.3353.

Grams, C. M.: A new perspective on Atlantic-European weather regimes and their life cycles. *In preparation for Quart. J. Roy. Meteor. Soc..*

Blocking and RWP in S2S models (J. Quinting)



Slide by **J. F. Quinting**

Quinting, J. F., and F. Vitart, 2019: Rossby Wave Packets and Blocking in the S2S Database. *Geophys. Res. Lett.*, **46**, 1070–1078, doi: 10.1029/2018GL081381.

Why are regimes relevant?

Flow-dependent predictability

Ferranti et al. (2015), *QJRMS*, doi:10.1002/qj.2411

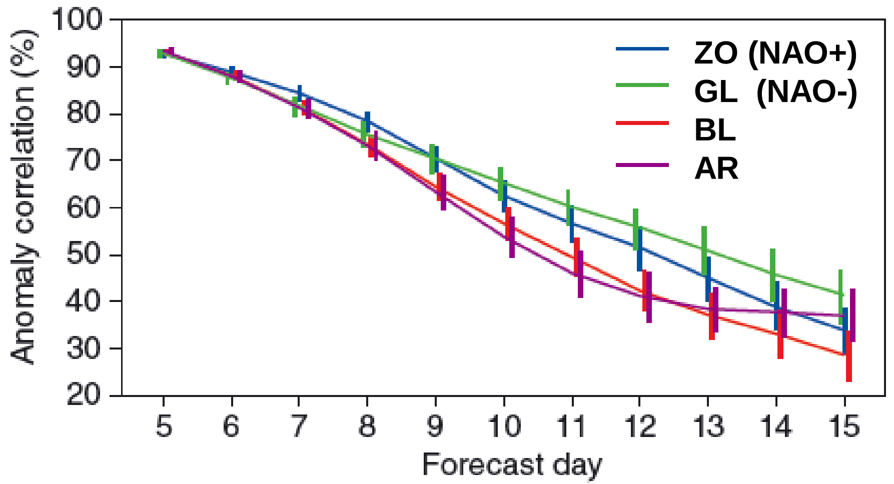


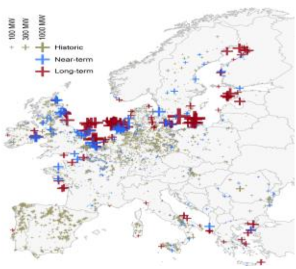
Figure 3. Anomaly correlation of the ensemble means over Europe (12.5°W–42.5°E, 35.0°N–75.0°N) for the four forecast categories as a function of forecast range. Red refers the BL regime, blue to the NAO+, green to the NAO− and violet to the AR regime. The bars, based on 1000 subsamples generated with the bootstrap method, indicate the 95% confidence intervals.

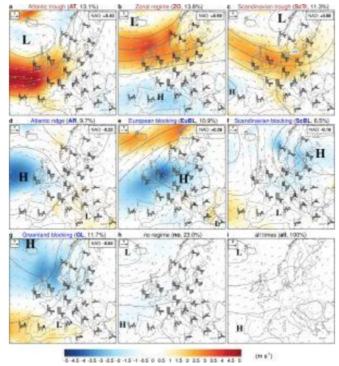
ECMWF Roadmap to 2025: "…we also aim to predict large-scale patterns and regime transitions up to four weeks ahead, …"

Why are regimes relevant?

Karlsruhe Institute of Technology

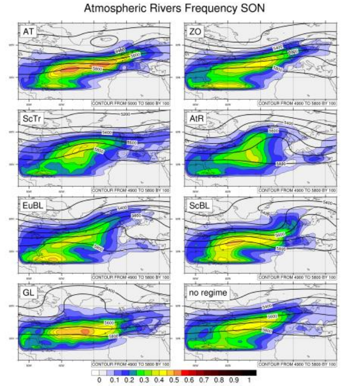
Wind power variability

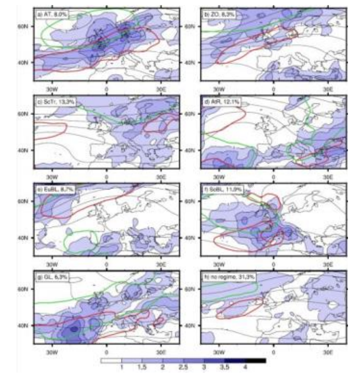




Beerli et al. (2017) 10.1002/qj.3158
Grams et al. (2017) 10.1038/nclimate3338

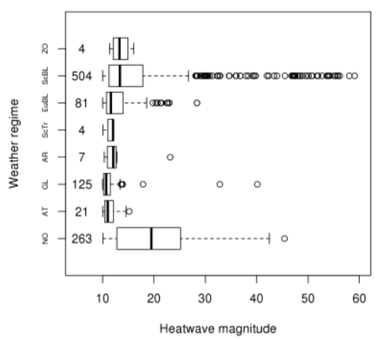
Modulation of heavy precipitation

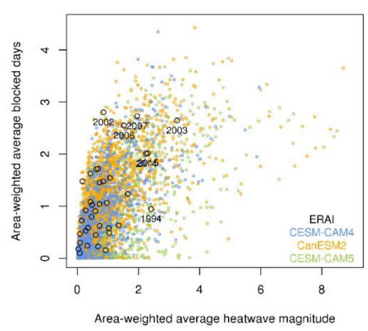




Pasquier et al. (2019) 10.1029/2018GL081194

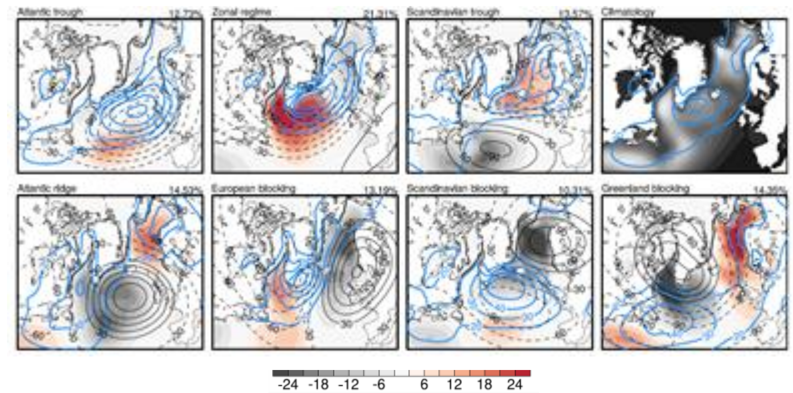
Heat waves





Quinting and Reeder (2017) 10.1175/MWR-D-17-0165.1
Schaller et al. (2018) 10.1088/1748-9326/aaba55

Cold air outbreaks

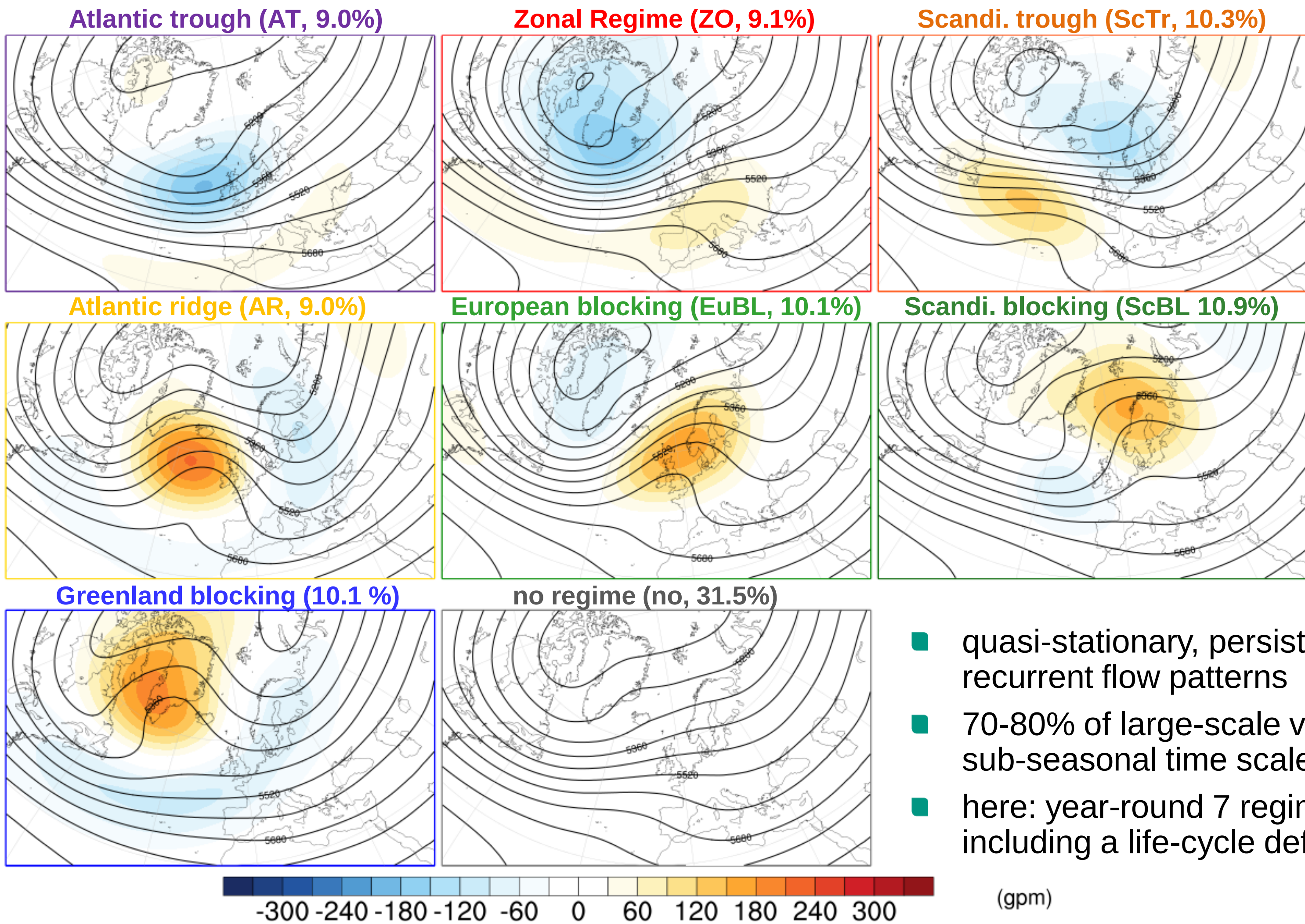


Papritz and Grams (2018) 10.1002/2017GL076921 plot by L. Papritz

Year-round weather regimes

Cyclonic regimes

Blocked regimes

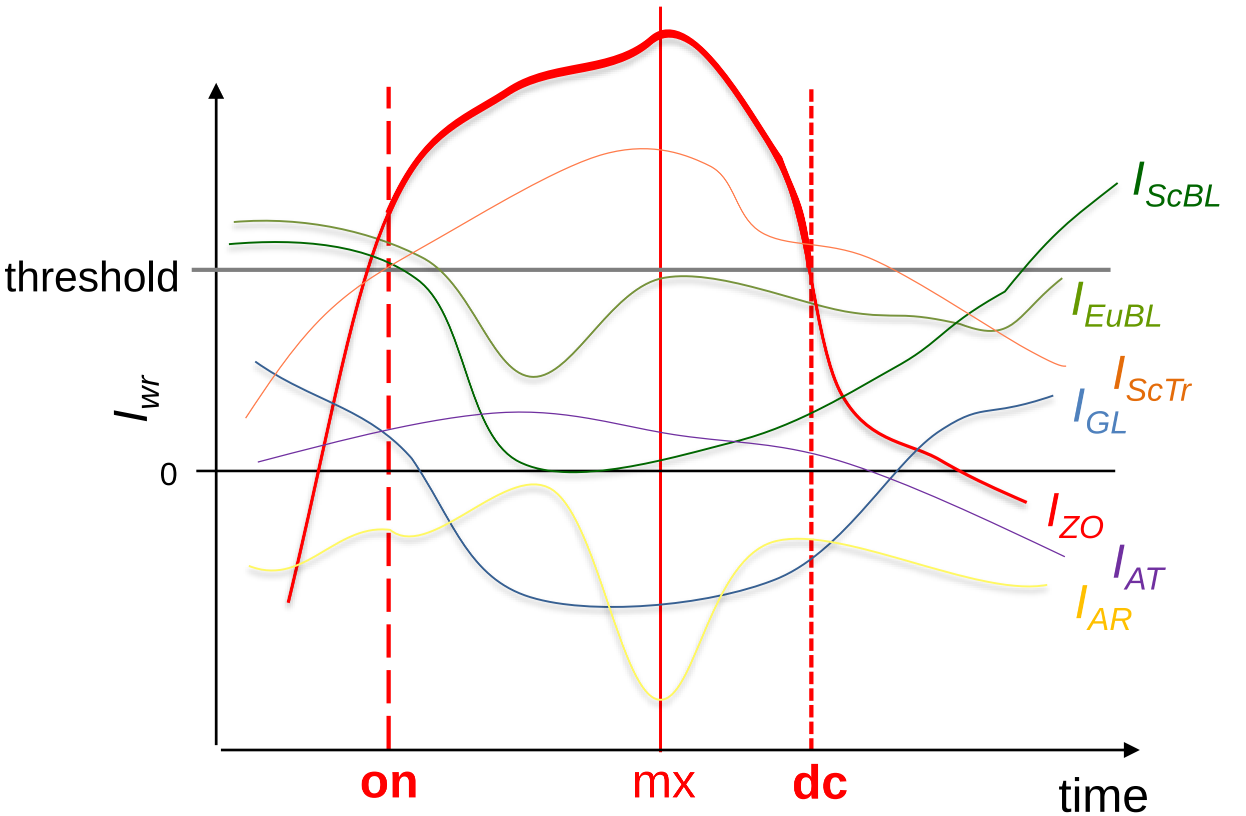


- quasi-stationary, persistent, recurrent flow patterns
- 70-80% of large-scale variability on sub-seasonal time scales
- here: year-round 7 regimes including a life-cycle definition

Grams, C.M., et al. (2017), doi:10.1038/nclimate3338.

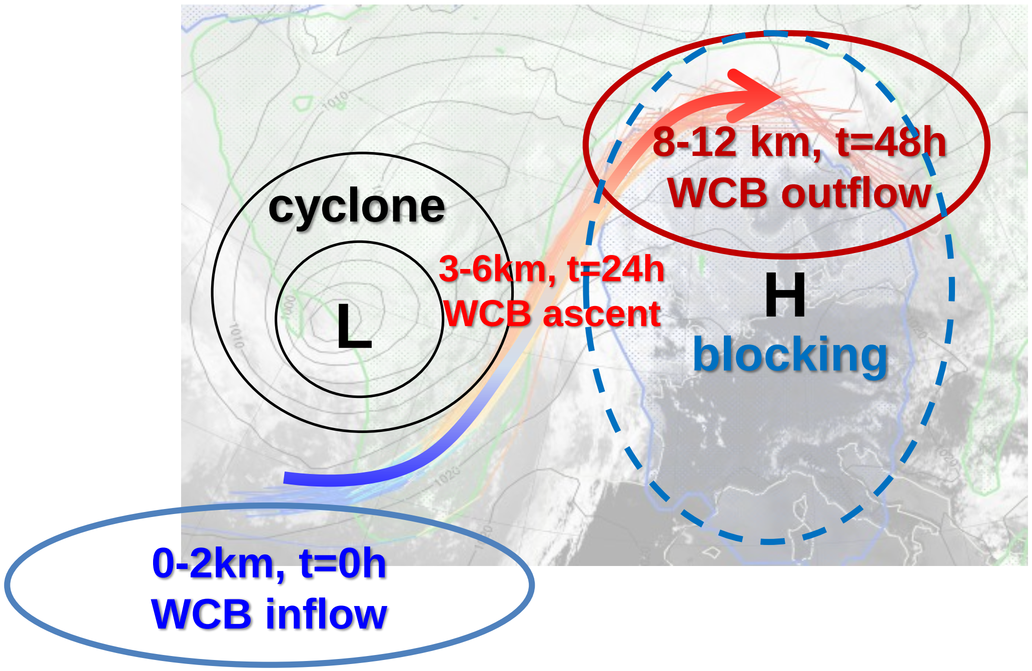
Weather regime life cycles

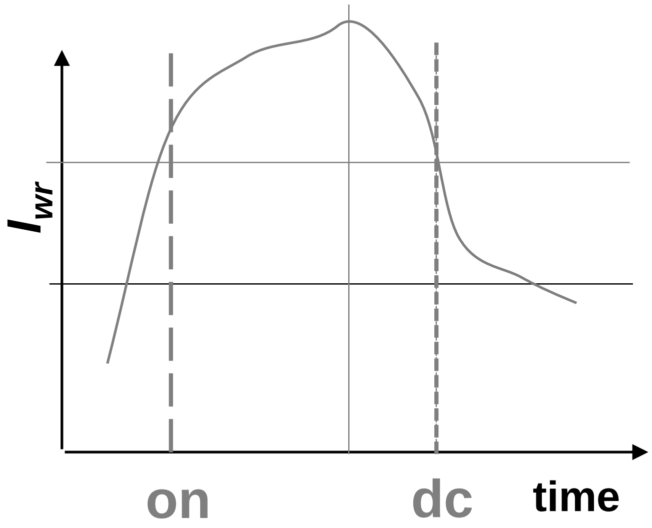
- Weather **regime Index** I_{wr} (Michel and Rivière, 2011, *JAS*, doi:10.1175/2011JAS3635.1)
- Definition of **onset,** maximum, decay for individual weather regime life cycles



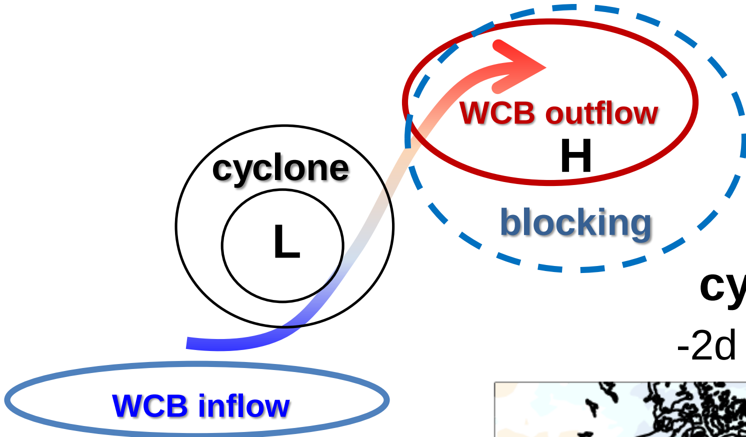
WCB activity during WR life cycles

- cyclone, **WCB inflow & outflow,** and **blocking** frequency anomalies **during weather regime** life cycle (Madonna et al. 2014, JCli, Sprenger et al. 2017, BAMS)
- lagged composites in period **around onset**



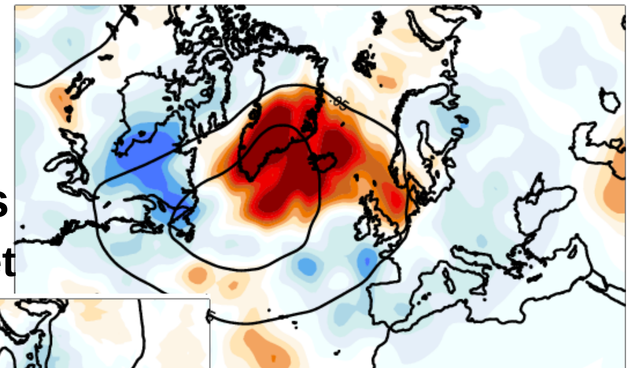


Lagged composites at EuBL onset



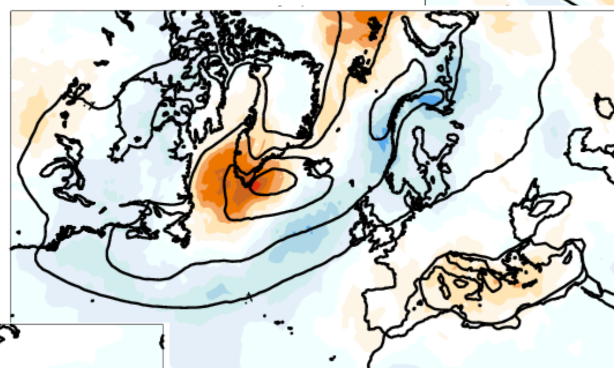
WCB outflow

-2d to **onset**



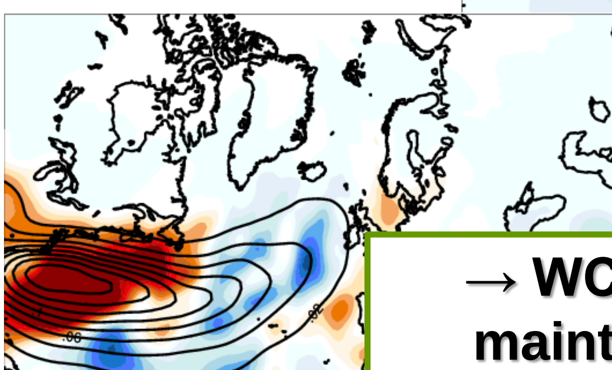
cyclones

-2d to **onset**



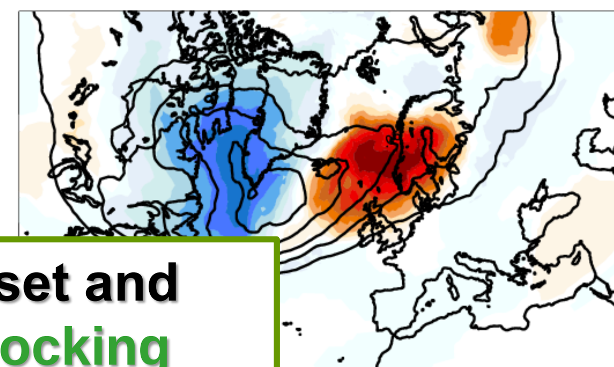
WCB inflow

-4d to -2d



blocking

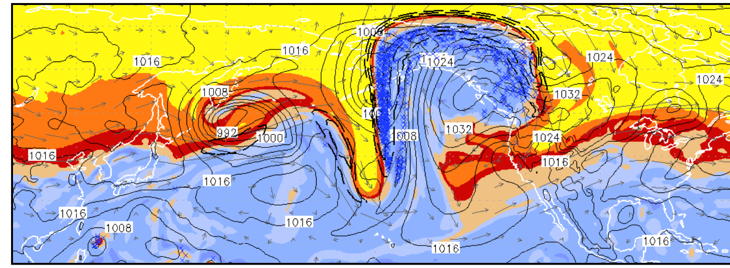
onset to +2d

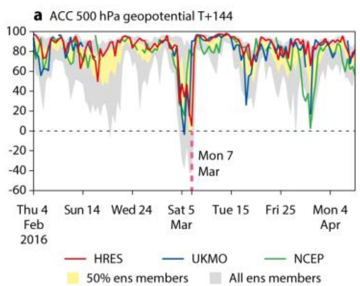


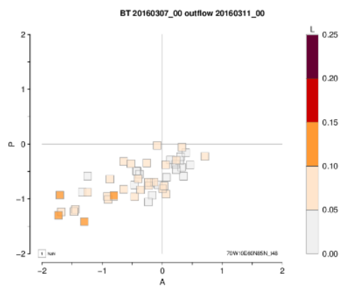
→ WCB activity supports onset and maintenance of European blocking

Summary

- Diabatic outflow are key to upper-level midlatitude flow modification

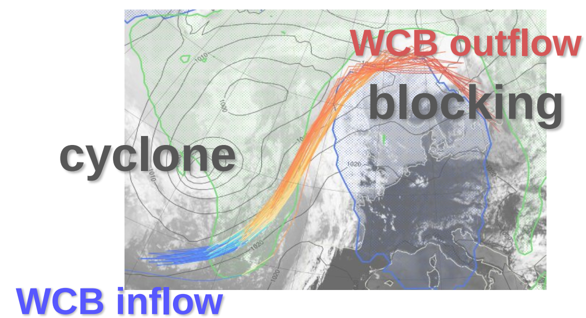






- Predictability challenge for large-scale flow due to upscale error growth in WCBs

- WCB outflow important for onset and maintenance of blocked regimes



Outlook

- YIG *SPREADOUT*: relevance for subseasonal forecast skill?