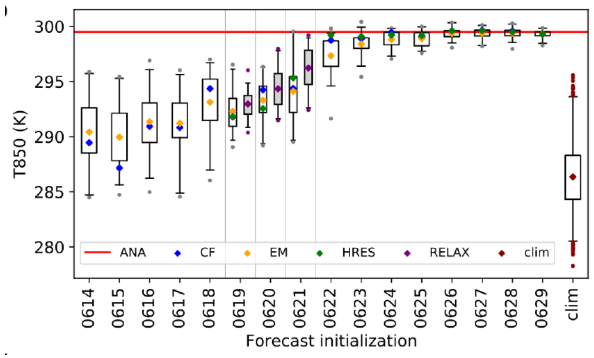
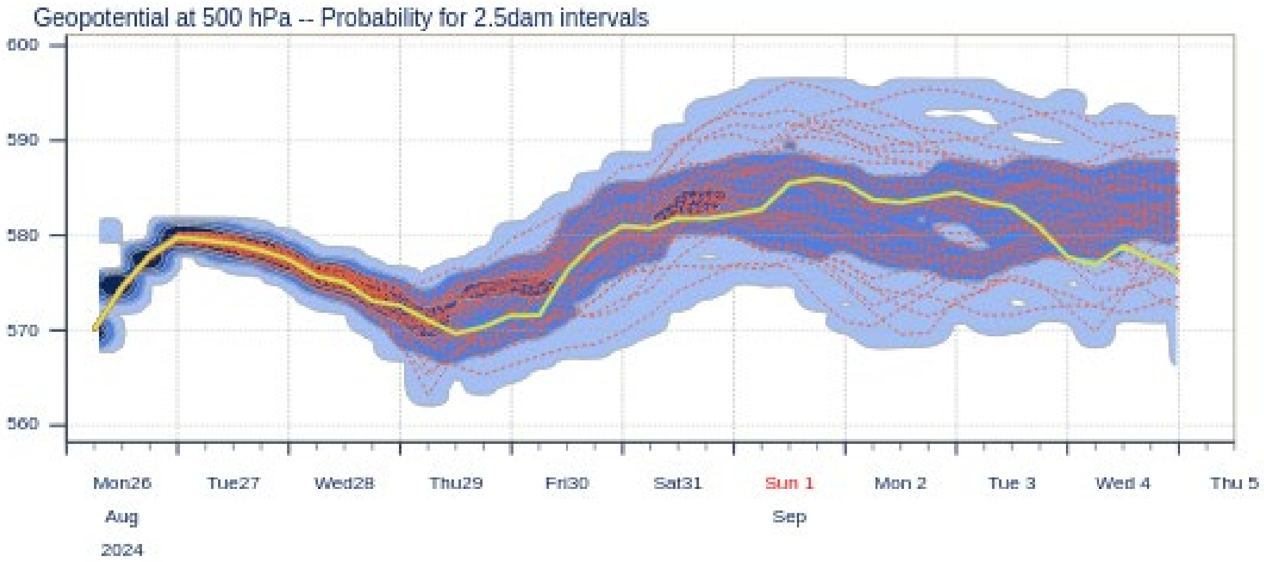
Diagnostics for investigating the representation of synoptic-scale processes in models and their benefit for medium- to extended-range prediction.

Christian M. Grams with many contributions from the former **LSDP@KIT Team and Friends**

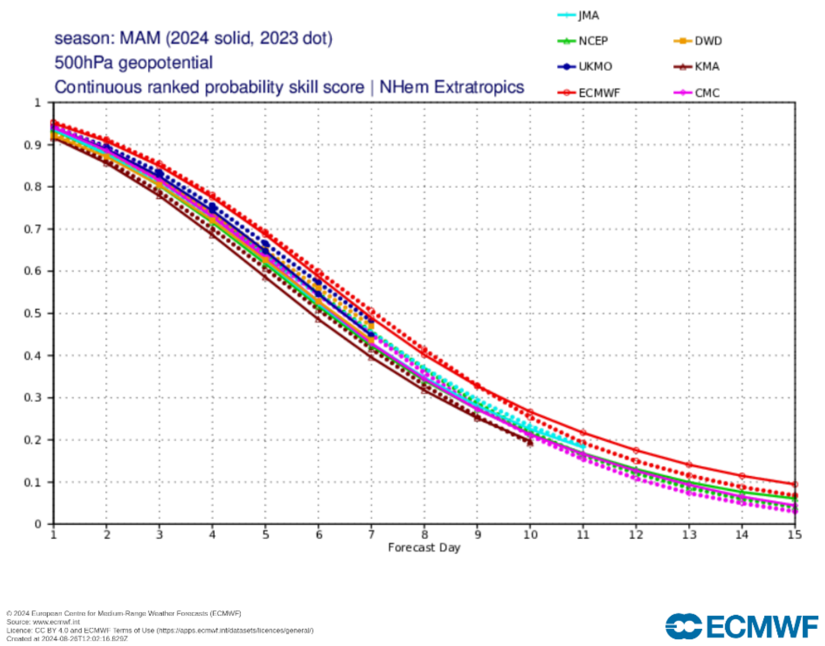
Dominik Bueeler (now at ETH Zurich), **Moritz Deinhard** (now at Munich Re), **Joshua Dorrington** (now at University of Bergen), **Seraphine Hauser** (now at University of Oklahoma), **Maria Madsen** (now at University of Oklahoma), **Fabian Mockert** (IMKTRO, KIT), **Annika Oertel** (IMKTRO, KIT), **Marisol Osman** (now at University of Buenos Aires), **Julian Quinting** (IMKTRO, KIT), **Jan Wandel** (now at Deutscher Wetterdienst), **Marta Wenta** (now at Axpo Solutions AG)



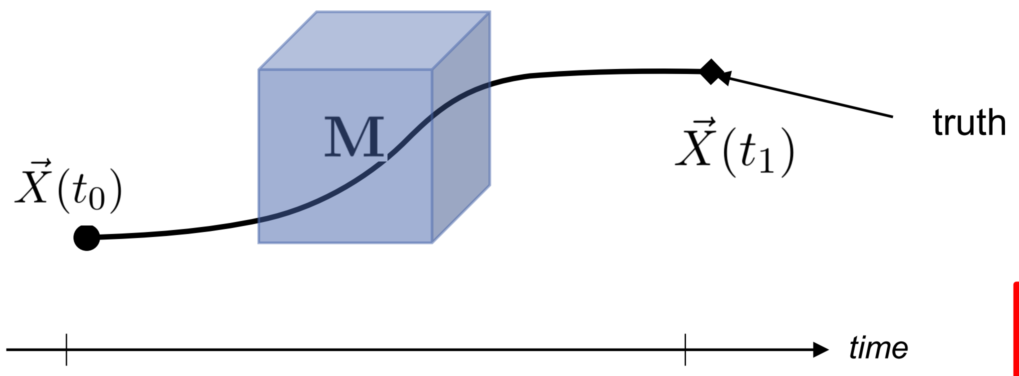
The forecasting challenge



Continuous ranked probability skill scores (CRPSS) of forecasts of upper-air parameters by TIGGE centres.



The forecasting challenge



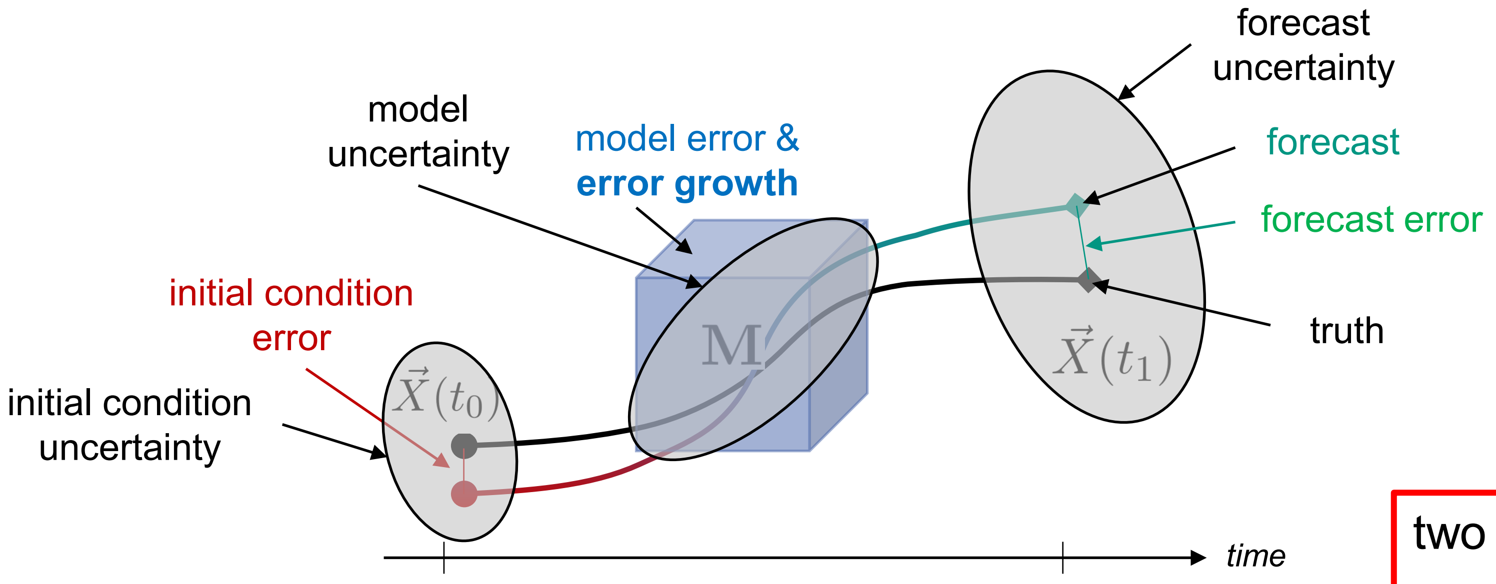
$$\vec{X}(t_1) = \mathbf{M} \cdot \vec{X}(t_0)$$

two key problems of NWP
a) **errors in NWP system**
b) **error growth**
and both interact ...

The forecasting challenge

error in forecast due to IC error, model error & **error growth**

- error growth results in range of possible forecast scenarios (**forecast uncertainty**)



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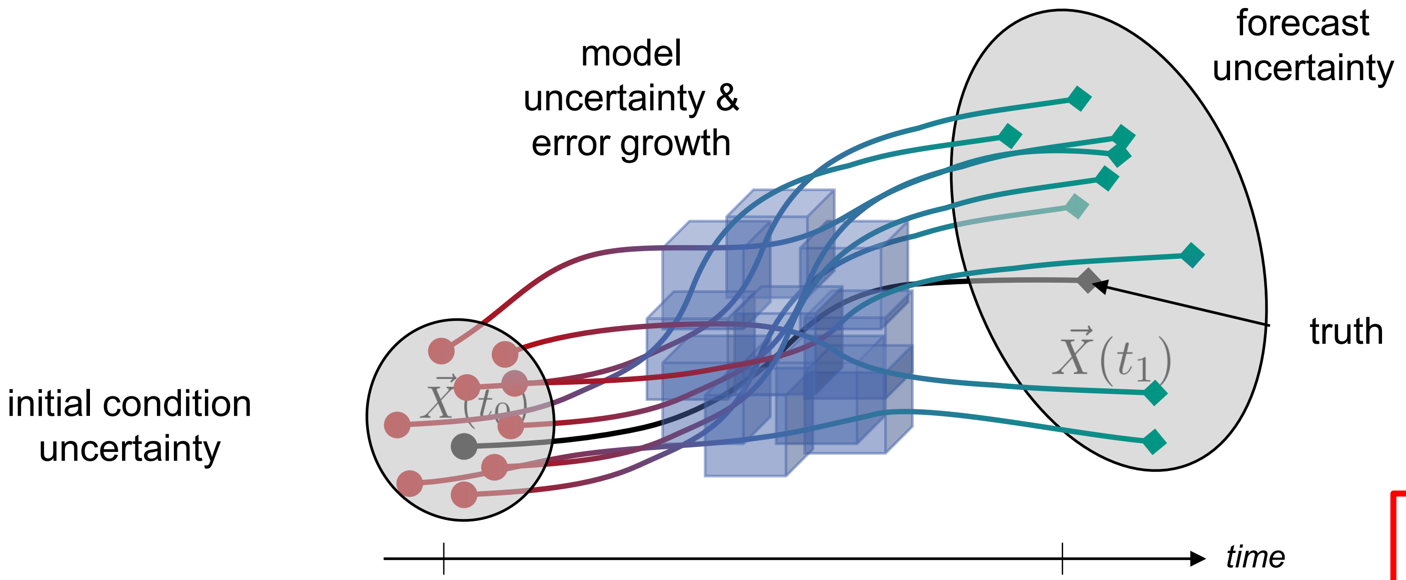
The forecasting challenge

error in forecast due to IC error, model error & **error growth**

- error growth results in range of possible forecast scenarios (**forecast uncertainty**)
- **ensemble prediction quantifies** this **uncertainty** by **accounting for model and IC uncertainty** in the model design and **predicting PDFs** rather than deterministic values of a target variable.



$$\vec{X}(t_1) = \mathbf{M} \cdot \vec{X}(t_0)$$

two key problems of NWP
a) **errors in NWP system**
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and both interact ...

upscale error growth

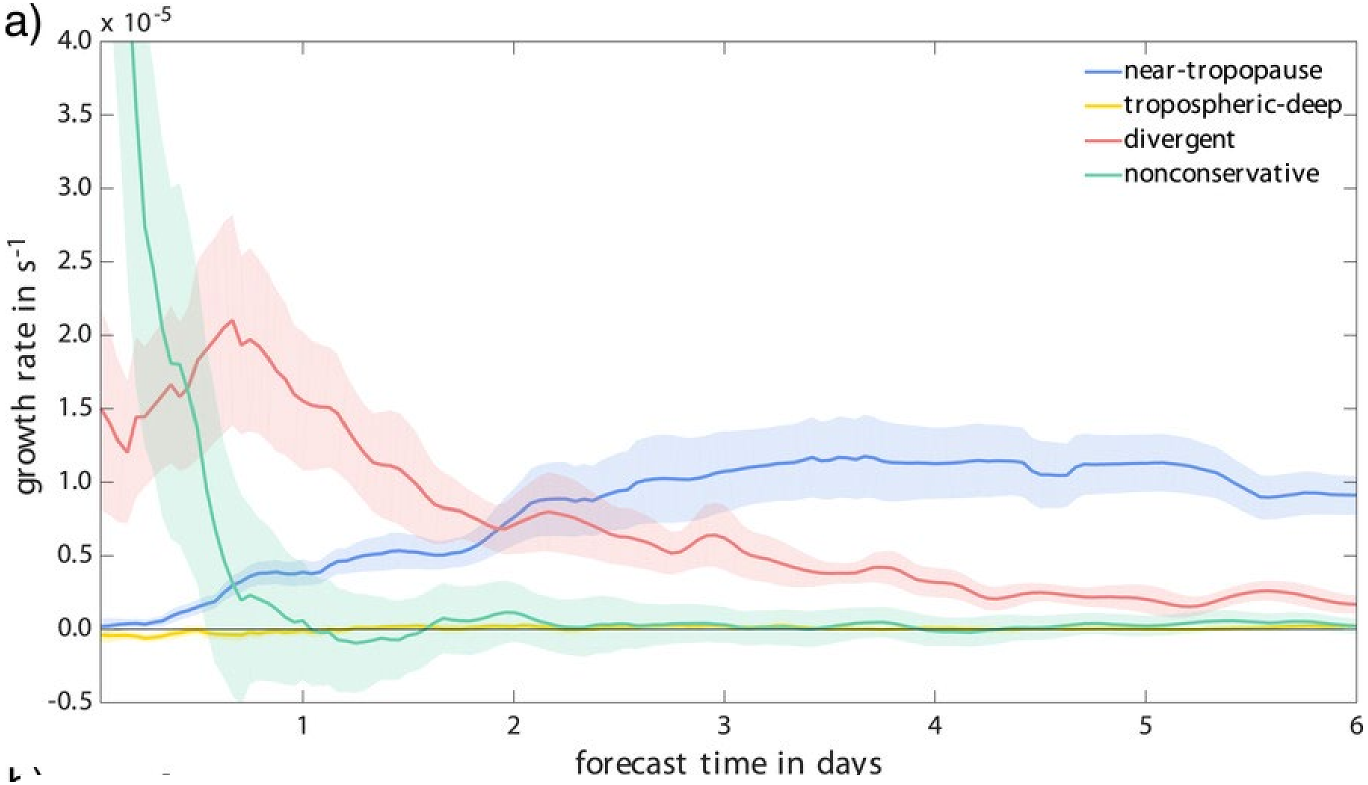
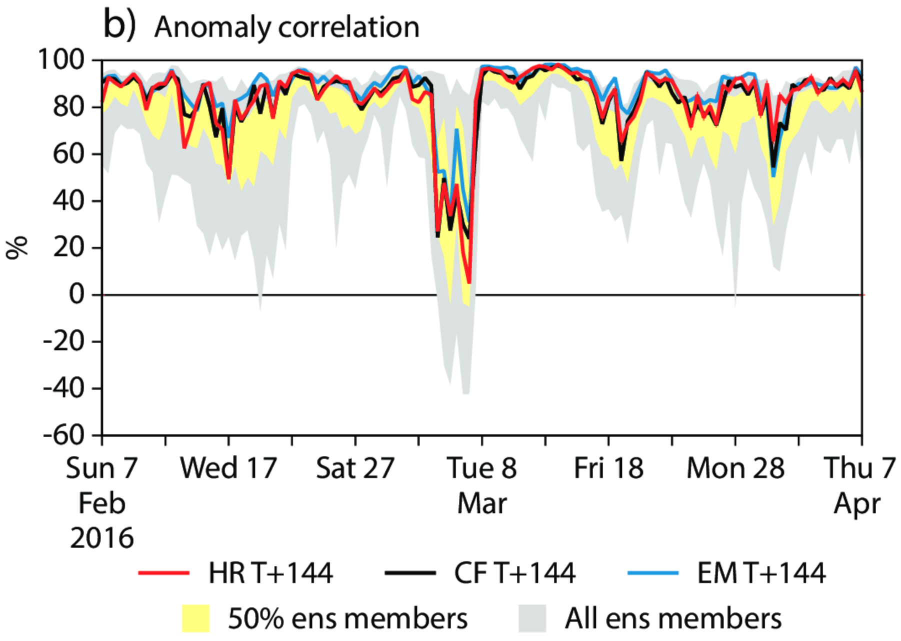


Figure 7 from Baumgart et al. 2019 https://doi.org/10.1175/MWR-D-18-0292.1

- upscale error growth to regime scale occurs in 3 stages
  - 0-12h small-scales
  - 12-48h meso-scales
  - >2d regime-scale

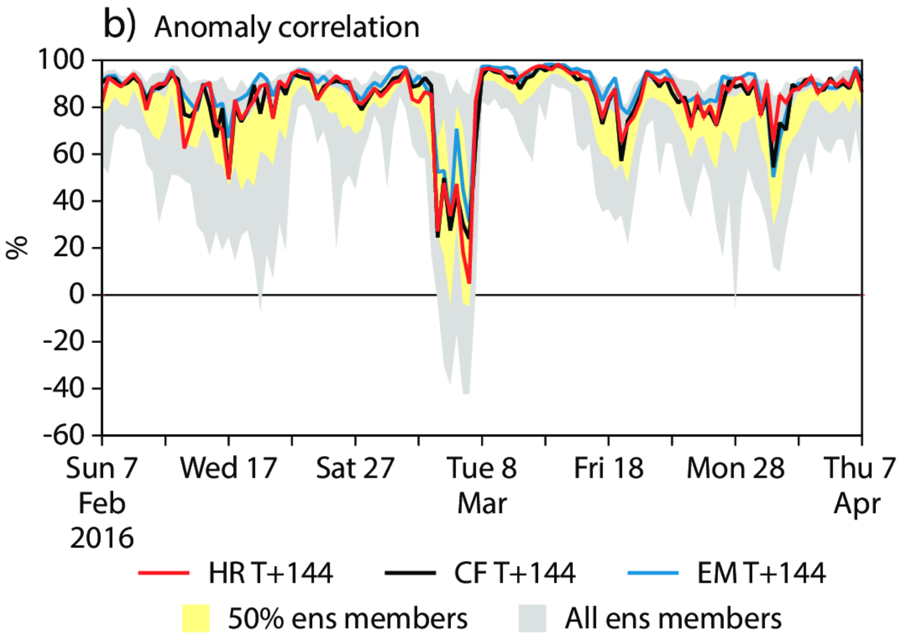
(e.g. Zhang et al. 2007, Baumgart et al. 2019, Selz 2019, Selz et al. 2022)

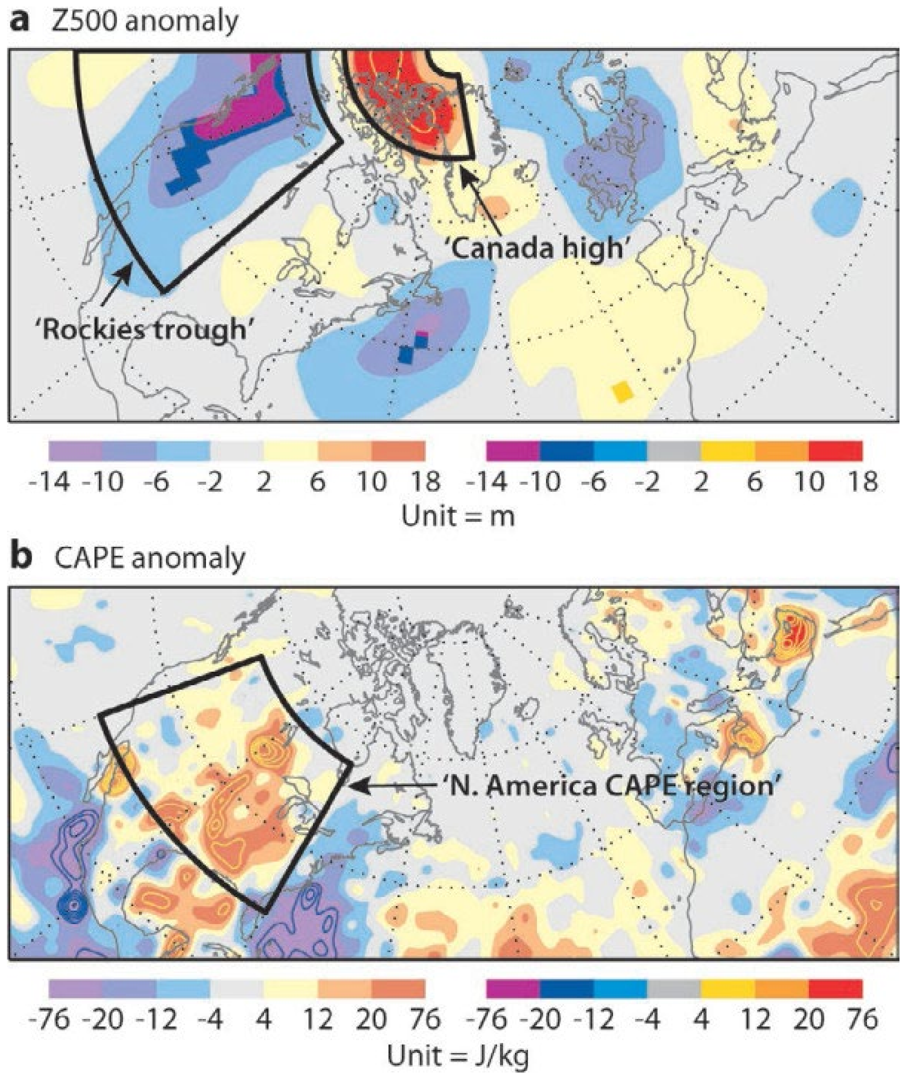
Flow-dependence – forecast busts



- forecast bust: Period with very low skill of NWP (e.g. Rodwell et al. 2013, Grams et al. 2018, Parsons et al. 2019)

Flow-dependence – forecast busts

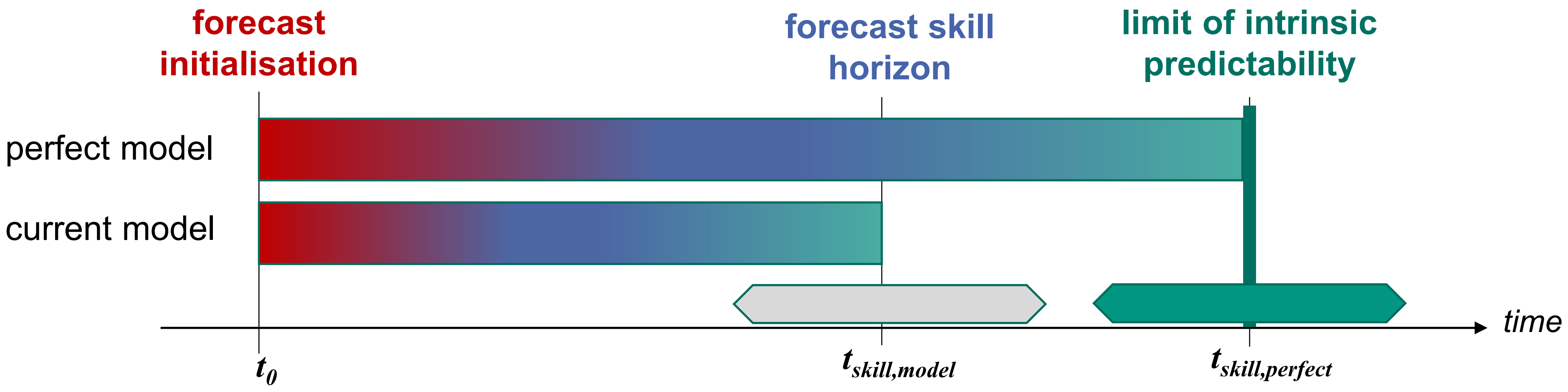




- forecast bust: Period with very low skill of NWP (e.g. Rodwell et al. 2013, Grams et al. 2018, Parsons et al. 2019)
- worst forecast for Europe associated with MCSs over North America (Rodwell et al. 2013) → 2nd stage of upscale error growth

Forecast Skill and Predictability

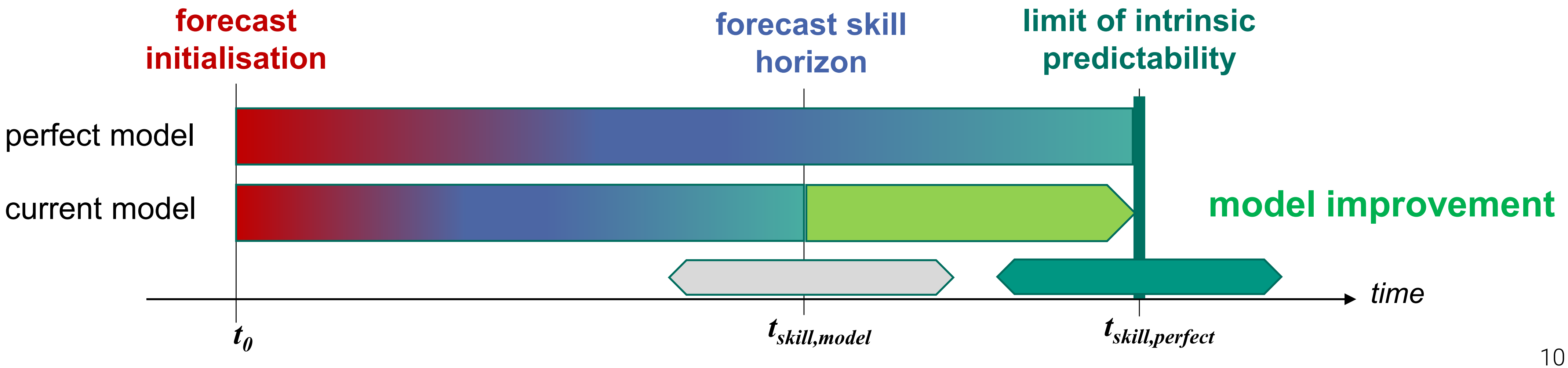
- **intrinsic predictability** – characteristic of the atmosphere
  - limited by upscale error growth
  - flow-dependent
  - limits the forecast skill horizon of a NWP system
- **practical predictability** – characteristic of a forecasting system



Forecast skill horizon

Potential to **increase forecast skill** horizon through …

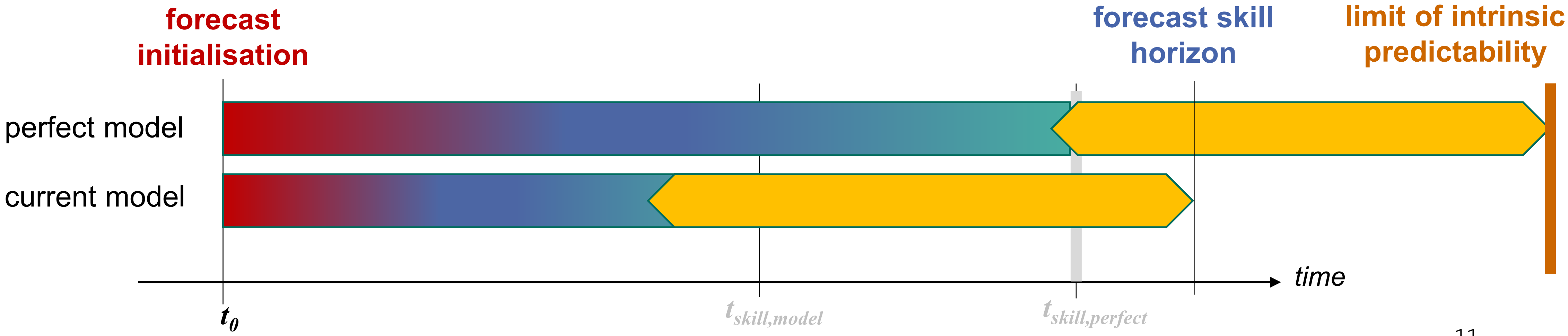
1. **Improvement of the NWP system** (reducing IC and model error)



Forecast skill horizon

Potential to **increase forecast skill** horizon through …

1. **Improvement of the NWP system** (reducing IC and model error)
2. **Alternate forecast question** (spatial-temporal aggregation & knowledge about sources of predictability)

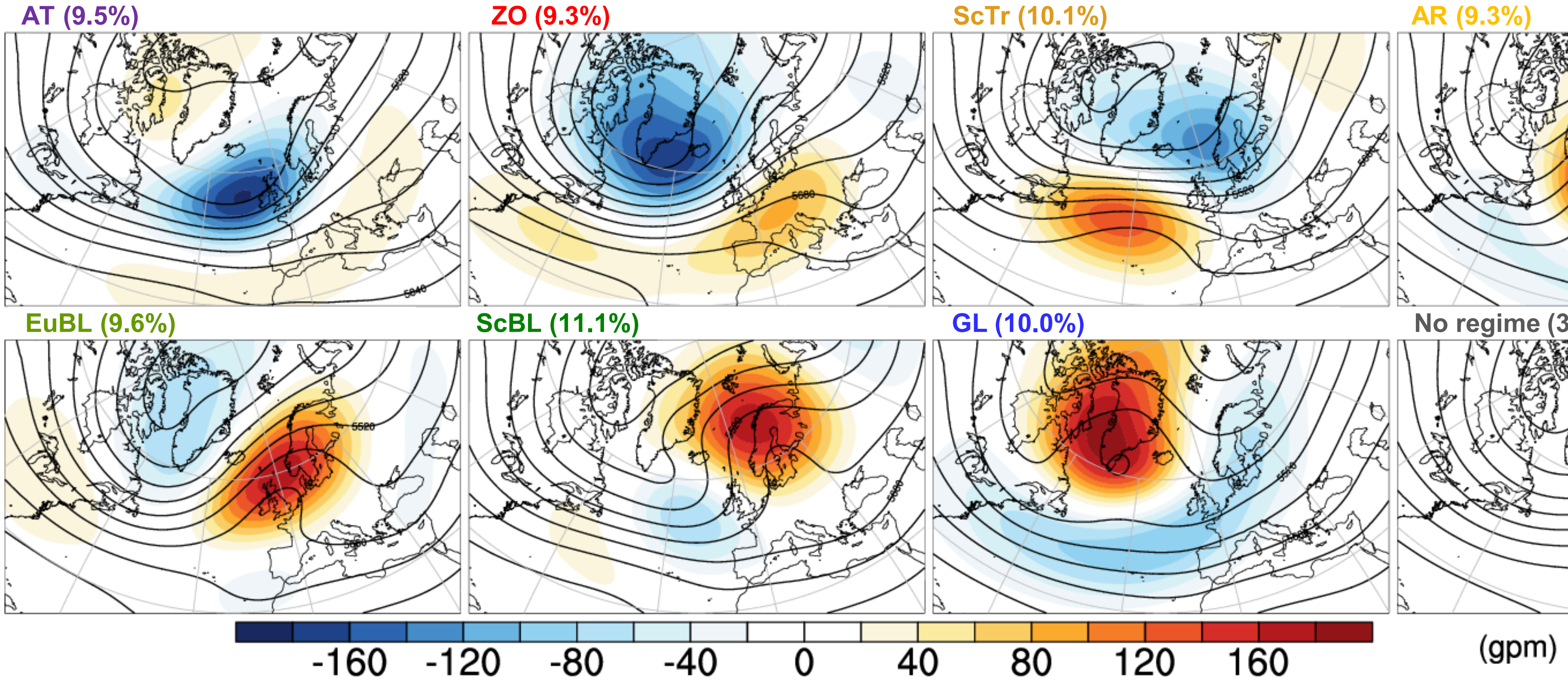


Outline

1. Predictability, forecast uncertainty, and upscale error growth
2. Weather regimes – a source of predictability?
3. The role of latent heat release in WCB airstreams
4. Forecast opportunities in the light of intrinsic limits of predictability
5. Conclusions

Weather regimes

cluster mean Z500 anomaly ($\overline{\phi'(\varphi,\lambda)}_{wr}$ shading) **and absolute values** (black contours)

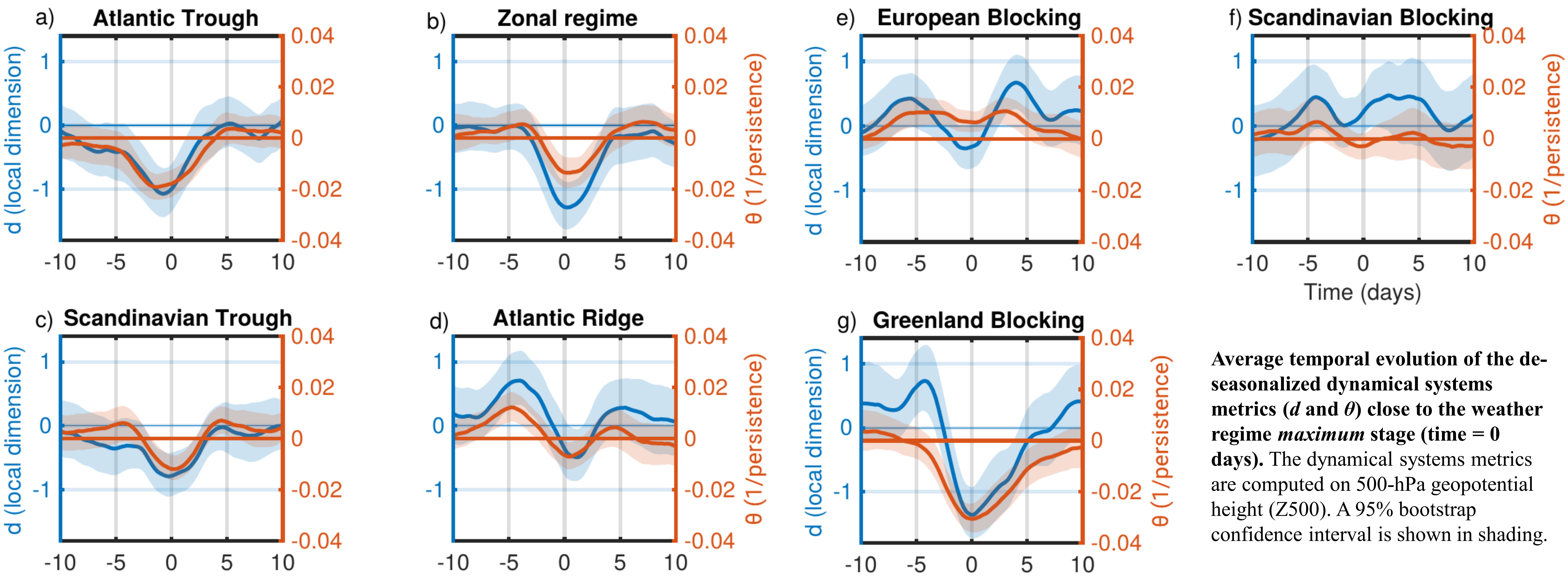


based on Grams et al. 2017, adapted to ERA5

Cyclonic regimes:
- **Atlantic trough**
- **Zonal Regime**
- **Scandinavian trough**

Blocked regimes:
- **Atlantic ridge**
- **European blocking**
- **Scandinavian blocking**
- **Greenland blocking**

Weather Regimes – intrinsic predictability



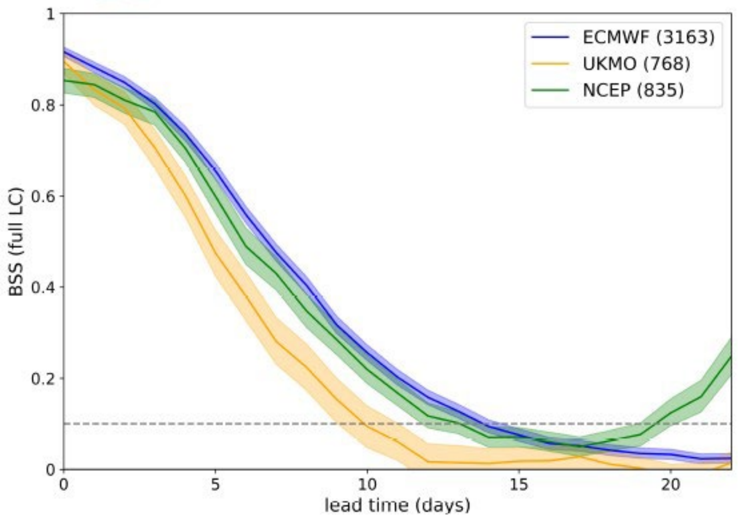
Average temporal evolution of the de-seasonalized dynamical systems metrics (*d* and *θ*) close to the weather regime *maximum* stage (time = 0 days). The dynamical systems metrics are computed on 500-hPa geopotential height (Z500). A 95% bootstrap confidence interval is shown in shading.

Hochman, ... Phys ... Weather Regimes ... 574.

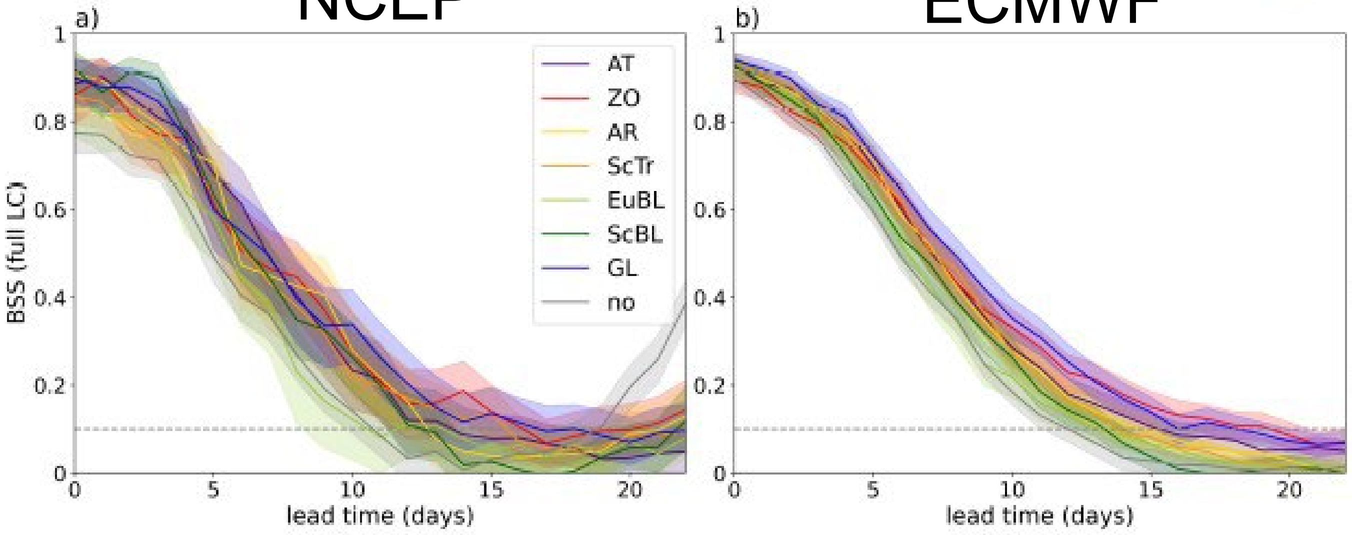
→ **EuBL least intrinsic predictability**

Weather regimes – practical predictability

year-round skill for WR LC attribution



Year-round daily skill individual WR life cycles

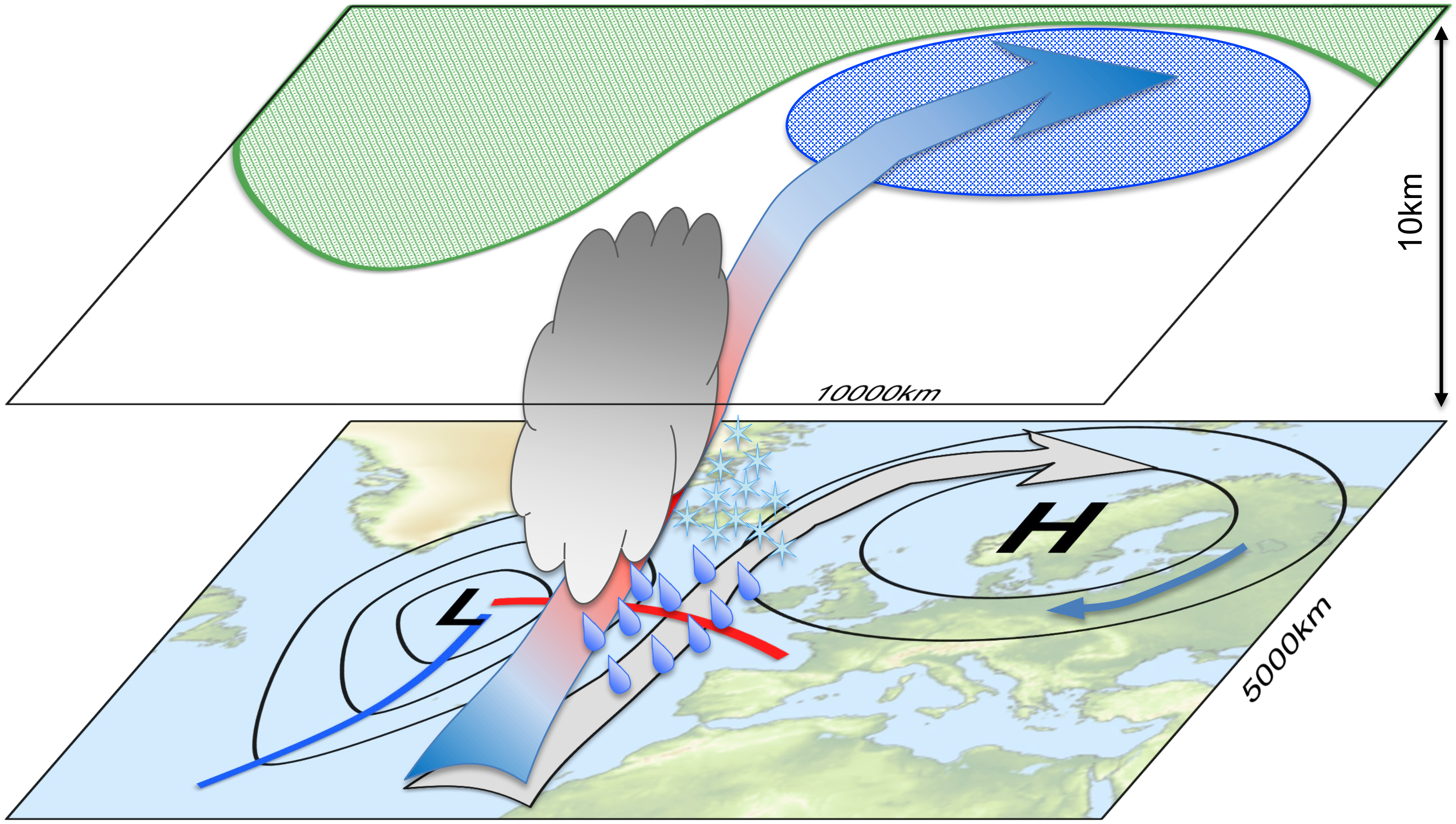


- skill in IFS extended-range reforecasts up to about 14 days
- skill horizon for EuBL (and no regime) is significantly shorter by 3-5 days than for other regimes
- skill horizon longest for ZO, GL (representing the NAO phases) driven by winter and likely due to high persistence and stratosph

→ **EuBL least forecast skill horizon**

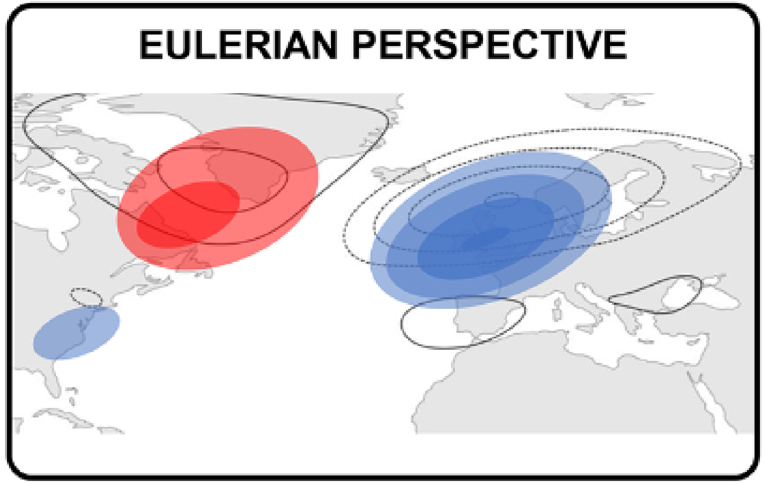
Osman, M., et al. 2023, doi:10.1002/qj.4512
Büeler, D., et al. 2021, doi:10.1002/qj.4178

Role of latent heat release



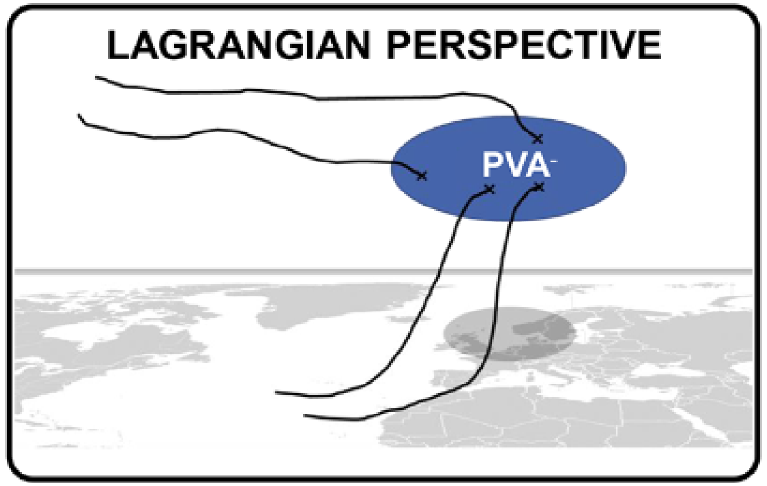
Pfahl, S. et al., 2015, *Nature Geosci.*, doi:10.1038/ngeo2487 , Grams and Archambault, 2016, *Mon. Wea. Rev.*, doi:10.1175/MWR-D-15-0419.1
Steinfeld and Pfahl, 2019, *Clim. Dyn.*, doi:10.1007/s00382-019-04919-6 , Steinfeld et al., 2020, *Weather Clim. Dynam.*, doi:10.5194/wcd-1-405-2020

Diagnostics to quantify contributions to blocking



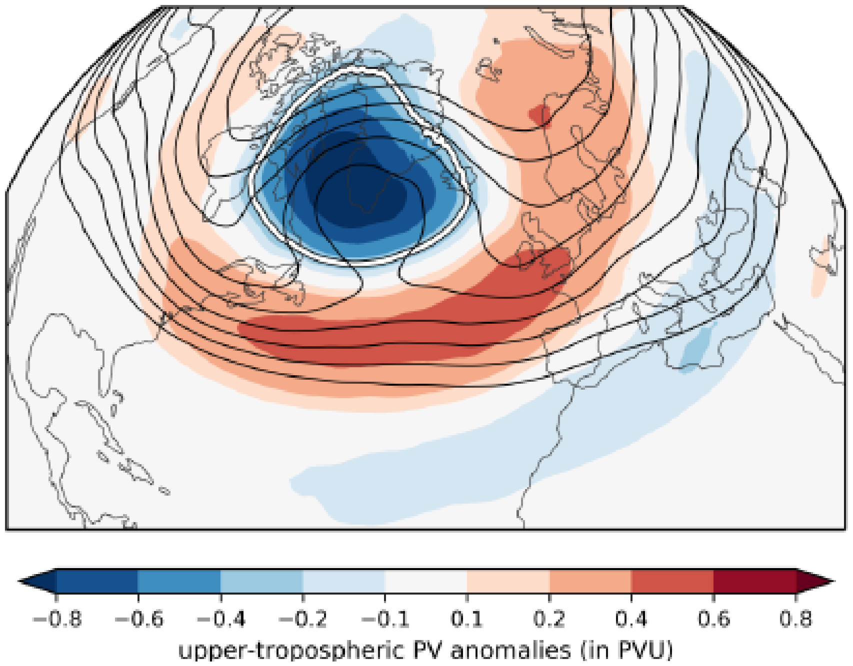
- e.g. Michel and Rivière 2011
- emphasises role of dry dynamics

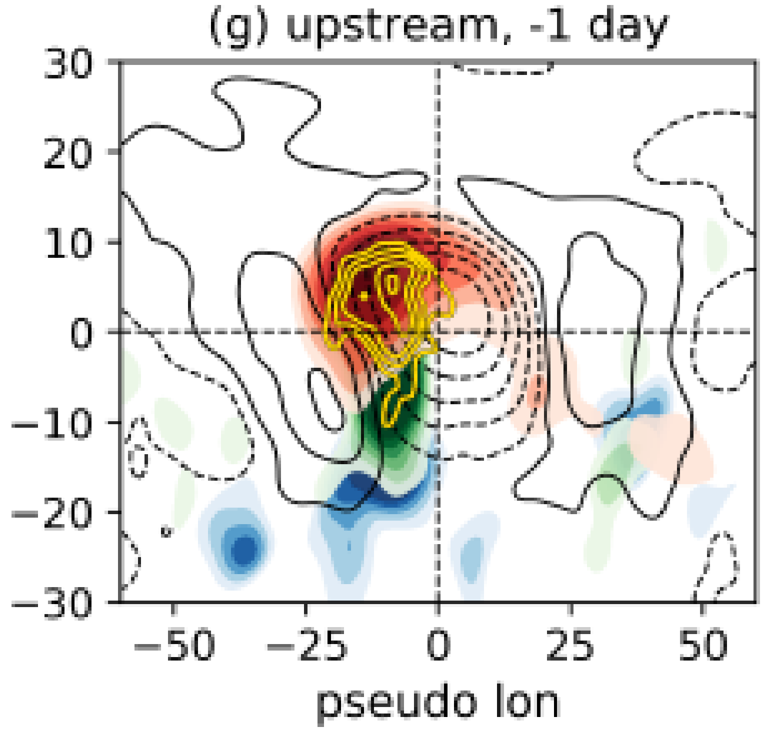
- Teubler and Riemer 2020 and Hauser et al. 2023 bring moist and dry dynamics in perspective
- contributions to amplitude by
  - barotropic dynamics (UP)
  - baroclinic interaction (LOW)
  - divergent wind (DIV, *indirect moist-diabatic contribution*)



- e.g. Pfahl et al. 2015
- emphasises role of moist dynamics

Quantifying the relevance for blocking – quasi-Lagrangian PV diagnostics



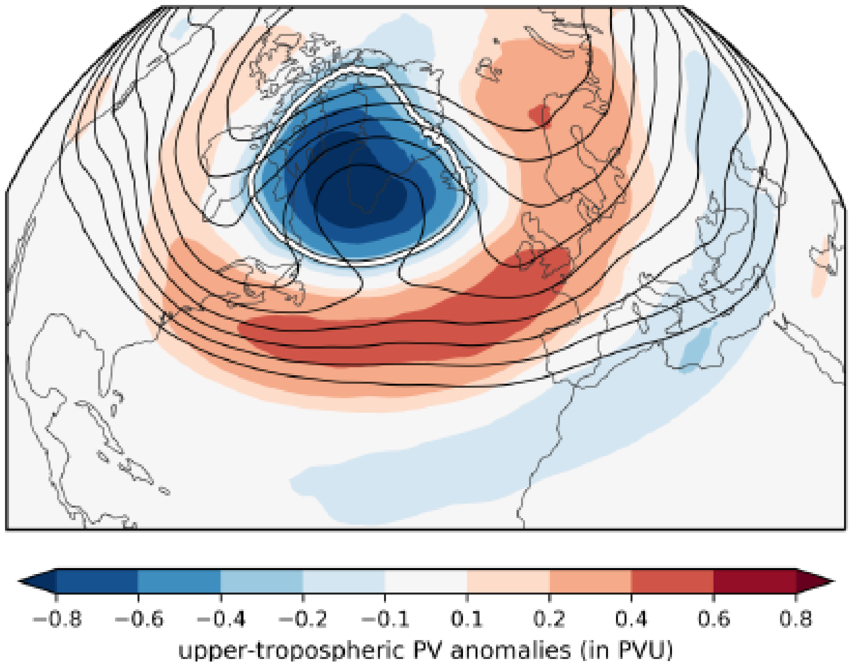


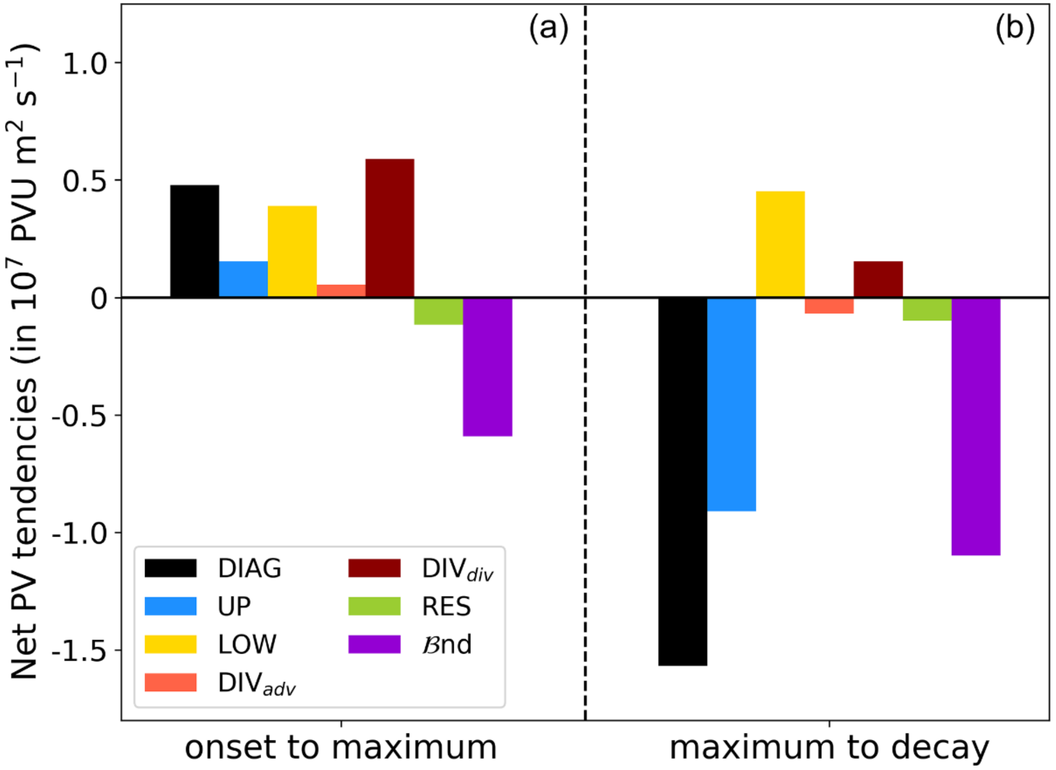
- PV amplitude evolution for blocking onset over Greenland.

→ **strong positive tendencies due to divergent wind components associated with WCB**

GL Onset study: Hauser et al. 2024, doi:10.5194/wcd-5-633-2024
PV diagnostics: Hauser et al. 2023, doi: 10.5194/wcd-4-399-2023

Quantifying the relevance for blocking – quasi-Lagrangian PV diagnostics



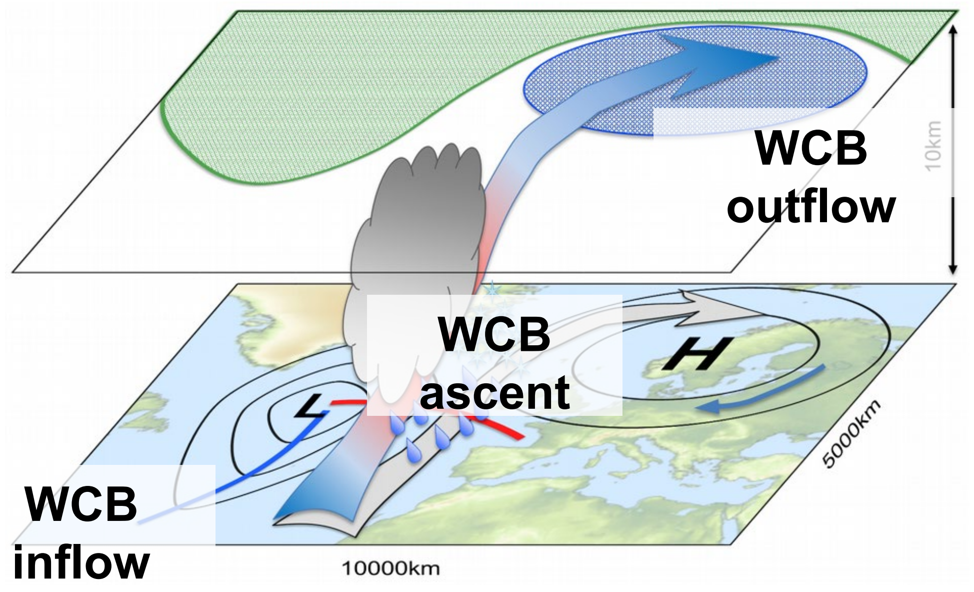


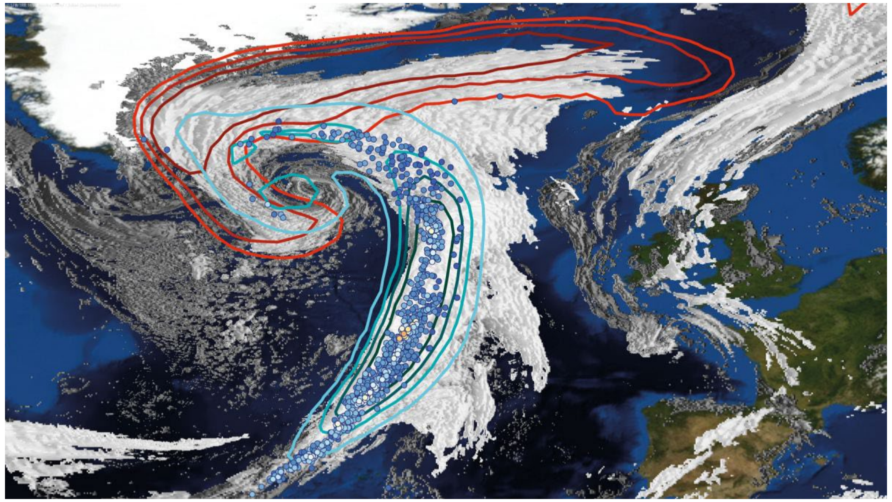
- PV amplitude evolution during Greenland blocking life cycle

  «downstream moist-baroclinic development» (Teubler and Riemer 2020)

GL Onset study: Hauser et al. 2024, doi:10.5194/wcd-5-633-2024
PV diagnostics: Hauser et al. 2023, doi: 10.5194/wcd-4-399-2023

WCB representation in models – ELIAS2.0





Example: dots Lagrangian air parcels in ascent phase. contours: conditional probability from Eulerian metric (plot: J. Quinting & A. Oertel)

- WCB identification requires trajectory calculation based on high spatio-temporal resolution

→ *feasible with reanalysis data and for case studies*

- lack of spatio-temporal resolution and huge data amount of S2S ensemble reforecasts requires different approach

- Eulerian metric for signature of WCB stages based on Unet-type convolutional neural network

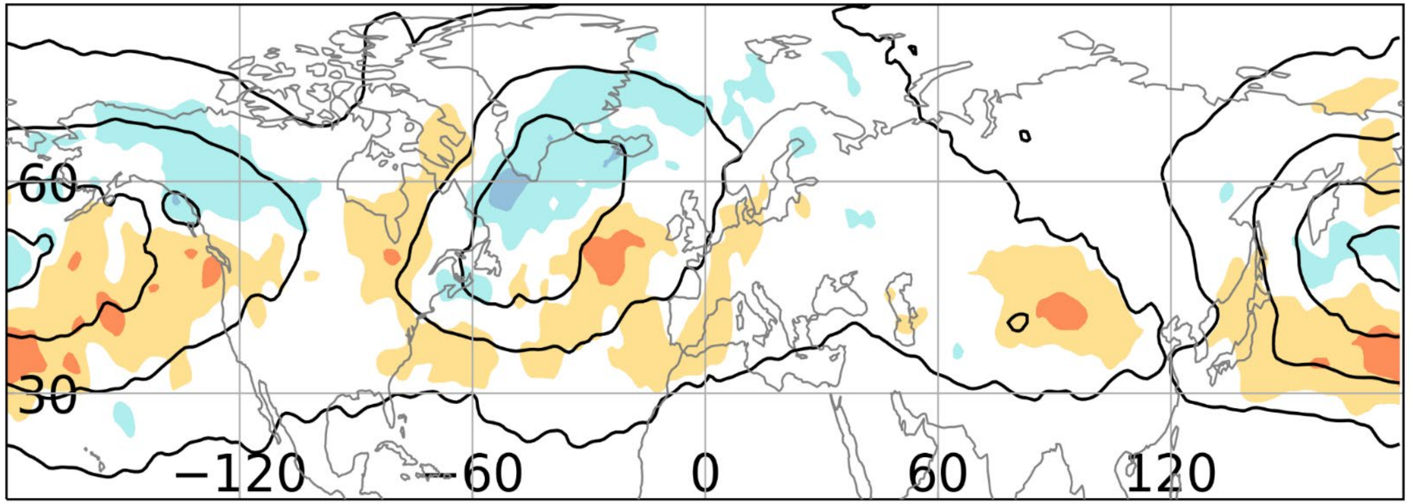
  → ***Quinting and Grams (2022)*, doi:10.5194/gmd-15-715-2022**

- Predictor selection and metric based on logistic regression

  → *Quinting and Grams (2021), doi:10.1175/JAS-D-20-0139.1*

WCBs in models – bias and skill

WCB outflow frequency bias (week 2)



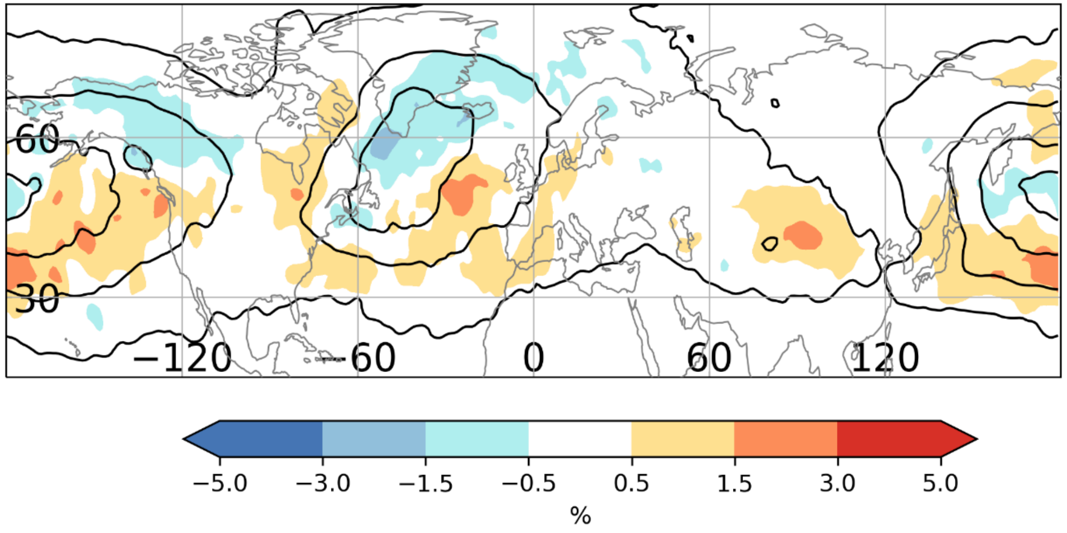
WCB outflow skill (weekly)

Wandel et al. 2021 doi:10.1175/JAS-D-20-0385.1 & Wandel 2023 (PhD thesis)

- underestimation of WCB outflow downstream of stormtracks
- daily WCB outflow skill vanishes after 7 days
- slightly more skill in North Pacific than North Atlantic
- skill for weekly mean frequency into week 2

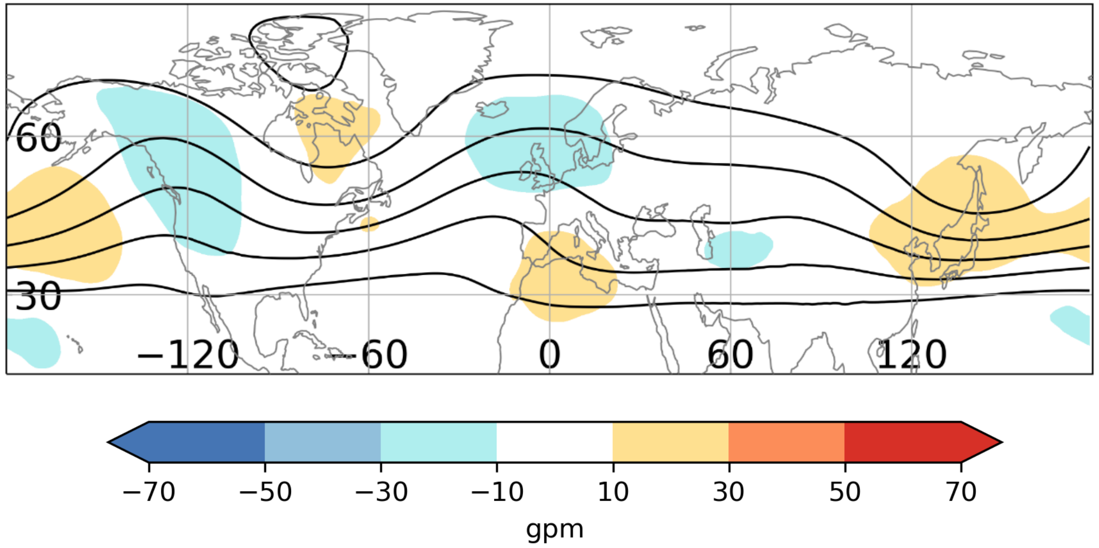
WCB outflow bias and bias in 300 hPa geopotential height in week 2 (DJF)

WCB outflow frequency bias



0.5, 5, 10, 15 %

300 hPa geopotential height bias



8400-9600 gpm (every 200 gpm)

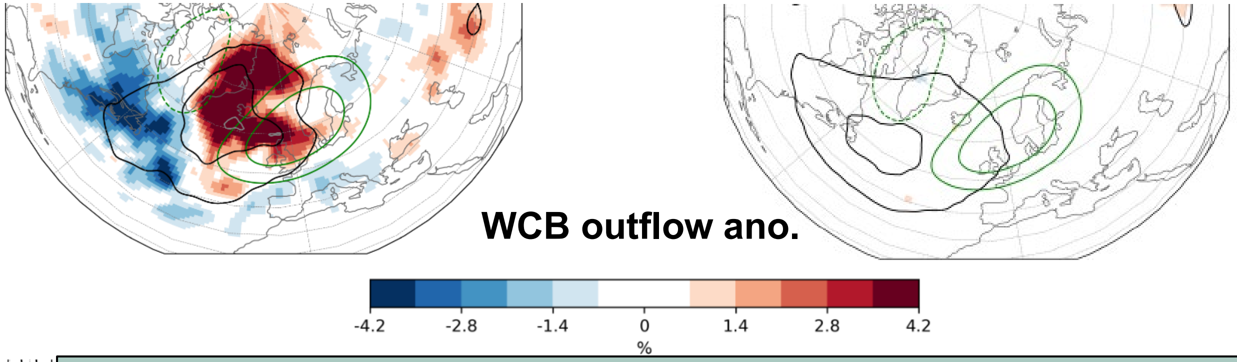
- WCB outflow biases coincide with biases in geopotential height

source: Jan Wandel

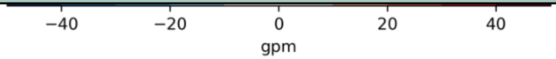
WCB outflow at EuBL onset in ERA-I in pentad 4

- EuBL onset **in ERA-I** at lead time **pentad 4 (15-19d)**: ERA-Interim, all members in IFS reforecast, verifying members (hits), members missing the onset (misses)

ERA-Interim (38 events) **all** (1078 members) **hits** (41) **misses** (1037)

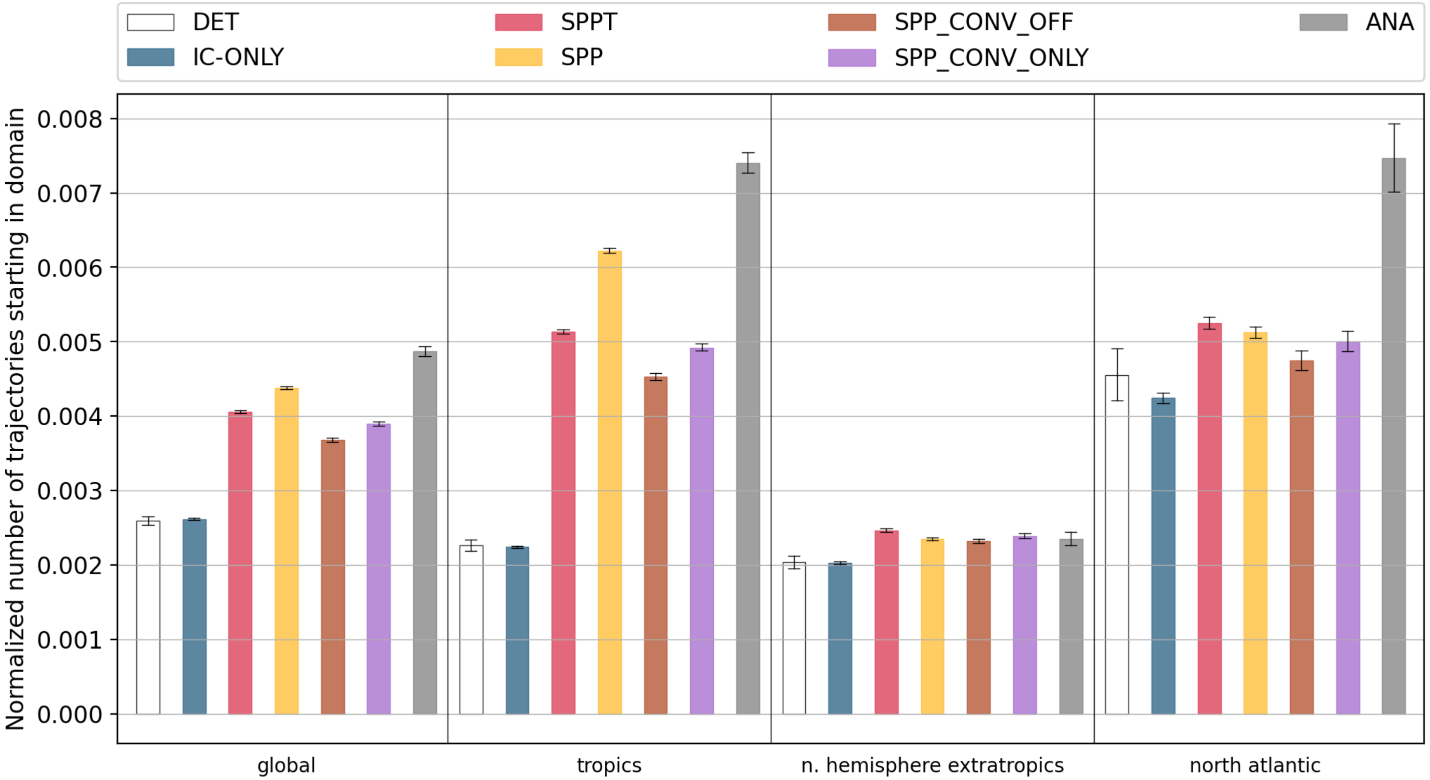


- NWP models struggle predicting regimes beyond week 2; lowest skill for EuBL blocking
- WCBs frequencies underestimated in model. Skill lost in week 2
- WCB activity prior to blocked regimes (in particular EuBL) challenges subseasonal prediction
- correct WCB representation is a window of forecast opportunity even at lead times > 2 weeks!



Wandel et al., 2024 *JGR-A* doi:10.1029/2023JD039791

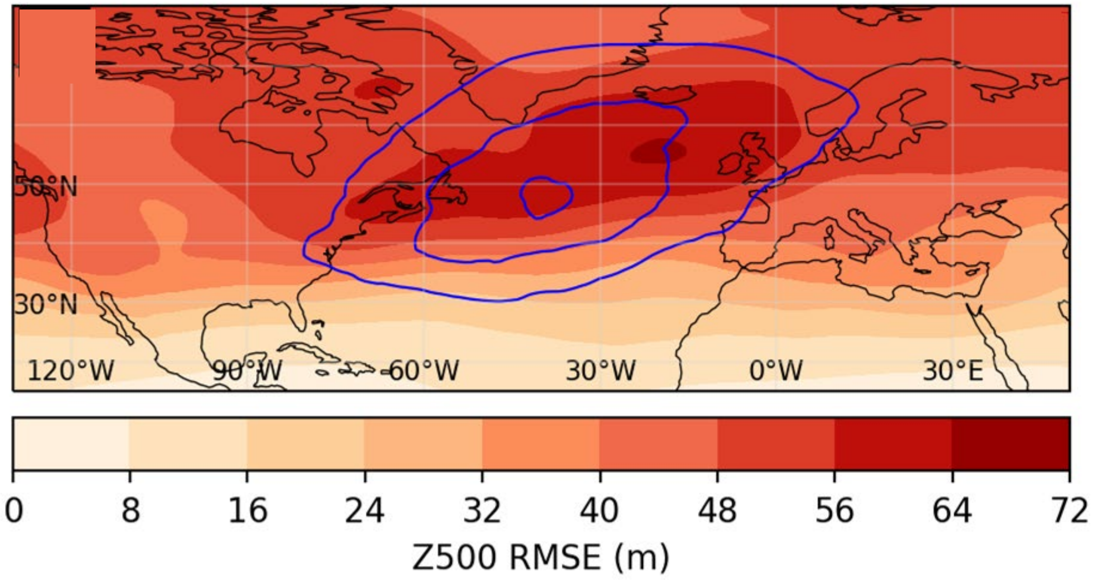
WCB sensitivity to model configuration



- systematic underestimation of ascending airstreams without stochastic perturbations
- perturbation are confined to regions with active convection scheme
- airstream characteristics do not change (LHR, outflow height,…)
- affects ω-distribution, precipitation, ridge area

Pickl et al. 2022, doi: [10.1002/qj.4257](https://doi.org/10.1002/qj.4257)
Deinhard (born Pickl) and Grams, 2024, doi: [10.5194/wcd-5-927-2024](https://doi.org/10.5194/wcd-5-927-2024)

WCB role in error growth (DJF)



climatological RMSE

climatological WCB-outflow frequency

- co-occurrence of Z500 RMSE and WCB outflow

- WCB activity begins prior to maximum error growth
- WCB projects small IC error to upper-level RW

Pickl et al. 2023, doi: 10.1002/qj.4546

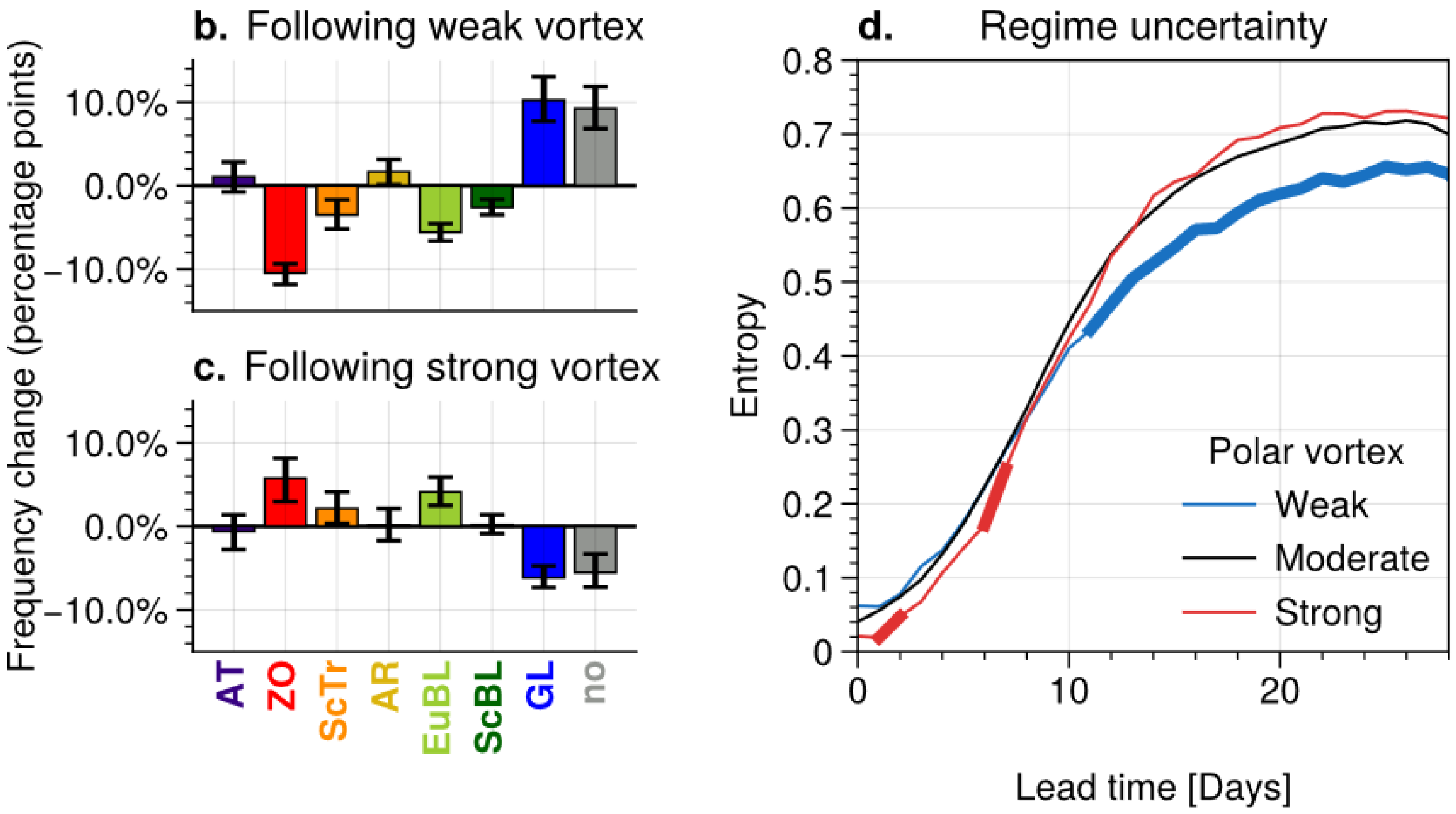
Forecast opportunities in light of intrinsic limits of predictability

arise from knowledge about flow-dependent predictability …

- WCB activity during onset of blocked regimes
- MJO teleconnection and WCB activity (Quinting et al. 2023)
- relationship of surface weather and regimes, for example
  - serial cyclone clustering (Hauser et al. 2023)
  - cold renewable energy droughts in Germany and UK (Mockert et al. 2023)
  - intra-regime weather variability (Spaeth et al. 2024, Gerighausen et al. 2024)
- Stratospheric influence on regime predictability (Beerli and Grams, 2019, Domeisen et al. 2020, Spaeth et al. 2024)
- detecting predictability barriers barriers and knowing when they will be overcome (González-Alemán et al. 2022, Oertel et al. 2023, Dorrington et al. 2024)

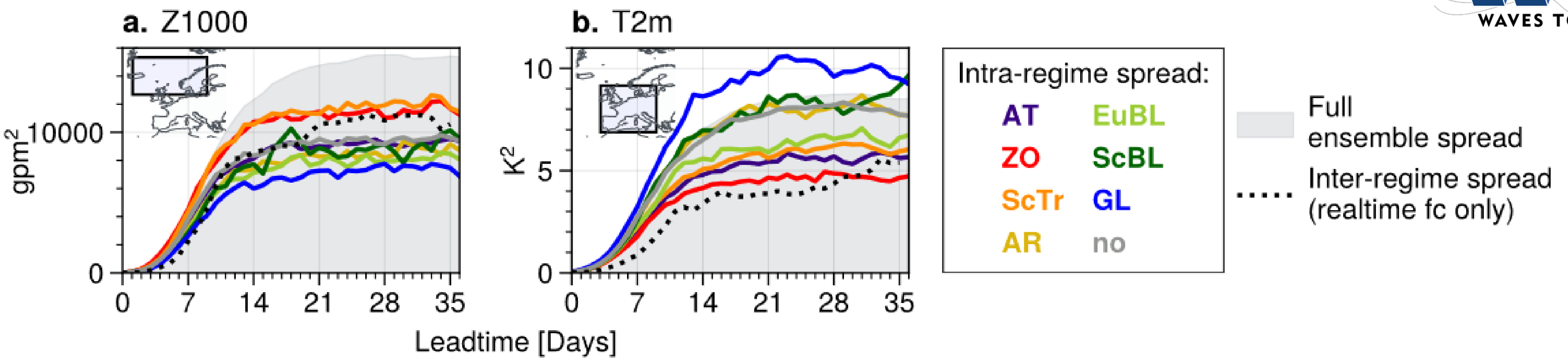
Regime-dependent changes in forecast uncertainty

(Spaeth et al. 2024, Gerighausen et al. 2024)



Regime-dependent changes in forecast uncertainty

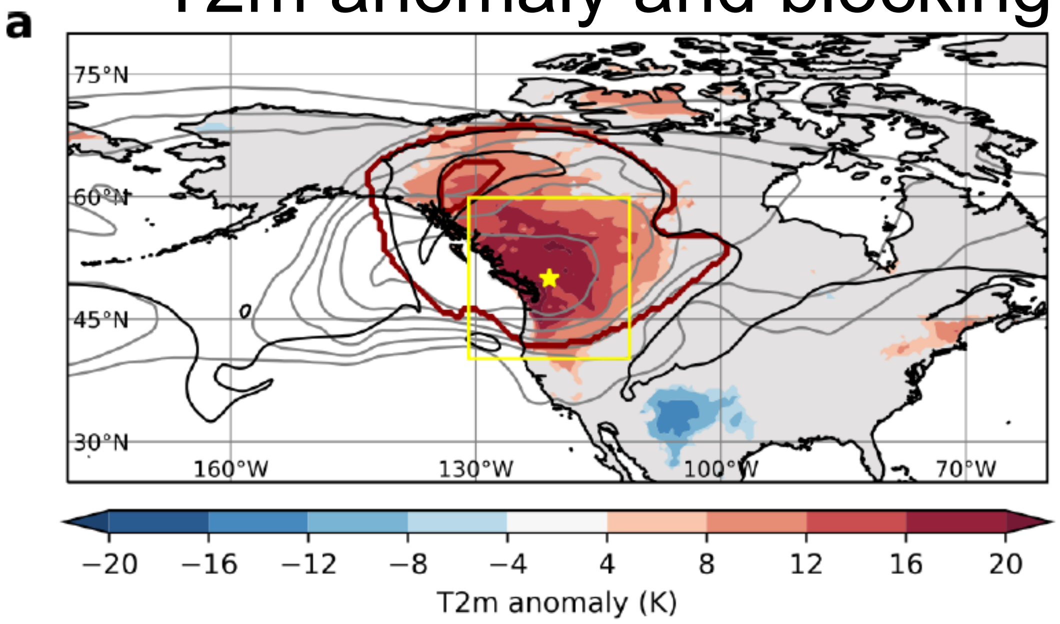
([Spaeth et al. 2024](), [Gerighausen et al. 2024]())



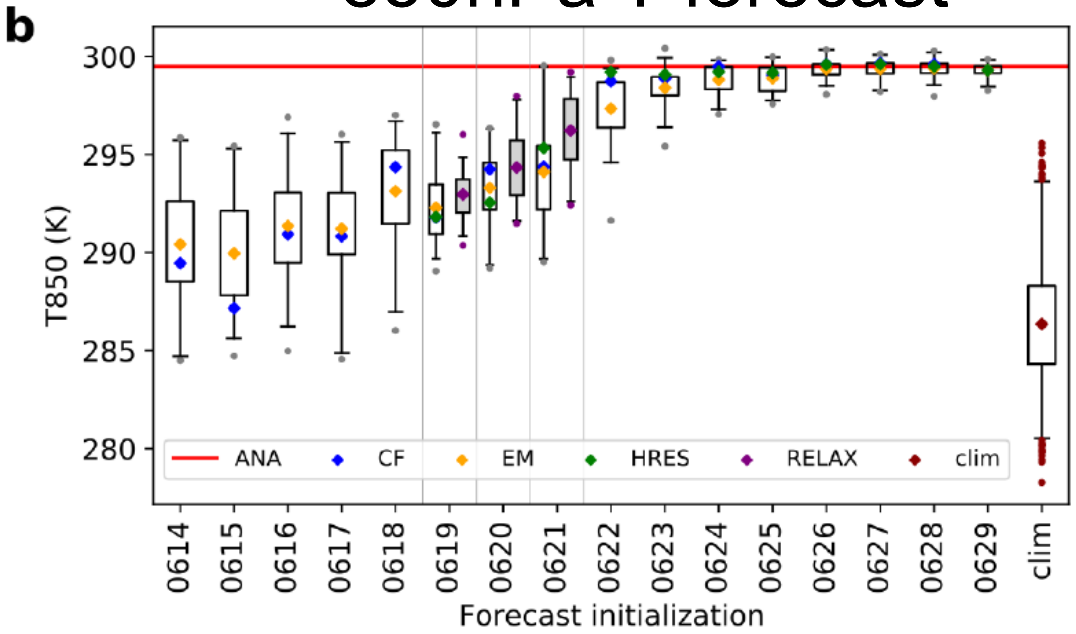
- weather regime indices during cold/warm UK Greenland blocking winter days
- T2m impact of GL depends on
  - amplitude of GL blocking
  - duration
  - co-projection in another regime

Predictability barriers

T2m anomaly and blocking



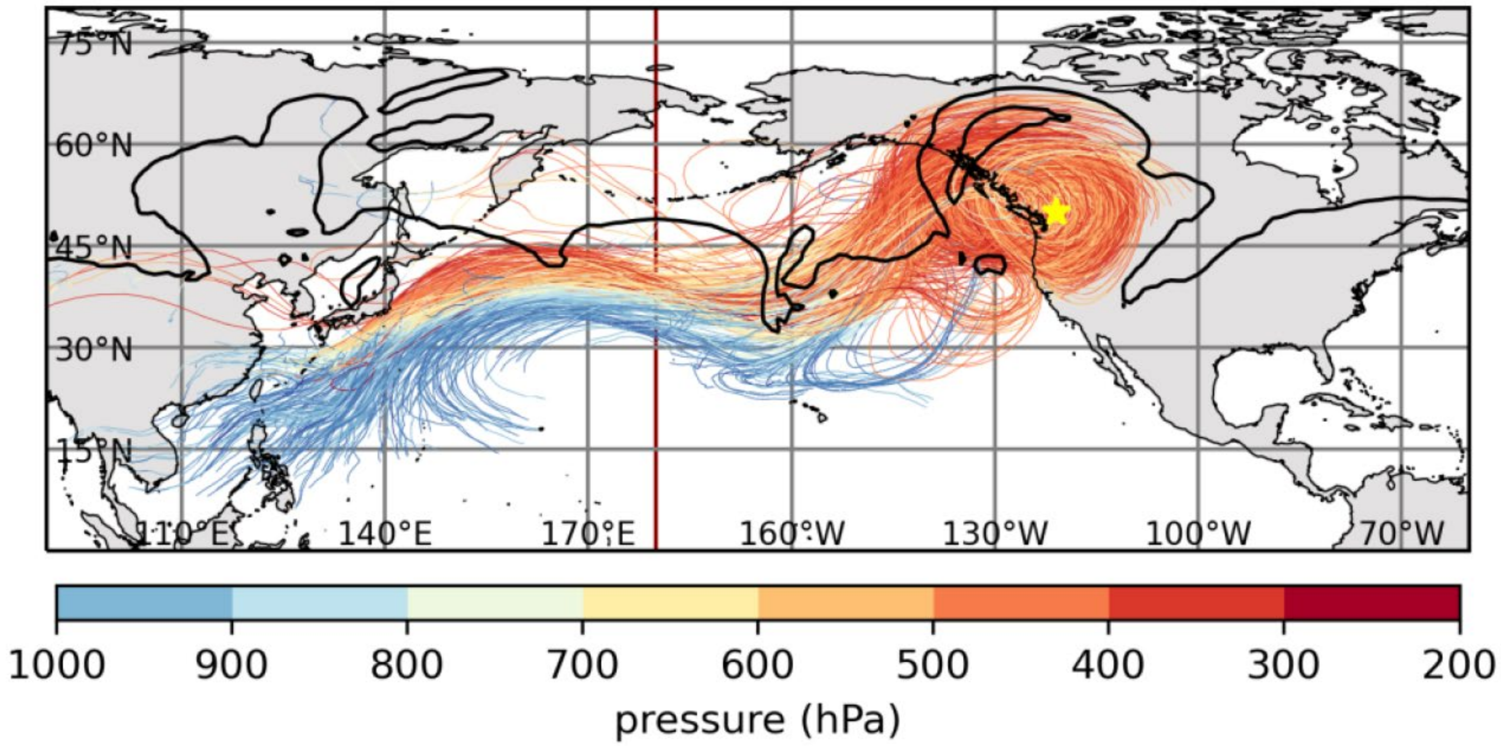
850hPa T forecast



Oertel et al., 2023, *Geophy. Res. Let.* doi:10.1029/2022GL100958

Predictability barriers

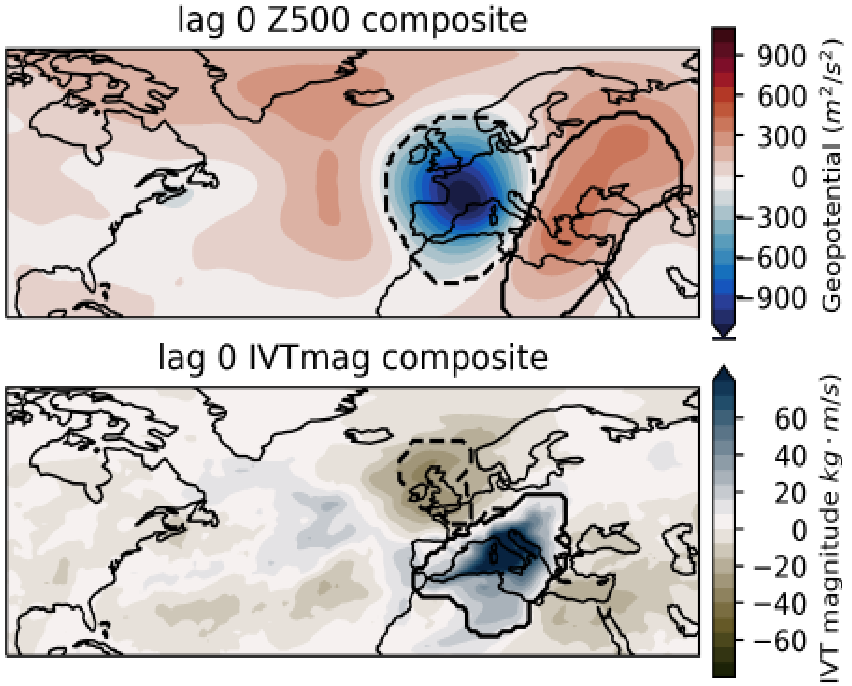
a



- WCB activity and downstream development reduced intrinsic predictability
- **How to know a priori about when the forecast becomes more reliable?**

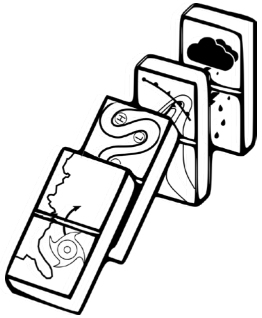
Oertel et al., 2023, *Geophy. Res. Let.* [doi:10.1029/2022GL100958](https://doi.org/10.1029/2022GL100958)

Predictability barriers – identification using event-prone regime approach



- ensemble precursor forecast indicates Emilia-Romagna floods in May 2023 up to 8 days ahead
- predictability barrier around 8 May

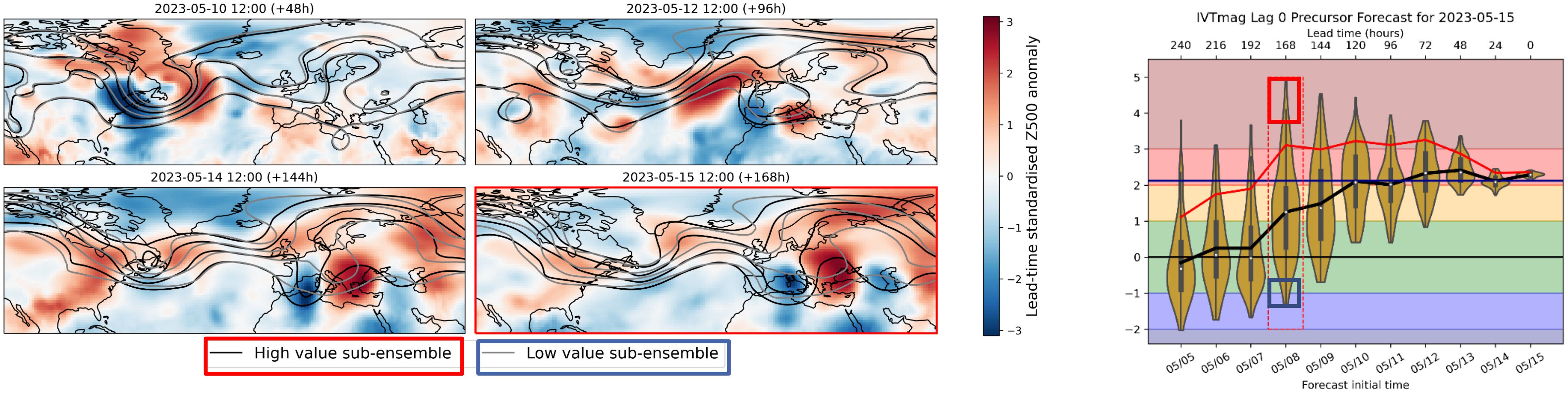
Domino – a framework for automated precursor analysis



Dorrington et al., 2024, doi:[10.1002/qj.4622](https://doi.org/10.1002/qj.4622)
https://github.com/joshdorrington/domino

Dorrington et al. 2024b doi: 10.5194/nhess-24-2995-2024

Predictability barriers – identification using event-prone regime approach



- subsetting ensemble according to IVT precursor activity identifies reasons and is sharper
- cyclogenesis near Newfoundland during 8-12 May reduces **intrinsic** predictability

Dorrington et al. 2024b doi: 10.5194/nhess-24-2995-2024

Conclusions

- “moist-baroclinic development” contributes substantially to forecast uncertainty on medium- to subseasonal time scales
- SPPT and SPP reduce systematic WCB biases
- still WCB activity contributes to flow-dependent situations of low intrinsic predictability
- forecast storylines help to overcome predictability barriers

What is ultimate predictability and what is holding NWP back?

The predictability of the atmosphere is intrinsically limited. However, this is flow-dependent and linked to a chain of synoptic events. We have to think more in dynamical “forecast storylines”, know about the critical event causing a “predictability barrier”, and benefit from knowing when the barrier will be overcome.

contact: christian.grams@meteoswiss.ch

References

Mentioned Papers:

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 Using a Stochastic Convection Scheme. *Mon. Wea. Rev.*, **147**, 1713–1731, doi:10.1175/MWR-D-18-0292.1.

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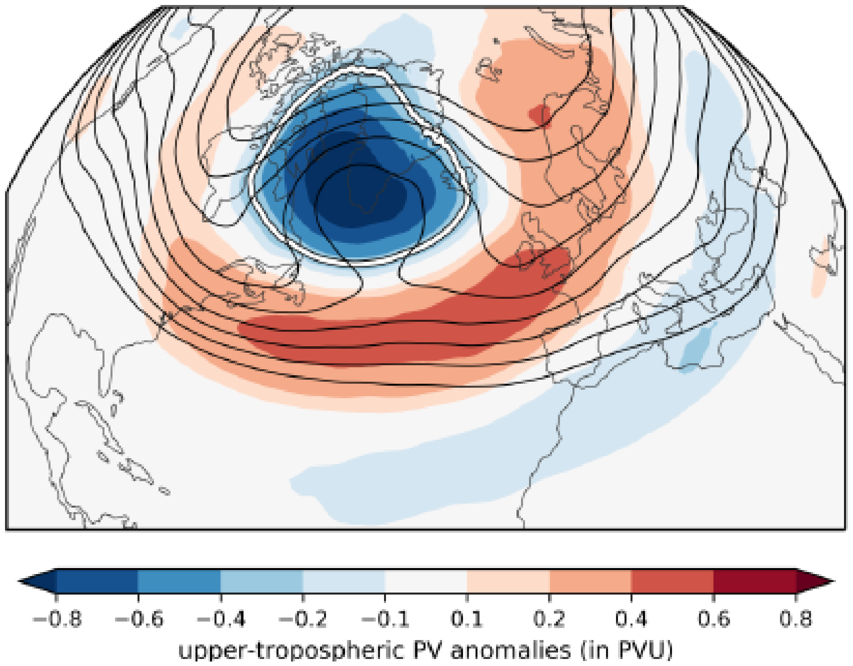
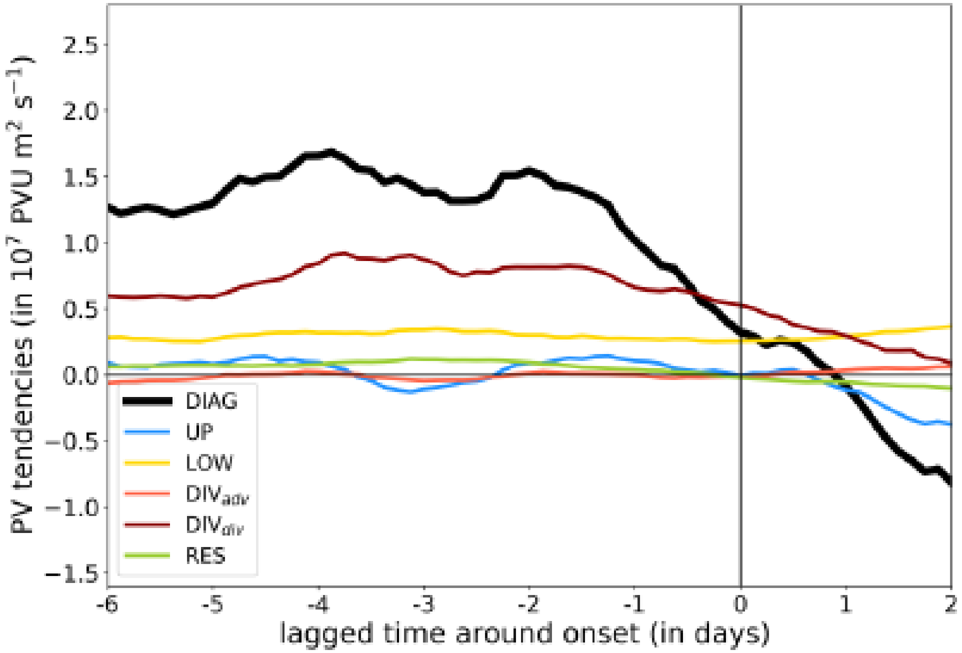
Quantifying the relevance for blocking – quasi-Lagrangian PV diagnostics



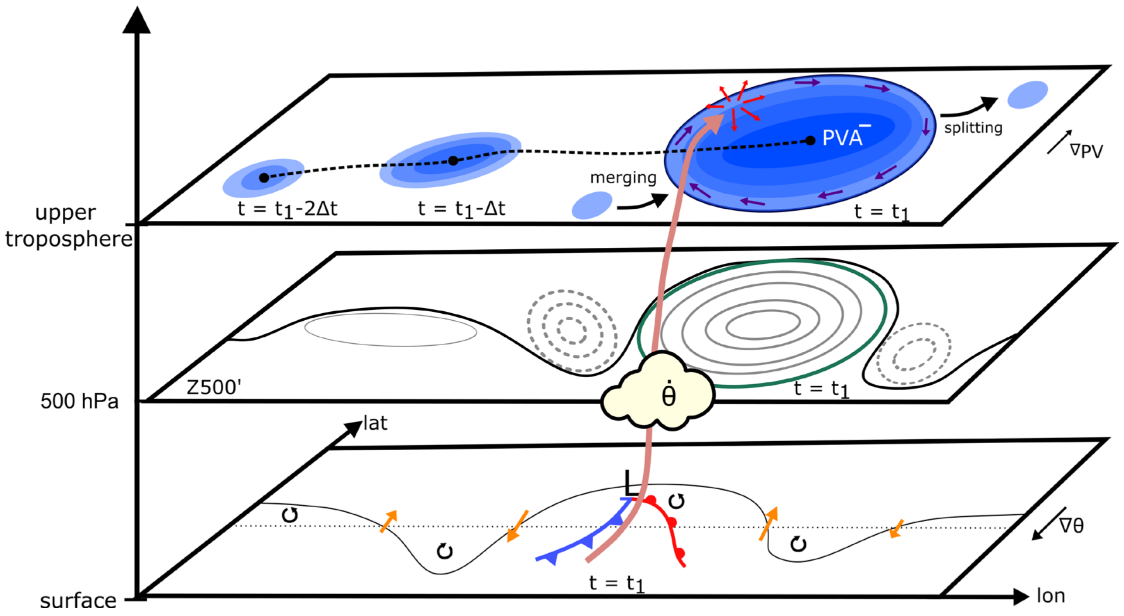


- PV amplitude evolution for blocking onset over Greenland.

→ **strong positive tendencies due to divergent wind components associated with WCB**

GL Onset Study: Hauser et al. 2024, doi:10.5194/wcd-5-633-2024
PV diagnostics: Hauser et al. 2023, doi: 10.5194/wcd-4-399-2023

Quantifying the relevance for blocking – quasi-Lagrangian PV diagnostics



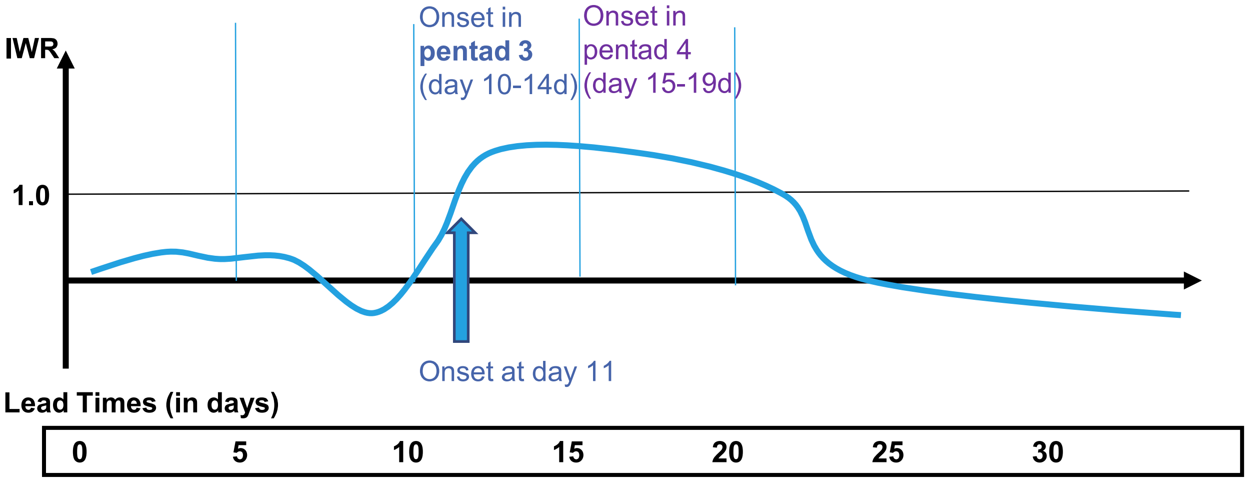
- tracking of upper-level PV anomalies associated with blocking
- contributions to amplitude evolution by
  - barotropic dynamics (**UP**)
  - baroclinic interaction (**LOW**)
  - divergent wind (**DIV**, *indirect moist-diabatic contribution*)

GL Onset Study: Hauser et al. 2024, doi: 10.5194/wcd-5-633-2024
PV diagnostics: Hauser et al. 2023, doi: 10.5194/wcd-4-399-2023

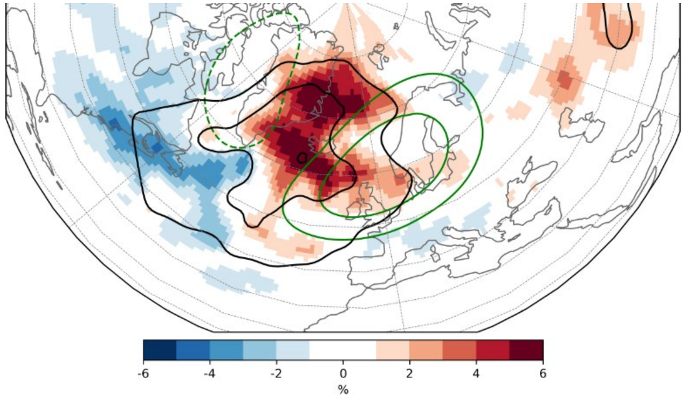
WCB outflow at EuBL onset

example **ERA-Interim** anomalies
for ERA-I onset **lead time 10-14d (pentad 3)**

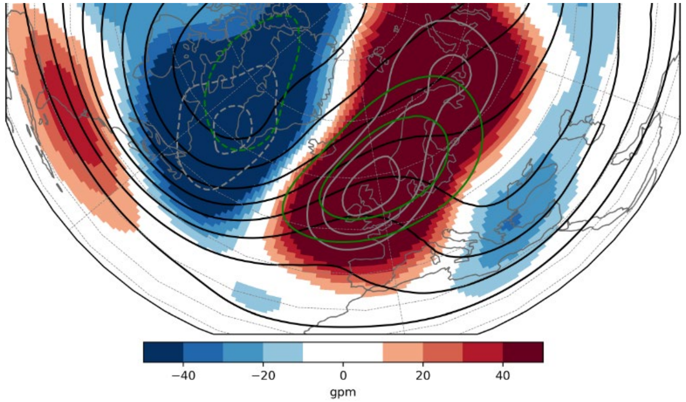
- **EuBL onset in ERA-Interim at given lead time window**
- focus on leadtime pentads rather than weeks, as WCB skill is lost after 10 days
- WCB outflow frequencies based on ELIAS2.0 for ERA and model at these lead times (not necessarily an EuBL onset in model)



WCB outflow freq. anomaly



Z500



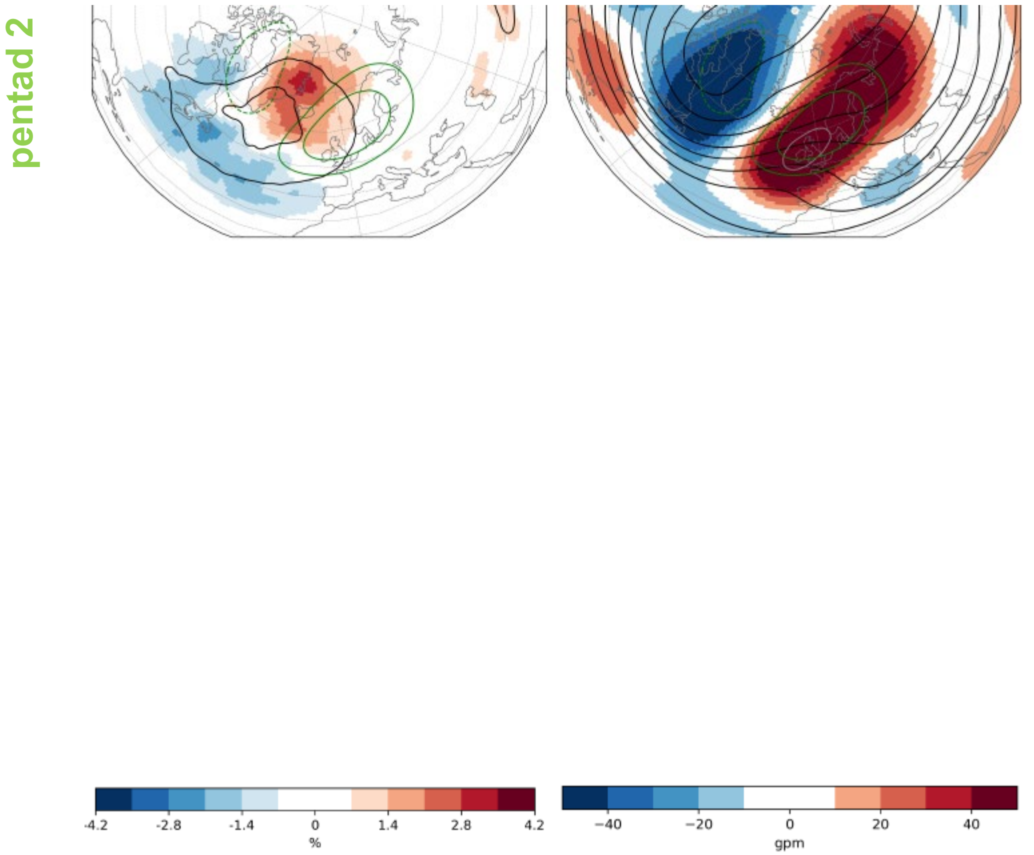
Wandel et al., 2024 *JGR-A* doi:10.1029/2023JD039791

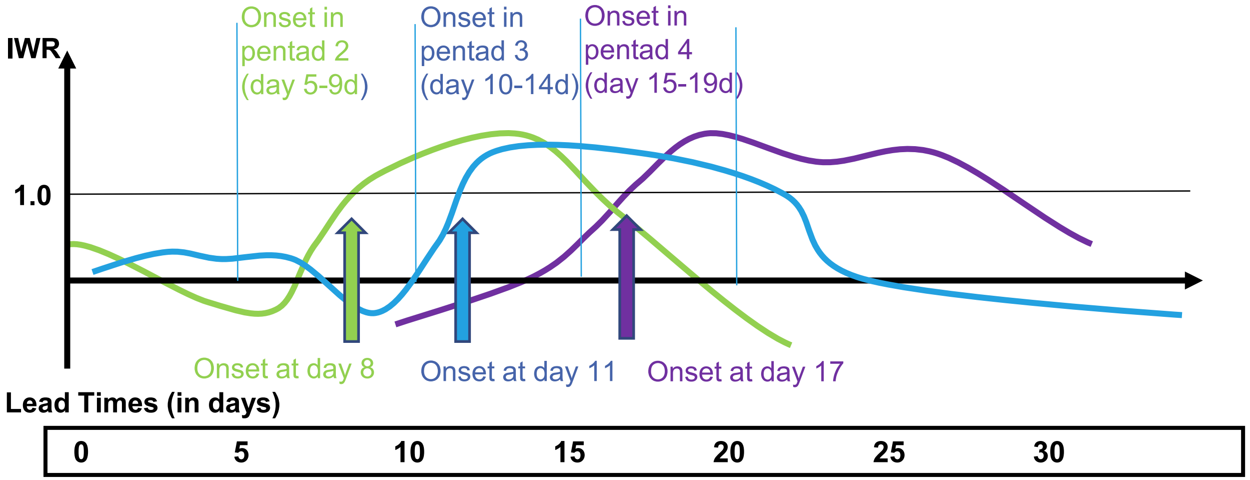
WCB outflow at EuBL onset in ERA-I in pentad 4

Reforecast anomalies
for ERA-I onset **in different pentads**

- **EuBL onset in ERA-Interim at given lead time window**
- focus on leadtime pentads rather than weeks, as WCB skill is lost after 10 days
- WCB outflow frequencies based on ELIAS2.0 for ERA and model at these lead times (not necessarily an EuBL onset in model)

WCB outflow **Z500**





Wandel et al., 2024 *JGR-A* doi:10.1029/2023JD039791

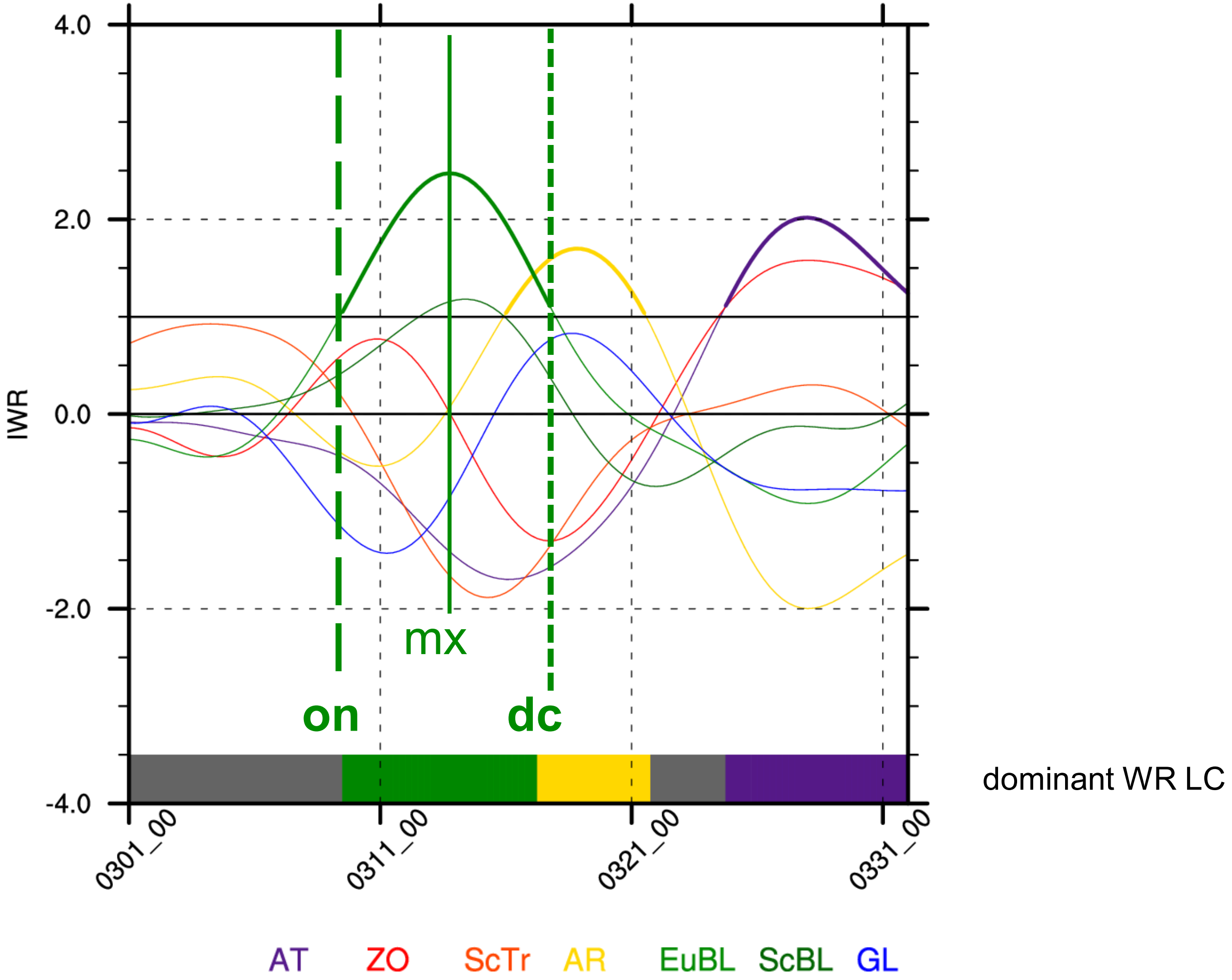
Weather regime life cycles

- Weather regime Index I_{wr} following Michel and Rivière (2011), *JAS*, doi:10.1175/2011JAS3635.1

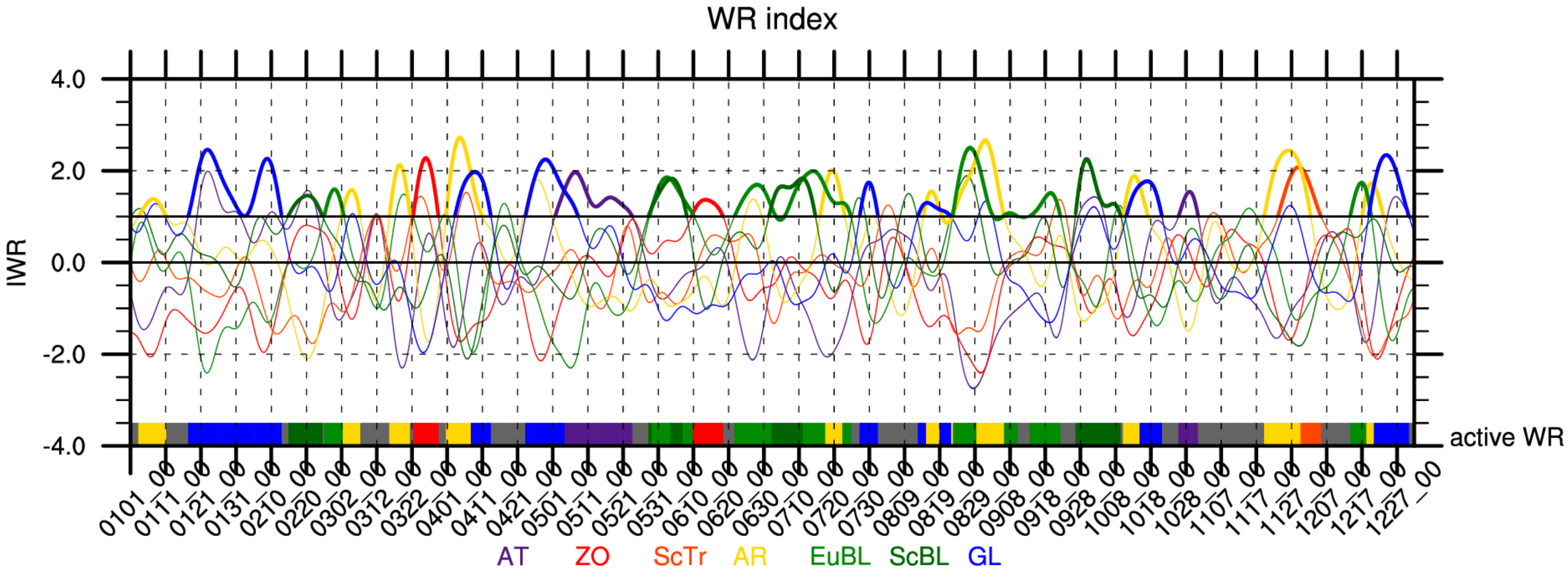
$$P_{wr}(t)=\phi'_{(\varphi,\lambda,t)} \cdot \overline{\phi'_{(\varphi,\lambda)}}_{wr} \qquad \overline{P_{wr}} = \frac{1}{N}\sum_{1979}^{2014} P_{wr}(t)$$

$$I_{wr}(t) = \frac{P_{wr}(t) - \overline{P_{wr}}}{\sqrt{\frac{1}{N-1}\sum_{1979}^{2014}(P_{wr}(t) - \overline{P_{wr}})^2}}$$

- Objective definition of **onset,** maximum, **decay** for individual weather regime LCs



Weather regimes 2021

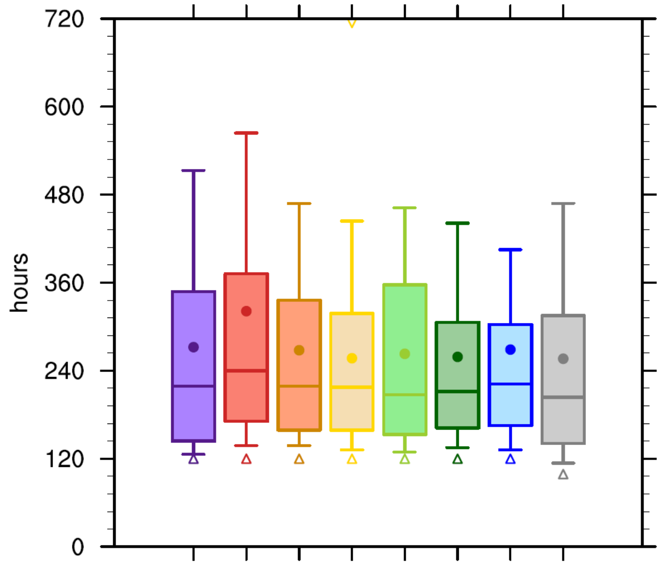


Weather regime characteristics

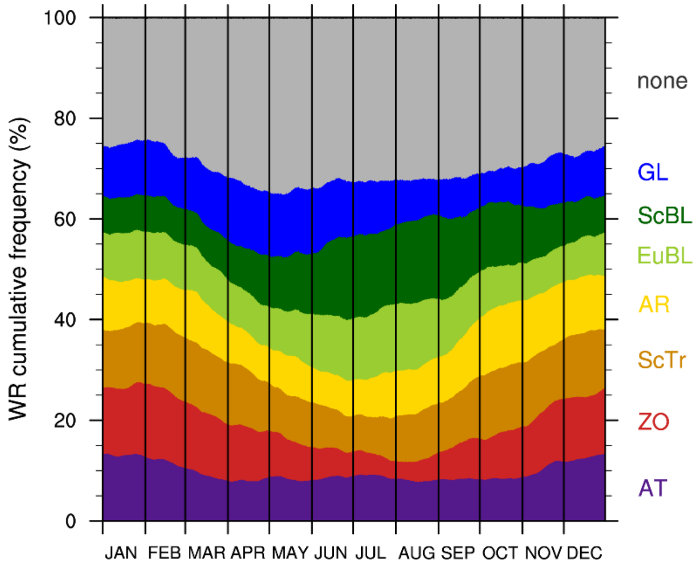
Cyclonic regimes:
- Atlantic trough
- Zonal Regime
- Scandinavian trough

Blocked regimes:
- Atlantic ridge
- European blocking
- Scandinavian blocking
- Greenland blocking

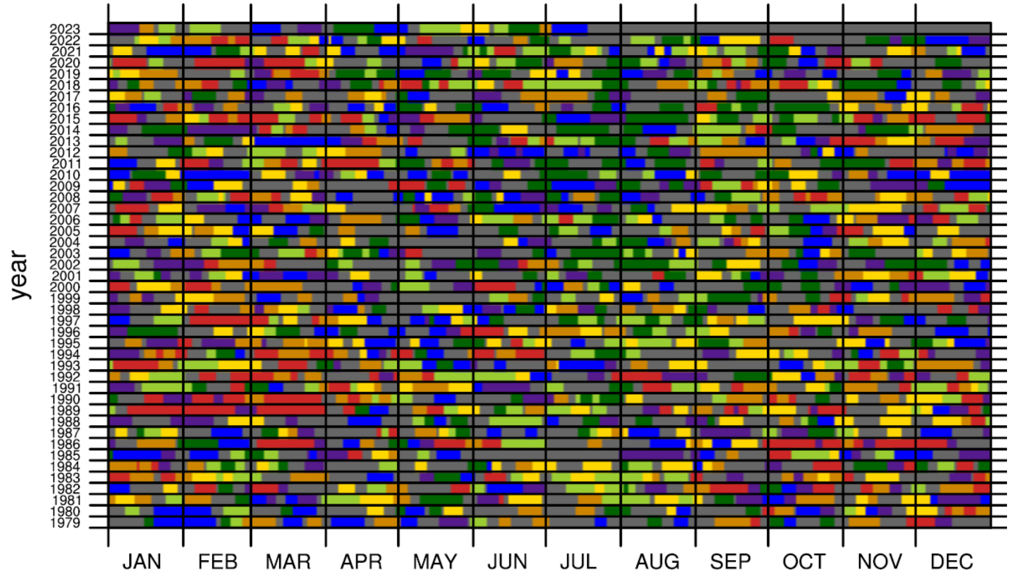
duration



frequency



interannual variability



An Eulerian WCB Metric (ELIAS2.0)

Predictor selection

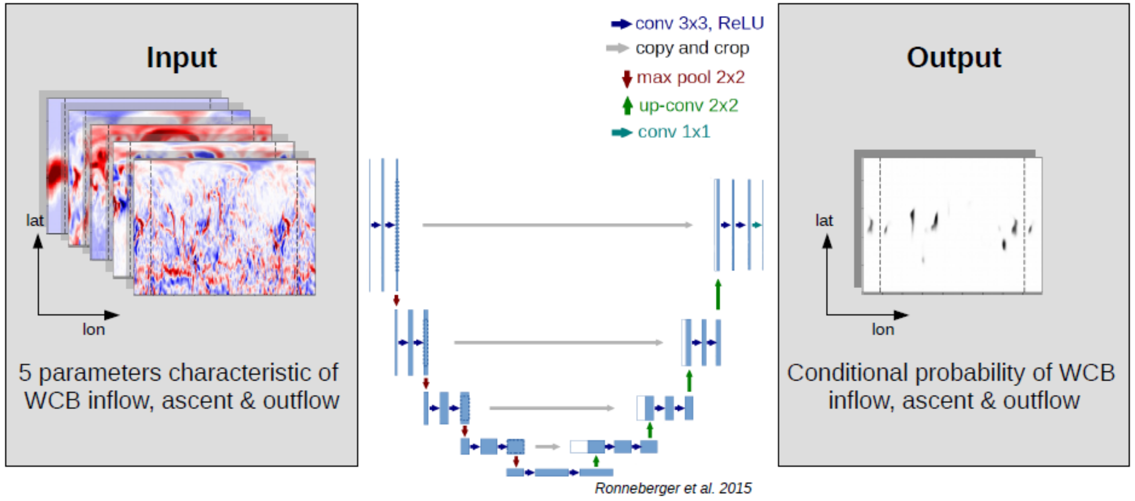
- Predictors based on standard input fields at pressure levels: T, qv, Z, u, v

P	WCB inflow	WCB ascent	WCB outflow
1	700-hPa thickness advection	850-hPa relative vorticity	300-hPa relative humidity
2	850-hPa meridional moisture flux	700-hPa relative humidity	300-hPa irrotational wind speed
3	1000-hPa moisture flux convergence	300-hPa thickness advection	500-hPa static stability
4	500-hPa moist potential vorticity	500-hPa meridional moisture flux	300-hPa relative vorticity
5	conditional probability of ascent (+24 h)*	30-d WCB ascent climatology**	conditional probability of ascent (-24 h)*

Quinting and Grams (2021), *JAS*, doi:10.1175/JAS-D-20-0139.1

UNet-type convolutional neural network

- trained on global ERA-Interim at 1.0° grid spacing



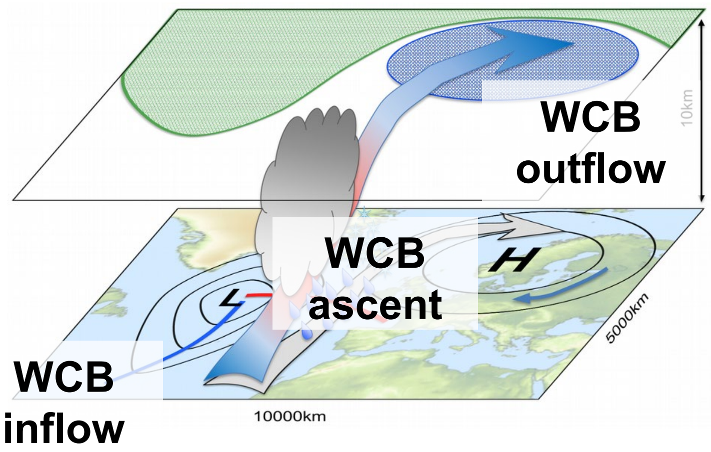
Quinting and Grams (2022), doi:10.5194/gmd-15-715-2022

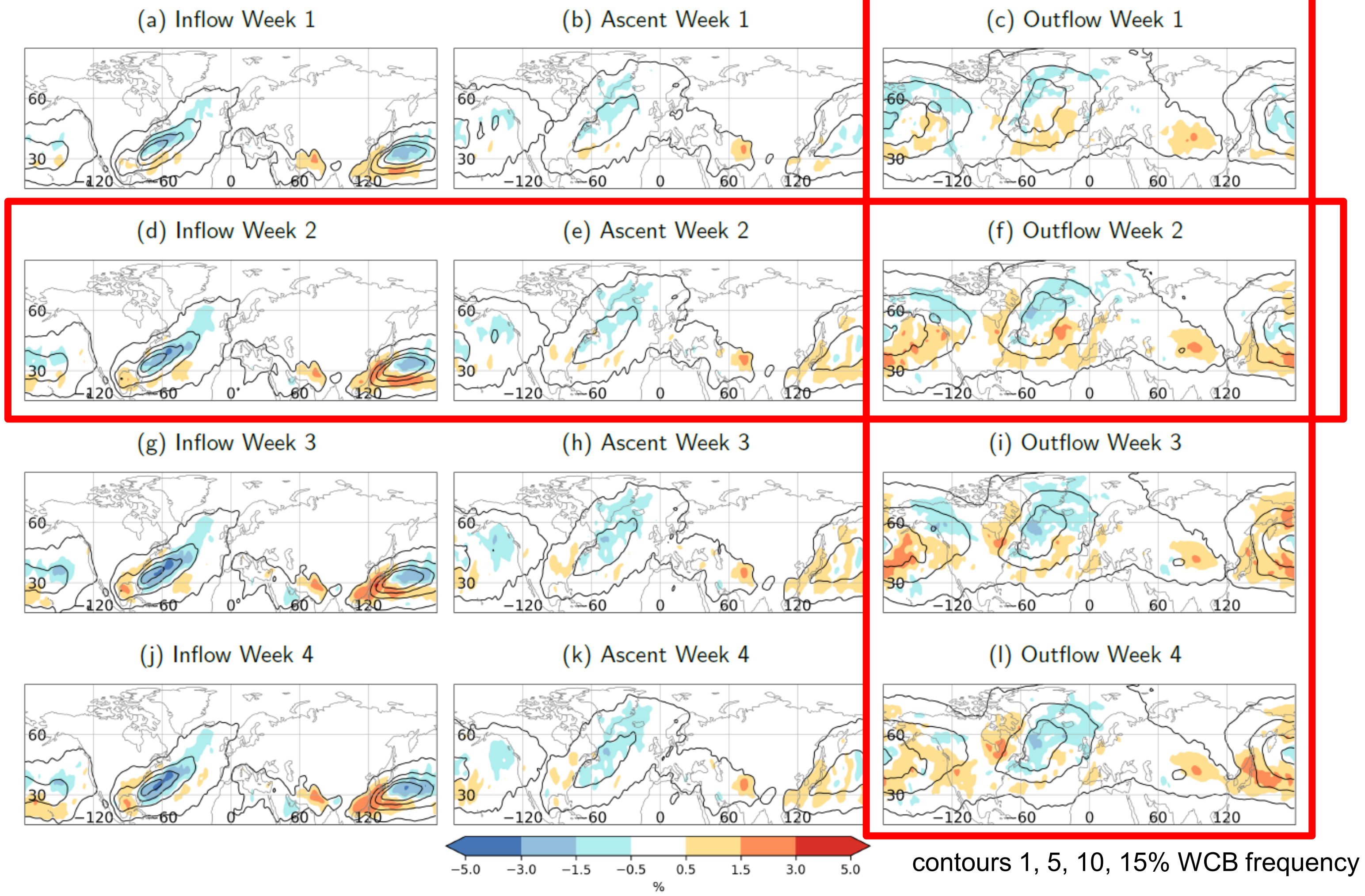
https://git.scc.kit.edu/nk2448/wcbmetric_v2

WCB frequency biases (DJF)

ECMWF S2S ensemble reforecasts
DJF 1997-2017 (~920 initial times)

→ Detection of WCB inflow, ascent, outflow mask in each member



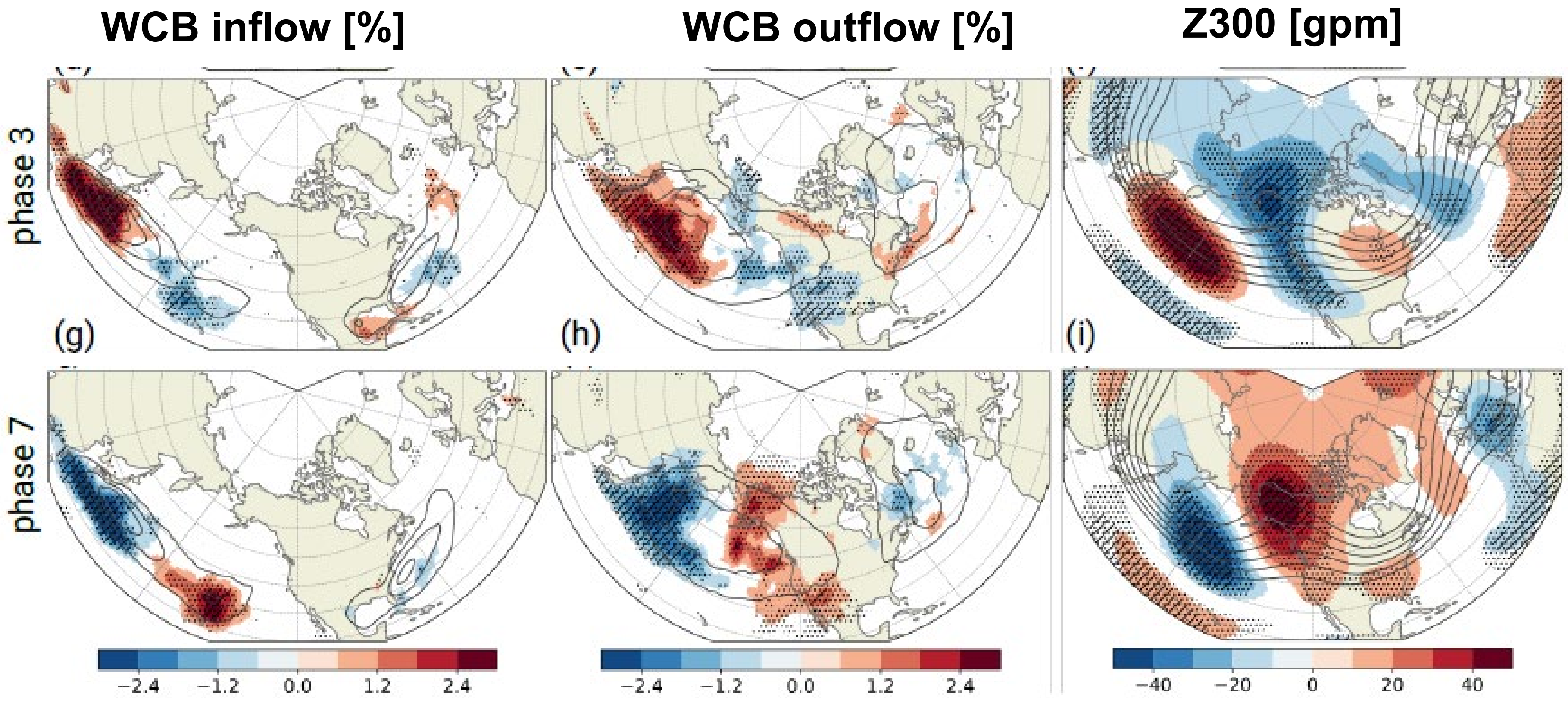


contours 1, 5, 10, 15% WCB frequency

Wandel, J., J. F. Quinting, and C. M. Grams, 2021: Toward a Systematic Evaluation of Warm Conveyor Belts in Numerical Weather Prediction and Climate Models. Part II: Verification of Operational Reforecasts. *Journal of the Atmospheric Sciences*, 78, 3965–3982, doi:10.1175/JAS-D-20-0385.1.

A potential modulation of the MJO teleconnection by WCB activity (led by Julian Quinting)

- systematically enhanced WCB activity
  - in WPAC after phase 2/3 along with zonally-oriented flow
  - in EPAC after phase 6/7 along with blocked flow



0-4 d after active MJO (pentad 1)

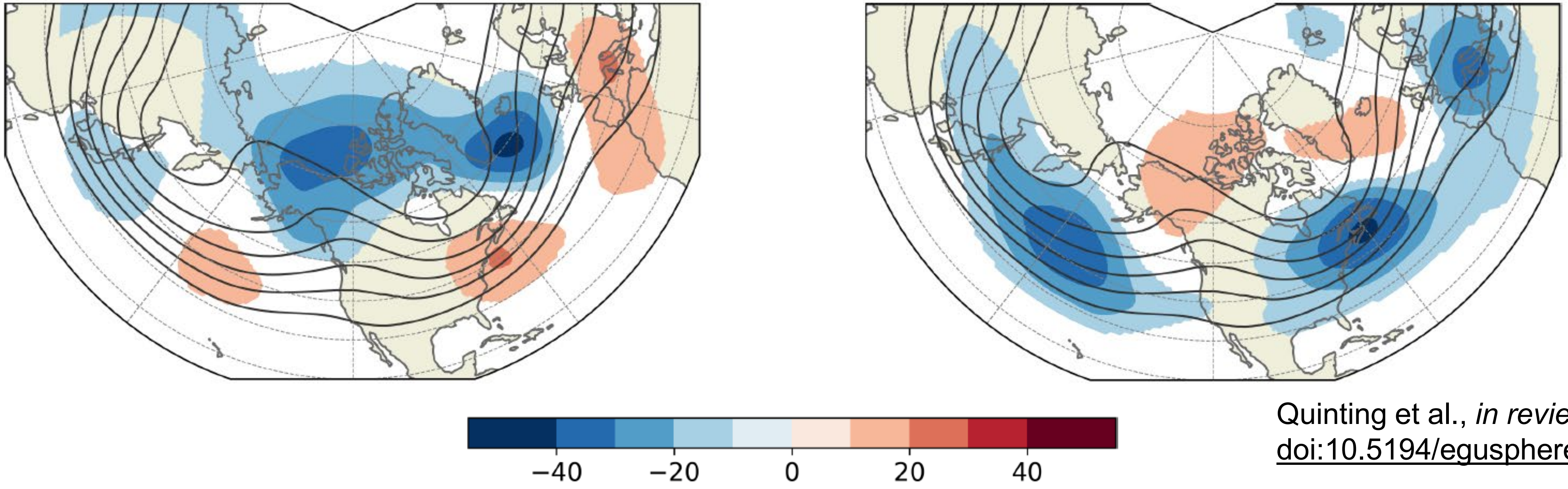
Quinting et al., *in review for WCD*
doi:10.5194/egusphere-2023-783.

A potential modulation of the MJO teleconnection by WCB activity (led by Julian Quinting)

- canonical NAO+ (ZO) regime respone after Ph2/3 and NAO- (GL) after 6/7

Z500 anomaly [gpm] pentad 3 (10-14d) after active MJO

Phase 2/3 **Phase 6/7**

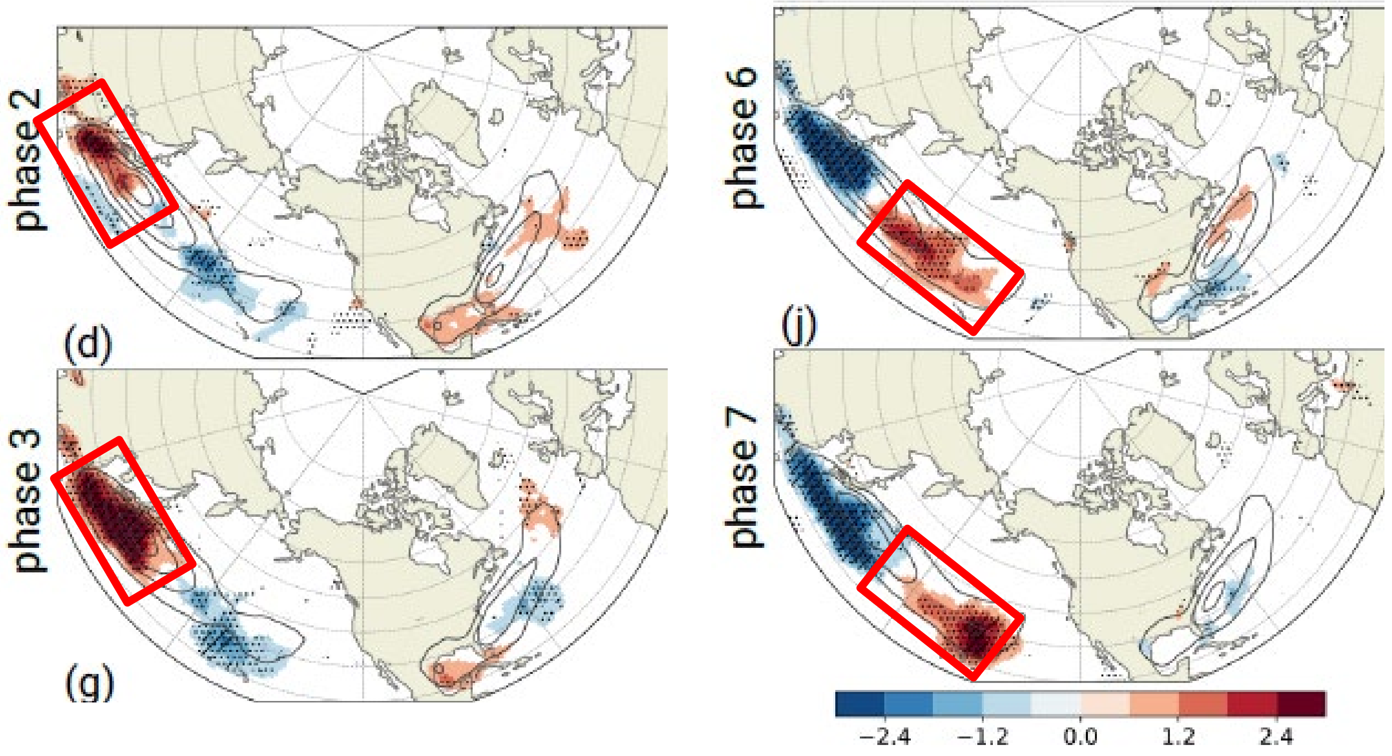


Quinting et al., *in review for WCD*
doi:10.5194/egusphere-2023-783.

A potential modulation of the MJO teleconnection by WCB activity

- stratification according to low (lower 33%) and high (upper 33%) of WCB activity in WNPAC

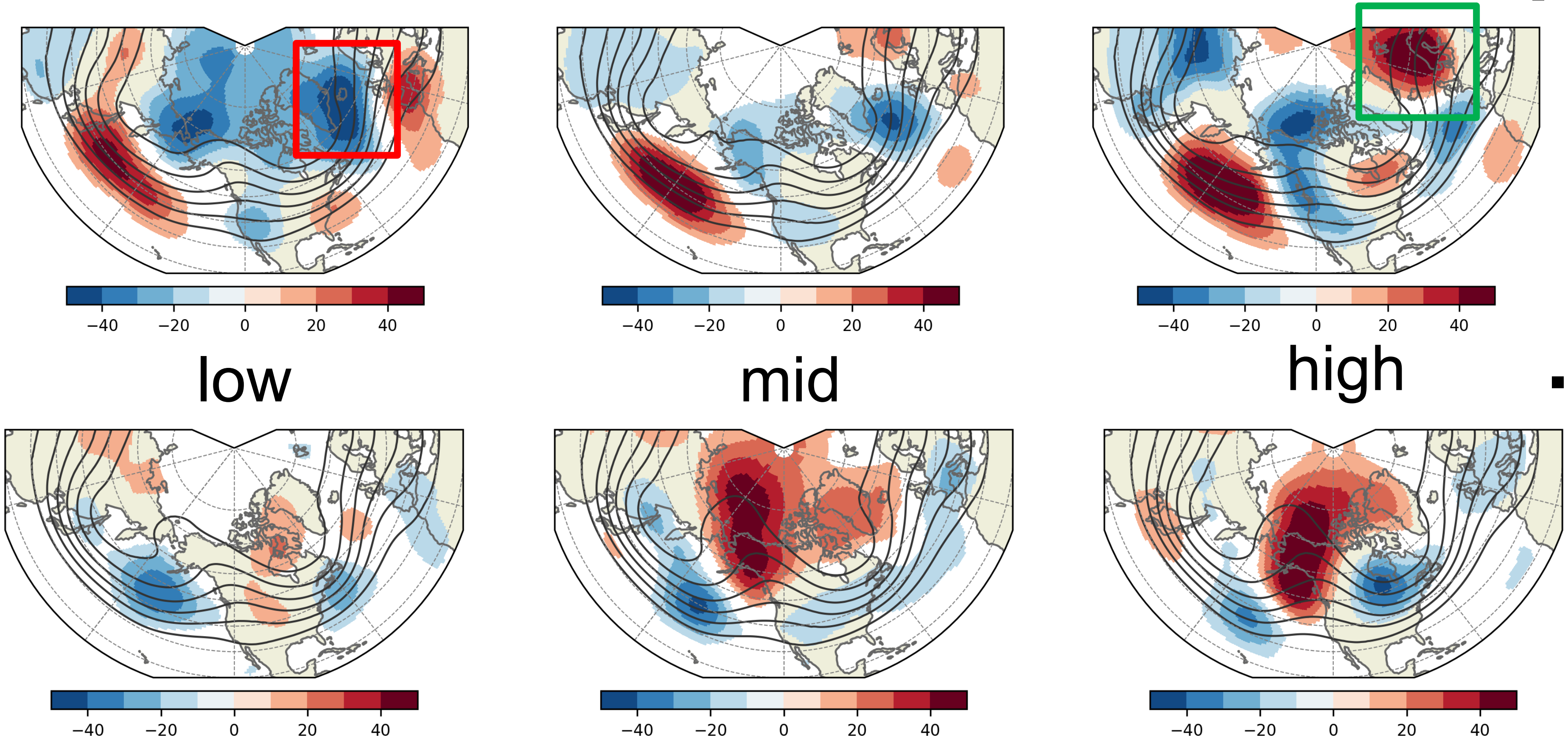
WCB inflow (%) pentad 1 (0-4d)



Quinting et al., *in review for WCD*
doi:10.5194/egusphere-2023-783.

MJO teleconnection after Ph 2 and 7 with high/low WCB activity.

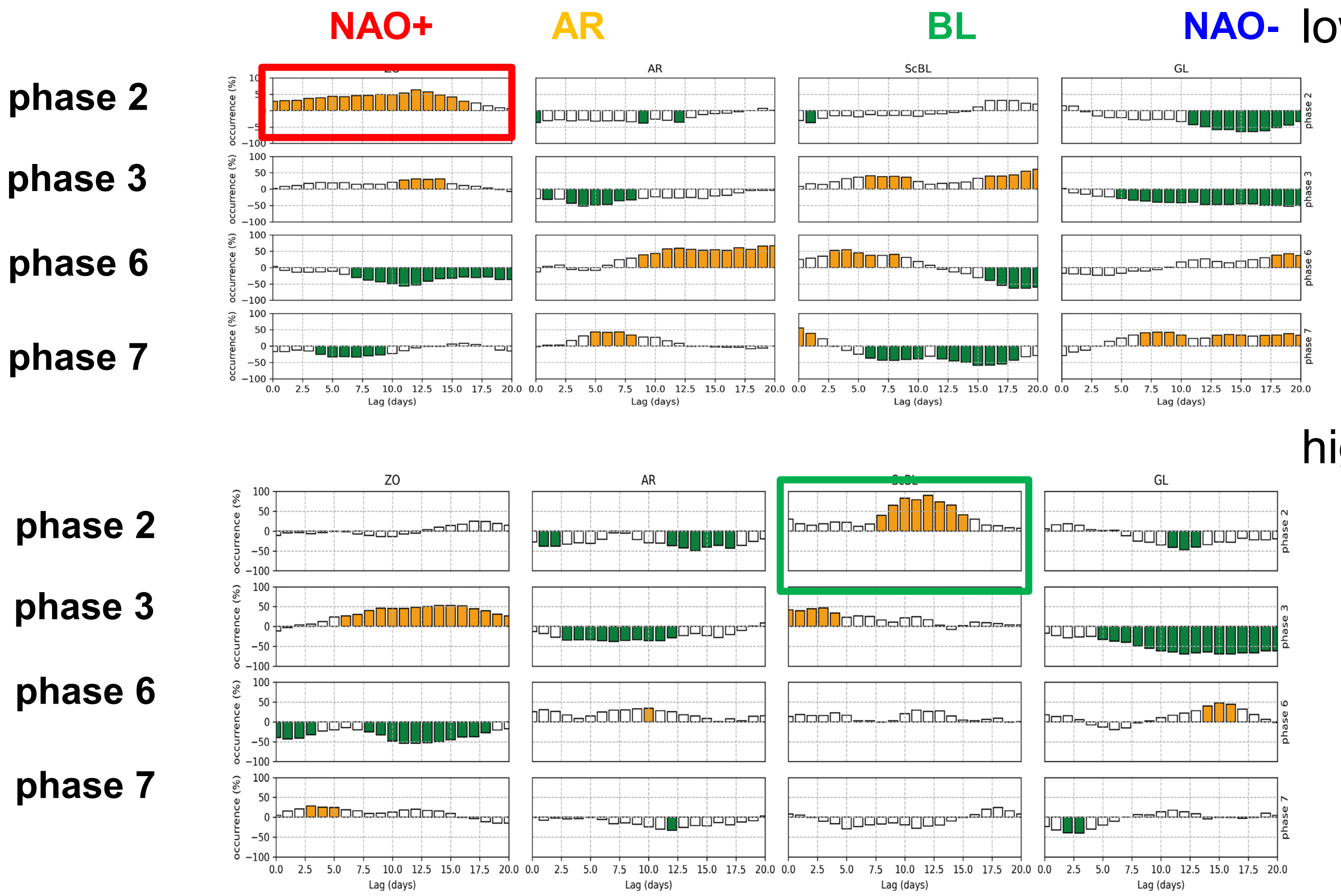
Z500‘ pentad 2 (5-9d)



- Ph 2:
  - low WCB activity → **NAO+**?
  - high WCB activity → **BL**?
- Ph 7:
  - low & high WCB activity → indifferent picture
  - intermediate WCB activity → NAO- response

Quinting et al., *in review for WCD*
doi:10.5194/egusphere-2023-783.

Regime occurrence after low / high WCB activity



low WCB activity

- **NAO+** response after ph 2
- weak AR/NAO- response after ph 6/7

high WCB activity

- **BL** response after ph 2
- indifferent response after ph 6/7

Quinting et al., *in review for WCD*
doi:10.5194/egusphere-2023-783.

Forecast skill horizon

Potential to **increase forecast skill** horizon through …

1. **Improvement of the NWP system** (reducing IC and model error)
2. **Alternate forecast question** (spatial-temporal aggregation & knowledge about sources of predictability)