External forcing of European summer heatwaves and associated circulation

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Why Study heatwaves

Mitigate impacts on key issues

- Human health
- Infrastructure
- Ecosystems and agriculture

Heatwaves are increasing in frequency and intensity.

- Increased understanding of underlying causes of heatwaves allows for greater prediction and preparation, mitigating negative effects.

Eight more die as India faces 'longest' heatwave

Asia · 11 Jun 2024

Greece fires trigger huge ammo depot explosions

Europe · 28 Jul 2023

Balkans hit by blackouts as heatwave persists

21 Jun 24

How hot will it get in southern Europe heatwave today?

17 Jul 23

Domeison *et al.* (2023); Russo, Sillmann and Fischer (2015); Portner *et al.* (2022).

Outline of talk

- Definitions and data
- **PART 1: Examine heatwave trends from 1940 to 2024.**
- **PART 2: Attribute contributions to trends to different forcing agents using large ensemble data (HadGEM3-GC31-LL).**
- **PART 3: Use of self-organising maps (SOMs) to classify associated atmospheric circulation patterns.**
- Summary and Discussion

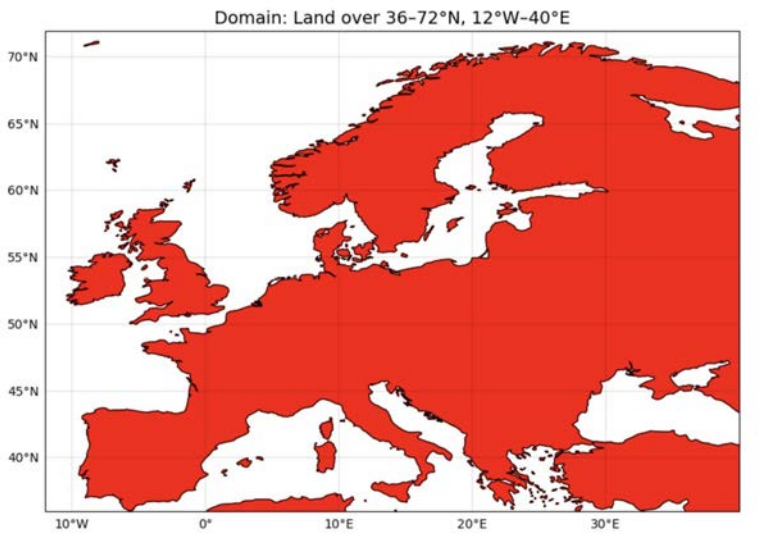
Data

ERA5 Reanalysis

- 1940-2024
- Resolution of 31km

HadGEM3-GC31-LL

- The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP)
- 1850-2020
- N96 grid; resolution of 135km



Variables

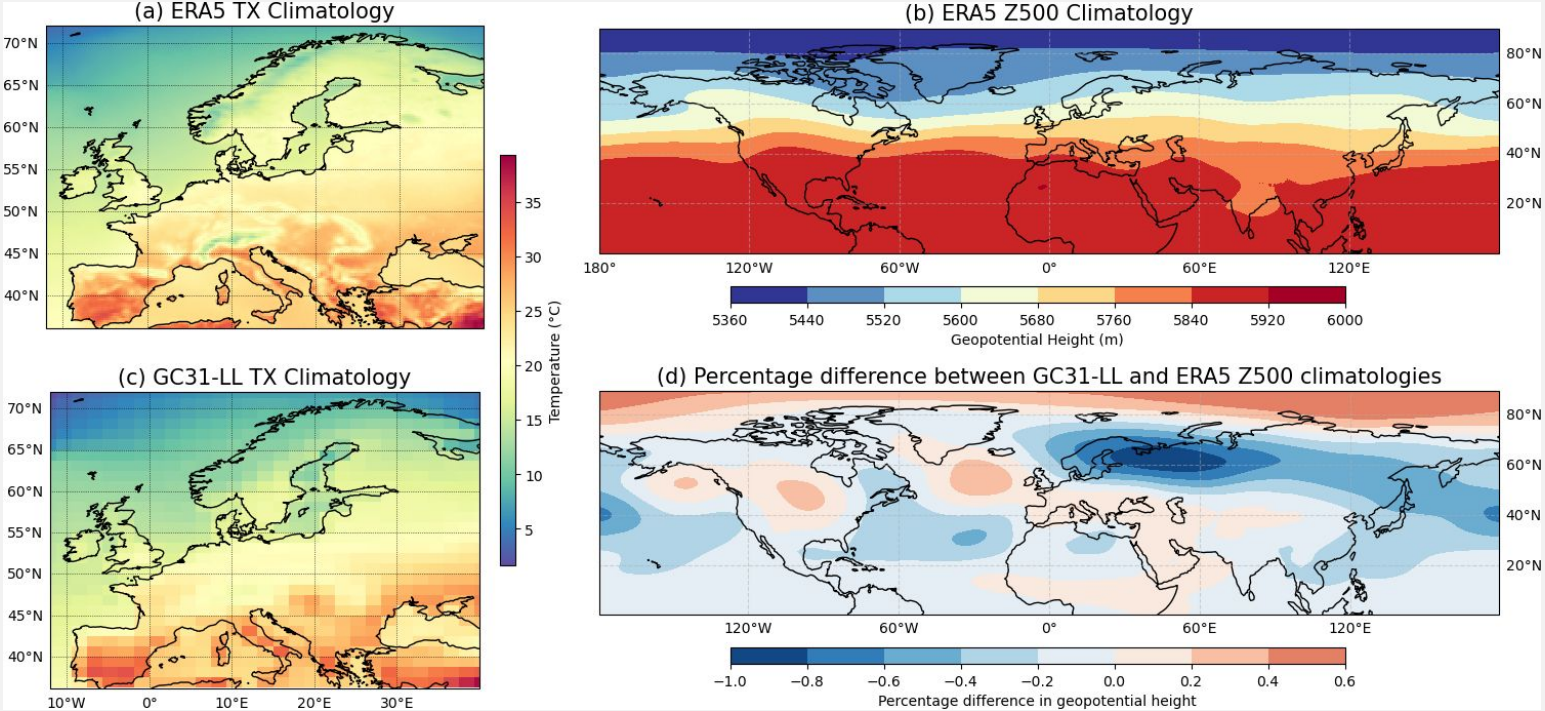
- TX (daily maximum temperature) is used to define heatwaves
- Z500 (daily mean geopotential height at 500hPa) is used for corresponding circulations.

HadGEM3-GC31-LL experiments and available data

Experiment name	Description	Number of ensemble members for TX	Number of ensemble members for Z500
hist-GHG	Well-mixed greenhouse-gas-only historical simulations	55	5
hist-aer	Anthropogenic-aerosol-only historical simulations	55	5
hist-sol	Solar-only historical simulations	50	0
hist-volc	Volcanic-only historical simulations	50	0
hist-totalO3	Ozone-only historical simulations	50	0
hist-nat	Natural forcings (solar + volcanic)	60	10
historical	All forcings, extended to 2020 using future scenario experiment SSP2-4.5	55	5

Based on Smith *et al.* (2022) Table 1

Suitability of GC31-LL to analyse European heatwaves



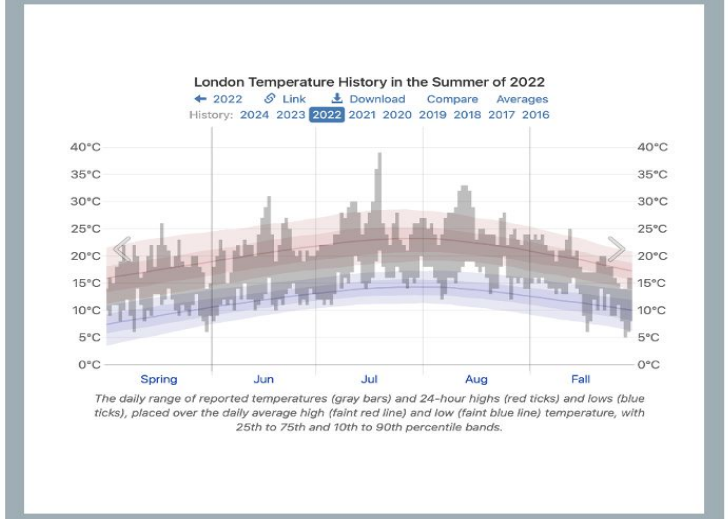
1980-2010 climatologies: (a) Summer TX (°C) over Europe from ERA5, and (c) from the HadGEM3-GC31-LL all-forcings ensemble mean (55 members); (b) Z500 (m) over the Northern Hemisphere from ERA5; (d) percentage difference in Z500 between the GC31-LL all-forcings mean (5 members) and ERA5.

Heatwave definition

A heatwave occurs if there is a period of three or more days above the heatwave threshold, where the heatwave threshold is defined as the 90th percentile of TX anomalies.

- TX: daily maximum temperature
- Anomaly based (calculated using a fixed climatology)
- Defined for every grid point

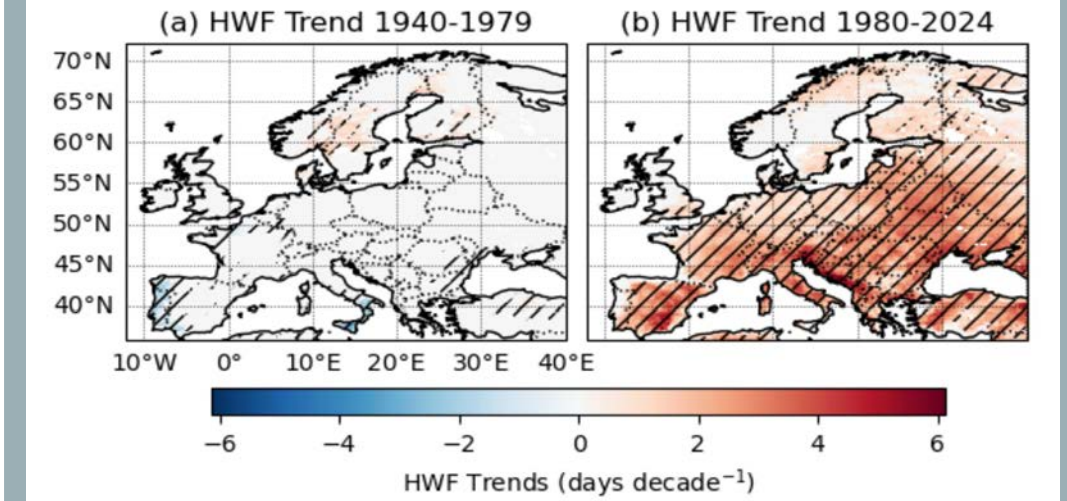
Heatwave Frequency (HWF): The number of days which contribute to heatwaves for each grid point for each summer (June-August).



https://climpact-sci.org/indices/, Perkins and Alexander (2013); weatherspark.com

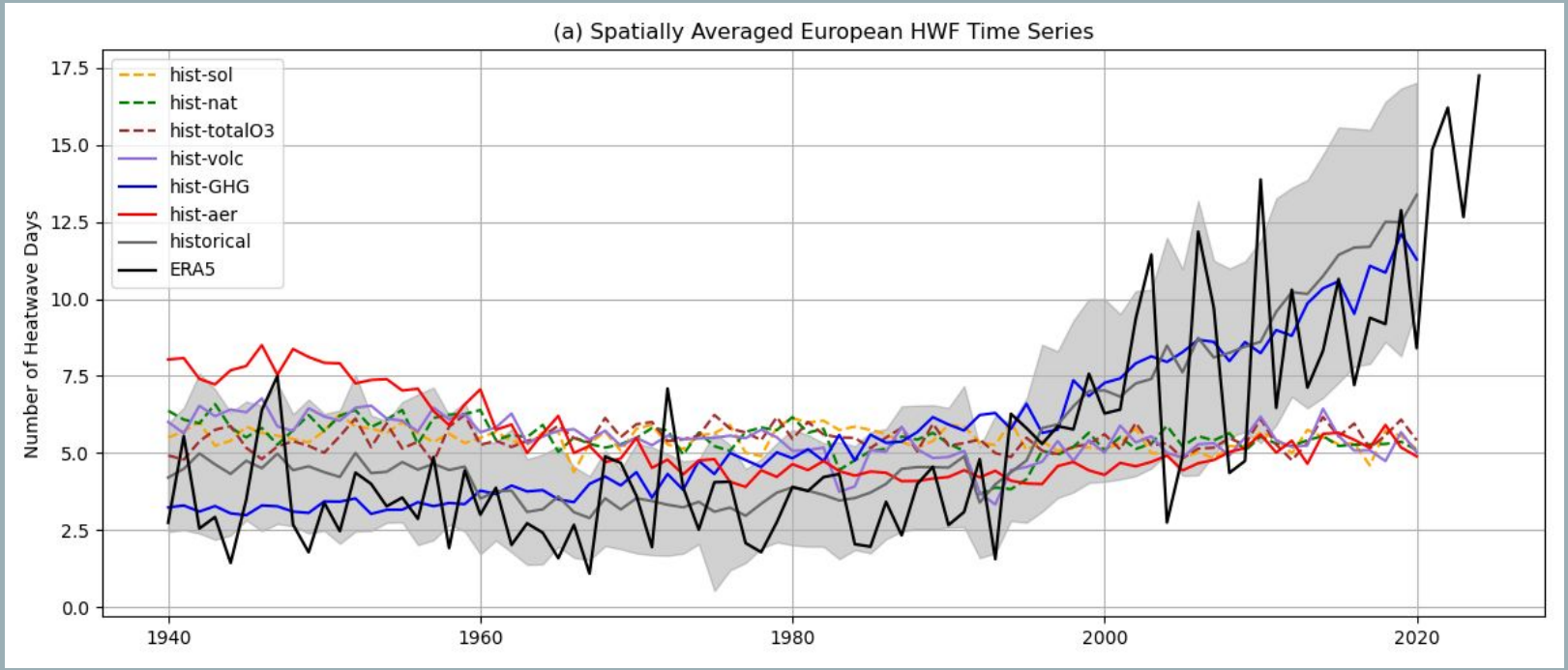
Part 1: Trends in ERA5

Thiel-Sen trends and Mann-Kendall significance at the 5% level indicated by hatching



- Limited trend in early period
- Strongest positive significant trends in Southern Europe in 1980-2024 (regional average of 2.1 days per decade)

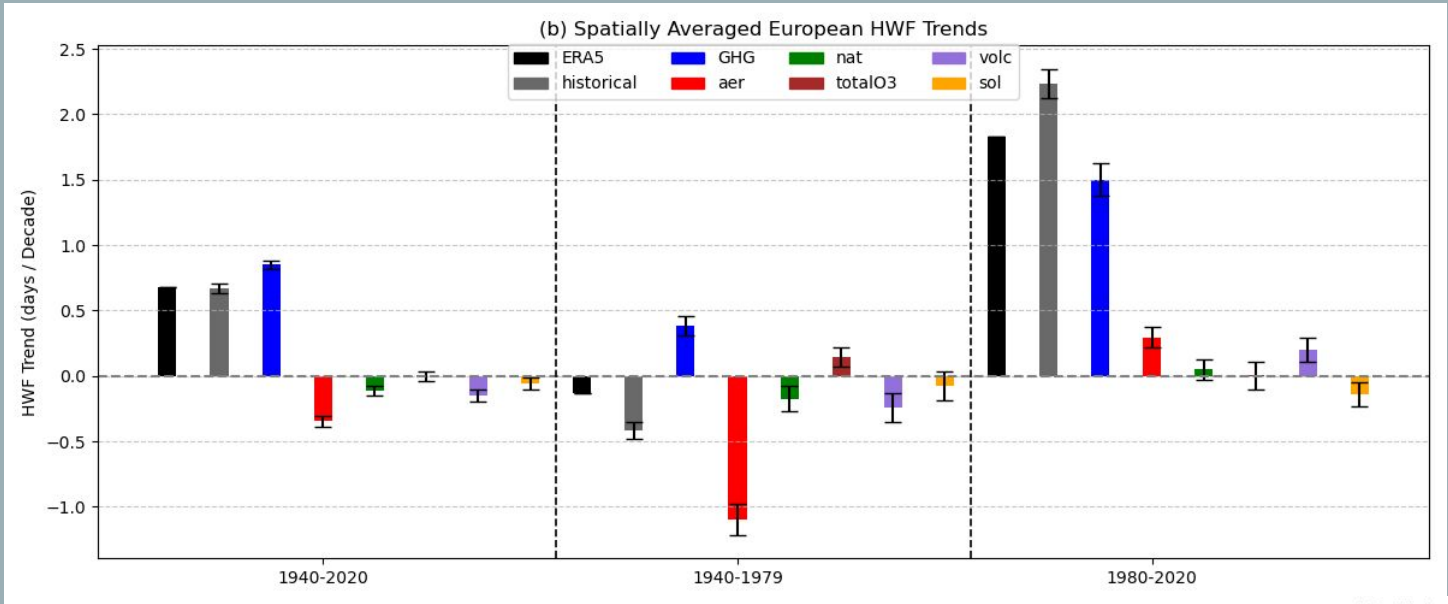
Part 2: Trend attribution using GC31-LL



HWF spatially averaged over Europe for ERA5 (black) and ensemble averages for all (grey) and single forcing experiments. The standard deviation of the all-forcings model experiment is shown shaded in grey.

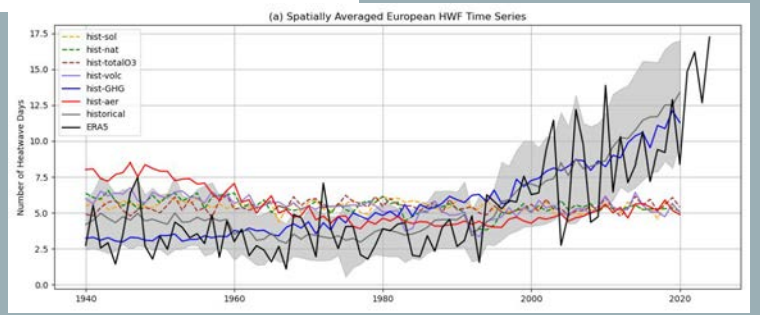
High trend agreement between ERA5 and GC31-LL all forcings.

Part 2: Trend attribution using GC31-LL



Thiel-Sen trends for HWF for three time periods with error bars showing the 95% confidence interval calculated using bootstrapping.

- Trends in the model largely due to GHGs and aerosols.
- The model does not reproduce ERA5's HWF trend in Northern Europe.



Part 3: Categorising circulation patterns

What is a self-organising map?

- Self-organising maps (SOMs) are a type of artificial neural network used for unsupervised machine learning, enabling the classification of data into a specified number of clusters.

- Here, to classify atmospheric circulation patterns during heatwaves
  - 20°–90°N and 90°W–90°E
  - Trained on 10% of summer days from 1950-2014, those with the largest land area covered by heatwaves.

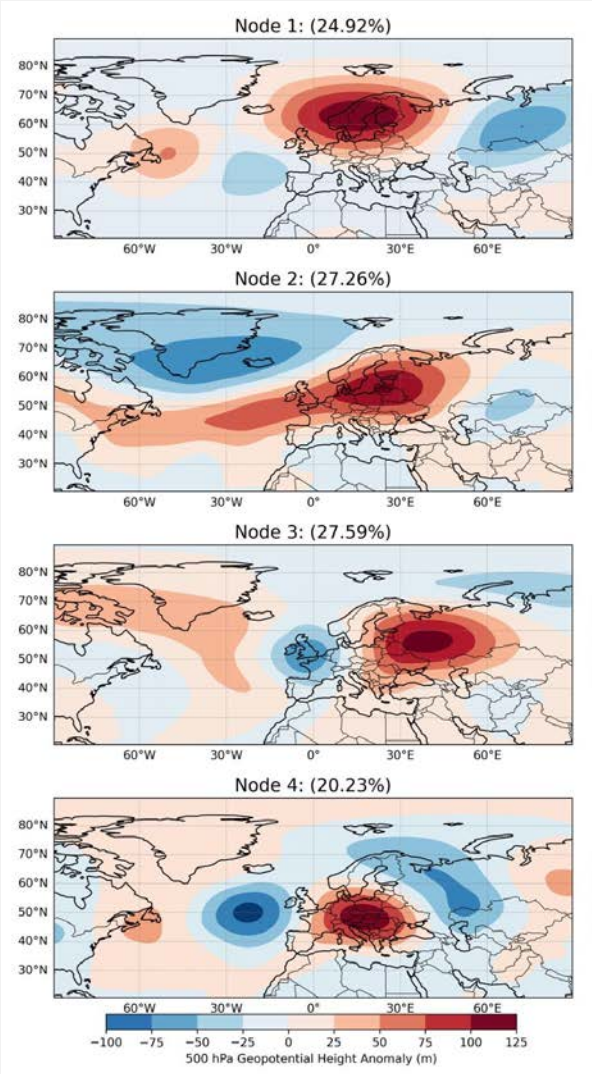
```python
def train_som(data, x, y, input_len, sigma, learning_rate, num_iteration):
    som = minisom.MiniSom(
        y,
        x,
        input_len = input_len,
        sigma=sigma,
        learning_rate=learning_rate,
        neighborhood_function='gaussian',
        activation_distance='euclidean',
        sigma_decay_function = 'asymptotic_decay',
        decay_function = 'asymptotic_decay',
        )

    # Initialize SOM weights
    som.random_weights_init(data)

    # Train SOM
    som.train(data, num_iteration=num_iteration, random_order=True, verbose=True)

    return som
```

Lee (2013), Johnson (2008)



Scandinavian blocking

SNAO+ Dipole between Greenland and Northern Europe

Russian Blocking

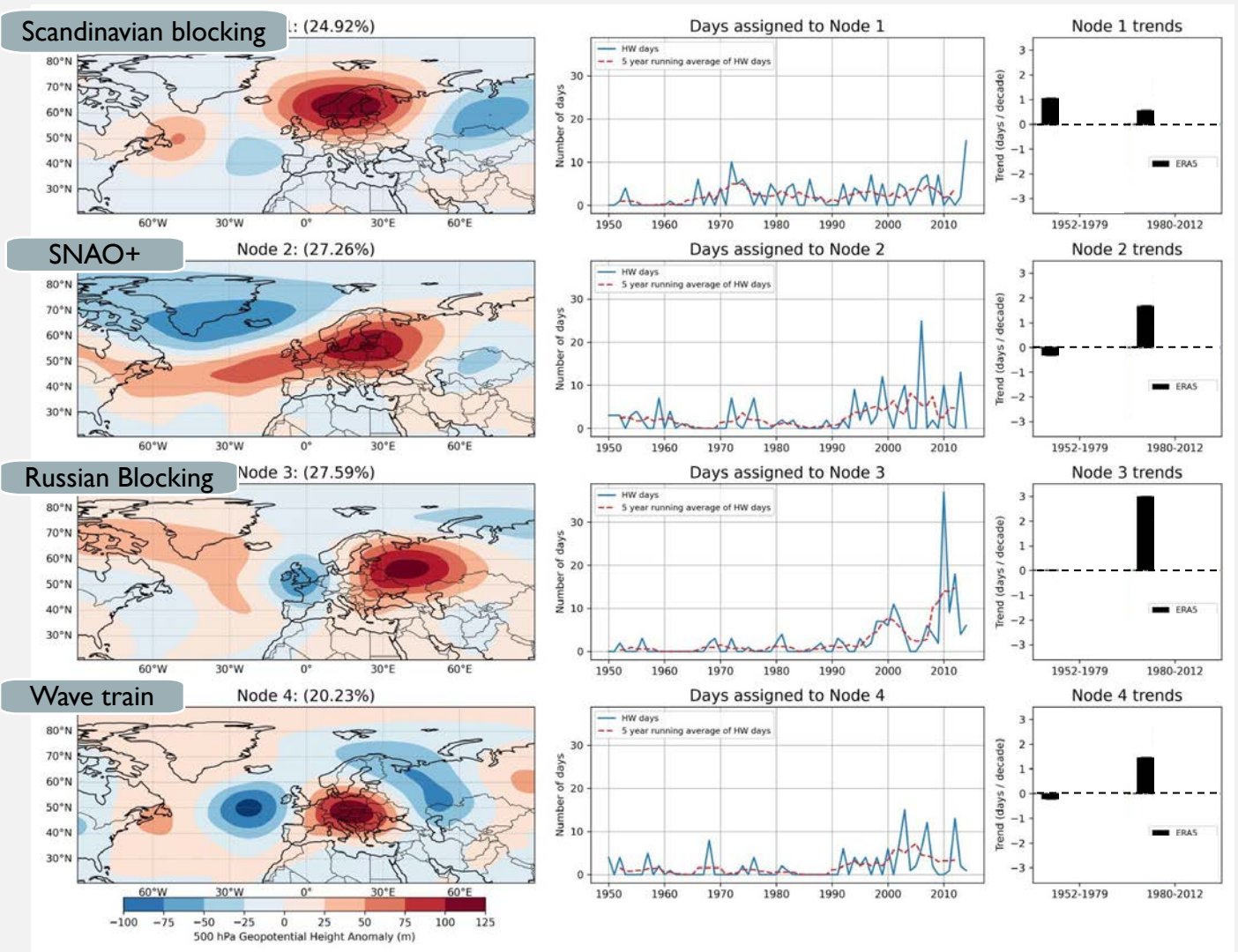
Midlatitude wave train, with a high-pressure centre over central Europe.

ERA5 circulation patterns

Geopotential height anomaly at 500hPa SOM patterns for ERA5 and percentage of days assigned to that node.

Nodes 3 and 4 – reminiscent of circumglobal wave pattern

Trends in ERA5 nodes

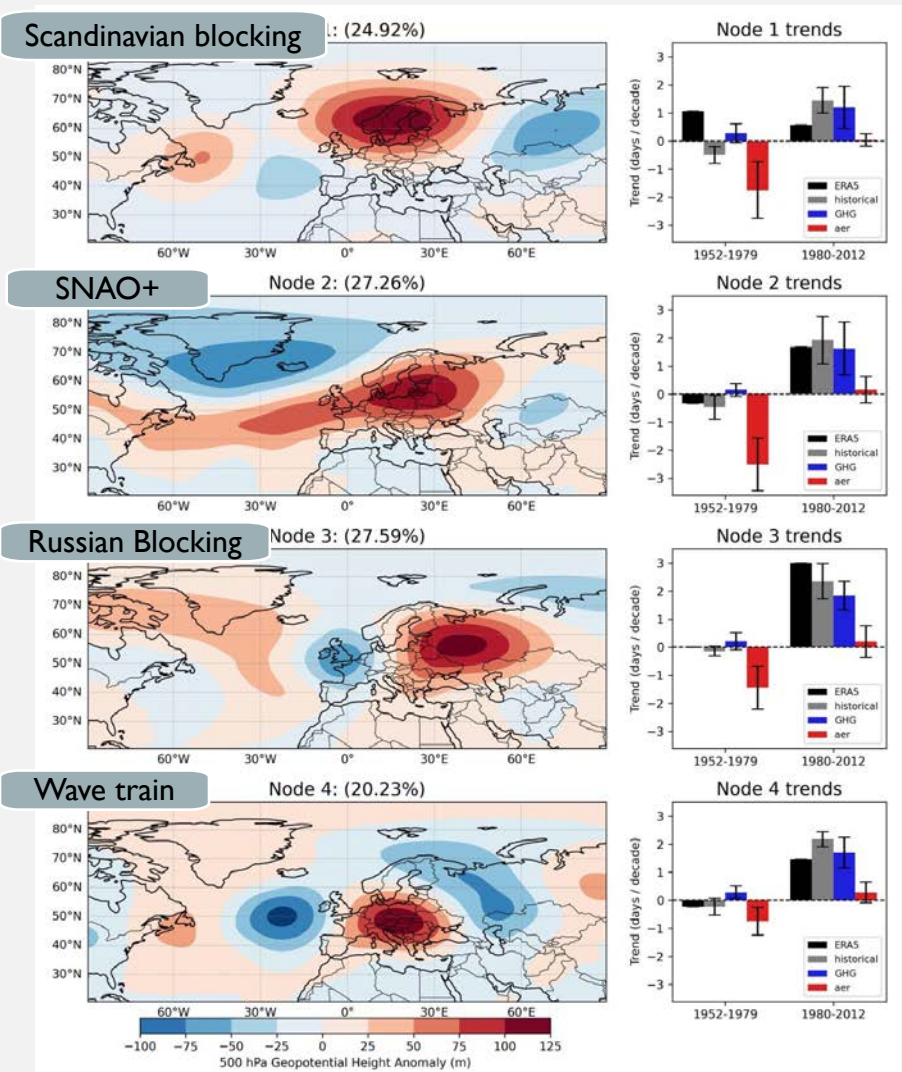


(**centre**) days assigned to each node per year (blue) and the five-year running average (red)

(**right**) the Theil-Sen trends (days/ decade) for 1952-1979 and 1980-2012.

- Node 2-4: large trend in later period, limited or negative in early.
- Node 1: More stable

Attribution of circulation using GC31-LL



(**right**) the Theil-Sen trends for ERA5, and 5-member ensemble averages for GC31-LL all-forcings, hist-GHG and hist-aer. Error bars show the 95% confidence interval on ensemble means.

- GHG dominant in latter period
- Aerosol dominant in early period
  - But much greater trend than all forcings
- All nodes show similar pattern in model
  - Mismatched with ERA5 for node 1 – relates to Northern European HWF trend.
- Small ensembles (5 members)

Future Work

My plan for the next few months:

- More models to account for model bias and uncertainty.
- Incorporate other drivers such as land-use and soil moisture effects.
- Investigate improvements to SOM method/ other methods for attribution of circulation.
    - Comments very welcome!

Future uses:

- Expand to include impacts metrics (for each forcing)
- Translation of basic science to application.

Summary of key results

1. ERA5 Trends in HWF are strongly positive after 1980, particularly in Southern Europe.
2. The dominant contributor to positive trends is well-mixed GHGs, while aerosols exert a significant cooling effect prior to 1980.
3. Atmospheric circulation patterns from SOMs may explain the difference between Southern and Northern heatwave trends in ERA5, but the model doesn't fully replicate this.

Any questions?

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Acknowledgements

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References

S. E. Perkins and L.V. Alexander. On the measurement of heat waves. *Journal of climate*, 26(13):4500–4517, 2013.

D. M. Smith, N. P. Gillett, I. R. Simpson, P. J. Athanasiadis, J. Baehr, I. Bethke, T. A. Bilge, R. Bonnet, O. Boucher, K. Findell, et al. Attribution of multi-annual to decadal changes in the climate system: The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP). *Frontiers in Climat*e, 4:955414, 2022.

N. C. Johnson, S. B. Feldstein, and B. Tremblay. The continuum of Northern Hemisphere teleconnection patterns and a description of the NAO shift with the use of self-organizing maps. *Journal of Climate*, 21(23):6354–6371, 2008.

M. Lee, S. Lee, H. Song, and C. Ho. The recent increase in the occurrence of a boreal summer teleconnection and its relationship with temperature extremes. *Journal of Climate*, 30(18):7493–7504, 2017.

S. Lee and S. B. Feldstein. Detecting ozone-and greenhouse gas–driven wind trends with observational data. *Science*, 339(6119):563–567, 2013.

D. Domeisen, E. Eltahir, E. Fischer, R. Knutti, S. Perkins-Kirkpatrick, C. Schar, S. Seneviratne, and A. Weisheimer. Prediction and projection of heatwaves. *Nature Reviews Earth & Environment*, 4(1):36–50, 2023.

S. Russo, J. Sillmann, and E. M. Fischer. Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, 10(12):124003, 2015.

H. O. Pörtner, D. C. Roberts, H. Adams, C. Adler, P. Aldunce, E. Ali, R. A. Begum, R. Betts, R. Bezner Kerr, et al. Climate change 2022: impacts, adaptation and vulnerability. Technical report, IPCC, 2022.