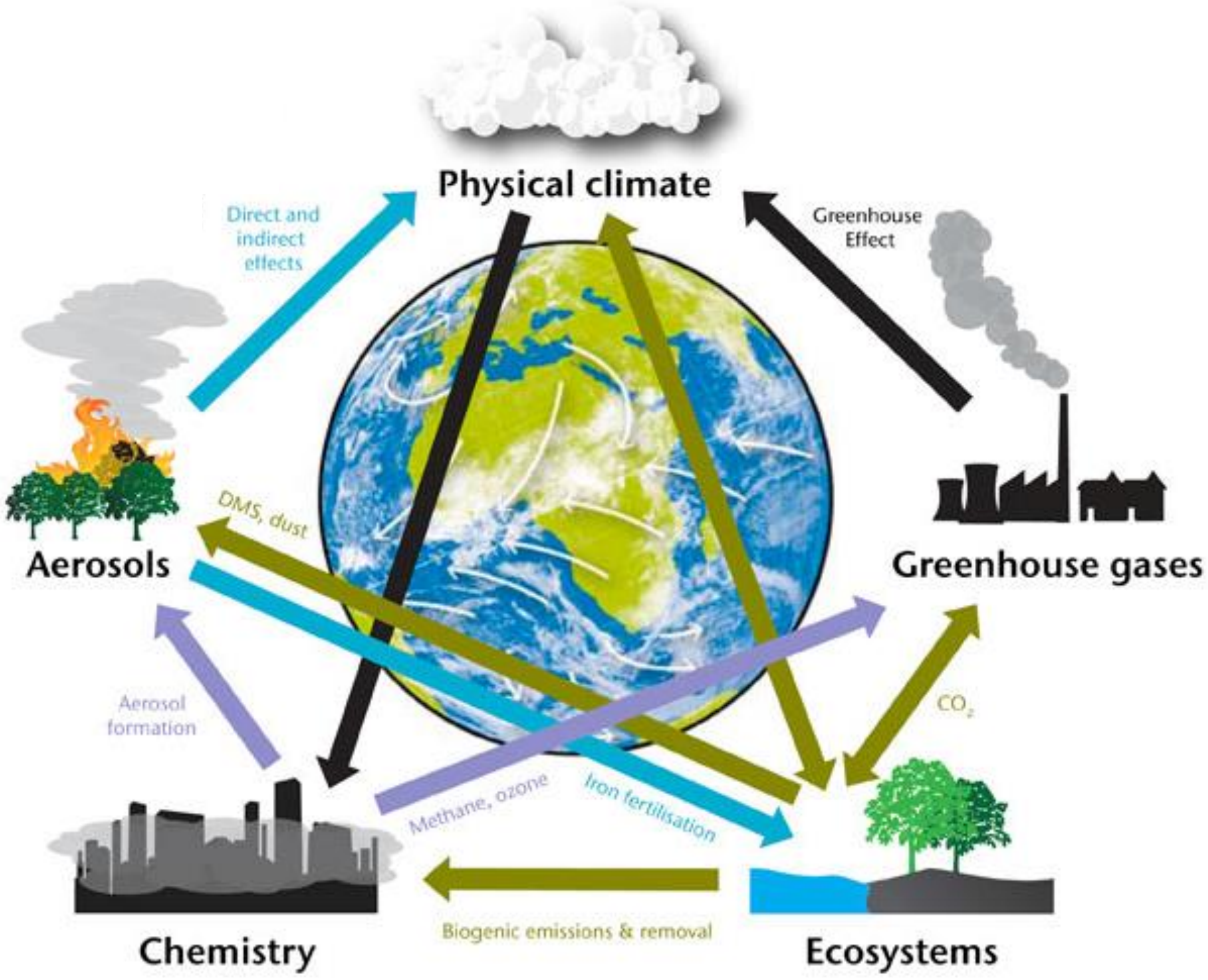
UKESM2

development pathway, progress and plans towards CMIP7

Jane Mulcahy, Colin Jones, UKESM development team, GC development team and many collaborators

The Earth System



Earth system models represent both the physical climate and carbon cycle,
as well as other important components of the **coupled** Earth system
e.g. atmospheric chemistry, aerosols, vegetation, marine biogeochemistry, cryosphere

What is UKESM?

- UKESM is the UK's Earth System model jointly developed by the Met Office and NERC (Natural Environment Research Council).
- UKESM consists of the HadGEM3 global coupled physical climate model plus additional components that model key biogeochemical, chemistry, aerosol and vegetation and cryosphere processes.
- UKESM1 released to the community in February 2019 and provided a significant part of the UK's contribution to CMIP6.
- In 2023 an updated version UKESM1.1 was released.
- Currently developing UKESM2 → CMIP7 and beyond.

CMIP7 plans

CMIP7 Fast Track & Timelines

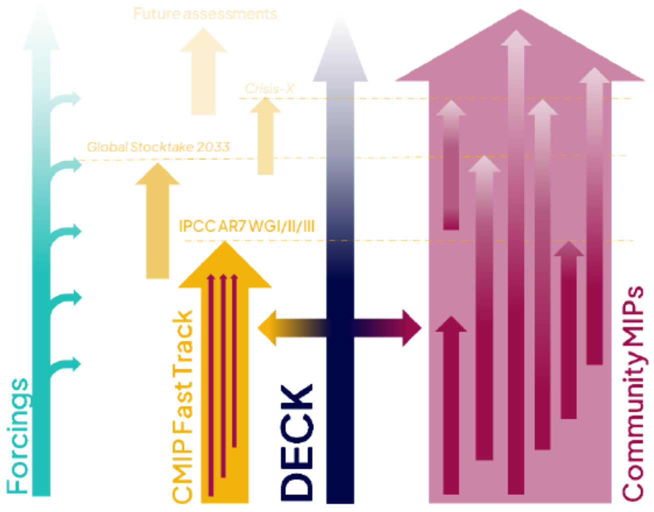
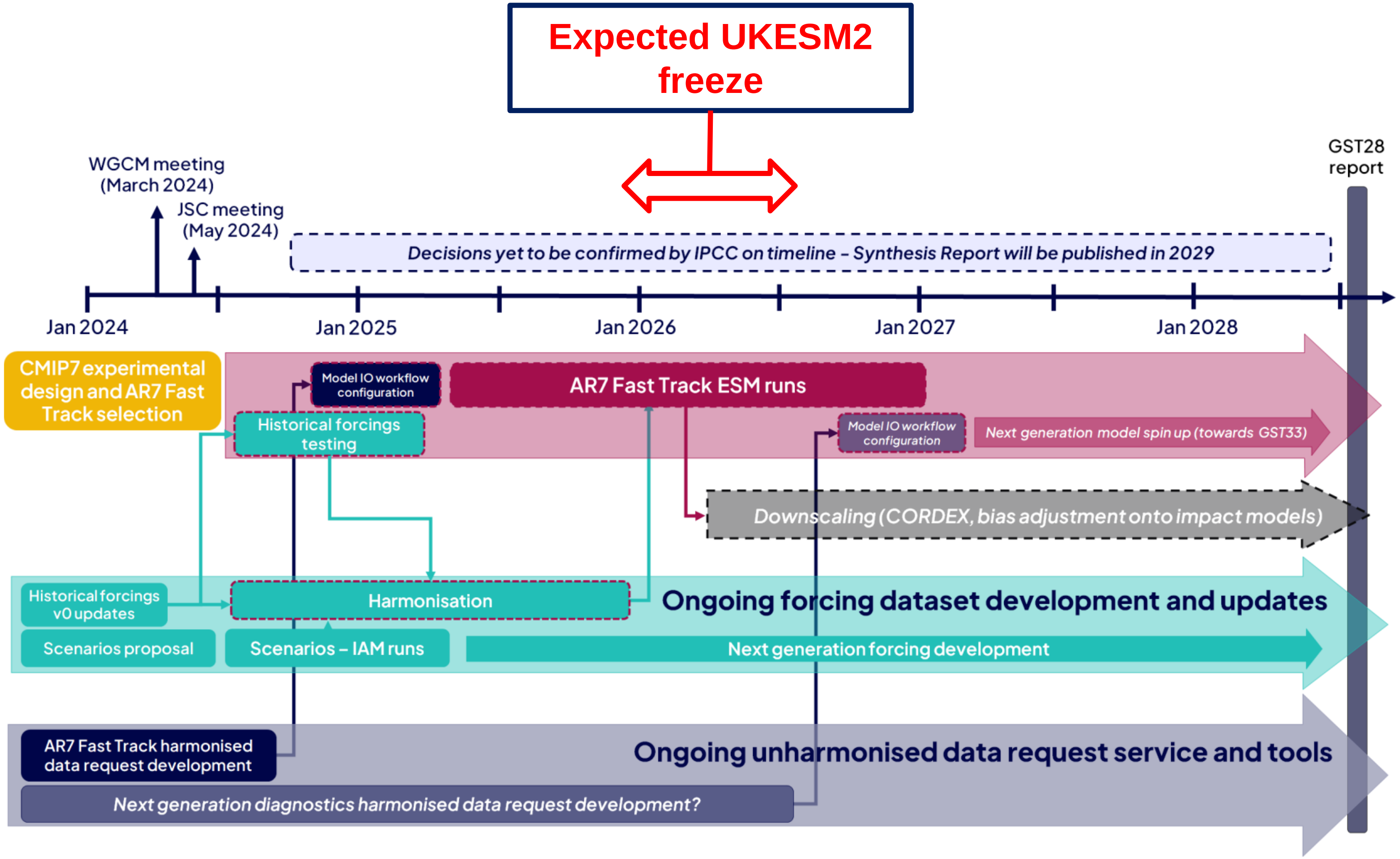


Figure 1: Schematic representing the evolving CMIP experiment structure.

Proposed Back-up for Fast Track:
UKESM1.3

Configuration for Community MIPs:
UKESM2



Figures: https://wcrp-cmip.org/cmip7

UKESM1.3

UKESM1.3

UKESM1.1 (Mulcahy et al, 2023)

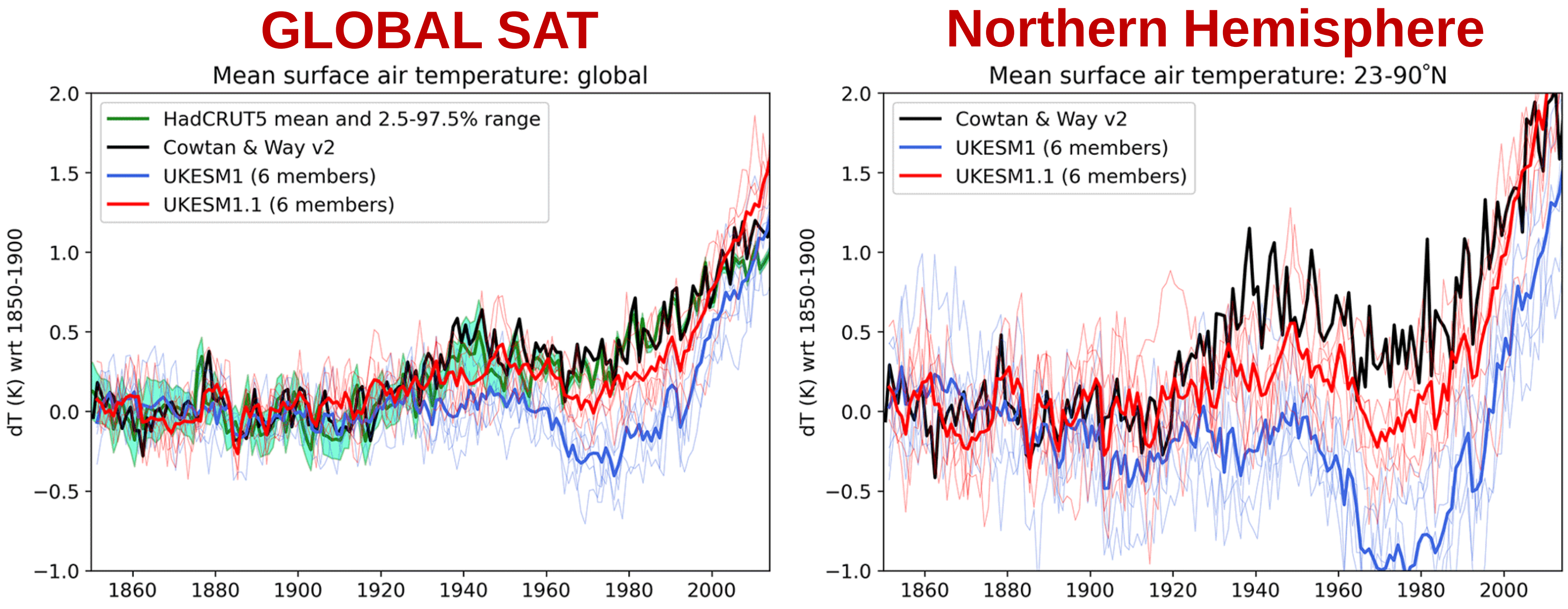
plus

Emission-driven CO_2 and CH_4

Interactive ice-sheets

Currently running variant of this (CH_4 emissions not included)

UKESM1.1



Significant improvement in the historical GMST record.

EffCS = 5.3K

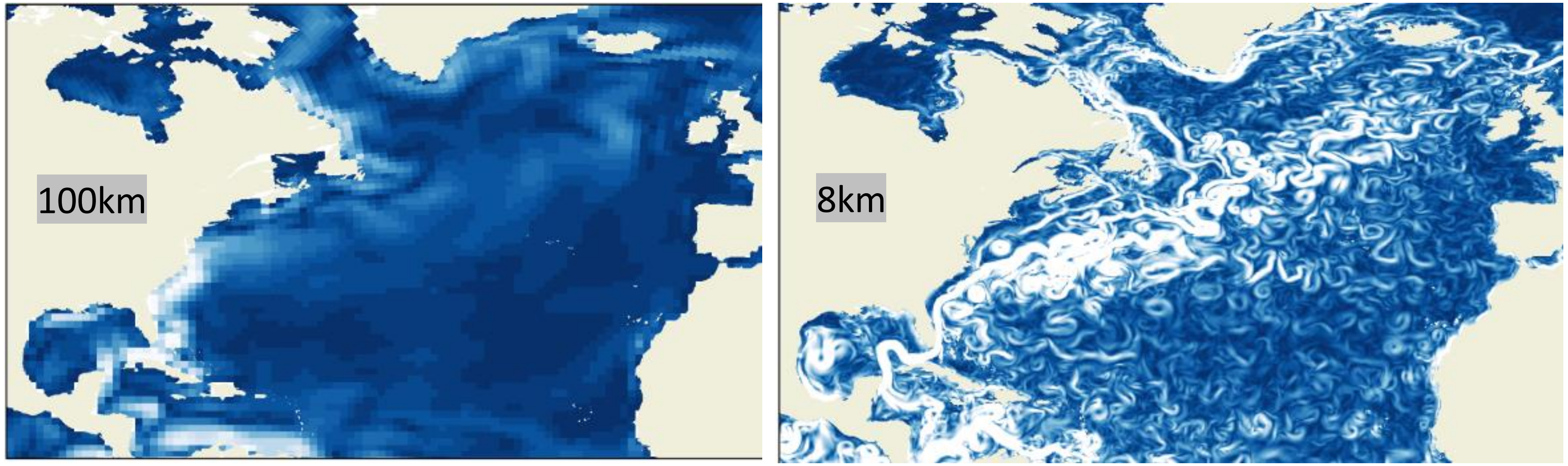
Mulcahy et al., (2023) GMD [*https://doi.org/10.5194/gmd-16-1569-2023*](https://doi.org/10.5194/gmd-16-1569-2023)

UK Delivery to CMIP7

UKESM

- Emissions driven focus – UKESM-based model UKESM1.3 or UKESM2
- Possibly a physical model – GC5-based contribution with more “central” value for ECS
- High-resolution frontiers simulations (subset of FT) – *GC5-EERIE*
- *UKESM2* contributing to longer term Community MIPs

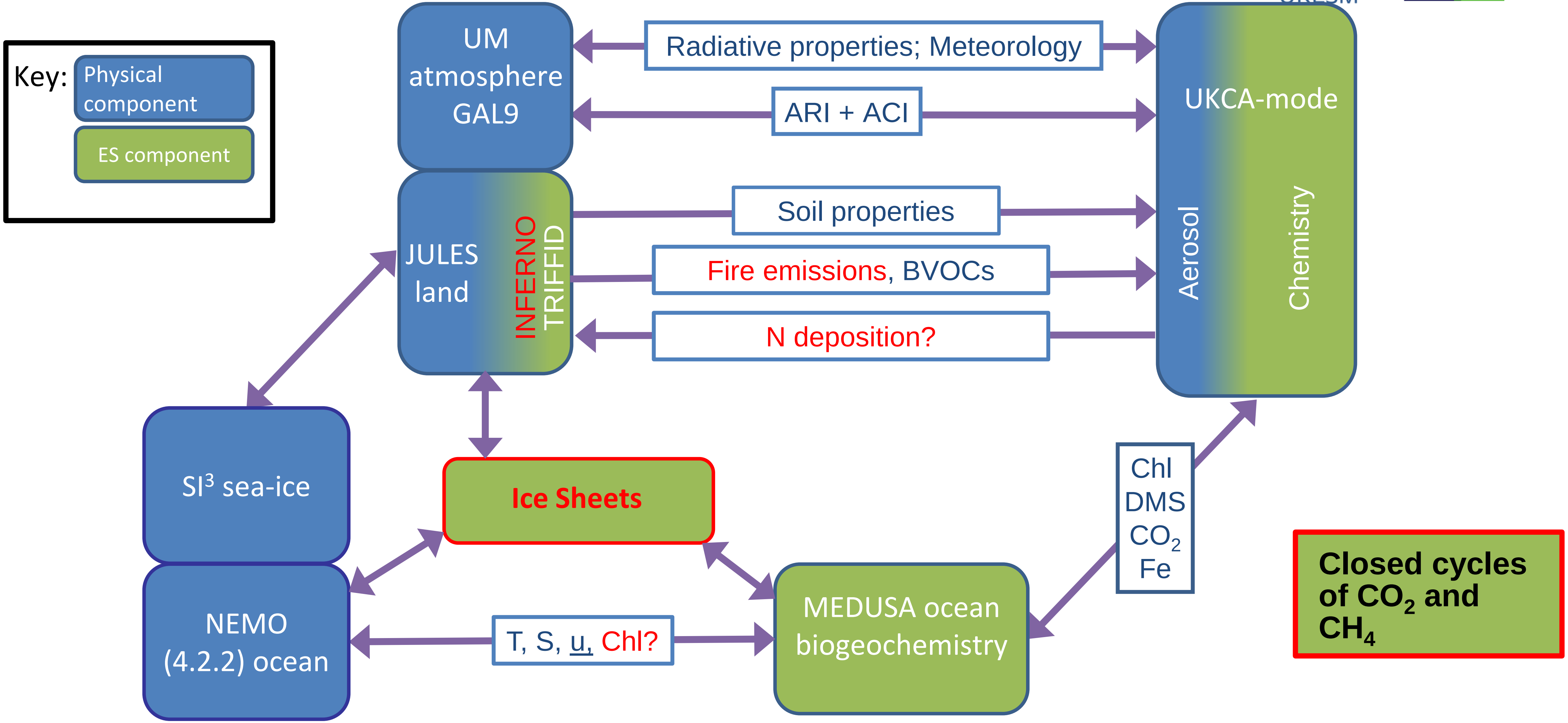
GC5-EERIE N640-O12 (20km atmos, 8km ocean)



Malcolm Roberts

UKESM2

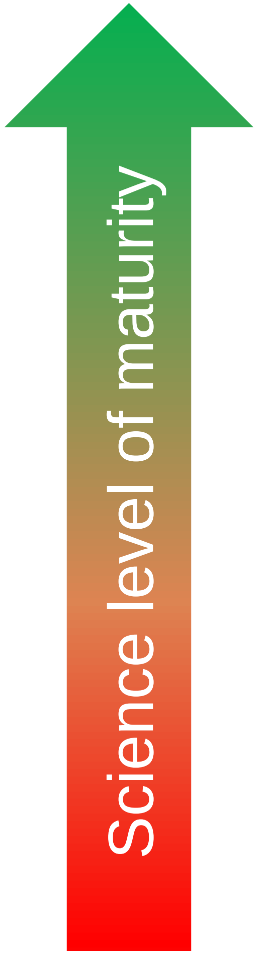
UKESM2 structure & couplings



Physical Component: HadGEM3-**GC5**

Resolution: **N96L85** (atmos ~135km, model top 85km) and **1° L75** (ocean)

UKESM2 key new science capability



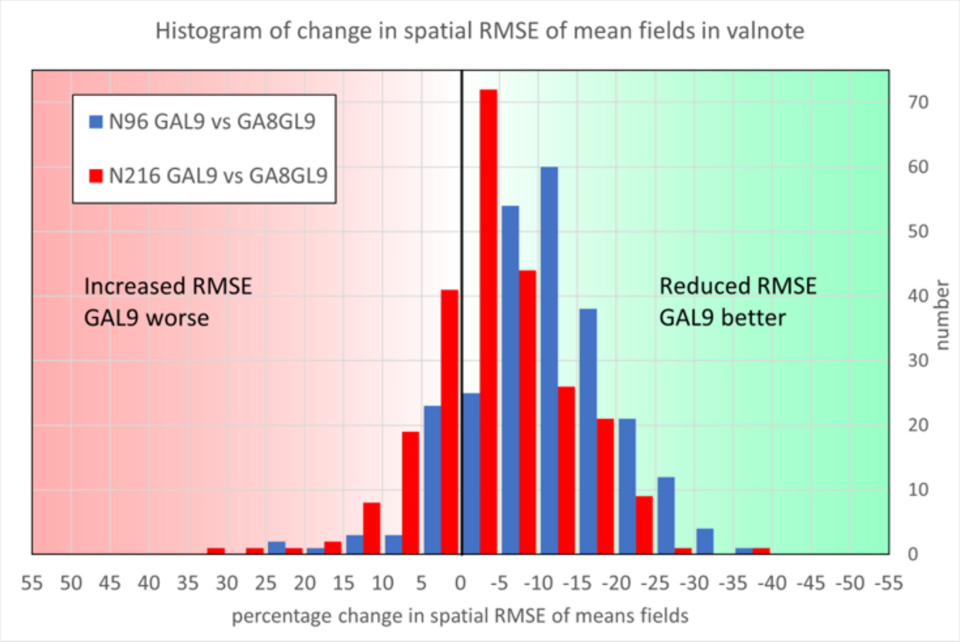
- Emission-driven configuration for both CO_2 and CH_4 as standard
- Interactive fire; coupled to atmospheric composition & carbon-cycle + dynamic vegetation
- Nitrate aerosol
- GC5-central physical model
- Interactive ice sheets for Greenland and Antarctica in the standard model
- Package of UKCA composition improvements
- Permafrost coupled to C and N cycle and wetlands
- Nitrogen coupling atmosphere → land surface

HadGEM3-GC5 physical climate

UKESM

Met Office

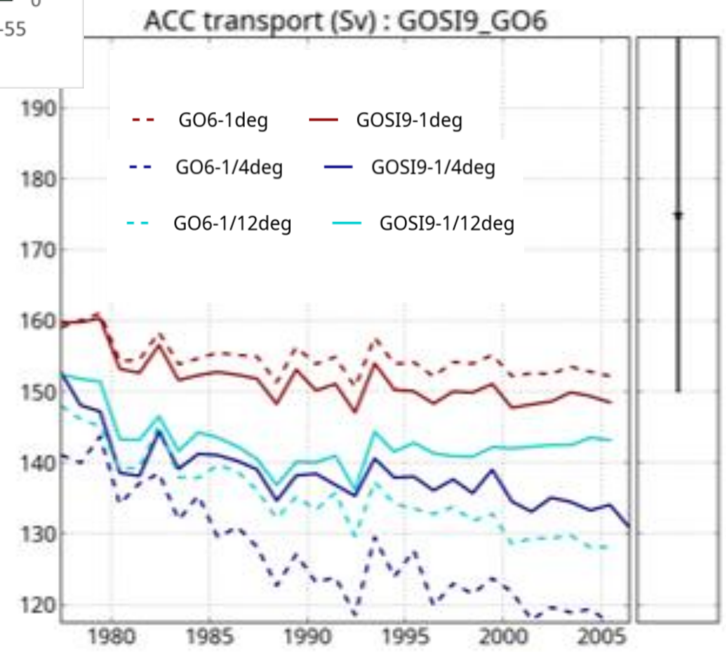
UKRI Natural Environment Research Council



(Credit: Martin Willett)

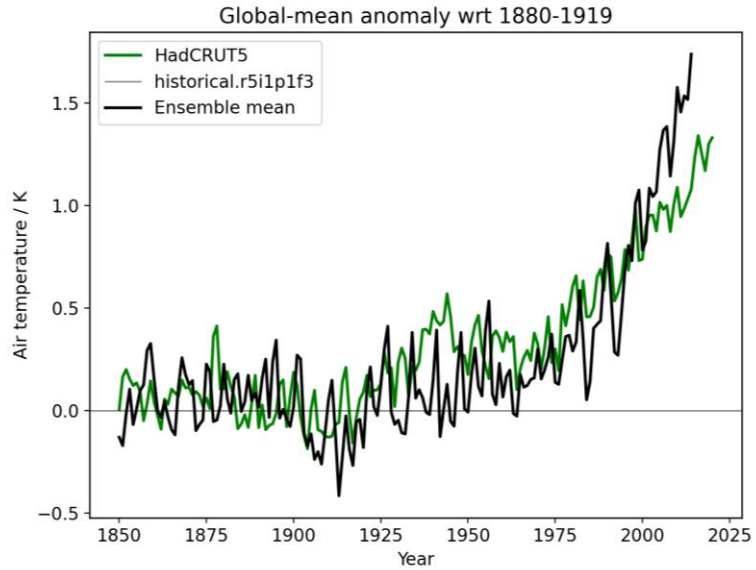
GC5 = **GAL9** atmosphere + land configuration + **GOSI9** ocean & SI

GC5-emergent: General present-day performance improved relative to previous configurations



(Credit: Catherine Guiavarch)

Transient historical performance

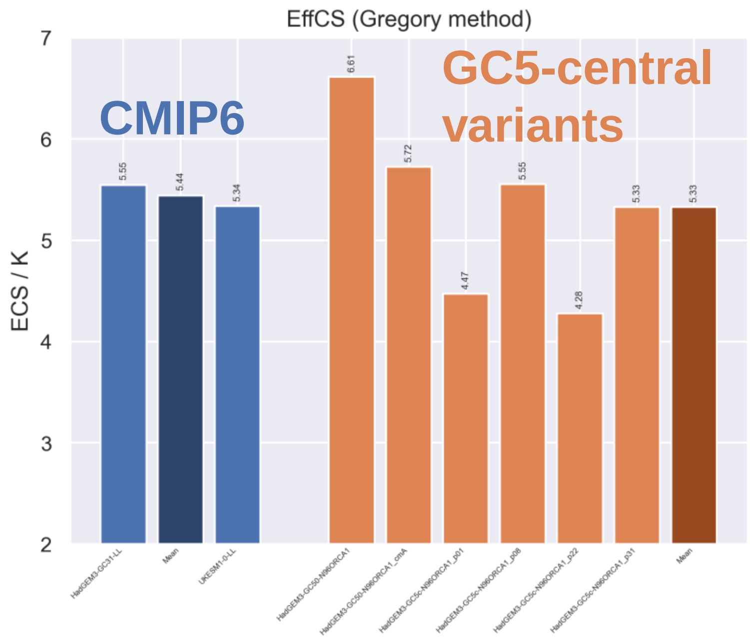


GC5 *historical* simulation warms too fast over recent decades. EffCS is very high (>6K).

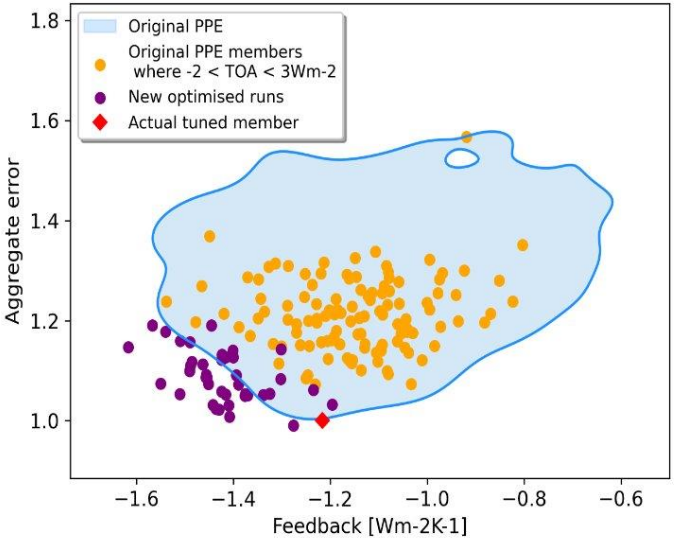
GC5-central

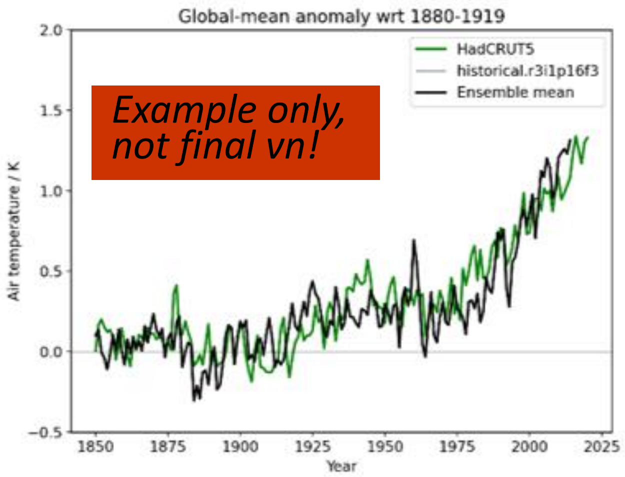
Preliminary results!

Use a PPE and emulator approach to produce a GC5 parameter set which has an EffCS within the IPCC AR6 *very likely* range and improved historical performance *without unacceptably degrading overall climate metrics*.



Based on Peatier et al., (2022) GAL9 PPE: 5-yr runs of *amip* and *amipFuture-p4K:* 503 members, perturbing 73 parameters. Targets $l_{4K} < -1.4\ \mathrm{W\ m^{-2}\ K^{-1}}$.





Alejandro Bodas-Salcedo, David Sexton, John Rostron

The move towards emission driven simulations

Captures full uncertainty in future emission pathways

UKESM

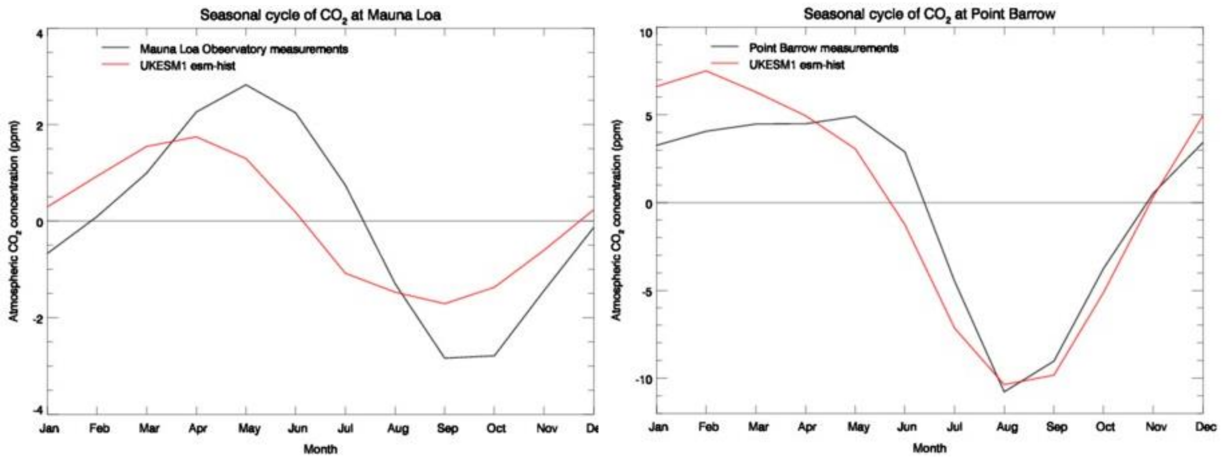
Met Office

Natural Environment Research Council

Sellar et al. 2019, https://doi.org/10.1029/2019MS001739

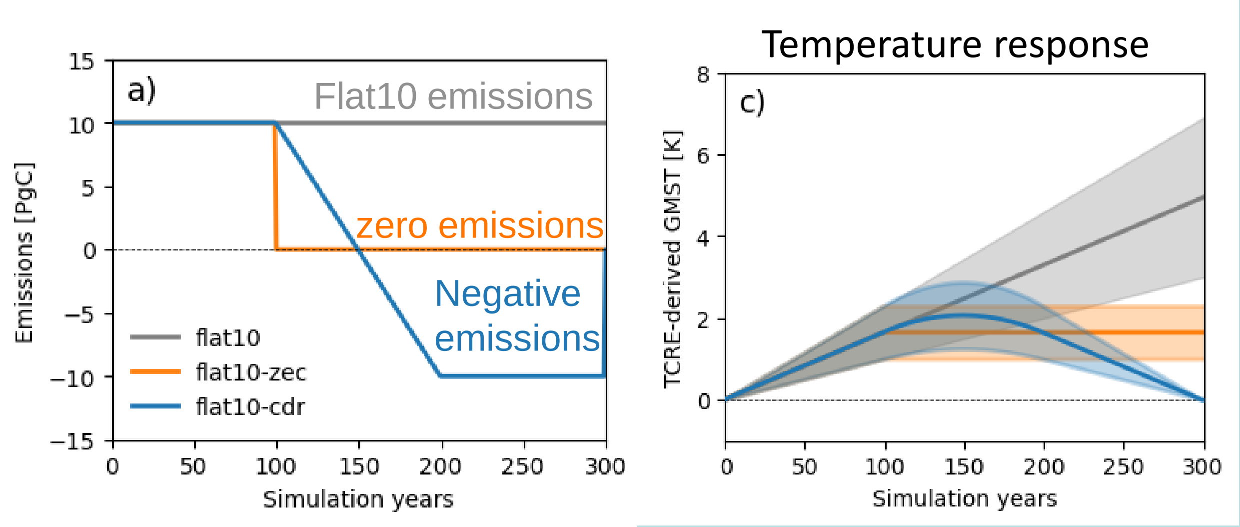
Captures:

- Diurnal & seasonal cycles in plant uptake and respiration
- Interactive land use emissions of CO2
- Important feedbacks, eg: feedback of CO2 forcing on carbon sinks; fire; permafrost



Important for carbon budgets, system response/reversibility to zero or negative emissions → TCRE and ZEC

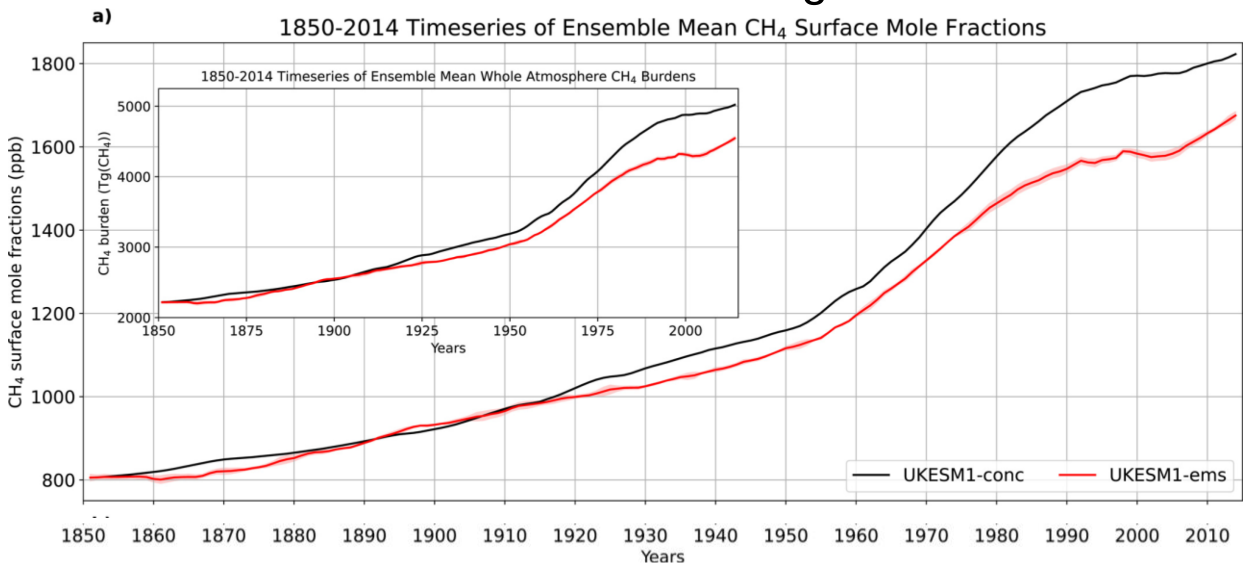
Diagnosed via Flat10 experiments now in Fast Track



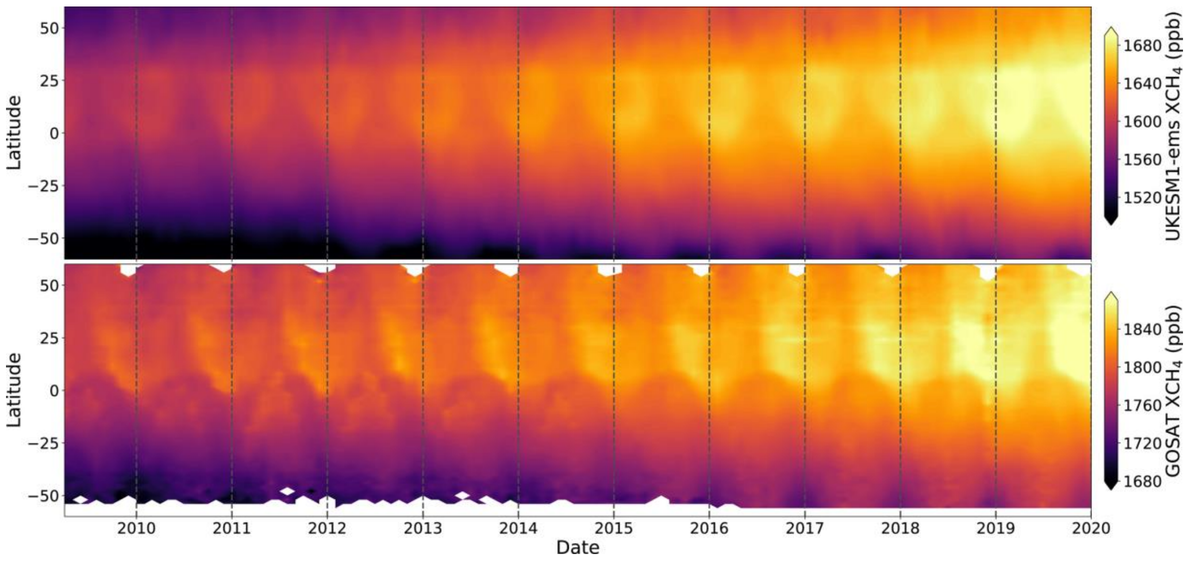
CH_4 emission driven capability

Simulating the global methane cycle fully interactively

Comparison of **concentration** and **emission** driven UKESM1 configurations



Comparison of emission driven configuration vs GOSAT



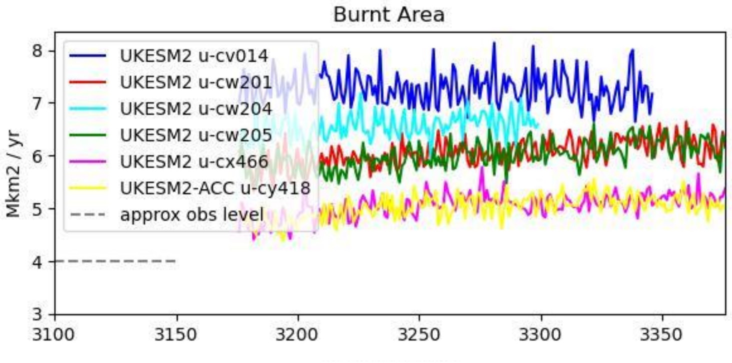
Enables important couplings and feedbacks between global wetlands and atmospheric chemistry.

Folberth et al., (2022) JAMES https://doi.org/10.1029/2021MS002982

Interactive fire

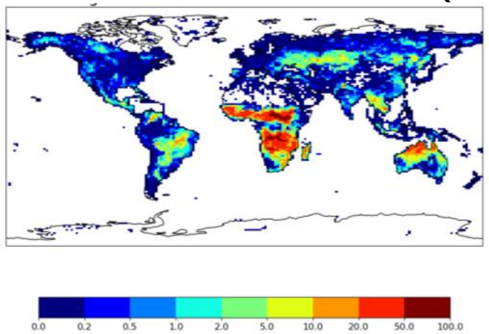
INFERNO: Interactive Fires and Emissions algorithm for Natural envirOnments
Coupling fire to vegetation dynamics, carbon cycle and atmospheric composition

UKESM

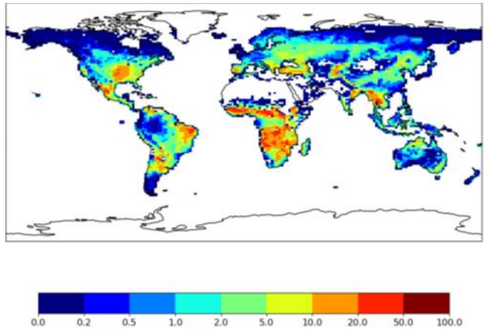


Control
Fire
Fire + Acclim
OBS

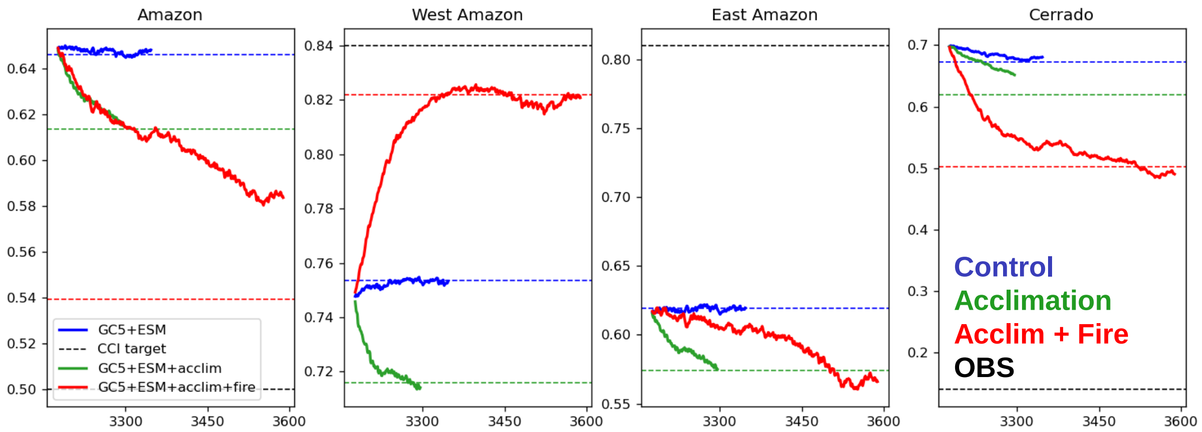
Observations: GFED4 (PD)



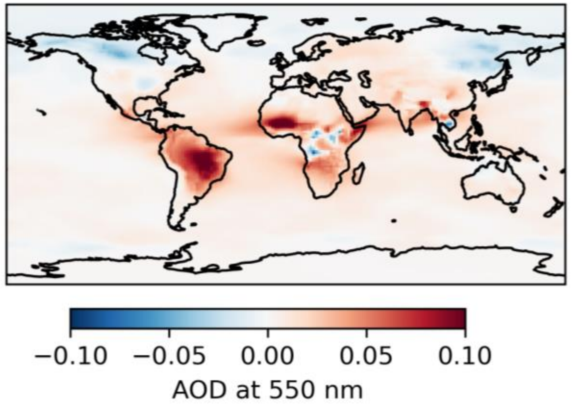
UKESM2 proto (PI)



BLE tropical tree fraction



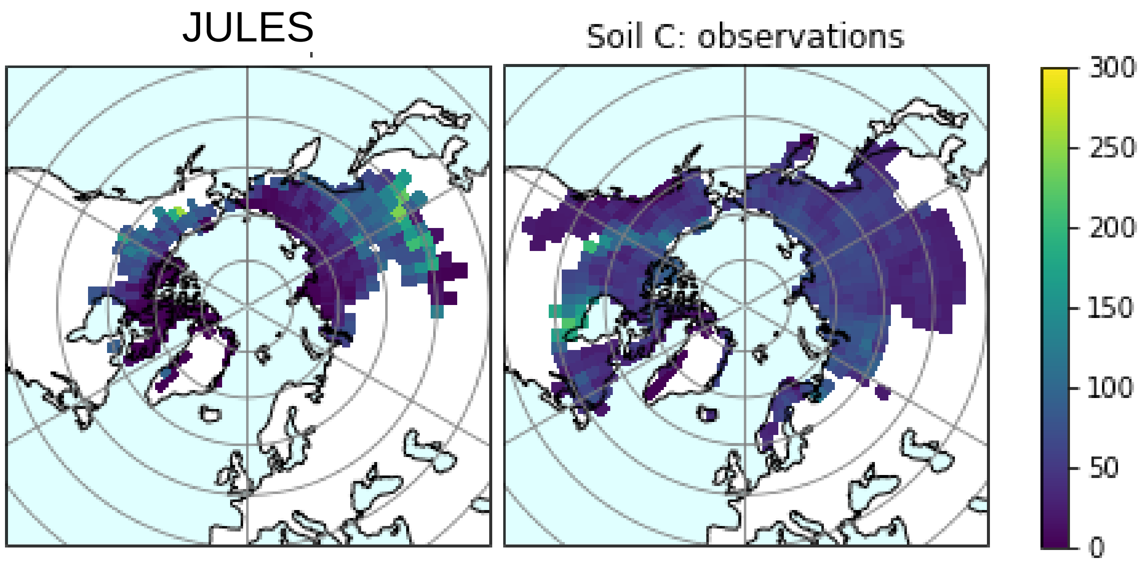
Change in AOD



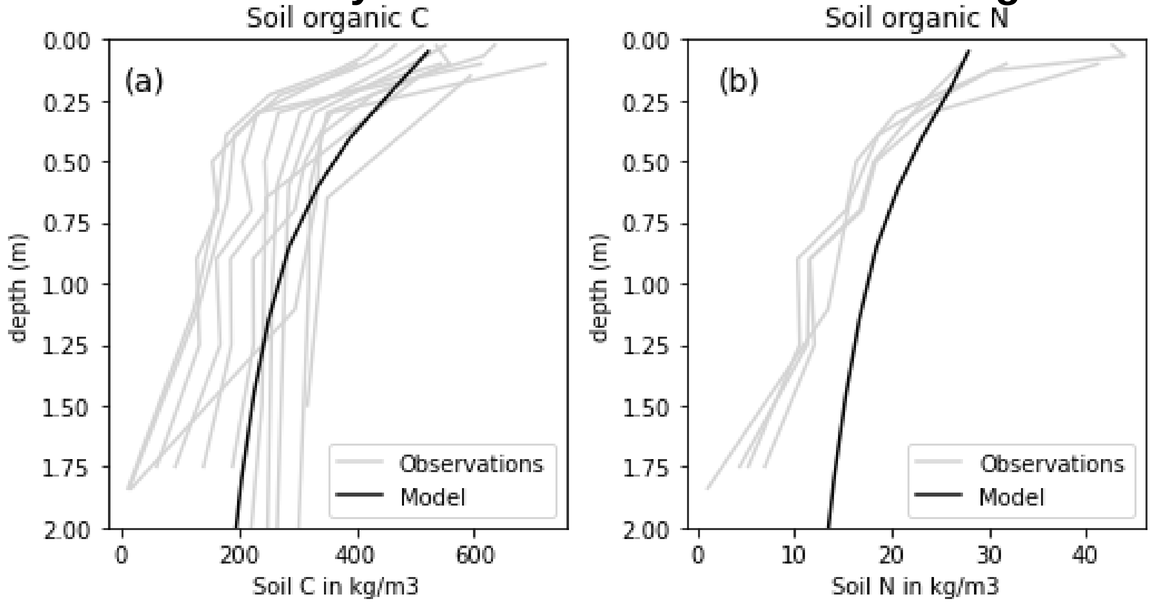
Low AOD bias in NH high latitude. Missing peat fires

Chantelle Burton, Eddy Robertson, Phil Harris, Joao Teixera, Amy Peace

Permafrost carbon



Vertically resolved soil carbon and nitrogen



Implementation of a vertically resolved soil carbon and nitrogen in UKESM.

Developments to-date are in offline JULES simulations.

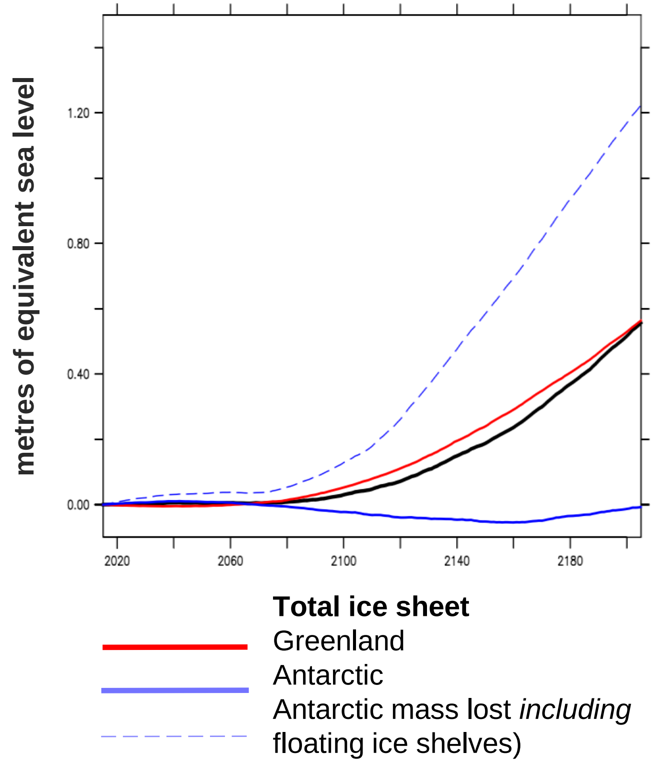
Overall good comparison of total soil C and vertically resolved carbon against observations. 863 Gt C in permafrost in JULES comparable with observations

Ice Sheets

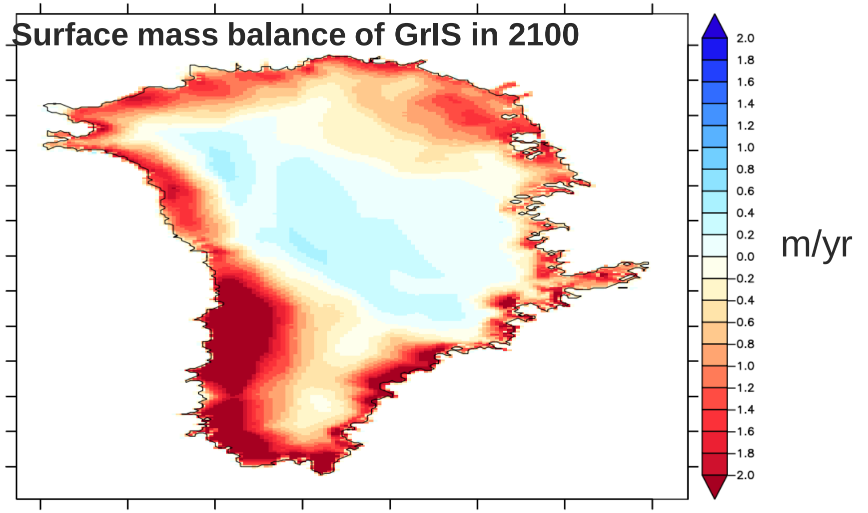
Unicicles: Interactive models of the Greenland and Antarctic ice sheets

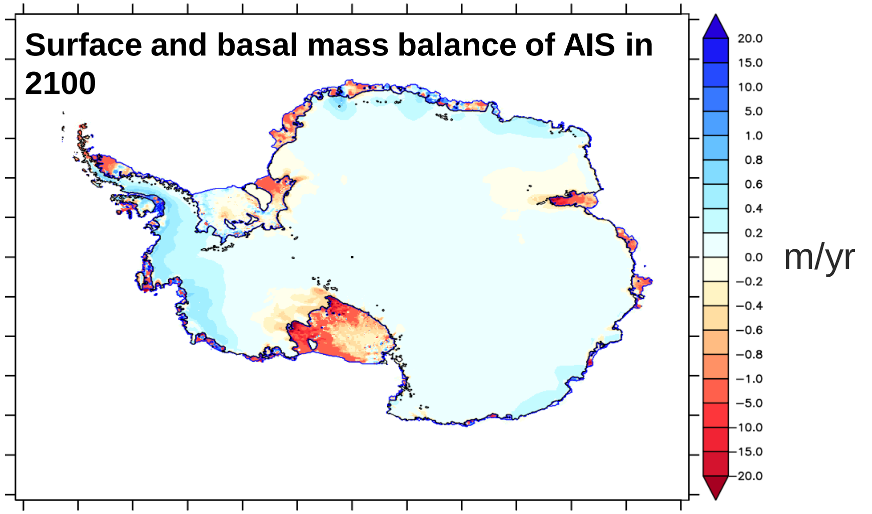
Captures physical feedbacks between ice sheets and the climate system consistent with global climate projections enabling:

- sea level rise projection in UKESM
- Investigation of climate tipping points for ice sheets



UKESM1-ice SSP5-8.5ext





Smith et al., (2021) JAMES https://doi.org/10.1029/2021MS002520
Siahaan et al. (2022), The Cryosphere, https://doi.org/10.5194/tc-16-4053-2022

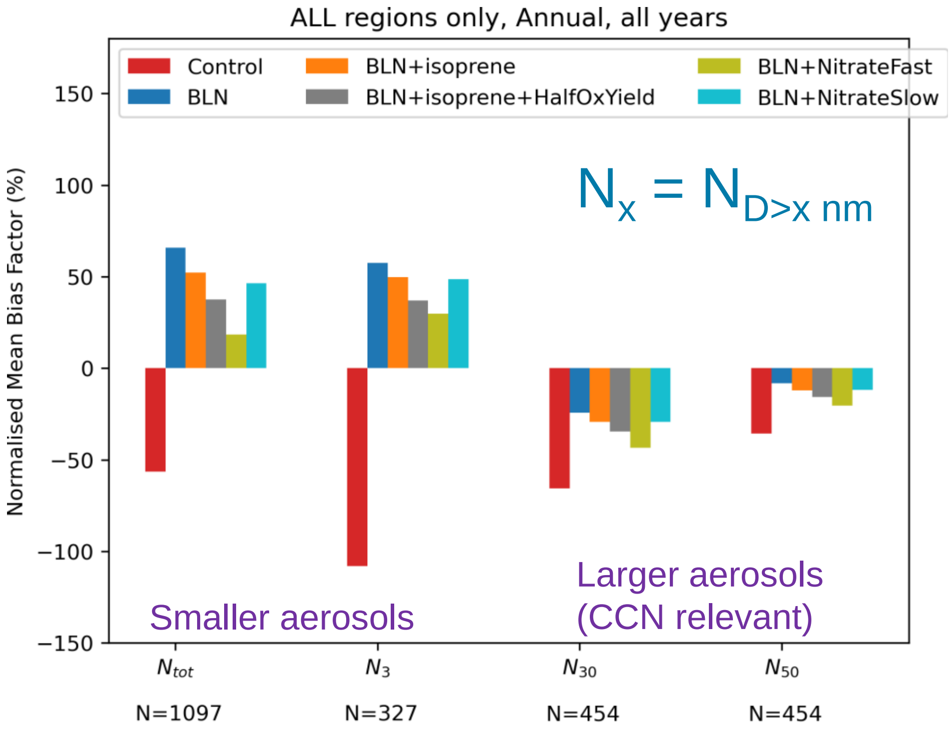
Atmospheric composition

Dan Grosvenor, Catherine Hardacre, Steven Turnock, Amy Peace, Steph Woodward, James Keeble, Luke Abraham

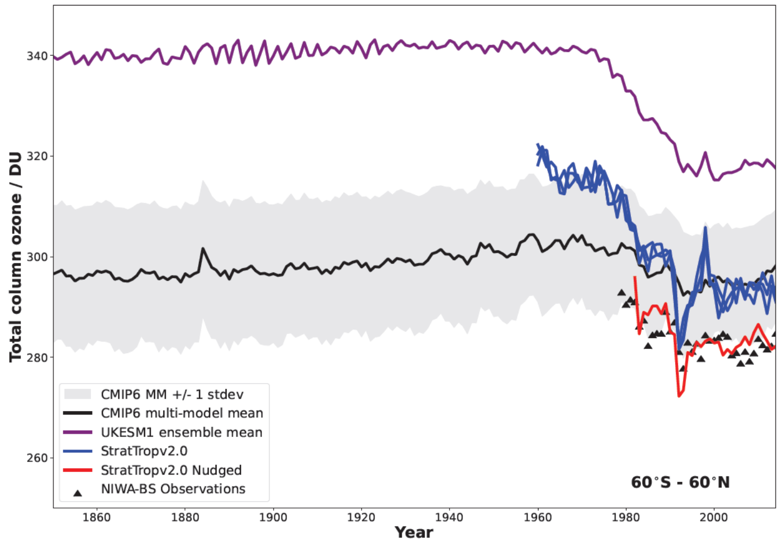
<u>Key developments:</u>

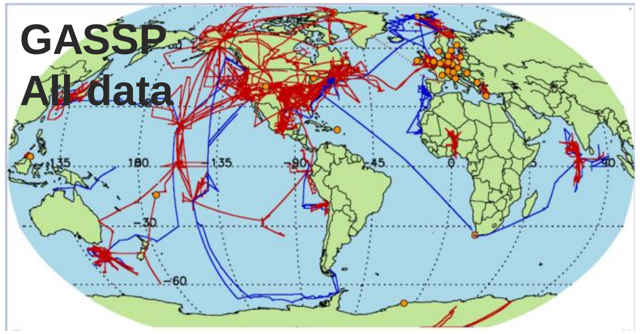
- Interactive fire emissions of OC, BC, SO_2, CO_2, CH_4, NOx
- Nitrate aerosol
- Boundary layer nucleation of aerosol particles (Metzger (2010))
- iBVOC → Isoprene source of secondary organic aerosol
- Interactive cloud water pH →aerosol aqueous phase chemistry
- 3 mode mineral dust simulated via GLOMAP-mode
- Improve stratospheric ozone biases

Aerosol number concentration bias



Improvements in simulation of stratospheric ozone: Total Column Ozone (60S-60N) comparison
(from Keeble et al. (2020), doi:10.5194/acp-21-5015-2021)





Summary

UKESM

- Key new science capability (eg: interactive fire, nitrate aerosol, emission-driven CO_2 and CH_4) is at advanced stage of development and are being tested now in coupled UKESM2 prototype. Other developments in standalone fully coupled package testing .
- Ambition to include as many interactive couplings in UKESM as possible where we believe these coupled feedbacks are important in future climate simulations.
- HadGEM3-GC5 emergent configuration has a high ECS of >6K. GC5-central targets a set of parameter settings which brings ECS within IPCC very likely range.
- CMIP7 Fast Track timelines are very challenging. We have a UKESM1.3 configuration ready for use in the FT to meet IPCC timelines if needed and are now spinning this up in parallel to finalising UKESM2.
- In CMIP7 FT we will run CO_2 & CH_4 emission driven only (no concentration driven runs, apart from the necessary 1%CO_2, 4XCO_2 and a parallel piControl for these simulations).
- HadGEM3-GC5 physical model configurations (including a high resolution version) will also very likely contribute to CMIP7.