Identifying causes of short-range forecast errors in maximum temperature during recent Central European heat waves using the ECMWF-IFS ensemble

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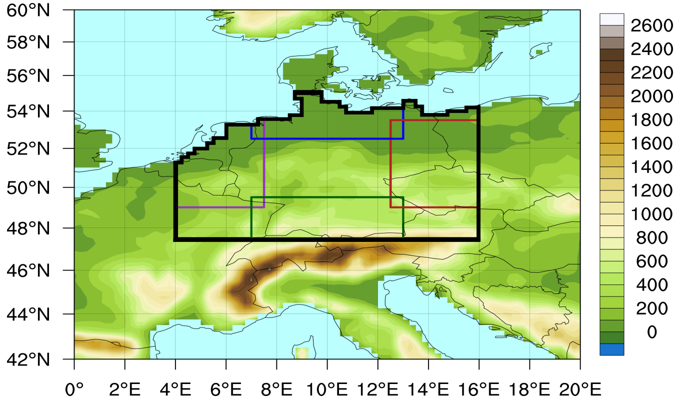
Predictability of Central European heat waves

- Many studies focus on predictability of extreme heat on synoptic to subseasonal time scales (say 5 – 30 days)
- However, also short-range **3-day forecasts** of maximum temperature (**Tmax**) can exhibit substantial errors even on somewhat large spatial scales (whole Central Europe)



Region of interest:
Central Europe (CE)
(4-16°E, 47.5-55°N)

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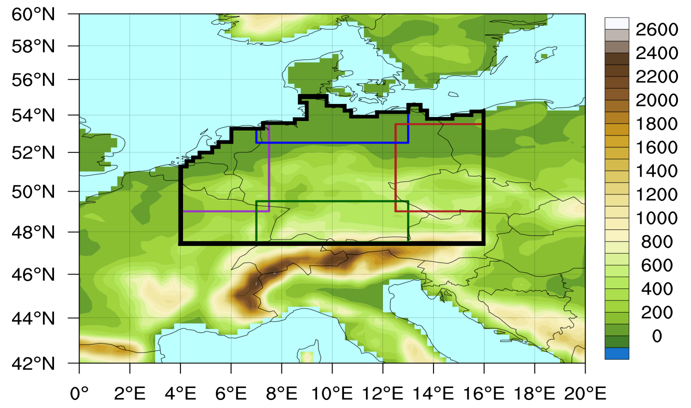
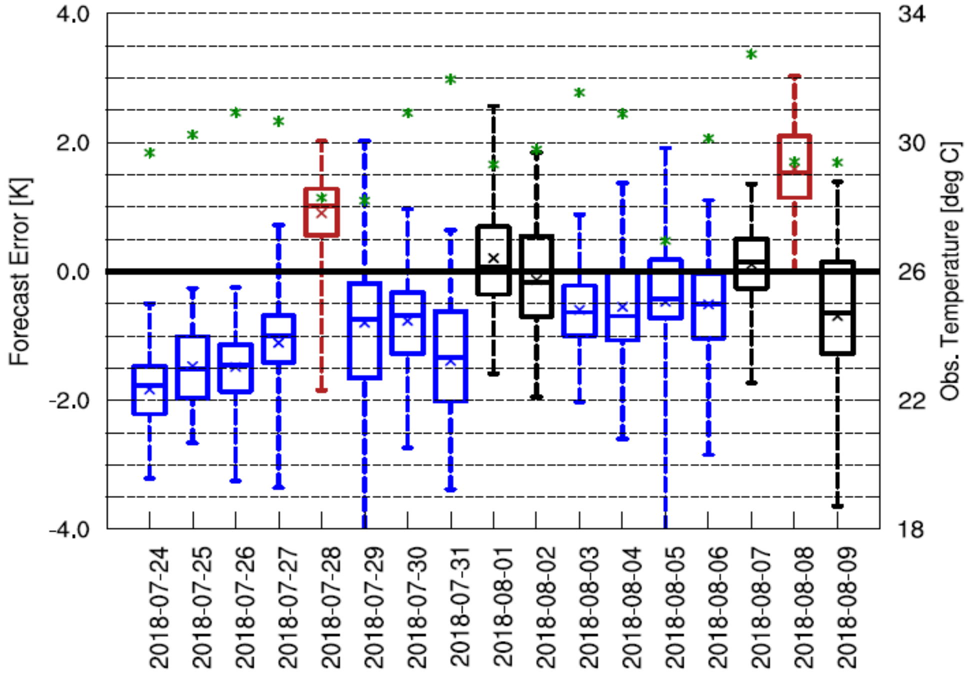


Region of interest: Central Europe (CE) (4-16°E, 47.5-55°N)

- Example: extreme European heat wave 2018 (24th July - 9th August)

3-day ECMWF ensemble **forecast error** for **maximum 2m temperature (Tmax)** averaged over the Central Europe domain (only over land)



against ERA-5 “observations”

Research questions:

1) **What are the main physical processes causing short-range Tmax forecast errors and are there differences between regular summer days and heatwaves? (this talk)**

2) Does the history of the air mass (origin, diabatic heating) play a role for forecast quality?

- A mix of **Eulerian and Lagrangian** perspective in this study
- We assume that **errors in the large-scale synoptic flow** play **no substantial role** on the 3-day forecast scale

Data

- Investigated time period: **Summer months (JJA) 2015-2020**
- **ECMWF-IFS 3-day ensemble forecasts** (**50 members**) are evaluated against the respective forecast days' 0-18h control forecast, here called ***quasi-analysis*** (not against ERA-5 due to reasons of consistency and disregarding a general Tmax bias)
- **Split** the data **into heatwave (marked red)** and **non-heatwave days**:
  - Heatwaves diagnosed similarly to *Russo et al. 2015*

  → In at least 10% of the area, Tmax has to surpass the local 90% percentile for at least 3 days

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Methods

- **Eulerian:** Grid point-wise application of a **multi-variate linear regression model** (MLRM)

  1) First construct forecast error fields of Tmax and other variables of interest – for each day and ensemble member individually (against the ECMWF-IFS control “quasi-analysis”)

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  1) First construct forecast error fields of Tmax and other variables of interest – for each day and ensemble member individually (against the ECMWF-IFS control "quasi-analysis")
  2) Use Tmax forecast error as a predictand and forecast errors of multiple other quantities as predictors within a MLRM (done so in *R*)
  3) Within the "relaimpo" package in *R,* the so-called "relative importance" of individual predictors (how much of r^2 of the MLRM is due to the inclusion of this predictor) is found via the so-called lmg metric

RQ1: Quantification of Tmax error sources

First Slide:
Results of the MLRM for non-heatwave days

Second slide:
Results of the MLRM for only heatwave days

WAVES TO WEATHER

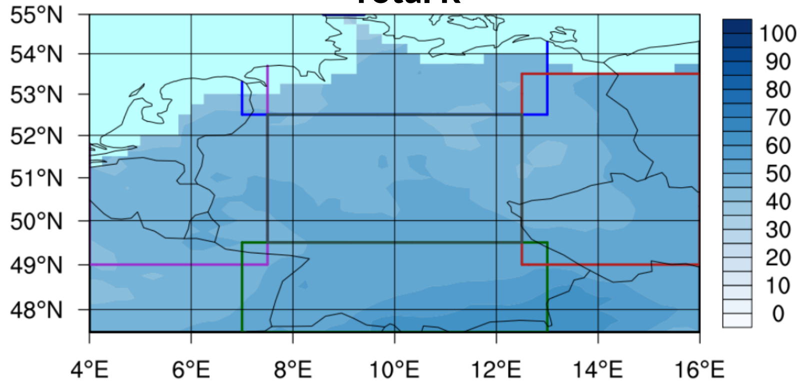
Regular summer days:

Errors in downward SW radiation dominant error source.

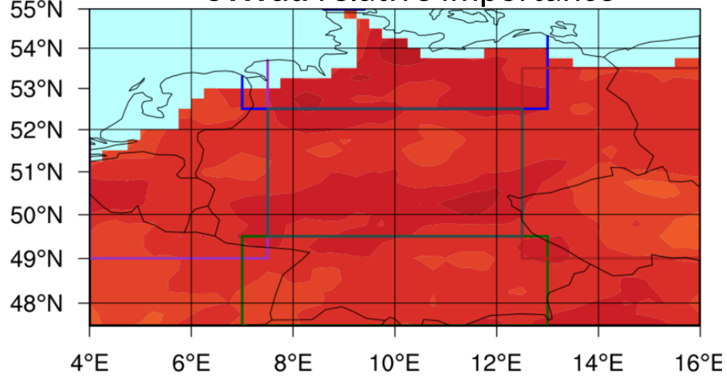
R^2 total and relative importance of multiple predictor variables for “explaining” Tmax forecast errors in a multi-variate linear model

non-heatwave days 2015-2020 all 50 ensemble members included

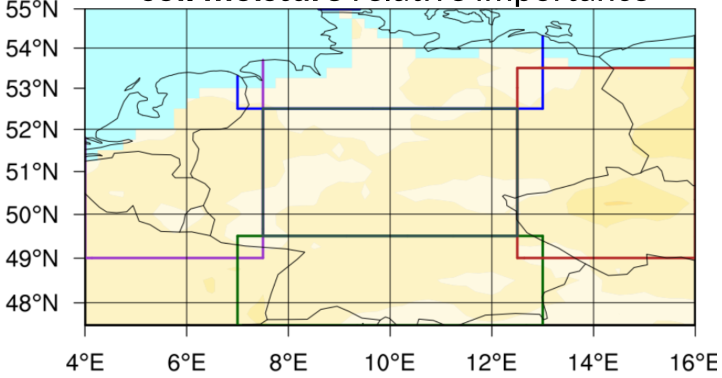
Total R^2



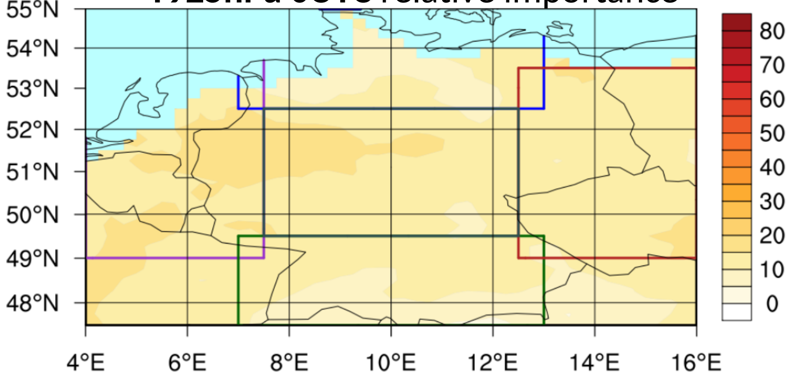
SWrad relative importance



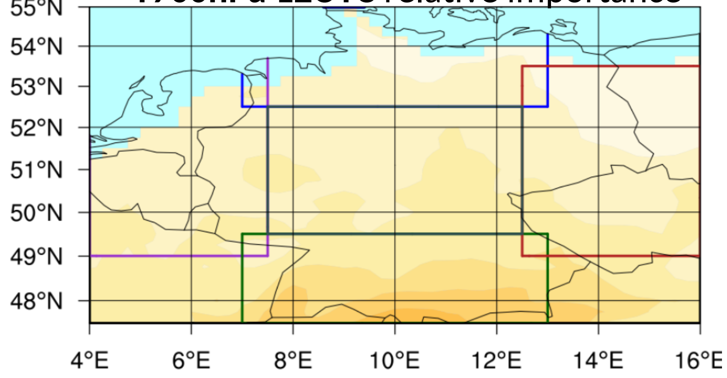
soil moisture relative importance



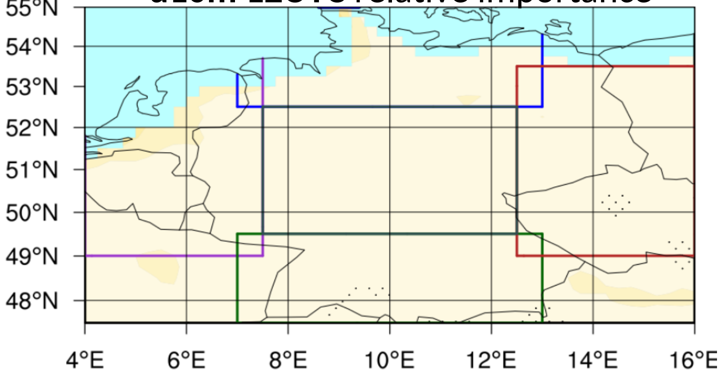
T925hPa 0UTC relative importance



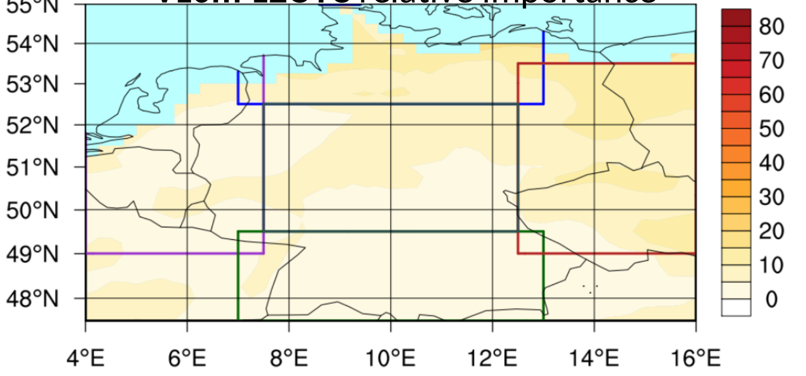
T700hPa 12UTC relative importance



u10m 12UTC relative importance

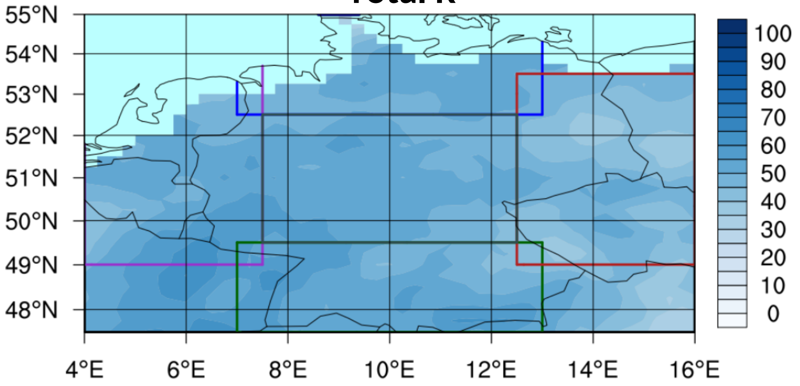


v10m 12UTC relative importance



Heatwaves only:
Other error sources gain importance and dominate regionally.

Total R^2



R^2 total and relative importance of multiple predictor variables for "explaining" Tmax forecast errors in a multi-variate linear model

only heatwave days 2015-2020 all 50 ensemble members included

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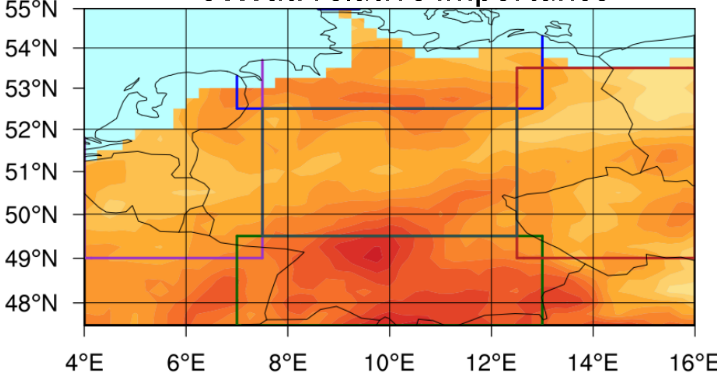

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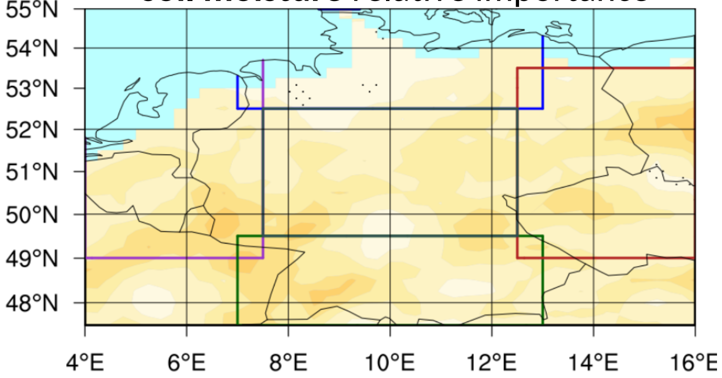

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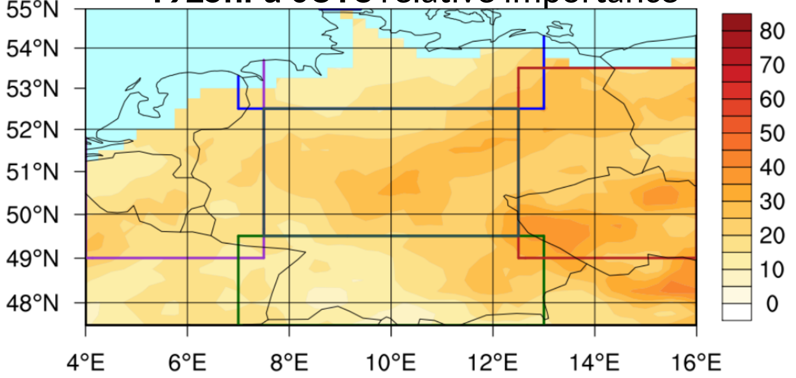

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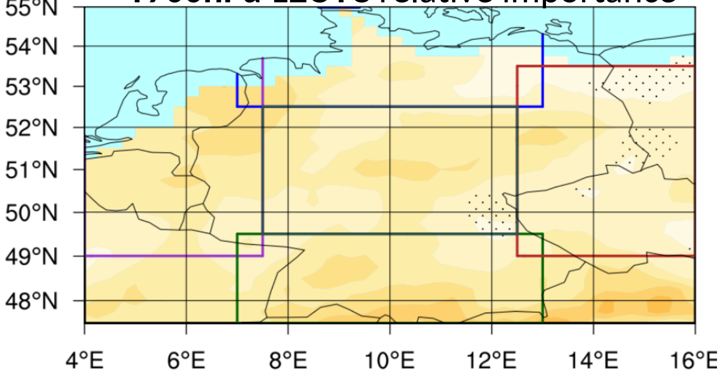

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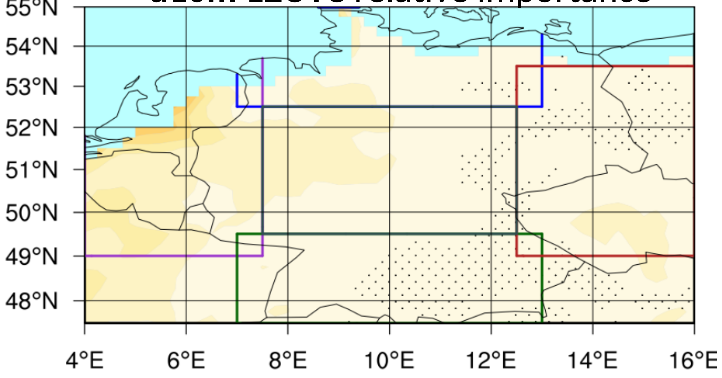

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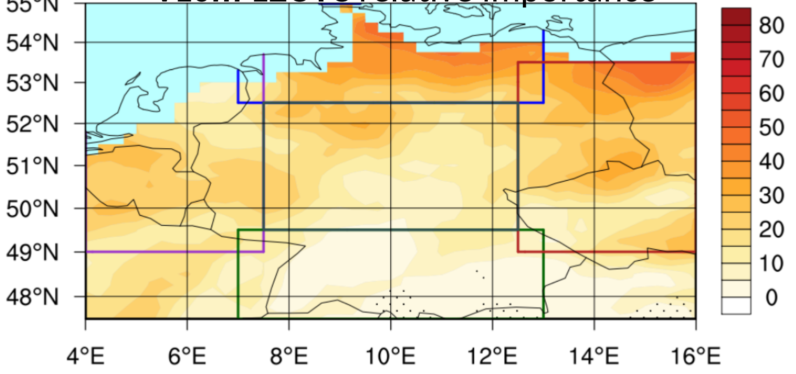

Conclusions – Combining Eulerian and Lagrangian points of view:

- In Central Europe, summer **Tmax forecast errors at three days lead time** are **dominated by short-wave radiation errors** mainly due to forecast errors in low-level cloudiness, **particularly outside of heat waves**

- **Within heat waves**, errors in short-wave radiation are only dominant in an area-integrated view, but **regionally other error sources may become equally important** for **Tmax** forecast quality:
  - the error in the nocturnal residual layer temperature is most or second most important in many regions
  - soil moisture errors generally (surprisingly) little important overall
  - near the coasts, near-surface wind errors dominate

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- Main finding from Lagrangian extension of study by means of trajectory analysis:
Particularly during heat waves, **errors in diabatic heating of PBL** air may accumulate over the span of 72 hours which is associated with the **travel history of air masses**, particularly **residence time over land**

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Revised article in "Weather and Forecasting" currently under review:
Lemburg and Fink (2022). "Identifying causes of short-range forecast errors in maximum temperature during recent Central European heatwaves using the ECMWF-IFS ensemble."

Additional Slides

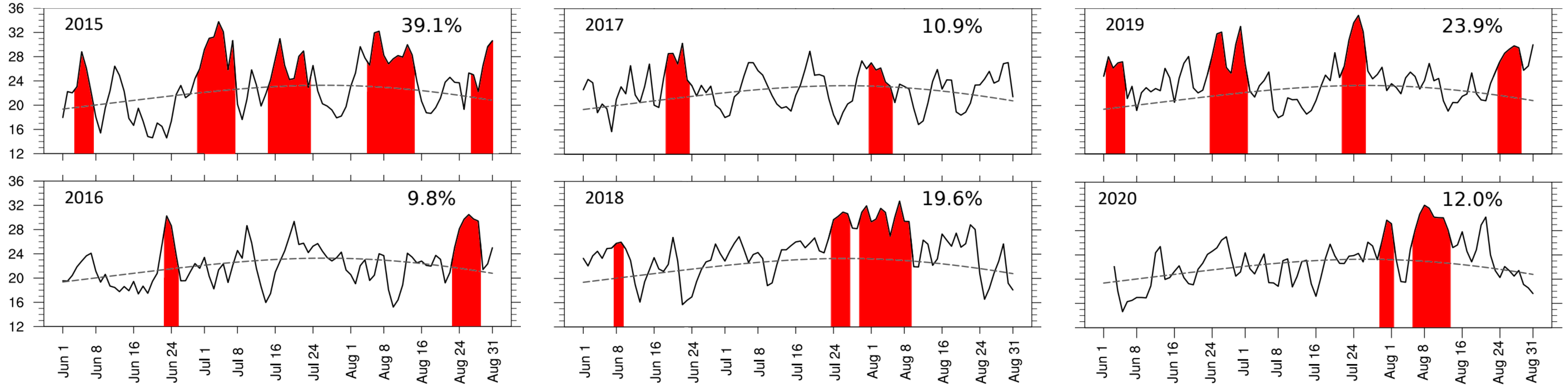
Data

- Investigated time period: **Summer months (JJA) 2015-2020**
- **ECMWF-IFS 3-day ensemble forecasts** (50 members) are **evaluated against** the respective forecast days' 0-18h control forecast, here called ***quasi-analysis*** (not against ERA-5 due to reasons of consistency and disregarding a general Tmax bias)
- Variables of interest: mainly near-surface or boundary-layer related thermodynamic quantities, downward short-wave radiation, soil moisture and near-surface wind

- **Split** the data **into heatwave (marked red)** and **non-heatwave days**:
  - **Heat wave days** are diagnosed percentile-based similarly to *Russo et al. 2015*

  → In at least **10%** of the area, **Tmax** has to surpass the local **90% percentile** for at least **3 days**

Overview of Central Europe area-averaged Tmax of summers 2015-2020 (dashed line 30yr climatology)



“Eulerian Conclusions“ so far:

RQ1: What are the main physical processes causing short-range Tmax forecast errors and are there differences between regular summer days and heatwaves?

- Outside of heat waves, errors in short-wave radiation can be identified as clearly dominant Tmax error sources for all grid points in the whole Central European domain (mainly due to errors in low cloud cover)
- Within heat waves, errors in short-wave radiation are only dominant in an area-integrated view, but regionally other error sources may become equally important for Tmax forecast quality:
  - the error in the nocturnal residual layer temperature is most or second most important in many regions
  - soil moisture errors generally (surprisingly) little important overall
  - near the coasts, near-surface wind errors dominate

What we also find (not shown explicitly):

- ECMWF-IFS shows a slight cold bias in heat waves over Central Europe (-0.4K) which is more pronounced on clear-sky days (-0.6K) and low wind speed days (-0.8K)
- These biases related to situations with clear skies and little synoptic forcing also show outside of heat waves, but much less pronounced

A Lagrangian extension of the study

- The purely Eulerian view has a drawback:
  By associating errors in Tmax forecast with errors in other quantities grid point-wise,
  you presuppose a purely local relationship and no memory at all

- Without any large errors in large-scale circulation, and in presence of some advection, the transport of an air mass to the region of interest may have been modeled correctly, but the air mass might have been subject to different diabatic heating depending on the local conditions in a remote area some hours prior

→ Does the history of the air mass (origin, diabatic heating) play a role for Tmax forecast quality?

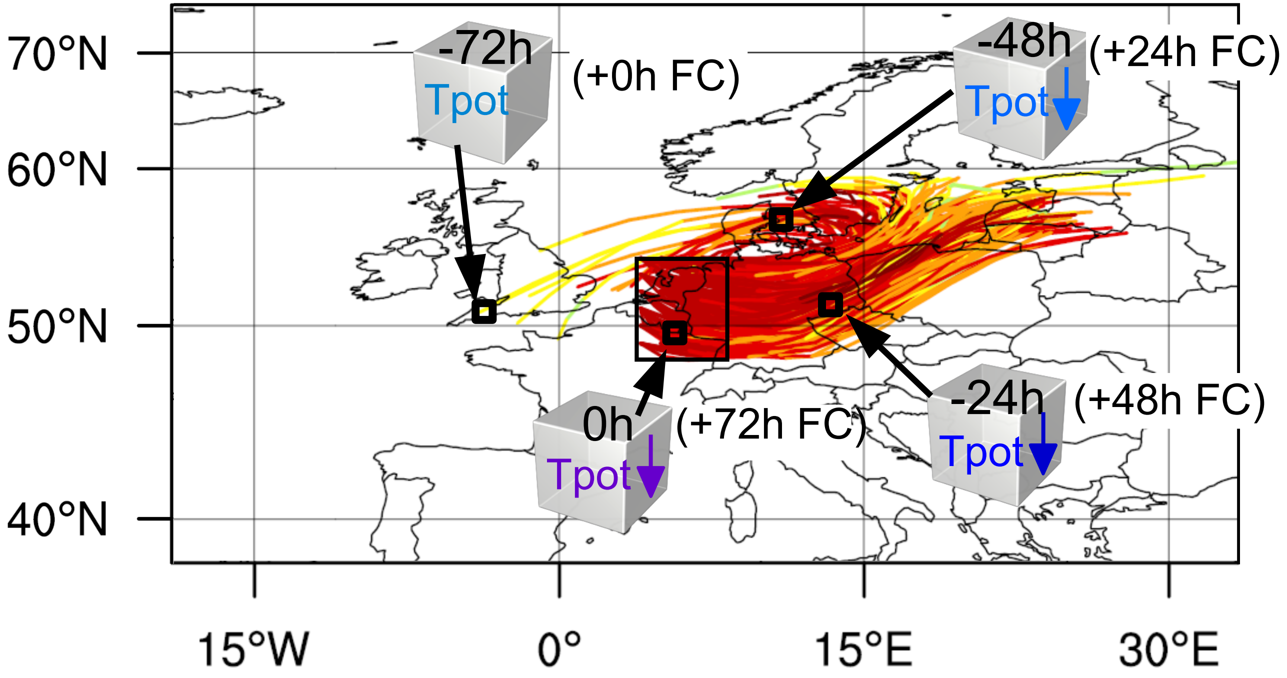
Unique opportunity:
50-member ECMWF forecasts saved on model levels (disadv.: lower spat. res. and only avail. for 2018-2020)

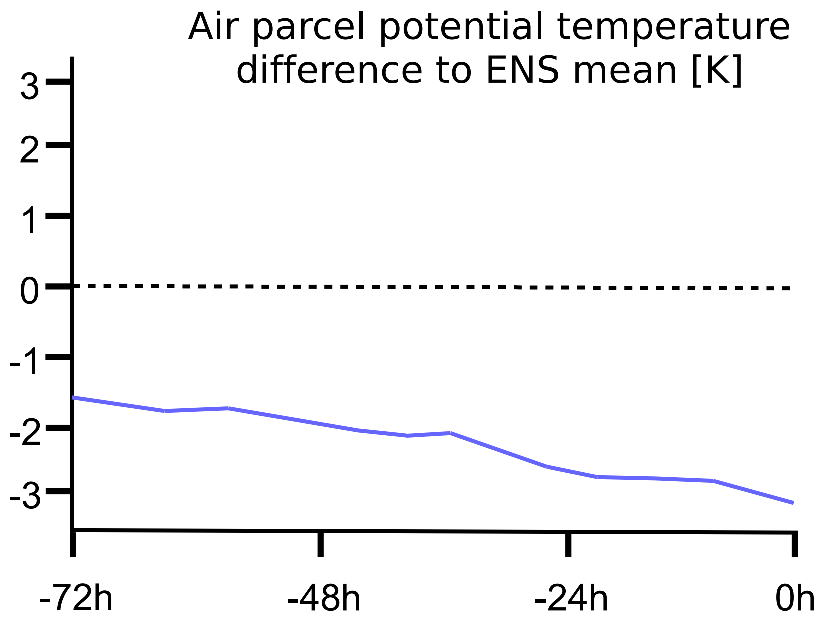
1. For each Central Europe subregion, calculate **backward trajectories** with LAGRANTO using as input ECMWF-EPS forecast with lead times up to 72h (starting from +72h forecast, then going back in 6h steps)

2. Find **10 warmest** and **10 coldest** ensemble members for each days and compare trajectory origin and temporal evolution of traced variables against ensemble mean

The **backward trajectories** are calculated from **ECMWF-EPS forecasts** (1°, 6h resolution) and were started within 7°-13°E; 52.5-55°N box (**Western CE** region) 25hPa above ground level

Example of one air parcel that has an initially **lower potential temperature** and undergoes also **less diabatic heating** in the span of 72 hours compared to the ENS mean

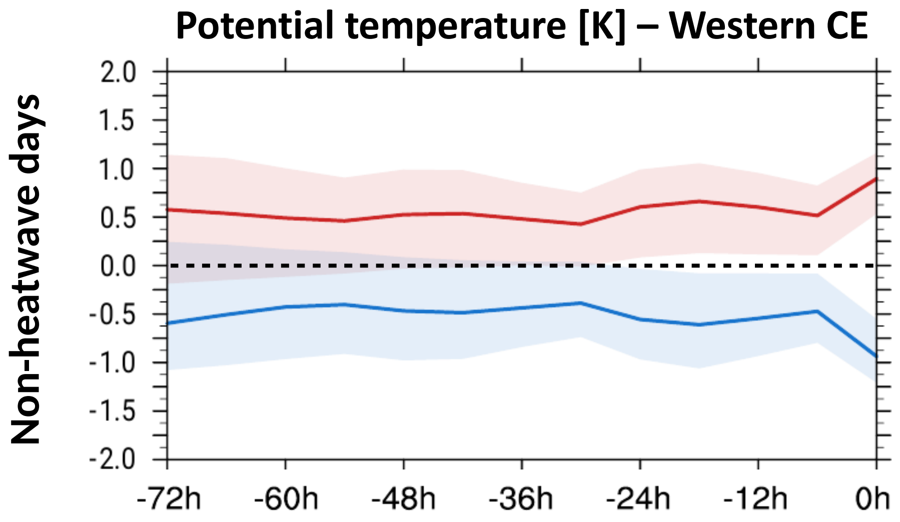


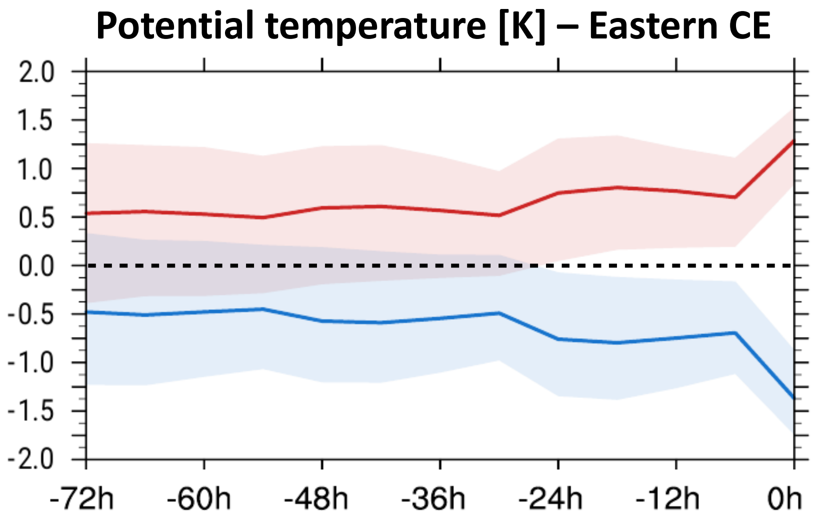


→ Next slide: Systematic comparison
Composite difference of air mass potential temperature between day-wise respective 10 warmest and 10 coldest ensemble members for all summer days 2018-2020 split into non-heatwave / only heatwaves

Temporal evolution of **potential temperature** (diabatic heating) in backward trajectories for the day-wise respective 10 warmest and 10 coldest ensemble members for all summer days 2018-2020 split into non-heatwave (top) and only heatwaves (bottom) – Western CE (left) and Eastern CE (right) comparison

Shown is the 2018-2020 averaged difference to ensemble mean (interquartile range depicted by light shadings)





Regular summer days:
Largest spread in potential temperature on forecast day 3 in both east and west CE.

Temporal evolution of **potential temperature** (diabatic heating) in backward trajectories for the day-wise respective 10 warmest and 10 coldest ensemble members for all summer days 2018-2020 split into non-heatwave (top) and only heatwaves (bottom) – Western CE (left) and Eastern CE (right) comparison

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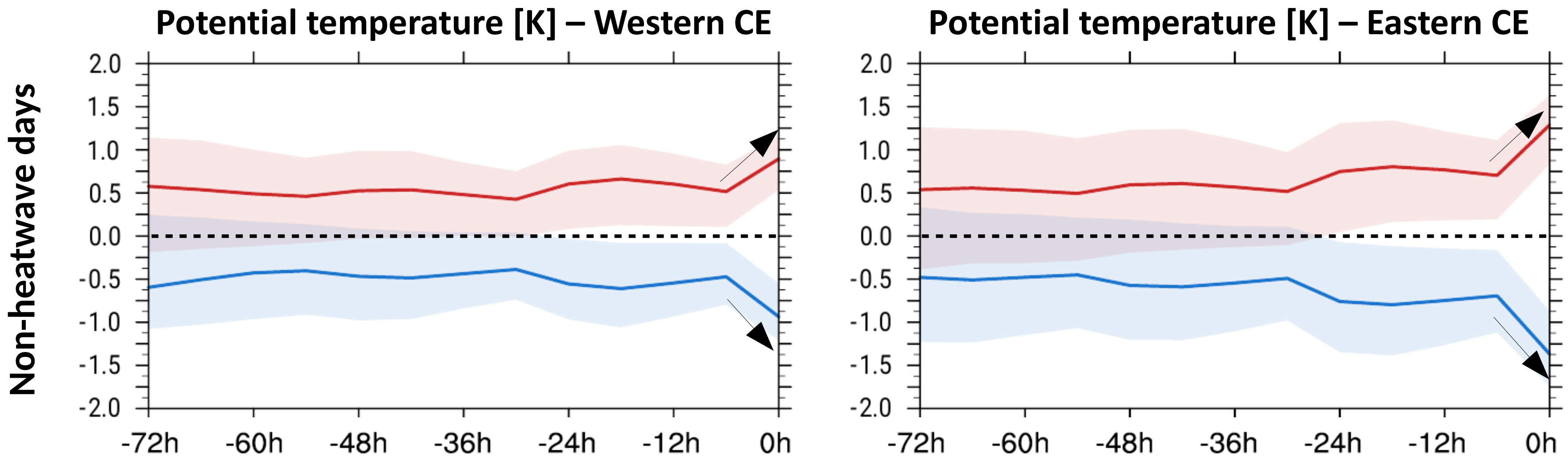

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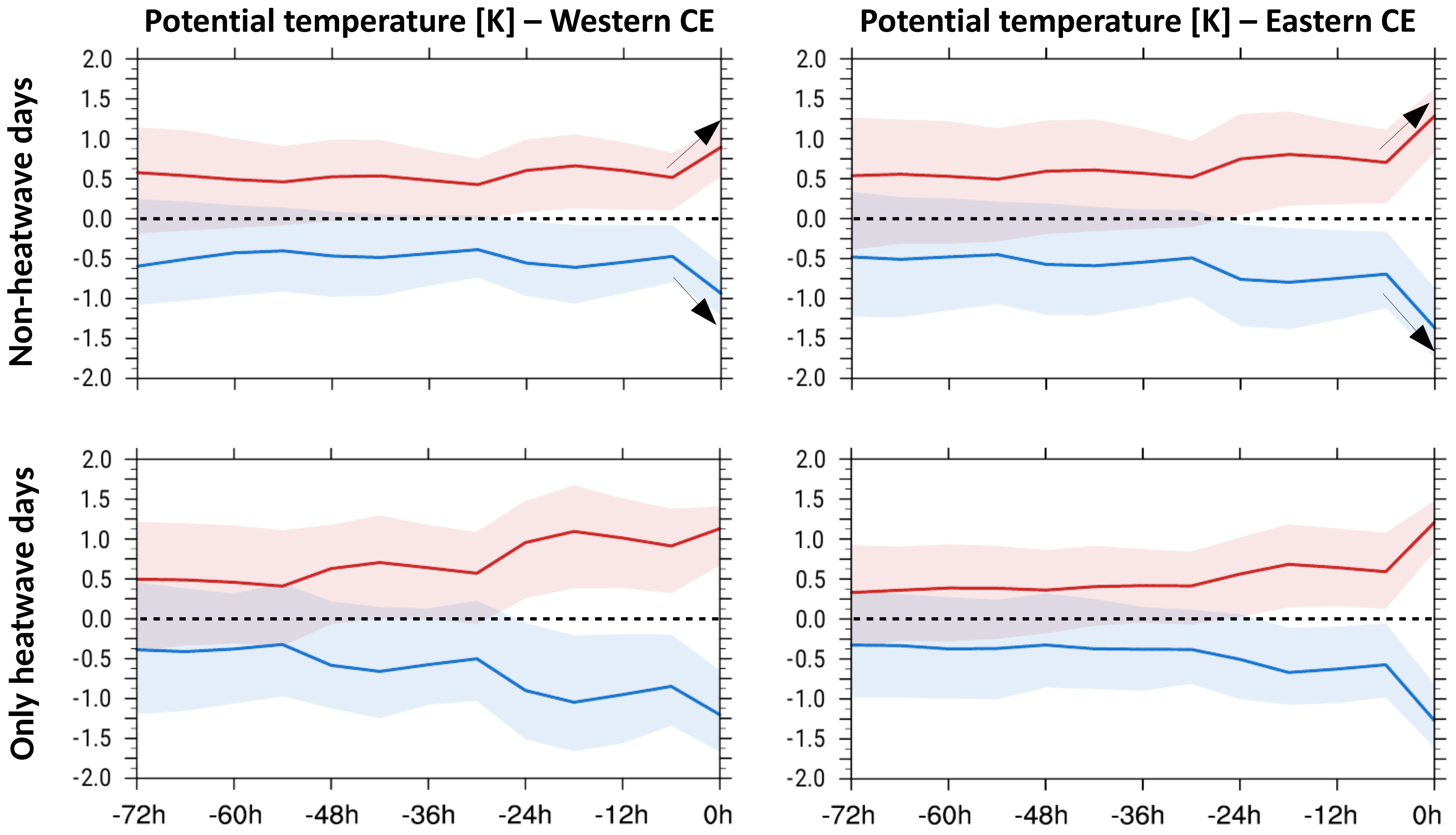

Regular summer days:
Largest spread in potential temperature on forecast day 3 in both east and west CE.

Heatwaves:
In contrast to east CE, strong day-to-day accumulation of error in potential temperature in west CE.

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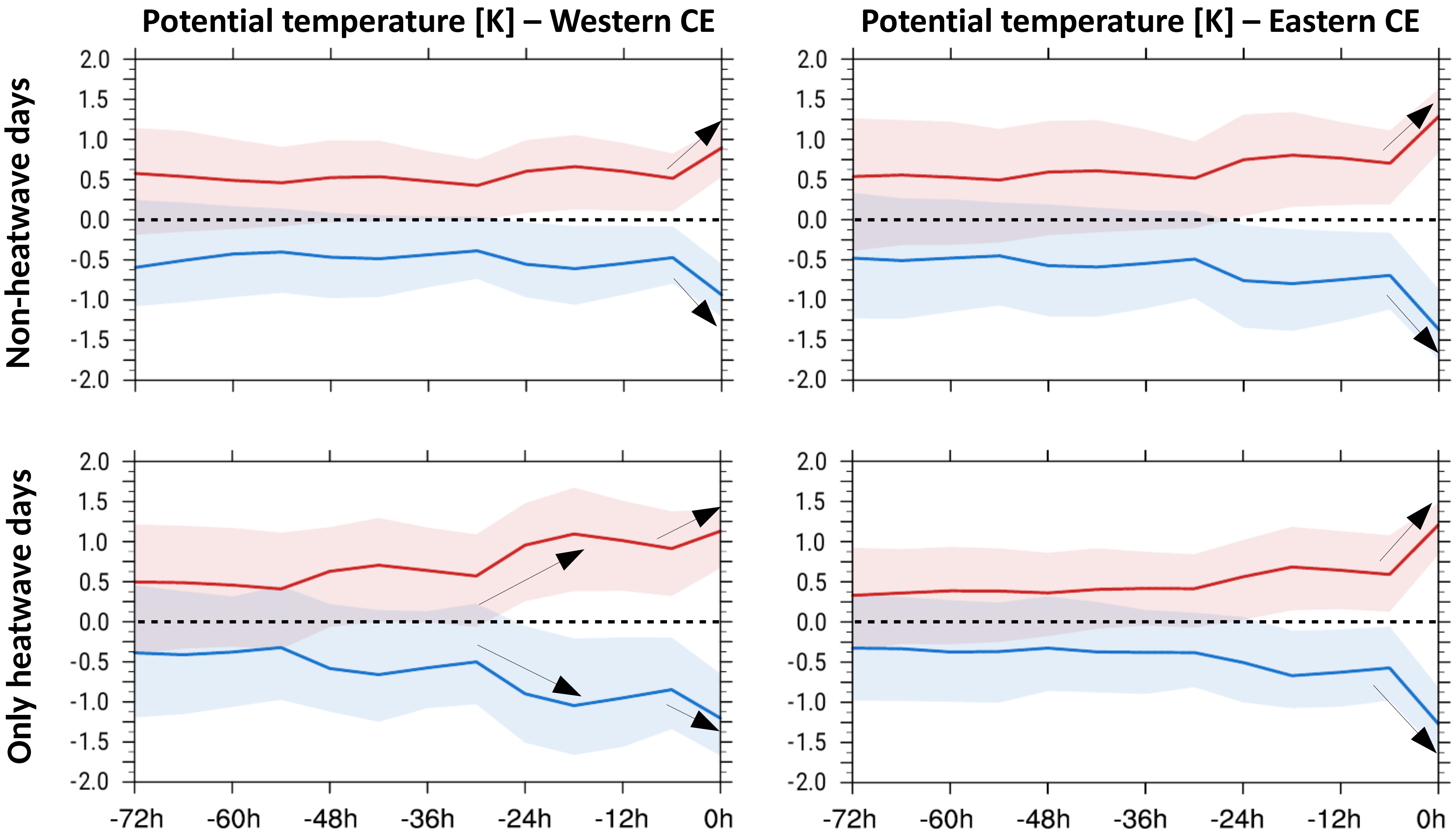

Regular summer days:
Largest spread in potential temperature on forecast day 3 in both east and west CE.

Heatwaves:
In contrast to east CE, strong day-to-day accumulation of error in potential temperature in west CE.

Temporal evolution of traced **total cloud cover** in backward trajectories for the day-wise respective 10 warmest and 10 coldest ensemble members for all summer days 2018-2020 split into non-heatwave (top) and only heatwaves (bottom) – Western CE (left) and Eastern CE (right) comparison

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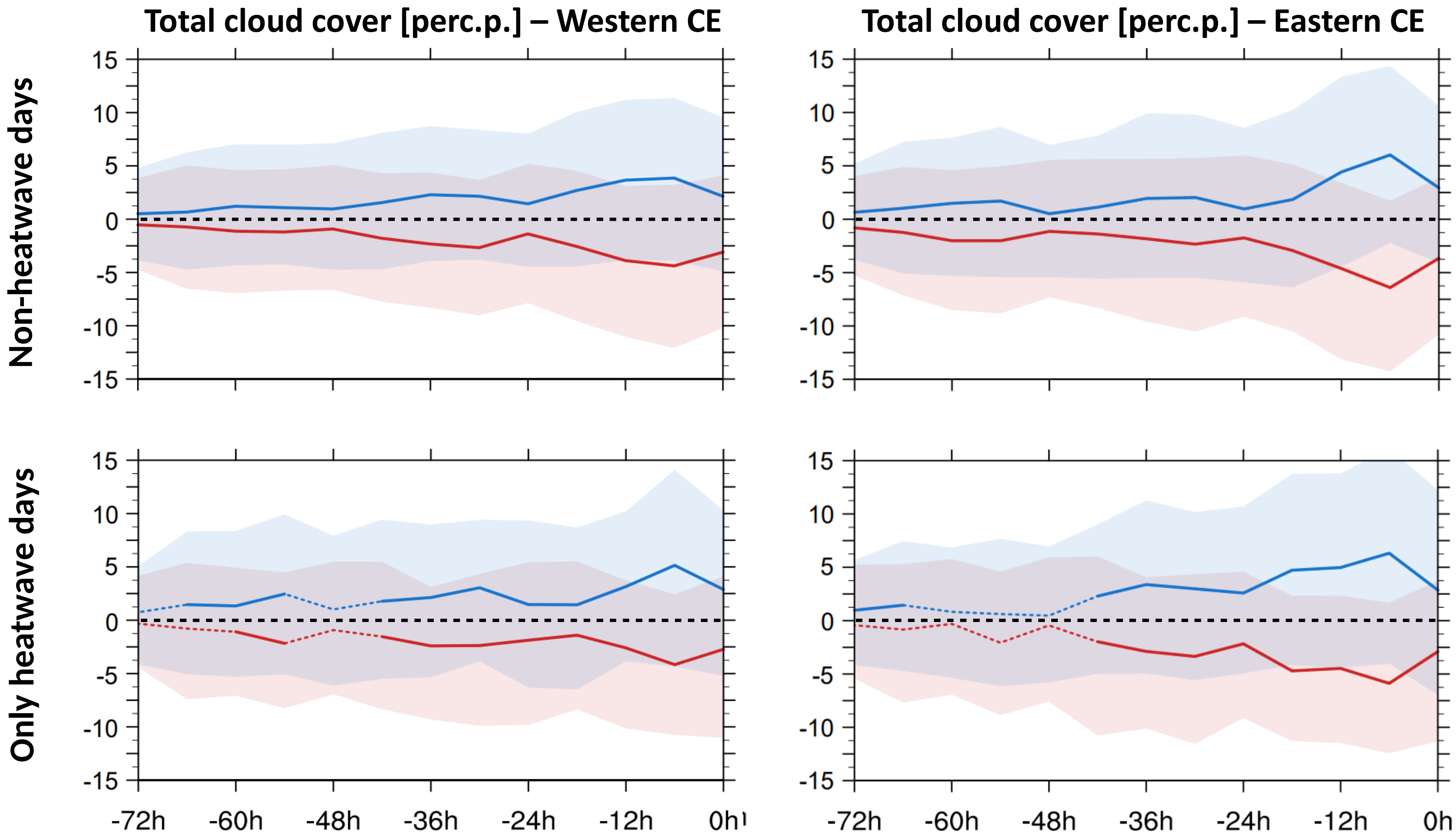

Errors in traced cloud cover do not explain differences between west and east CE.

Temporal evolution of **potential temperature** (diabatic heating) in backward trajectories for the day-wise respective 10 warmest and 10 coldest ensemble members for all summer days 2018-2020 split into non-heatwave (top) and only heatwaves (bottom) – Western CE (left) and Eastern CE (right) comparison

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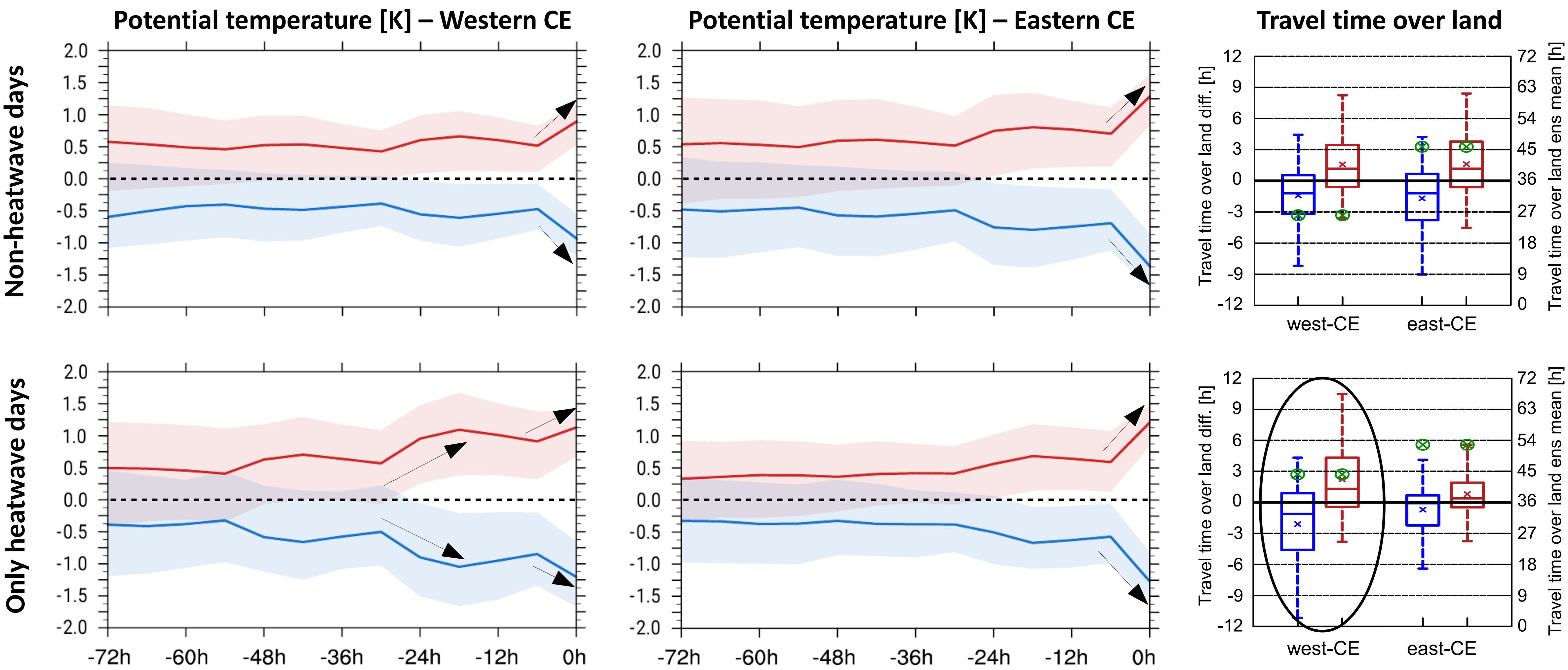

Additional „Lagrangian Conclusions“

RQ2: Does the history of the air mass (origin, diabatic heating) play a role for forecast quality?

- Particularly during heatwaves, PBL air masses may be subject to over- or underestimations of diabatic heating that may accumulate until forecast days 3; in western CE, highest error growth on forecast day 2
- Diabatic heating errors are generally consistent with errors in traced total cloud cover but errors in this quantity do not explain found differences between HW and non-HW days and western and eastern CE
- Errors in simulated residence time over land important for Tmax errors in western CE heat waves