Towards global coupled k-scale modeling within an ~~UK~~NCAS climate modelling strategy

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National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

University of Reading

Outline

1. Context:
   a. On models, policy, and
   b. Uncertainty.
2. Brief introduction to the NCAS modelling strategy
   a. A wee bit of a direction of travel
   b. On data tooling.
3. What large-ensembles tell us about some of our choices.

Why do we have models? Plural?

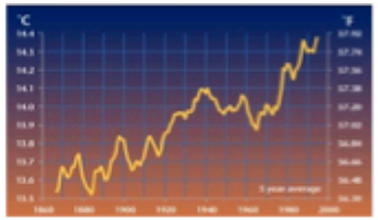
The usual answer is because we think multiple models help us assess model uncertainty. Other answers include: "Politics".

However, those answers are implicitly addressing a different question: Why do we have multiple versions of a models which purport to address the same problem?

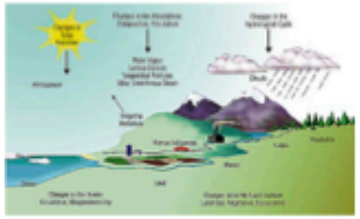
But a more interesting set of questions are:

1. Why do we pretend that one model is fit for all applications?
2. What does it mean for a model to be fit for purpose?
3. What can we afford to do anyway?

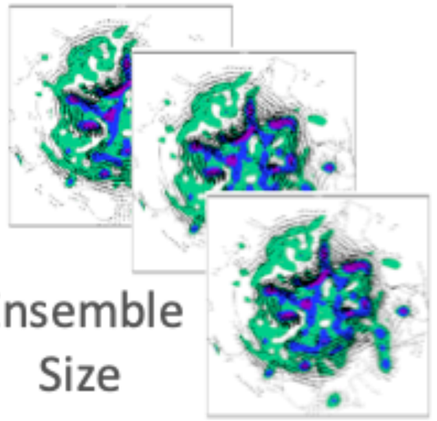
Computing is finite, science is not!



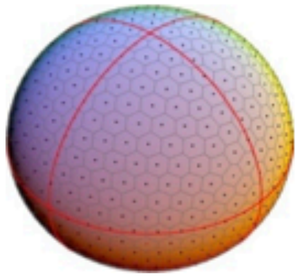
Duration



Complexity

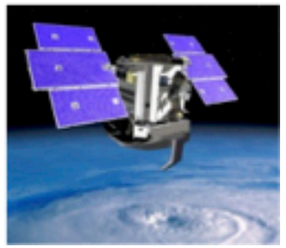


Ensemble Size



Resolution

Data Assimilation



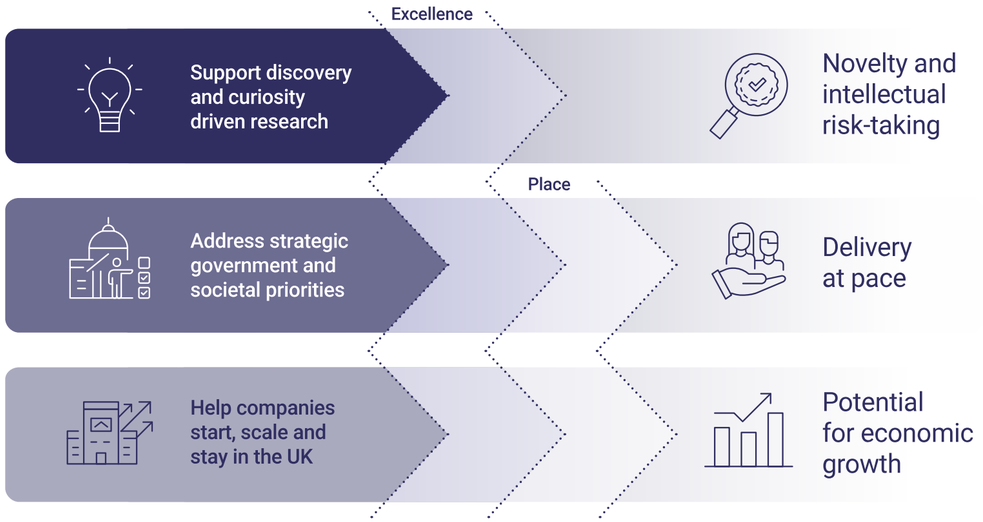
Variability Scenarios Extremes

The tension between science and policy

SCIENCE DRIVERS

1. To understand the climate processes operating at local, regional and global scales across timescales from months to centuries and how they might change in the face of anthropogenic influences .
2. To understand the role of global teleconnections for near- term climate change and predictability, and the role of the tropics in shaping the climate at mid and high latitudes (and vice-versa).
3. To address and understand systematic uncertainties and biases in both our understanding and our models.

POLICY PULL

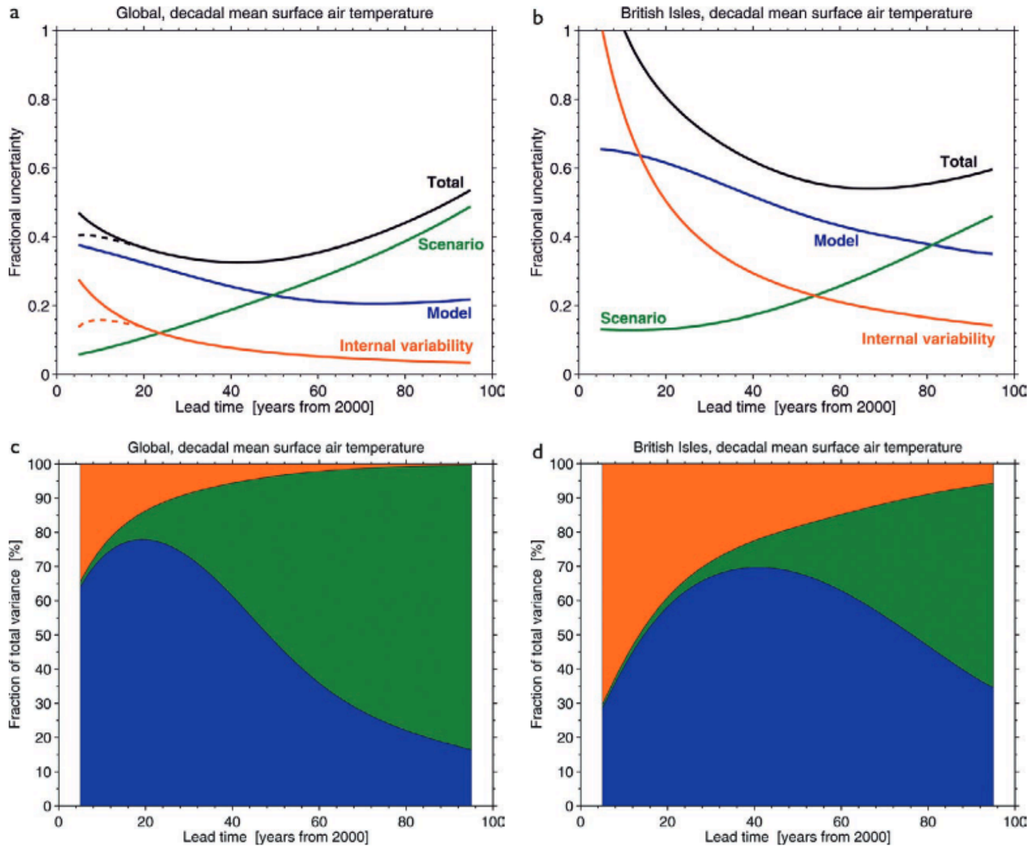


UK research is pivoting towards a very UK "industry" focus (albeit the UK PLC has some global interests). Climate is not a headline requirement, but "climate resilience" is embedded throughout.

We need large-scale models which deliver in both directions!

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On uncertainty - gobal scales



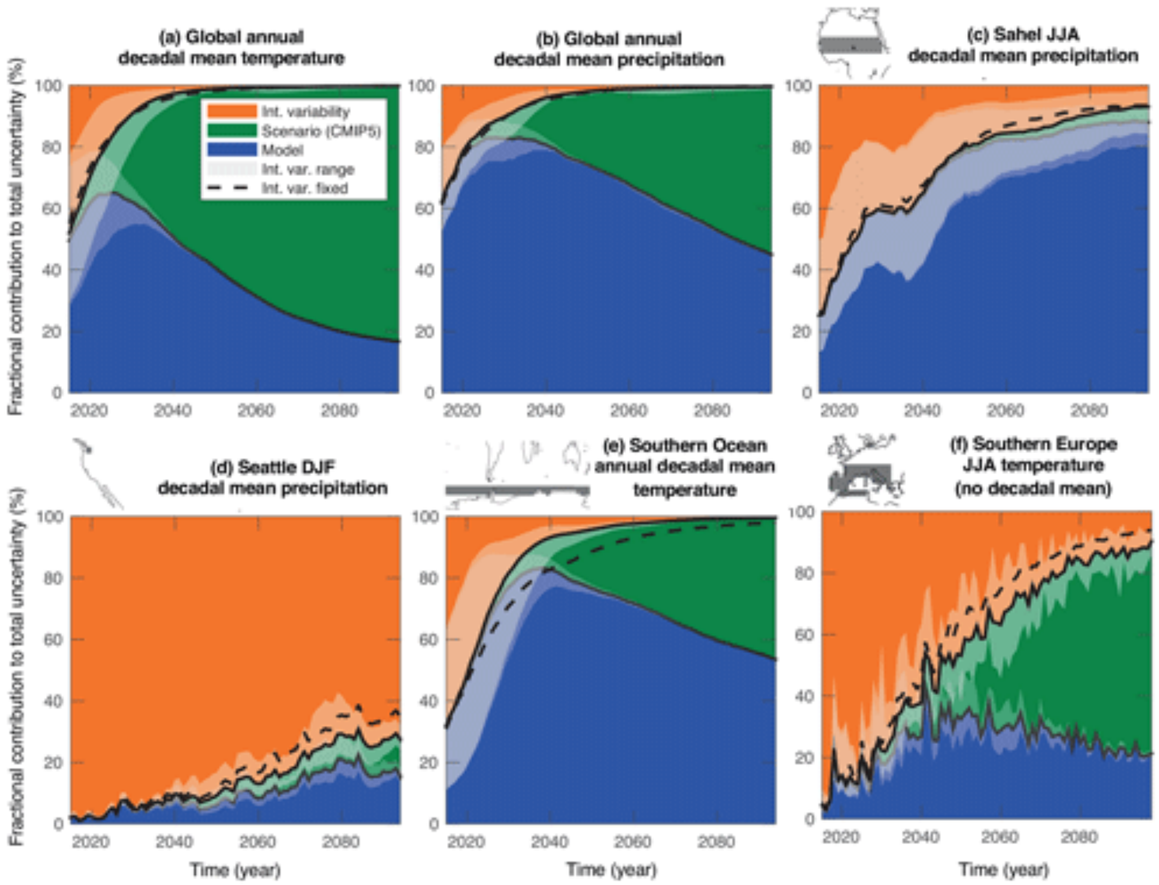
They said:

1. At the global scale uncertainty in decadal mean temperature rapidly becomes dominated by scenario uncertainty.
2. The importance of scenario uncertainty is relatively less when we are interested in regional climate.
3. At the regional scale, it is 50 years before scenario uncertainty becomes important.

- It seems clear that regional results need revisiting with models more representative of regional-scale processes.

(Hawkins & Sutton, 2009: The Potential to Narrow Uncertainty in Regional Climate Predictions. https://doi.org/10.1175/2009BAMS2607.1)

On uncertainty - Regional Scales



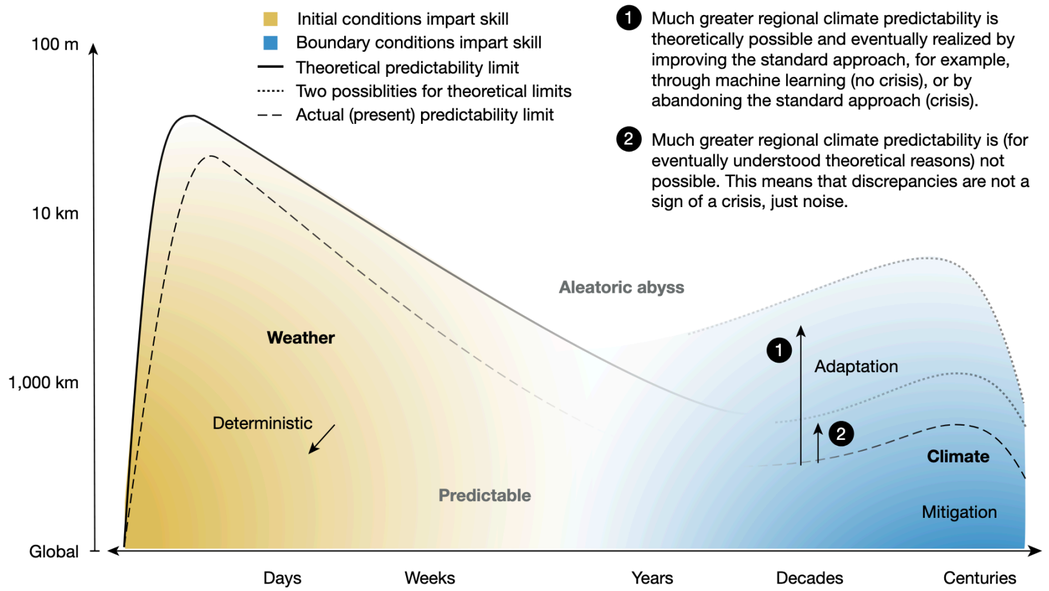
Making use of Single Model Large Ensembles (SMLEs) to revisit uncertainty.

Broad conclusion: ***Model uncertainty is still dominant in many regions, but somewhat reduced relative to internal variability*.**

(Lehner et al 2020: Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. https://doi.org/10.5194/esd-11-491-2020)

And it seems clear that as we go to higher resolution, the influence of natural variability is unlikely to fall.

On Regional Predictability



Possible that "regional climate predictability is (for eventually understood theoretical reasons) not possible. This means that *discrepancies are not a sign of a crisis, just noise.*"

One person's noise is another persons's signal!

(Shaw and Stevens 2025: The other climate crisis: https://doi.org/10.1038/s41586-025-08680-1)

Three World Class Modelling-Systems

PROCESS-FIDELITY

- ~1 SYDP, one at a time.

A state-of-the-art, high-resolution physical coupled climate model capable of simulating decades of the future at ultra-high fidelity.

Building on the HRCM programme

- Using hundreds of nodes to run. In one machine for many months per run.

VARIABILITY

- ~2 SYPD, multiple jobs at a time

Exploiting single-model large-ensembles of global historical and future climates to understand natural variability and key teleconnections.

Building on CANARI

- Using dozens of nodes, in one or two machines for a year or more.

EARTH-SYSTEM

- ~10 SYPD, multiple jobs at a time

Incorporating major earth-system components and feedbacks (carbon cycle, ice sheets, methane) integrated over centuries.

Building on UKESM and TERRAFIRMA

- Up to a couple of dozen nodes, each run resident for up to a few months, multiple platforms.

(This slide says nothing about use of AI or hybrid models, it simply outlines pragmatic zones of compromise between feasibility and goals.)

Technical Enablers and Infrastructure

AI AND WORKFLOW INTEGRATION

Harnessing modern data science to accelerate discovery and optimize massive computational workflows.

- **Model Enhancement**: Exploiting AI/ML architectures to improve physical climate parameterizations.
- **Workflow Optimization**: Streamlining end-to-end orchestration, diagnostic checks, and data pipeline management.
- **Advanced Analysis**: Enhancing diagnostic capabilities to extract information from complex global model outputs. Support training of climate model emulators.

INTER-COMPARISON AND DATA STANDARDS

Sustaining the vital data frameworks that enable global academic and policy collaboration

- **Standards and Conventions**: Direct support for global metadata conventions (CF, CMIP) to guarantee interoperability.
- **Software Libraries:** Maintenance of open-source diagnostic and post-processing software ecosystems.
- **International Impact**: Delivering and underpinning data pipelines for inter-comparison projects and assessments.

Delivering support for the major modelling programmes as well as individual science projects across the community.

Compute, Hardware and Partnerships

COMPUTATIONAL UNDERPINNING

State-of-the-art climate simulations depend heavily on specialized high-performance computing systems for computation, massive data storage, and diagnostic processing.

Core Hardware Dependencies:

- Large CPU platforms provided by the UKRI Digital Research Infrastructure
- (Soon) Large GPU platforms provided by the UKRI DRI
- JASMIN Massive data analysis system.

Other dependencies:

- Met Office Monsoon collaboration platform.
- EuroHPC

KEY PARTNERSHIPS

UK National Climate Science Partnership

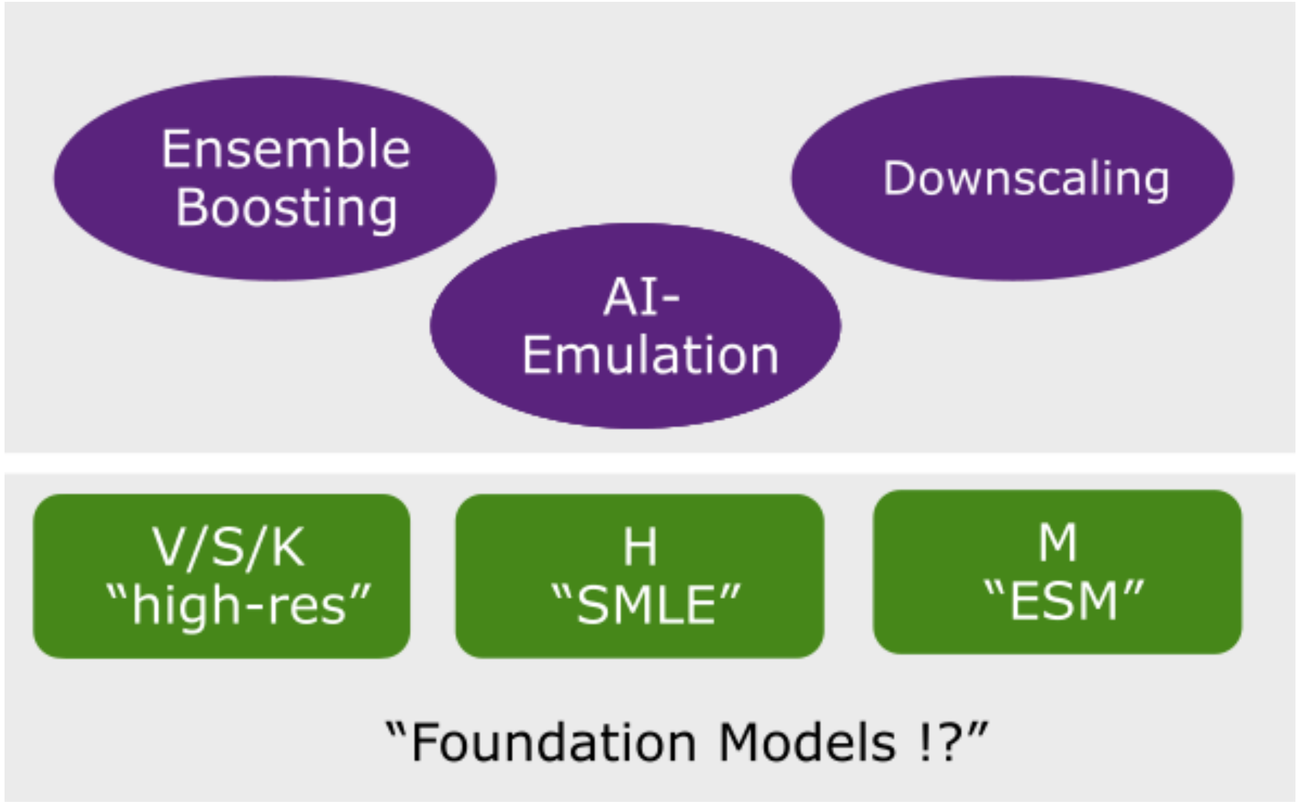
UK National Climate Science Partnership: Linking the national capability of the Met Office Hadley Centre and key NERC research centres.

enes-RI
EUROPEAN NETWORK FOR EARTH SYSTEM MODELLING
RESEARCH INFRASTRUCTURE

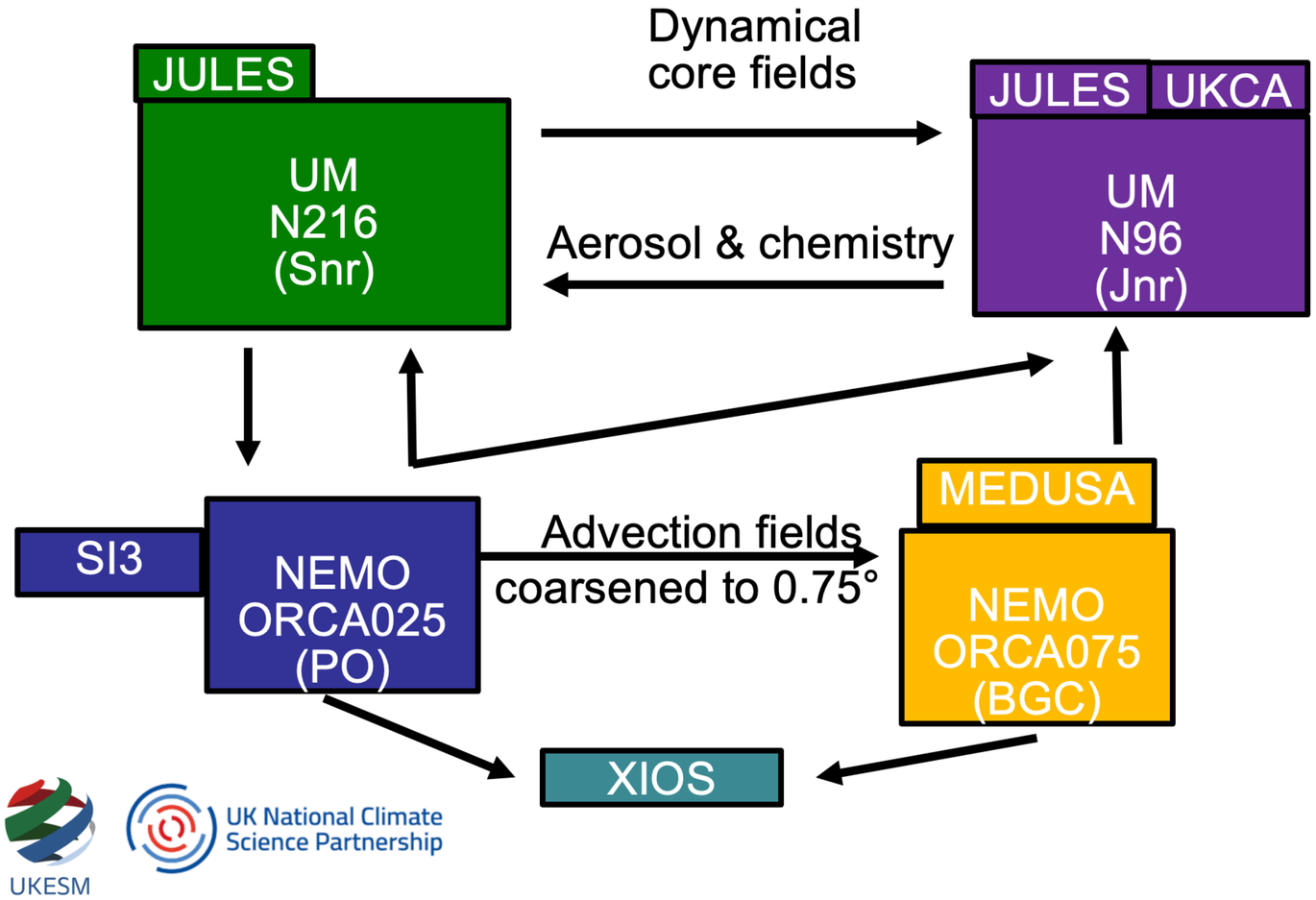
The ENES Research Infrastructure: Delivering long-term collaboration around shared data and modelling infrastructure in European earth system modelling.

Choices and Directions of Travel

Can we blur the distinction between our modelling systems and create hybrid models which are better fits for some tasks than their parents?

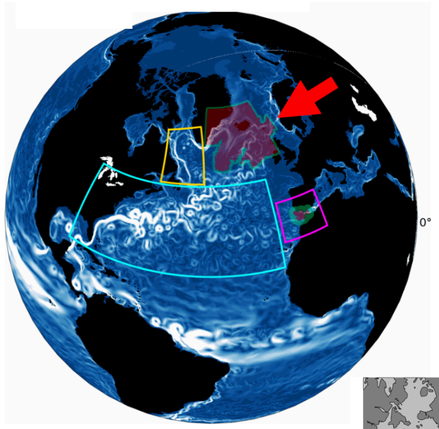


UKESM2



(Courtesy of Marc Stringer, NCAS UKESM team member)

Nested Oceans

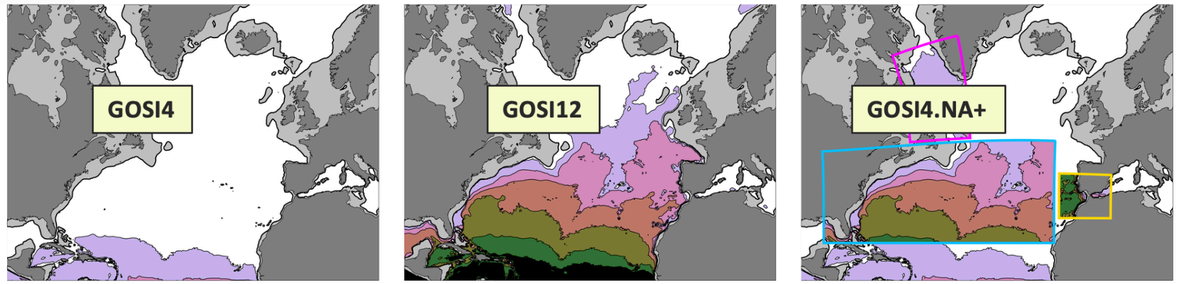


The GOSI4.NA+ configuration (Diego Bruciaferri)

Met Office Hadley Centre

GOSI4.NA+, a 1/4° configuration using:

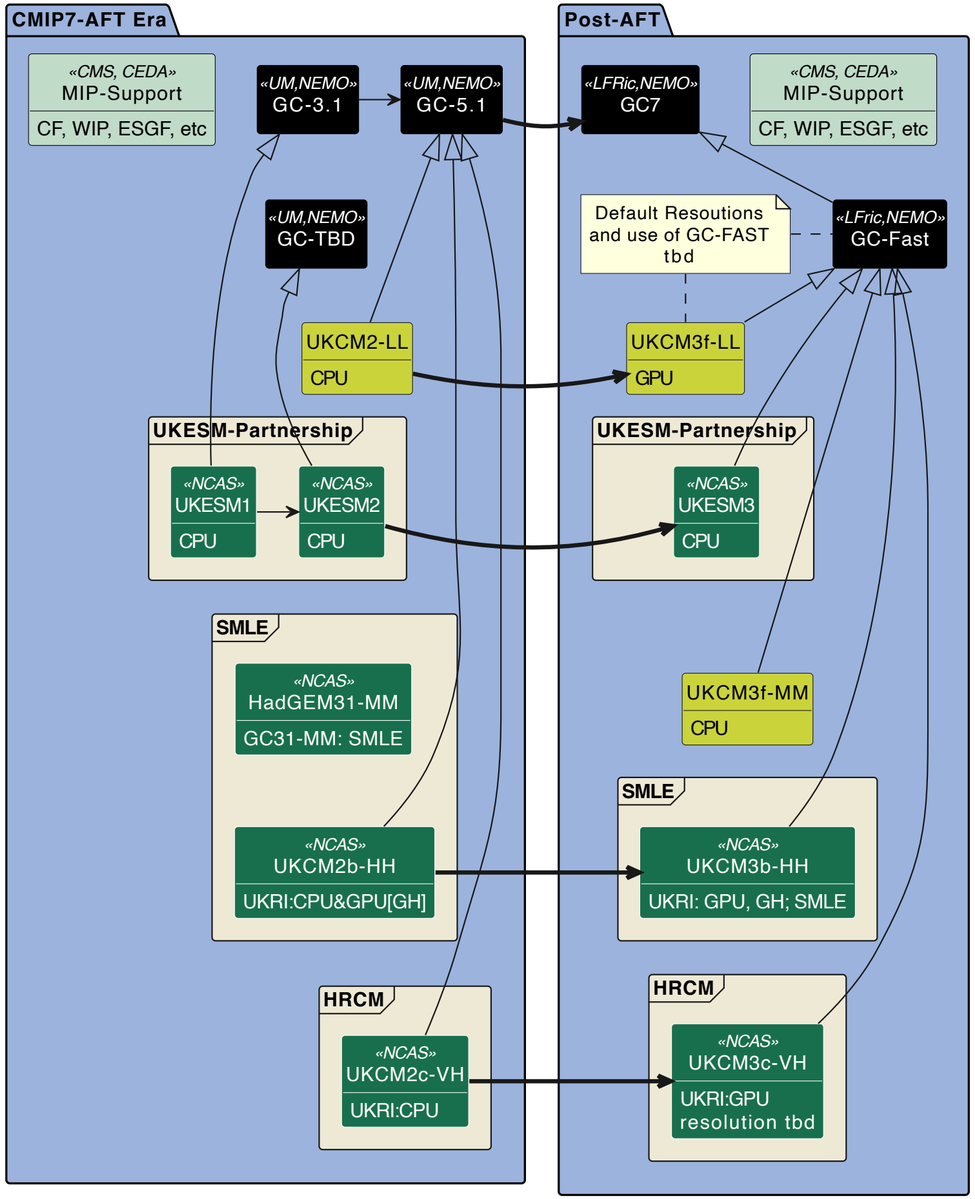
- **Localised ME coordinates** in the **NOVF** area (Bruciaferri et al. 2024)
- **1/12°** zoom around the **Gulf Stream** area
- **1/20°** zoom in the **Labrador Sea**
- **1/20°** zoom + **localised ME coordinates** around the **Gibraltar Strait** area



(My Ph.D Student Gabrielle Ching-Johnson building a coupled N216O25-NA+ model.)

LFRic, GPU, and hardware

Nomenclature	Atmos Resolution	Ocean Resolution
L (low)	~100km	~1 degree
M (medium)	~50-60km	~1/4 degree
H (high)	~20-25km	~1/12 degree
V (very-high)	~10km	~1/36 degree
S (storm)	~5km	
K (km)	~1km	

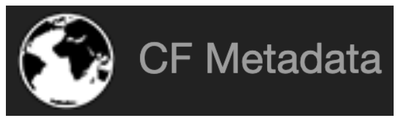


On Data Formats and Data Libraries

Clearly our modelling programme spans many different communities, with differing levels of religious commitments to particular file formats:

- Until there are simpler solutions for *managing* climate data, we will stick to NetCDF.
- Doing so depends on ensuring that we write *defragmented* NetCDF (i.e. NetCDF which is already cloud optimised).

We are currently investing in a `cf-python` based data stack, with `cf-plot`, `cf-python`, `cfdm`, `pyfive`, and `xnetcdf` as key components - all integrated into `xconv2`.







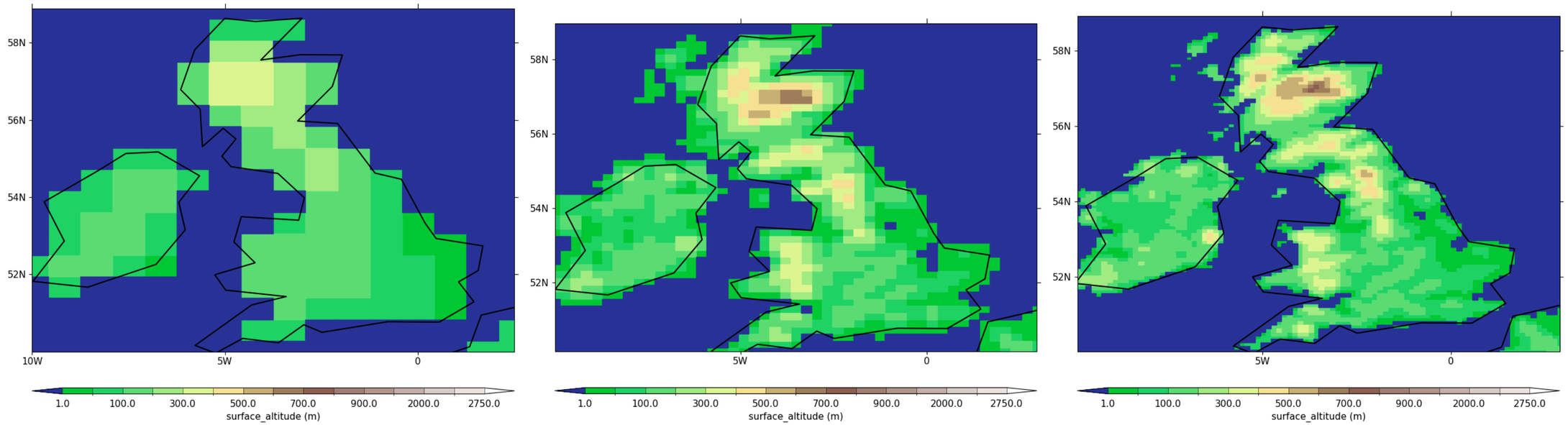



We make choices when we build models

- Regional models.
- Aqua-planet models (is an aqua-planet model different)?
- "CMIP-class" models, choosing one version for "best fit to acceptable climate sensitivity" and another "for best fit to observations".
  - "Model calibration" is an explicit statement about purpose.
- Even at k-scale we make choices about sub-models and coupling and ...
- When we build AI models and emulators, we train on specific datasets for specific purposes. An AI model is targeted at an application.

*We **always** build a model with a primary purpose in mind, we may not be able to use it for other purposes*.

Three model grids - N216, N640, N1280



An introduction to CANARI



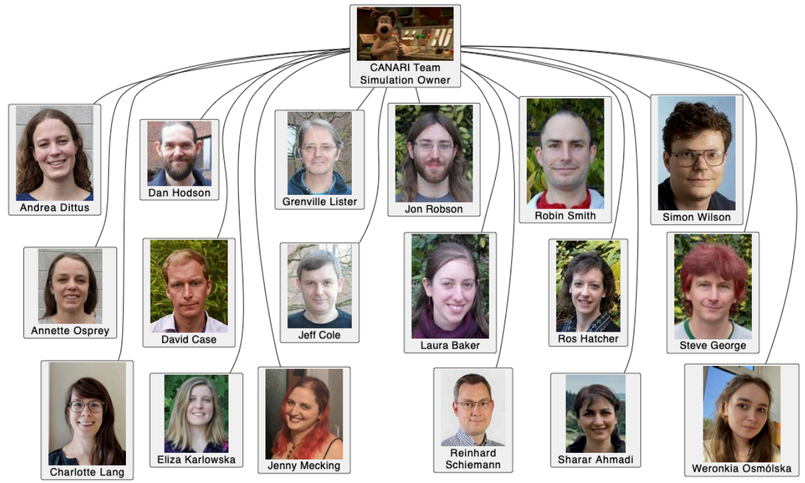
CLIMATE CHANGE IN THE ARCTIC-NORTH ATLANTIC REGION AND IMPACTS ON THE UK

40 ENSEMBLE MEMBERS

N216O25 (Unified Model Atmosphere ~60km, NEMO 0.25 degrees)

- HIST simulation from 1950, SSP370 simulation from 2015
- (Full boundary conditions for CORDEX and some other key nests, and for "interesting storms")
- 6 Petabytes of data including restarts and boundary conditions (we have monthly restarts so we can re-investigate interesting periods).

(Schiemann et al, 2026, Submitted to GMD.)

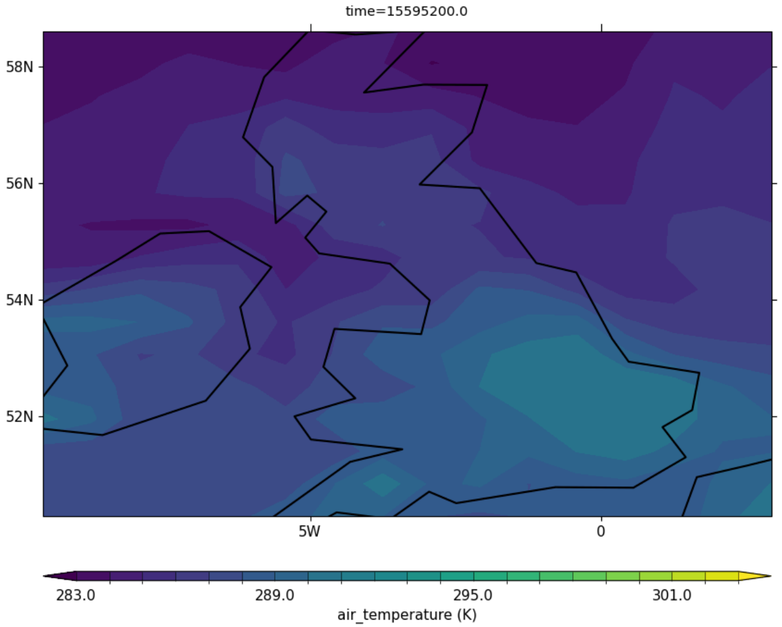


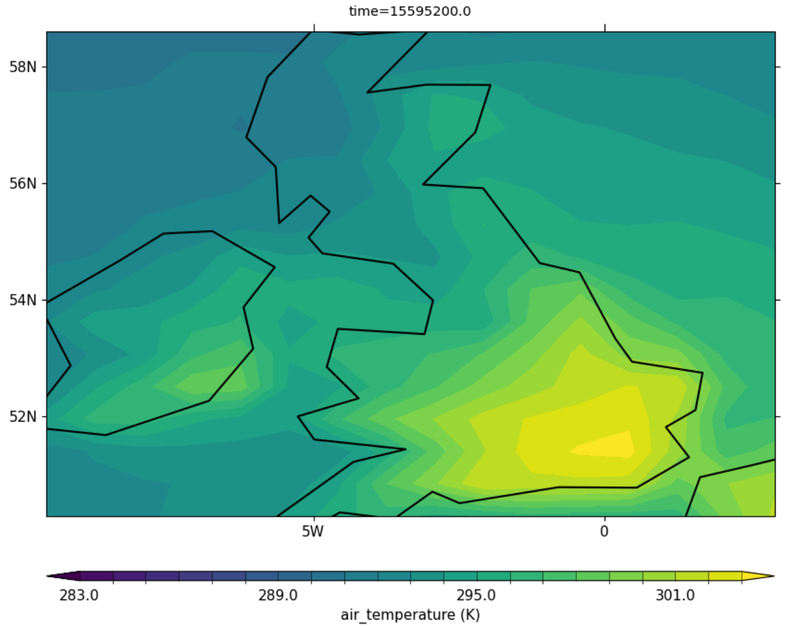
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CANARI - in the future

1. We plan to try and run CANARI class large ensembles at intervals when we have suitable advances in modelling and data storage.
2. But right, now,m otivated by the news that this summer is already the hottest summer recorded in the UK in terms of days where the daily maximum temperature somewhere was over 30C, I asked myself, how might this change in the future?
   a. Of course we know this in general principles, but given we have CANARI on hand, I wondered, what does that ensemble tell us about the possible futures?
   b. What can we learn from this for our modelling strategy?

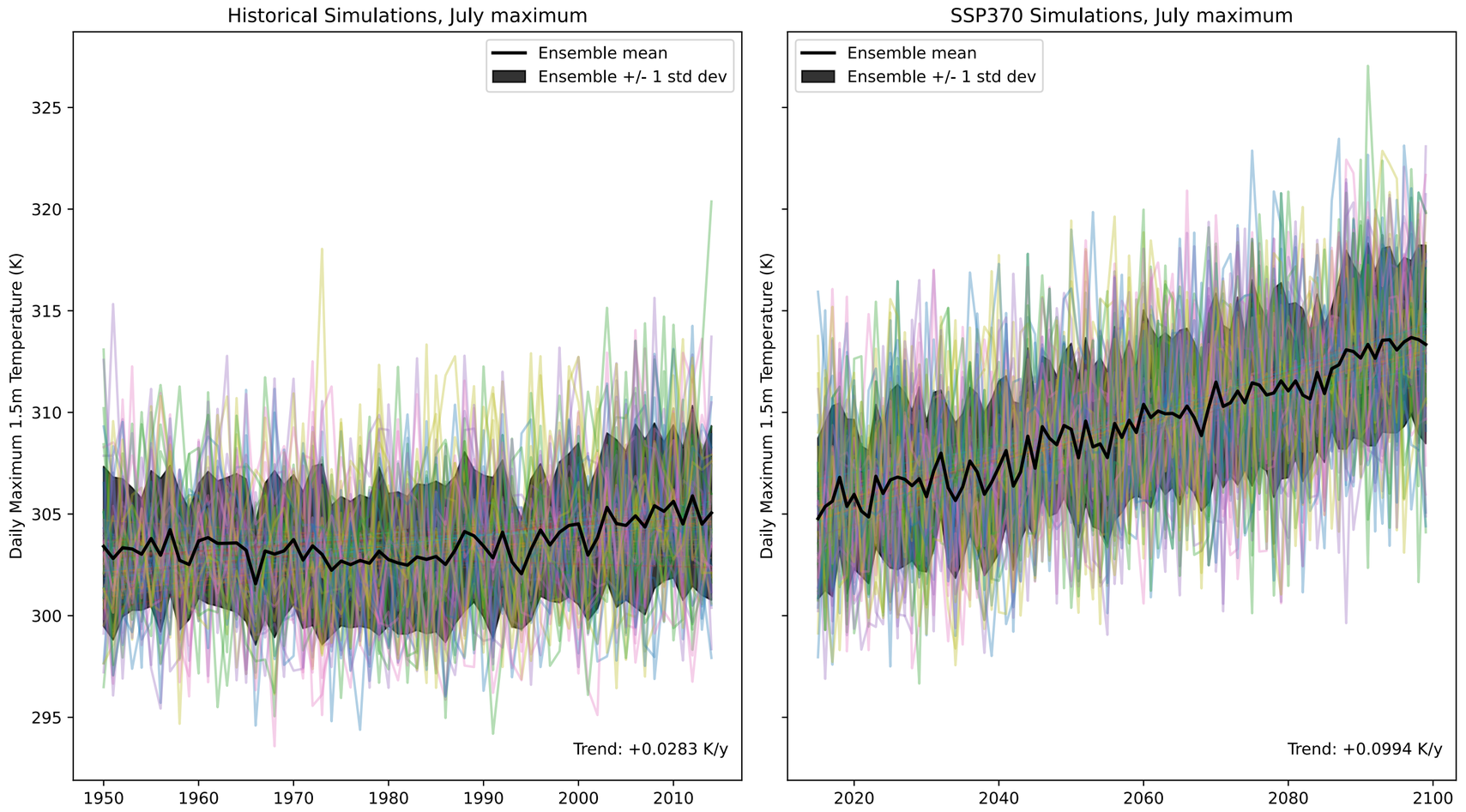
Considering just the UK box



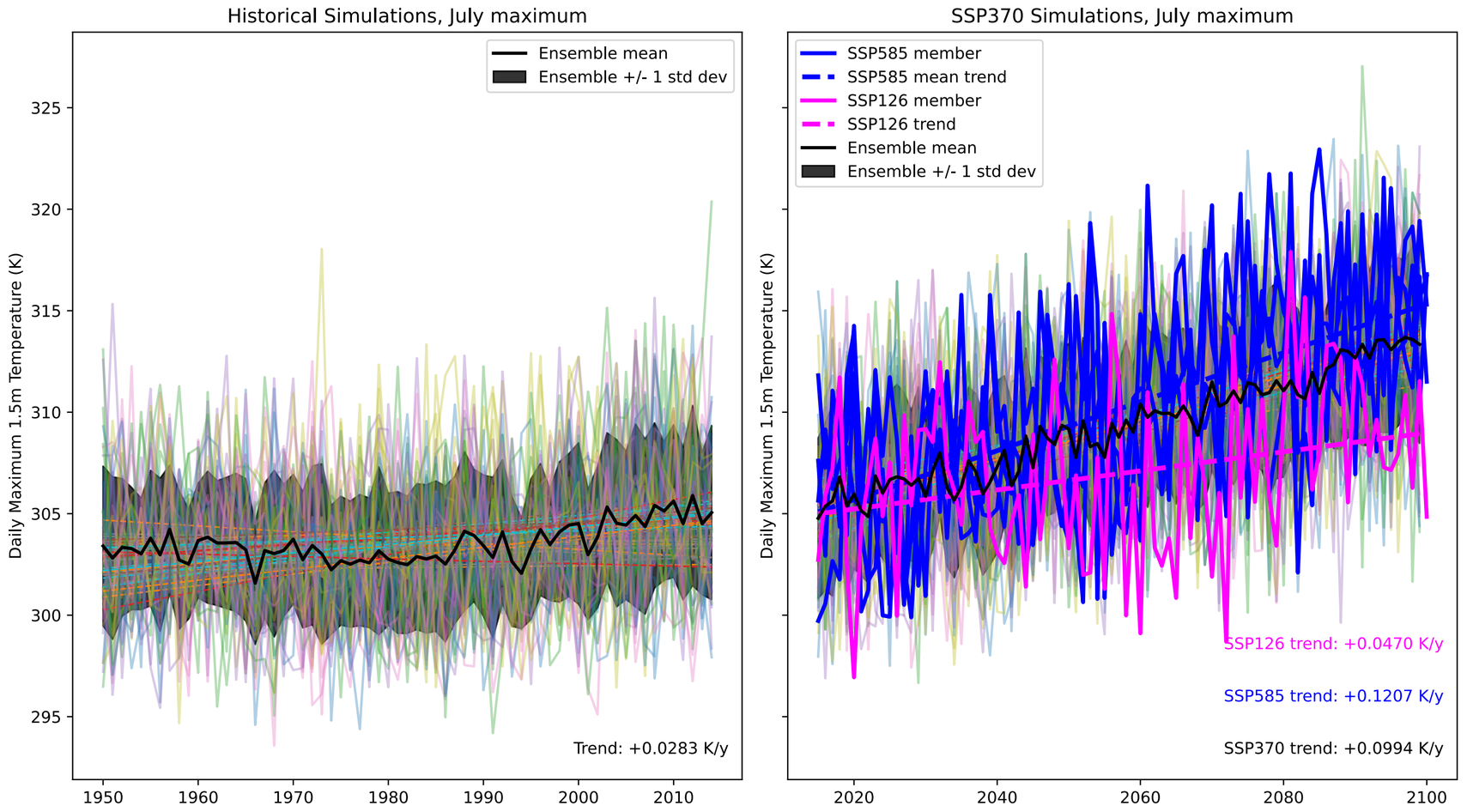


Extract a 16x16 grid box from the daily maximum surface temperature output, and subspace to July values only. The examples above are the first day of the first July in a future simulation, and the last day of the last July in the same simulation.

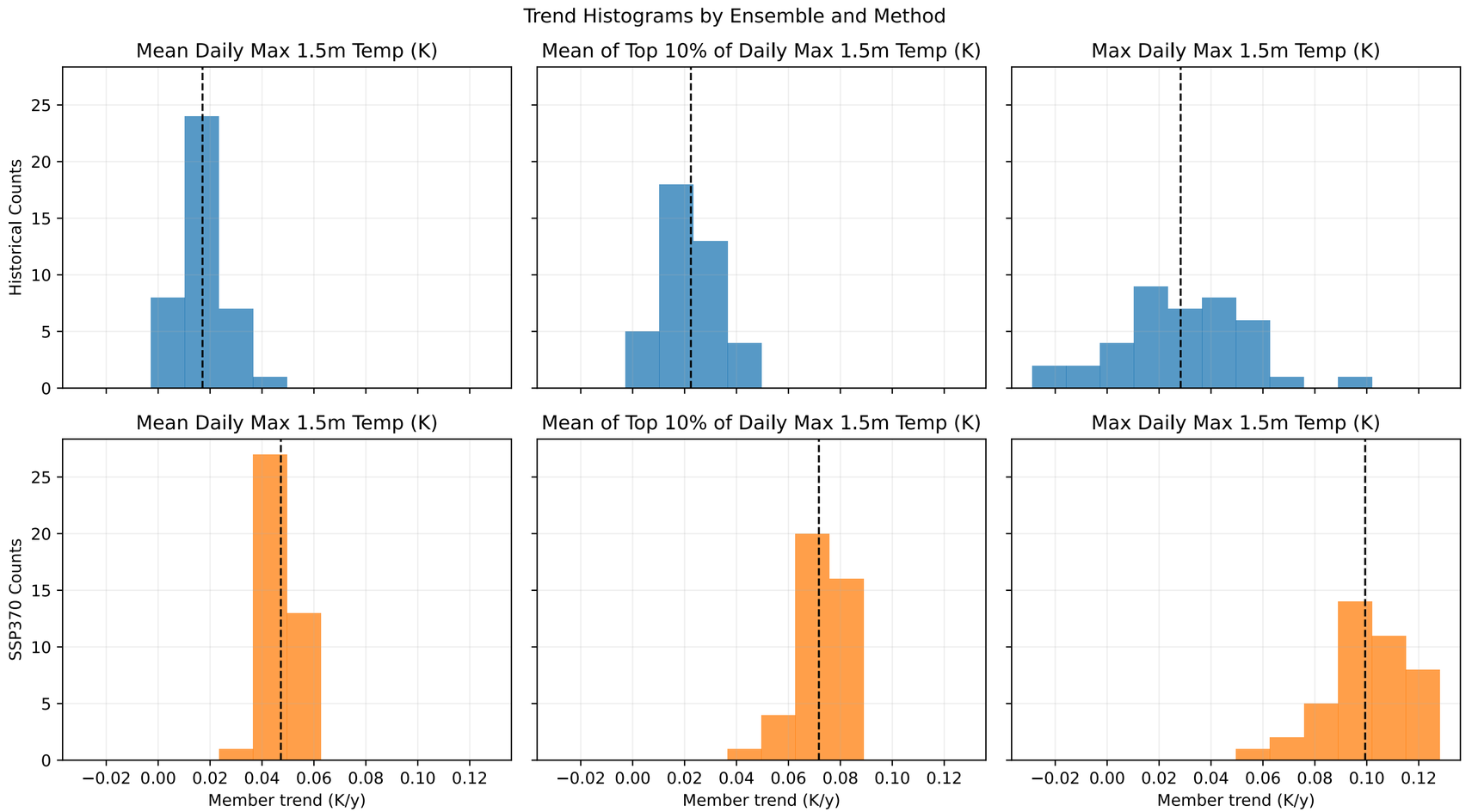
Results - July Max



With some CMIP examples



Back to CANARI - Mean, Upper-Decile,



What has this to do with km-scale?

1. The CANARI SMLE shows the well known expectation that *extremes* will get "more extreme" faster than *means*.
2. The real climate, if it behaves like one of these ensemble members, could behave quite differently in trend, than the ensemble-mean trend!
   a. Different simulations result in very different trends, though each simulation spends roughly the same amount of time out of the ensemble-mean trend envelope.
   b. One could not reliably use a ensemble of a few members to evaluate trends!

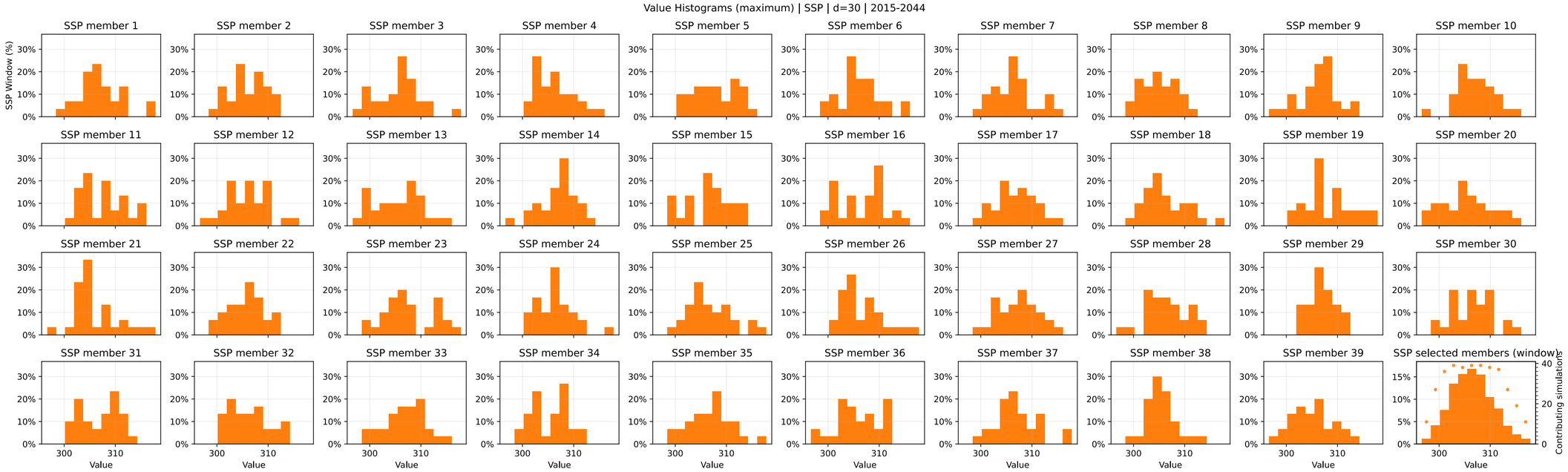
But that's not the whole story!

Interested in extremes not trends?

1. We clearly know that higher resolution models represent things on a more local scale and for the same synoptic situation represent weather phenomena with much more fidelity.
2. Are statistics of extreme events from such simulations representative?
3. Would we gather enough story lines from, say an ensemble of three thirty year simulations, to examine realistic extremes?

Duration? Members? SSP370 Now

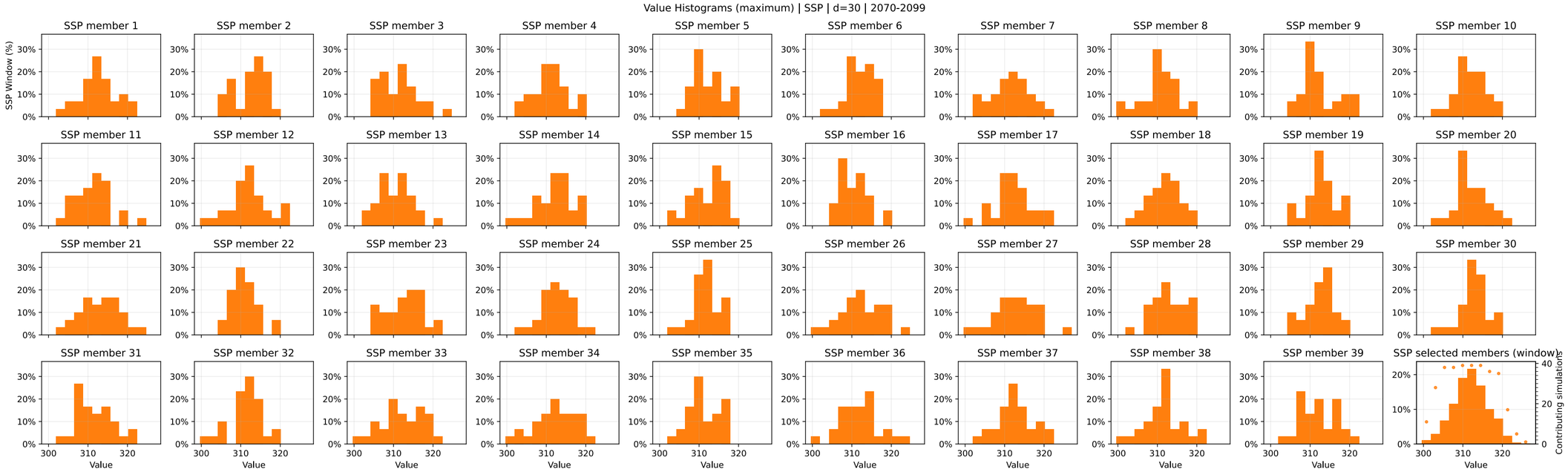
Maximum:



- Quite different experiences living in some of these worlds!

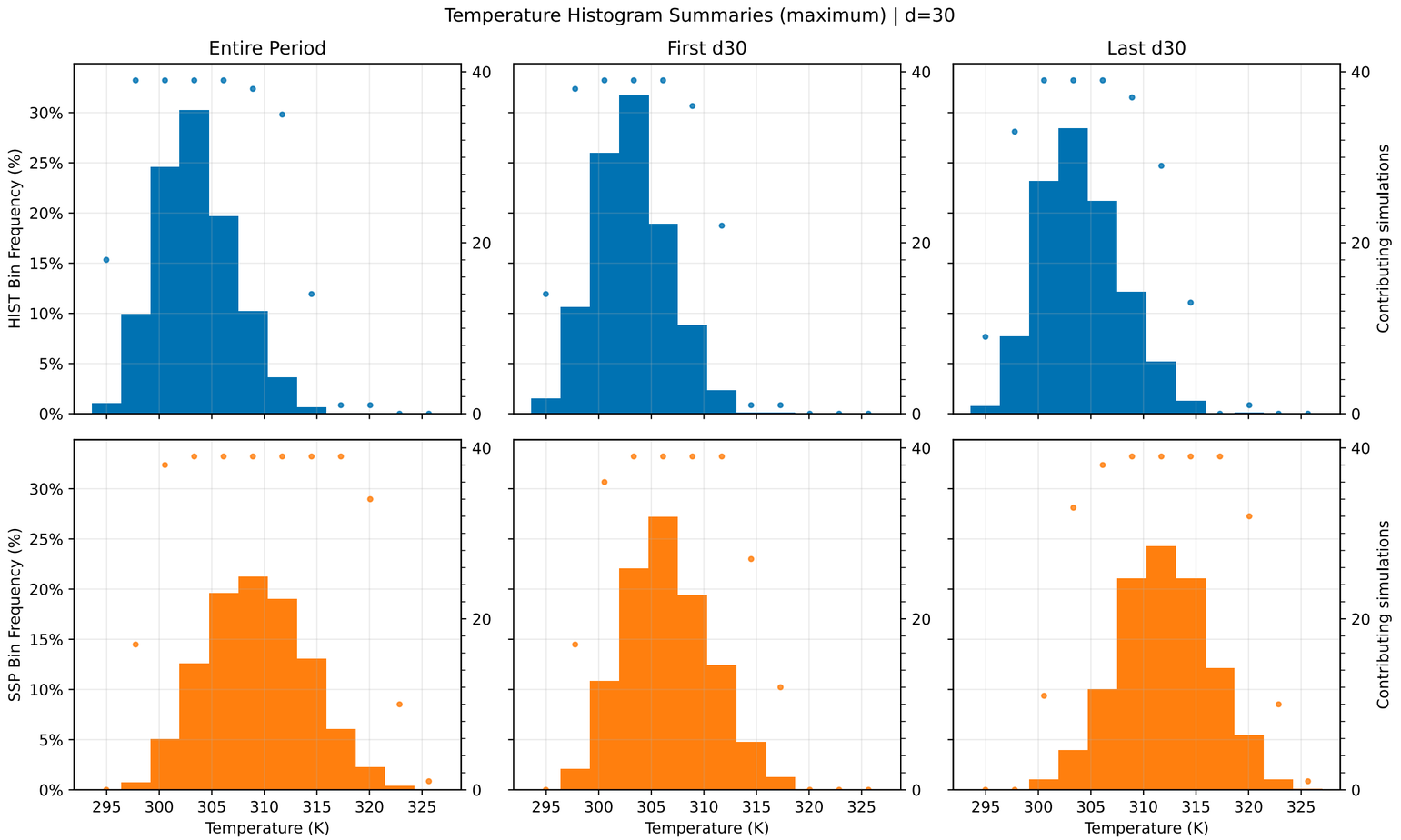
Duration? Members? SS370 From 2070

Maximum:



- Can't see consistent changes in distributions between ensemble members.

How many simulations?

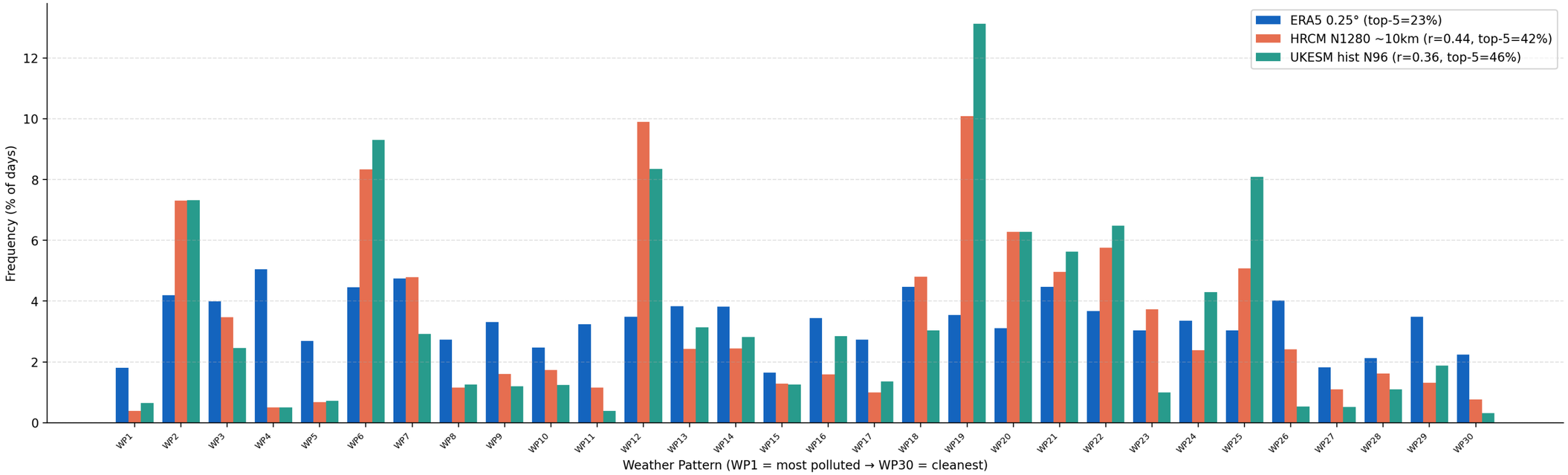


- Only a handful of the simulations explore the tails of the distribution.

But what about upscale affects?

Do they make certain classes of events more or less common?

We can look at this by looking at weather patterns (here, work in progress by Ankit Bhandekar, Ph.D student at the University of Reading and NCAS, looking at air pollution in India):



At least for the Indian region, it appears not! But we will repeat this work for Europe as the orography in the Indian region may be constraining things, whereas the North Atlantic and the jet stream may introduce local upscale effects.

So have we learnt?

- We need quite a large ensemble to say useful things about the likely trend in future climate.
- We may not need 40 members to sample enough of the natural variability to see into the long-tail of extremes in the UK variability - but we probably do need at least ten members. (This is consistent with a lot of other work done on ensemble size ...)
- We don't really know if upscale affects will affect the distribution of weather events in the UK region, though clearly we need high resolution to understand the consequences.
- **We still need multiple model configurations and we still need new large ensembles.**