The predictability of European heat waves

Andreas H. Fink

Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology
Karlsruhe, Germany

EUROPEAN GEOSCIENCES UNION – GENERAL ASSEMBLY

Geosciences Information for Teachers Workshop (GIFT) 2023

24-26 April 2023

Weather Prediction vs. Climate Projection

Climate Projections:

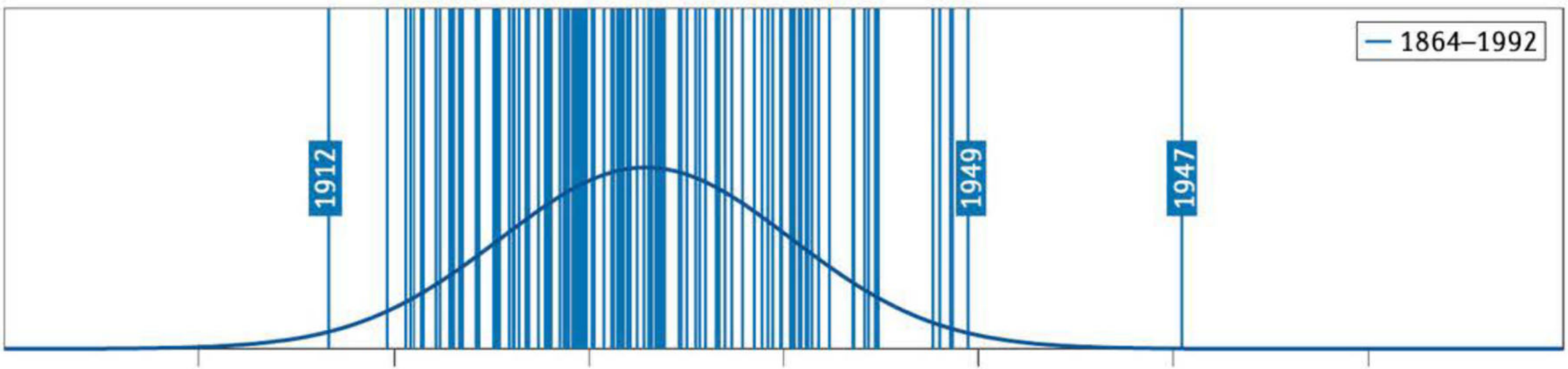
- This is a **boundary value problem** and we **project**, for example, the **climate** for a 30-year period at the end of the 21st century.
- We use **Earth System Models** and the boundary conditions are prescribed **increasing greenhouse gas emissions**, aerosols, and land use change, etc.

Weather and Climate Prediction:

- This is an **initial value problem**. We **forecast** for example surface temperature distributions for a given location and time.
- **Forecast lead times** are up to 10 days (weather forecast), less than 3 months (sub-seasonal) and up to nine months (seasonal).

Observed trends in heat waves

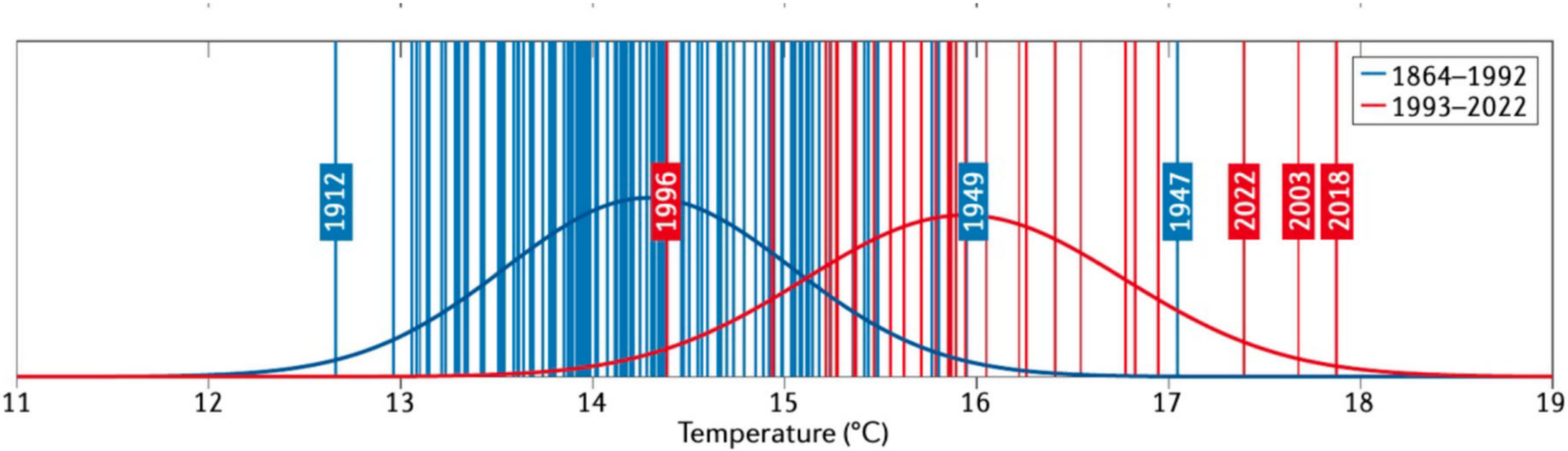
April – September summer temperatures in Switzerland, 1864 –1992



Domeisen et al. (2023)

Observed trends in heat waves

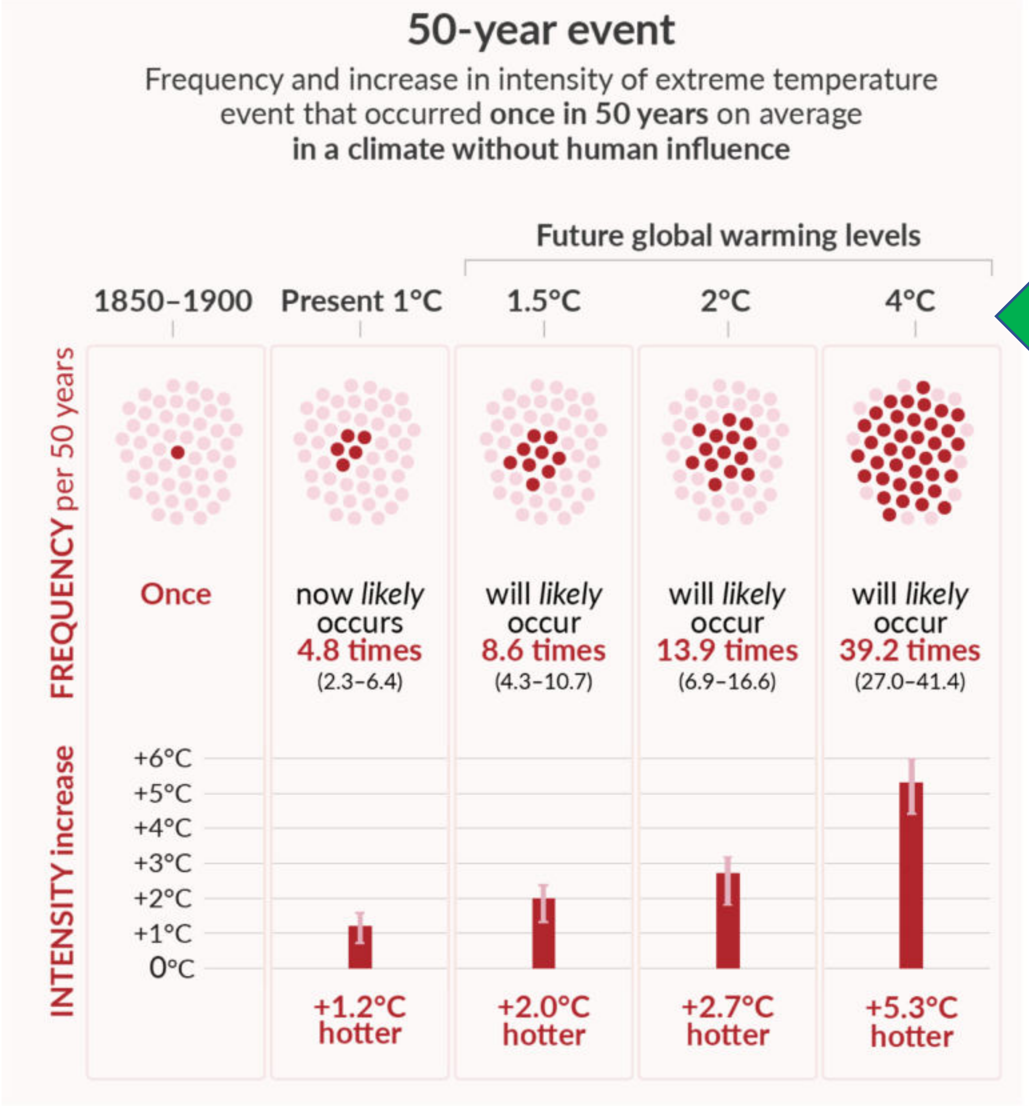
April – September summer temperatures in Switzerland, 1864 –2022



Coldest summers of the modern period (1993-2022) are already warmer than average summer temperatures from 1864-1992!!

Domeisen et al. (2023)

And the trend will continue/strengthen

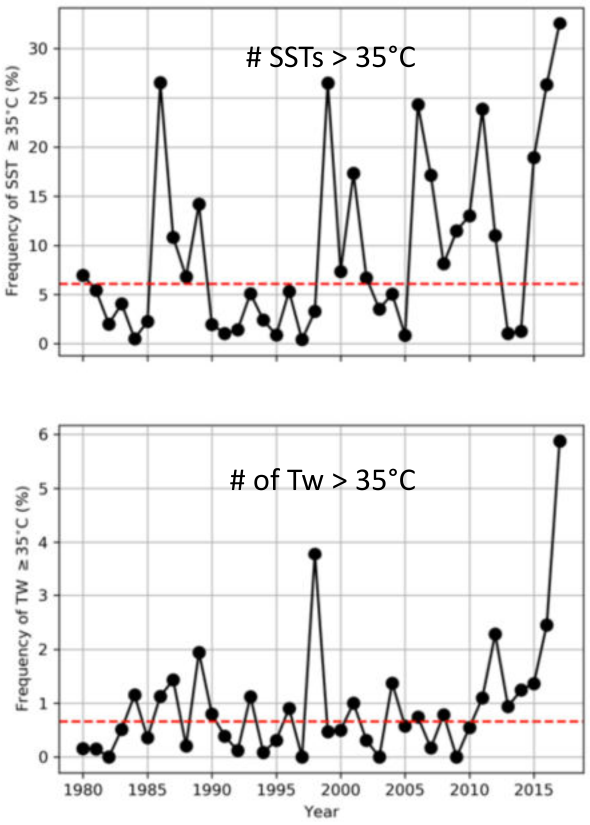


IPCC (2021)

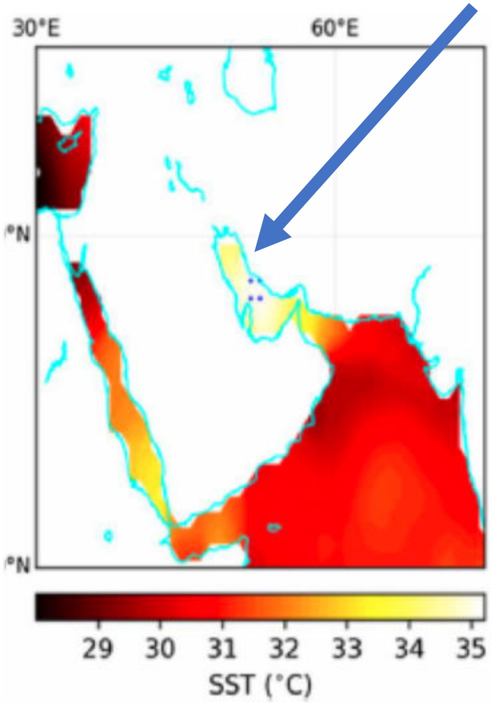
Heat waves will be more frequent, more intense (and of longer duration).

“An extreme summer such as that of 2018 is expected to occur every two out of three years in Europe in a 1.5 C warmer world and **virtually every single year in a 2 C warmer world**” (Rousi et al. 2023).

Some scary consequences



Monthly mean SST > 35°C in 2017



All time maximum sea surface temperature (SST)

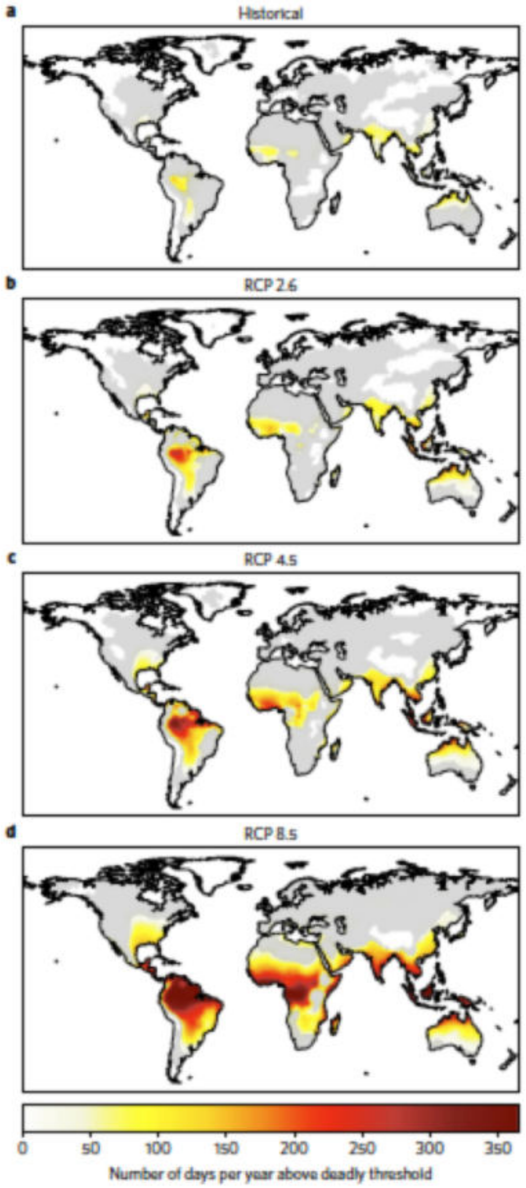
Raymond et al. (2020)

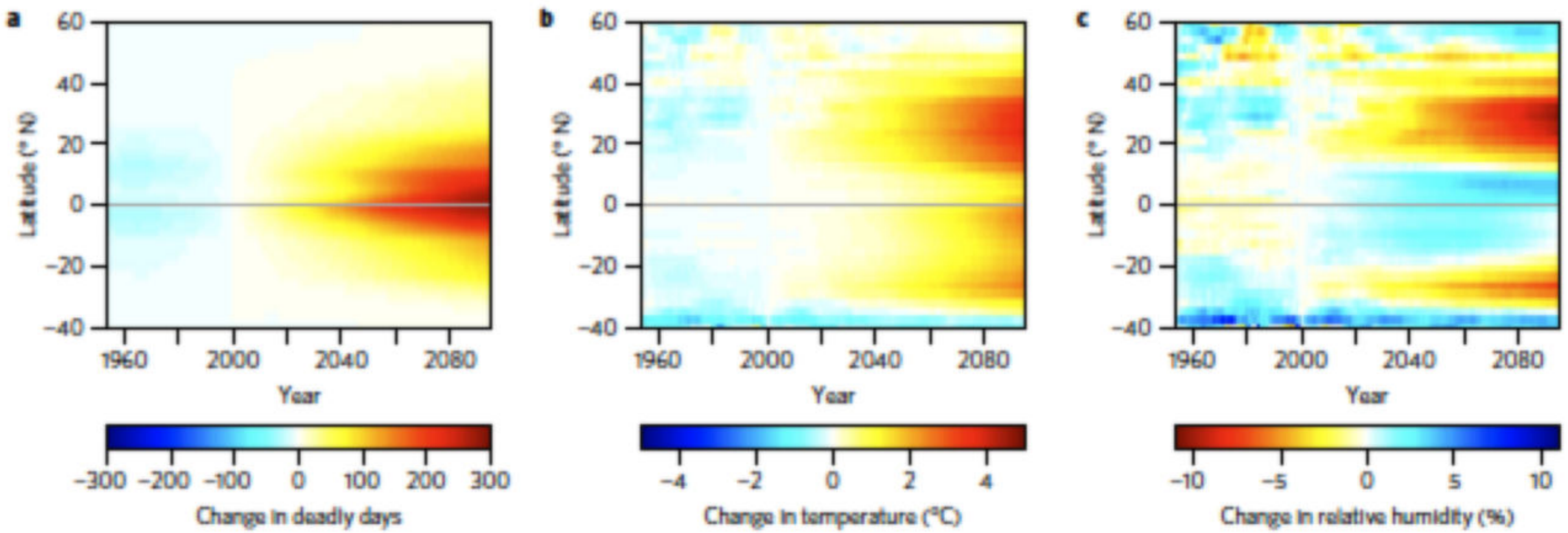
If the wet-bulb temperature (T_w) exceeds 35°C for more than six hours, **humans die** due to **hyperthermia.**

Tw >= 35 is currently already observed for short time periods in and at the shores of the Persian Gulf in summer.

In this region, the Read Sea, and the Indus/Ganges valleys, heat waves may become literally deadly in the coming decades.

Some scary consequences





Large increase in number of “deadly days” (here in terms of excess death) especially in the hot and humid tropics.

Mora et al. (2017)

Need of Early Warning of Heat Waves

Immense societal impacts of heat waves in Europe:

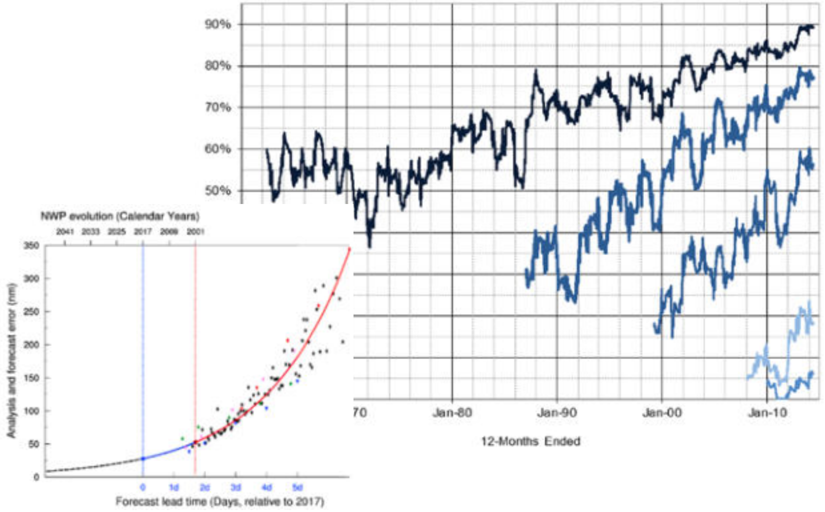
- **Excess deaths**, 15000 in 2022 (WMO 2023), 70000 in 2003 (Robine et al. 2008).
- They are often **compounded** with **drought**, with aggregated impacts ranging from reduced yields and forest mortality to more wildfires.
- Low river flows and warm river waters impact on transport and power supply, e.g. in 2003 (Fink et al. 2004).

Early warning requires **accurate** and **reliable** surface temperature (and rainfall) **forecasts** at time scales from days to weeks for a better preparedness of health systems, city officials, power industry, and agriculture.

Importance of weather prediction

Society needs **better forecasts**...

and they are **getting them!**



Forecasts are improving at about
1 day per decade

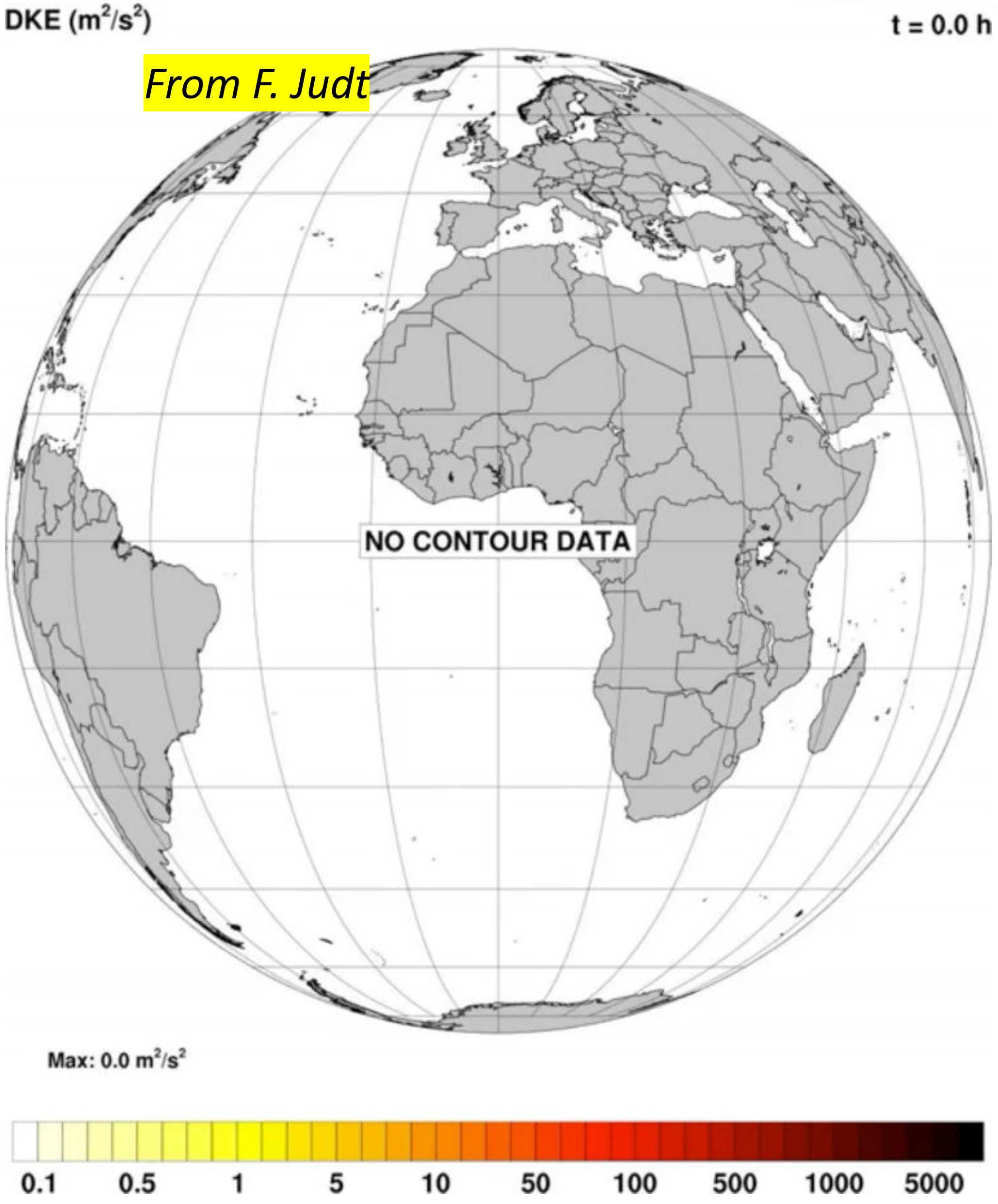
But there is **a limit…**

Source: Waves two Weather Consortium

Intrinsic limit differs with scales and climates

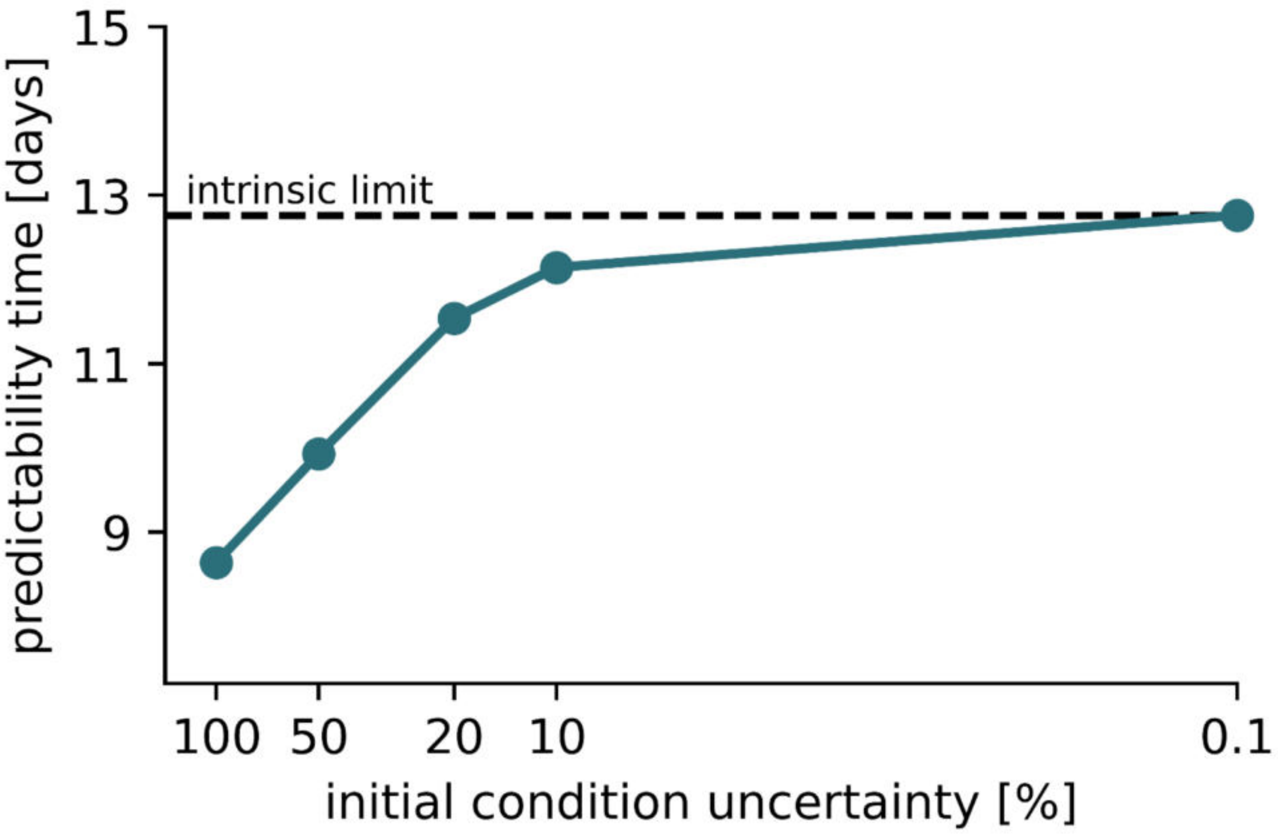
- The atmosphere is a **non-linear, chaotic system**.
- Tiny uncertainties in initial conditions can lead to **large prediction errors** after a few days.
- **Predictability** is therefore **fundamentally limited**, not only by technical and scientific deficits.

We call this "**intrinsic**" or "**theoretical predictability**"



How close are we to the intrinsic limit?

Predictability of **midlatitude cyclones**



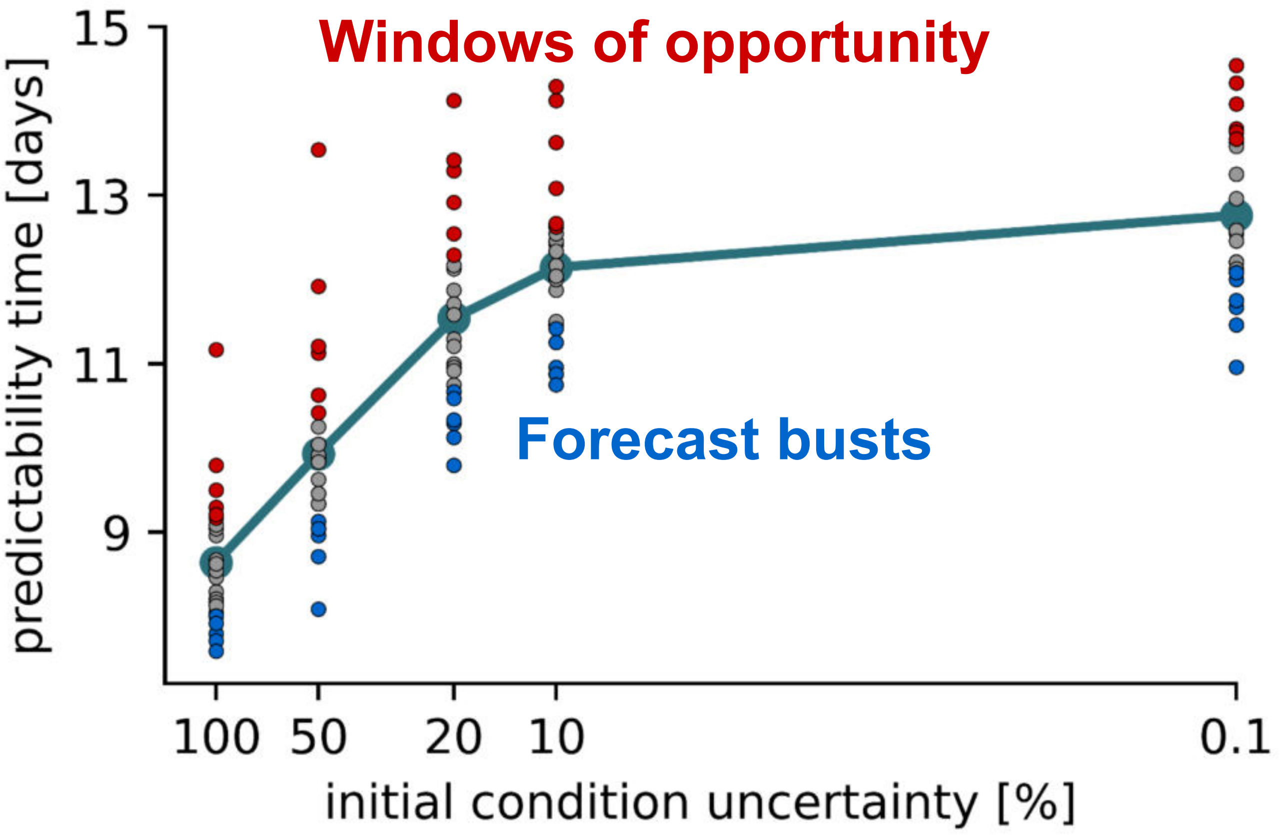
Error growth experiments show predictability time of about **2 weeks** on average

Intrinsic limit reached when initial uncertainty reduced to **10%** of present level

Source: Waves two Weather consortium, after Selz et al. (2023)

How close are we to the intrinsic limit?

Predictability of **midlatitude cyclones**



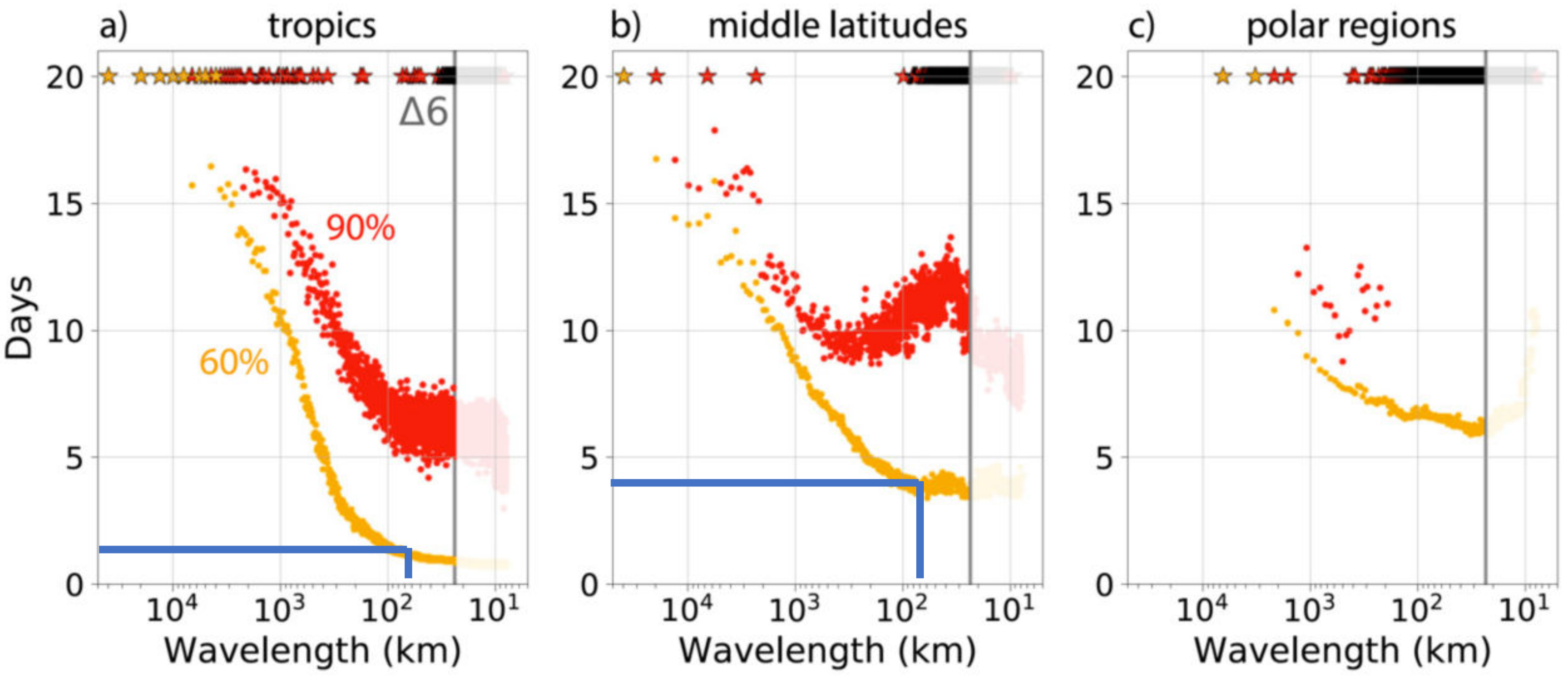
Predictability is **flow-dependent**

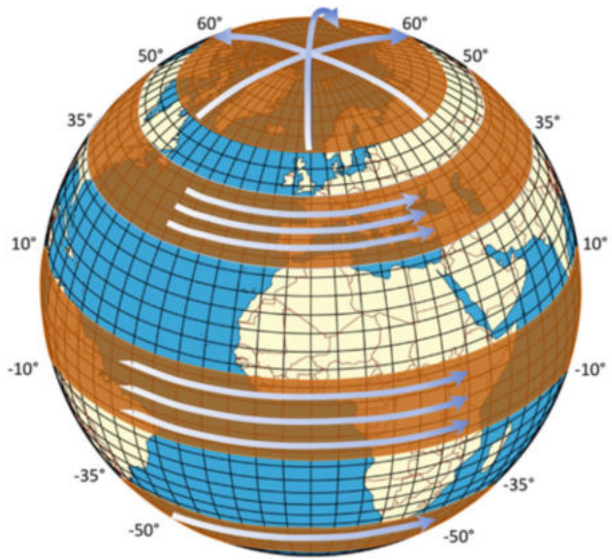
Challenge:

Windows of opportunity

Source: Waves two Weather consortium, after Selz et al. (2023)

Intrinsic limit differs with scales and climates



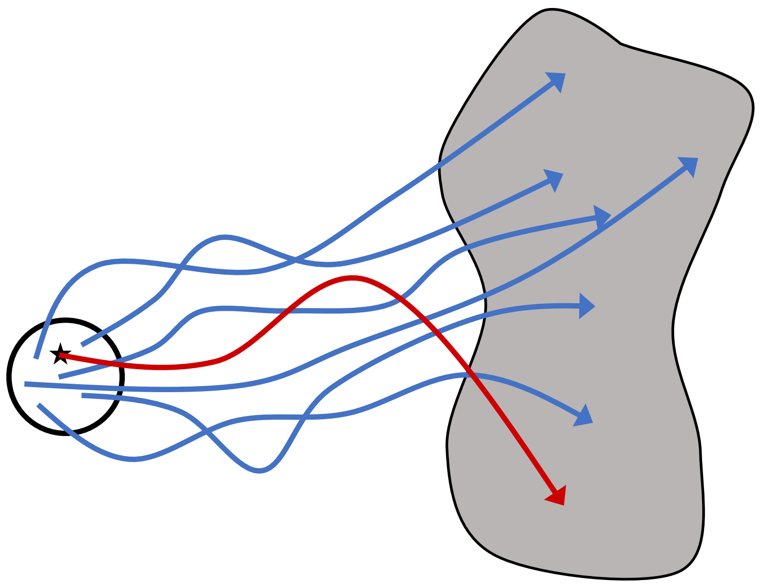


Judt (2020)

- 60% limit of useful predictive skill; 90% limit of predictability.
- Tropics: useful skill on small scales only for little more than 24h, but on large scales “saturation” it is not reached even after 20 days.
- Low (high) predictability due to small-scale convection (planetary-scale tropical wave phenomena, e.g., Madden-Julian Oscillation).

Different sources of uncertainty

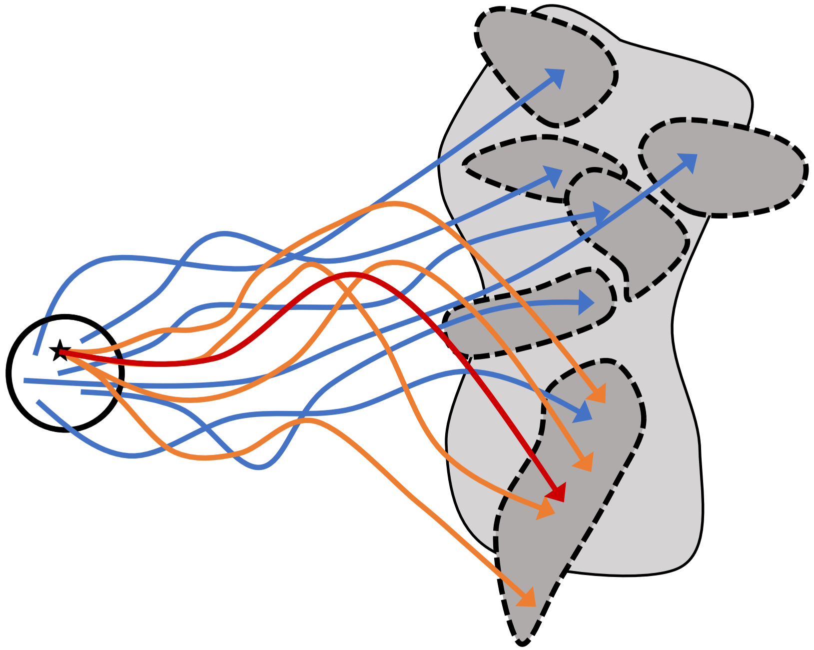
initial condition uncertainty



Source: Waves two Weather Consortium

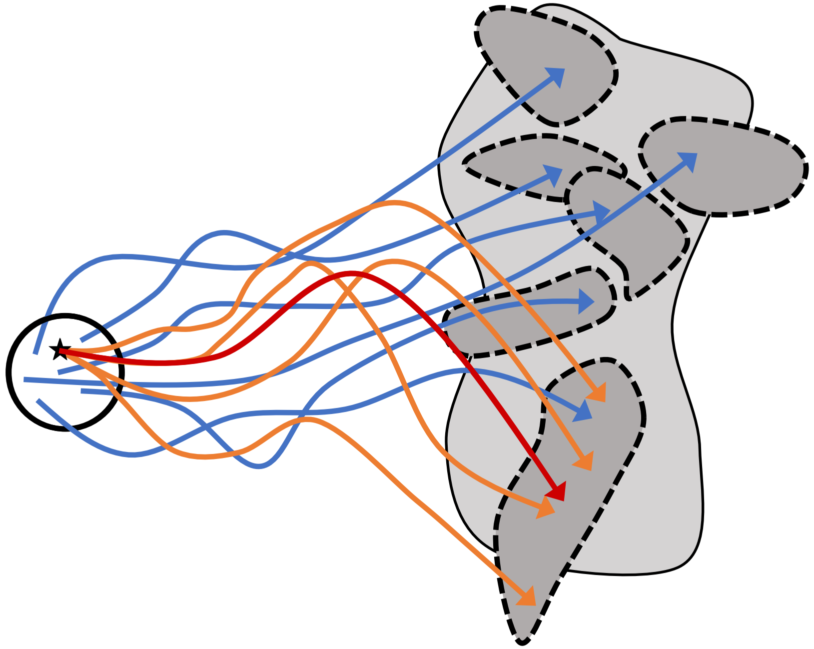
Different sources of uncertainty

model error & initial condition (IC) uncertainty



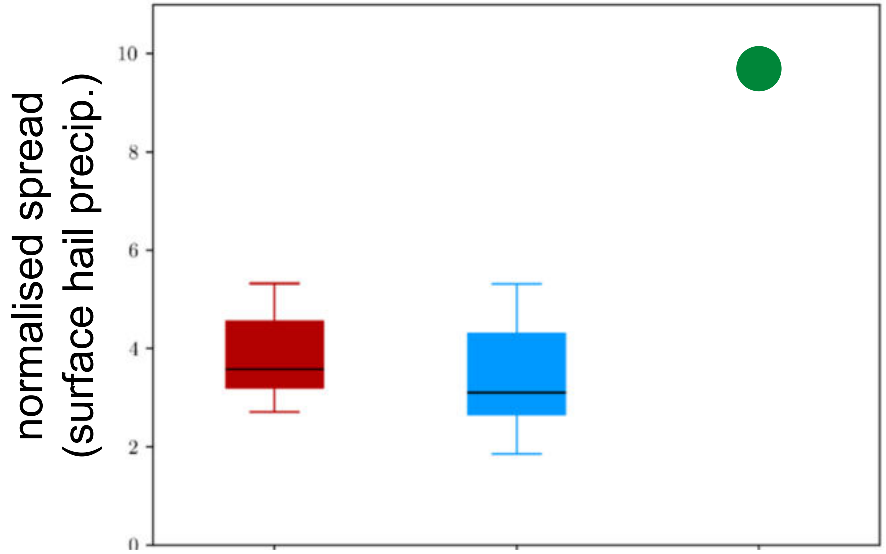
Source: Waves two Weather consortium

model error & initial condition (IC) uncertainty



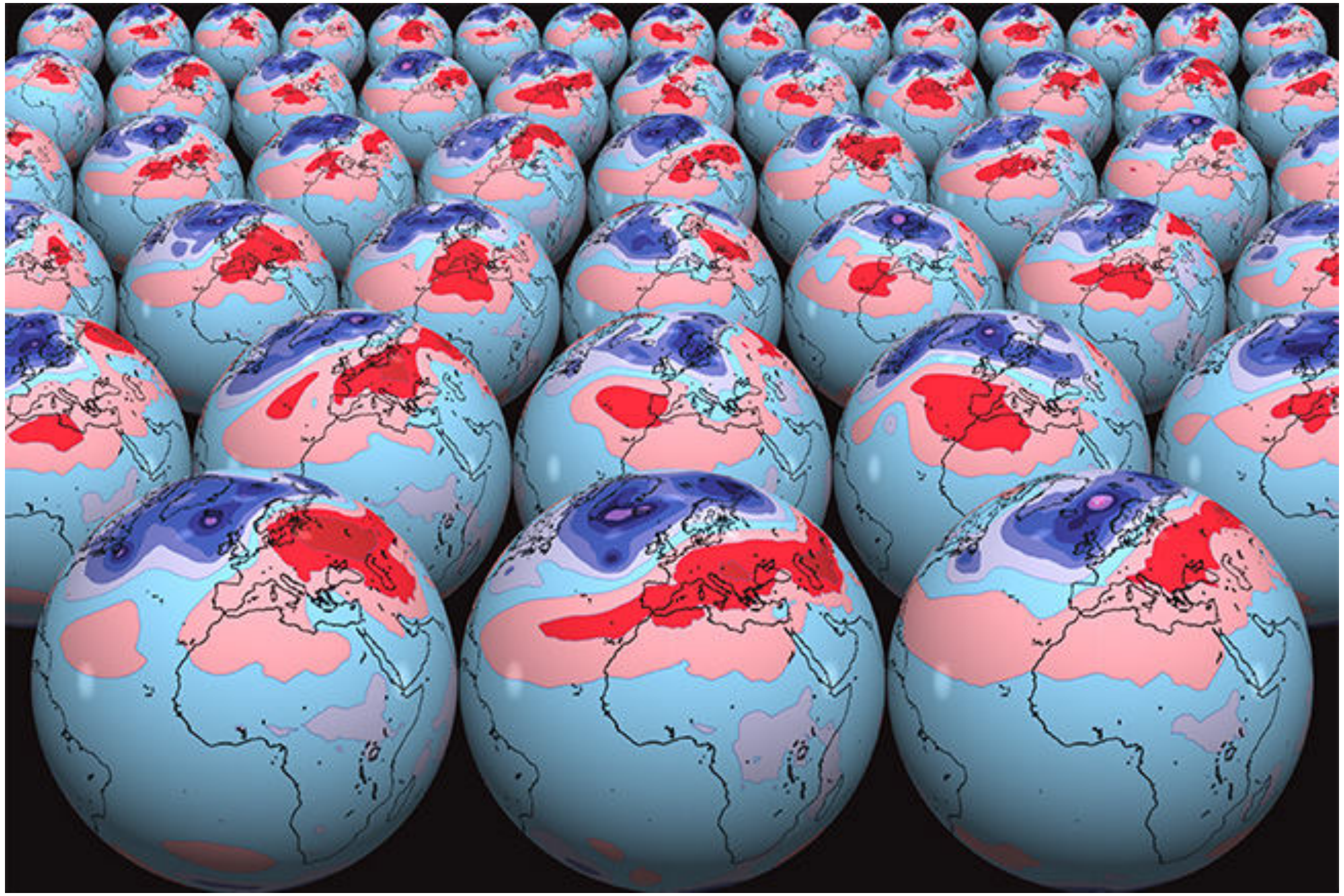
What uncertainties dominates?

combined initial condition and perturbed parameter ensembles with ICON



Source: Waves two Weather consortium

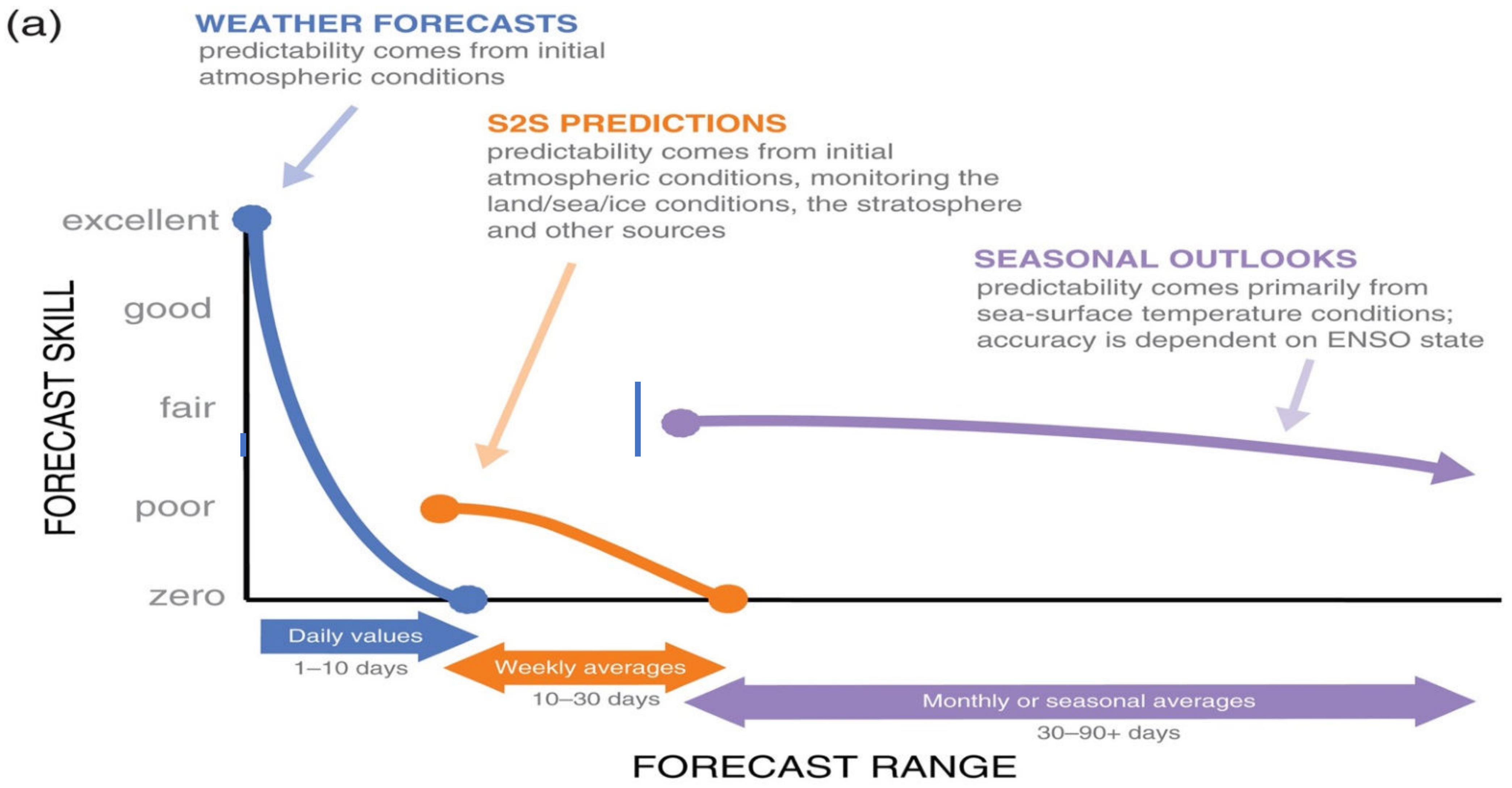
How meteoroligsts deal with weather chaos



https://www.ecmwf.int/en/about/media-centre/fact-sheet-ensemble-weather-forecasting

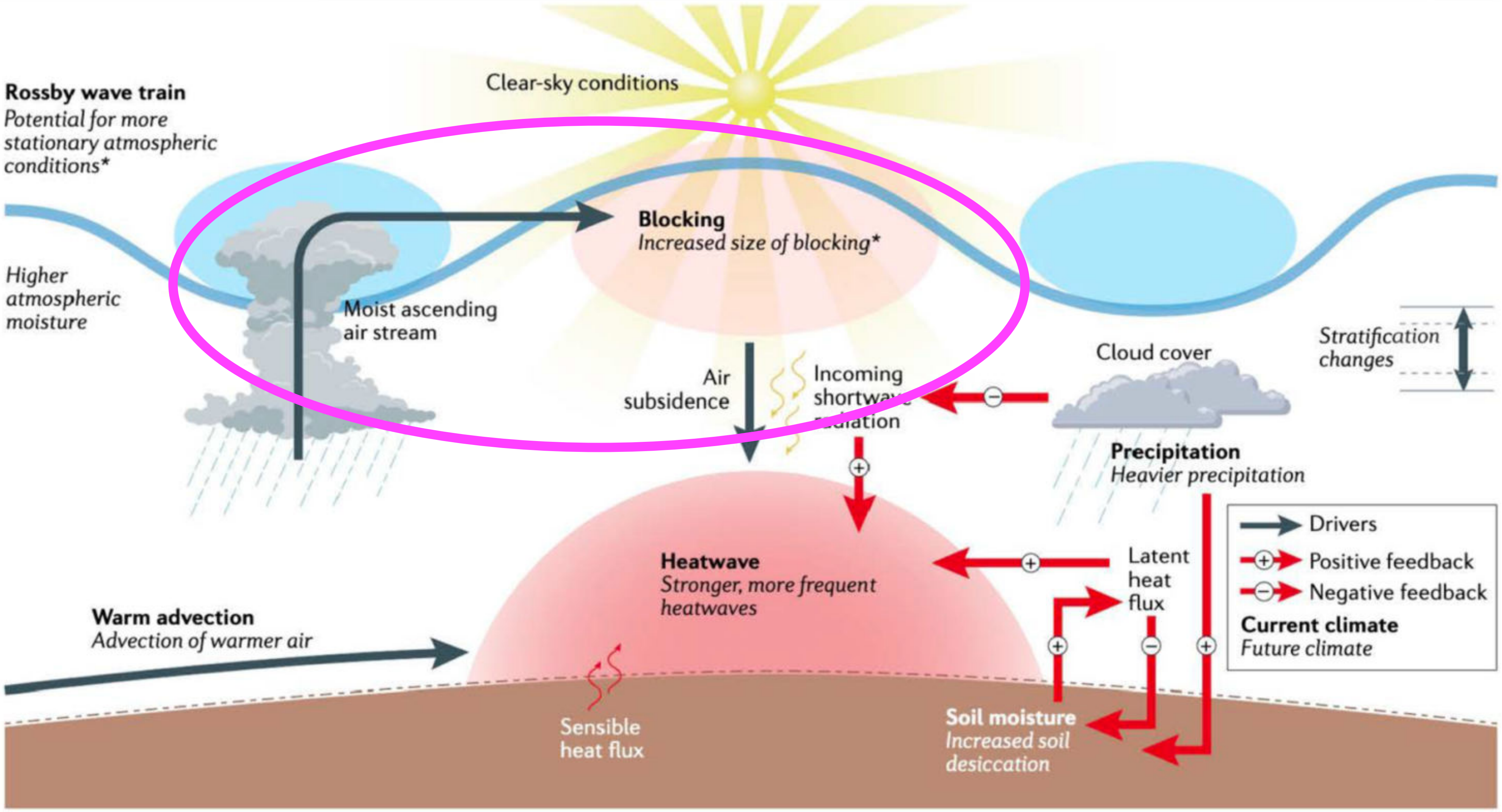
- Instead of one, we calculate an ensemble of 50 (weather forecast) or 100 (sub-seasonal) predictions.
- Each starts from slightly different initial conditions.
- From this we calculate rain probabilities, temperature distribution or estimate weather risks.

The subseasonal „predictability desert“



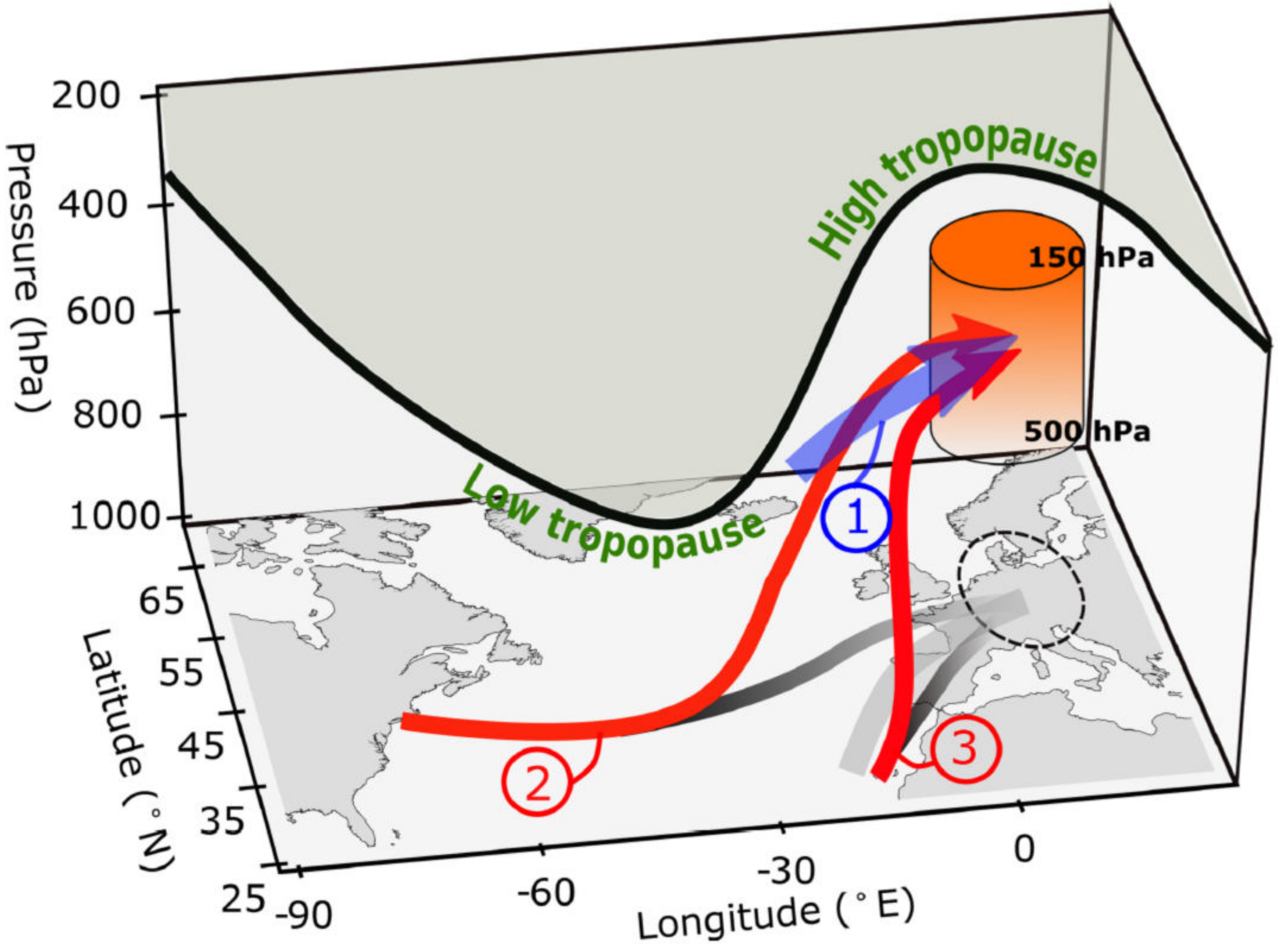
White et al. (2017)

Drivers and feedbacks of heatwaves



Domeisen et al. (2023)

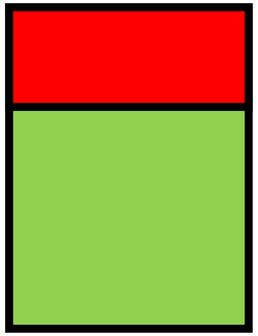
Role of upstream precipitation



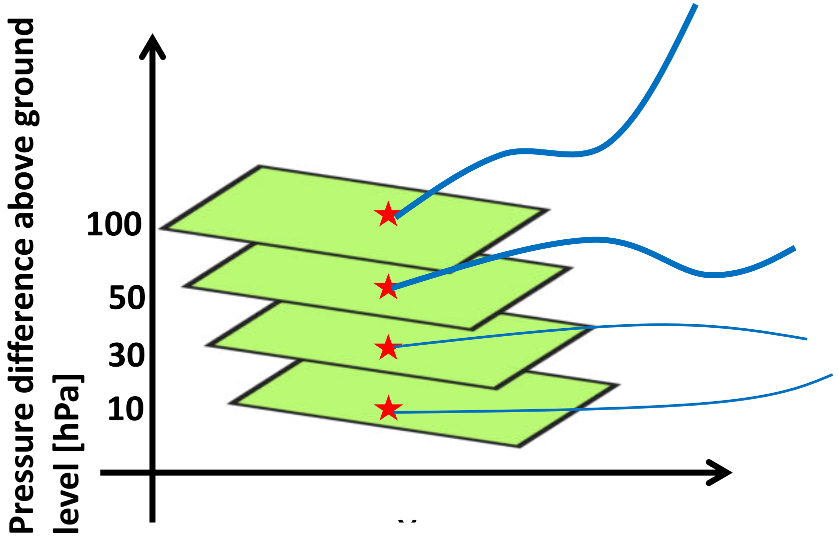
Zschenderlein et al. (2020) & Rousi et al. (2023)

- Pre-requisite of a heat wave in Europe is an upper-level ridge/high (“Blocking”).
- For its initiation and maintenance, upstream precipitation over the West Atlantic and SW of Iberia is important.
- Not easy to predict.

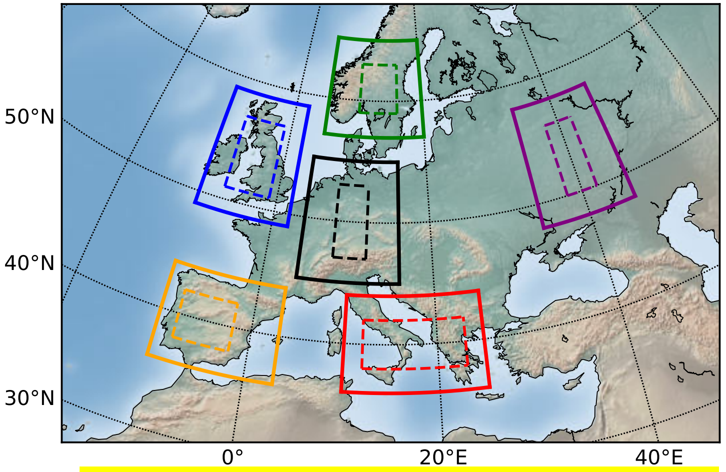
What causes extreme surface temperatures



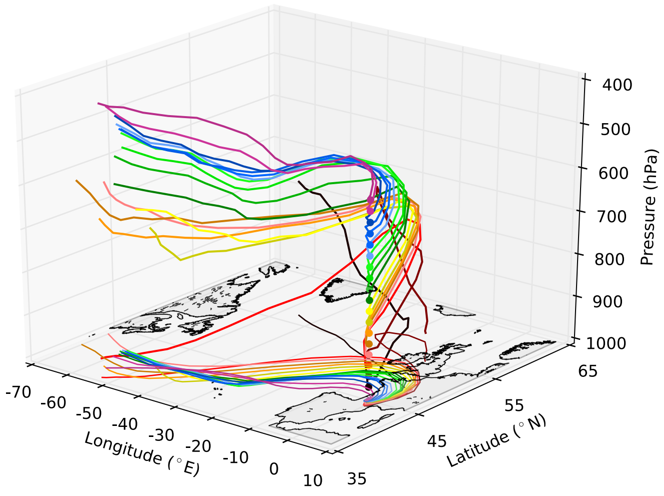
Trajectories initialised from land grid points that fulfil heat wave criterion



European regions studied

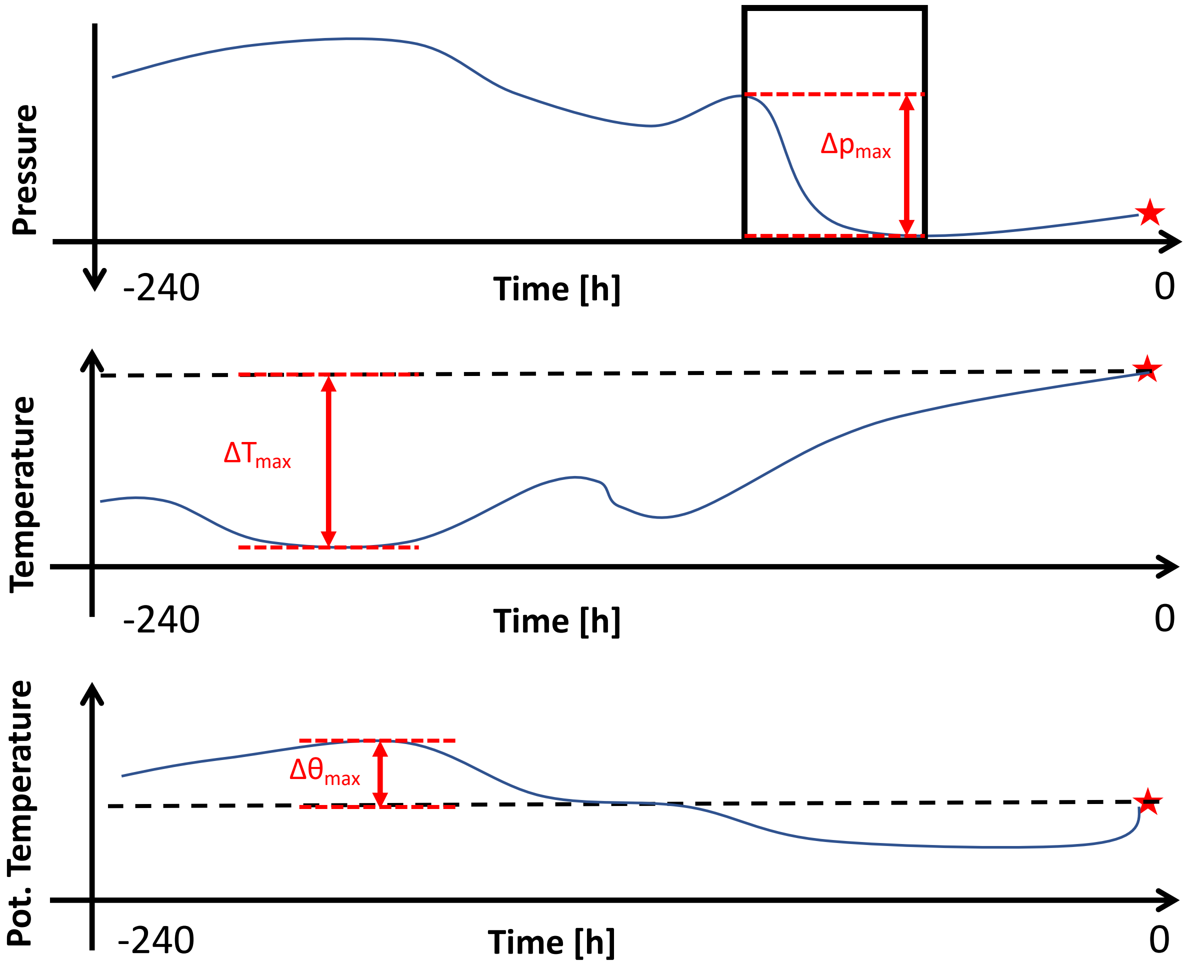


Zschenderlein et al. (2018; 2019)



Starting level: 975-900, 875-800, 775-700, 675-600, 575-550 hPa

Pressure and temperature changes along air parcel trajectories ending in heat waves



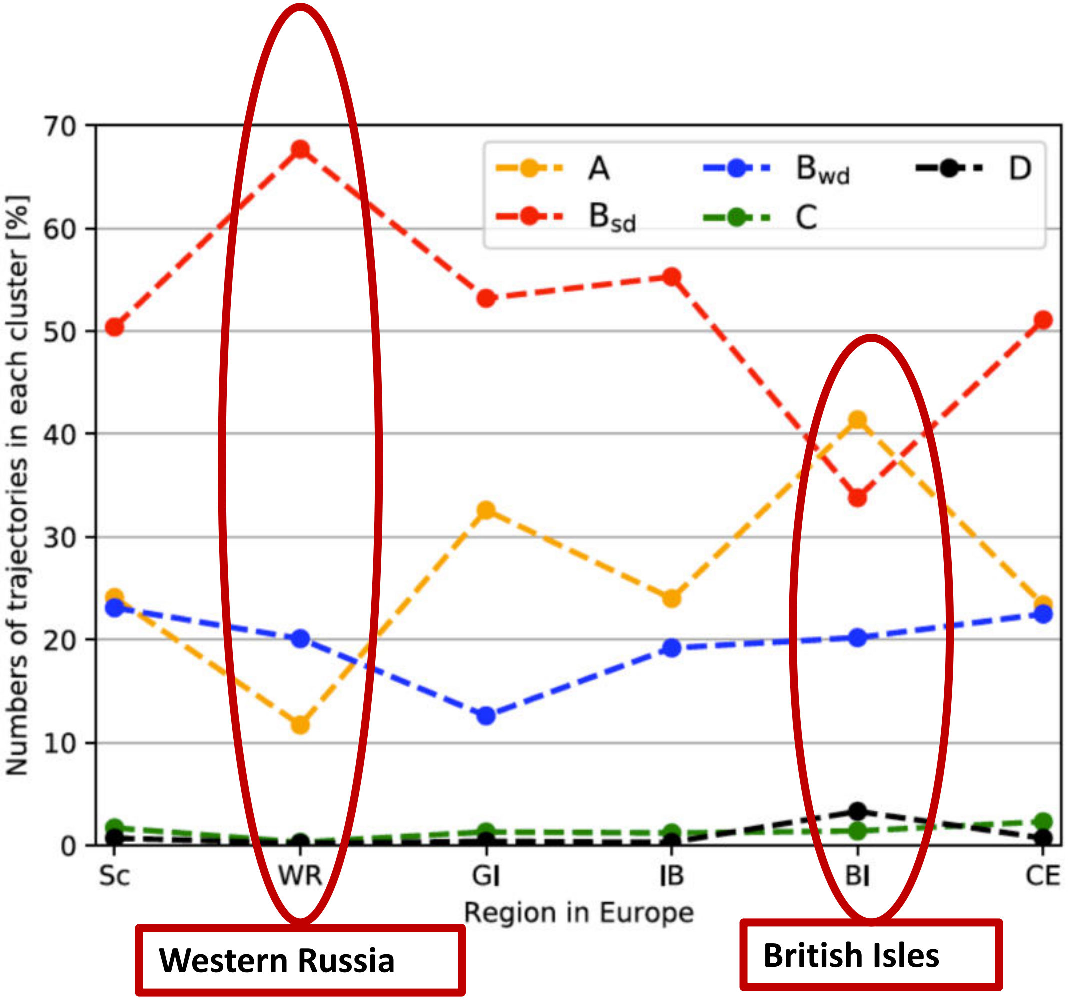
Zschenderlein et al. (2019)

Δp_{max} in 48 h Vertical displacement

$(T_0 - T_i)_{max} = \Delta T_{max}$ Temperature change

$(\theta_0 - \theta_i)_{max} = \Delta\theta_{max}$ Diabatic temperature change (e.g. radiative cooling; heating near ground)

Processes determining heat waves in Europe



Zschenderlein et al. (2019)

Cluster A

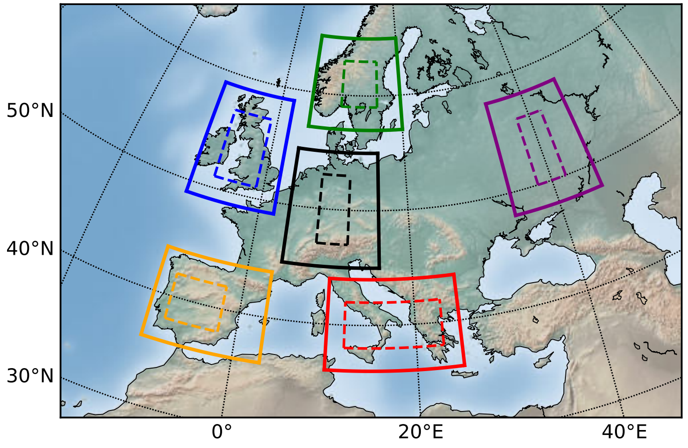
overall diabatic cooling and subsidence

Cluster B_{sd}

overall diabatic heating and subsidence of more than 100 hPa/48h

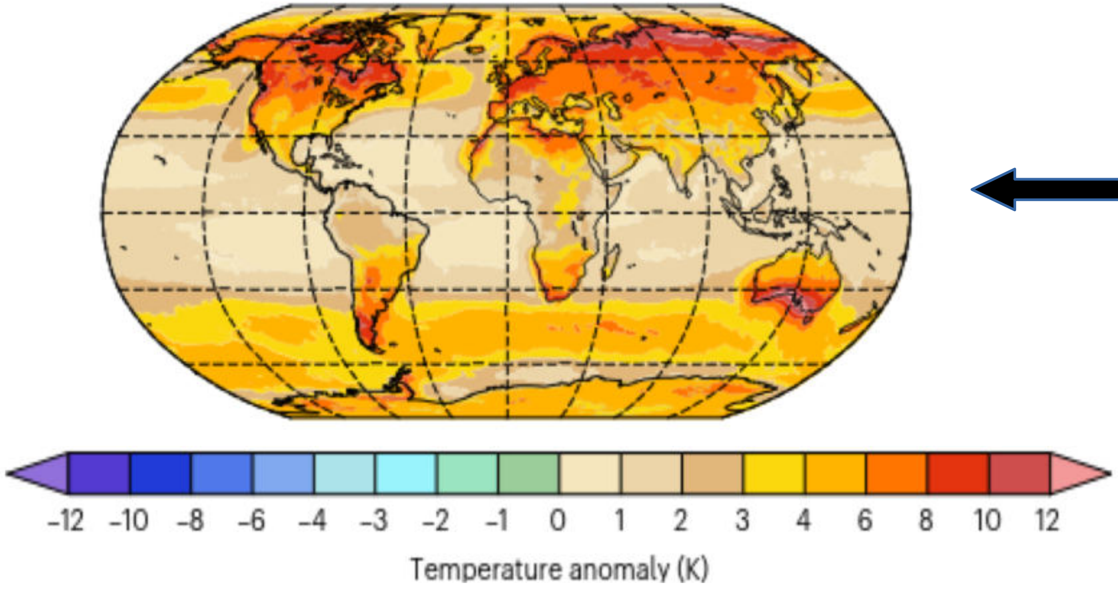
Cluster B_{wd}

overall diabatic heating and nearly no vertical motion

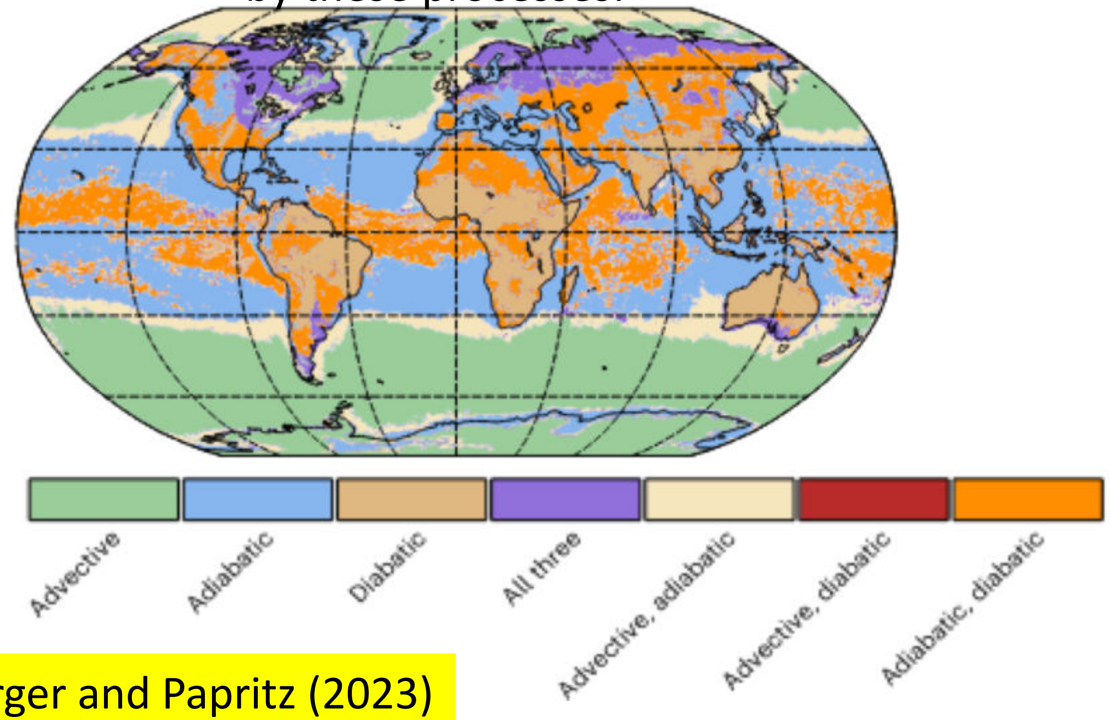


Driving processes of heat waves

T’ of the hottest days



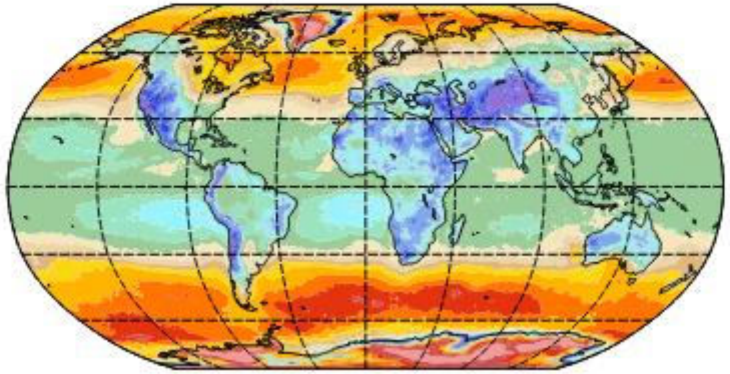
is on average created
by these processes:



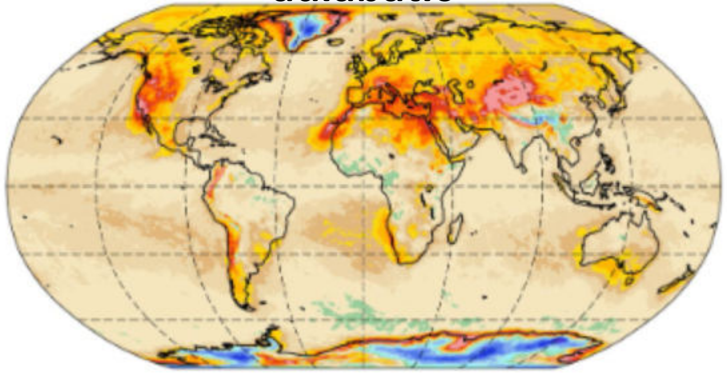
T’ decomposition for all three terms:

Roethlisberger and Papritz (2023)

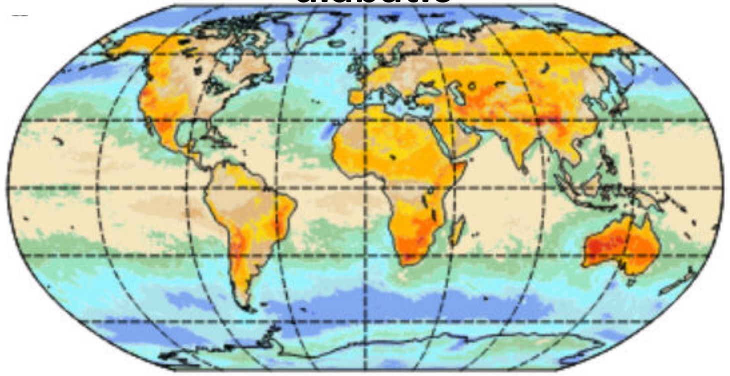
advective



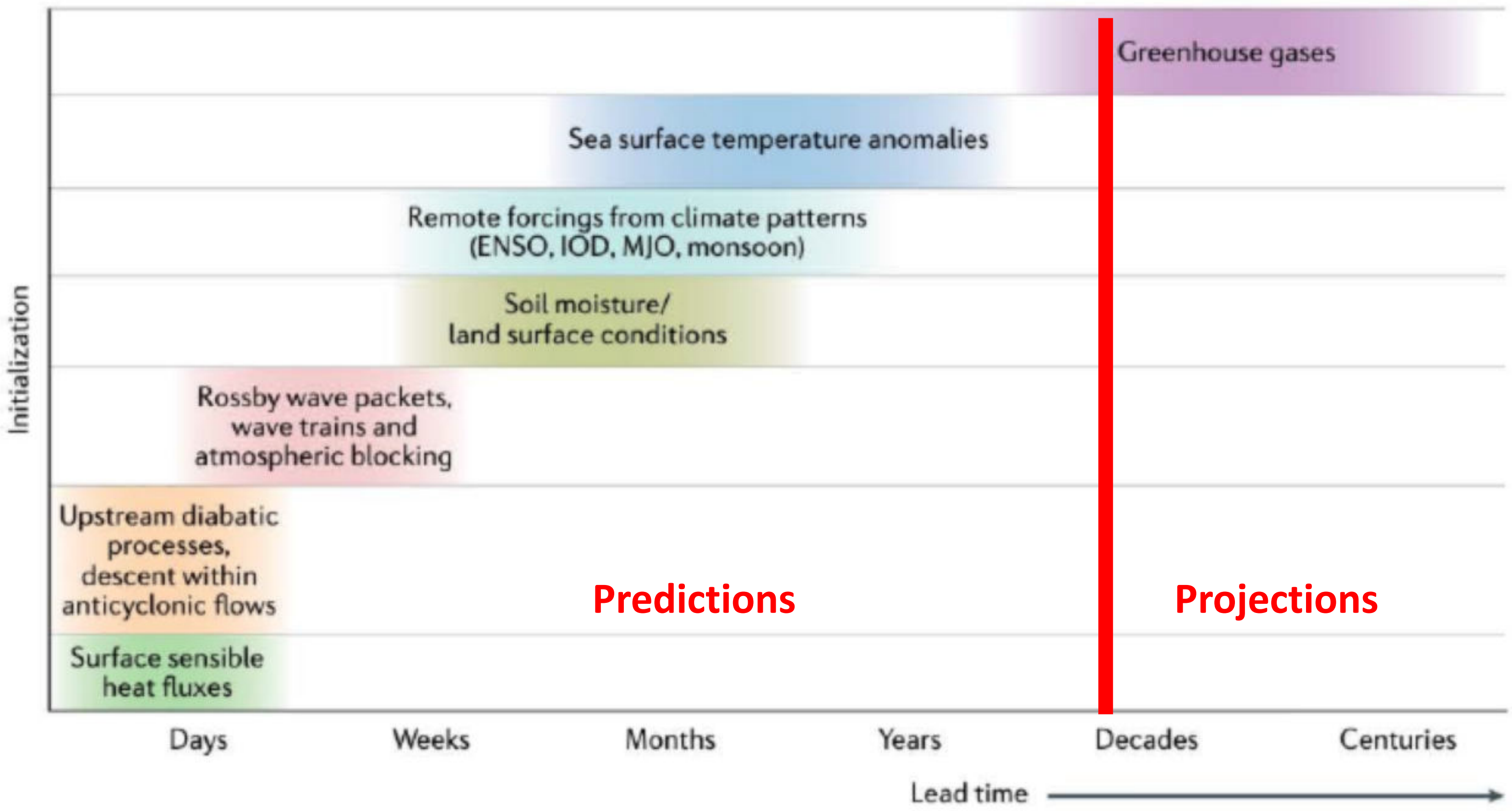
adiabatic



diabatic



Predictors for heatwaves over timescales from days to centuries.



Domeisen et al. (2023)

3-day forecast, research questions:

1) What are the main **physical processes** causing **short-range** (i.e., 3-day) T_{max} forecast errors in **Europe** and are there differences between regular summer days and heatwaves?

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

Method

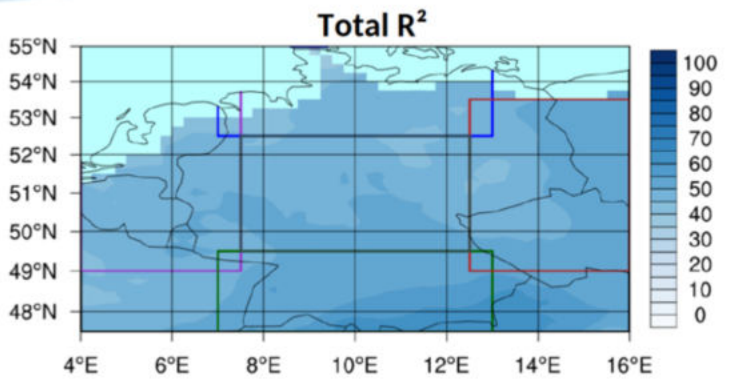
Eulerian approach:

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

1. First construct forecast error fields of T_{max} and other parameters of interest –
   for each day and ensemble member individually.

2. Use T_{max} forecast error as a predictand and forecast errors of multiple other quantities
   as predictors within a MLRM.

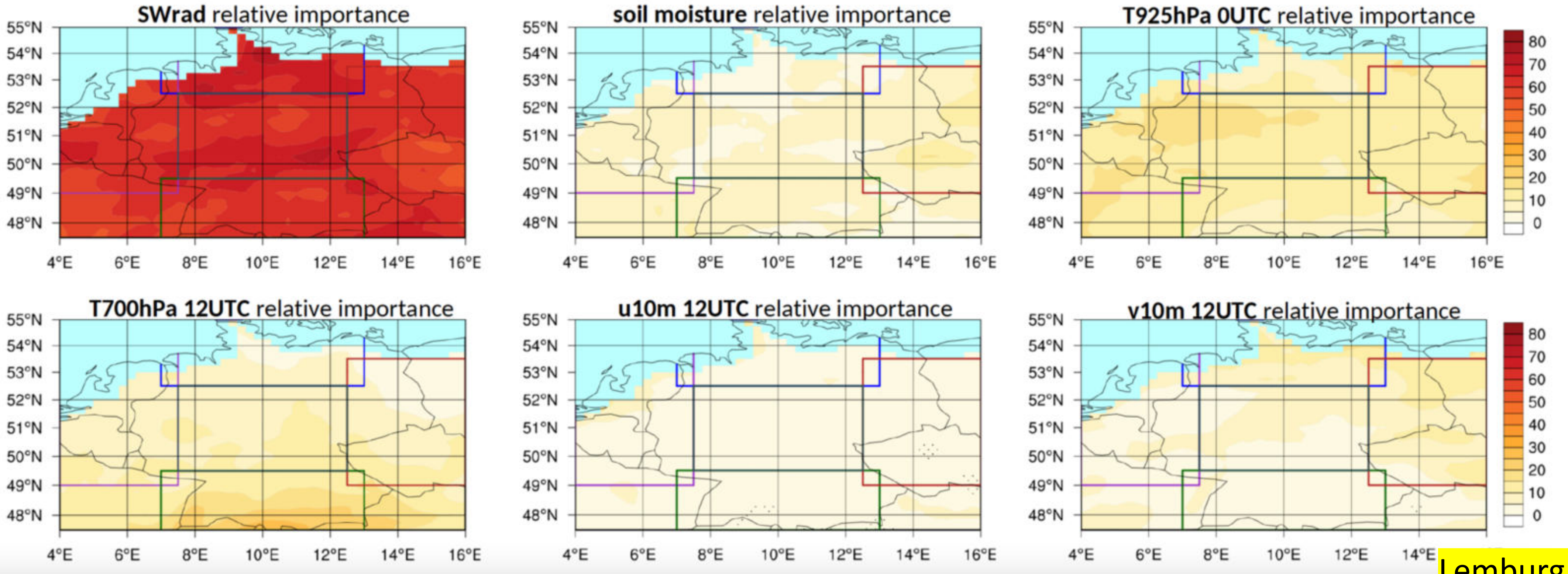
Results of the MLRM for non-heatwave days



R^2 total and relative importance of multiple predictor parameters for "explaining" T_{max} forecast errors in a multi-variate linear model (MLRM)

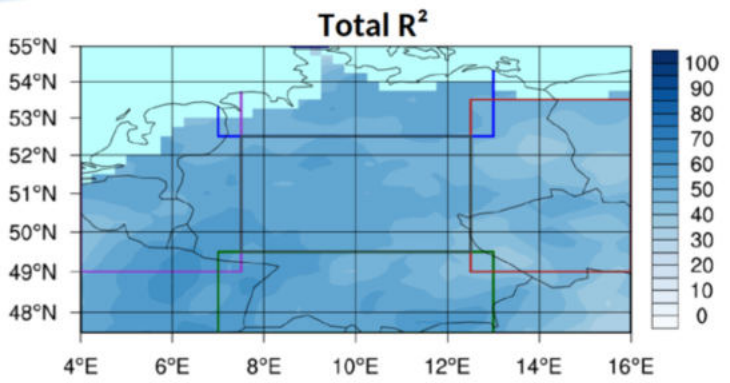
All 50 members included, for non heatwave days, 2015-2020

Errors in downward shortwave radiation (Swrad) dominant error source



Lemburg & Fink (2022)

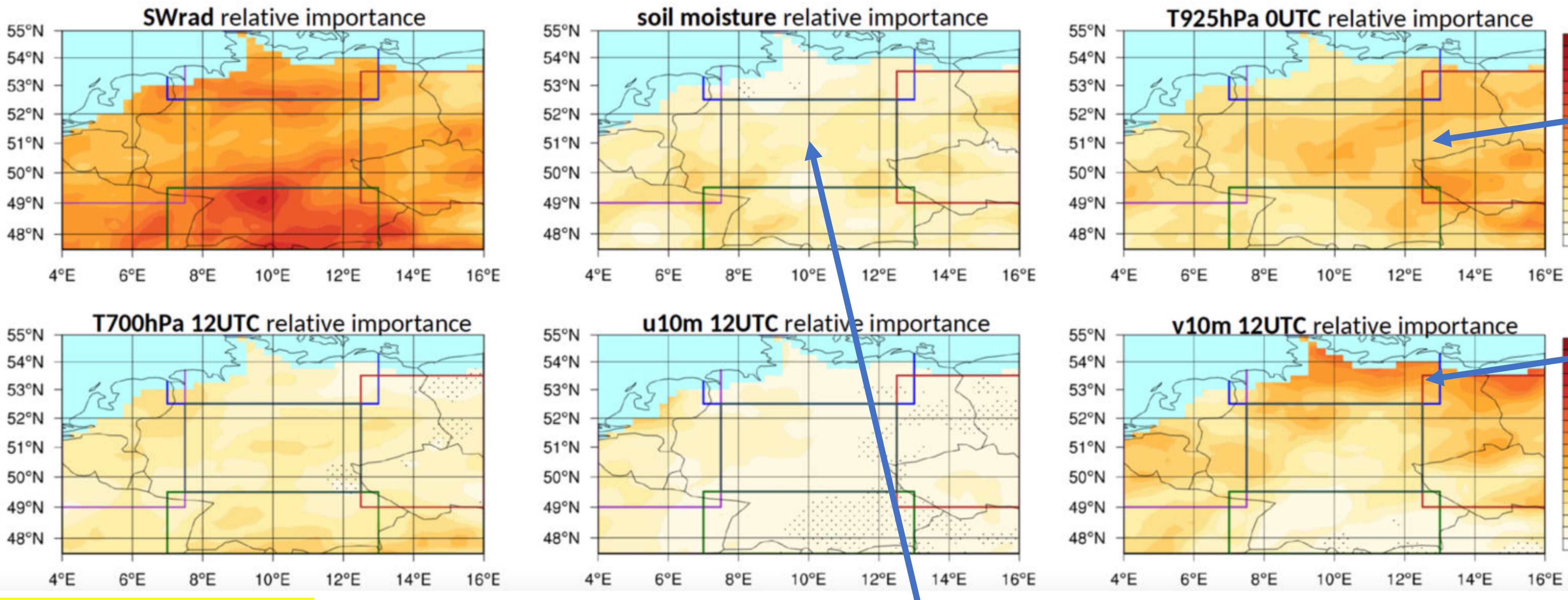
Results of the MLRM for heatwave days



R^2 total and relative importance of multiple predictor parameters for "explaining" T_{max} forecast errors in a multi-variate linear model (MLRM)

All 50 members included, for heatwave days, 2015-2020

Other error sources gain importance and dominate regionally.



Proxy for nightime residual layer

Proxy for ventilation/sea breeze

Soil moisture surprinsingly unimportant

Lemburg & Fink (2022)

Conclusions: Eulerian & Lagrangian view

- In Central Europe, summer T_{max} 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 T_{max} errors:

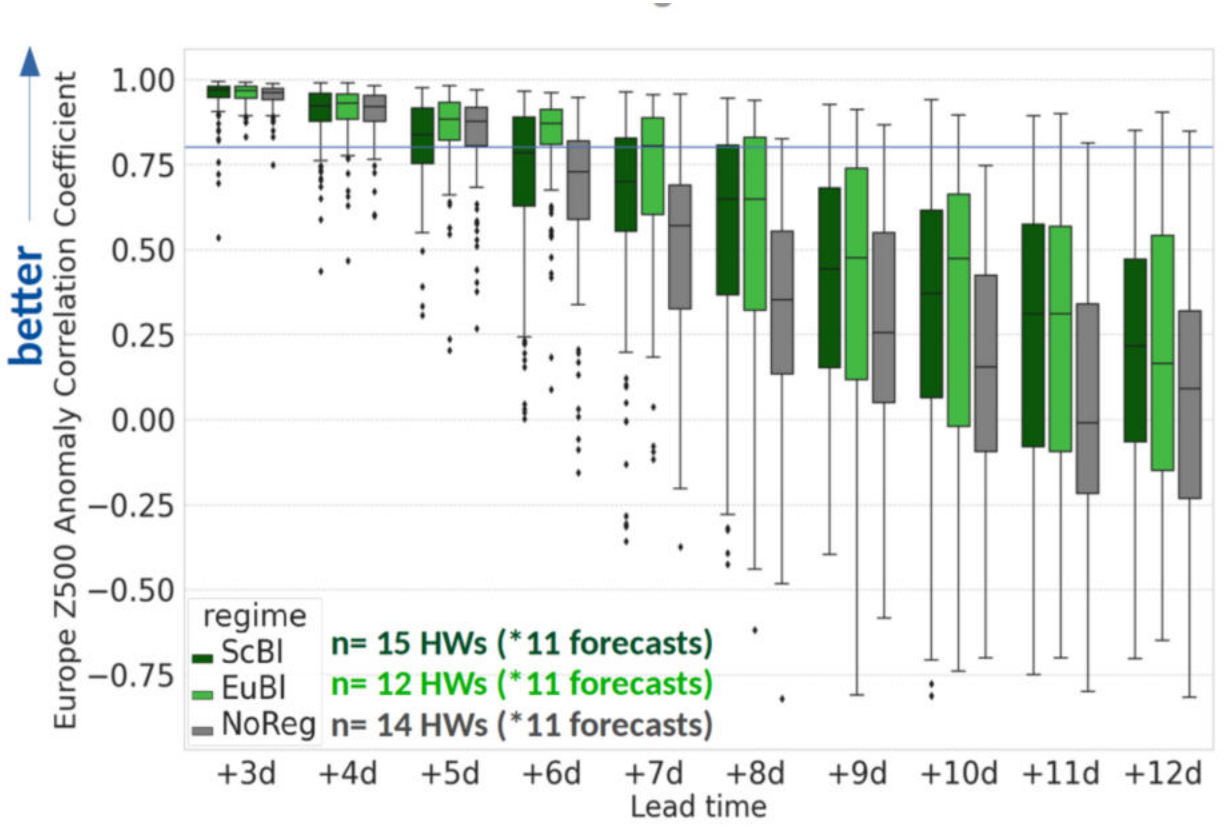
– the error in the nocturnal residual layer temperature is most or second most important in many regions
– soil moisture errors generally (surprisingly) little important overall
– near the coasts, near-surface wind errors dominate

Lagrangian extension of study by 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.

Lemburg & Fink (2022)

Windows of forecast opportunities and why?

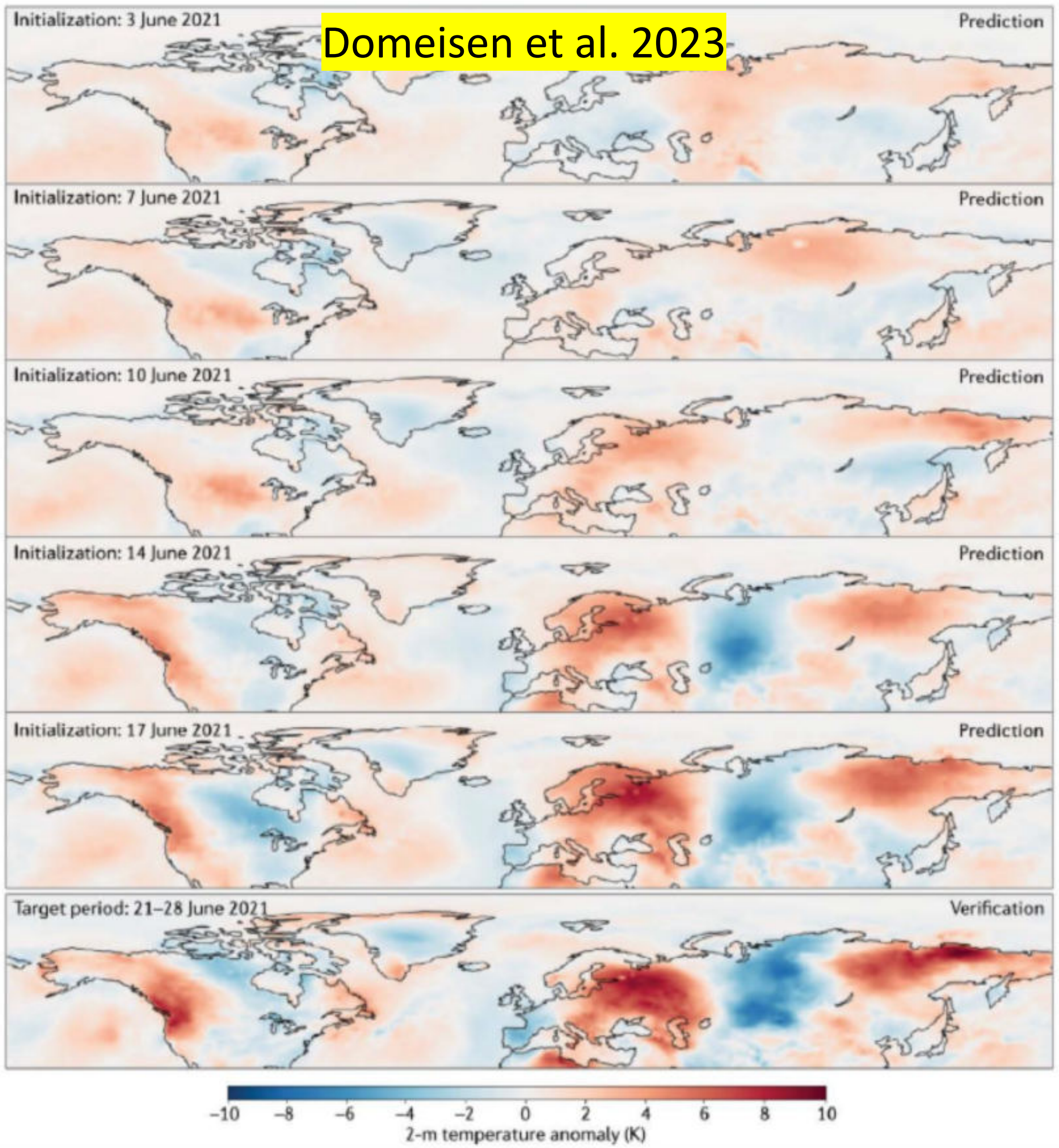


Predictability of 49 Central European heat wave onsets (2001-2018) measured by 500-hPa geopotential anomaly correlation coefficient (ACC) as function of lead time, stratified by analyzed weather regime; based on 11-member ECMWF S2S hindcast ensemble.

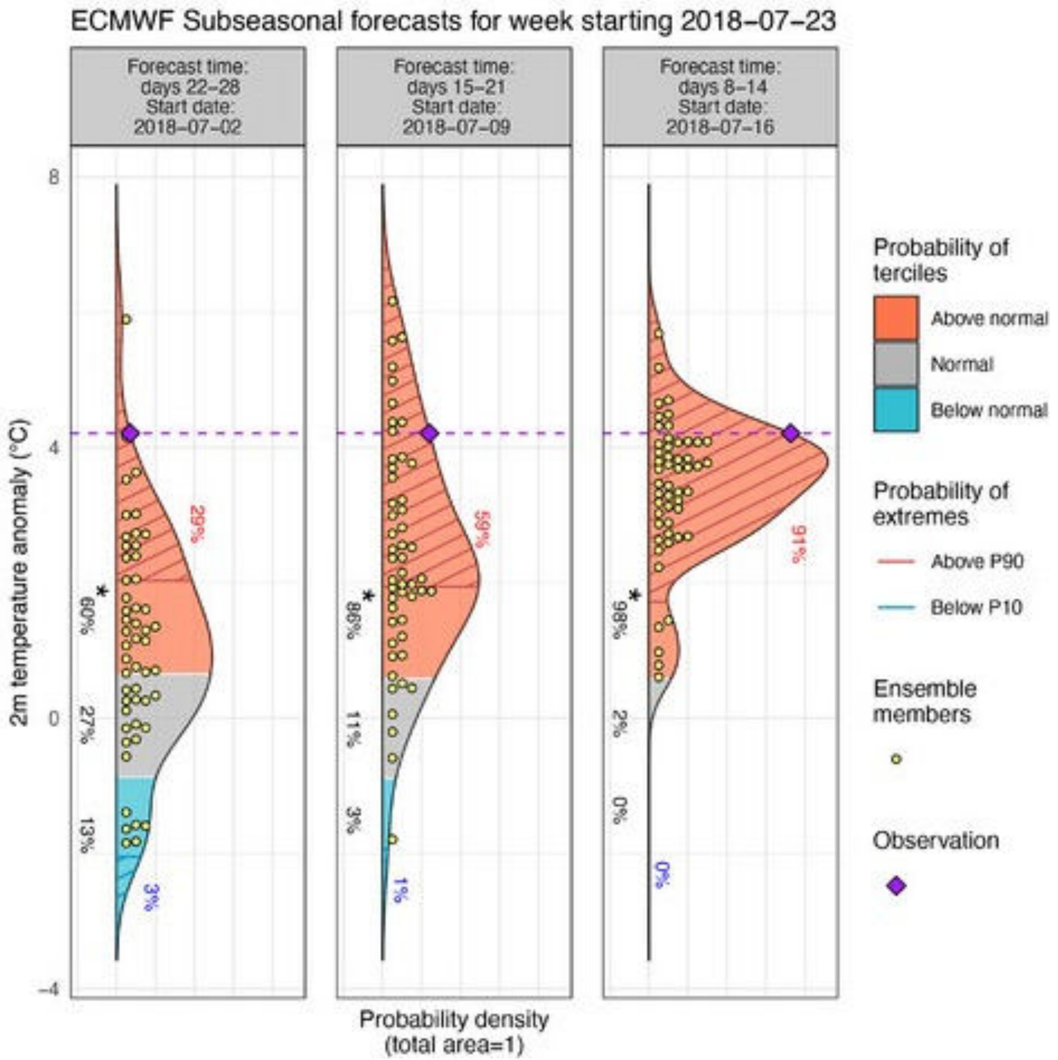
Lemburg & Fink (in preparation)

- The ensemble spread significantly reduces at around a lead time of seven days.
- The European blocking appears to be better predictable when compared to „no regime“.
- We are currently looking for heat waves that had „unsual“ high predictability between 7 & 14 days.

Sub-seasonal predictability



Domeisen et al. 2023



Domeisen et al. 2022

Take home messages

- Europe will experience **heat waves of unprecedented strength** and impacts in the next decades (like the Canadian 2021 heat wave).
- To mitigate the impacts, a better preparedness and improved **early warning** is mandatory.
- Atmospheric phenomena have an **intrinsic limit of predictability** and to assess uncertainties, **ensemble prediction systems** are indispensable.
- In some cases, a **skillful increased probability** of past heat waves was evident at forecast lead times of **2-3 weeks** (**subseasonal**).
- At such long lead times, large-scale processes in the **Tropics**, **soil moisture anomalies** over North America etc. are likely sources of predictability.
- Uncertainty (e.g. the spread of the ensemble) improves a lot at around **day 7**.
- At **3-day lead times**, forecast error can be linked to errors in the prediction of cloudiness and the very turbulent boundary layer.

Thanks for your attention

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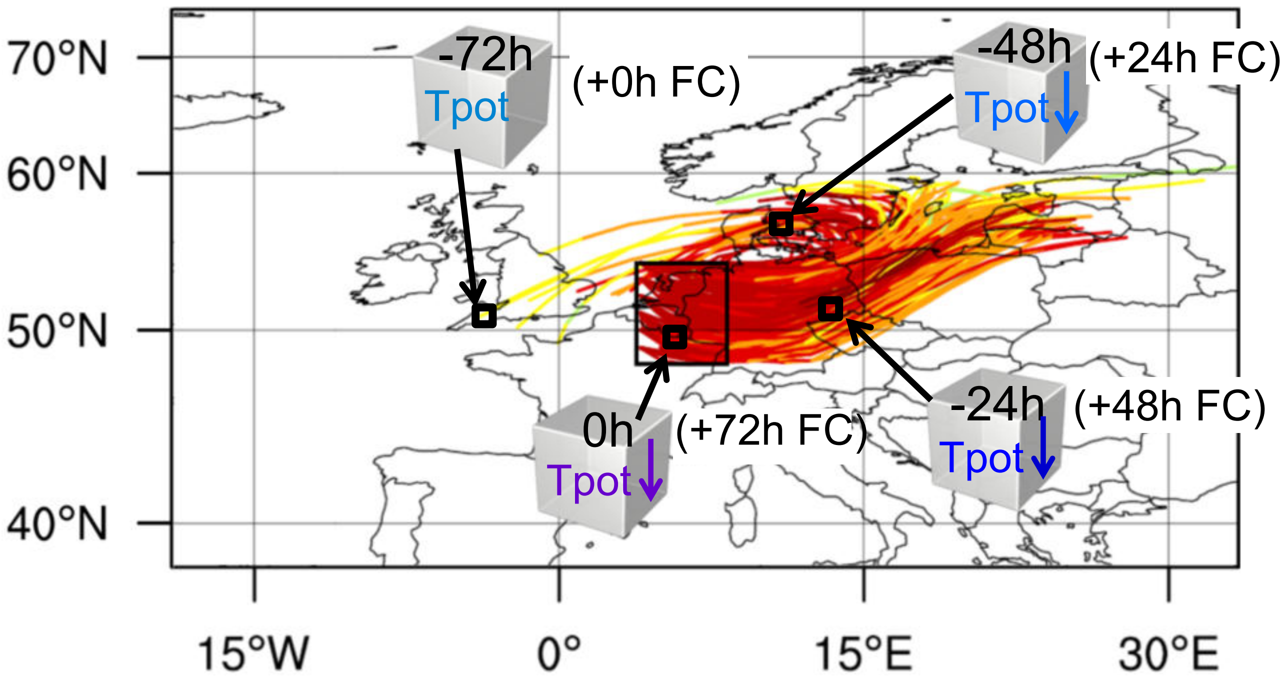
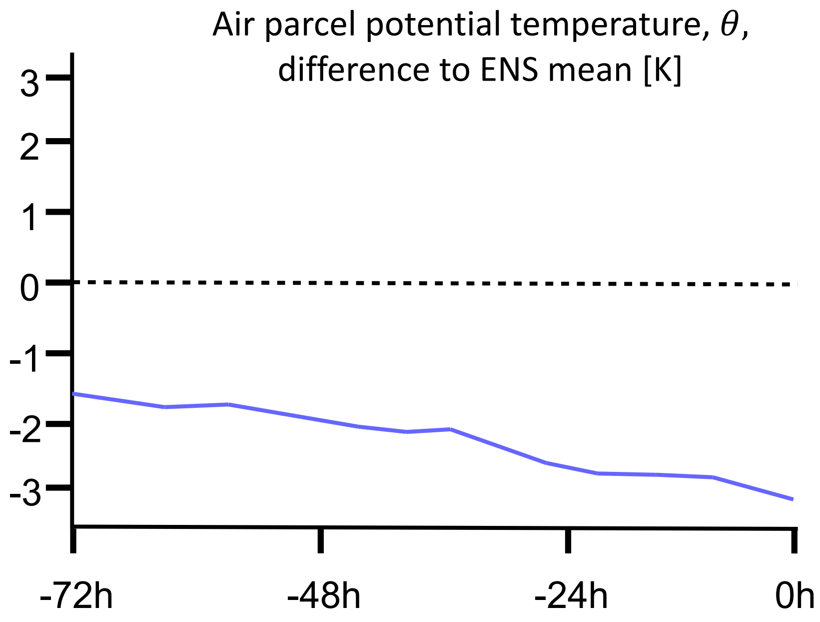
“Waves two Weather”: Large German Research Initiative to understand intrinsic and to improve practice predictability of weather, please visit: https://www.wavestoweather.de (German and English). The project is presented in Craig et al. (2021, doi: 10.1175/BAMS-D-20-0035.1)

A Lagrangian extension

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





Backward trajectories started within 7-13°E; 52.5-55° (western CE region) 25hPa above ground

→ Next slides: Systematic comparison (Research question 2)

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/heatwave days.

Lemburg & Fink (2022)

Differences in travel time over land

JJA 2018–2010, for western and eastern Central European (CE) sub-regions,
averaged difference to ensemble mean (interquartile range depicted by light shadings)

Lemburg & Fink (2022)