Investigating European heatwaves and their medium-range predictability in relation to weather regimes

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Predictability of European heatwaves

- Heatwaves are the “easiest” to predict extreme weather phenomena in the mid-latitudes due to their spatial scale and the important role of slowly-evolving boundary conditions
- However, this is only true when using probabilistic and somewhat forgiving metrics
- A timely and accurate prediction of heatwave onsets at medium-range is much more challenging!
  → Strongly relies on the adequate representation of large-scale Rossby wave dynamics
- Dynamical regime (often, but not necessarily large-scale atmospheric blocking flow) may be important for inherent or practical predictability of European heatwaves

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Research questions:

1) **What are the most frequent weather regimes around heatwave onset in different European regions and how does the predictability depend on the respective weather regime?**

2) **Can we identify certain (dynamical) atmospheric or lower boundary precursors that affect the predictability of European heatwaves?**

This is a statistical, hindcast ensemble data driven study! **(in this talk: focus on Central Europe)**

Data and Methods

1) **Objectively identify heatwaves** (HWs) over period **2001-2018 (MJJAS); ~50 each** for different European regions (ERA5 Tmax anom. local and regional mean > 90th percentile for at least 3 days)

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ECMWF-S2S hindcasts: 11 ENS members; merged over multiple annual iterations → thereby daily init dates, **focus of this talk**)

GEFS v12 reforecasts: 5 ENS members; already available with daily init dates (ongoing, **no explicit results shown in this talk**)

Lead times of interest: **3-12 days**, focus on (extended) medium range: **9-11 days**

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3) **Stratify heatwaves** by **Euro-Atlantic weather regimes *(Grams et al. 2017)*:**
→ **reduce complexity of atmospheric flow field** by projecting it onto the **seven** main **modes of synoptic-scale variability** in this domain (based on EOF analysis and subsequent k-mean clustering)

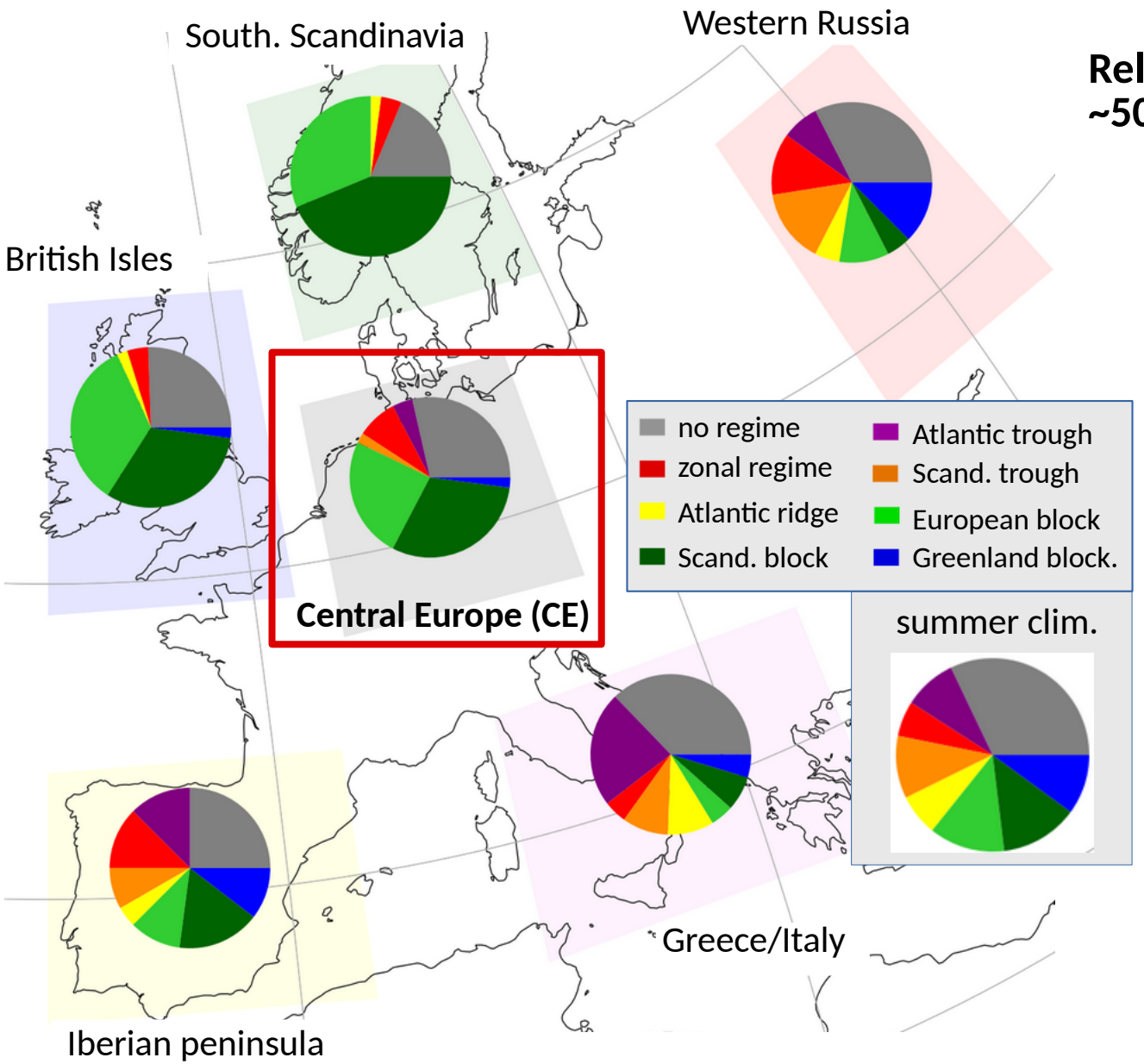
4) Stratify **heatwaves** by **medium-range predictability** (9-11 days) w. r. t. multiple metrics:

Focus in this talk: **1) 500hPa geopotential anomaly correlation coefficient**
2) Area-averaged error in 2m Tmax Extreme Forecast Index (EFI)

Results

1) Statistical overview over heatwave predictability in relation to Euro-Atlantic weather regimes

2001-2018 Climatology: Euro-Atlantic weather regimes during HW onsets



Relative fraction of weather regimes at onset of ~50 HWs each in different European regions

→ Whereas northern **mid-latitude Europe heatwaves** are mainly **associated with classic blocking regimes**, **more diverse picture for Central Europe:**

„no regime“ **also important** and to some extent **zonal** and **Atlantic trough** (close to summer clim.)

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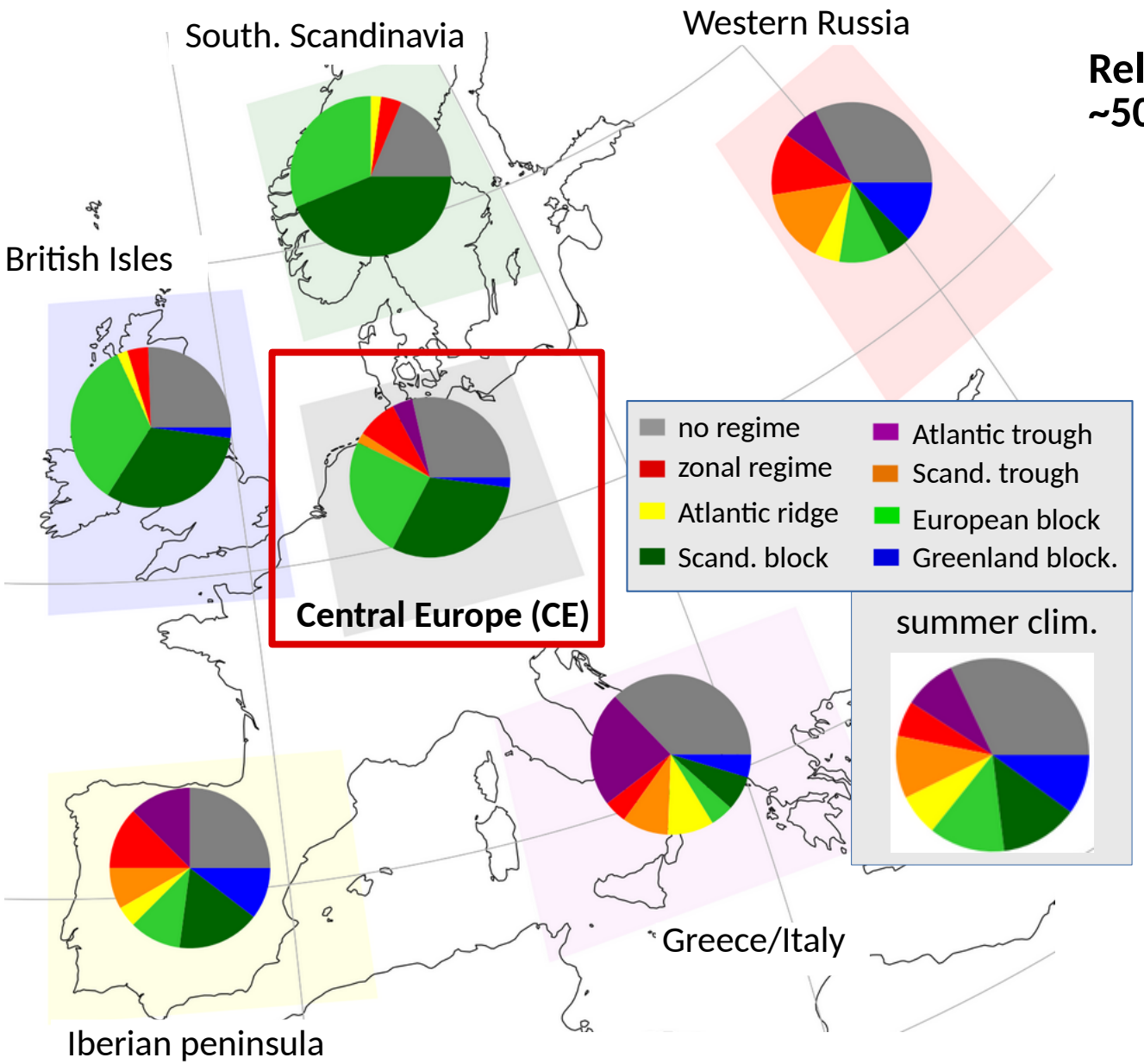

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Next slide: Focus on **regime-dependent predictability of HW** onsets over **CE:**

1) w. r. t. to **capturing large-scale circulation**
→ 500hPa geopotential anomaly correlation

2) w. r. t to **capturing extremeness of 2m Tmax**
→ Tmax Extreme Forecast Index

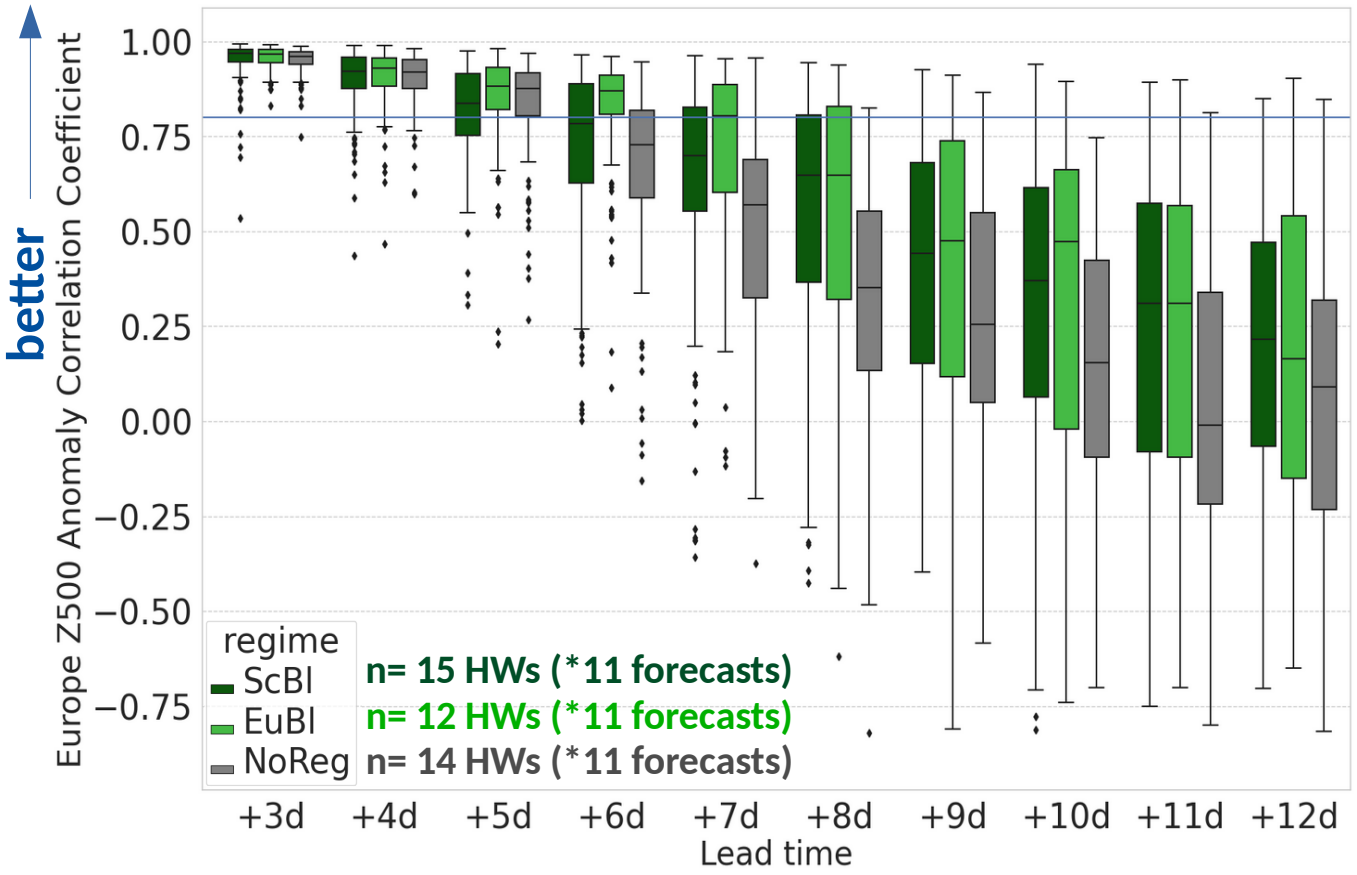
Forecast skill for Central European heatwave onsets

– Comparison of predictability of heatwave onset between three dominant regimes –

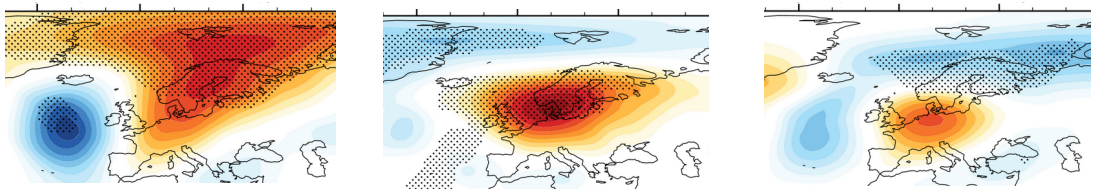
Based on 11-member **ECMWF-S2S Hindcasts** 2001-2018

First Metric: 500hPa geopotential ACC

Second Metric: Area-avg. error in 2m Tmax EFI



Avg. HW onset Z500 anomaly w. r. t. weather regime



→ In terms of Z500 ACC, predictability is highest for **European blocking**-type heatwaves (better than same-regime nonHW days), followed by **Scandinavian blocking;** **"no regime"** Z500 ACC score worst, also worse than on nonHW days

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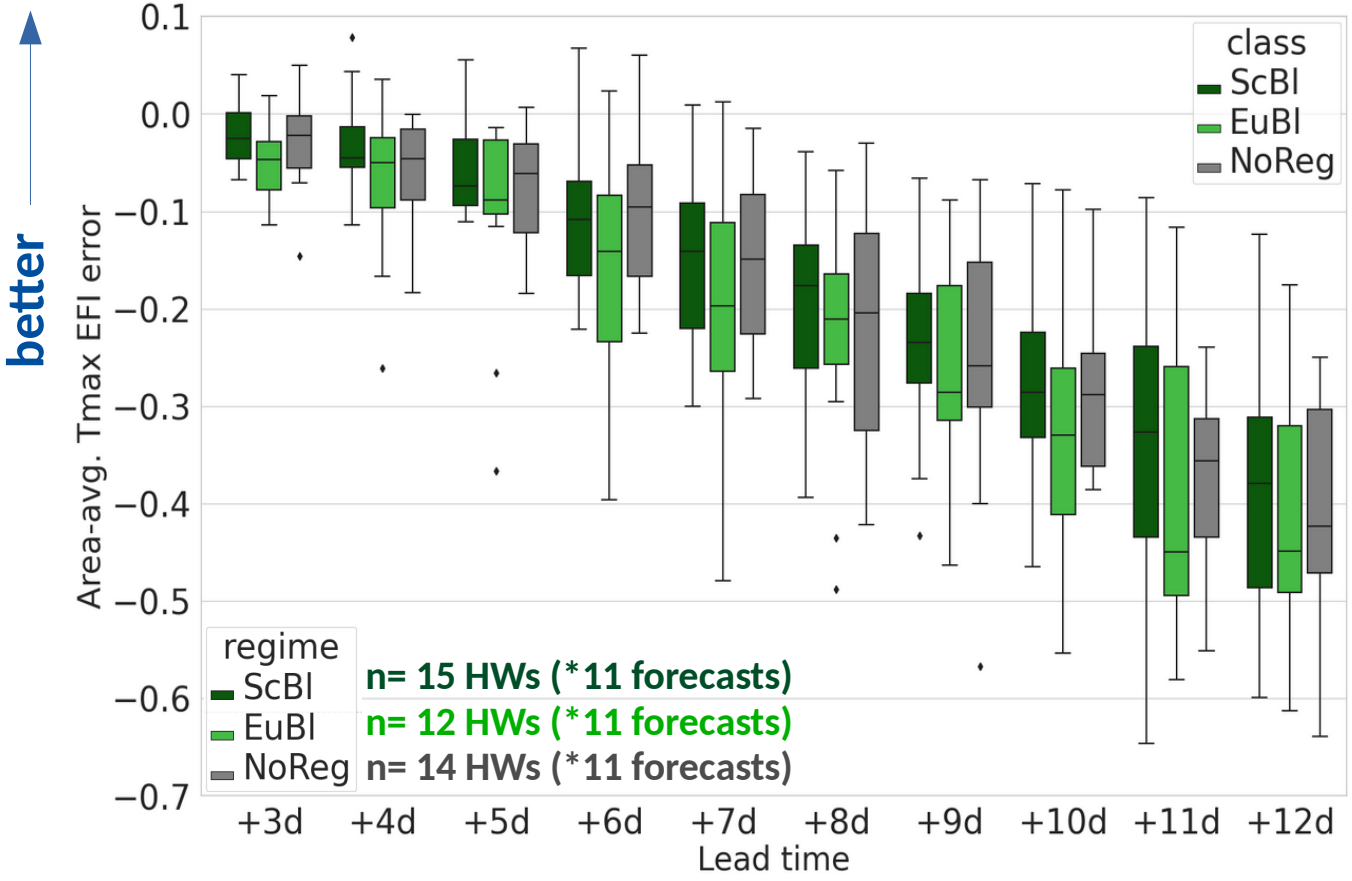

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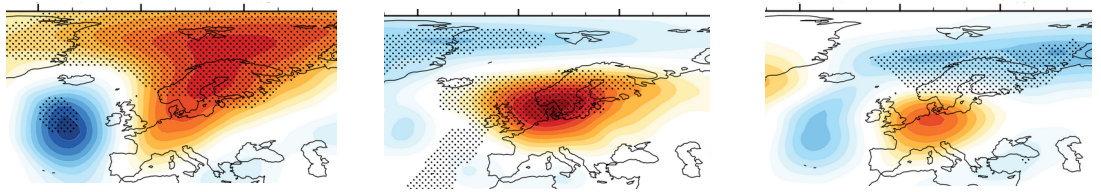

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→ Different picture for Tmax EFI metric

→ Hypothesis: Z500 ACC is probably more forgiving for a large-scale blocking less prone to phase errors → **"no regime"** punished

Results

2) What distinguishes well predicted from poorly predicted heat waves?

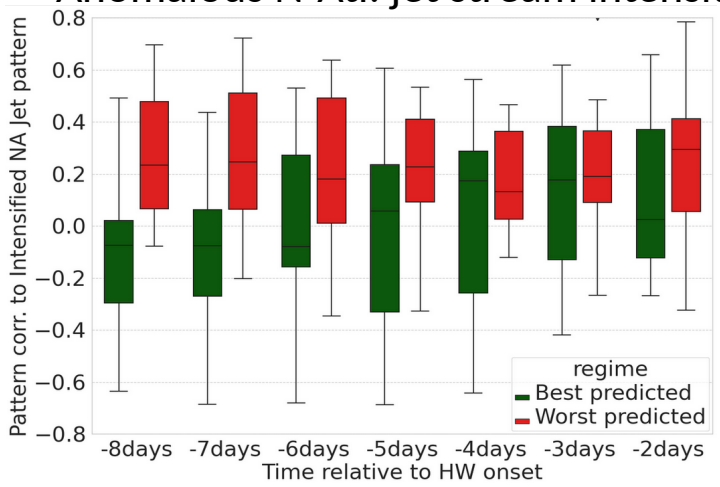
Method:

Compare best-predicted against worst-predicted heatwaves again according to the two metrics Z500 ACC and Tmax-EFI

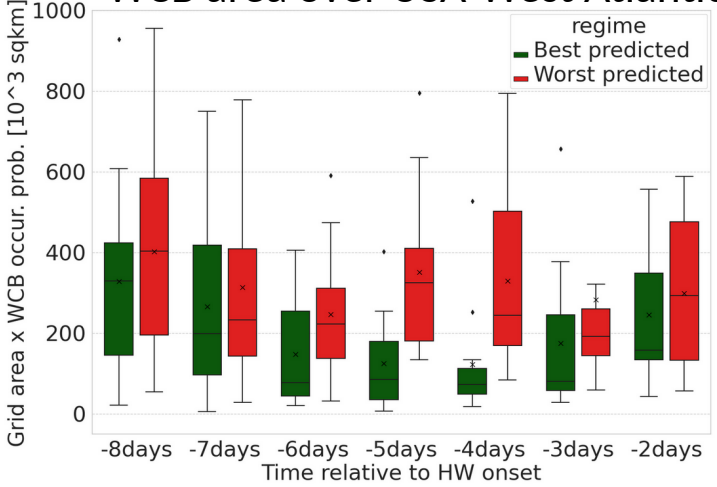
CE heatwave predictability depends on initial atmospheric state and the soils

Compare **analyzed states** some days **prior to 12 best-predicted HWs** and **12 worst-predicted HWs**

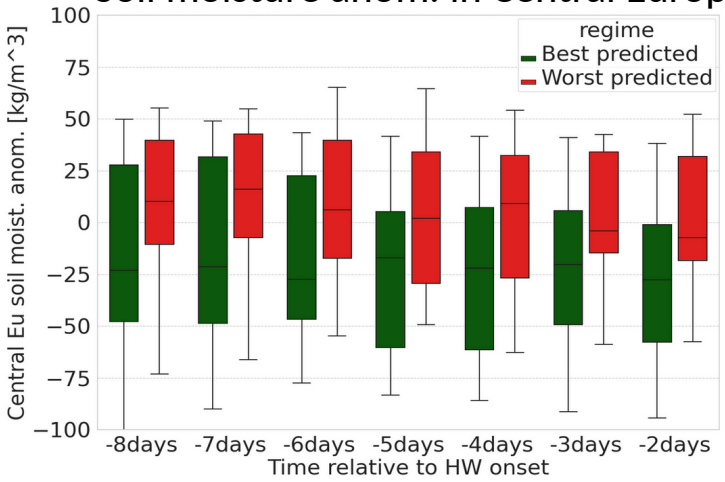
Anomalous N-Atl. jet stream intensity



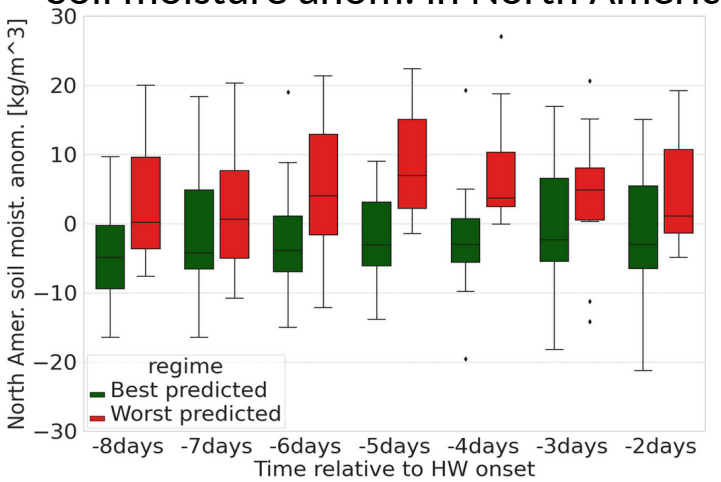
WCB area over USA-West Atlantic



Soil moisture anom. in Central Europe



Soil moisture anom. in North America



Selection metric: 500hPa geopotential ACC

Selection metric: 2m Tmax EFI

Dynamical precursors:

→ **Stronger than normal North Atlantic jet** stream and **enhanced warm conveyor belt (WCB) activity** over West Atlantic/ North America seem to **impair predictability of heatwave onsets in Central Europe** (w. r. t. Z500 ACC, “getting flow pattern right”)

Anomalous soil moisture:

→ **Predictability of HW onsets** seems to **correlate with pre-existing soil moisture anomalies** (both local and remote over NA)

CE heatwave predictability depends on initial atmospheric state and the soils

Compare **analyzed states** some days **prior to** **12 best-predicted HWs** and **12 worst-predicted HWs**

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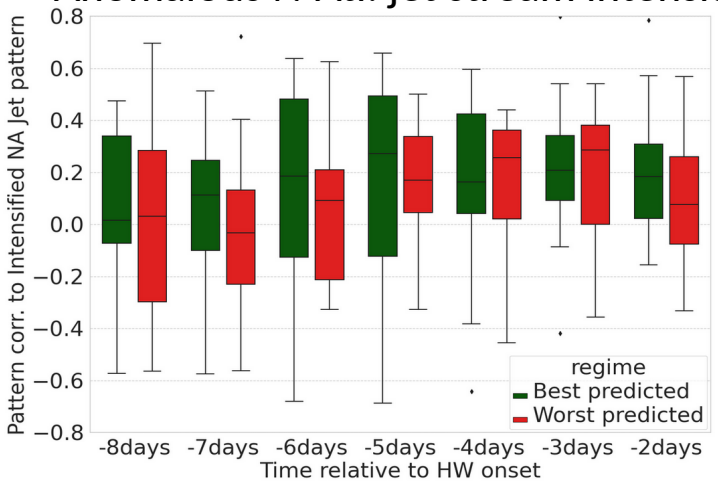

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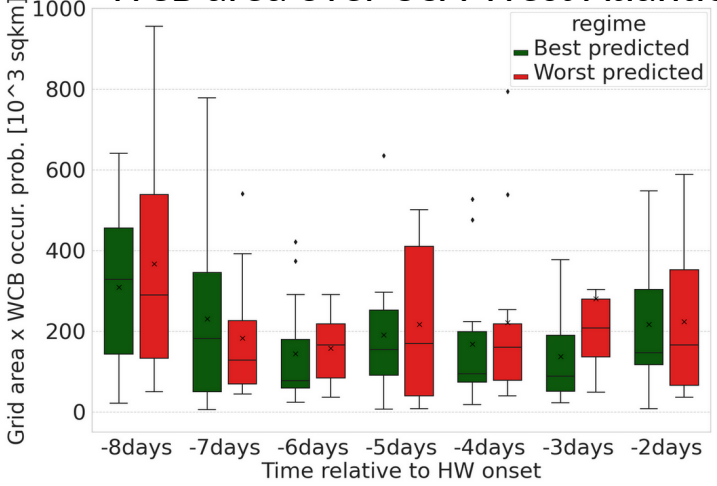
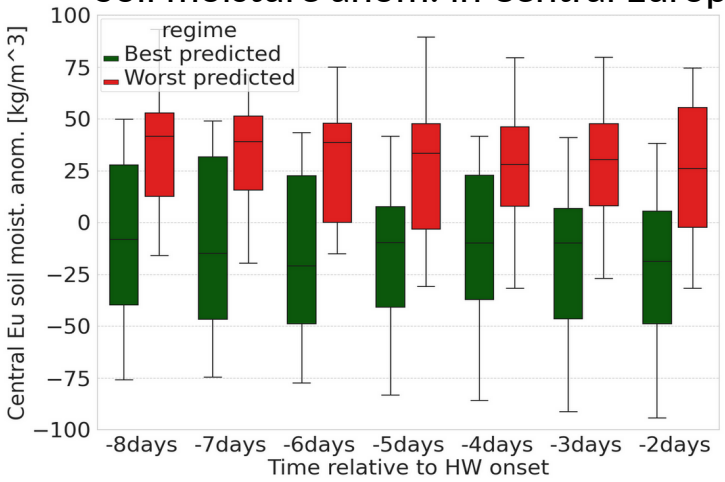


Soil moisture anom. in Central Europe



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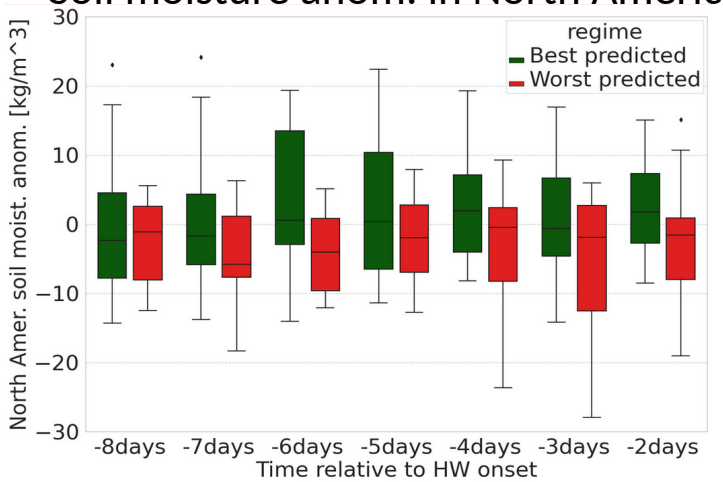

Selection metric: 500hPa geopotential ACC

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Dynamical precursors:

→ Same dynamical precursors affecting Z500 ACC no longer seem to play a role

Anomalous soil moisture:

→ **Important** for capturing the extreme-ness of **maximum temperature** is only the pre-existing **regional soil moisture anomaly** over Central Europe

Conclusions – medium-range predictability of European heatwaves

- While heatwaves in northwestern mid-latitude Europe are mainly associated with typical blocking regimes (as expected), Central Europe (CE) also frequently sees “no regime” heatwaves
- **When evaluating medium-range predictability of heatwaves, the target metric really matters!**
  - **Z500 ACC predictability**: For CE, European blocking-type heatwaves seem to have best medium-range practical predictability, whereas “no regime” heatwave feature lowest predictability
  - **Tmax-EFI predictability**: No clear signal, metric likely more soil moisture dependent
- **Understanding windows of forecast opportunity** by looking at the initial state of atmosphere/soils:
  - **Z500 ACC predictability**: Worst predictable CE HWs at medium-range show intensified jet over Atlantic one week prior and enhanced warm conveyor belt activity over the Western Atlantic ~5 days prior; soil moisture anomalies over North America may also play a role for downstream predictability
  - Both, **Z500 ACC predictability** and particularly **Tmax extremeness forecast** affected by pre-existing regional soil moisture anomalies over Central Europe

Thank you for your attention! *For questions and comments: alexander.lemburg@kit.edu*

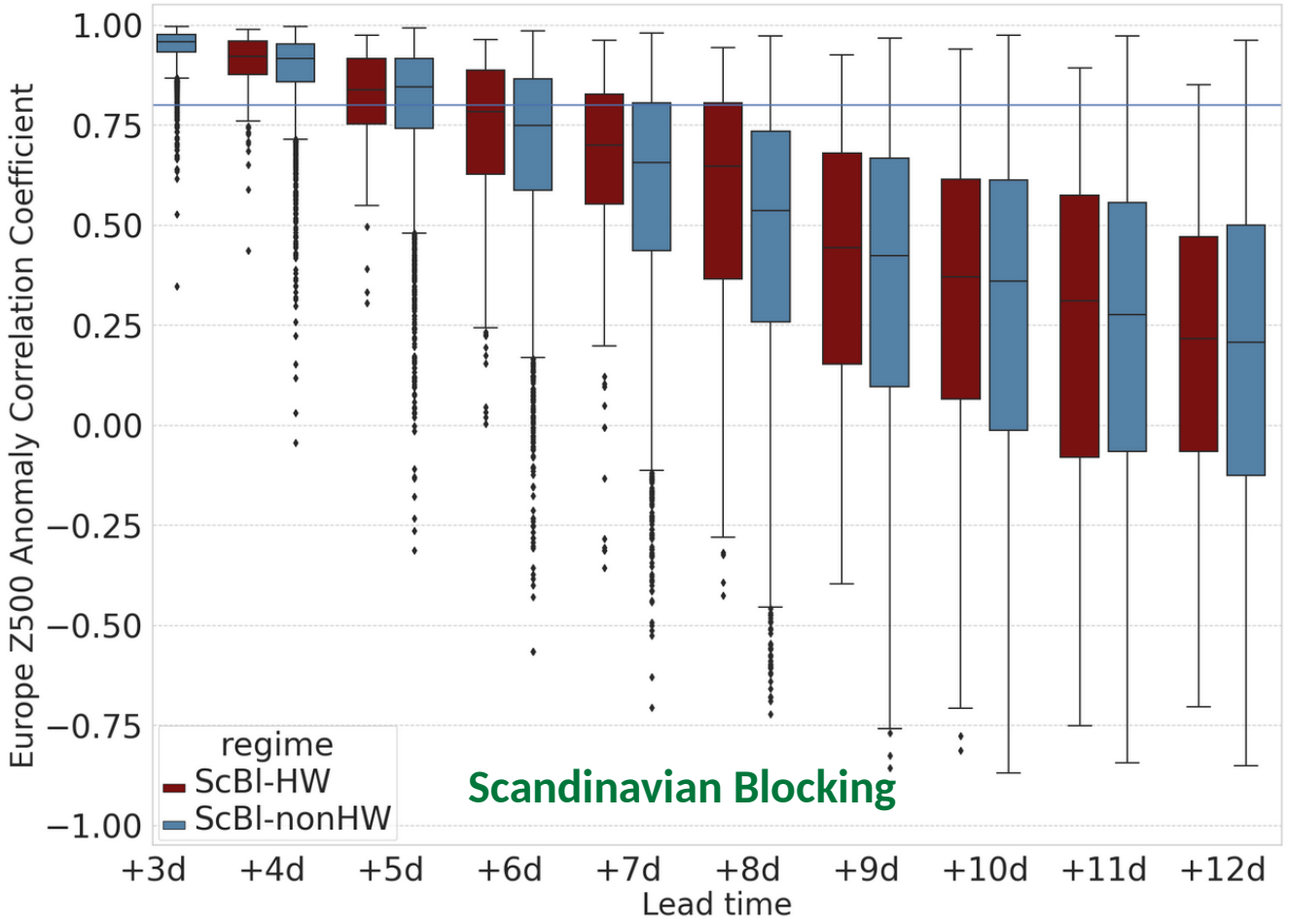
Additional Slides

Forecast skill for Central European heatwave onsets

– Comparison against all 2001-2018 nonHW days for the three dominant regimes individually –

Metric: 500hPa geopotential ACC (red: 49HWs, blue: all same-regime nonHW days)

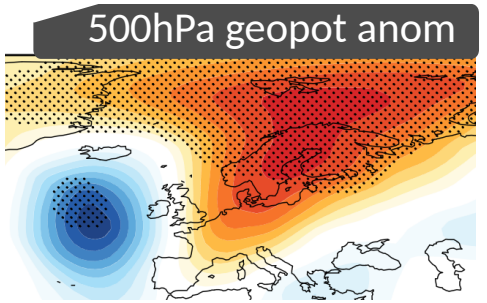
Based on 11-member **ECMWF-S2S Hindcasts** 2001-2018



Scandinavian blocking

European blocking

7 days earlier



→ Central European heatwaves associated with **Scandinavian blocking** show “normal” levels of predictability in terms of Z500 ACC

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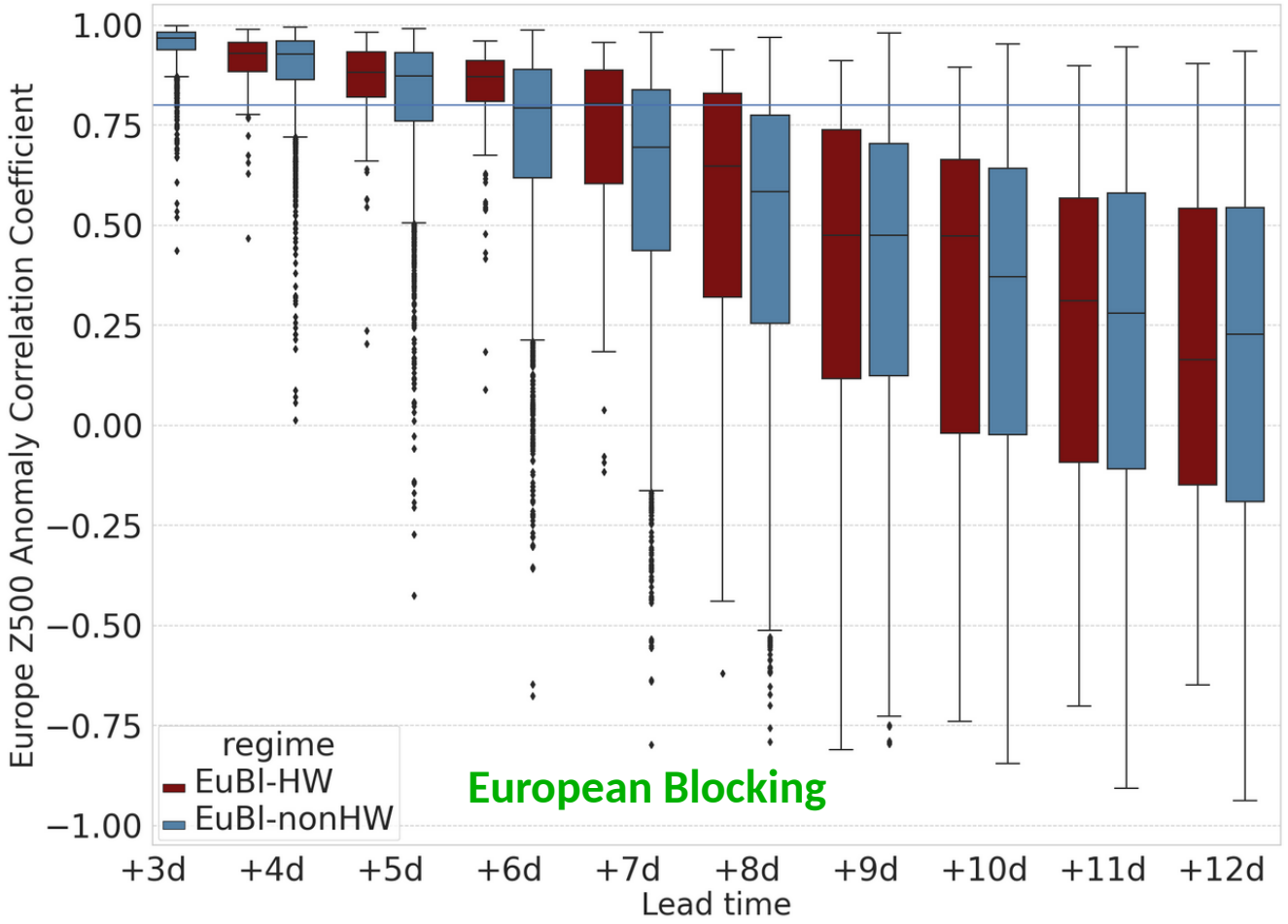

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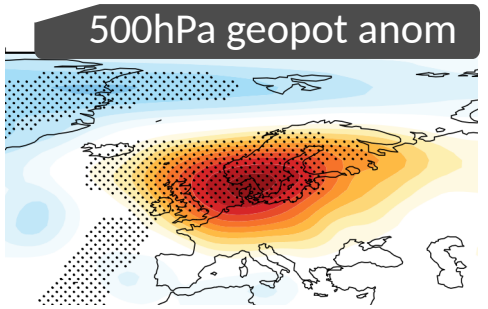

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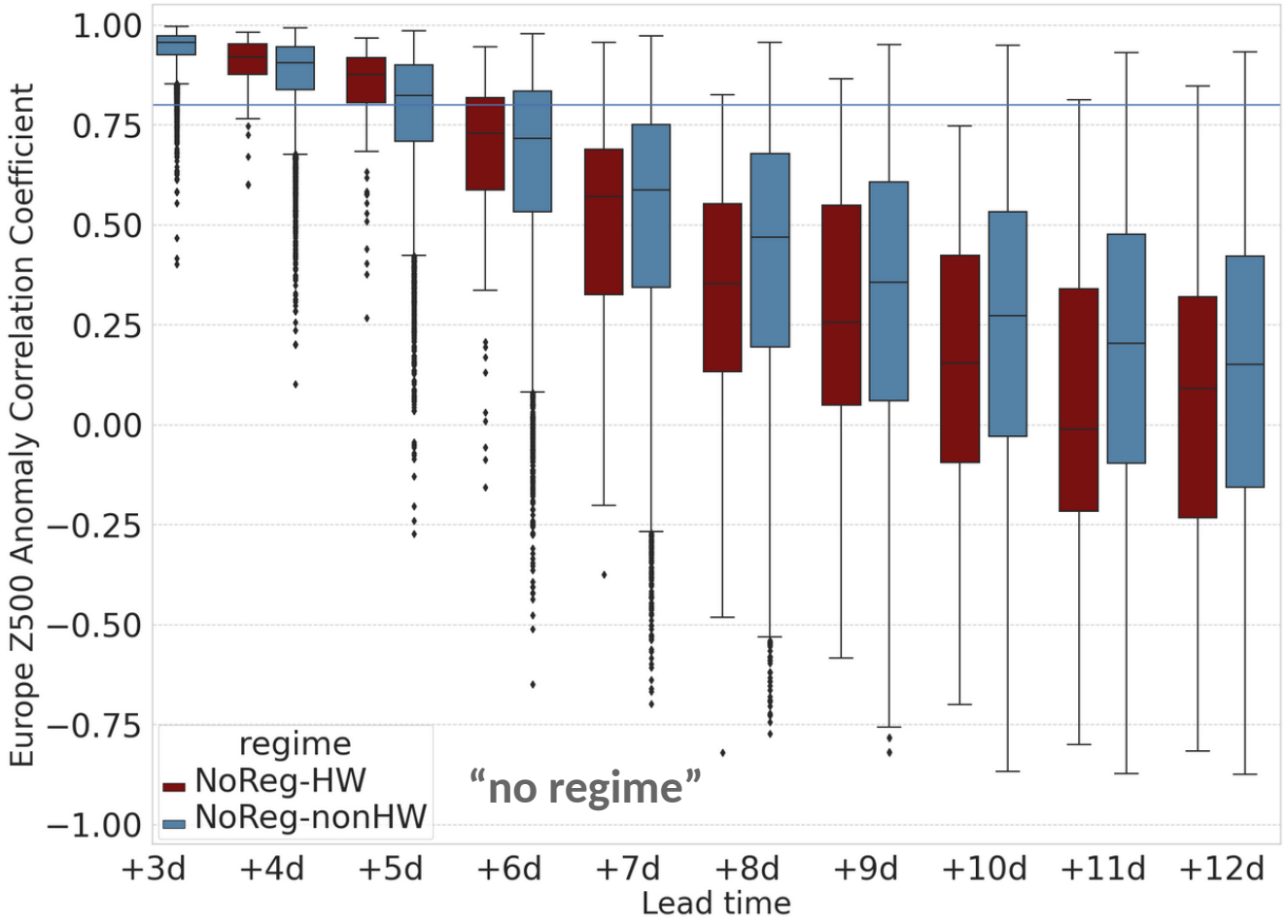

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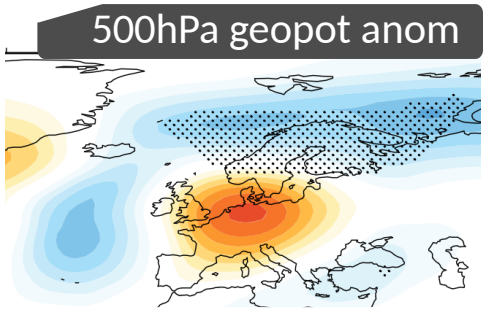

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→ **European blocking-type** HWs show slightly better predictability and less uncertainty up until lead times of 7 days (after that, normal predictability)

→ **No regime-type** HWs show worse predictability at medium-range compared to average summer time non-HW predictability of that regime

An important interim conclusion:

→ **It really makes a difference how we define predictability!**

- **Predictability in terms of the correct representation** of the large-scale circulation (**Z500 ACC**, focus of this talk)
- **Predictability in terms of capturing the likelihood of abnormal heat** (Tmax-EFI; a measure of how extreme the ensemble forecast's Tmax CDF is compared to climatology; more sensible to soil moisture)

12 **Best predicted heatwaves** according to **Z500 ACC:**
2006-07-17, **2004-08-05**, 2006-07-04, **2018-07-24**, 2003-05-04, **2018-07-30**, 2015-08-06, **2003-06-10**, **2007-06-07**, **2002-07-29**, 2008-05-08, 2018-05-07

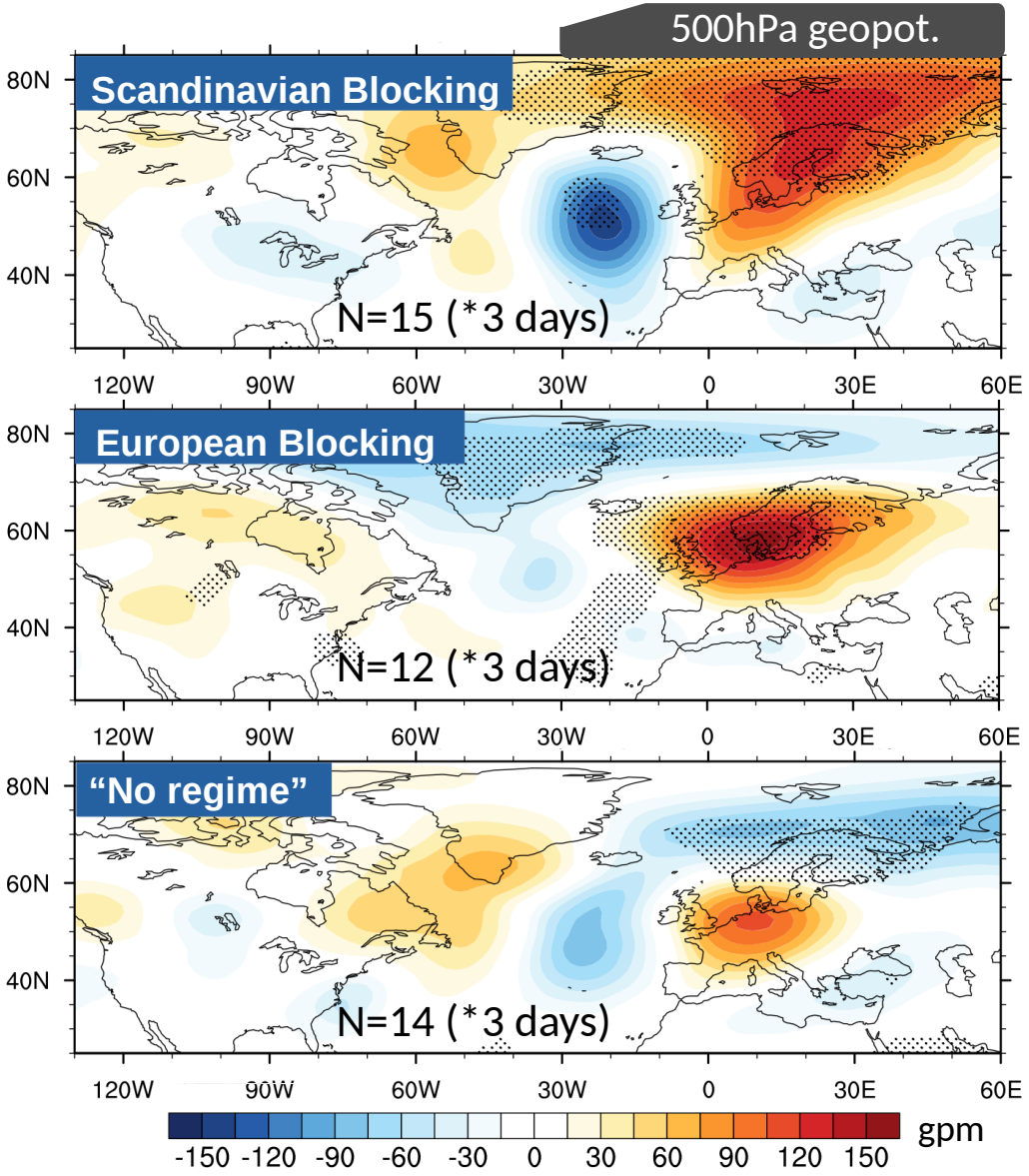
Best predicted heatwaves according to **Tmax-EFI:**
2018-07-30, 2003-08-02, **2018-07-24**, **2004-08-05**, **2015-08-28**, **2003-06-10**, 2016-05-07, 2004-06-08, **2002-07-29**, 2017-06-19, **2007-06-07**, **2003-05-30**

→ **Intersection is only 50%**

For **worst predicted** heatwaves, intersection of only 33%, there is even **cross group intersections** (best in Tmax-EFI, worst in Z500 ACC; right heatwave for the wrong dynamical reasons?)

Anomaly to summer-time climatology for the three dominant HW regimes

Stippling denote significant difference compared to all heatwaves



- **At HW onset**

→ Regionally dry soils already at onset – more large-scale for EuBL-type HW

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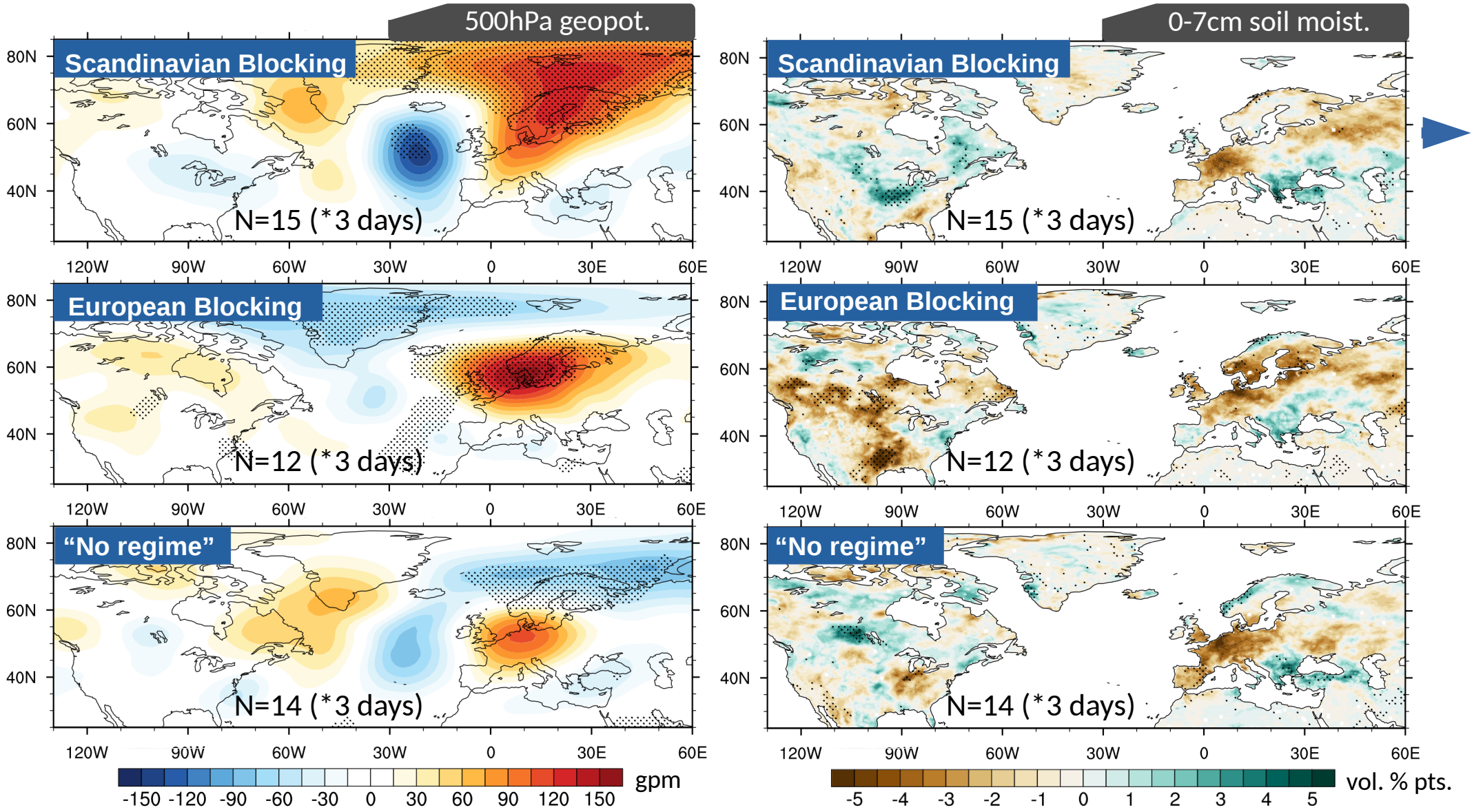

At HW onset

7 days earlier

→ Anomalously dry soils over North America before EuBL-type CE heatwaves

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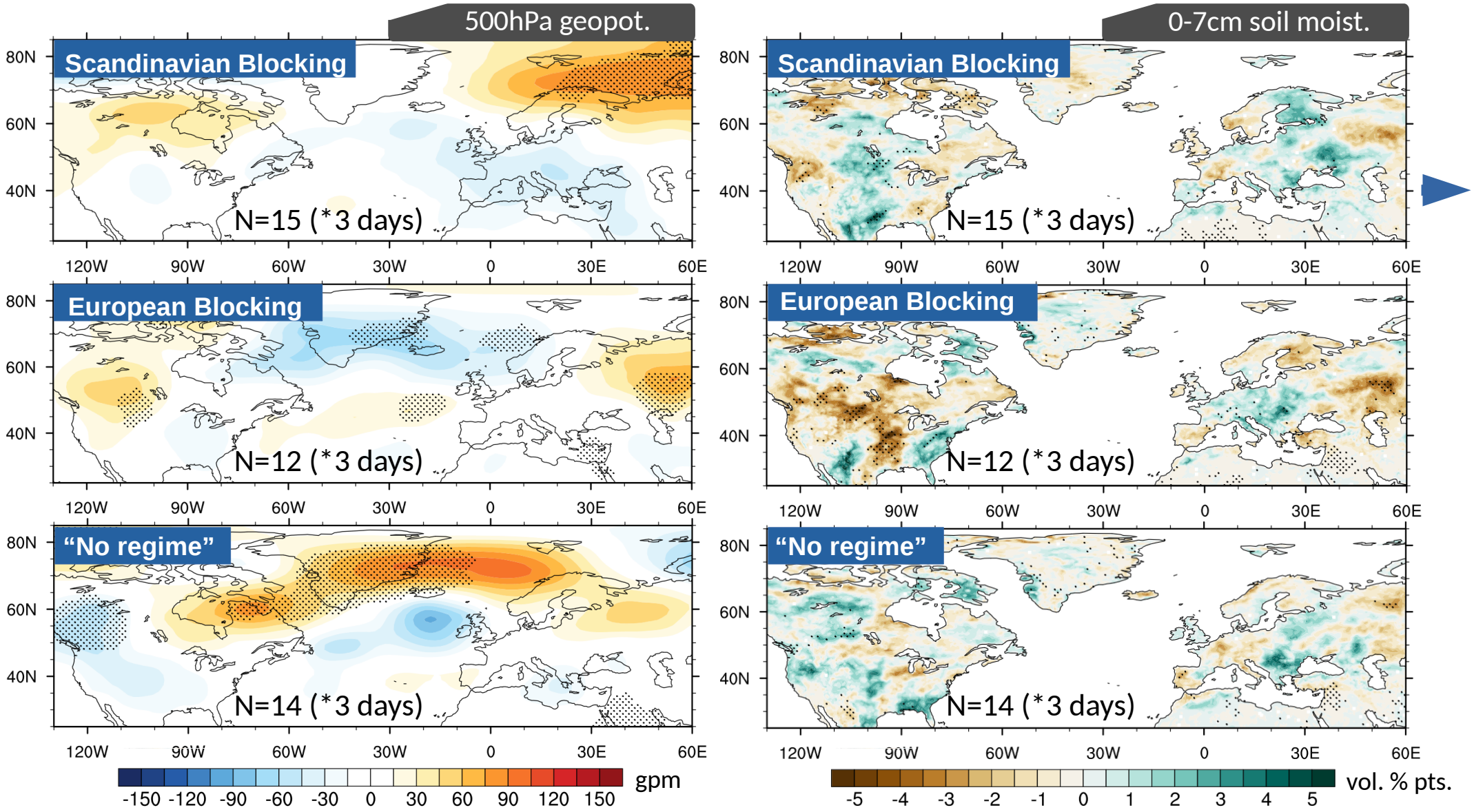

At HW onset

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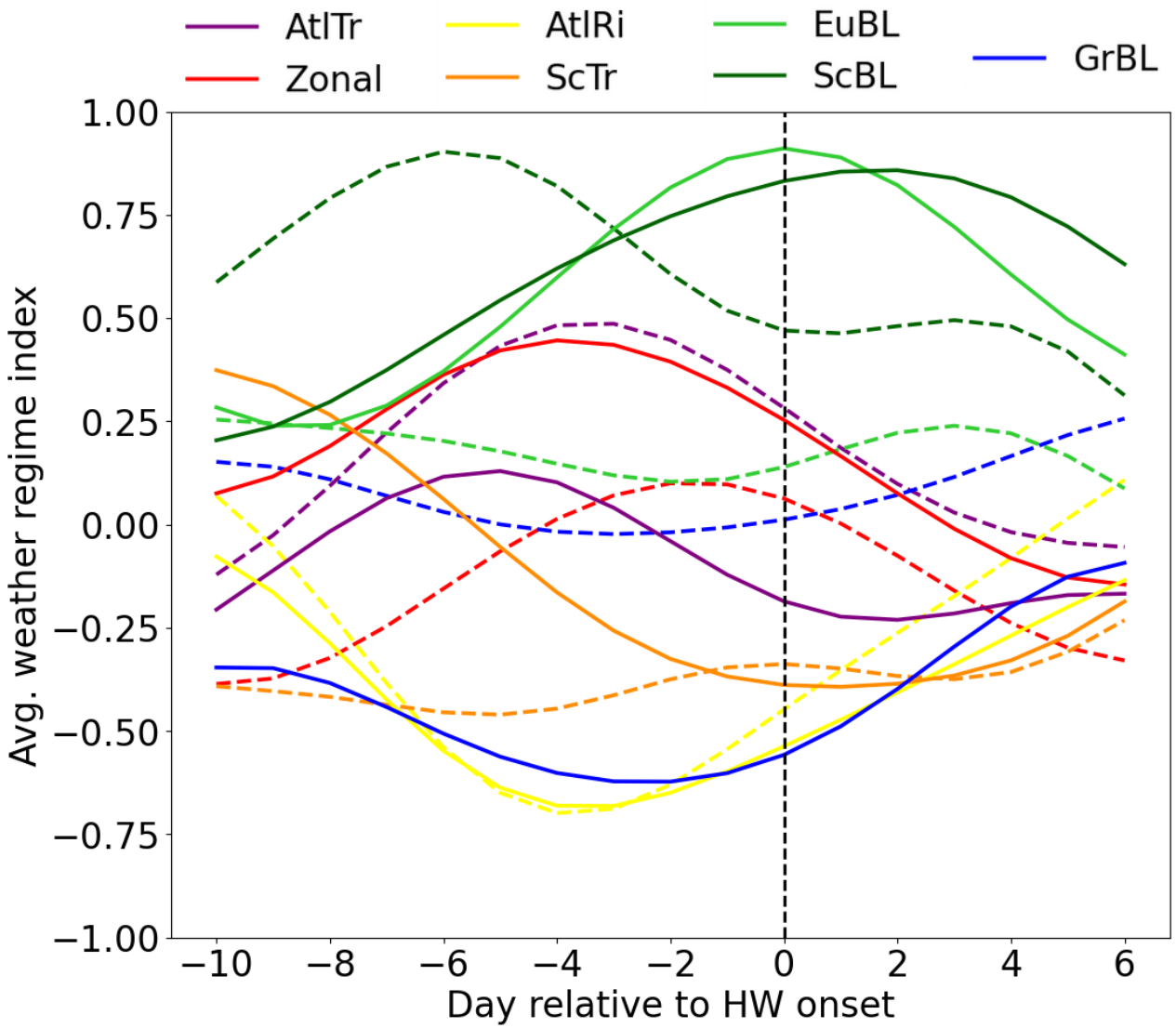
Analyzed weather regimes indexes averaged over best predicted HWs (solid) and worst predicted HWs (dashed) w.r.t. two different predictability measures



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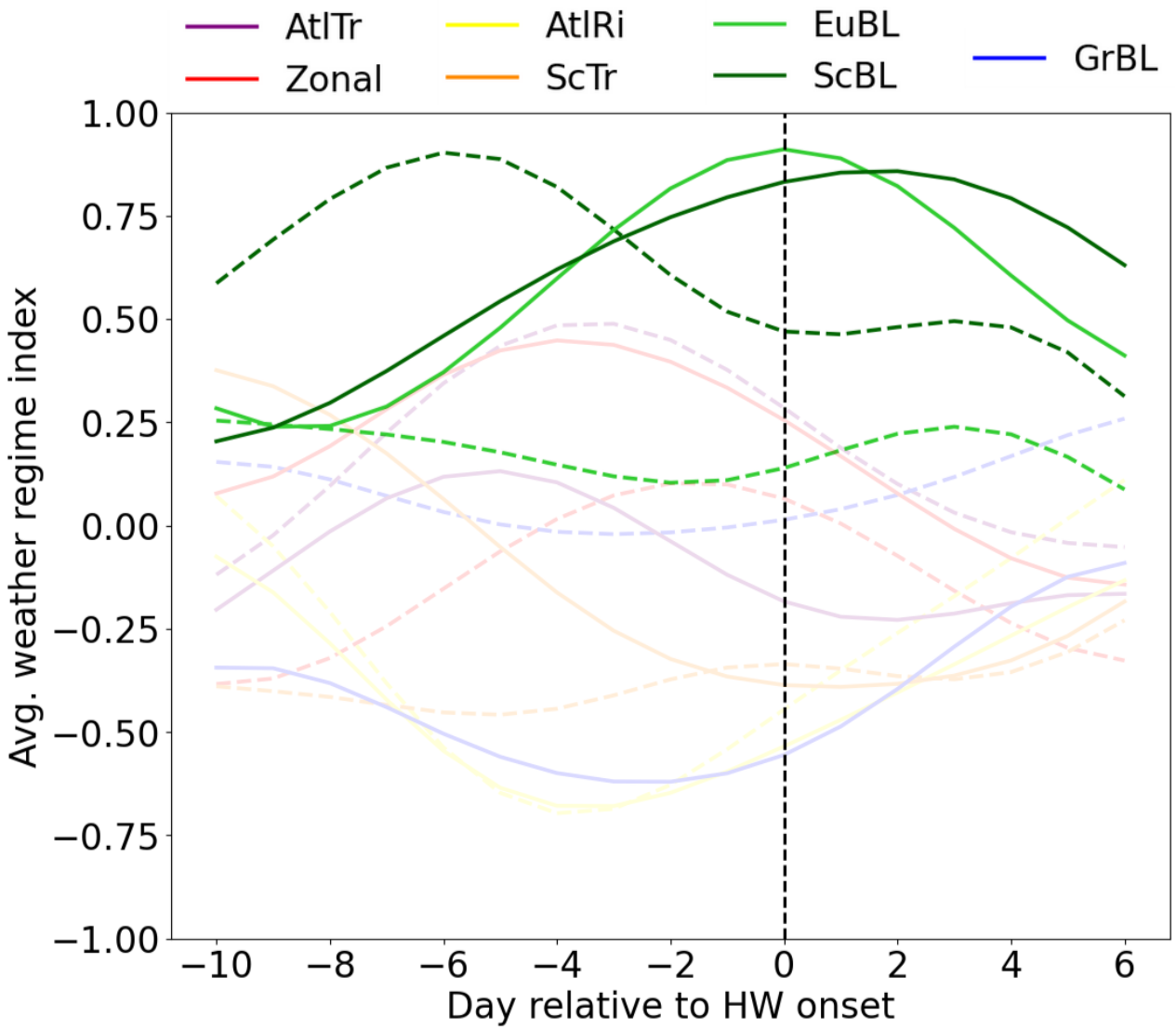

Selection metric: 500hPa geopotential ACC:

→ Better **predictable HW** onsets often show slow gradual increases in **classic blocking regime** magnitude some 5 days earlier

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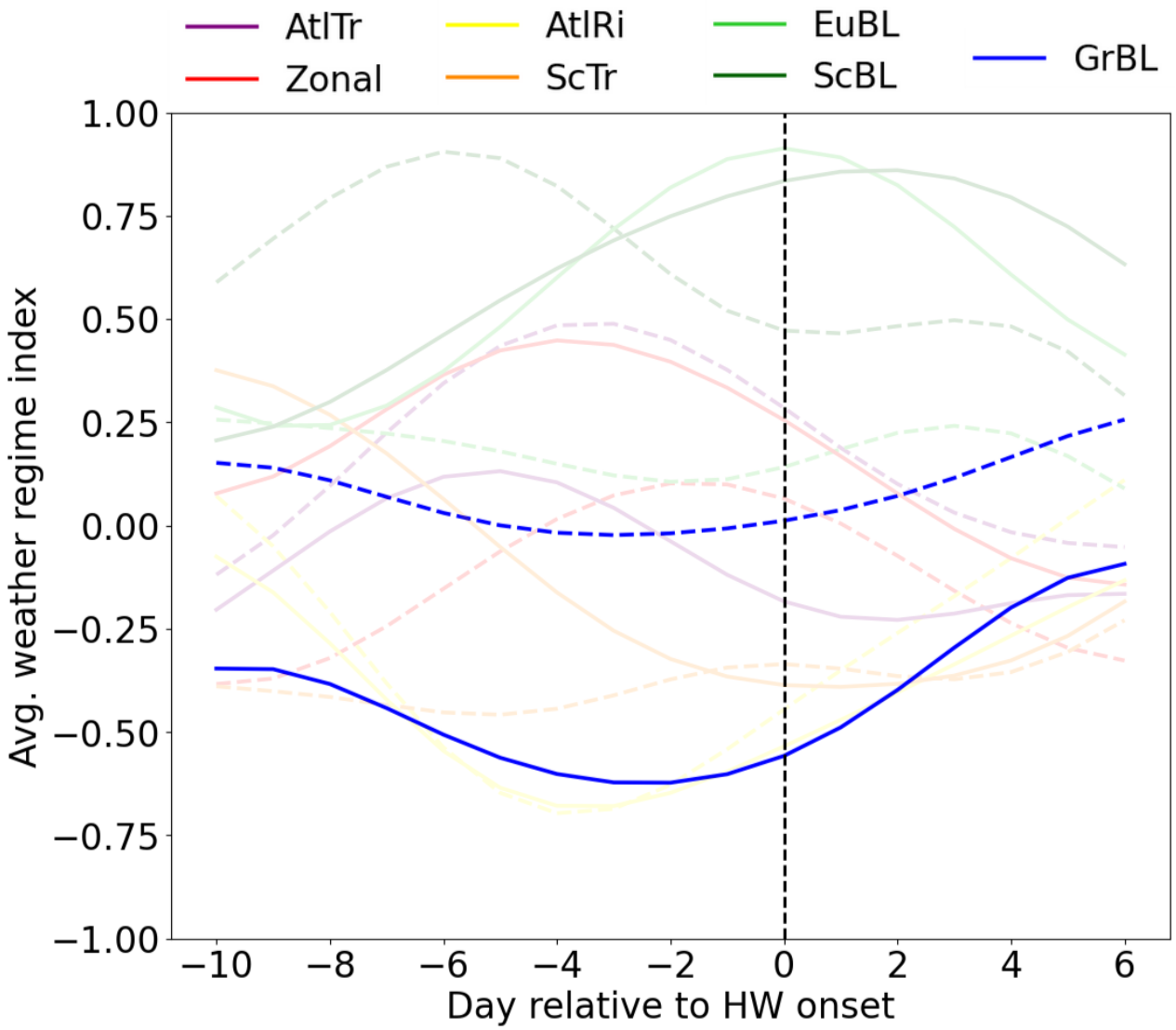

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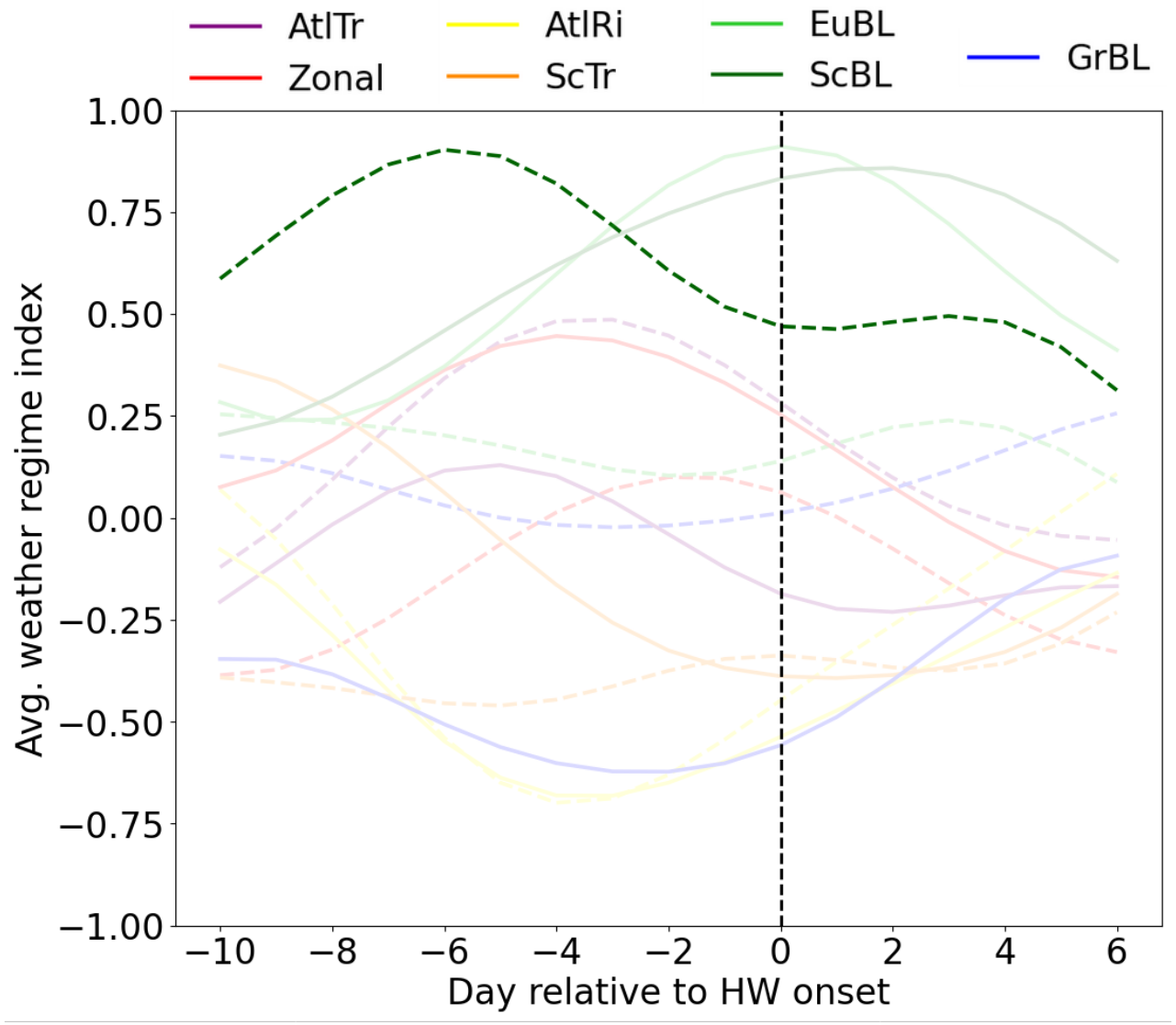

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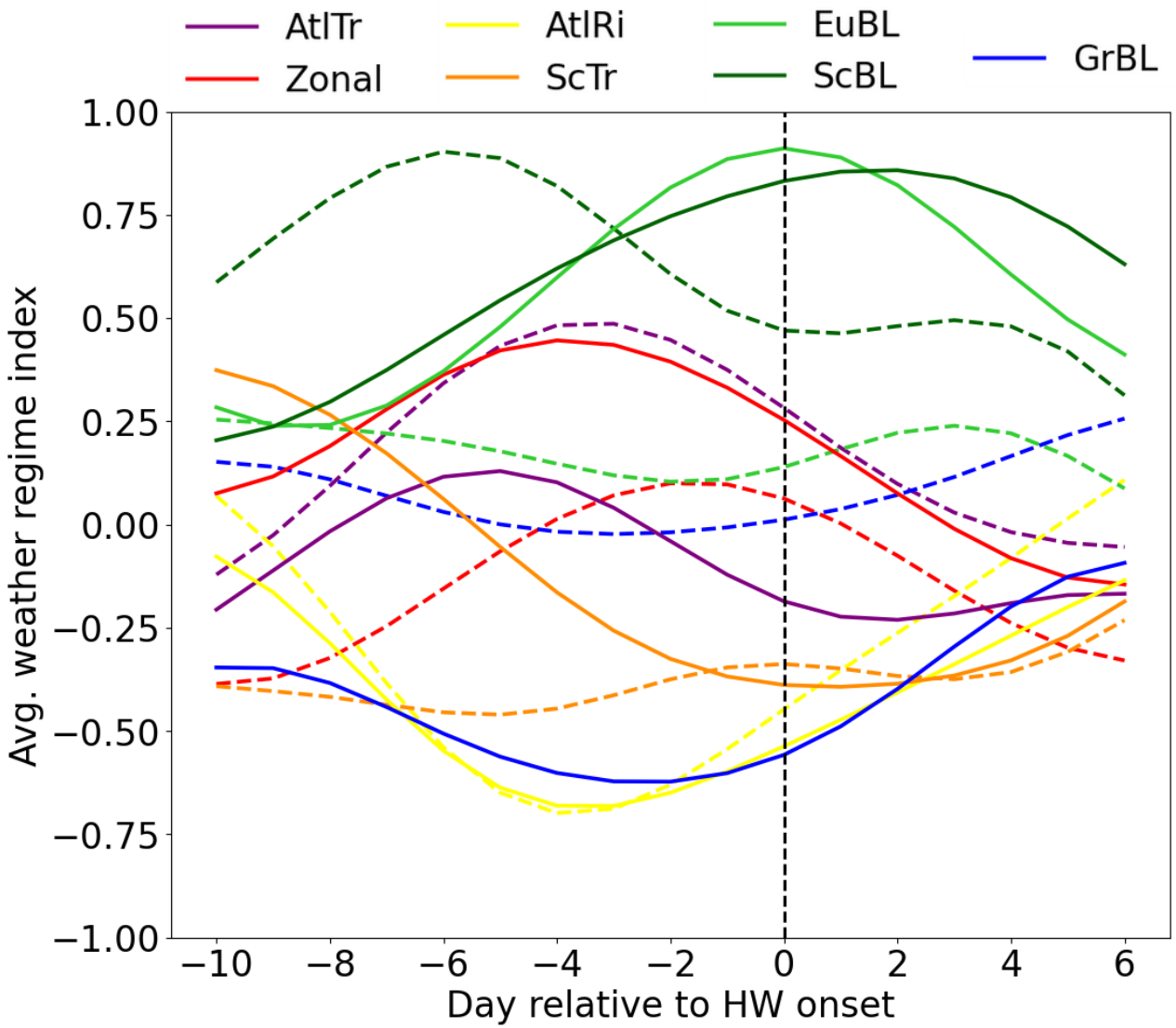

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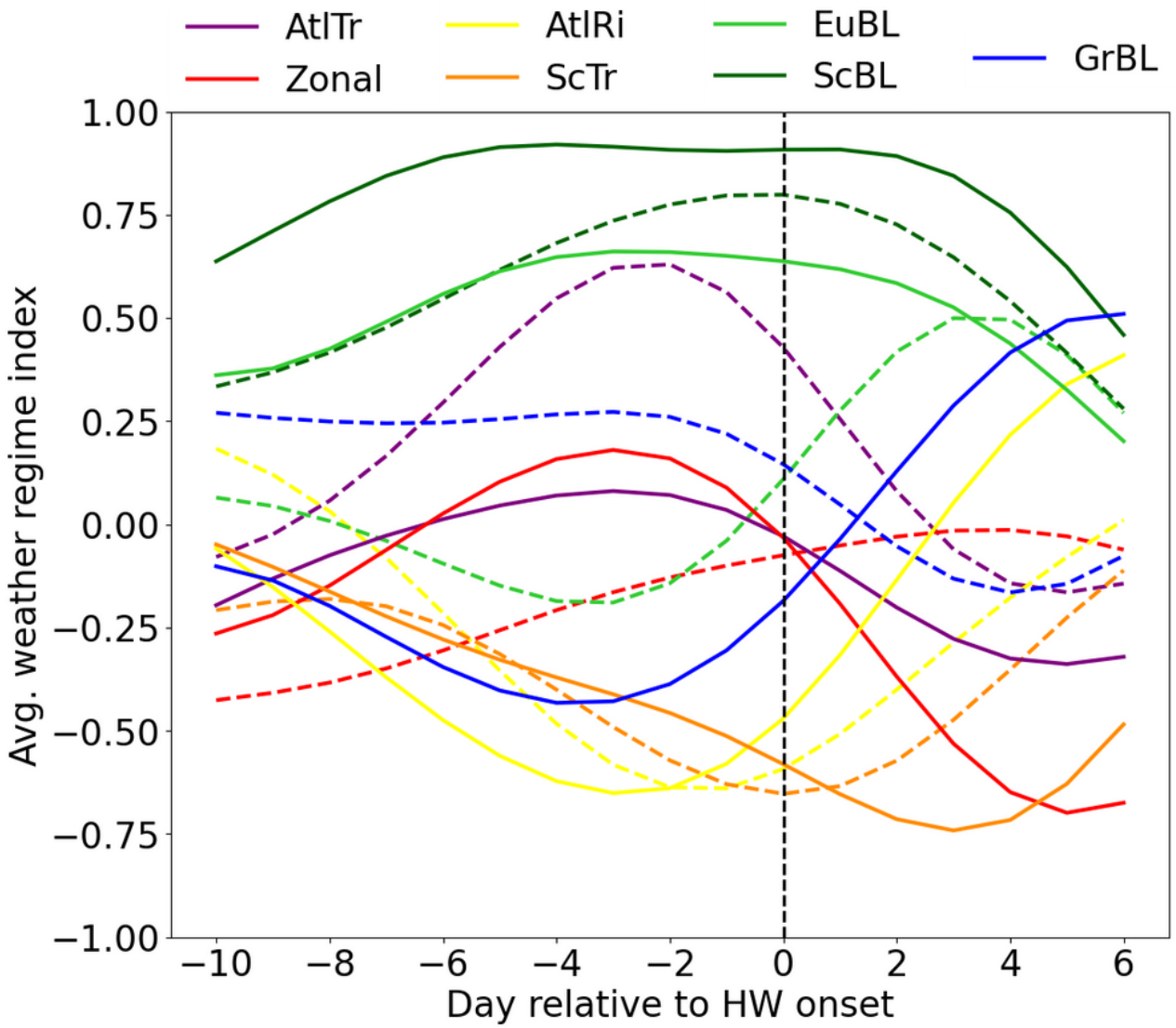

Changing the metric to distinguish between best and worst forecasts!

Selection metric: 2m Tmax EFI error

→ Biggest difference here to the Z500 ACC: Predictability in terms of Tmax-EFI is large when blocking regimes already exist for some 7-10 days

→ Likely related to soil moisture: When a blocking already exists, soils might be drier than normal, increasing the likelihood of extreme temperatures in the ensemble forecast

Again – An important interim conclusion:

→ **It really makes a difference how we define predictability of heatwaves!**