Met Office
Hadley Centre

Earth System Modelling: An Introduction

Fiona M. O'Connor

UKCA Virtual Training Workshop, January 2024

Overview

- What do we mean by the Earth System?
- Why is ES Science relevant to climate?
- Climate Models → Earth System Models
- UK's Current Earth System Model & Plans
- Recent ES Science Highlights

What is the Earth System?

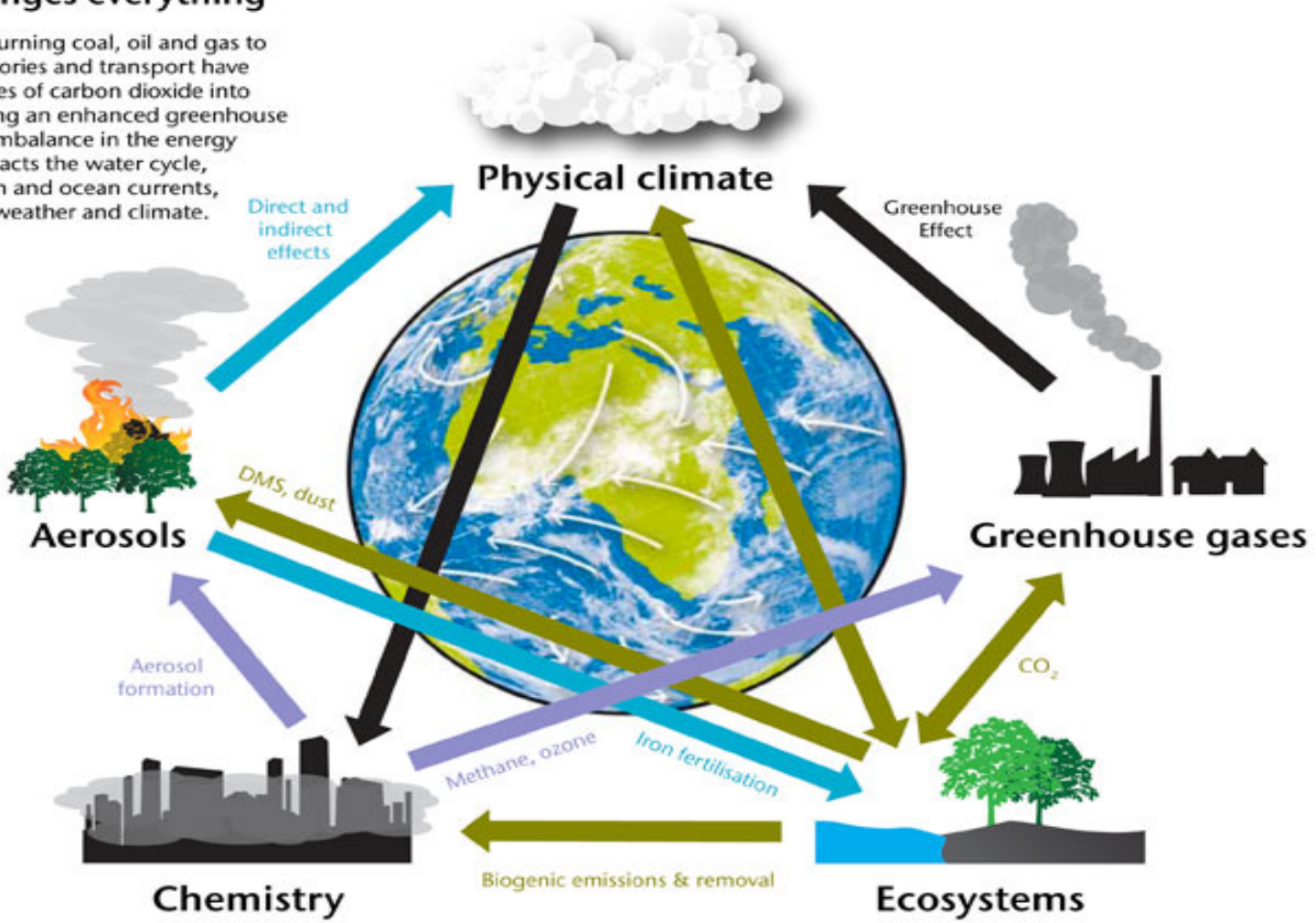
- hy are we interested in ES Science?
- imate Models -> Earth System Models
- rrent UK ESM: UKESM1
- t ES Science Highlights

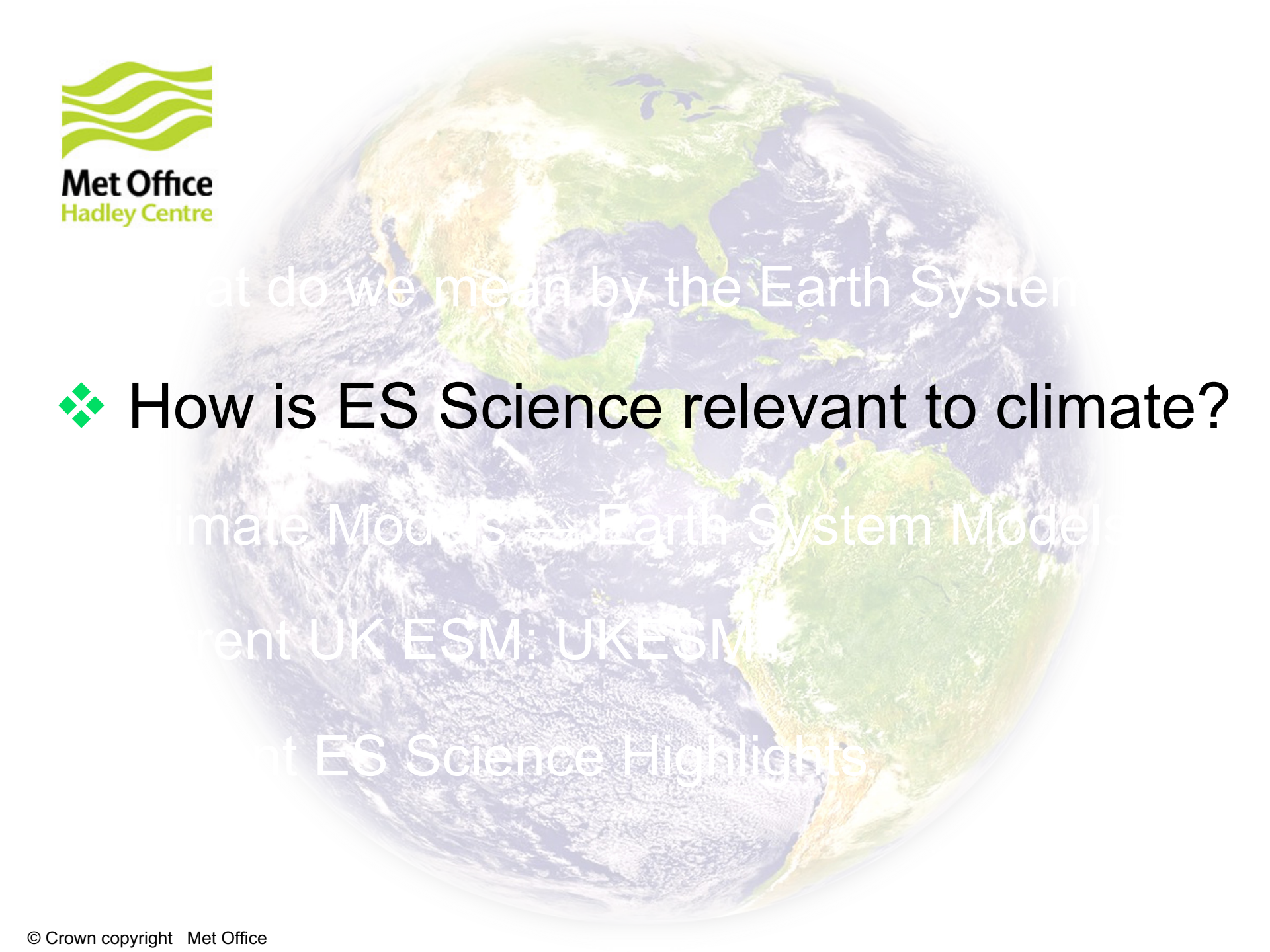
What is the Earth System?

Met Office

One thing changes everything

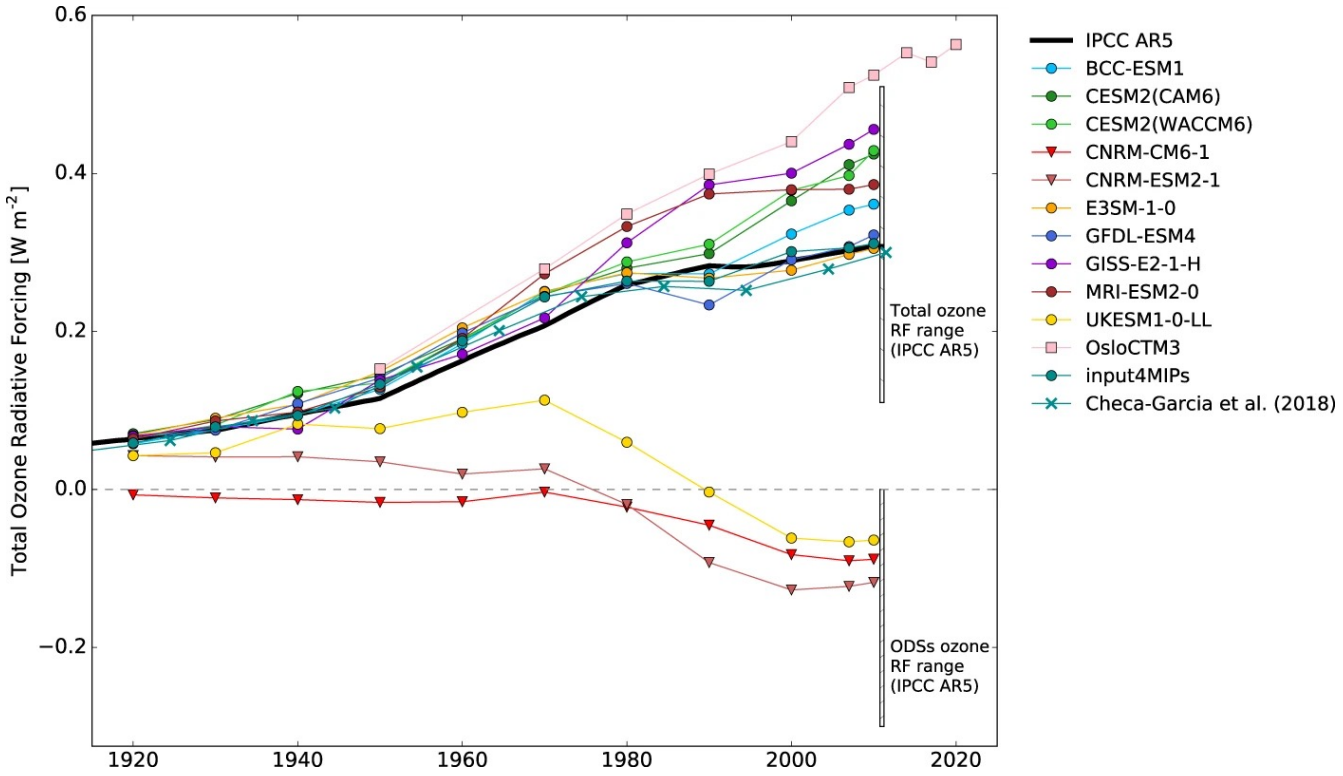
Human activities like burning coal, oil and gas to power our homes, factories and transport have released huge quantities of carbon dioxide into the atmosphere, causing an enhanced greenhouse effect. This causes an imbalance in the energy cycle that, in turn, impacts the water cycle, atmospheric circulation and ocean currents, leading to changes in weather and climate.





- How is ES Science relevant to climate?

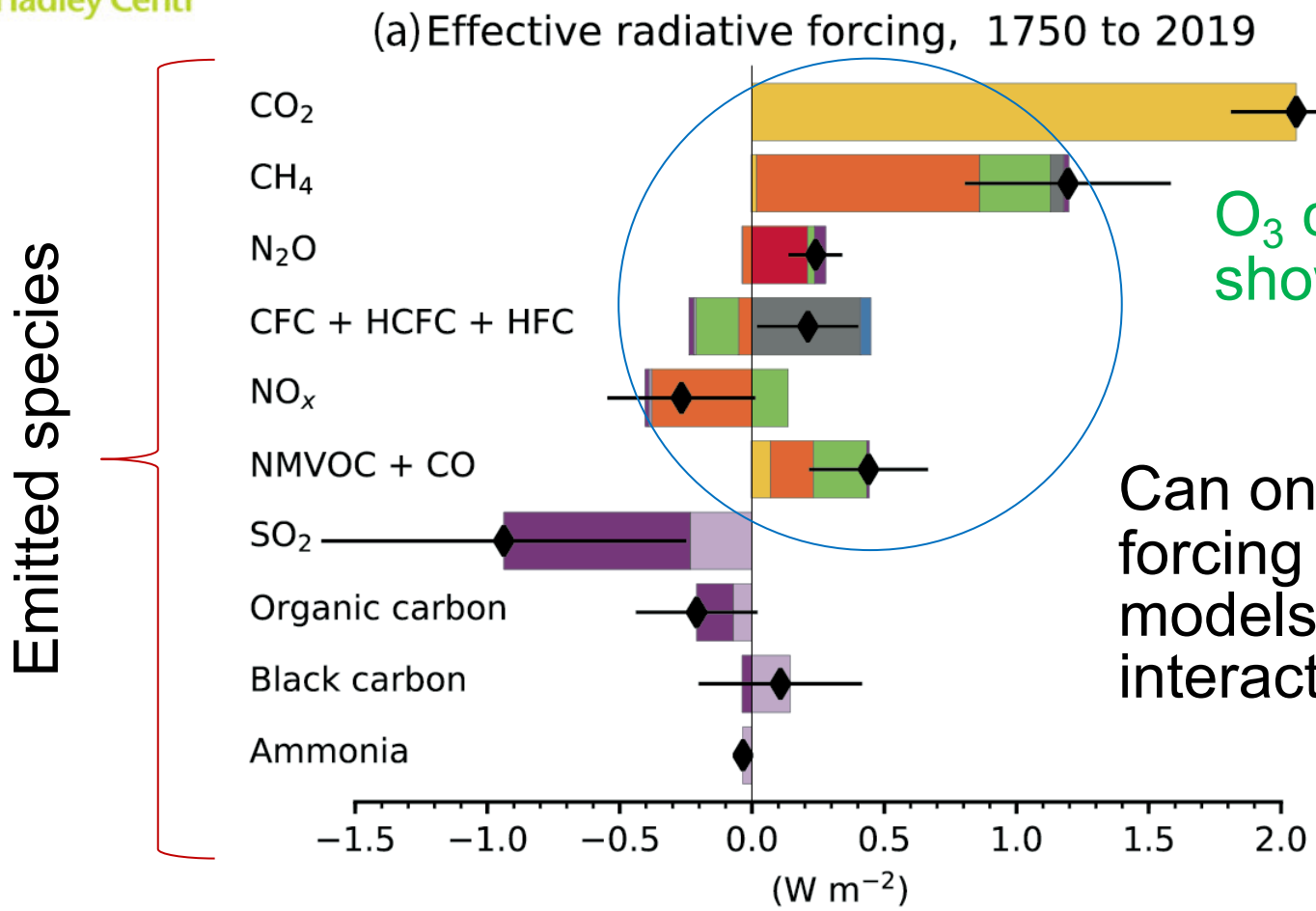
Why? – Climate Forcing (1)



Total O_3 forcing of 0.4 W m^{-2} at the present day … equivalent to a 3-bar electric fire running *all day every day* over the area of a football pitch!

Skeie et al., npj Climate Atmos. Sci., (2020)

Why? – Climate Forcing (2)

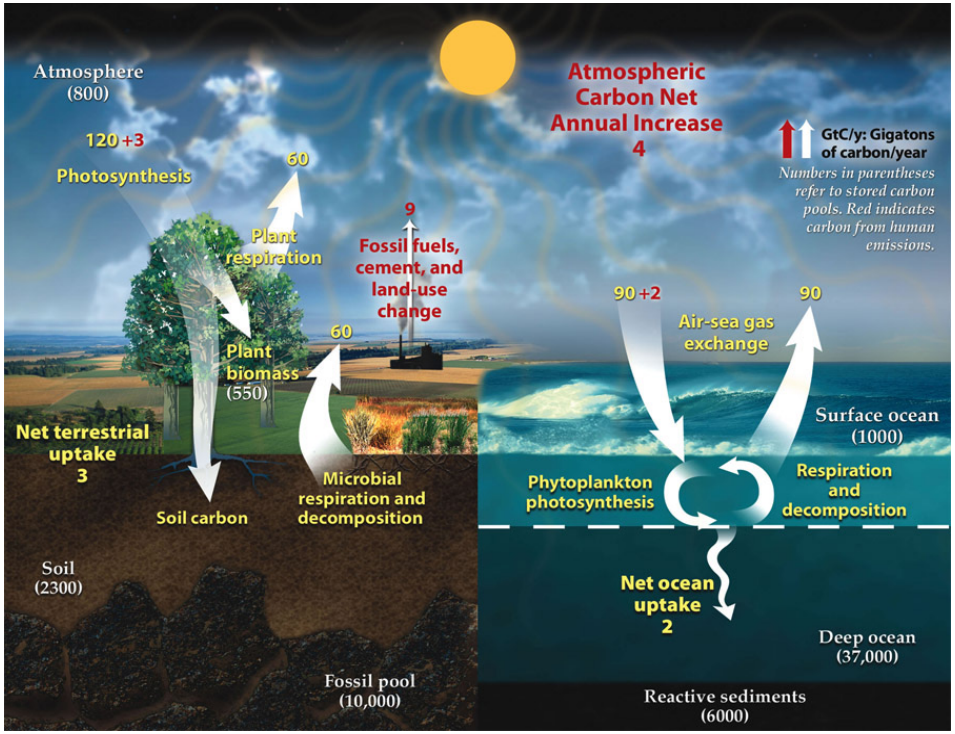


O_3 contribution shown in green

Can only quantify this forcing through models that include interactive chemistry

IPCC 6th Assessment Report (AR6), 2021

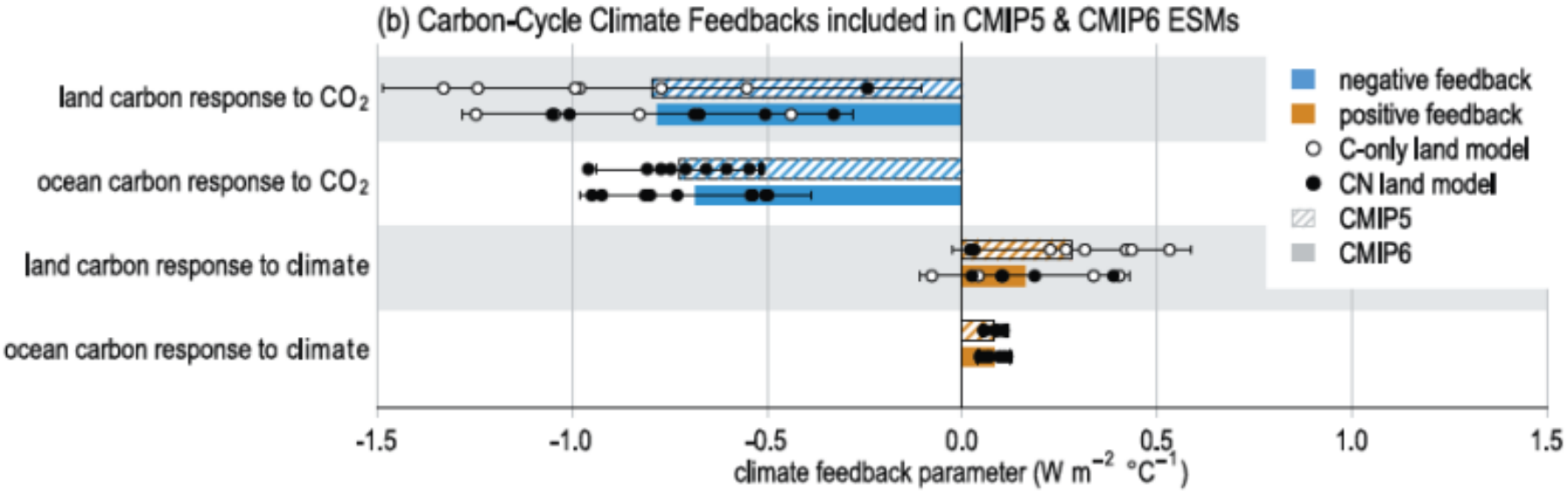
Why? – Carbon Cycle Feedbacks (1)



Earth's carbon sources/sinks may be sensitive to climate change or increased CO_2 loading, changing the rate of uptake of (emitted) CO_2 from the atmosphere by the global biosphere

Why? – Carbon Cycle Feedbacks (2)

Response of C uptake to changing atmospheric CO_2 and climate – Large uncertainties, esp. in terrestrial carbon cycle

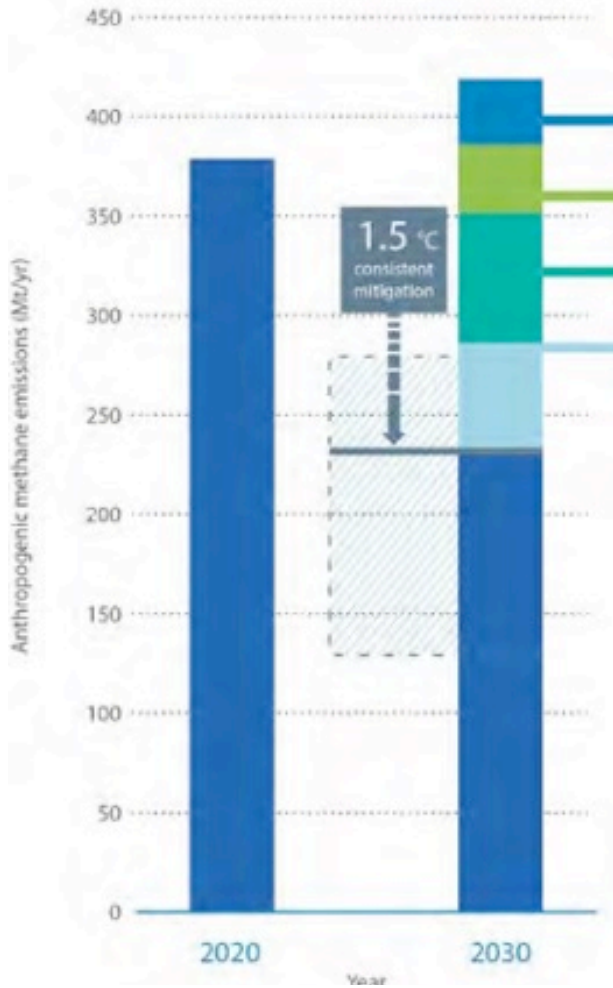


- Rising CO_2 increases photosynthesis & ocean uptake (-ve feedback)
- Rising temperature decreases both land & ocean uptake (+ve feedback)

IPCC 6th Assessment Report (AR6), 2021

Why? Mitigation & Policy Advice

Met Office Hadley Centre



	Avoided warming (2040-2070)	Avoided deaths per year	Avoided ER visits per year	Avoided crop losses (Mt/yr)	Avoided work hours lost (10^9 hrs/yr)
AGRICULTURE	0.04	40 000	120 000	4	11
WASTE	0.05	45 000	135 000	5	13
FOSSIL FUELS	0.09	80 000	250 000	8	24
ADDITIONAL	0.10	90 000	270 000	9	25
TOTAL	0.28	255 000	775 000	26	73

Remaining global anthropogenic methane emissions

Range of methane mitigation consistent with the IPCC 1.5°C pathways

Shindell et al., UN GMA (2021)

Met Office
Hadley Centre

at do we mean by the Earth Syste

hy are we interested in ES Science?

- Climate Models → ES Models

t Generation ESM: UKESM1

t ES Science Highlights

Development of Models (1)

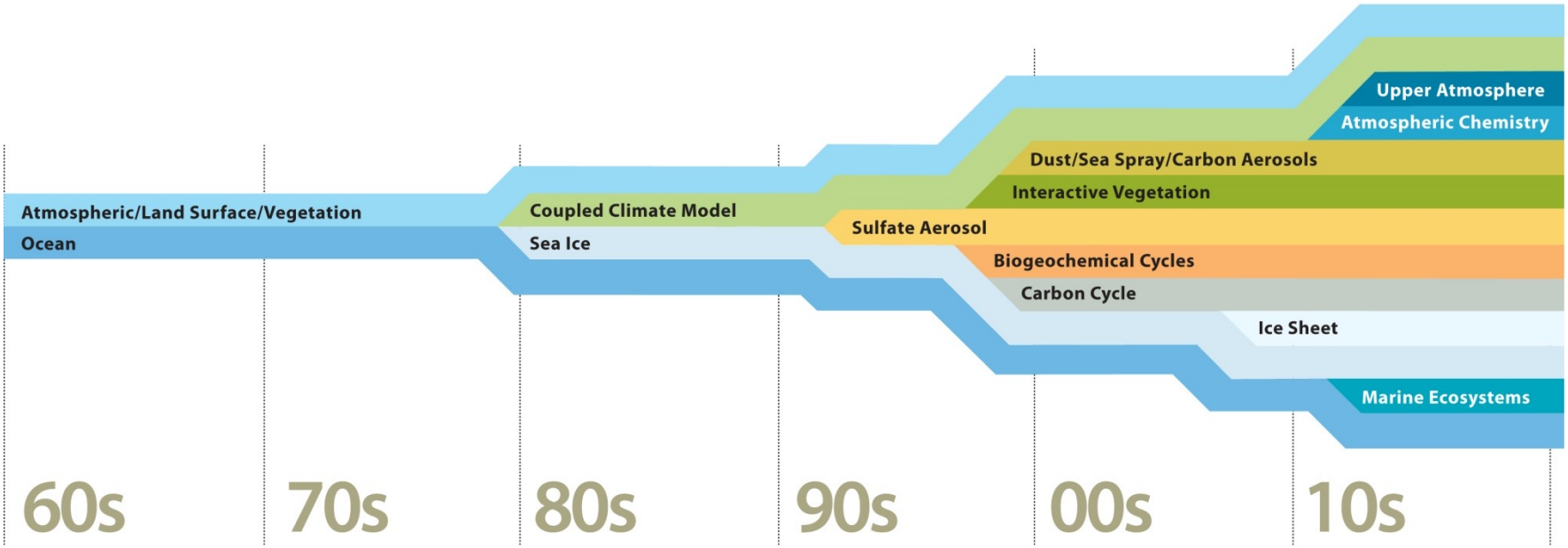
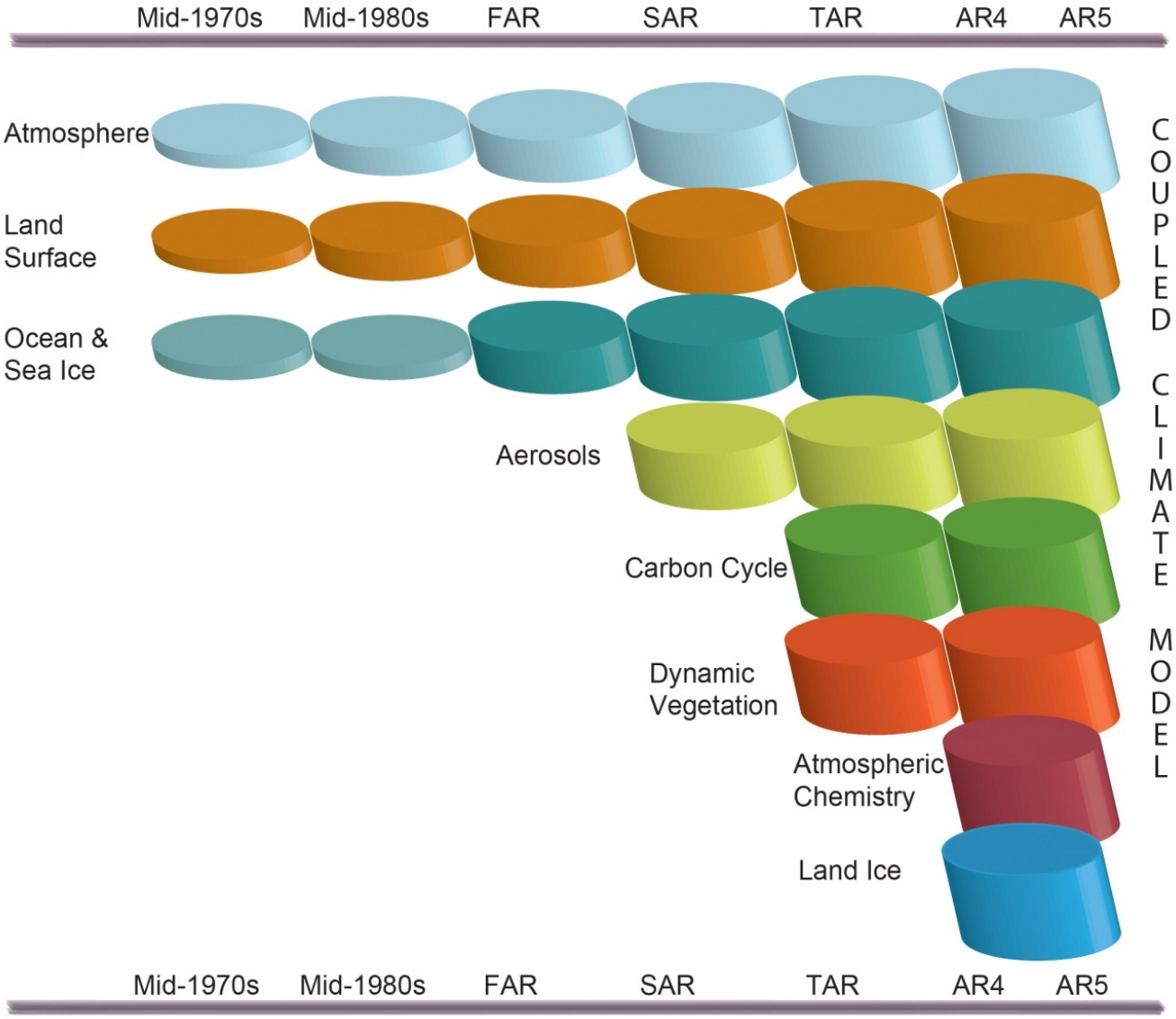


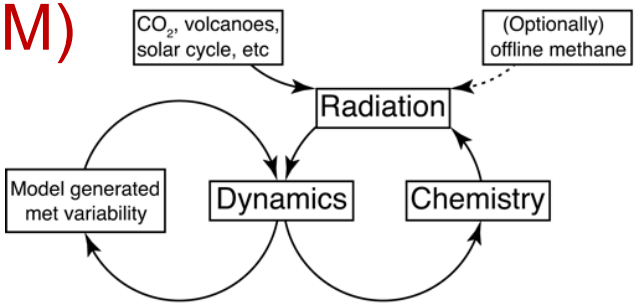
Figure courtesy of UCAR

Development of Models (2)

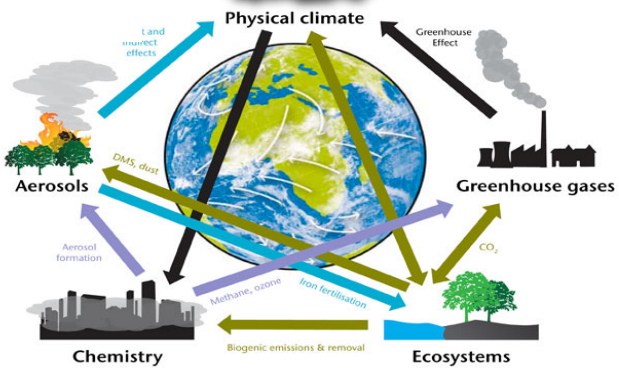


Types of Chemistry Models

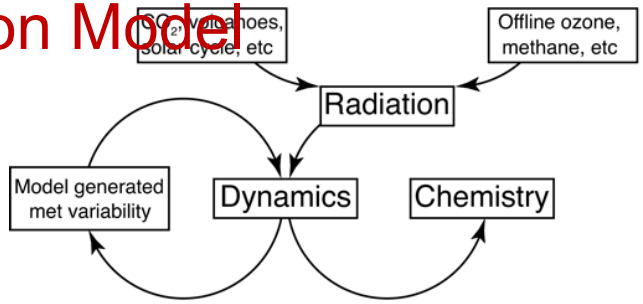
5. Chemistry Climate Model (CCM)



6. Earth System Model (ESM)



4. Chemistry General Circulation Model



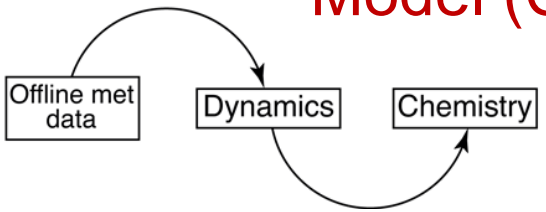
1. Box model

UKCA

2. Lagrangian model

UKCA

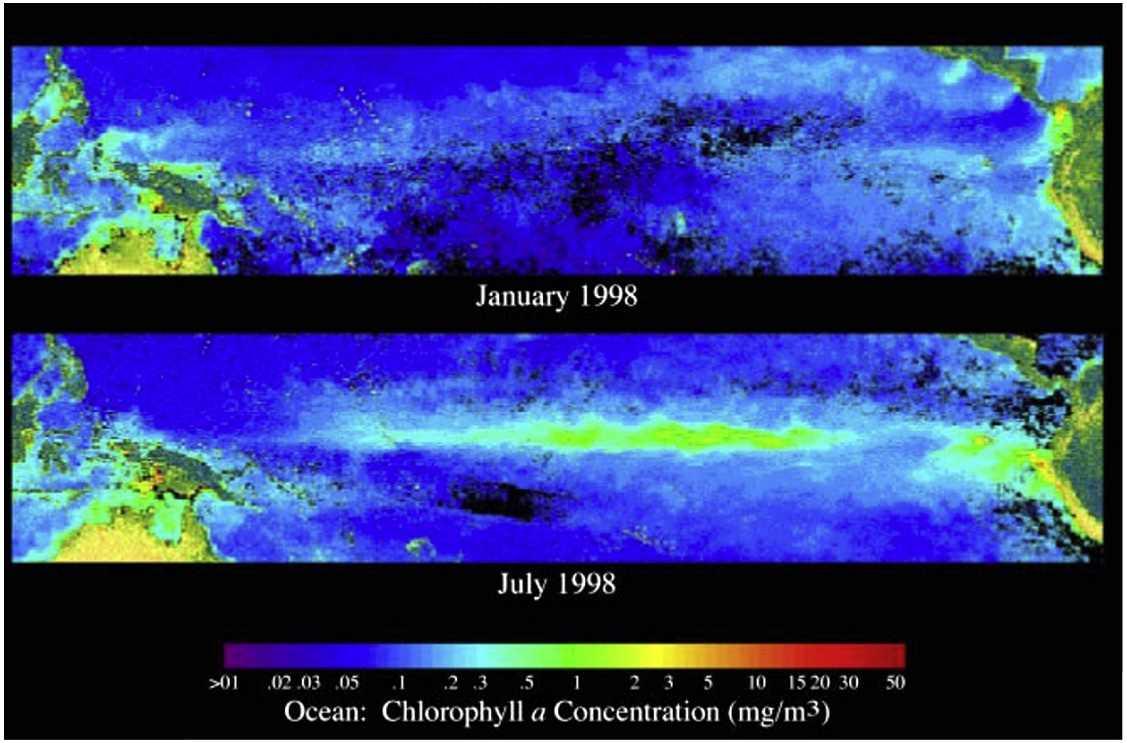
3. Chemistry transport Model (CTM)



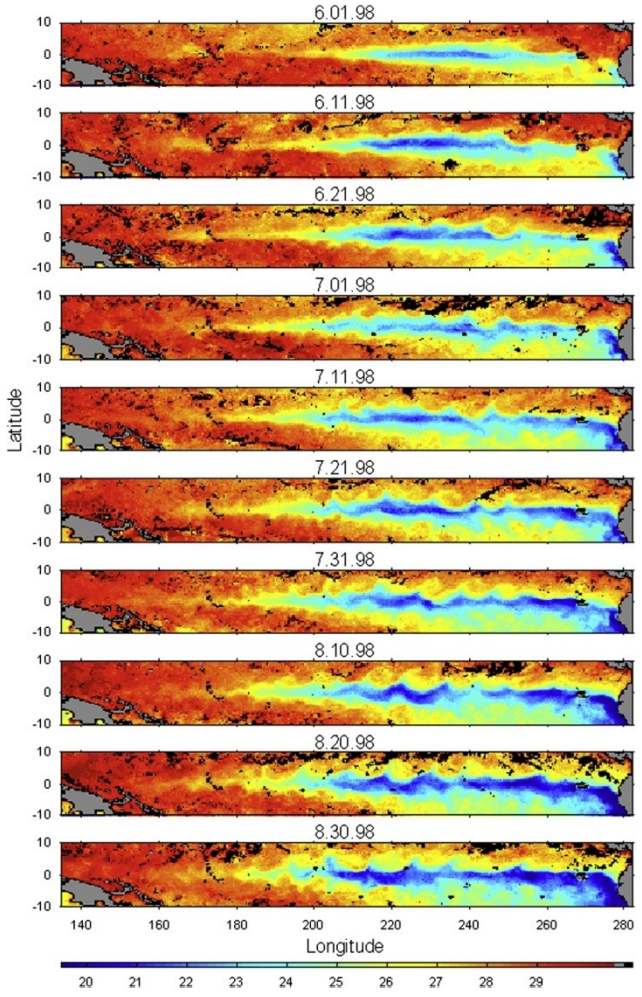
Young et al., Elementa (2018)

Physical climate variability and the carbon cycle interact strongly

Ocean biological activity, upwelling, carbon outgassing and nutrient transport

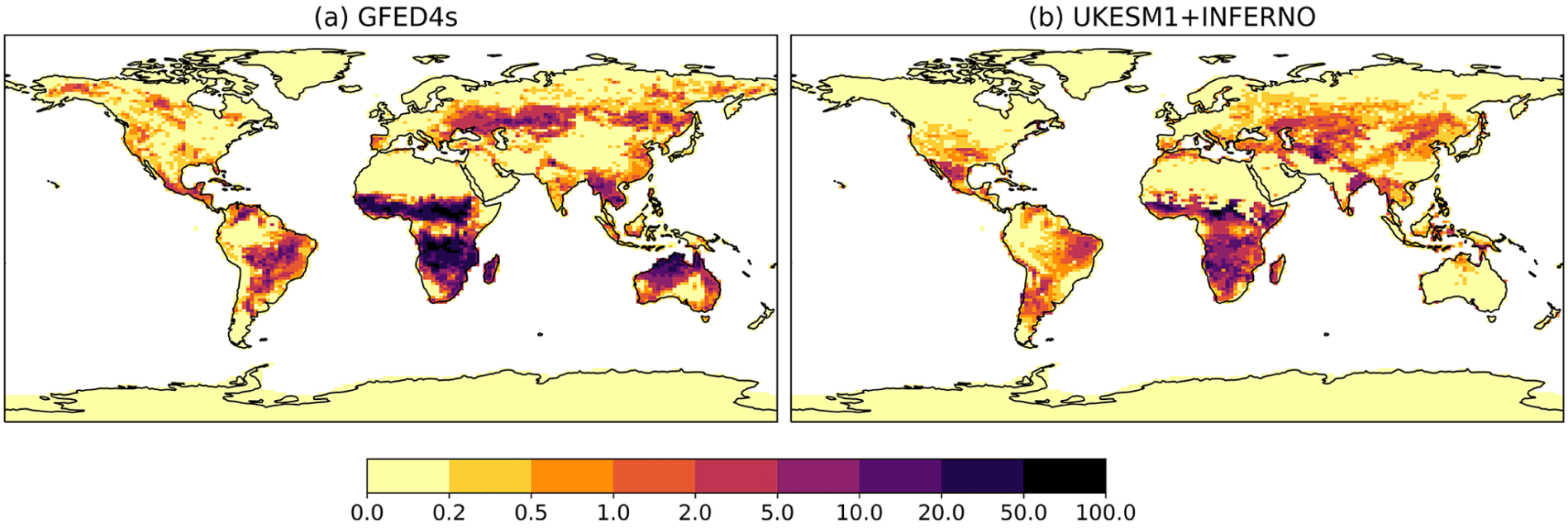


Evolution of summer 1998 La Nina



An Earth System Model is only as good as the core physical/dynamical climate model that is simulating underlying climate processes and variability

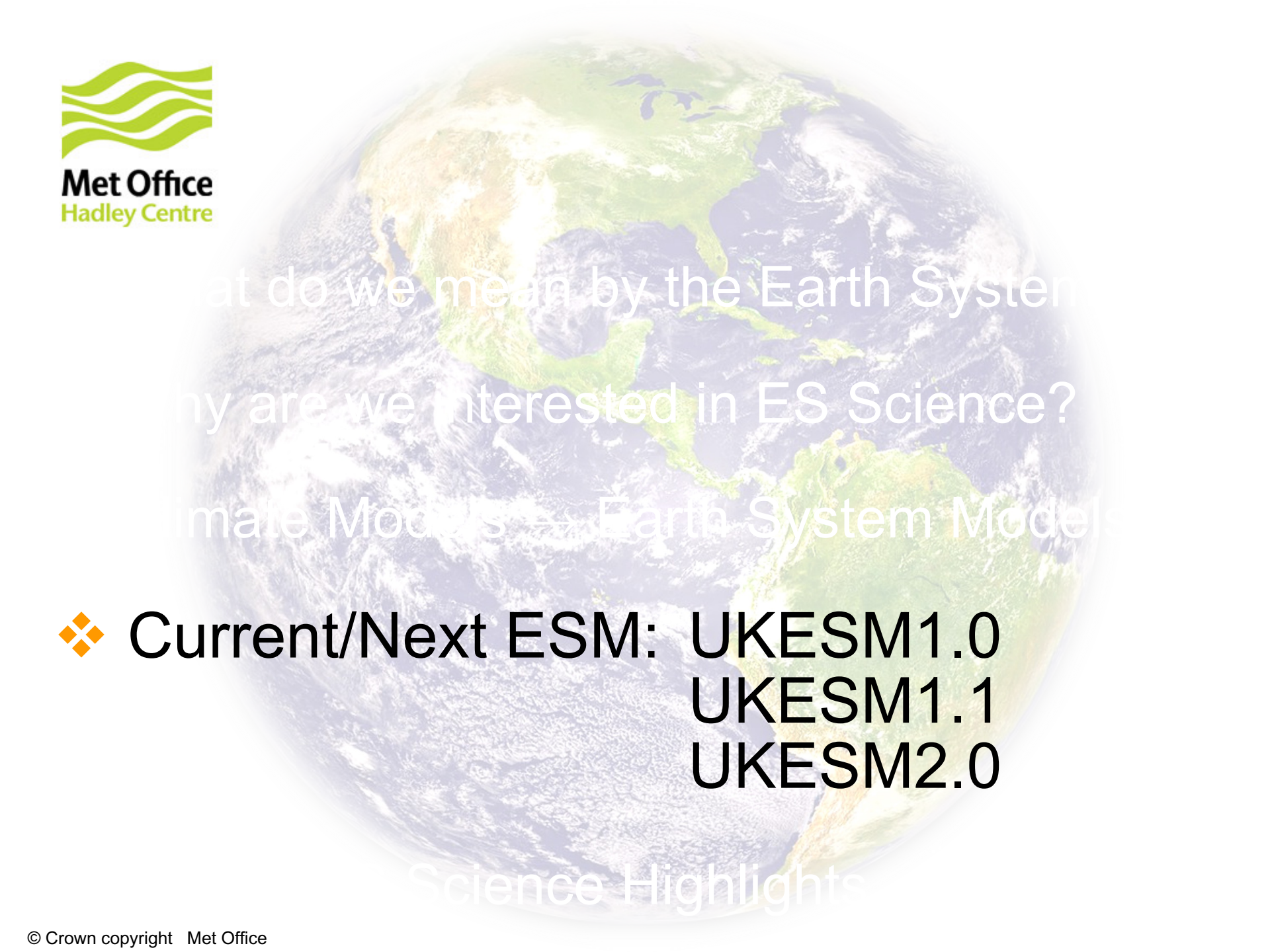
Modelling fire occurrence in the Earth System is sensitive to the underlying vegetation and meteorology



- Overestimation of tree fraction in savanna biomes
- Underestimation of fire size in these regions (e.g., SHSA)

Teixeira et al., GMD (2021)

Met Office
Hadley Centre



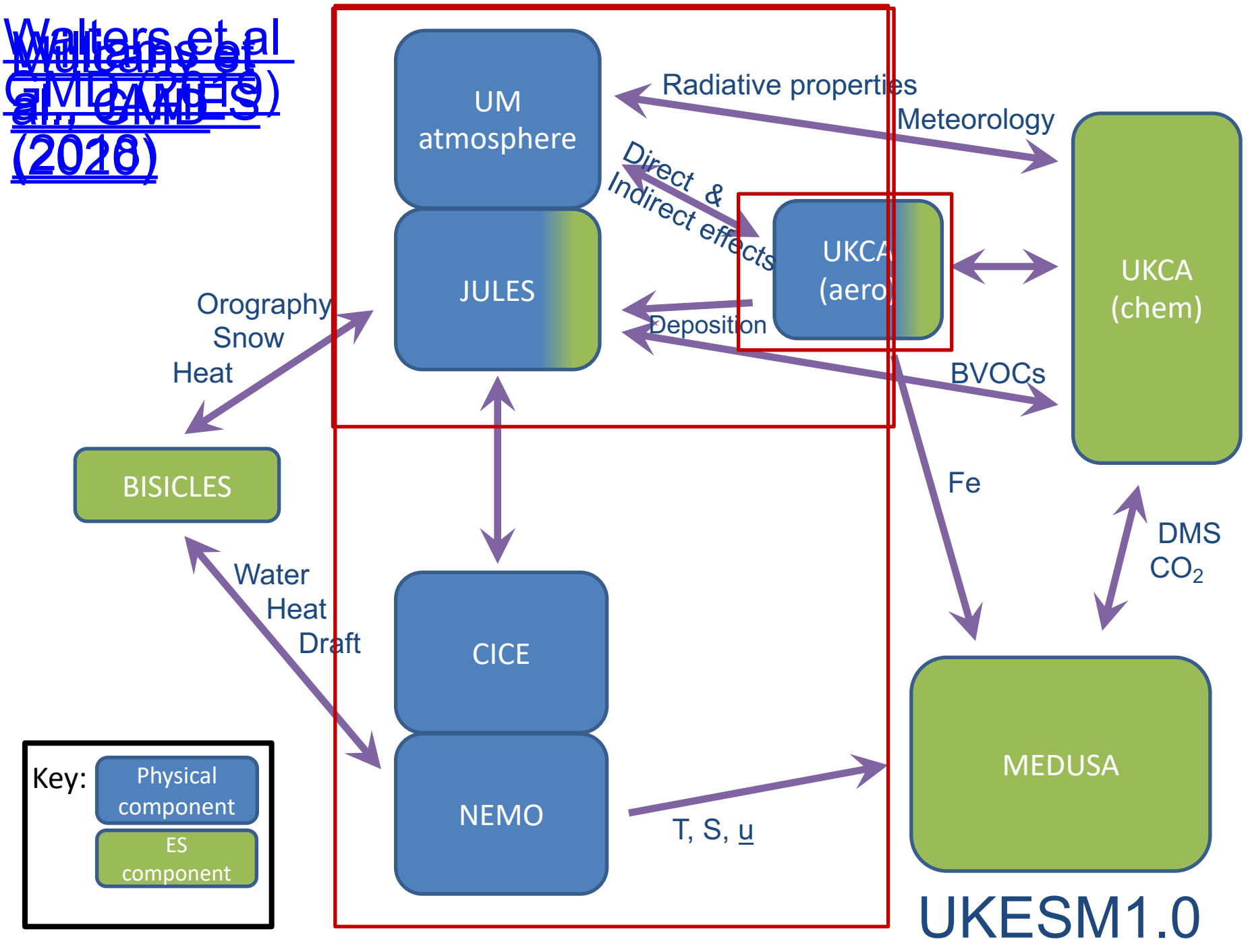
What do we mean by the Earth System

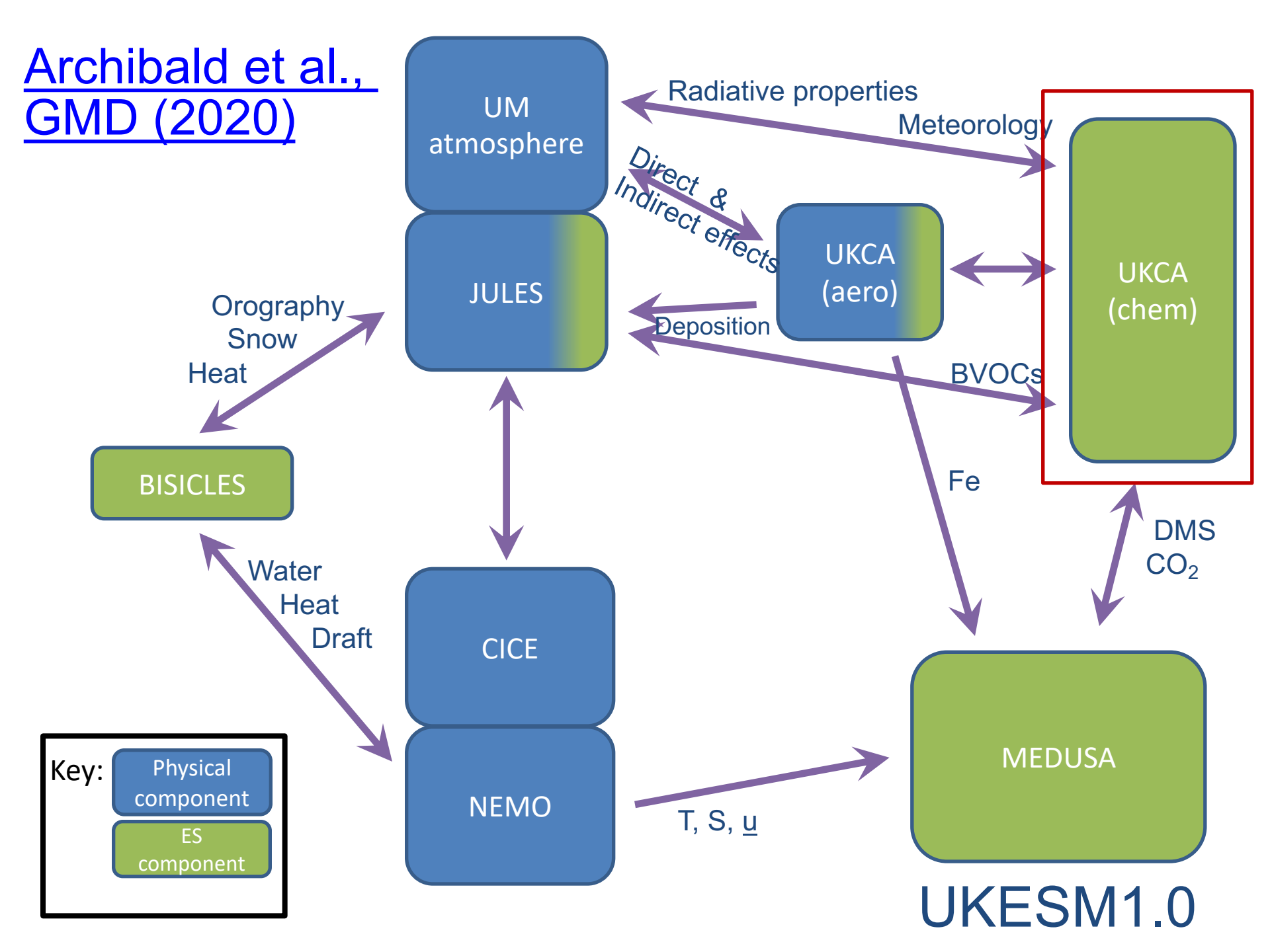
Why are we interested in ES Science?

Climate Models → Earth System Models

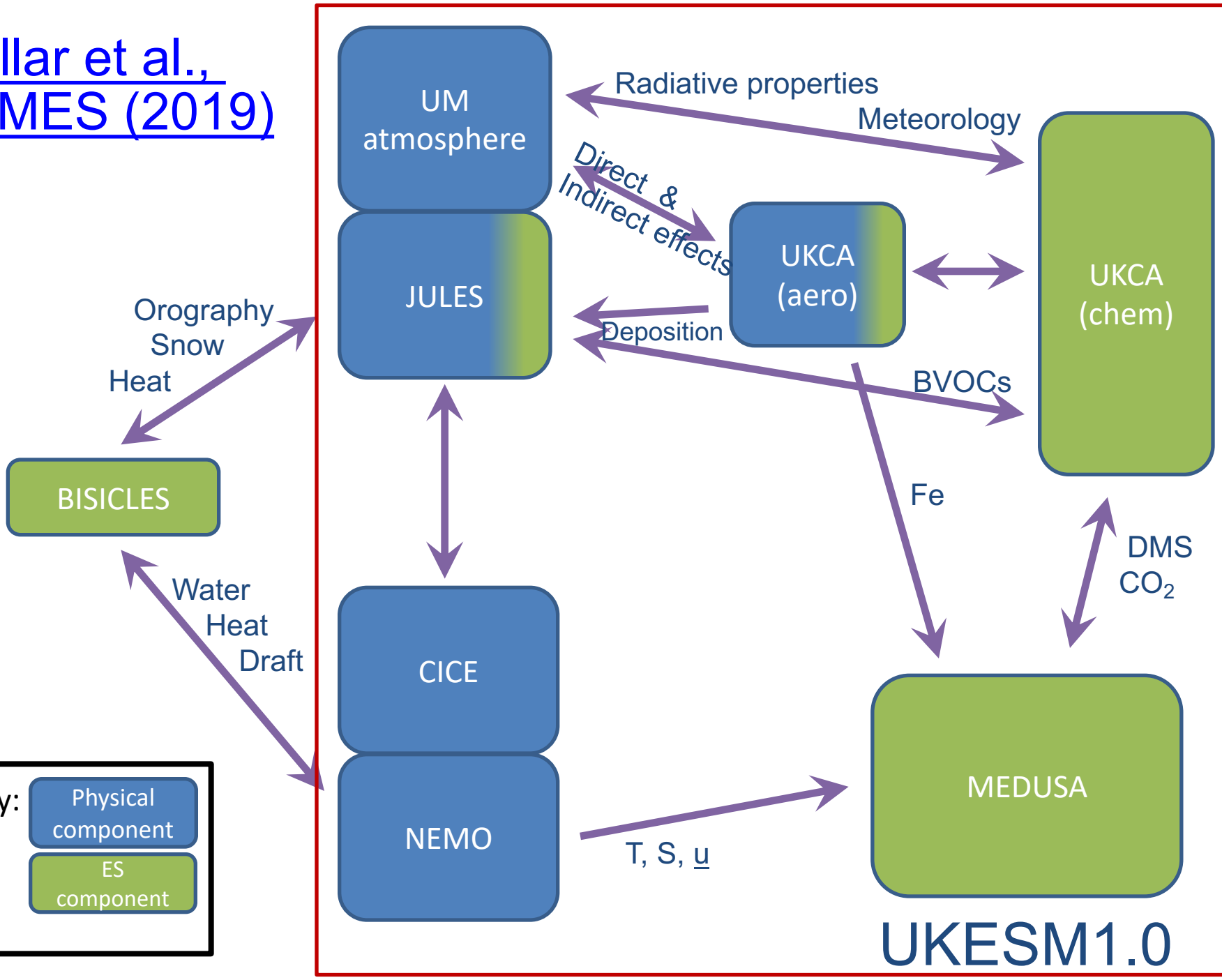
- Current/Next ESM: UKESM1.0
  UKESM1.1
  UKESM2.0

Science Highlights


Walters et al (2019)
Walters et al (2019)
Walters et al (2019)
UM atmosphere
JULES
UKCA (aero)
UKCA (chem)
Radiative properties
Meteorology
Direct & Indirect effects
Deposition
Orography
Snow
Heat
BVOCs
Fe
DMS
CO_2
BISICLES
Water
Heat
Draft
CICE
NEMO
T, S, u
MEDUSA
Key:
Physical component
ES component
UKESM1.0


Archibald et al., GMD (2020)
UM atmosphere
JULES
UKCA (aero)
UKCA (chem)
Radiative properties
Meteorology
Direct & Indirect effects
Deposition
Orography
Snow
Heat
BVOCs
Fe
DMS
CO_2
BISICLES
Water
Heat
Draft
CICE
NEMO
T, S, u
MEDUSA
Key:
Physical component
ES component
UKESM1.0

Sellar et al., JAMES (2019)



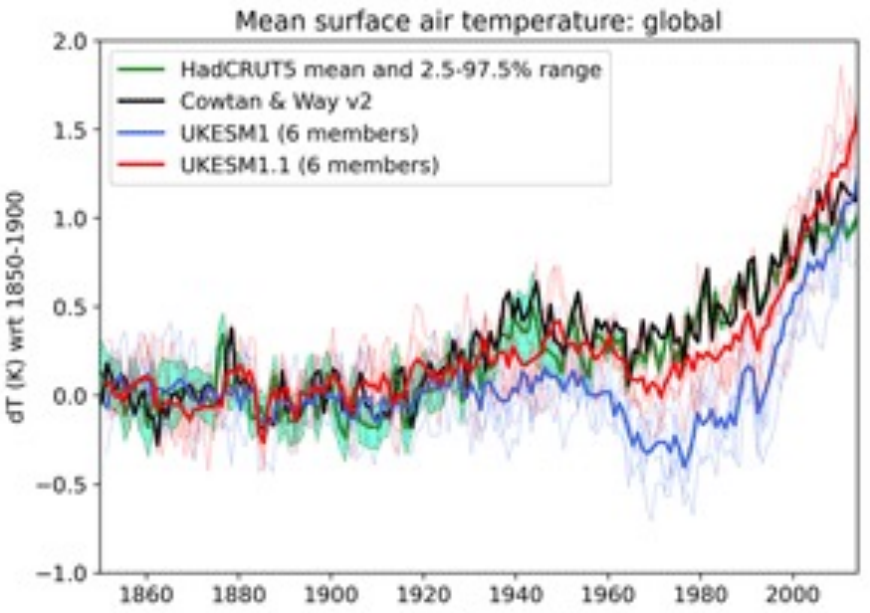
UKESM1.0 → UKESM1.1

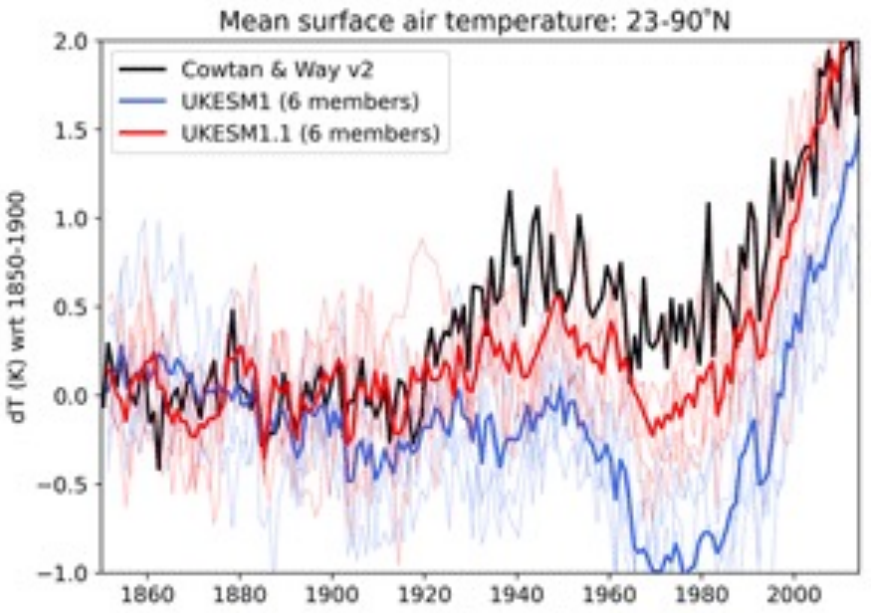
Met Office Hadley Centre

Globe

23-90°N

Δtemp wrt 1850-1900





- Improved SO_2 dry deposition
- Reduced magnitude of aerosol forcing
- Bugfixes & re-tunings

UM-Based

Mulcahy et al., GMD (2023)

UKESM1.1 → UKESM2.0

Met Office
Hadley Centre

UK Earth System Model (UKESM2)

UKESM2 is targeted for use in CMIP7 (release date, ~early 2026)

UKESM2 (early 2026)

- New physical base: HadGEM3-GC5
- Emission driven CO_2 and CH_4
- Interactive AIS and GrIS ice sheets
- Nitrate aerosol
- Improved stratospheric O_3 chemistry
- Interactive fire
- Thermal acclimation of vegetation
- Permafrost (physics & BGC) coupled to C & N cycle and wetlands
- Variable cloud water pH
- Boundary nucleation of new aerosol
- Dust treated via modal scheme
- Improvements to ocean BGC
- Improved treatment of SOA

Workhorse resolution
Atmos: 1.25 x 1.875° L85
Ocean: 1°L75

Hybrid resolution
Atmos 60km/135km L85
Ocean 0.25°/0.75° L75

ee-UKESM1.1-ice

Back-up for CMIP7 fast-track

(e.g. if GC5_central is late)
ee-UKESM1.1-ice (frozen)

- UKESM1.1 (Mulcahy et al. 2023)
  Improved treatment of SO_2 and SO_4
  Improved historical SAT vs UKESM1.0

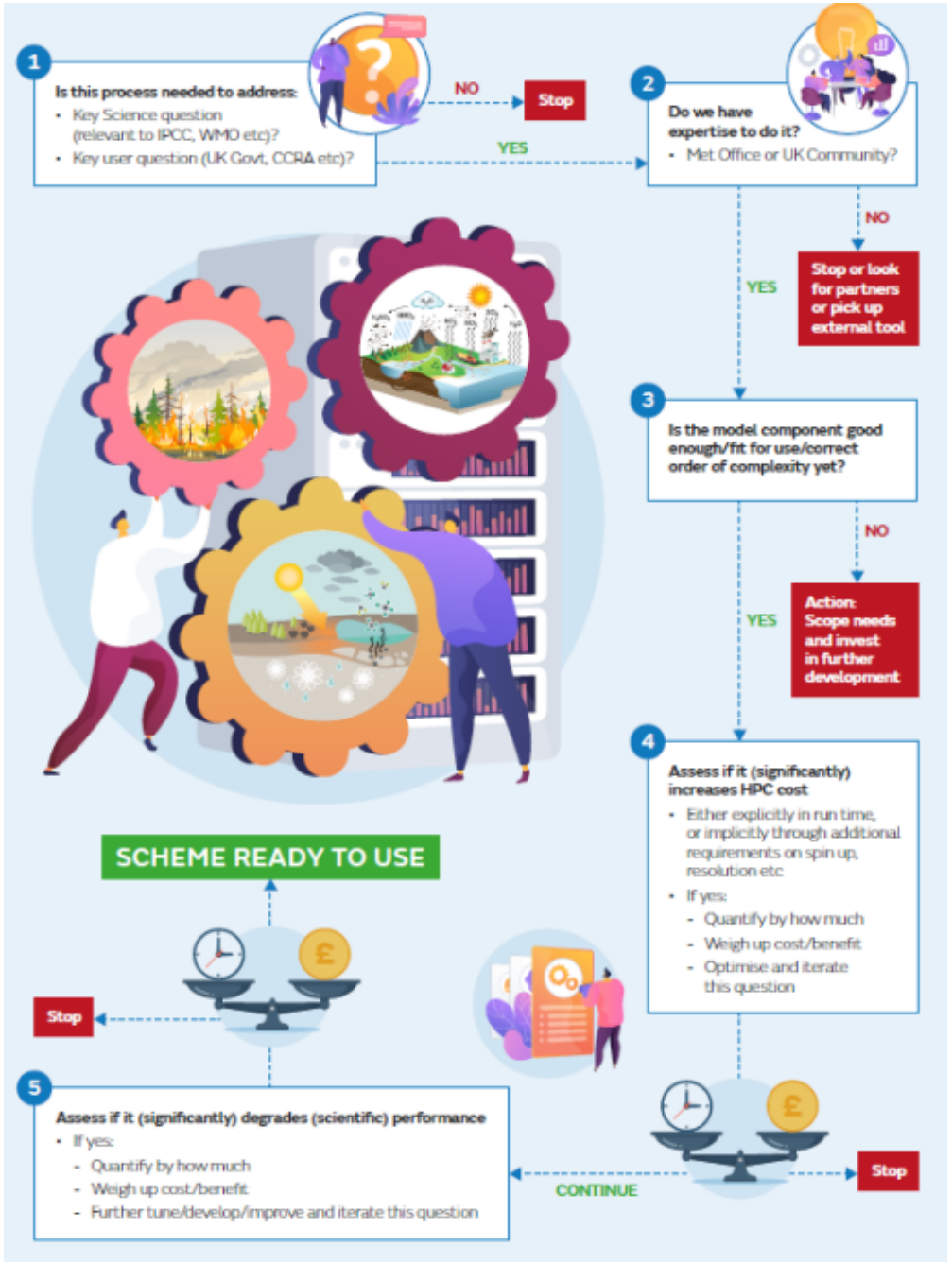
New configuration will run in:

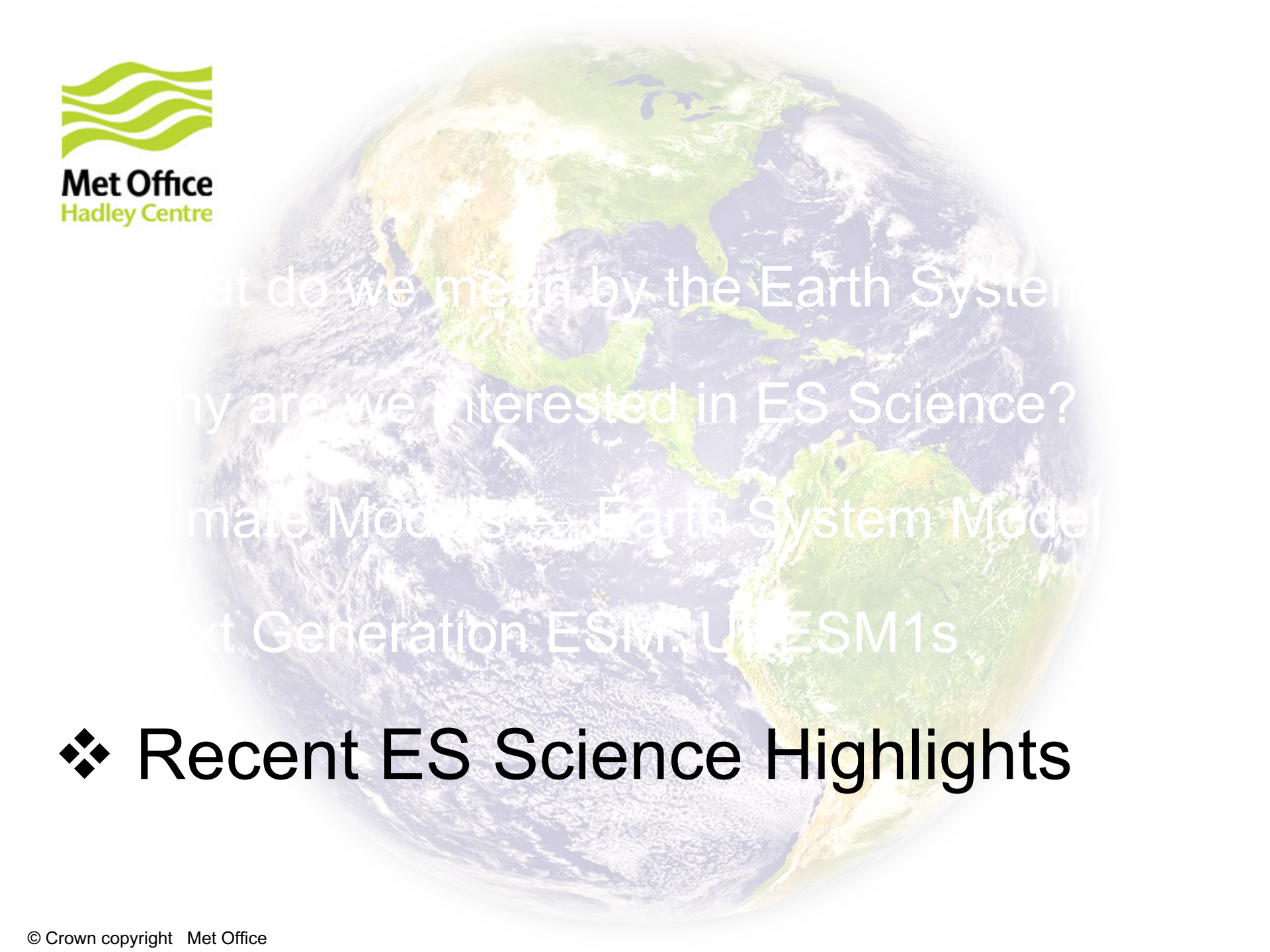
- emission mode for both CO_2 and CH_4
  i.e. full/closed cycles of both gases
- Interactive AIS and GrIS ice sheets

UM-Based

Decision making

- Important?
- Expertise?
- Fit for purpose?
- Computational cost?
- Scientific performance?



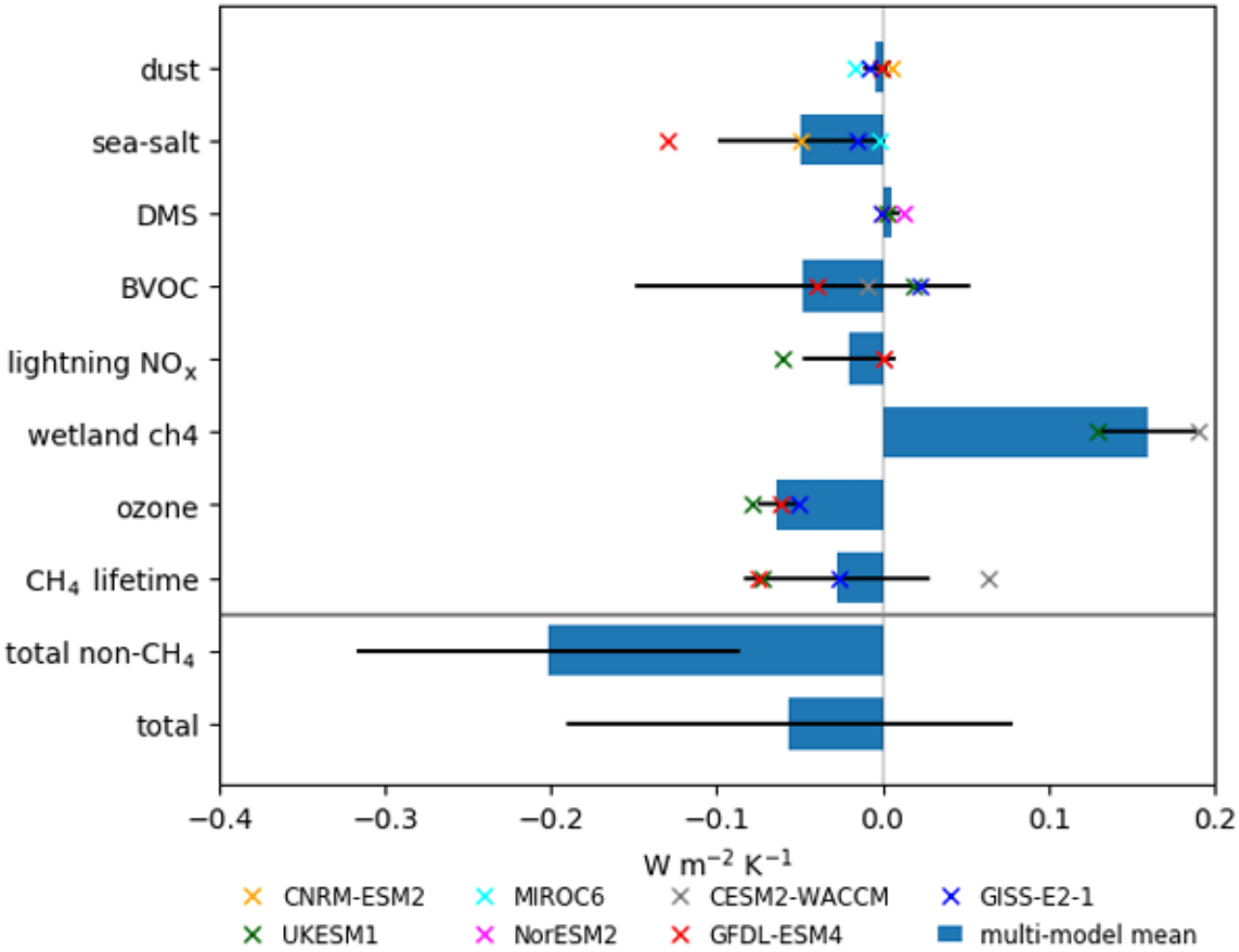


- Recent ES Science Highlights

Biogeochemical Feedbacks

Met Office Hadley Centre

[Thornhill et al., ACP (2021)]

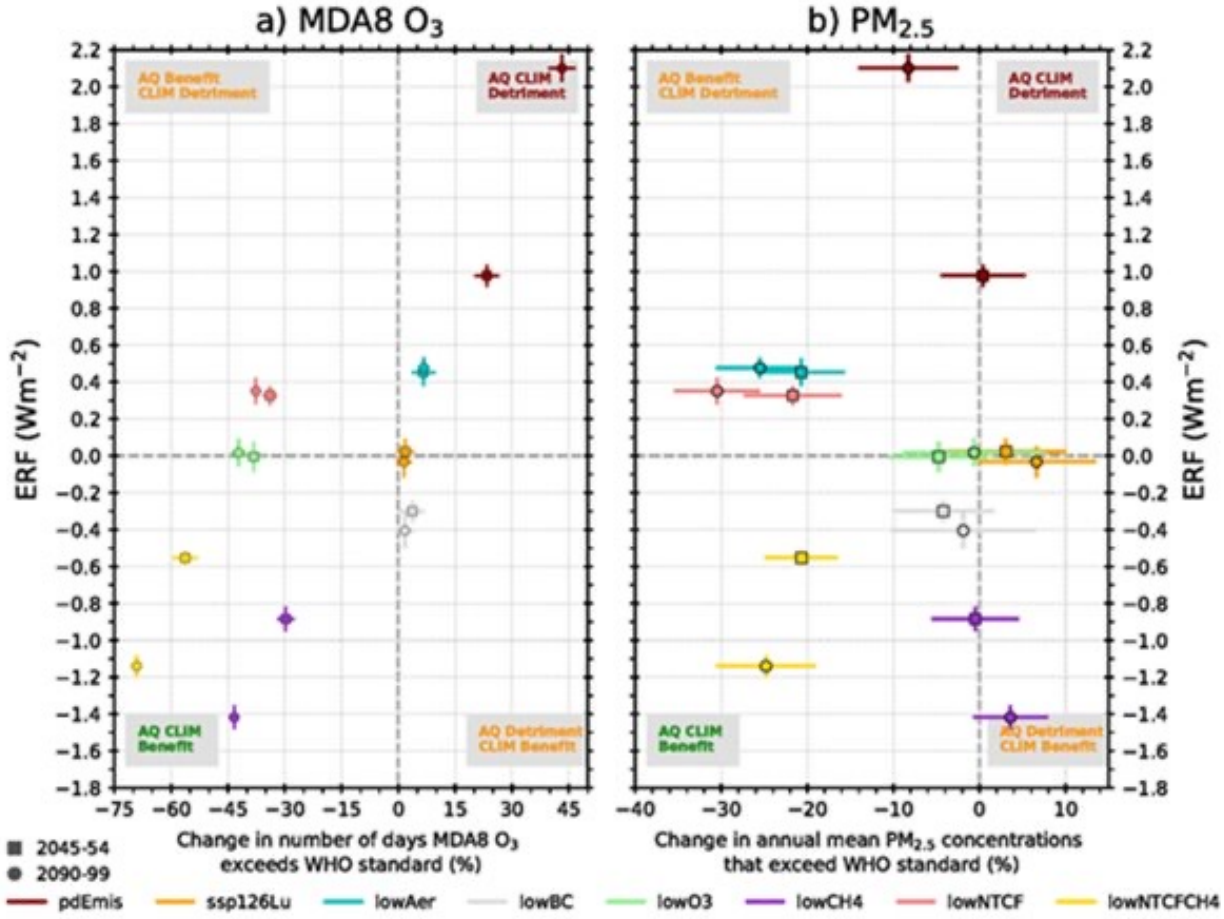


First multi-model assessment of different non-CO2 biogeochemical feedbacks

Mitigation & Policy Advice

Met Office
Hadley Centre

Cooling Warming



Assessment of climate & air quality impacts from different mitigation pathways, e.g., aerosols, land use, methane, etc..

Turnock et al., Earth's Future (2022)
Turnock et al., Geohealth (2023)

Conclusions

Concluding Remarks

- The Earth System
- Motivation behind studying Earth System Science
- Development of Climate Models into Earth System Models
- Brief overview of UKESM1, UKESM1.1, & UKESM2
- Recent ES Science Highlights

Met Office
Hadley Centre

Thank you for listening!
Any questions?