The NCAS Climate Modelling Programme Now and in the future (with a look at the future of UK summers)

Bryan Lawrence
and a cast of thousands

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Outline

1. Modelling Context
2. An NCAS modelling strategy
3. Earth-System Modelling
4. Process-Fidelity Modelling
5. CANARI and UK summers
6. Technology Futures

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Context

1. On models and modelling.
2. Computing Constraints
3. Models for science or policy?
4. Uncertainty: globally, regionally?

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Why do we have models (plural)?

Lots of answers, some better than others:

- ~~Politics (not invented here, sovereignty)~~
- To address model uncertainty (if we believe they are independent in useful ways)
- To address different purposes constrained by available HPC, and our toleration of uncertainty
  - Scientific Understanding of processes across time and spatial scales
  - Prediction/Projection

In all cases, we evaluate the utility of the model for the purpose in hand. The question then arises, to what extent can we balance the resources necessary to build, evaluate, and use multiple models? What should our strategic approach be?



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From a funding perspective we have a tension between science and policy!

Science Drivers

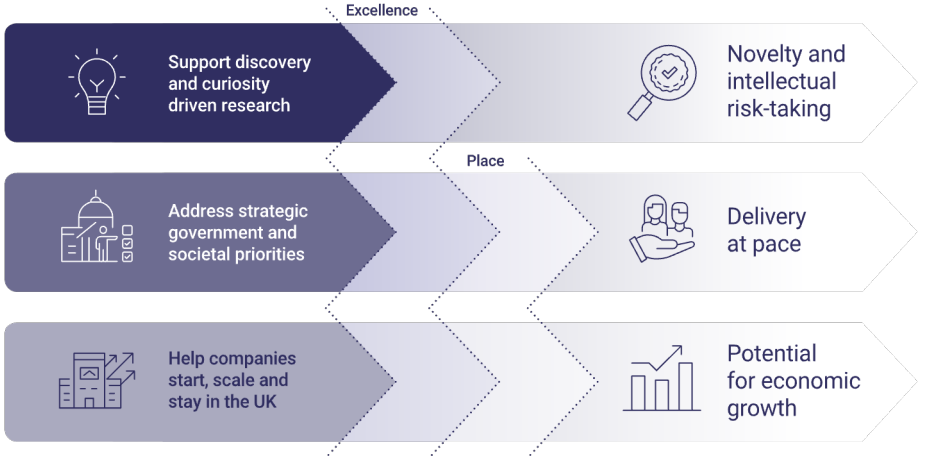
We (scientists) think like this. We want to

- **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 .
- **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).
- Address and **understand** systematic uncertainties and biases in both our understanding and our models.

(These are the science goals written into our NCAS climate modelling strategy)

Policy Drivers

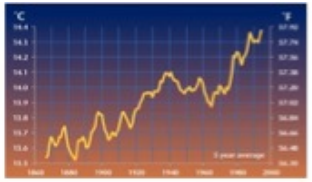
UKRI investments target very different things:



Our science objectives must deliver on these objectives too!

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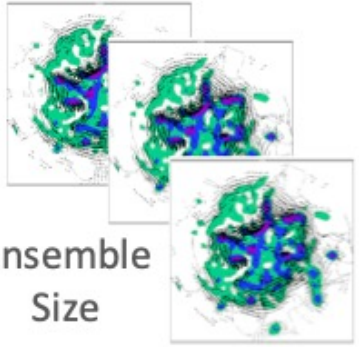
Computing is finite.
Science is not!



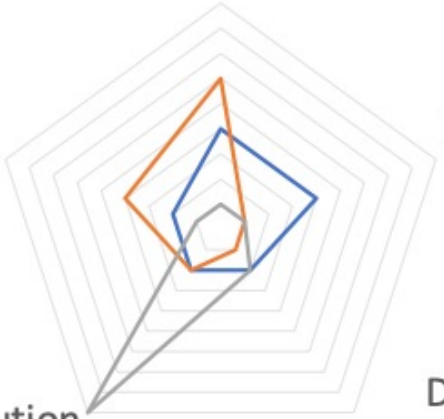
Duration

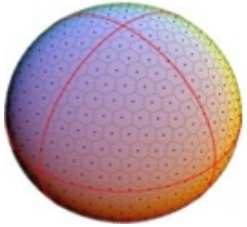


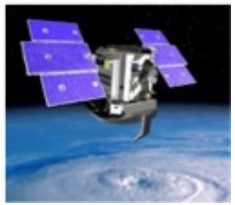
Complexity



Ensemble Size

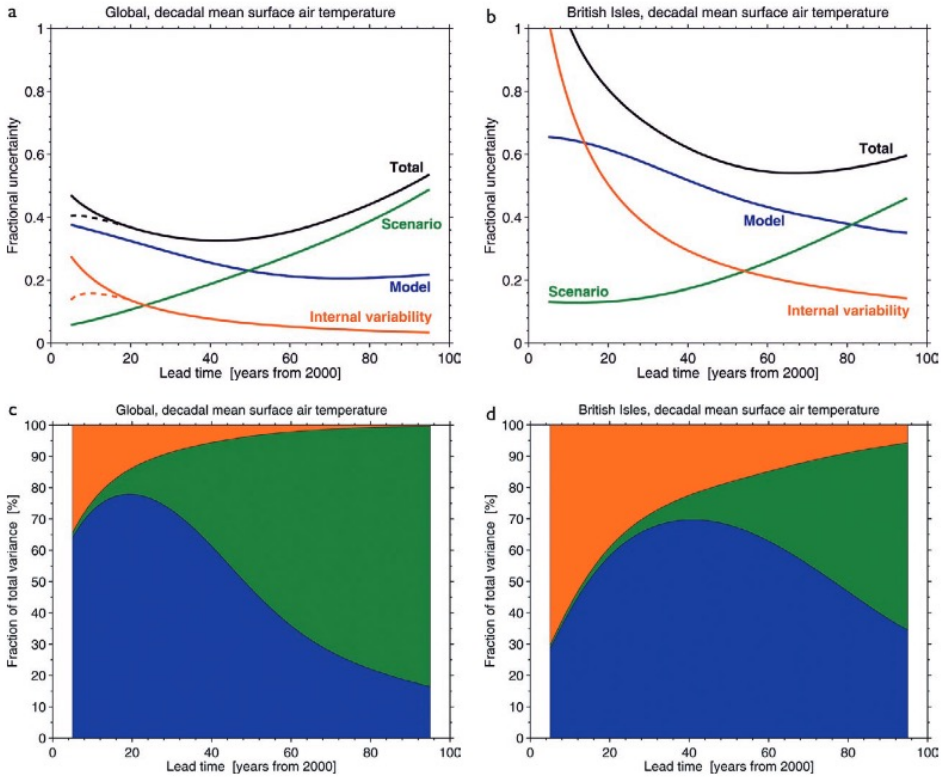






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On uncertainty at global scales



They said:

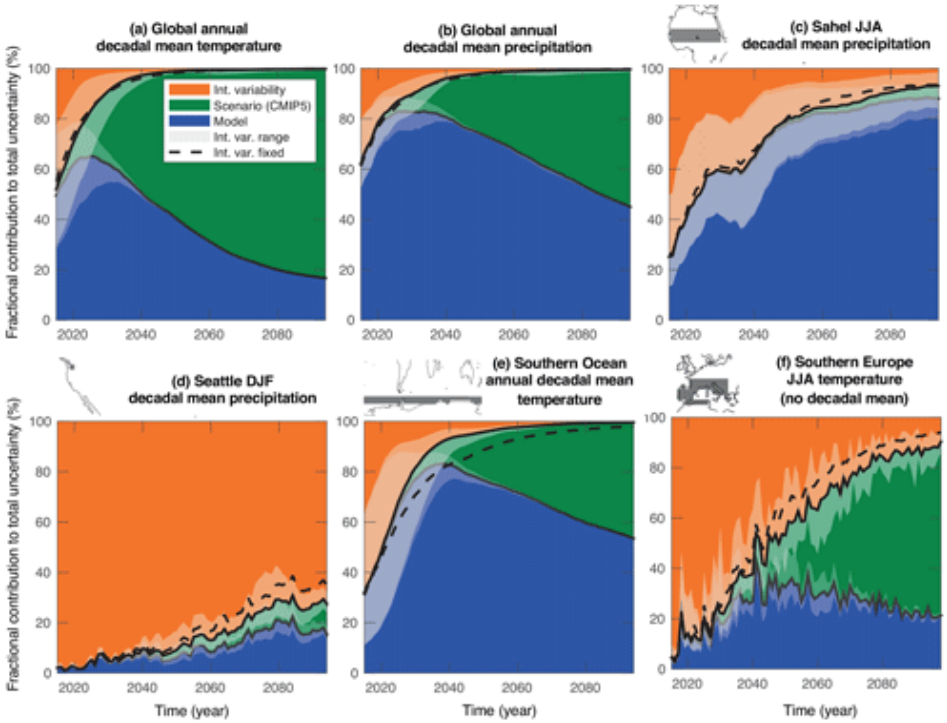
- At the global scale uncertainty in decadal mean temperature rapidly becomes dominated by scenario uncertainty.
- The importance of scenario uncertainty is relatively less when we are interested in regional climate.
- At the regional scale, it is 50 years before scenario uncertainty becomes important.

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.

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On uncertainty at global scales



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

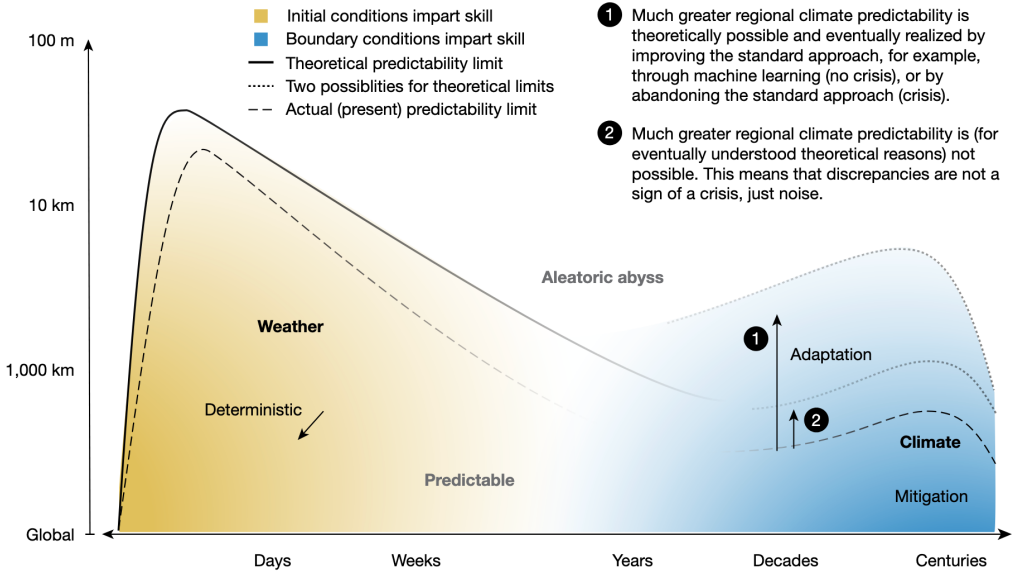
- Broad conclusion: ***Model uncertainty is still dominant in many regions, but somewhat reduced relative to internal variability.***

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

(Lehner et al 2020: Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6.)

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On uncertainty at global scales



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.*"
- (But one person's noise is another person's signal!)

(Shaw and Stevens 2025: The other climate crisis.)

"aleatoric?" – "having an element of chance"

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NCAS Modelling Strategy

1. Choices!
2. Three world class modelling systems!
3. Technical Enablers
4. Compute, hardware, and Partnerships

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Three world class modelling systems

01. PROCESS-FIDELITY

~1 SYPD

ONE JOB AT A TIME

Ultra-High Resolution Physical Coupled Model

State-of-the-art physical climate simulation capable of projecting decades into the future at extreme fidelity.

Building on HRCM
Hundreds of nodes in 1 machine for many months per run.

02. VARIABILITY

~2 SYPD

MULTIPLE JOBS AT A TIME

Single-Model Large-Ensembles

Exploiting global historical & future climate ensembles to understand natural variability and key teleconnections. Intermediate resolution.

Building on CANARI
Many tens of nodes in 1 or 2 machines for a year or more.

03. EARTH-SYSTEM

~10 SYPD

MULTIPLE JOBS AT A TIME

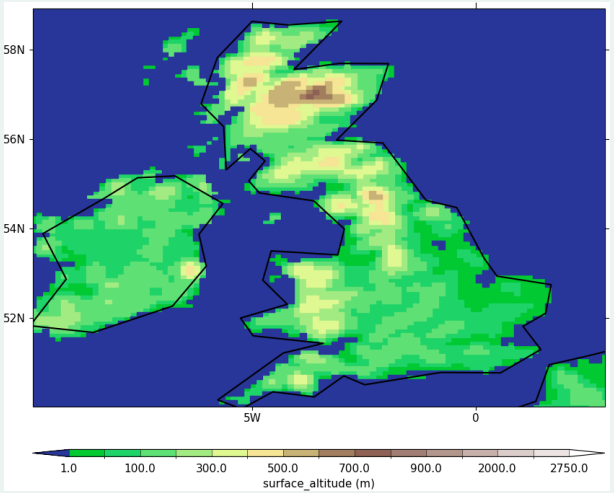
Full Earth-System Components

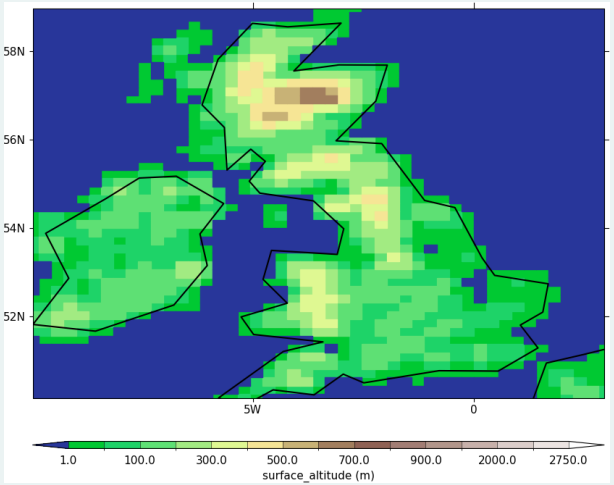
Incorporating major feedbacks (carbon cycle, ice sheets, methane) integrated seamlessly over centuries.

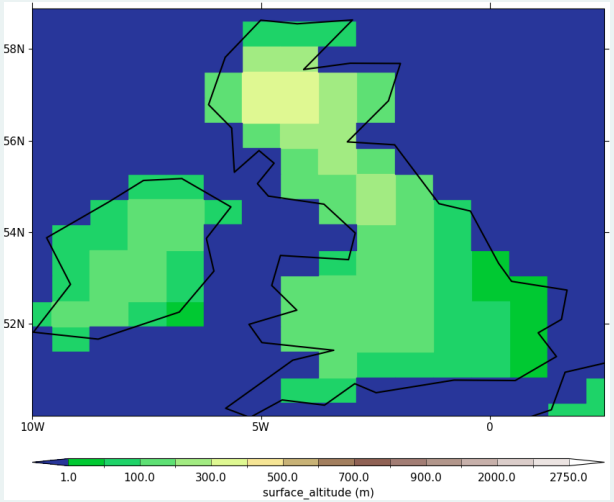
Building on UKESM & TERRAFIRMA
Up to a couple dozen nodes for months, multiple platforms.

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The target for the next five years:







10 km coupled global
Process Fidelity

20 km coupled global
Variability: Large Ensemble

60 km coupled global
Earth System Model

Technical Enablers and Infrastructure

AI & Workflow Integration

Accelerating discovery and optimizing computational workflows

- **Model Enhancement:** Exploiting AI/ML architectures to improve physical climate parameterizations.
- **Workflow Optimization:** Streamlining end-to-end orchestration, diagnostics, and data pipelines.
- **Advanced Analysis:** Training climate model emulators to extract insight from complex outputs.

Inter-Comparison & Data Standards

Sustaining frameworks for global collaboration

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

Delivering support for major modelling programmes and individual science projects across the community. **?????**

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Compute Hardware and Partnerships

Core Hardware Dependencies

- **UKRI DRI CPU Platforms:**
  Large-scale CPU computational base
- **JASMIN Infrastructure:**
  Massive storage and co-located data analysis system
- **Monsoon and EuroHPC:**
  Collaboration and large-project overflow.

(Soon) GPU Platforms
Accelerated UKRI DRI systems.

Key Partnerships

Sustaining frameworks for global collaboration

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.

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Earth-System Modelling

(slides from Colin Jones)

Just one exemplar activity from TERRAFIRMA and the UKESM partnership.

A quick intro to TIPMIP and two results from the work underway:

1. Reversibility of ice-sheet tipping.
2. Impact of ocean and land on carbon dioxide removal.

Based on

- Naughten et al. (Accepted, Nature Climate Change)
- Liddicoat et al. (In prep.)

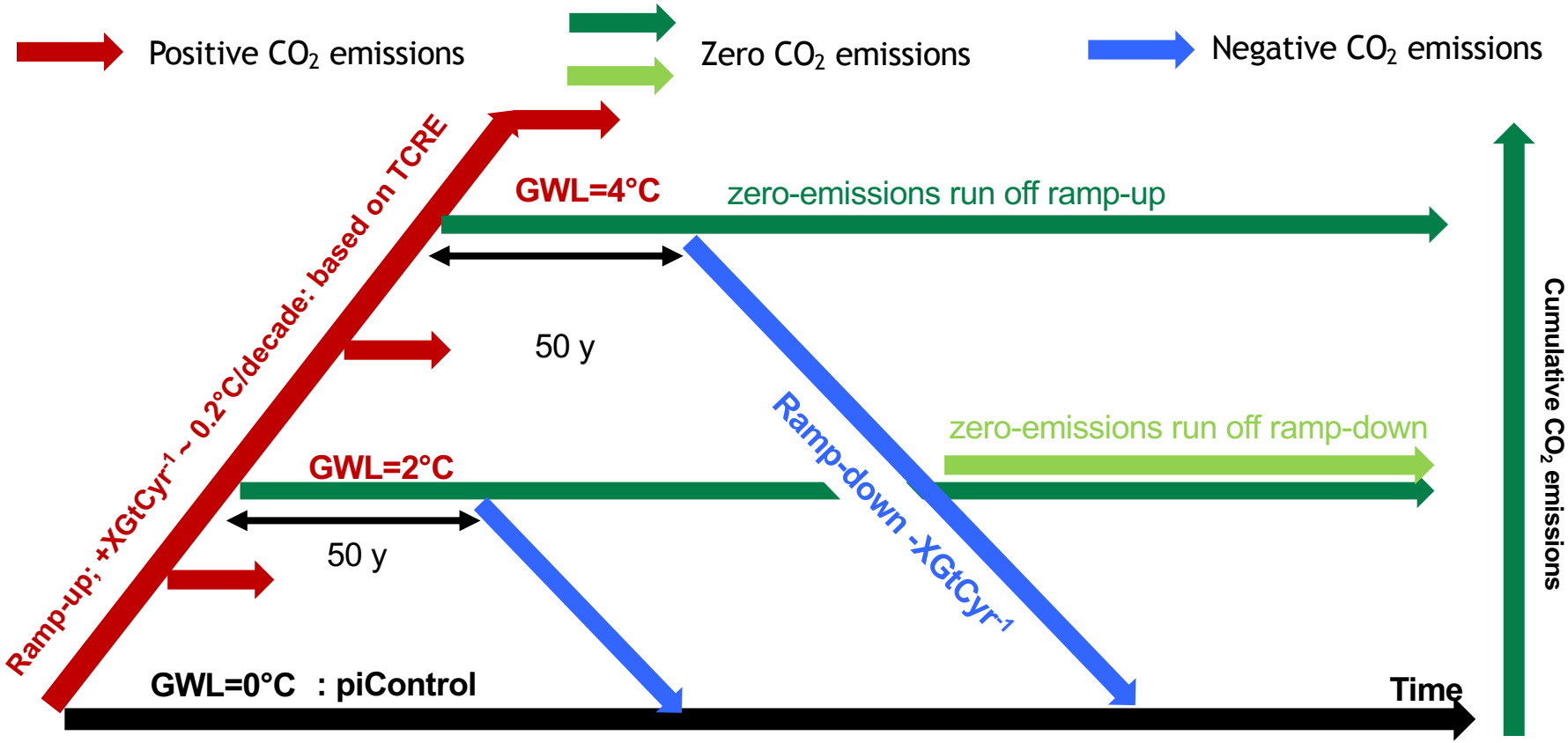
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UKESM

UK National Climate Science Partnership

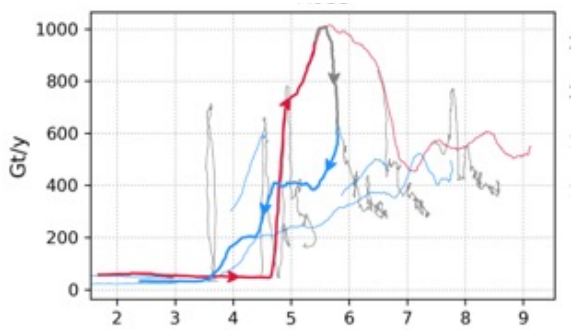
TIPMIP ESM Tier 1 experiment protocol: Experiments run in CO_2-emission mode

Atmospheric CO_2 concentrations are a prognostic model variable

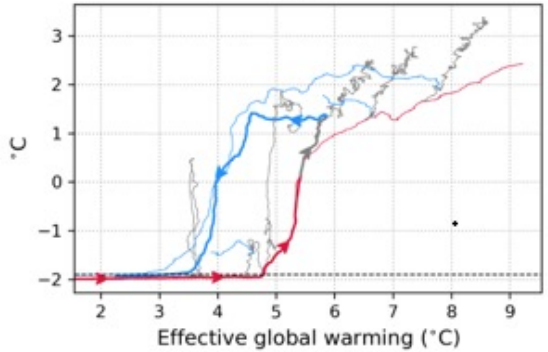


The Ross ice sheet tips (warm water to cold water cavity) in the UKESM1.2 TIPMIP ESM runs

Melt rate beneath ice shelves



Ocean temperature in ice shelf cavities

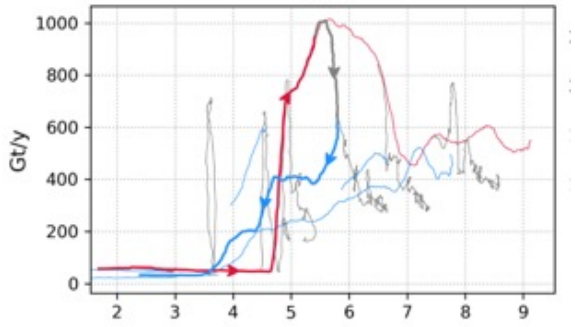


UKESM

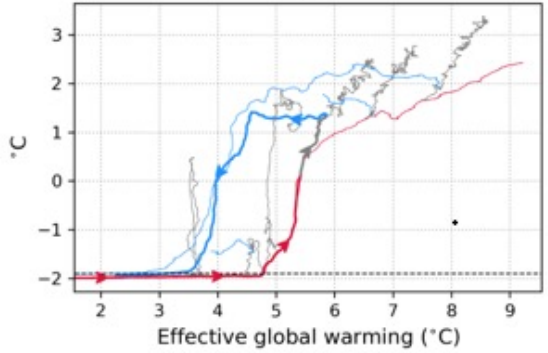
UK National Climate Science Partnership

The Ross ice sheet tips (warm water to cold water cavity) in the UKESM1.2 TIPMIP ESM runs

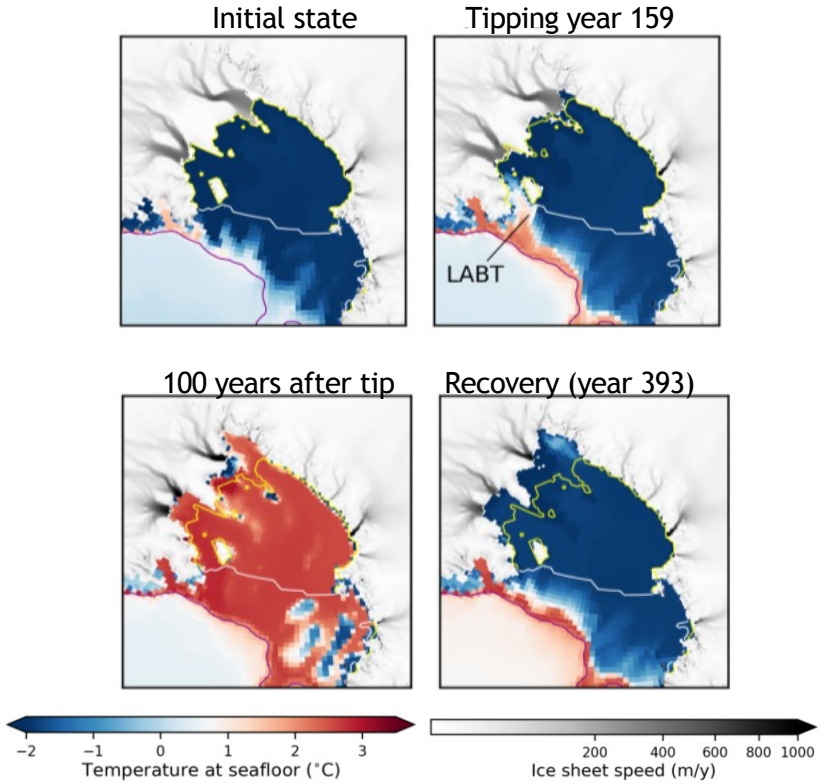
Melt rate beneath ice shelves



Ocean temperature in ice shelf cavities



The Ross Sea is rapidly flooded with S. Ocean water at GWL ~4°C, flipping from temperatures <0°C to >+2°C

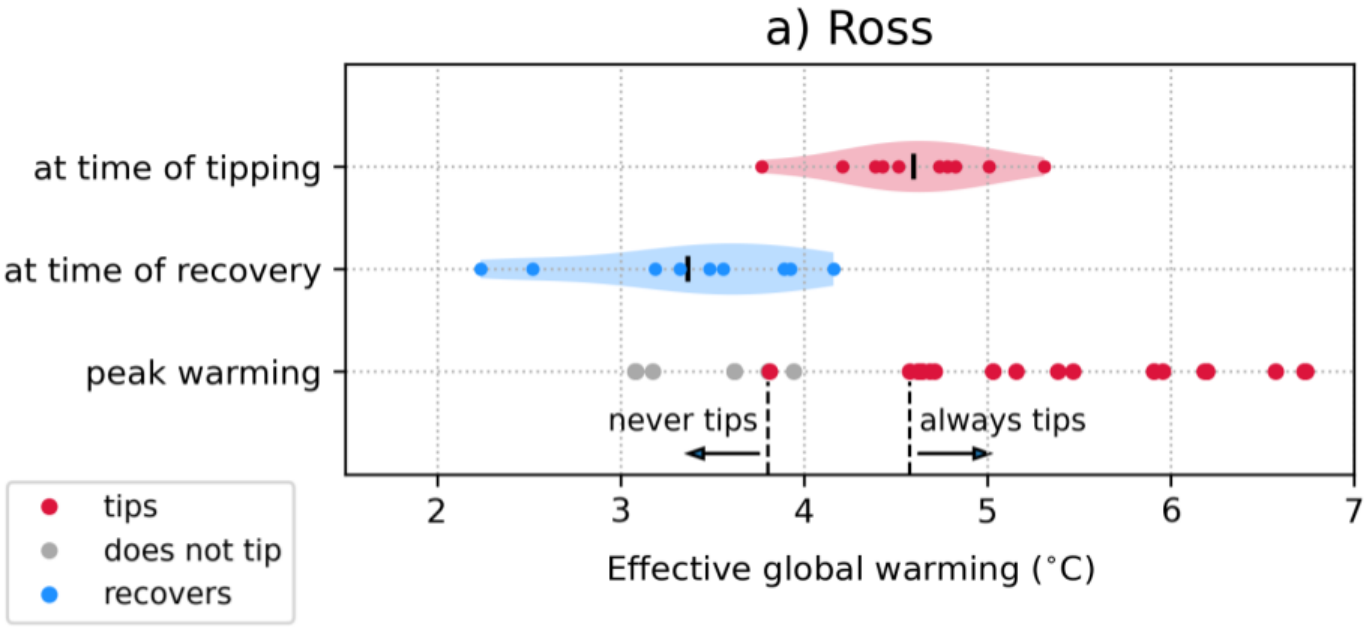


The cavity does recover during the cooling arm (light blue line) but takes ~200 years to do so
This does not mean ice already melted rapidly regrows

UKESM

UK National Climate Science Partnership

Ross ice sheet tipping statistics as a function of global warming in UKESM1.2



Above 3.7K of global warming Ross Ice sheet is at increasing risk of tipping leading to rapid/committed sea level rise

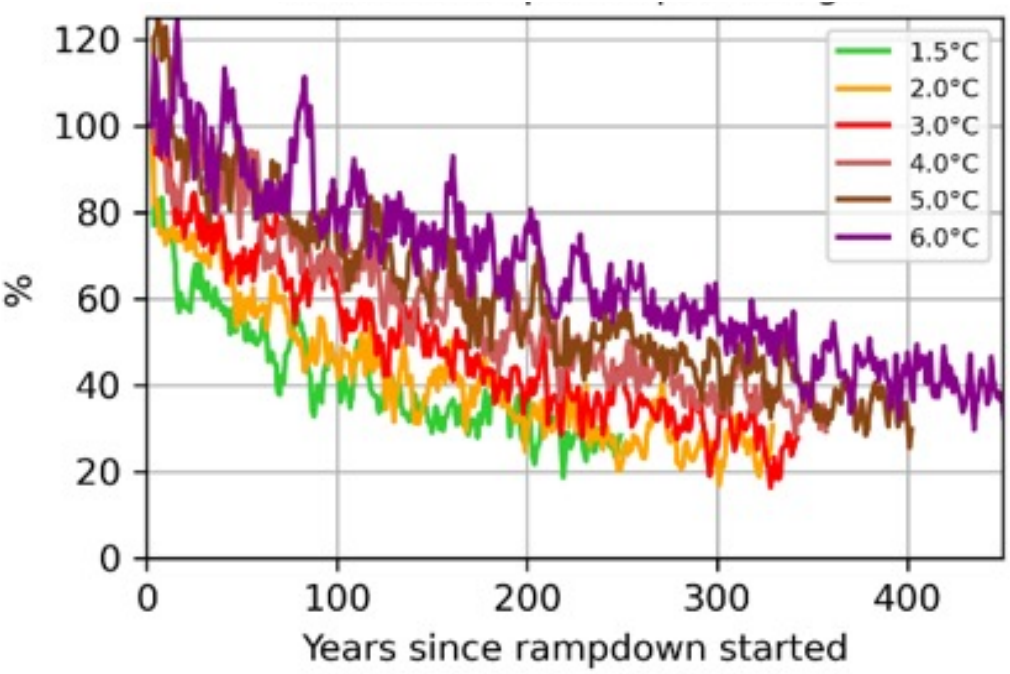
UKESM

UK National Climate Science Partnership

During the negative emission (cooling) phase carbon sequestered into the land and ocean during the ramp-up is emitted back into the atmosphere as the gradient of pCO_2 changes due to the prescribed CDR removal.

After ~150years the impact of prescribed CDR on atmospheric CO2 is decreased by ~50%

Residual CO_2 removal as % of prescribed negative emissions in UKESM1.2



UKESM

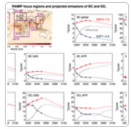
UK National Climate Science Partnership

International research; NCAS coordination and facilitation

RAMIP
Regional Aerosol Model Intercomparison Project

Model experiment description paper | 03 Aug 2023

The Regional Aerosol Model Intercomparison Project (RAMIP)



Laura J. Wilcox, Robert J. Allen, Bjørn H. Samset, Massimo A. Bollasina, Paul T. Griffiths, James Keeble, Marianne T. Lund, Risto Makkonen, Joonas Merikanto, Declan O'Donnell, David J. Paynter, Geeta G. Persad, Steven T. Rumbold, Toshihiko Takemura, Kostas Tsigaridis, Sabine Undorf, and Daniel M. Westervelt

RESEARCH ARTICLE | CLIMATOLOGY

Are Northern Hemisphere boreal forest fires more sensitive to future aerosol mitigation than to greenhouse gas–driven warming?

ROBERT J. ALLEN, BJØRN H. SAMSET, LAURA J. WILCOX, AND ROSIE A. FISHER Authors Info & Affiliations

SCIENCE ADVANCES • 29 Mar 2024 • Vol 10, Issue 13 • DOI: 10.1126/sciadv.adl4007

Article | Open access | Published: 14 July 2025

East Asian aerosol cleanup has likely contributed to the recent acceleration in global warming

Bjørn H. Samset, Laura J. Wilcox, Robert J. Allen, Camilla W. Stjern, Marianne T. Lund, Sharar Ahmadi, Annica Ekman, Maxwell T. Elling, Luke Fraser-Leach, Paul Griffiths, James Keeble, Tsuyoshi Koshiro, Paul Kushner, Anna Lewinschal, Risto Makkonen, Joonas Merikanto, Pierre Nabat, Larissa Narazenko, Declan O'Donnell, Naga Oshima, Steven T. Rumbold, Toshihiko Takemura, Kostas Tsigaridis & Daniel M. Westervelt

Communications Earth & Environment **6**, Article number: 543 (2025) | Cite this article

South Asian monsoon response to regional aerosol emission reductions: insights from RAMIP

Ankit Bhandekar*, Laura J Wilcox, Bryan N Lawrence, Nathan Luke Abraham, Fiona M O'Connor, Bjørn H Samset, Robert J Allen, Sharar Ahmadi, Annica M L Ekman, Maxwell T Elling

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Environmental Research: Climate, Volume 5, Number 3

Focus on the Role of Aerosols in Regional Climate Change

Research Article | Open Access

Multi-Model Impacts of Dust on African Air Quality and Mortality Under Regional and Global Anthropogenic Aerosol Changes

Joe Adabouk Amooli, Ron L. Miller, Kostas Tsigaridis, Sourangsu Chowdhury, Yanda Zhang, Catherine A. Toolan, Sharar Ahmadi, Robert J. Allen, Maxwell T. Elling ... See all authors

First published: 11 May 2026 | https://doi.org/10.1029/2025JD046135 | VIEW METRICS

PAPER • OPEN ACCESS

AMOC weakening in response to global and regional reductions in aerosol emissions

Robert J Allen*, Timothy Carson, Wei Liu, Laura J Wilcox, Bjørn H Samset, Sharar Ahmadi, Annica M L Ekman, Maxwell T Elling, Luke Fraser-Leach, Paul Griffiths Show full author list

Published 15 May 2026 • © 2026 The Author(s). Published by IOP Publishing Ltd

Environmental Research: Climate, Volume 5, Number 2

PAPER • OPEN ACCESS

Decomposing the global and regional aerosol effective radiative forcing associated with strong versus weak air quality policies by Mid-21st century

Robert J Allen*, Laura J Wilcox, Bjørn H Samset, Sharar Ahmadi, Annica M L Ekman, Maxwell T Elling, Luke Fraser-Leach, Paul Griffiths, James Keeble, Tsuyoshi Koshiro

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Environmental Research: Climate, Volume 5, Number 2

PAPER • OPEN ACCESS

Regional aerosol emission reductions alter tropical circulation

Joon-Gu Jeon, Robert J Allen*, Sang-Wook Yeh*, Chang-Eui Park, Laura J Wilcox, Bjørn H Samset, Sharar Ahmadi, Annica M L Ekman, Maxwell T Elling, Luke Fraser-Leach Show full author list

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Environmental Research: Climate, Volume 5, Number 4

Process Fidelity Modelling

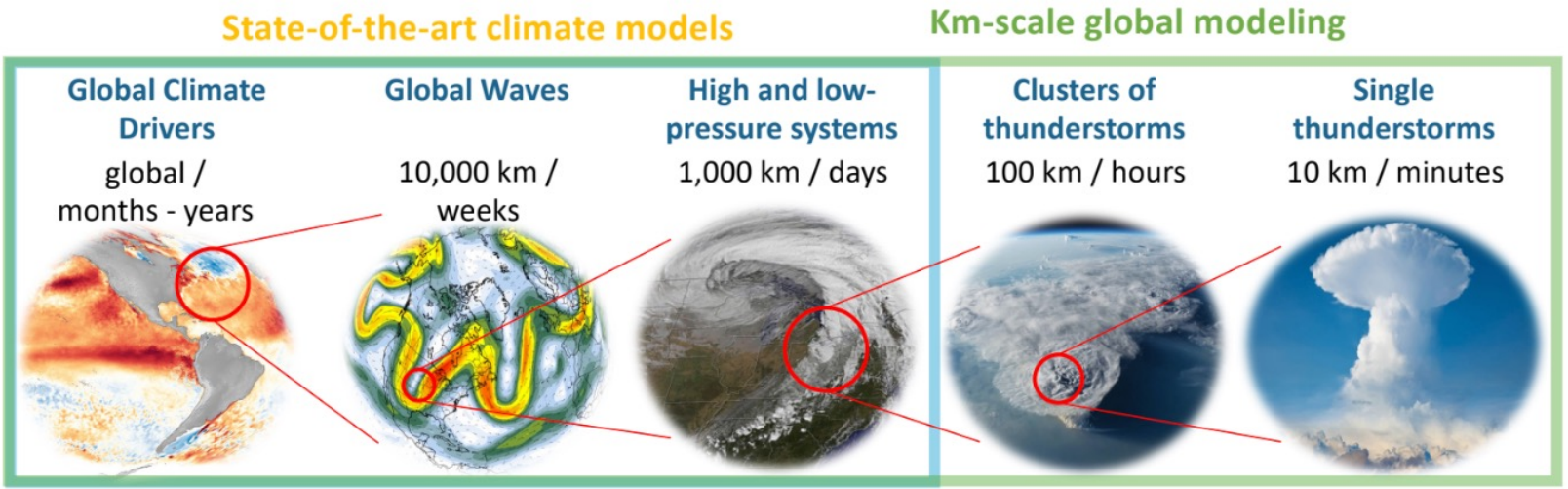
(slides from Pier-Luigi Vidale)

Two decades of (primarily) European investment on top of a joint Met Office NCAS project!

1. Rationale, the role of processes and weather in climate, from impact to upscale effects.
2. The importance of HighResMIP protocols.
3. Three quick examples of the influence of high resolution on:
    1. Cyclone simulation
    2. Mean state
    3. Climate projection and observations via ocean resolution

RazorEdge starting

Multi-Scale Interactions in the Earth System



Courtesy: A. Prein, IAC-ETH, 2026

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Context: From HighResMIP (CMIP6) to HighResMIP2 (CMIP7)

HighResMIP (CMIP6)

Haarsma et al. 2016

Tier 1 entry card	**highresSST-present** Atmosphere-only, 1950–2014 HadISST2 daily 0.25° SST and sea ice
Tier 2 coupled	**spinup-1950** (50 yr), **control-1950** (100 yr) **hist-1950** (1950–2014) **highres-future** (2015–2050) Future uses SSP5-8.5
Tier 3 atmosphere-only	**highresSST-future** 2015–2050, optionally to 2100
Extras targeted	**highresSST-smoothed**, -LAI, -p4K, -4co2 **highres-4co2** (coupled abrupt 4xCO2)

HighResMIP2 (CMIP7)

Roberts et al. 2025

Tier 1a entry card	**highresSST-present** Atmosphere-only, 1980–2022; ESA CCI daily 0.05° SST, OSI SAF sea ice
Tier 1b entry card	**spinup-1950** (50 yr), **control-1950** (100+ yr) Coupled; either 1a or 1b is enough
Tier 2 coupled	**hist-1950** (1950–2022) **highres-future-xxx** (to 2100) CMIP7 medium scenario
Tier 3 idealised	**highresSST-p4kuni, abrupt4xCO2-1950**
Tier 4 warming levels	**highresSST-pxxkpat** Patterned SST and sea ice, 2003–2022
Tier 5 one year	**highres-yrxxxx** (+**p4kuni**) Atmosphere-only, linked to DYAMOND3

Key protocol differences

Atmosphere-only forcing

1950–2014, HadISST2 0.25°

→ 1980–2022, ESA CCI 0.05°

Coupled future

2015–2050, SSP5-8.5

→ to 2100, CMIP7 medium scenario; highresSST-future dropped

New experiments

Three tiers, no idealised runs

→ +4 K SST, abrupt 4xCO2, warming levels, 1-year run

Model set-up

Kept close to standard resolution, MACv2-SP aerosol

→ optimised high-resolution models, any aerosol scheme, ~10 km aimed for

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Context: From HighResMIP (CMIP6) to HighResMIP2 (CMIP7)

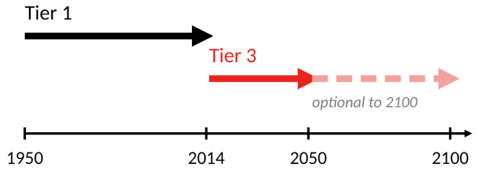
CMIP6 HighResMIP simulation design

(a) Atmosphere-land-only simulations

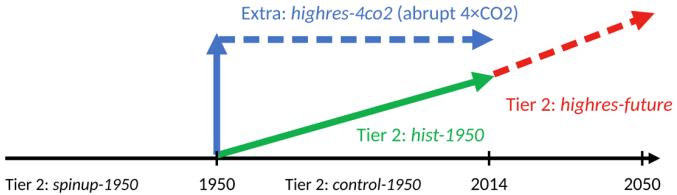
Tier 1 – *highresSST-present*

Tier 3 – *highresSST-future*

Other – *highresSST-smoothed, -LAI, -p4K, -4co2*



(b) Coupled atmosphere-land-ocean-sea-ice simulations



CMIP7 HighResMIP2 simulation design

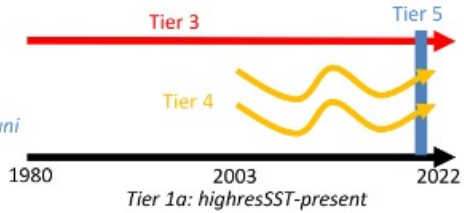
(a) Atmosphere-land-only simulations

Tier 1a – *highresSST-present*

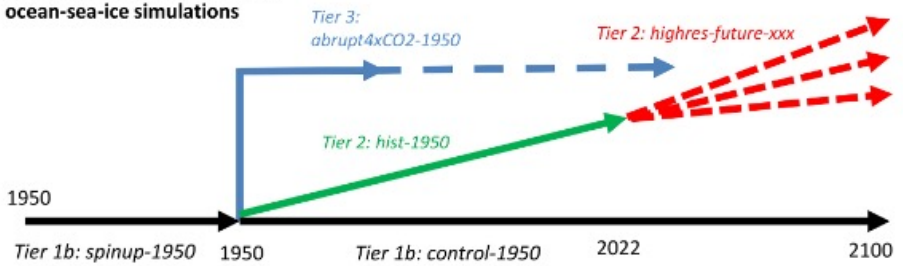
Tier 3 – *highresSST-p4kuni*

Tier 4 – *highresSST-pxxkpat*

Tier 5 – e.g. *highres-yr2020, highres-yr2020-p4kuni*



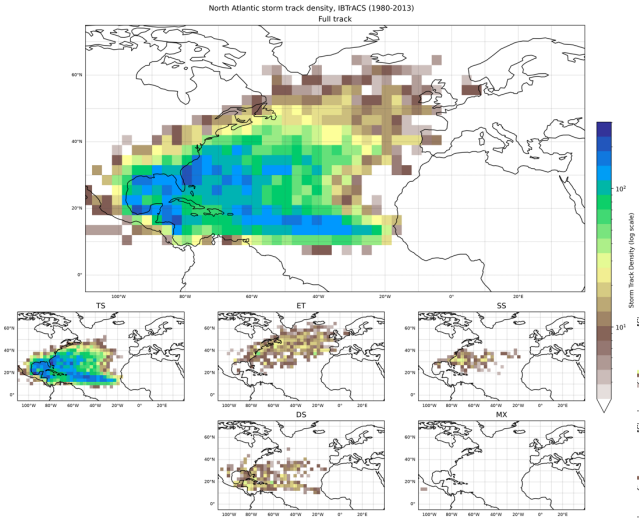
(b) Coupled atmosphere-land-ocean-sea-ice simulations



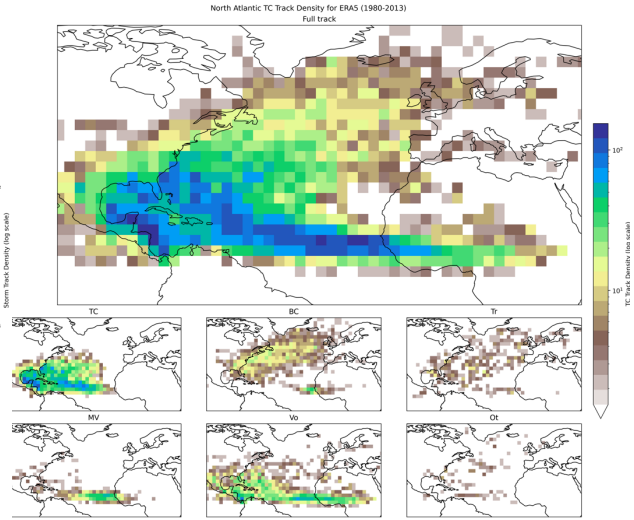
Our capability to reproduce every aspect of Cyclone of Tropical Origin (CTO)

The lifetime characteristics do matter for impacts.

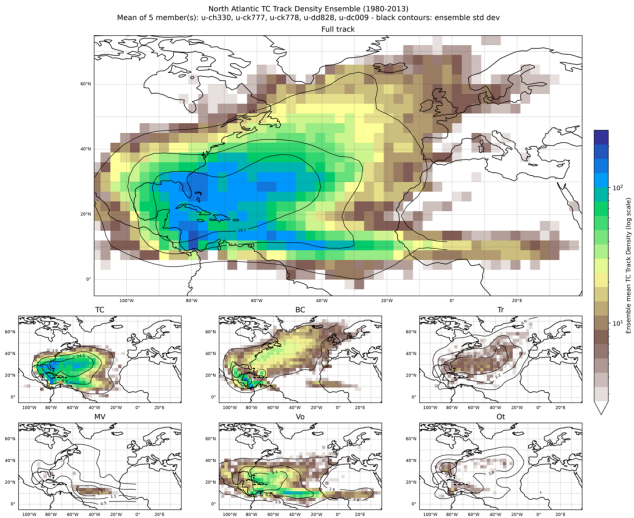
IBTrACS



ERA5



ENSEMBLE OF 10KM HADGEM3



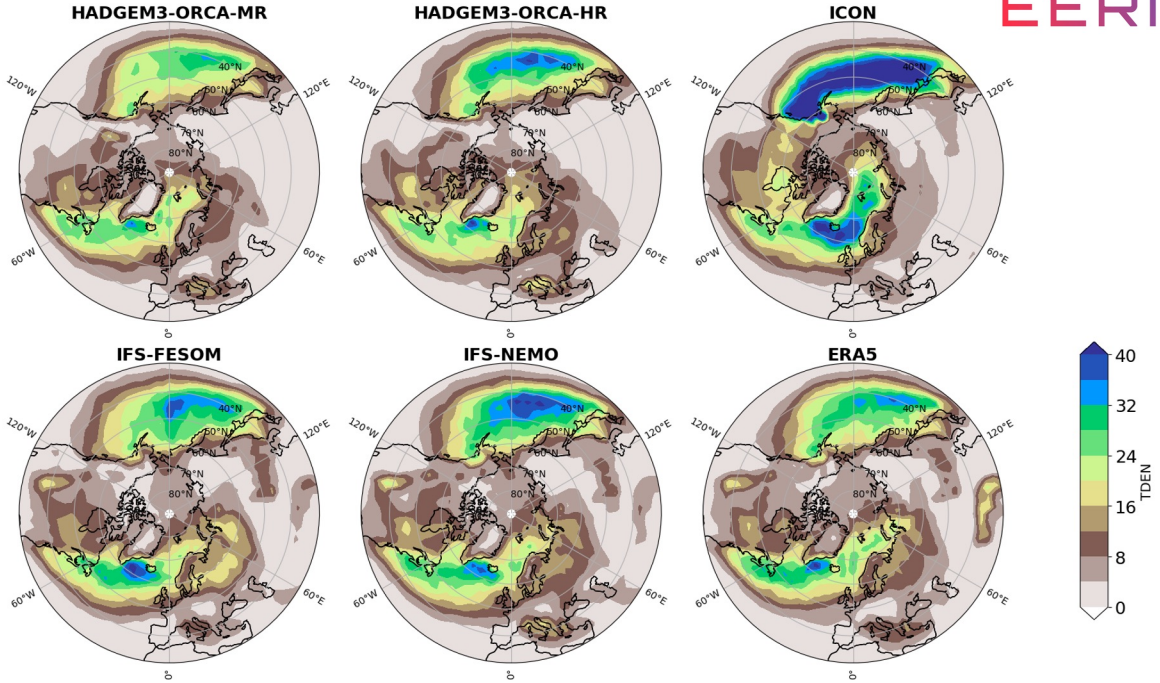
Vidale et al. 2027

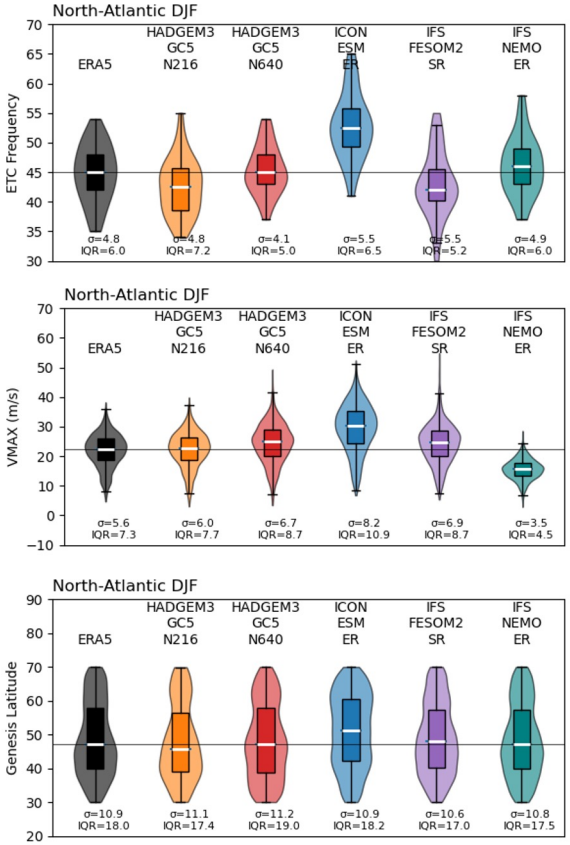
For the detailed nature of each cyclone's hazard, as they make landfall in British Isles and Europe see also Baker et al. J. Clim. 2022

Representation of extratropical cyclones in eddy-rich GCMs

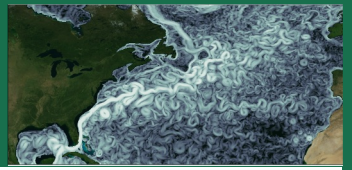
EERIE: A new generation of coupled GCMs using **HIGHRESMIP** protocol

- Explicitly **resolves ocean mesoscale features** such as fronts, eddies, and other meandering filaments are predominantly found near the WBC
- Ocean resolutions ~ 1/12º , atmospheric resolutions ~ 10 km

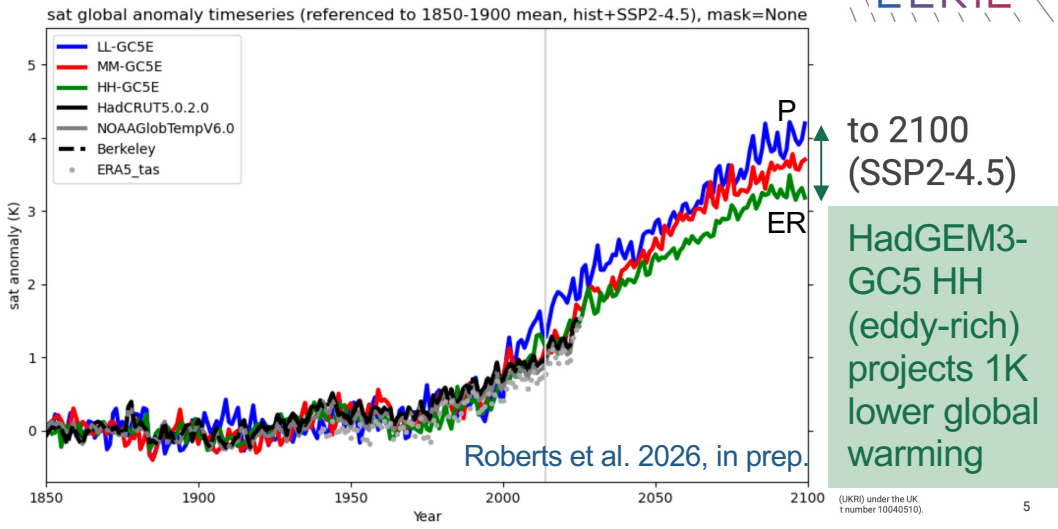




Climate trends: evolution of surface temperatures with eddy-rich (ER) versus parameterised (P) ocean

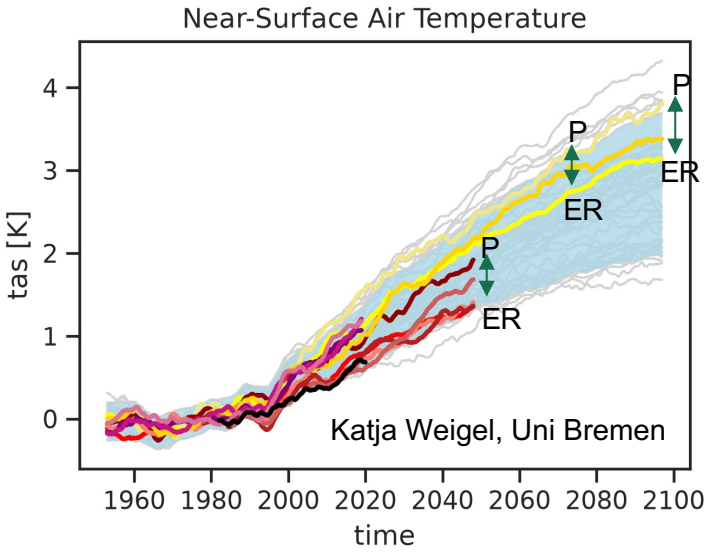


Historical SAT anomaly timeseries



HadGEM3-GC5 HH (eddy-rich) projects 1K lower global warming

Similar result in other EERIE models





The temperature response above is mostly oceanic and is also seen in other eddy-rich GCMs.
Why does it happen?

- Deeper mixing?
- Role of transports and stronger hydrological cycle?

HRCM action: 5 more ensemble members at 20-10 and 10-10km

Next Steps

Key takeaways: work on storms and their upscale effects, on the impact of resolution on the mean state, and the impact of high-resolution oceans on storms and climate change.

NCAS has

1. Several 10km HighResMIP atmosphere only simulations still to fully analyse;
2. Will contribute to ensemble members for HH HighResMip2,; and is
3. Starting coupled 10/10 simulations.

Data handling is a major constraint on fully exploiting these simulations!

We have UKRI funding to make the 10km AO runs available to the community in the next few months (as part of a project called “Ensembles4AI”, to support the provision of training sets for AI).

The 10/10 simulations are expected to be the bedrock of the next few years work before we get access to GPU versions of our models.



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Canari and UK summers (A cast of thousands)

1. An introduction to CANARI
2. Just one science example:
    1. What does CANARI tell us about maximum temperatures in future UK summers?
    2. How does that compare with other information we have? (CMIP, UKCP18)?
    3. To what extent can we attribute future changes to circulation change?
3. (And a quick look at some the nesting capabilities of CANARI)

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An Introduction to the CANARI Large Ensemble

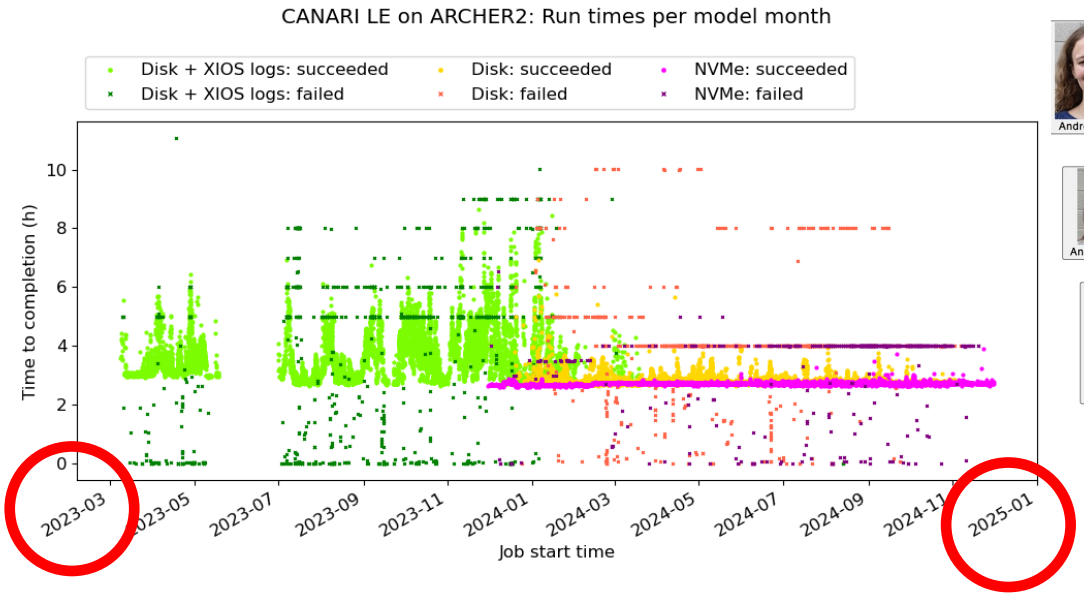
Climate change in the Arctic-North Atlantic Region and Impacts on the UK

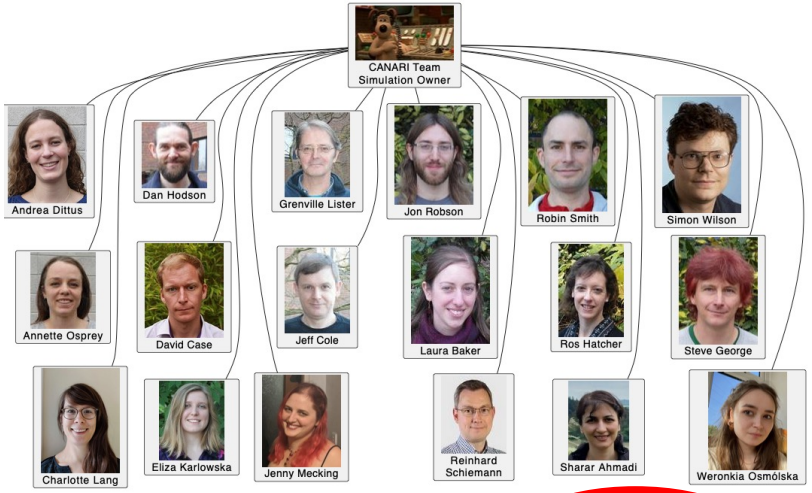
- **40 Ensemble Members. 150 years per member.**
  - Hybrid initialisation (8 macro, 5 micro)
- N216O25 (Unified Model Atmosphere ~60km, NEMO 0.25 degrees)
- 1950-2100: HIST followed by SSP370 simulation from 2015.
- 6000 years of simulation. 6 Petabytes of data.
  - Full boundary conditions for CORDEX
  - High frequency fields for storm-analysis.
  - Output for hi-res regional ocean simulations (NOC)
  - Output for hi-res UK hydrological models (UKCEH)
- Huge user community doing great science …

Schiemann et al, The CANARI HadGEM3 Large Ensemble: Design, and evaluation of historical experiments. GMD submitted 2026. (available in egusphere)

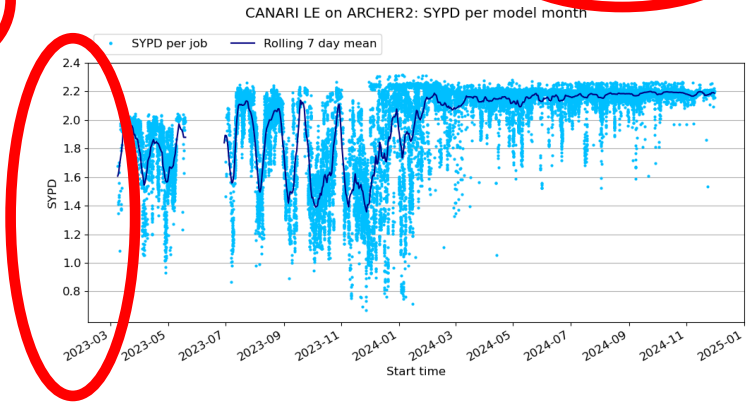
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A logistical nightmare



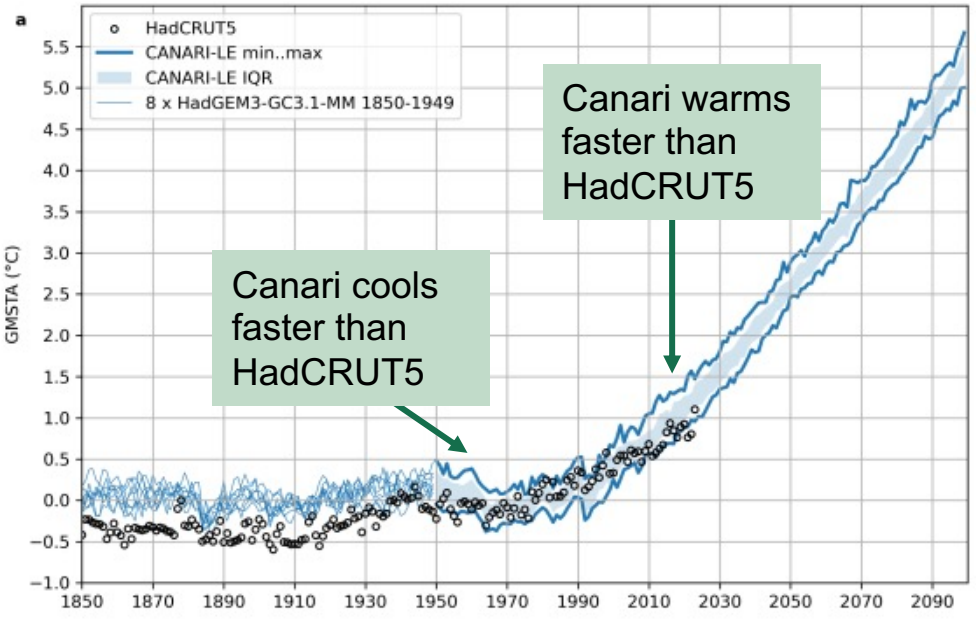


Simulations carried out by “volunteers”!



- **Unstable system** for the first year!
- Major impact of moving to **NVME disk** on stability.
- Huge difference in run-time speeds.
- **Data transfer and management** a burden on the core team!

CANARI Global Mean Trends

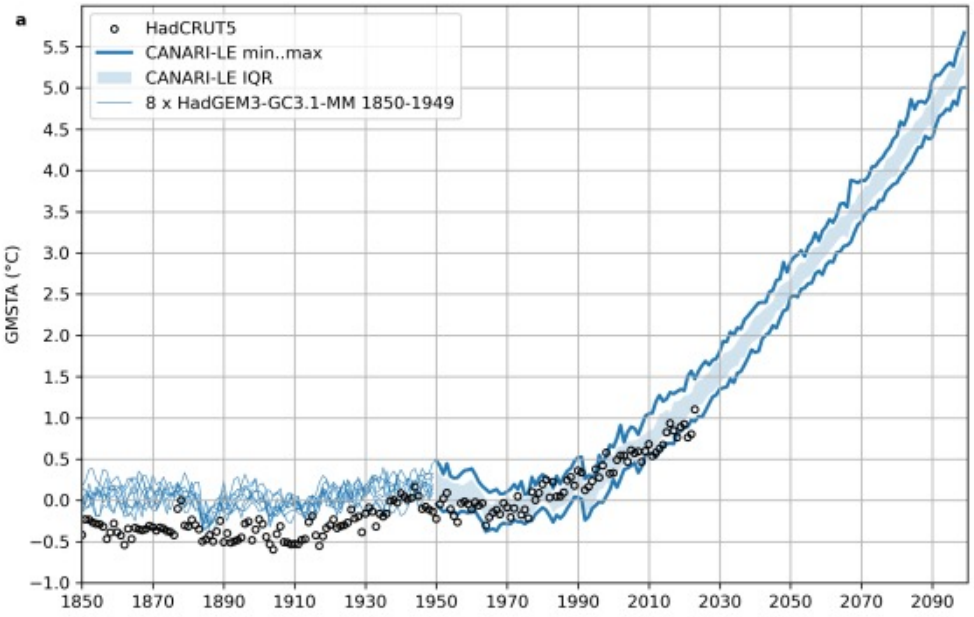


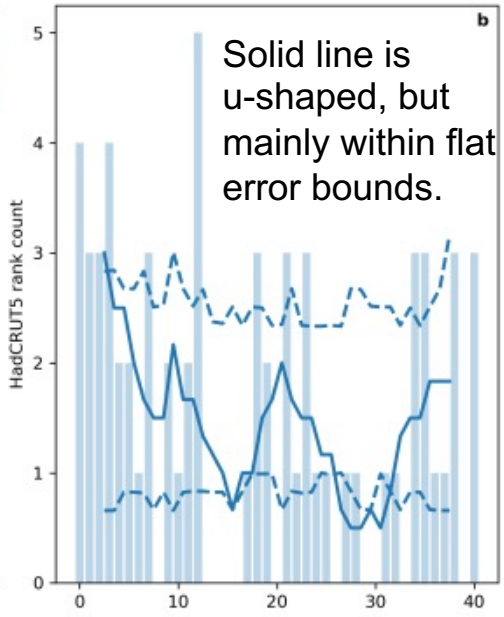
Global mean analysis carried out by Reinhard Schiemann who led on the LE, including most of the ensemble design and initialization work.

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CANARI Global Mean Trends

Rank histogram: count of HadCRUT5 values cf CANARI



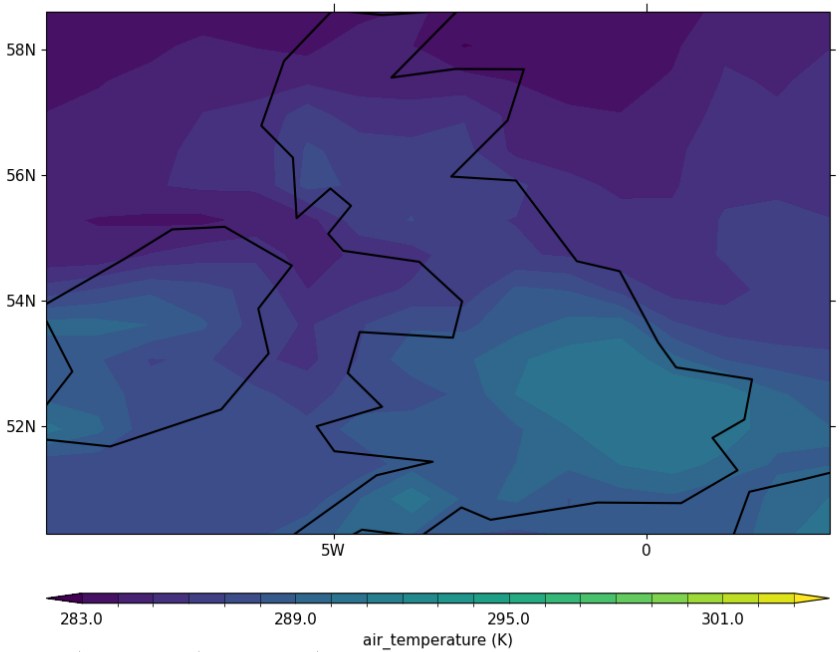


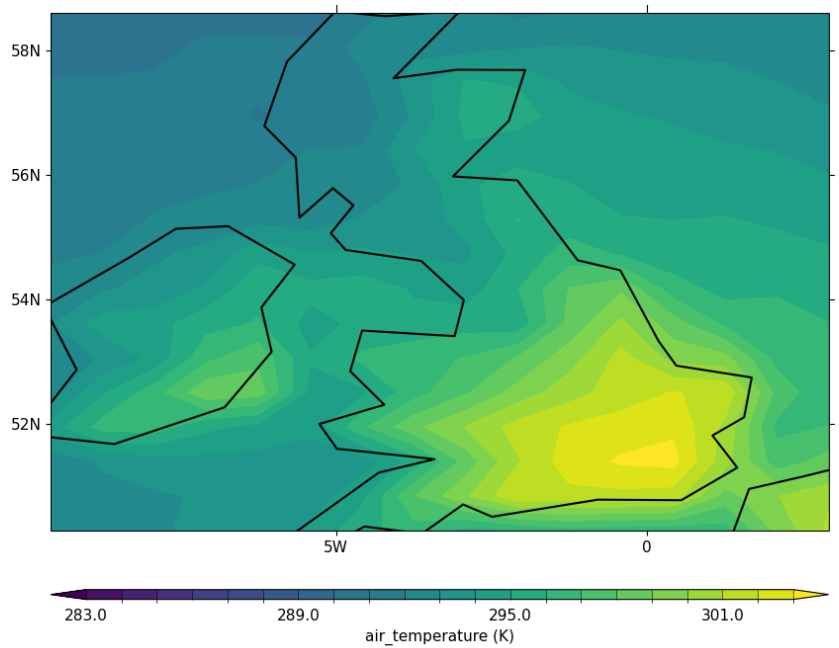
Interpretation: given the differences in the mean, the observations are basically statistically indistinguishable from the large-ensemble.

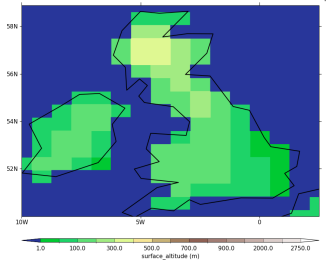
4 years for which HadCRUT5 is smaller than any member, and 3 where it is larger.

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What about the regional change? What about UK summer temperatures?



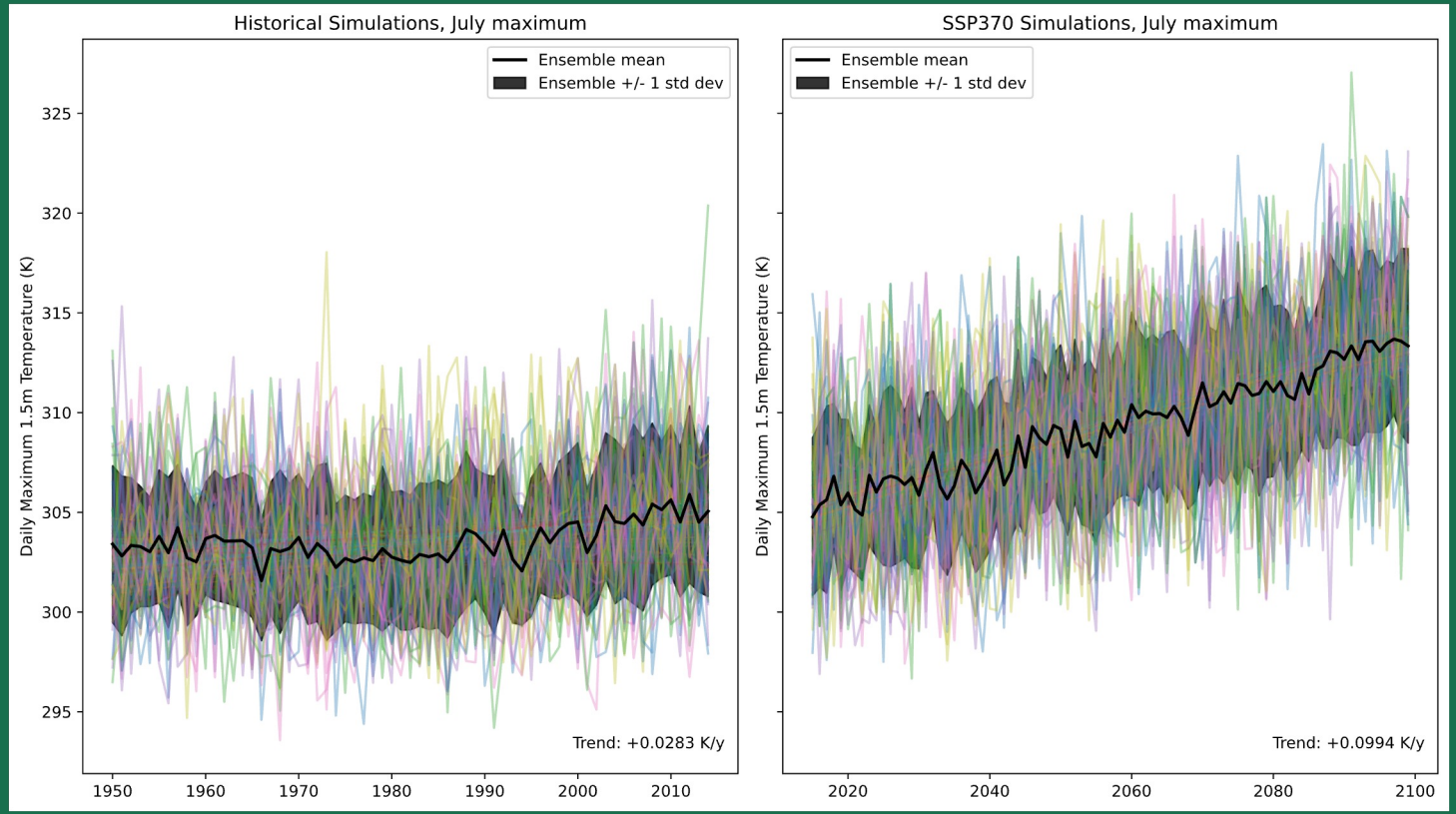




- Extract a 16x16 grid box from the daily maximum surface temperature output, and subspace to July values only.
- The examples above are the first day of the first July in a future simulation, and the last day of the last July in the same simulation.

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What is the maximum surface temperature seen in the UK (tasmax)?

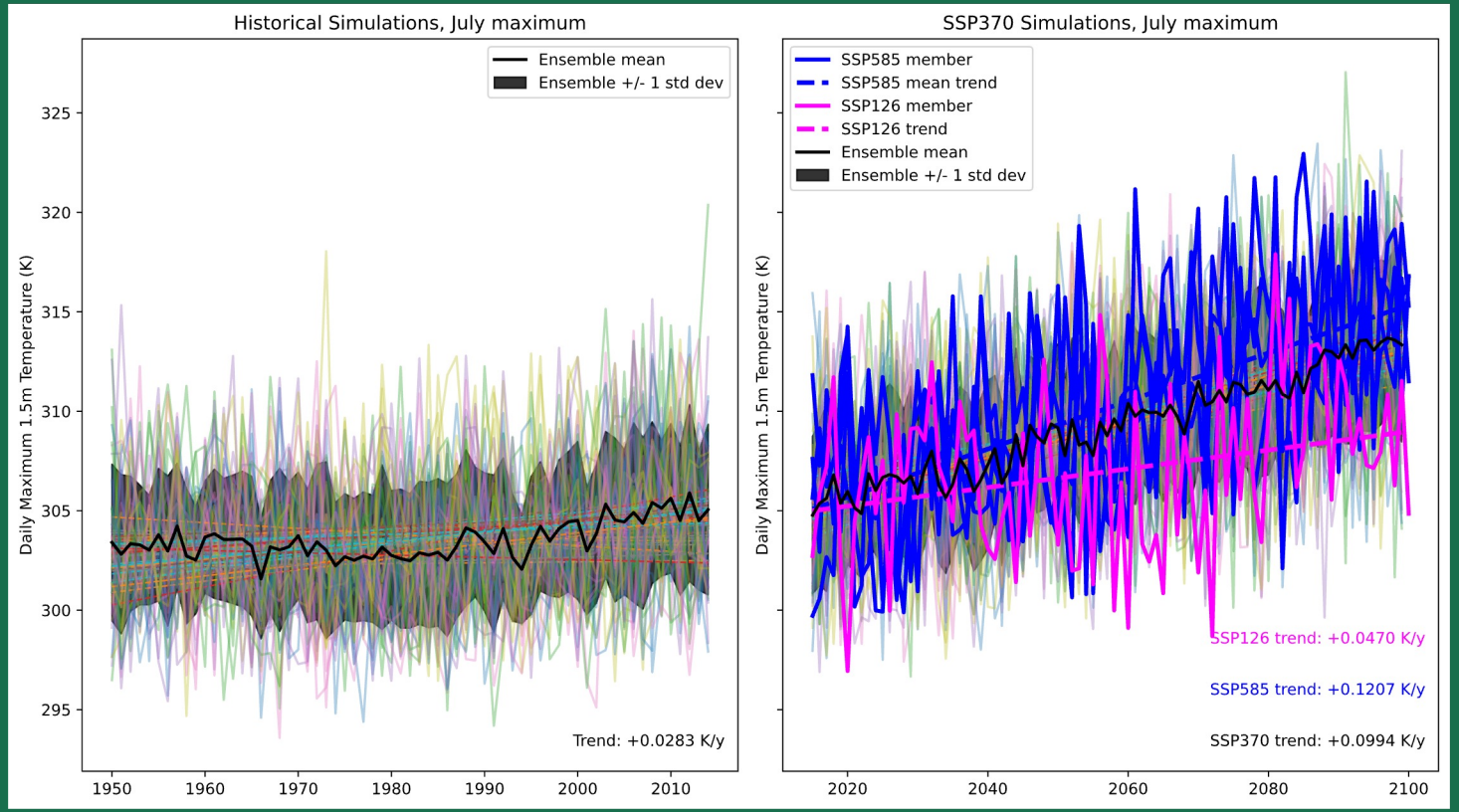


This is a hot model, but even so!

320K = 47C
325K = 52C

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The CANARI Large ensemble in comparison to other CMIP6 scenarios?

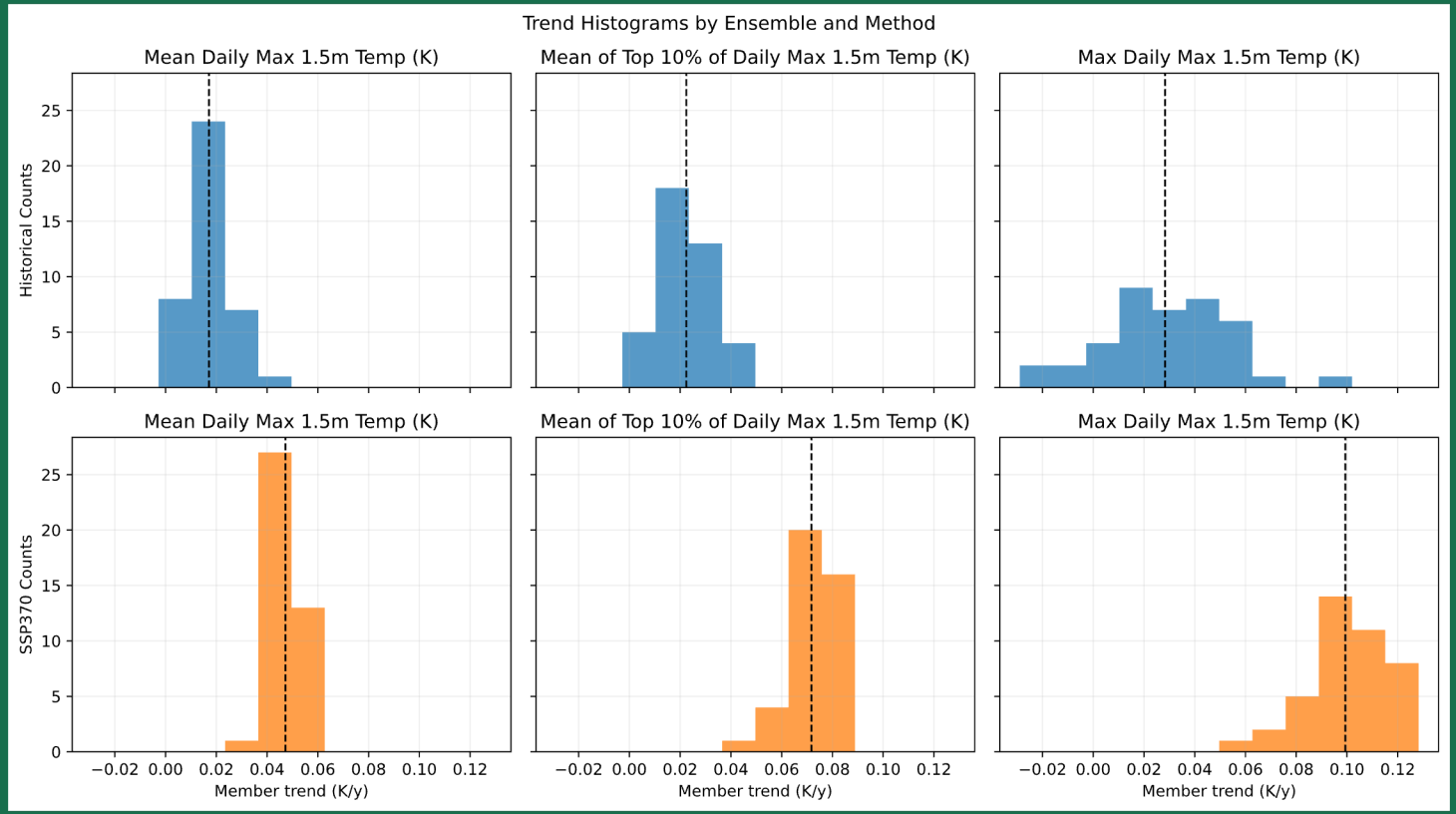


The CANARI Large ensemble encompasses the CMIP scenarios ensemble members!

Internal variability IS dominating over scenario uncertainty at the UK scale!

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Mean, Upper Decile of Max, and Maximum surface temperatures

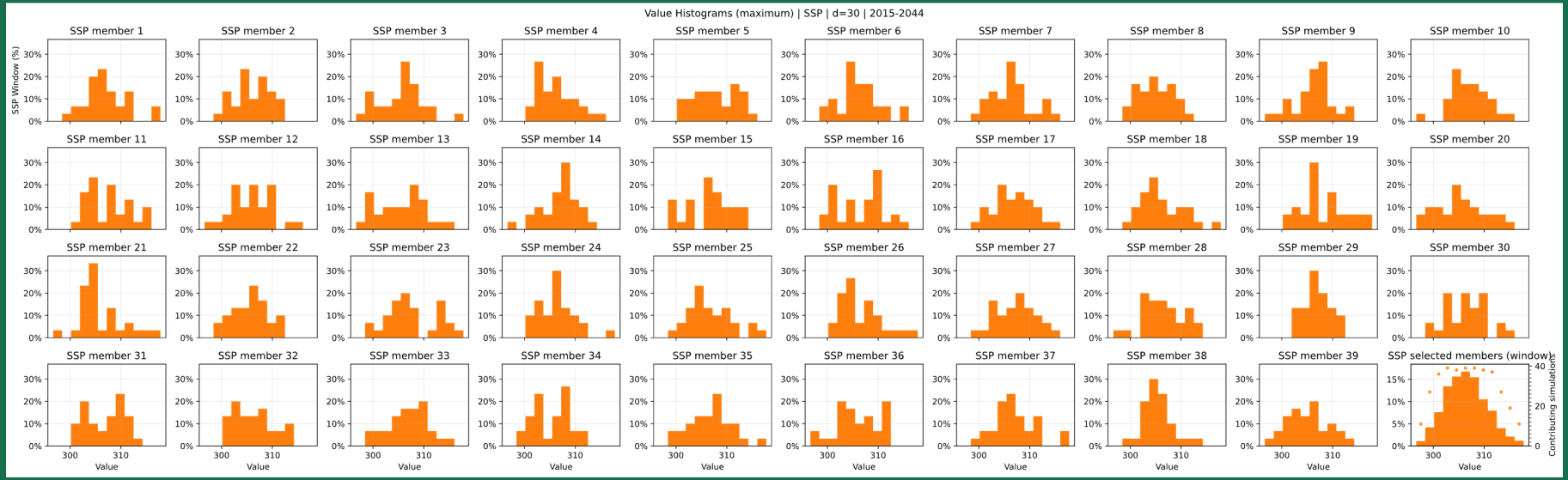


Demonstrating the the well-known expectation that *extremes* will get "more extreme" faster than *means*.

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How good a predictor would one member (historical climate) be of regional trend?

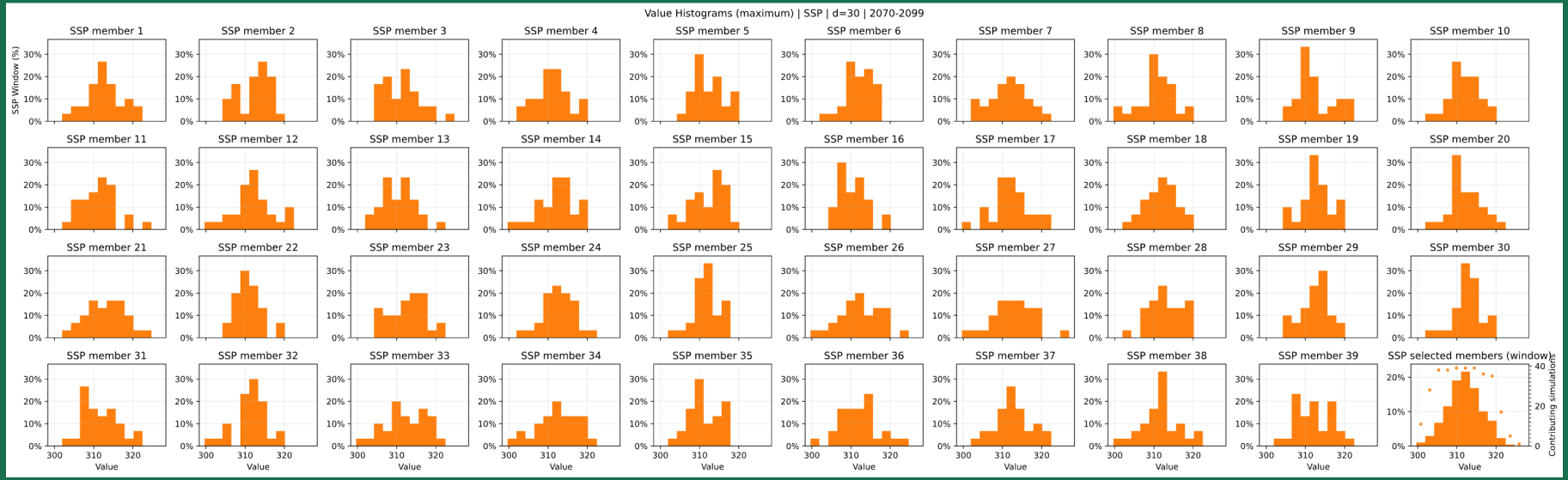
Maximum temperature values seen in the first 30 years of SSP370 as a function of member



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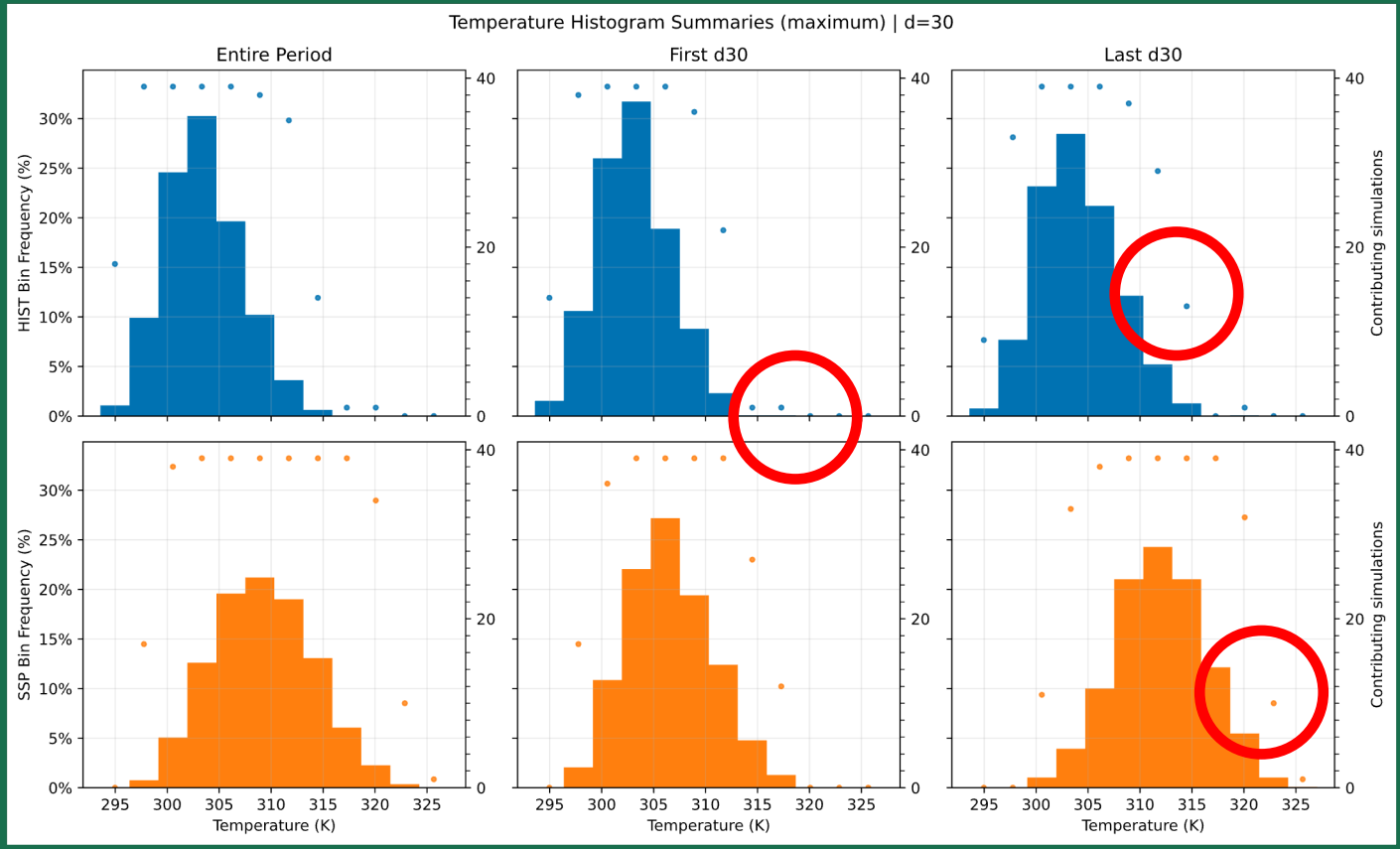
Maximum temperature values seen in the last 30 years of SSP370 as a function of member



30-year trends/distributions from one member will not be representative of what could happen! Maybe the past is not such a good predictor of the future in this ensemble! Could that be true of the real climate?

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How many simulations? How representative was past climate?



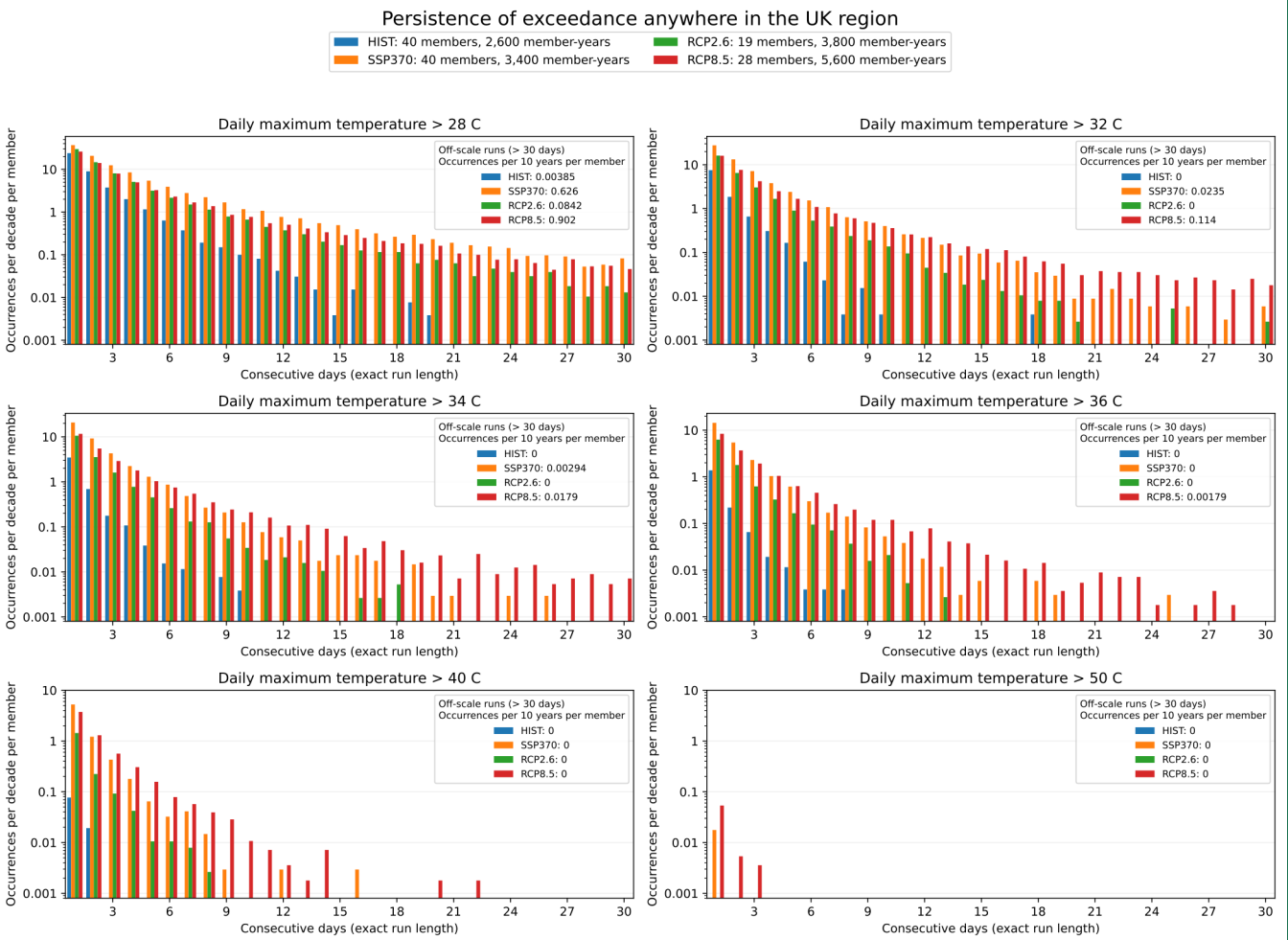
To see the possible extremes in UK summer temperature you need a lot of simulations.

Similarly, future extremes may not be likely, but they are not impossible!

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Duration of heat?

- Histograms of occurrence of temperatures anywhere in the UK exceeding specific values.
- Interpretation: 0.01 is one occurrence per 100 years of simulation.
- The RCP data here is from UKCP18 (a slightly different version of the model) than used in the trend analysis.
- Clearly even the historical period could have been hotter than observed … but the future is likely to see extended hot periods every decade!



But what is driving this variability? What is our theory of UK regional change?

- Clear consensus in the literature that it is not circulation change, but that's not necessarily based on large-ensembles and/or high-resolution models.
  - Suggest that thermodynamic processes are driving the increased temperature trend.
  - Are they driving the inter-year variability, or is that circulation?

- CANARI ensemble is only slightly bigger than the UKCP18 ensemble, but we have more diagnostics and more tools
  - Q1: … do we agree with the literature?
  - Q2: … what is driving the UK inter-year, inter-ensemble-member variability?

- An incomplete answer follows:
  - Q1: Yes – for the ensemble mean (the forced response)
  - Q2: Much bigger role for changing frequency of weather regime occurrences

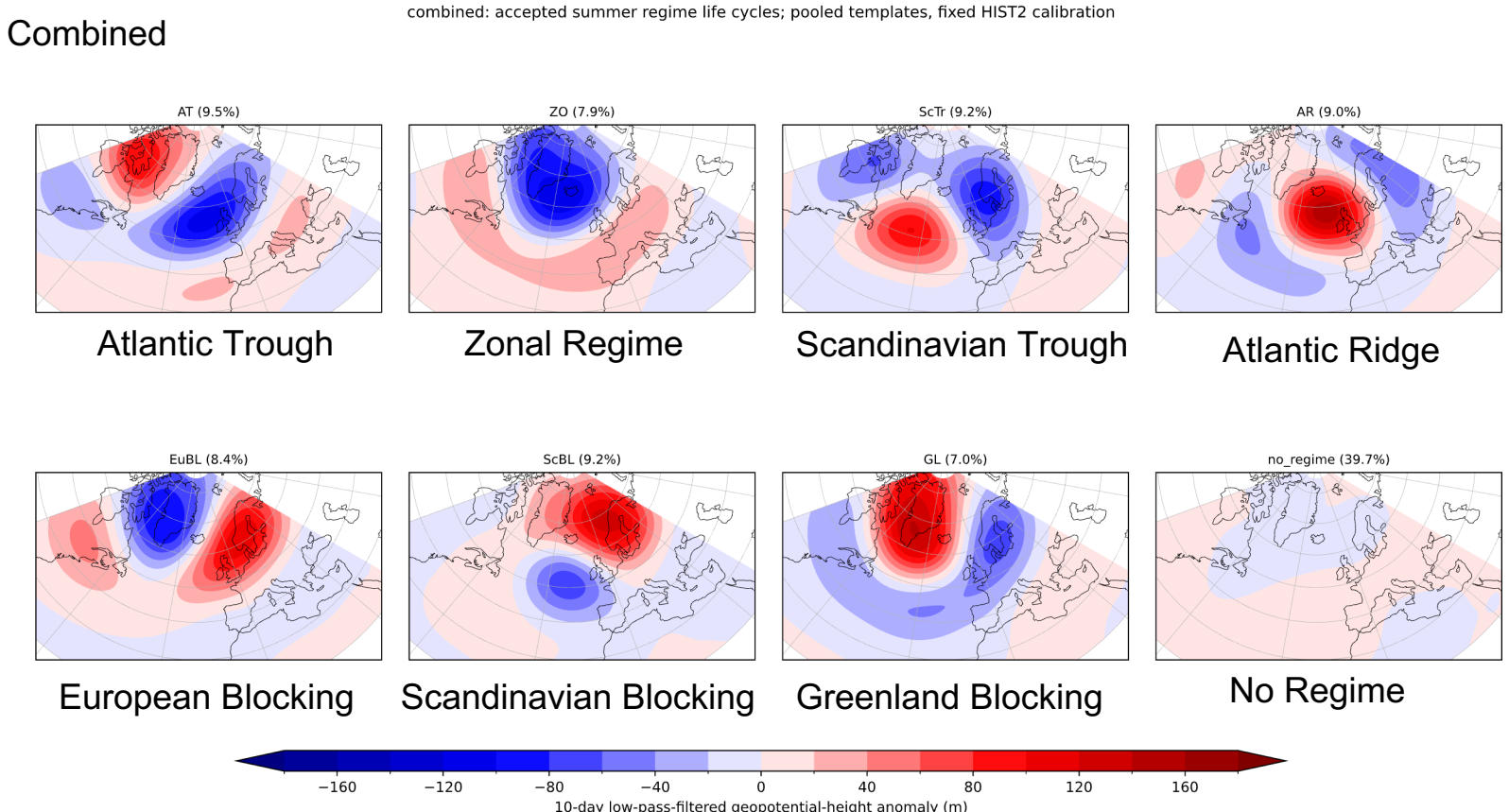


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Q1: Composite weather regimes in the CANARI ensemble

Methodology follows Grams (2026), but targeting summers only (verified against all periods).

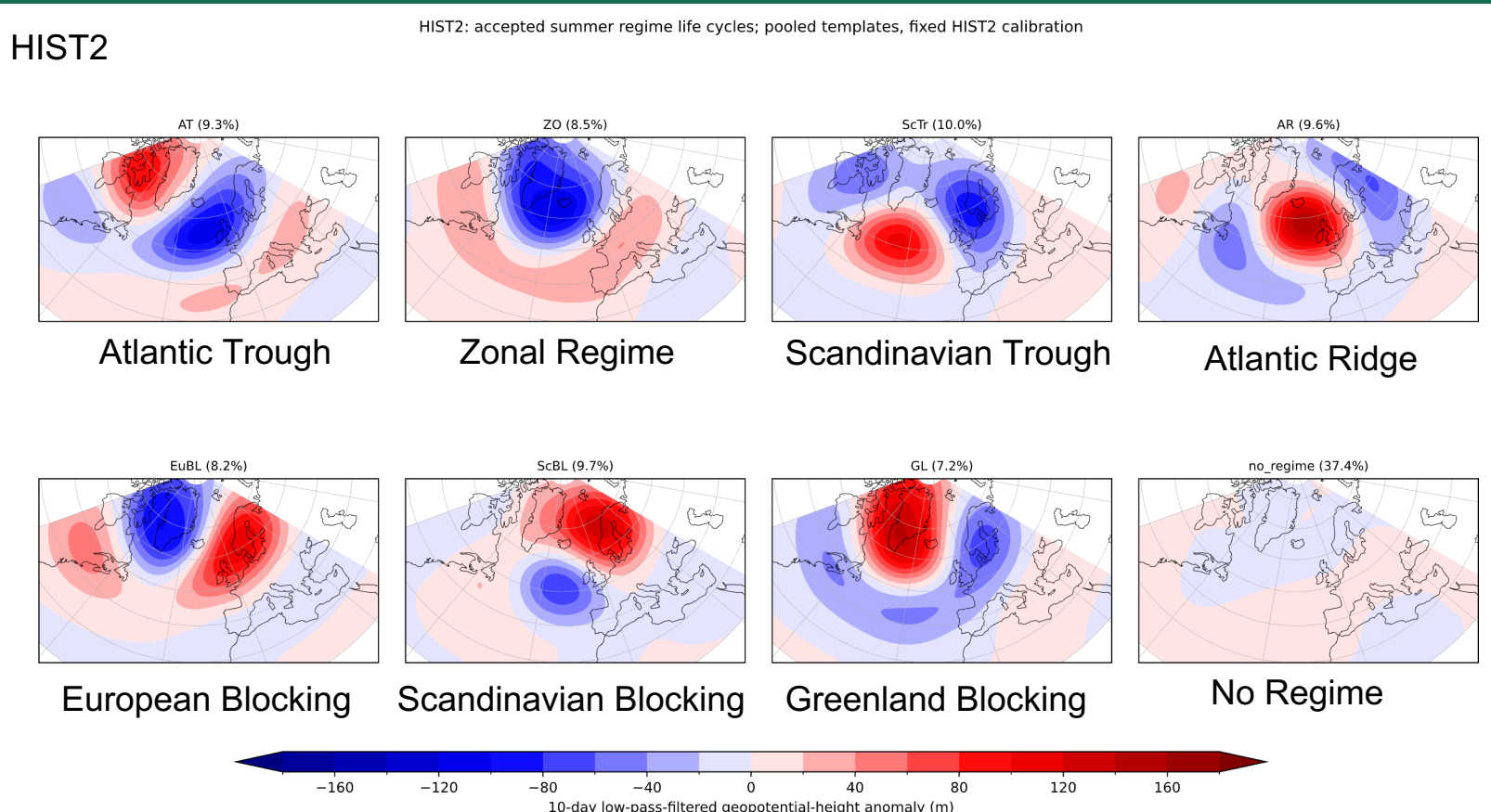
Initial analysis suggests neither the regimes, their frequency, or the underlying EOFS change significantly between HIST and SSP370!



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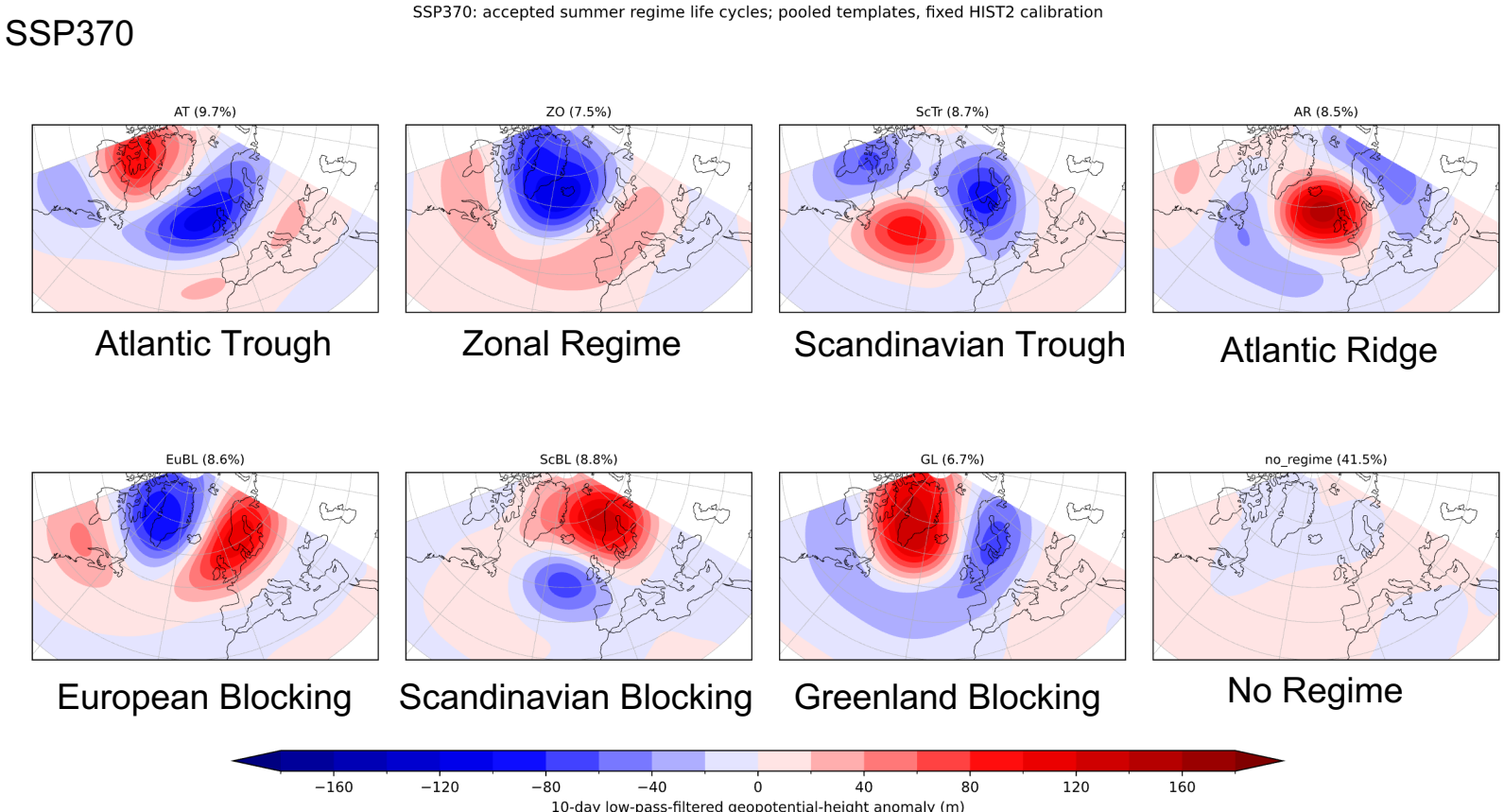
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Q1: Composite weather regimes in the CANARI ensemble

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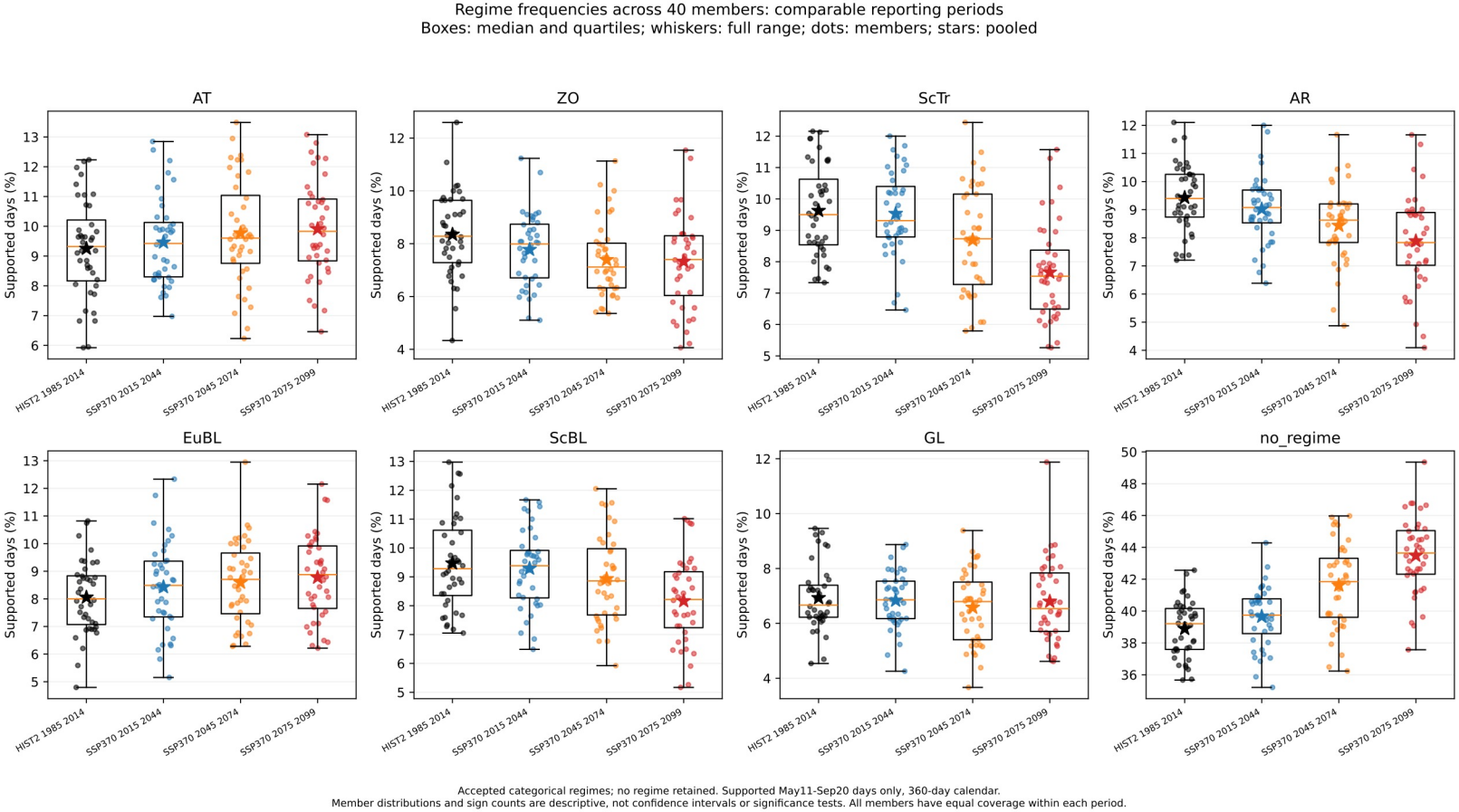


… but initial analysis can be deceptive

Modest decline in Atlantic Ridge and Scandinavian Trough?

Significant increase in no-regime!

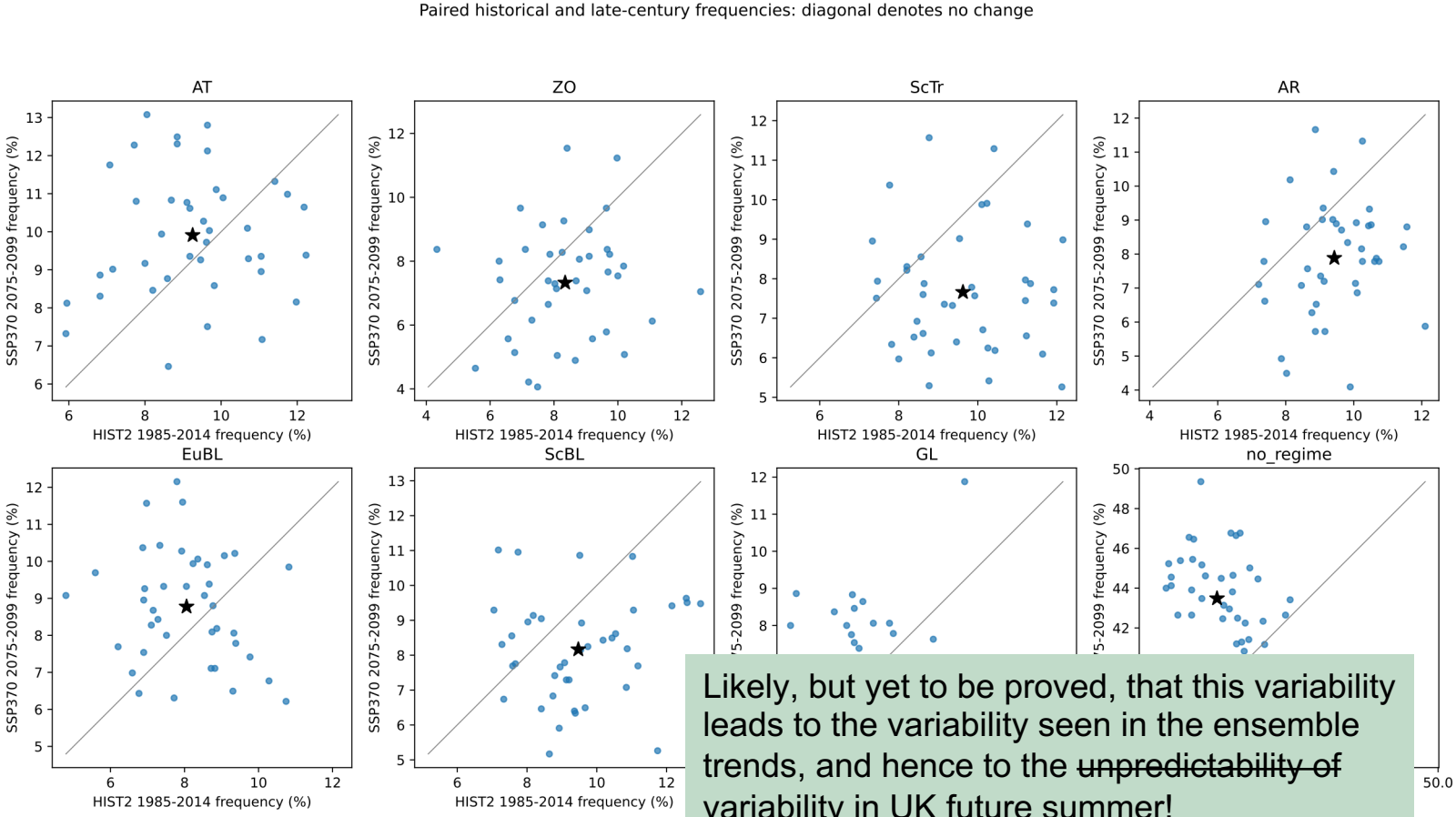
That's the forced response (if it's significant) but there is a lot of variability!



Q2: Do the ensemble members have differing regime frequencies?

Clearer signal in comparison of the frequency in each member between HIST and late SSP370!

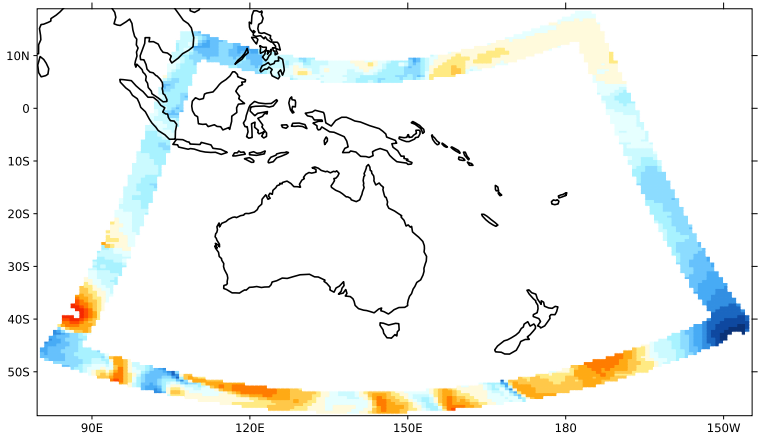
(Above the diagonal means the members frequency increased, below means decreased. Black star pooled ensemble.)



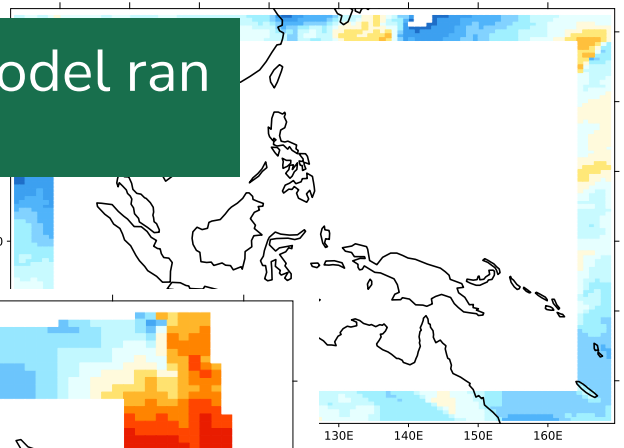
Likely, but yet to be proved, that this variability leads to the variability seen in the ensemble trends, and hence to the ~~unpredictability of~~ variability in UK future summer!

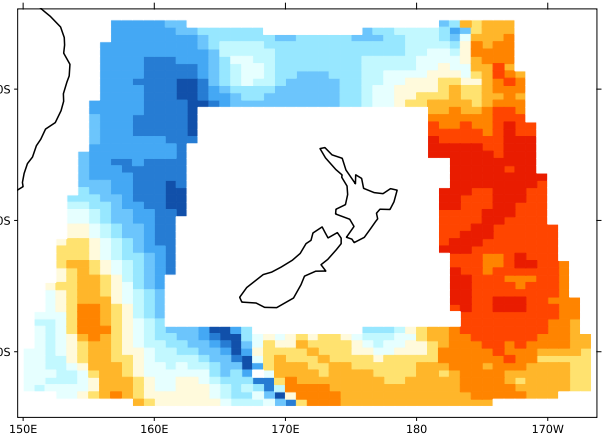
Accepted categorical regimes; no regime retained. Supported May11-Sep20 days only, 360-day calendar.
Member distributions and sign counts are descriptive, not confidence intervals or significance tests. All members have equal coverage within each period.

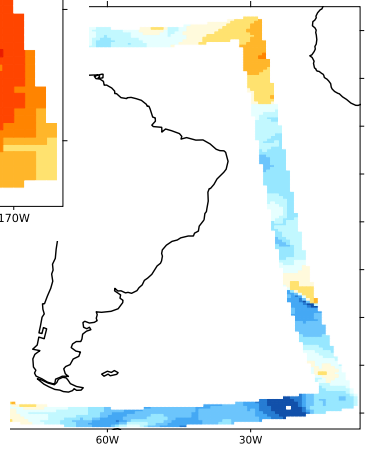
Many regional frames were written as the model ran (Not all shown here)

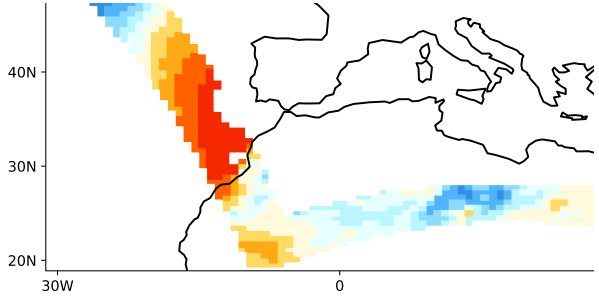


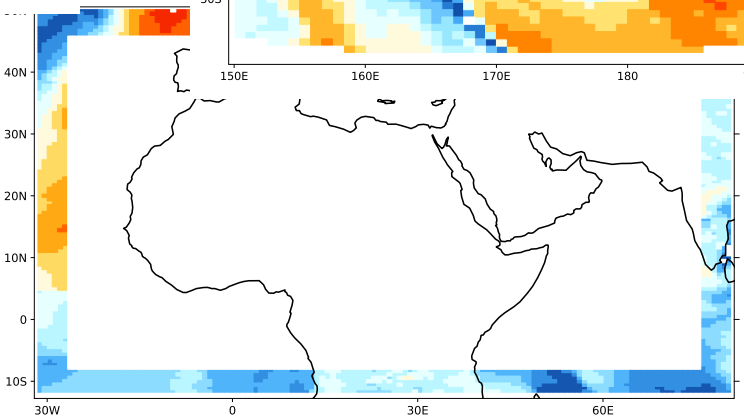












Timestep output for driving variables

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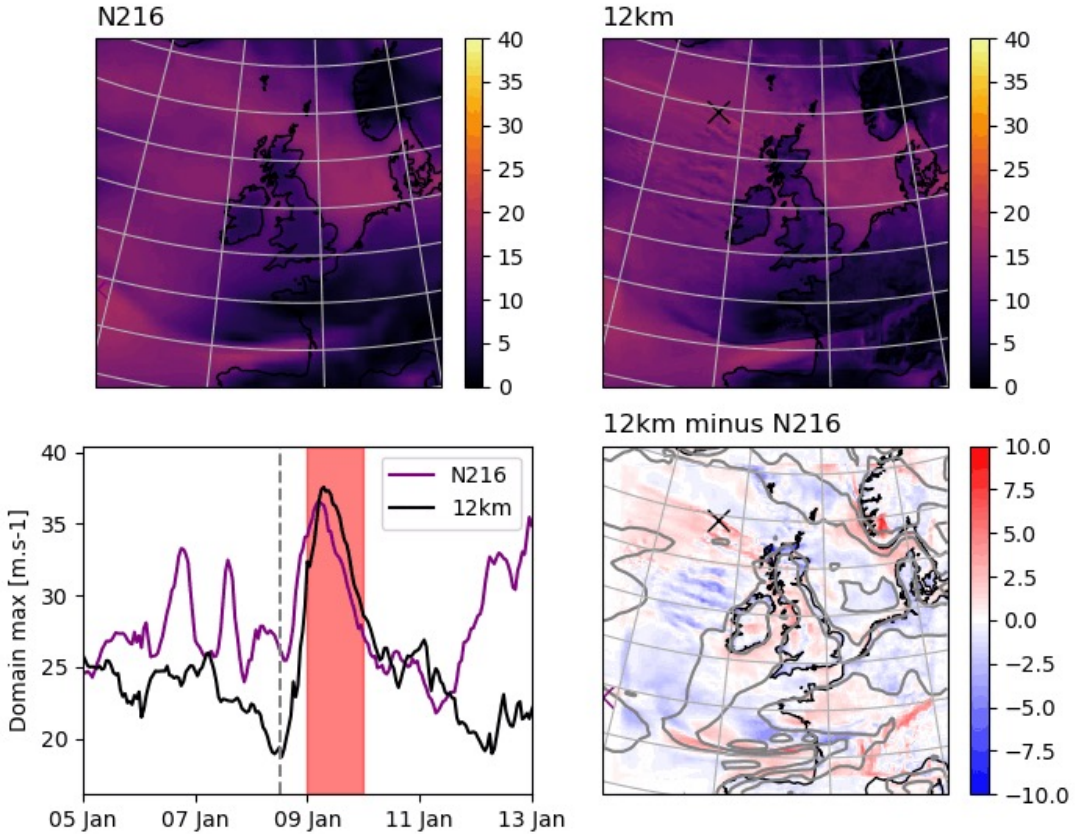
Storms – A UK illustration



Ben Harvey

Storms were identified during the simulations, and specific extra information was saved for these.

The most intense UK windstorm in 2,600 years of LE data simulation Cold conveyor belt is more intense and sharper in the 12km RCM than the GCM.



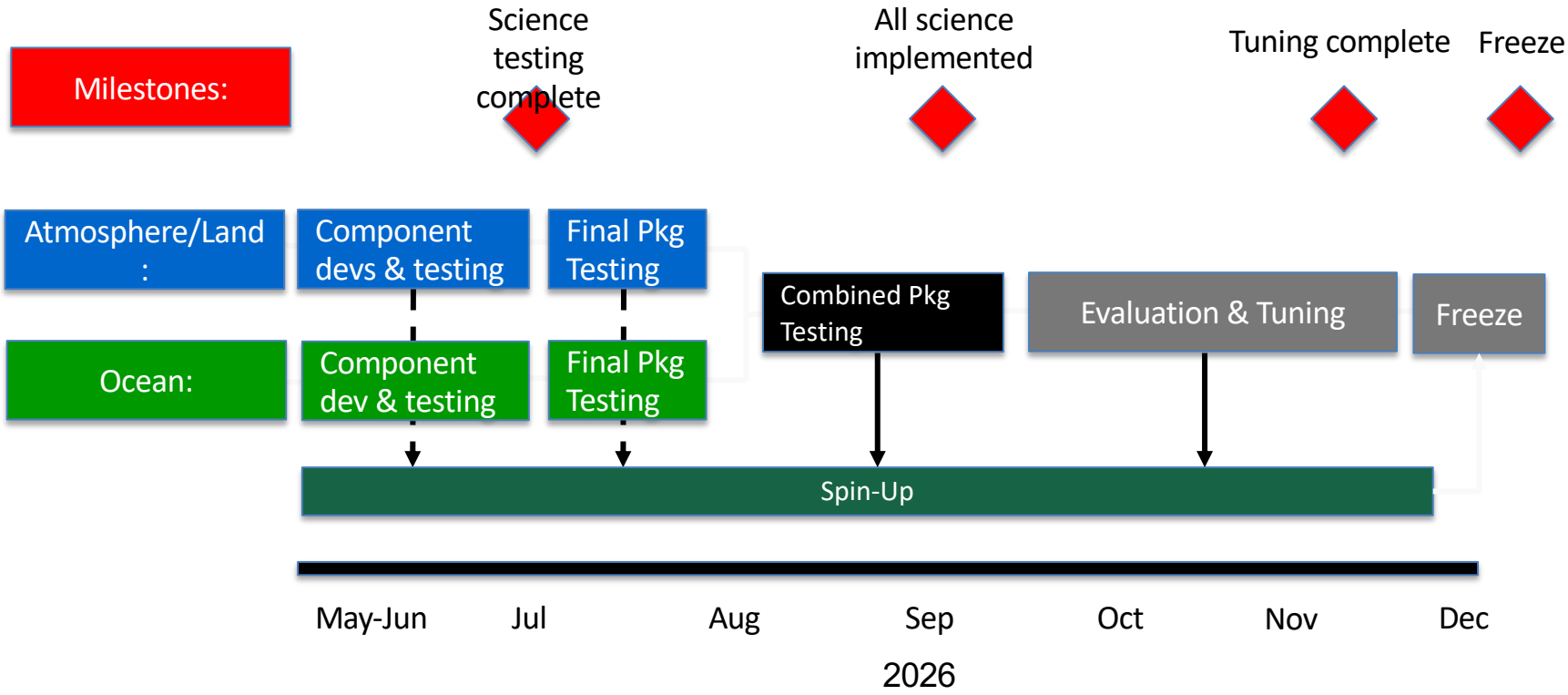
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Technology

1. Choices and Directions of Travel
2. Where do we need resolution?
    1. Can climate models benefit from inhomogeneous resolution?
3. Where are we going with GPUs? When?
4. Data formats and Data Libraries
5. Compression

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UKESM2 timeline for freeze



NCAS Modelling Roadmap

Transitioning from the Unified Model towards Next-Gen LFRic/NEMO Frameworks

RESOLUTION

Level	Atmosphere	Ocean
L (Low)	~100km	~1°
M (Med)	~50-60km	~1/4°
H (High)	~20-25km	~1/12°
V (Very-H)	~10km	~1/36°
S (Storm)	~5km	-
K (km)	~1km	-

MIP-Support Framework
CF, ESGF and other access via CMS, JASMIN & CEDA

CMIP7-AFT Era

UM/NEMO (GC-3.1 / GC-5.1)

- **UKESM1 & UKESM2** — UKESM-Partnership / NCAS — CPU
- **UKCM2-LL & UKCM3f-LL** — Low Resolution Standard — CPU
- **HadGEM31-MM & SMLE** — Medium Resolution Baseline — CPU
- **UKCM2b-HH (VH)** — High-Res UKRI Infrastructure — CPU

Post-AFT Era

LFRIC/NEMO (GC7 & GC-FAST)

- **UKESM3** — UKESM-Partnership / NCAS — CPU
- **UKCM3f-MM** — Medium Resolution — CPU, GPU
- **UKCM3b-HH & HRCM** — High Resolution GPU Pipeline — GPU
- **UKCM3c-VH (SV)** — Very-High Resolution Target — GPU

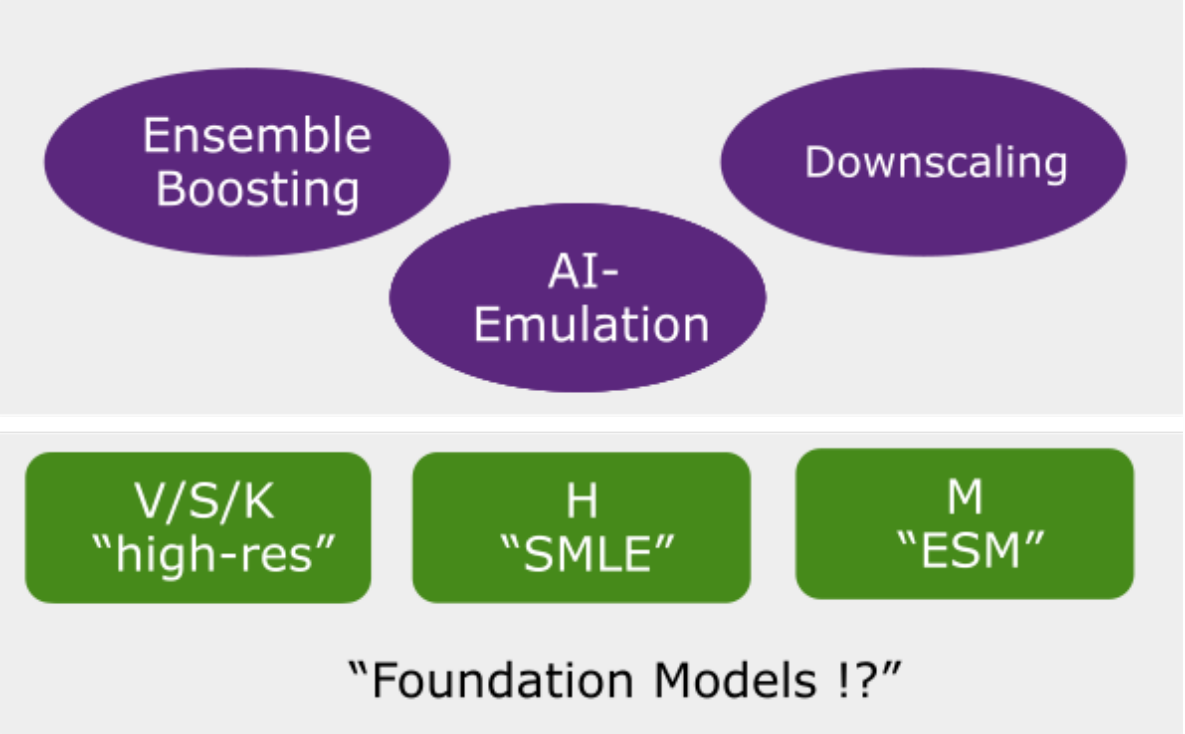
NCAS will support these models on new NCR & NNSS, to what extent we can support more variants will depend on funding and difficulty of porting.
(AI LLMs will help with some, but not all of this).

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK National Climate Science Partnership

The role of AI in climate modelling?

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



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How will AI change the way we do modelling?

An Ocean Model Ported by a Large Language Model: Experience and Lessons from FESOM2 (Fortran to C to C++/Kokkos)

N. Koldunov[1], S. K. Cheedela[1], S. Danilov[1], D. Sidorenko[1], S. Bever[1], and T. Jung[1,2]

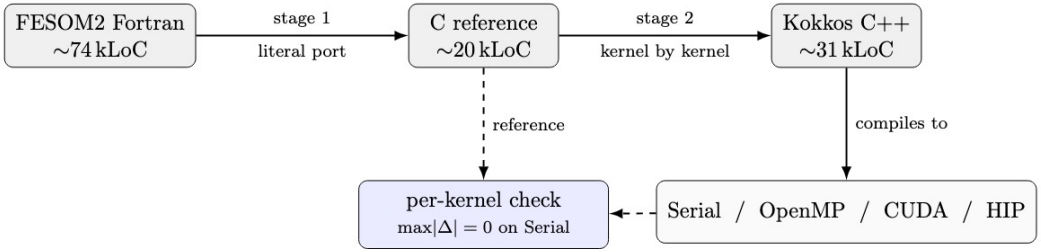
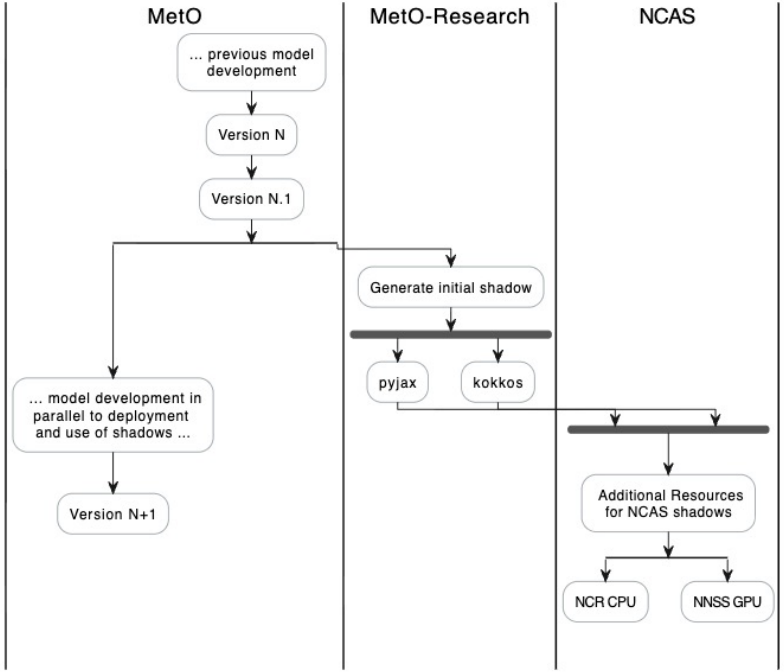


Figure 1: The two-stage porting workflow. Fortran is translated to a clean C reference (stage 1) and then wrapped in C++/Kokkos (stage 2); the C reference survives as a bit-identical Serial build against which every Kokkos kernel is checked.

FESOM2-JAX v1.0: a differentiable shadow of the ocean–sea-model FESOM2, cast onto GPUs

Nikolay V. Koldunov[1], Sergey Danilov[1], Suvarchal Cheedela[1], Dmitry Sidorenko[1], Sebastian Beyer[1], Patrick Scholz[1], Ivan Kuznetsov[1], Jan Streffing[1], Aleksei Koldunov[1], Dmitrii Pantiukhin[1], Svetlana N. Loza[1], and Thomas Jung[1,2]



This notion of shadows needs thinking through for the academic community

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FESOM2: from Fortran to portable GPU performance

LLM-assisted porting of a production ocean–sea-ice model — with scientific fidelity controlled by validation

Koldunov et.al. (2026). *An Ocean Model Ported by a Large Language Model: Experience and Lessons from FESOM2 (Fortran to C to C++/Kokkos)* (arXiv:2606.11356). arXiv.
https://doi.org/10.48550/arXiv.2606.11356

~74k	Fortran lines
~20k	C reference
~31k	C++ / Kokkos
5 years	simulated for validation

1 Fidelity-first translation

Mechanical changes only
indexing, memory layout and explicit data structures

No mathematical changes
equations, coefficients and numerical logic preserved

Two-stage strategy
separate numerical correctness from parallelisation risk

2 Validation before trust

Progressive test ladder
kernels → components → full model

Scientific check
5 simulated years; plausible output alone is not proof

Human oversight
domain experts define correctness and review differences

3 Data movement unlocks GPUs

Initial port: 3.8× slower
CPU-mediated MPI halo exchanges caused costly host–device copies

Keep halos GPU-resident
host–device traffic fell from ~13 to ~3 GB per step

Optimise access + solver
16.3 s → 2.7 s → 1.27 s; up to 3.7× faster than CPU node

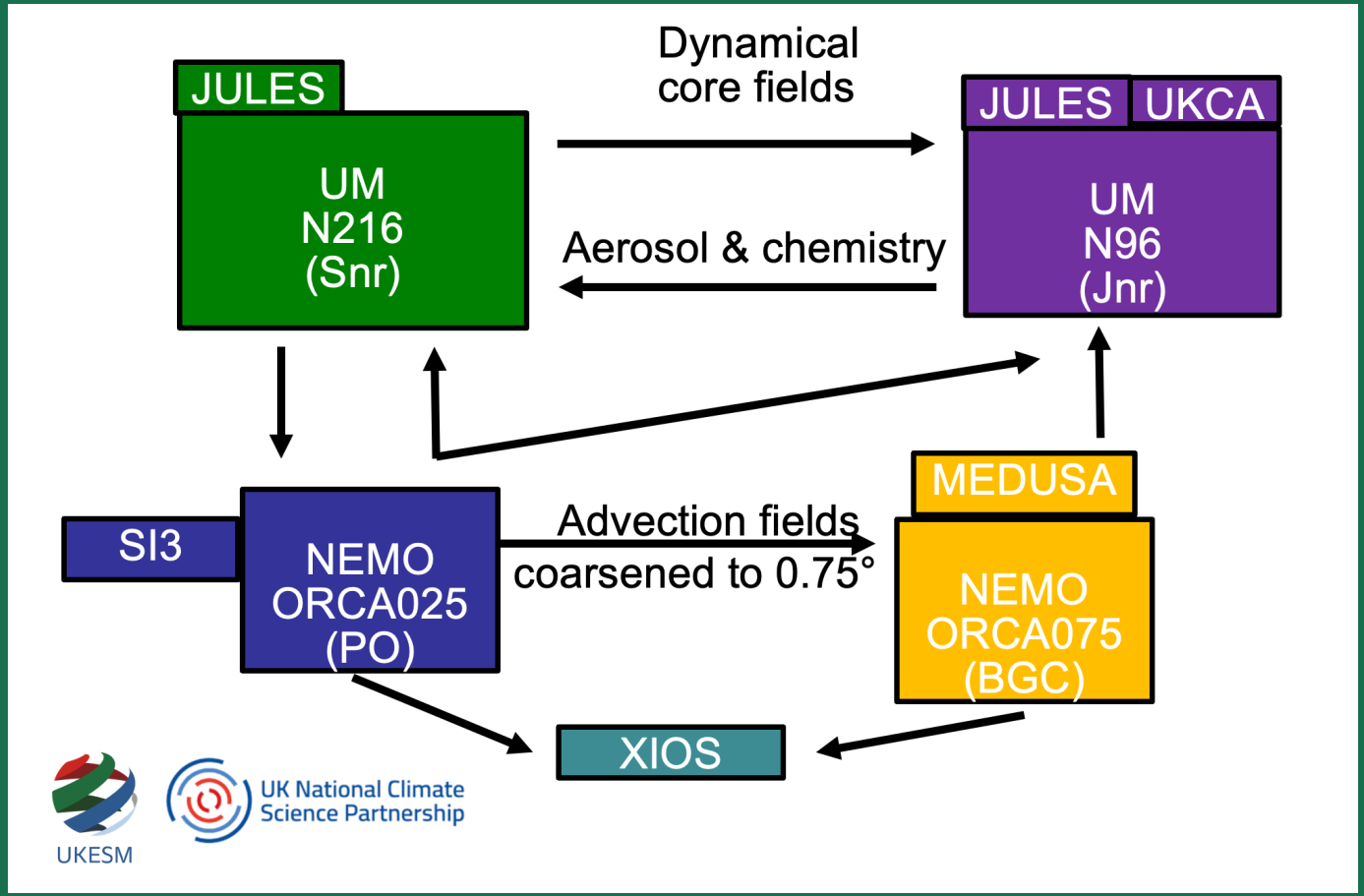
ONE KOKKOS SOURCE
4 GPU architectures

A100	MI250X	H100	GH200
Levante	LUMI	MareNostrum 5	JUPITER
~1.3 SYPD	~1.7 SYPD	~1.9 SYPD	~3.5 SYPD

SYPD = simulated years/day

The LLM accelerated translation, testing and profiling; scientific expertise and a disciplined validation process made the result trustworthy.

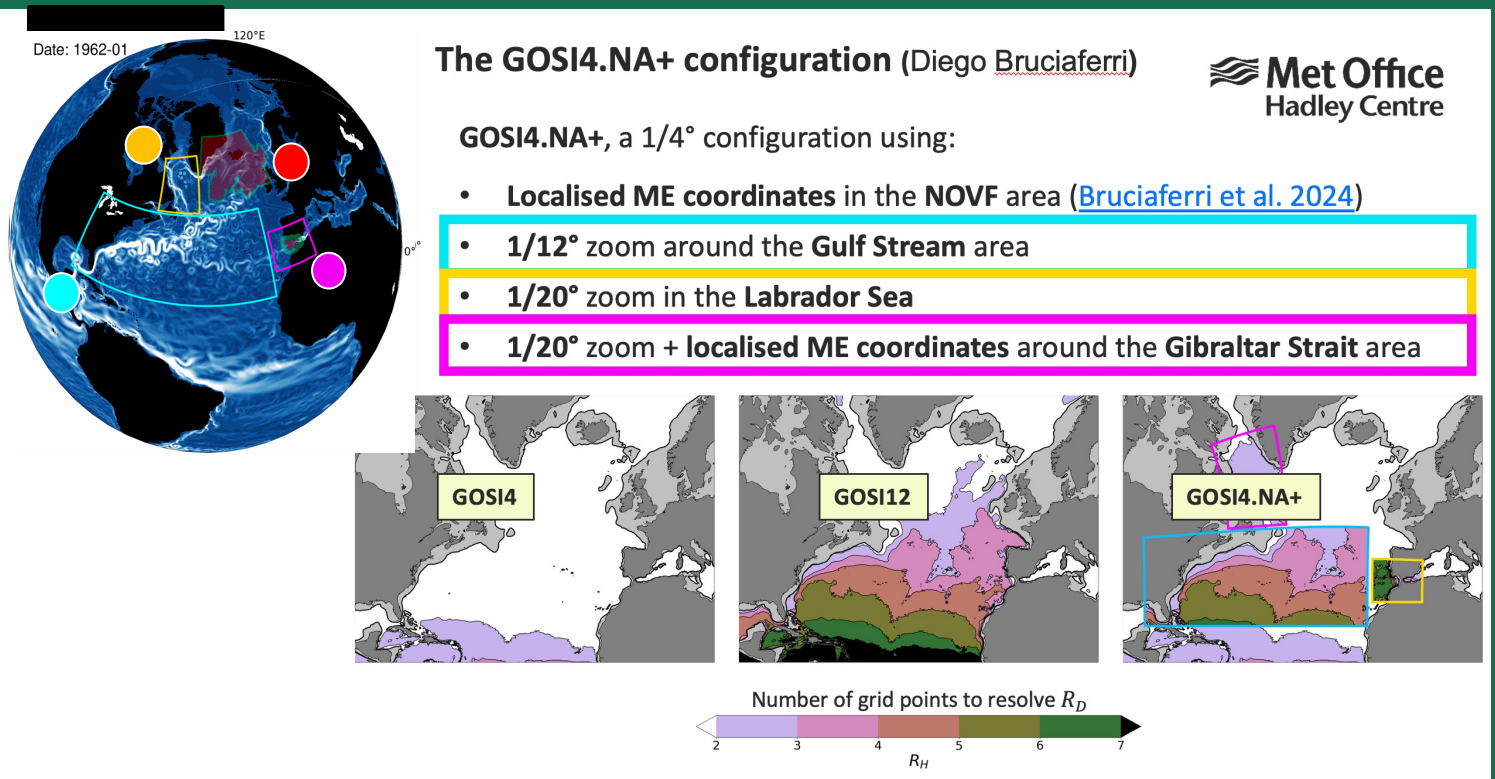
Where do we need resolution? Not for every process!



Mark Stringer (NCAS-CMS and UKESM core team)

University of Reading

Where do we need resolution? Not everywhere!



PhD Student Gabrielle Ching-Johnson building a coupled model based on this ocean

University of Reading

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***.

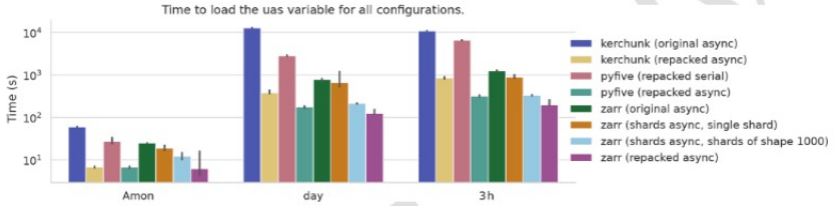


Figure 6. Measured mean time required to load the *uas* variable from different NetCDF files stored in an object store using various clients and configurations. The variable is accessed in its entirety, without a specific data access pattern, to illustrate the throughput capabilities of each configuration and client. Concurrent access to chunks is marked as *async*. Error bars display minimum and maximum times available in the sample.

- New insights on the suitability of NetCDF/HDF5 as storage format for climate cloud repositories. Cimadevilla et al, 2026 (GMD, to appear).
- pyfive: A pure-Python HDF5 reader. Lawrence et al, 2026. *Journal of Open Source Software.*

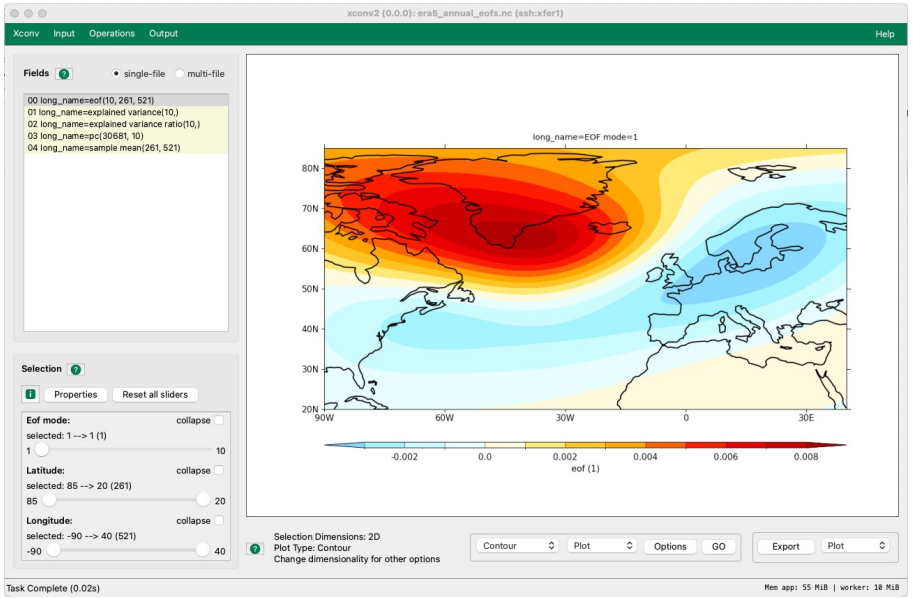
We have demonstrated that by using pyfive (pure-python HDF5 reader) we get the same if not better performance for remote access as is achieved with sharded Zarr.

On Data Formats and Data Libraries

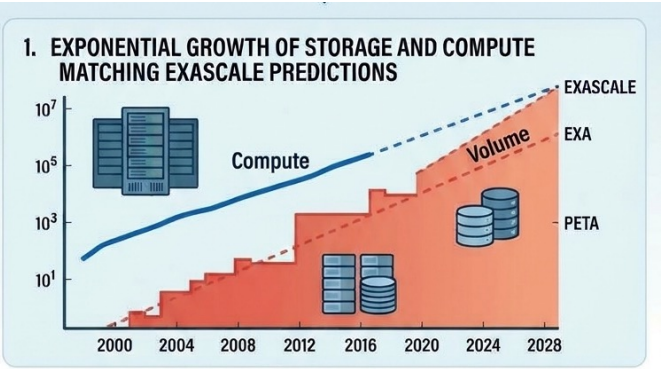
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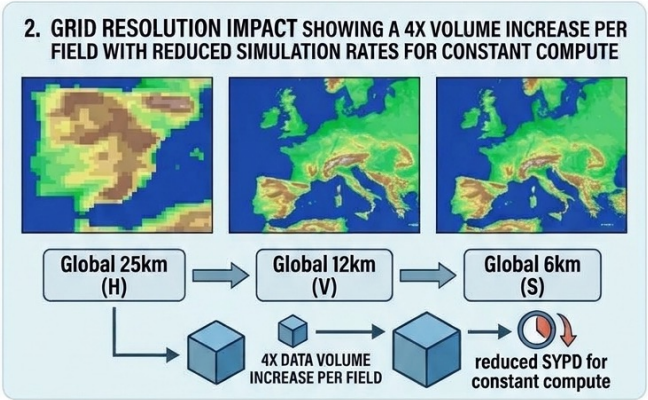
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Lots more functionality than xconv, and remote access as well (S3, HTTPS, SSH)







On data volumes and compression!

We are unlikely to be able to continue to store all the data we need with current compression techniques! Leads to some interesting questions:

1. What compression techniques can/should we use? How can we have confidence in them?

   Reichelt et.al. (2025), **ClimateBenchPress: A Benchmark for Compression of Climate Data**.

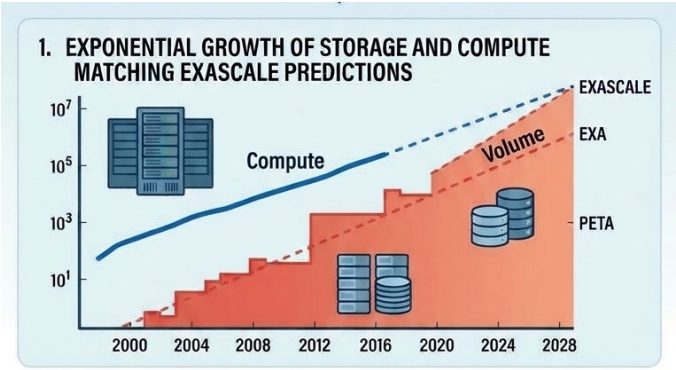
2. We need different compression for different variables. How much for what purpose?

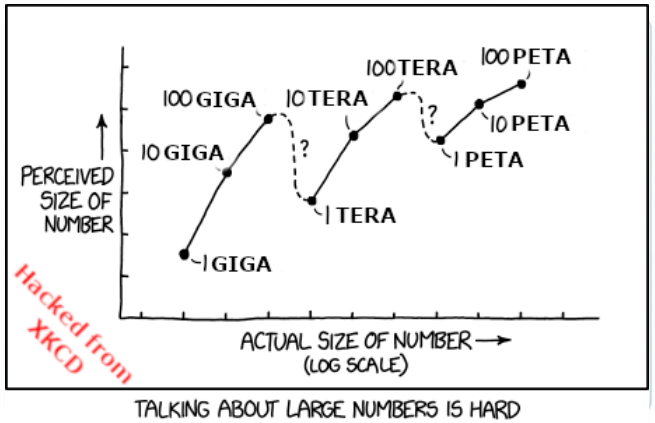
   Traditional lossless compression in “WGDOS” was different for climate or weather and different for each variable, can we inherit some of that and expand?

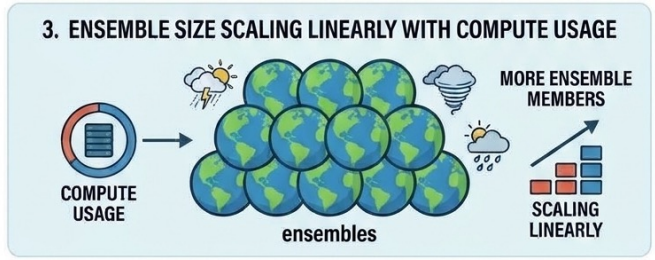
3. To what extent can we automate the use of lossless compression in a chunked/remote data access world?

   If we want remote access to data when/were is decompression done, and do your tools know how to decompress my decompression? What if compression needs longer runs of data than available in a chunk?

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Summary

1. Context of climate modelling: a trade-off between resources and applications.
    - Uncertainty matters
    - There is not one modelling ring to rule them all.

2. The importance of model intercomparison!
    - We have three strands of activity delivering useful results addressing both science and policy.
    - We want to sustain those three strands of activity going forward if we can sustain the effort (and can get the compute and storage).

1. It's going to get a tad hot in the UK
    - What's driving that seems to be mainly global warming (!) with variability coming from thermodynamic processes.
    - There is an important role for large-ensembles in interpreting results from long-duration and/or high-resolution results.

2. There is a lot technology underneath the modelling itself.