Earth System Modelling

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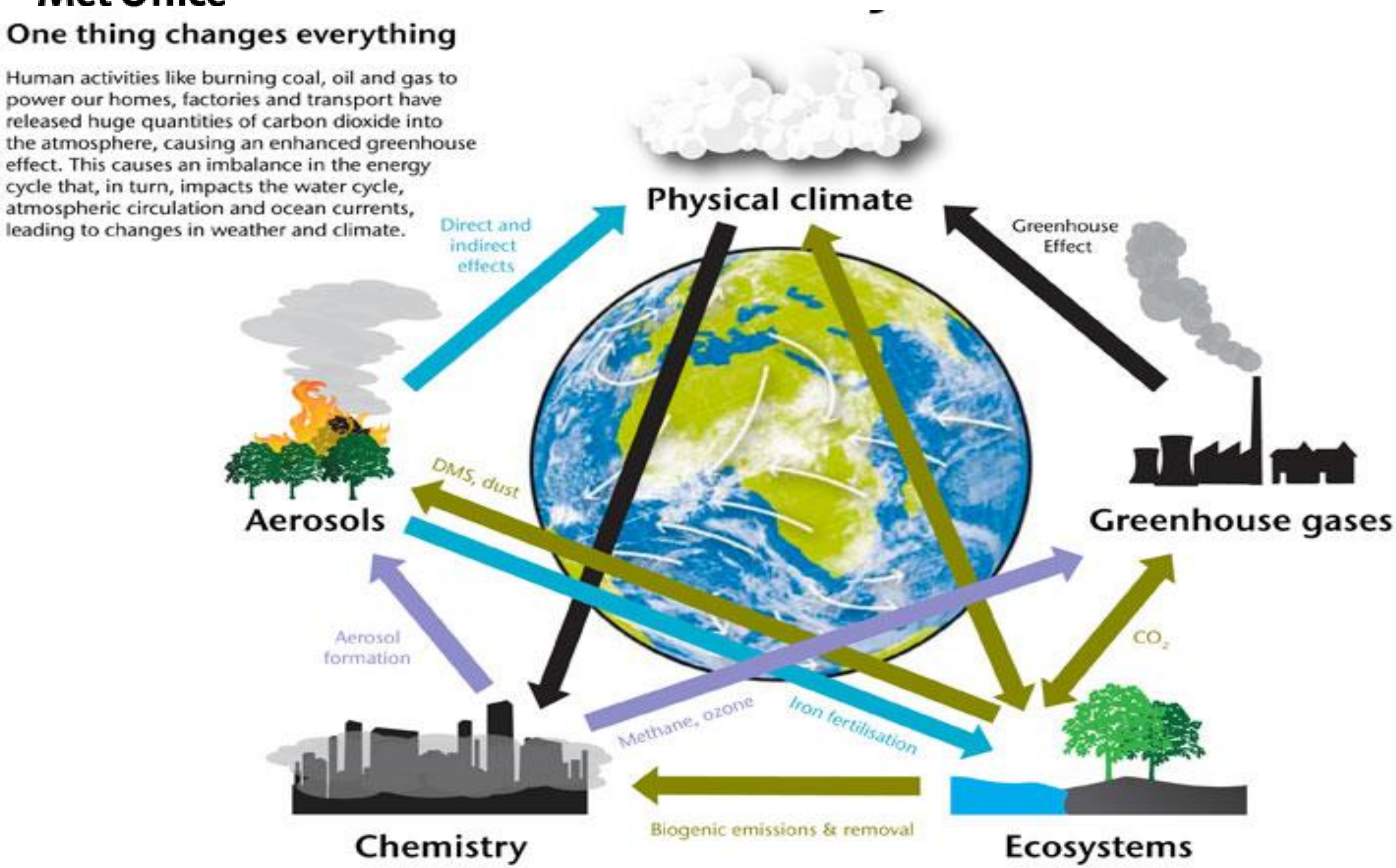
UKCA Training Workshop, Cambridge, January 2016

Overview

- What do we mean by the Earth System?
- Why are we interested in ES Science?
- Climate Models → Earth System Models
- The Earth System Model HadGEM2-ES
- Science Highlights involving HadGEM2-ES
- Next Generation ESM: UKESM1

What is the Earth System?

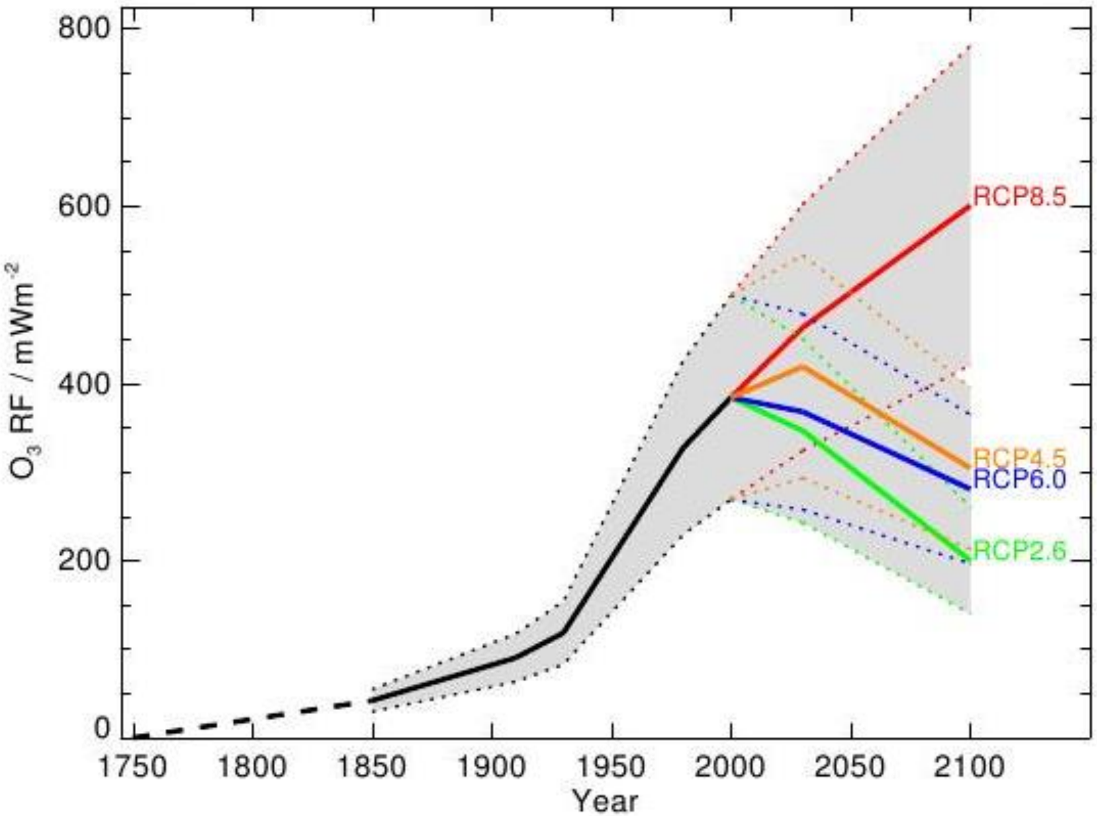
What is the Earth System?



Why do we study Earth System Science?

Why? – Climate Forcing (1)

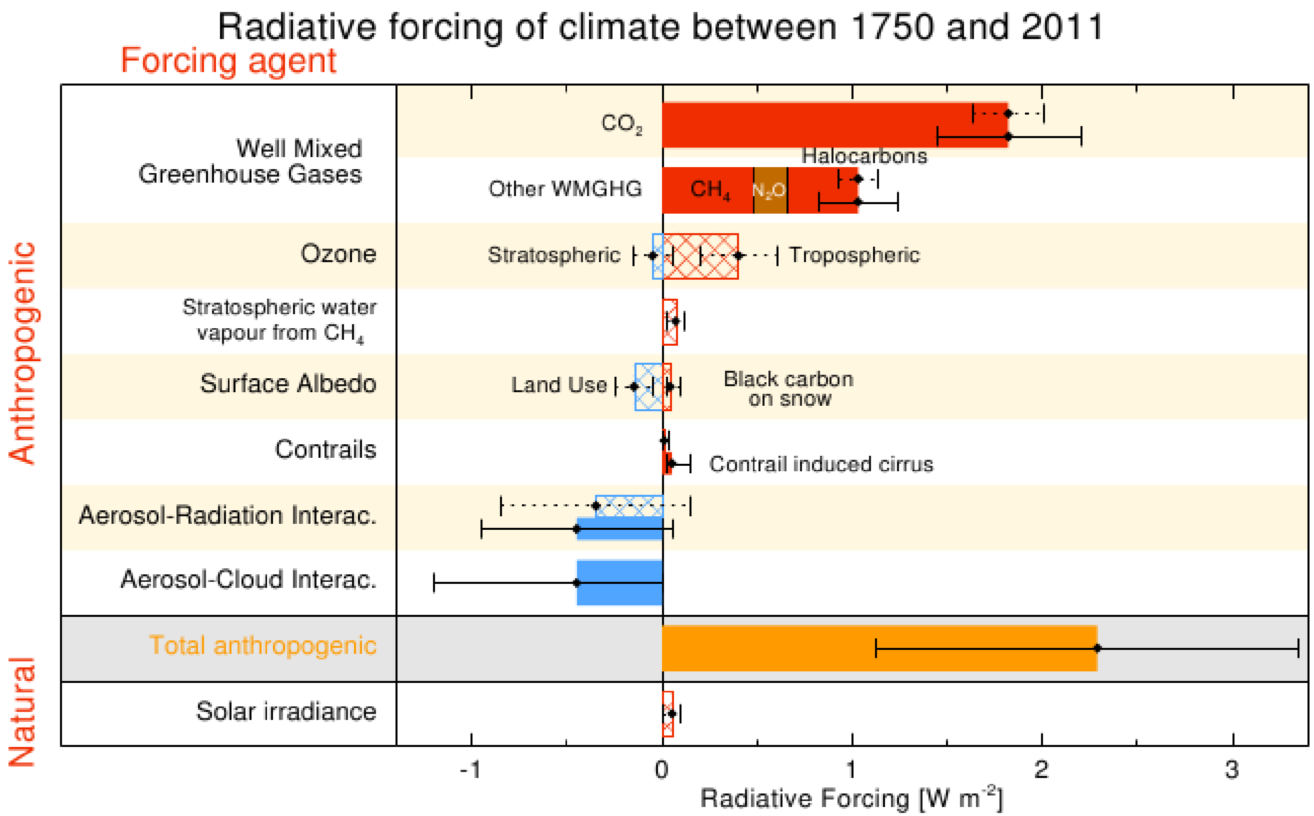
Tropospheric O_3 forcing



Multi-model study called Atmospheric Composition and Climate Model Intercomparison Project (ACCMIP) and included HadGEM2-ES

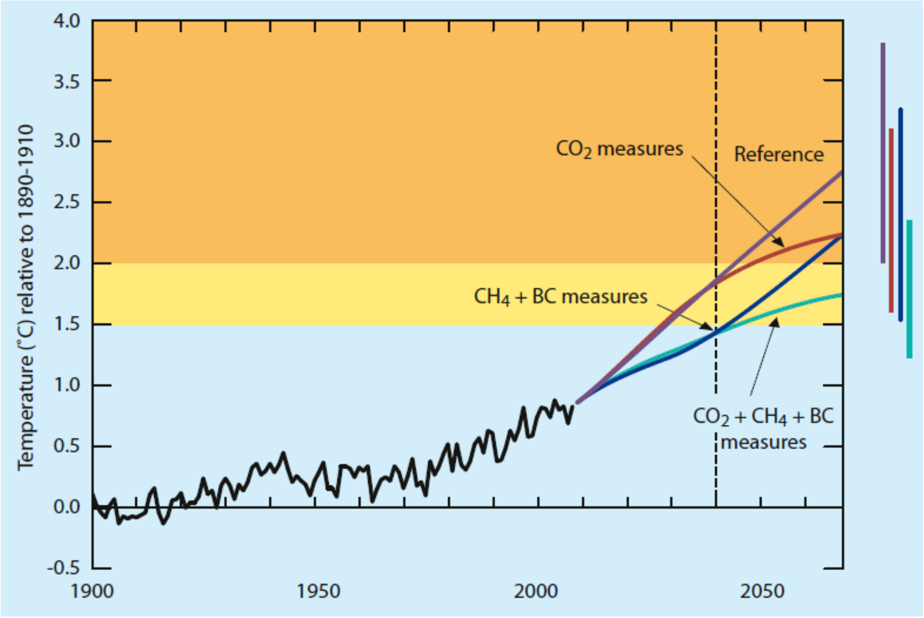
Stevenson et al., Atmos. Chem. Phys. (2013)

Why? – Climate Forcing (2)



Why? – Mitigation

Climate Change Mitigation refers to actions, which aim to reduce magnitude and/or rate of climate change



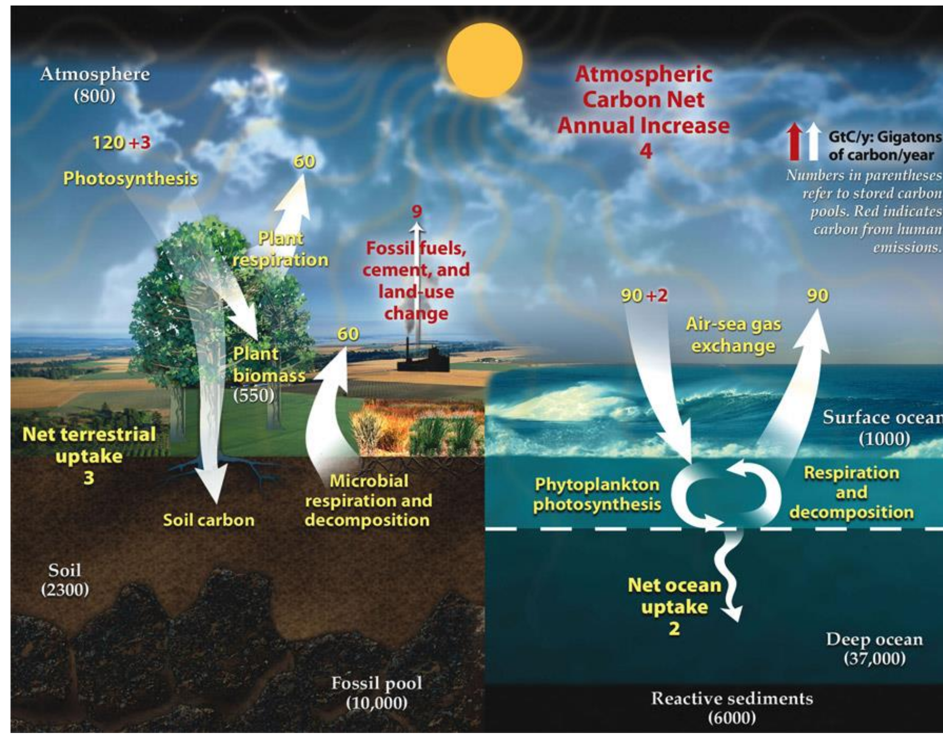
UNEP, 2011

CH_4 Emission Reductions:

- Technologically feasible although investment required
- Offer a near-term climate benefit
- Reduce tropospheric O_3 and improve air quality

Why? – Carbon Cycle Feedbacks (1)

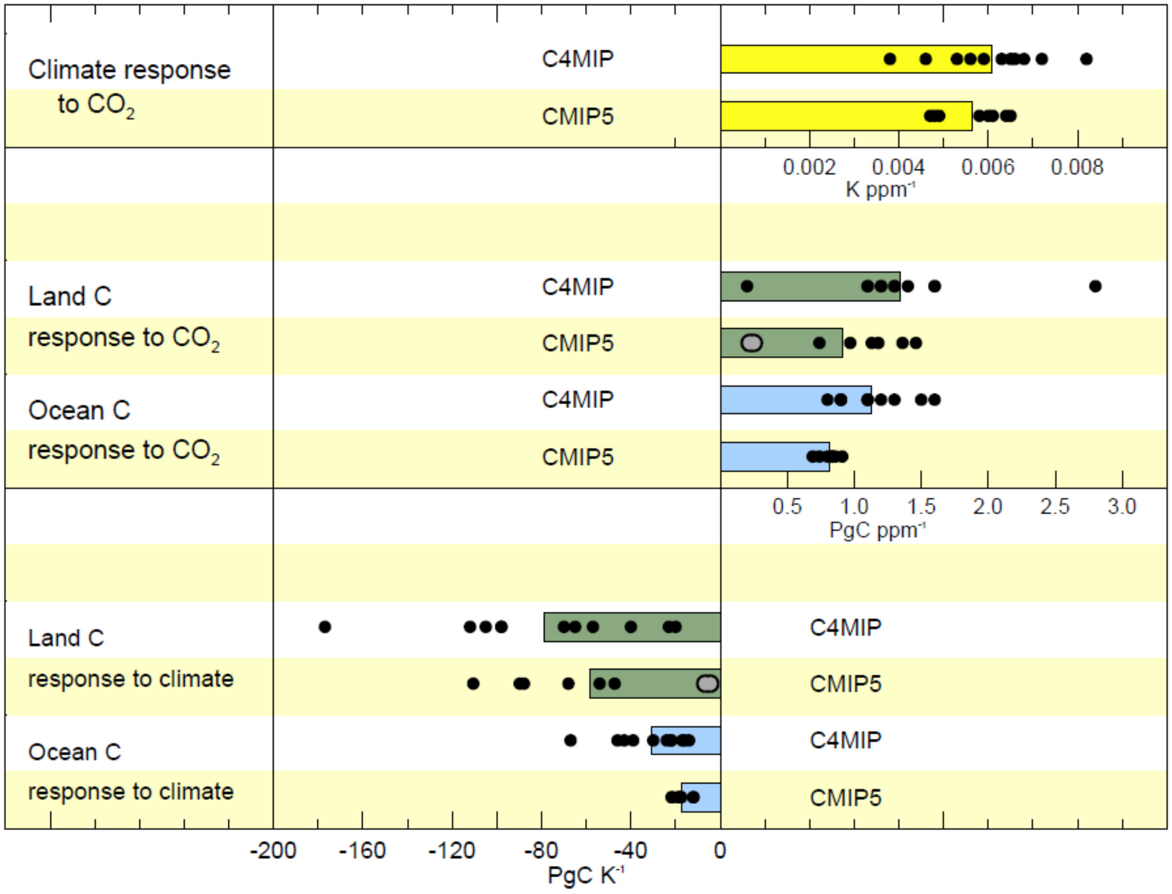
The carbon cycle is intimately linked to the physical climate system and requires an accurate simulation of associated biogeochemical cycles (e.g. H_2O, N_2, O_2)



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



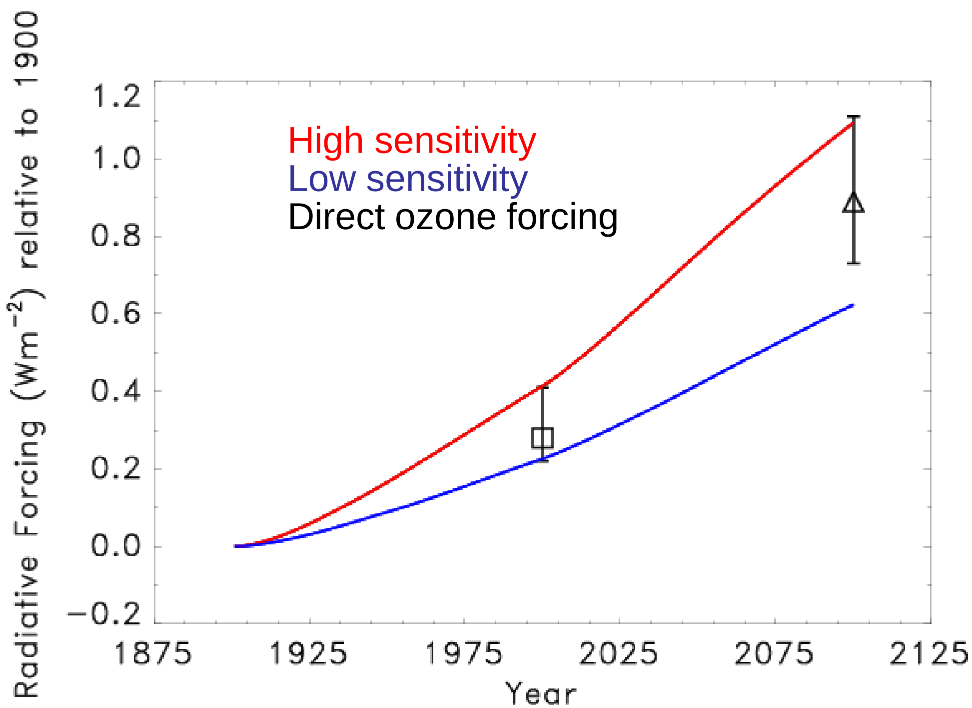
Models with a terrestrial Nitrogen cycle

Why? – Chemistry Climate Interactions (1)

- Ozone damage reduces the amount of carbon removed from the atmosphere by plants

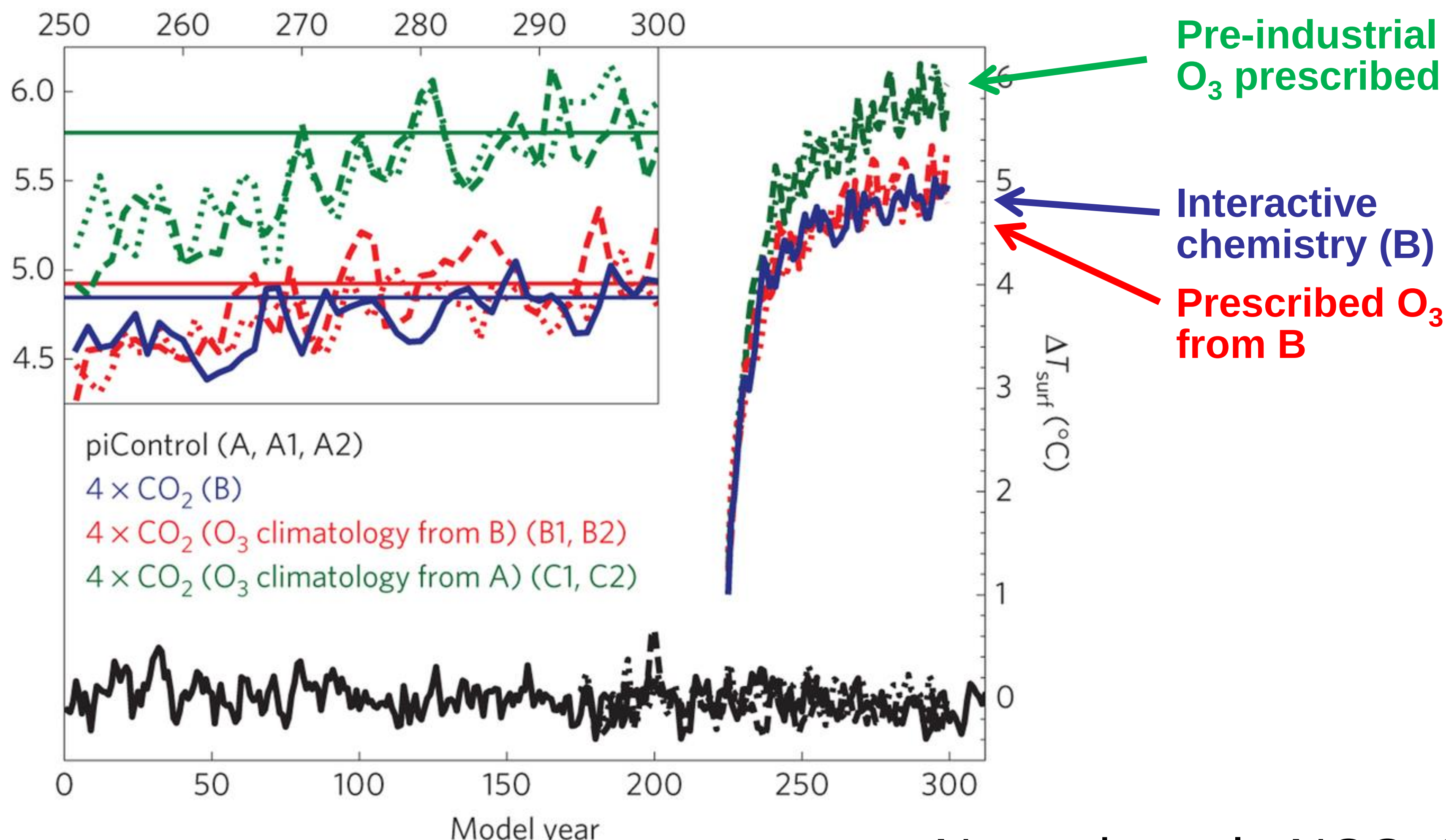
- Quantified RF over 20th & 21st Centuries

- Indirect forcing from the extra CO_2 is comparable to the direct radiative forcing from ozone



Sitch et al., Nature, 2007

Why? – Chemistry Climate Interactions (2)



Nowack et al., NCC, 2014

Evolution of Climate Models into Earth System Models

Development of Models (1)

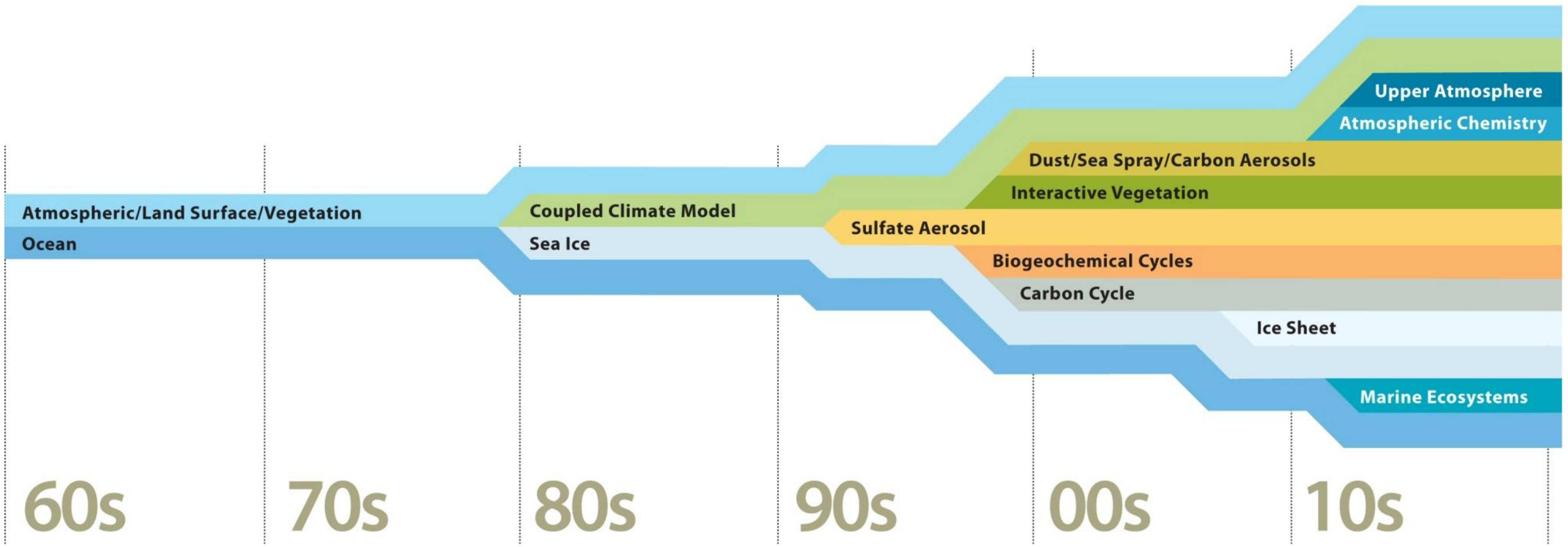
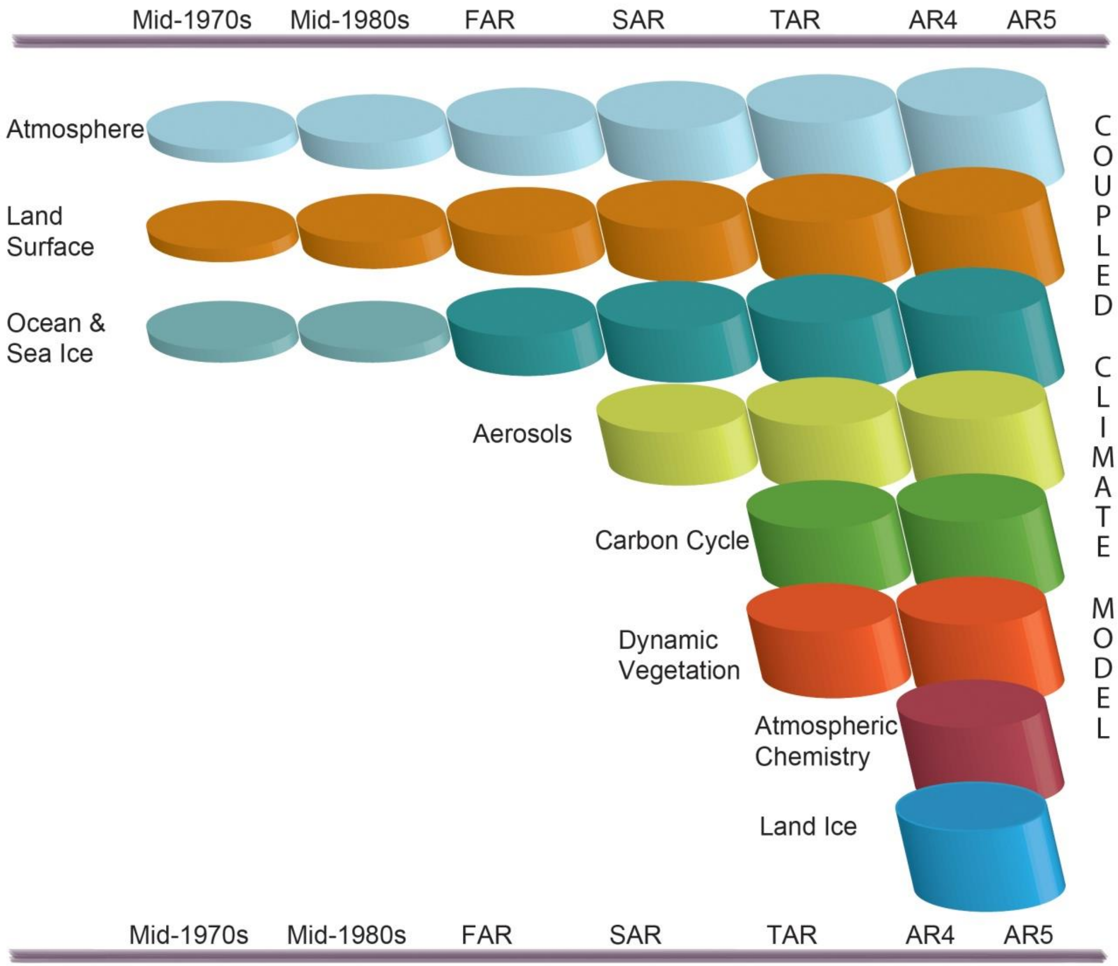


Figure courtesy of UCAR

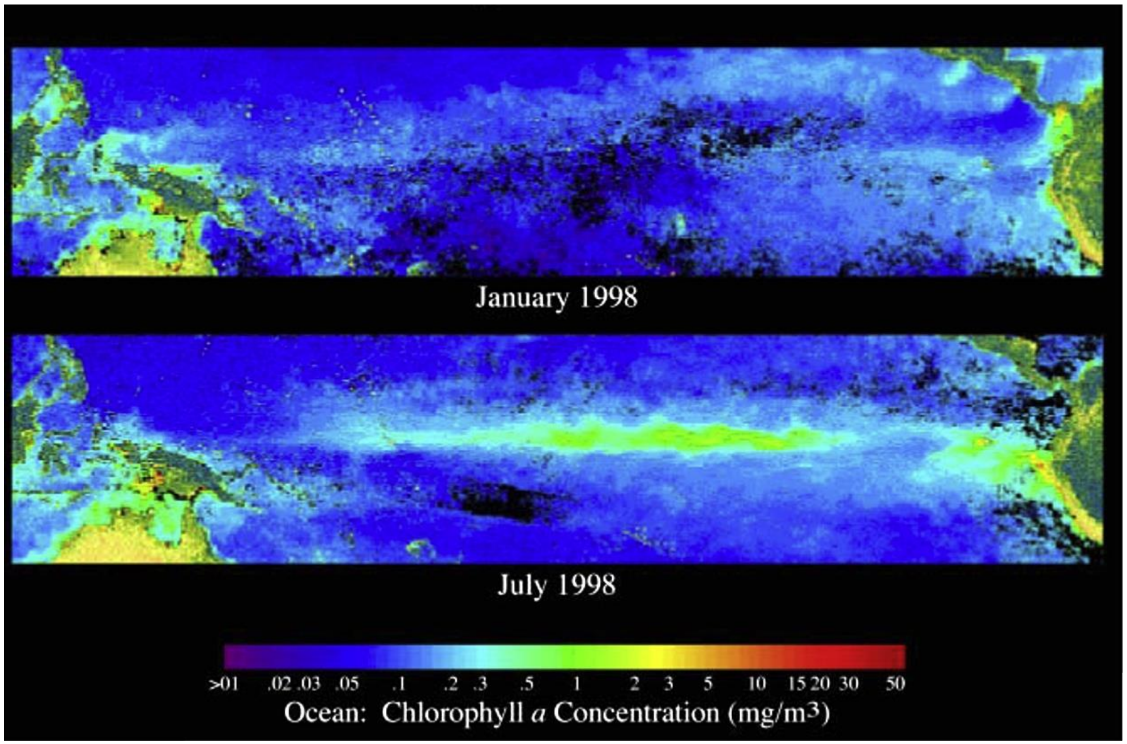
Development of Models (2)

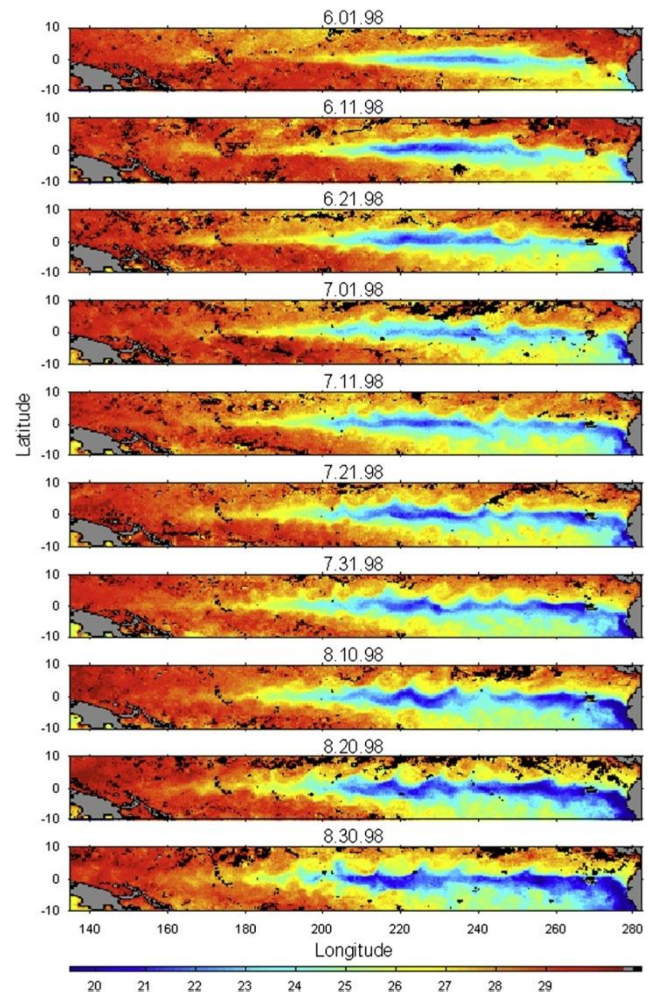


Physical climate variability and the carbon cycle interact strongly

Ocean biological activity, upwelling, carbon outgassing and nutrient transport

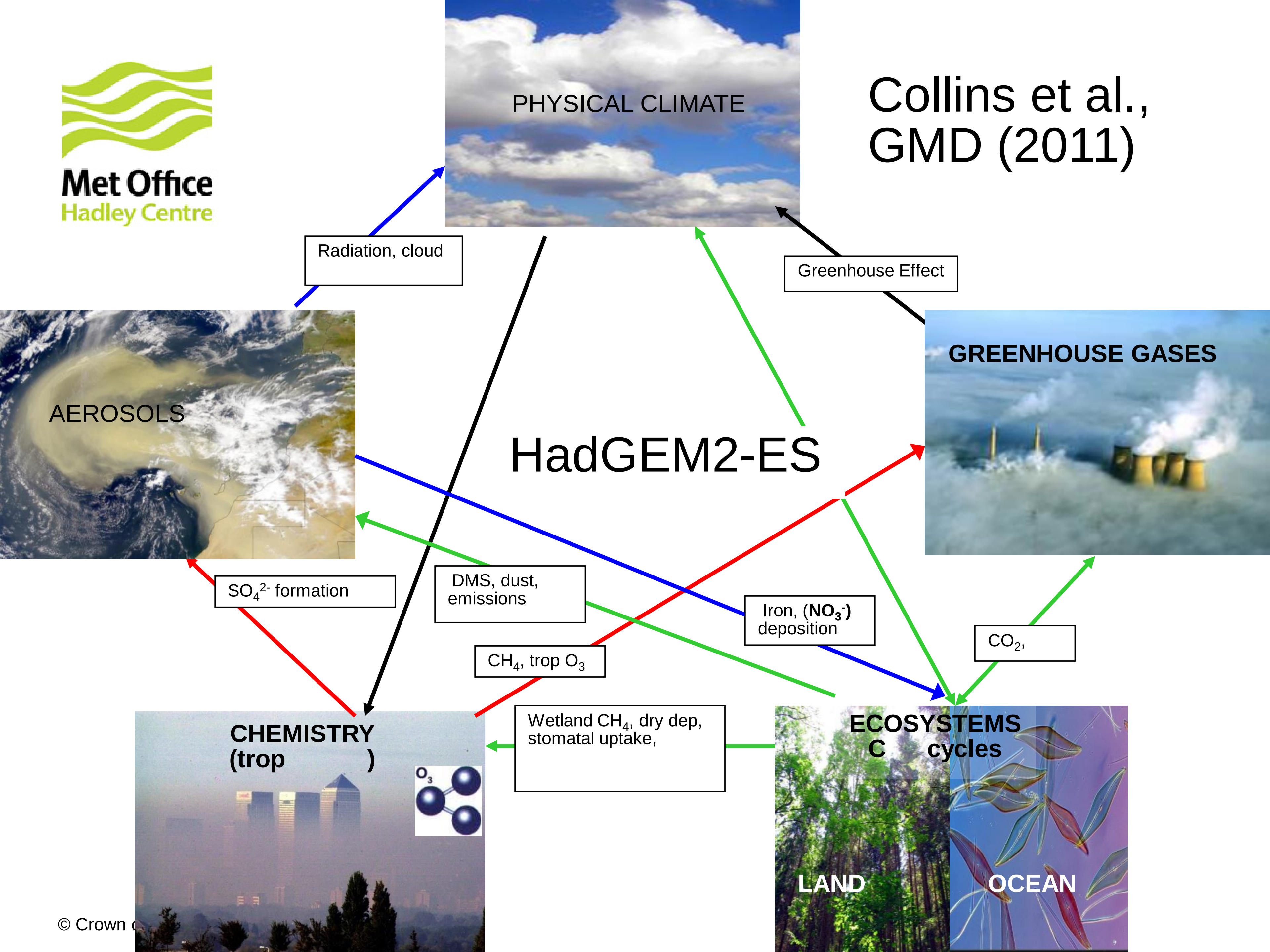
Evolution of summer 1998 La Nina





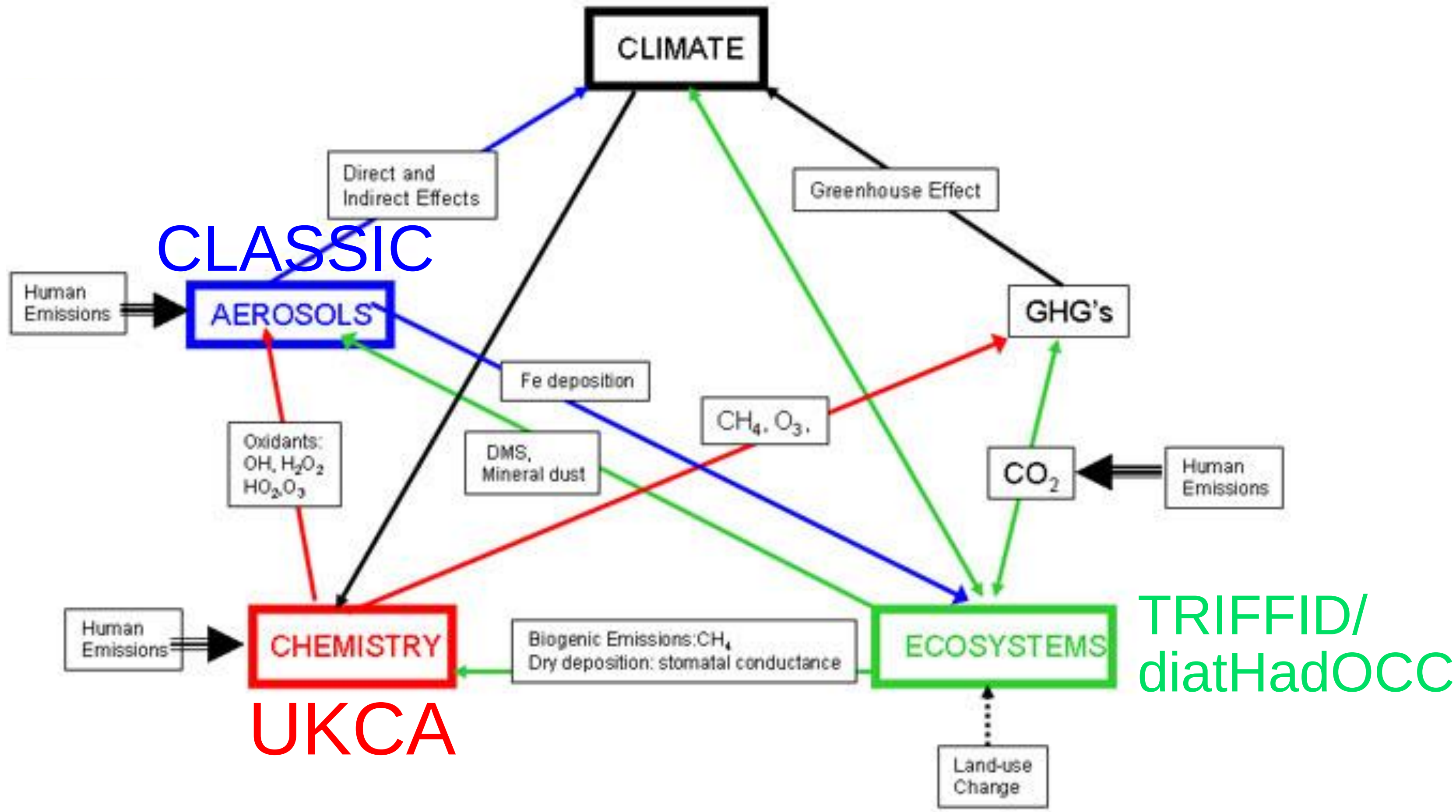
An Earth System Model is only as good as the core physical/dynamical climate model that is simulating underlying climate processes and variability

The Earth System Model HadGEM2-ES



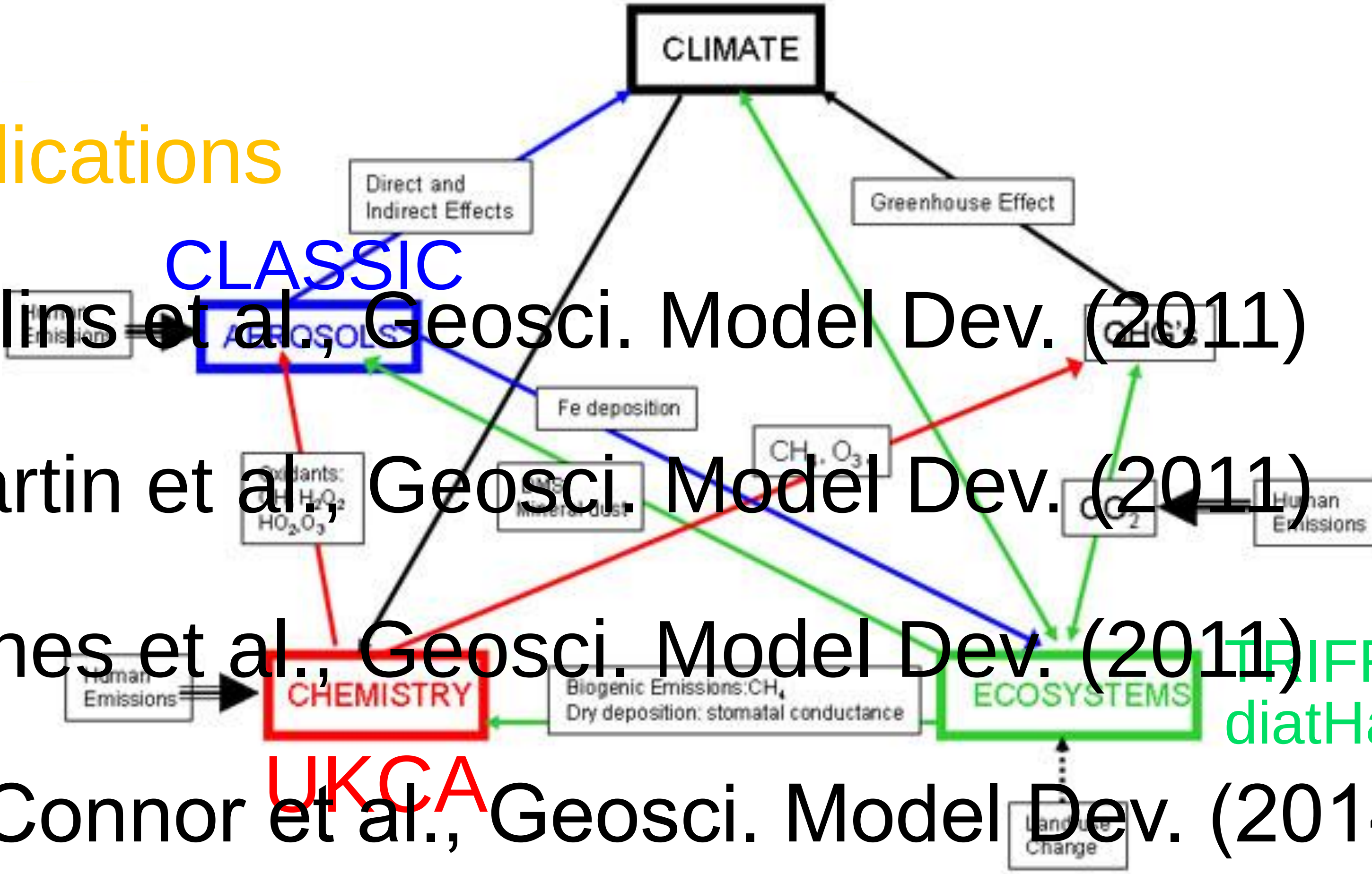
Met Office
Hadley Centre
Collins et al., GMD (2011)
HadGEM2-ES
PHYSICAL CLIMATE
AEROSOLS
GREENHOUSE GASES
CHEMISTRY
(trop)
ECOSYSTEMS
C cycles
LAND
OCEAN
O_3
Radiation, cloud
Greenhouse Effect
SO_4^{2-} formation
DMS, dust, emissions
Iron, (NO_3^-) deposition
CO_2,
CH_4, trop O_3
Wetland CH_4, dry dep, stomatal uptake,
© Crown

The Earth System Model, HadGEM2-ES



The Earth System Model, HadGEM2-ES

Publications



CLASSIC

- Collins et al., Geosci. Model Dev. (2011)
- Martin et al., Geosci. Model Dev. (2011)
- Jones et al., Geosci. Model Dev. (2011)
- O'Connor et al., Geosci. Model Dev. (2014)

TRIFFID/ diatHadOCC

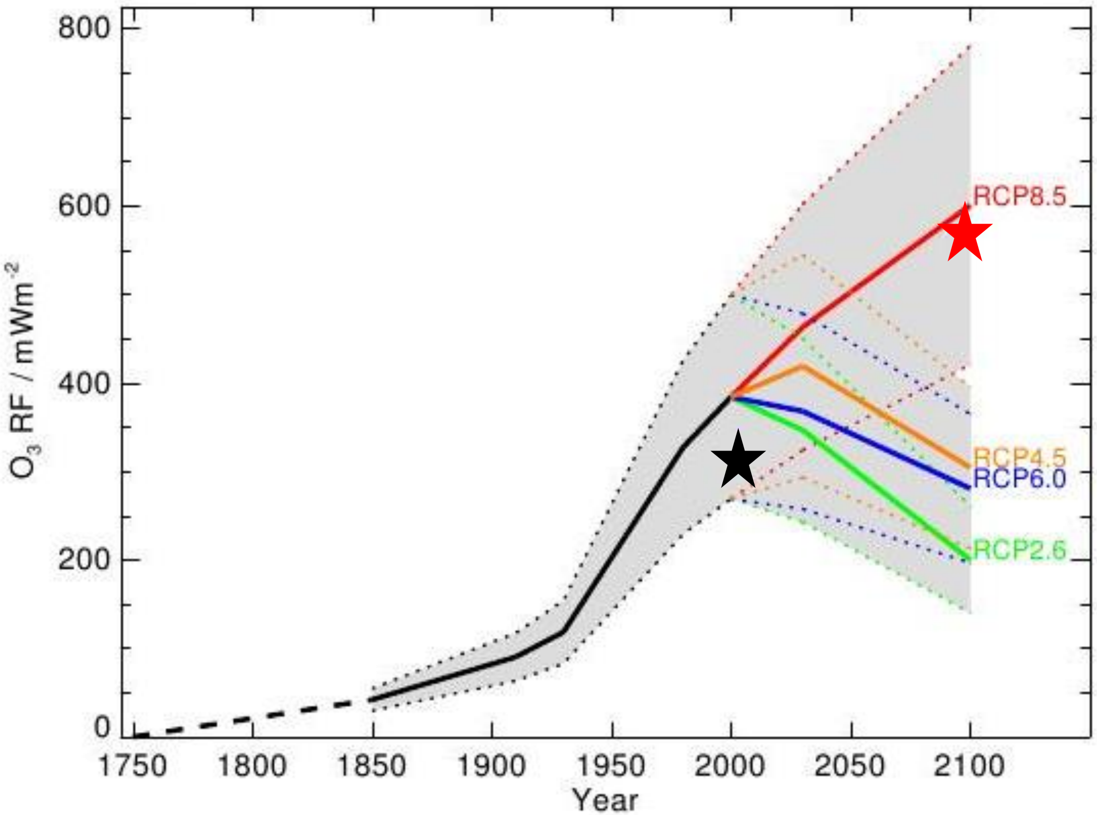
UKCA

Met Office
Hadley Centre

Science Highlights involving HadGEM2-ES

ACCMIP: Radiative Forcing by Tropospheric Ozone

Tropospheric O_3 forcing



Multi-model study called Atmospheric Composition and Climate Model Intercomparison Project (ACCMIP)

★ HadGEM2-ES

Stevenson et al., ACP (2013)

Megacities: HadGEM2-ES with ExtTC (1)

Species	2005		2050	
	Base	Megacities	Base	Megacities
Long-lived greenhouse gases[a]				
CO_2 ($Tg\ yr^{-1}$)	32,250.0	3870.0 (12%)[b]	68,280.0 (+112%)[c]	8194.0 (+112%)
CH_4 ($Tg\ yr^{-1}$)	321.4	22.5 (7%)	676.8 (+110%)	47.4 (+111%)
N_2O ($Tg\ yr^{-1}$)	8.0	0.3 (4%)	20.1 (+150%)	0.8 (+151%)
Short-lived climate forcers[d]				
NO_x ($TgN\ yr^{-1}$)	43.4	2.0 (5%)	37.1 (−15%)	0.8 (−60%)
CO ($Tg\ yr^{-1}$)	1080.4	35.8 (3%)	948.4 (−12%)	23.0 (−36%)
SO_2 ($TgS\ yr^{-1}$)	28.5	1.5 (5%)	13.2 (−54%)	0.5 (−66%)
BC ($Tg\ yr^{-1}$)	6.6	0.3 (5%)	4.5 (−32%)	0.1 (−66%)
OC ($Tg\ yr^{-1}$)	34.2	1.0 (3%)	28.0 (−18%)	0.7 (−30%)

[a] Based on EDGAR4.0 emission inventory.
[b] Percent contribution of megacities.
[c] Change in emissions relative to present-day level (reference year 2005).
[d] Based on CMIP5 RCP8.5 emission scenarios European Commission (2009).

relative change at present-day: contribution of megacities.

relative change in future: change from present-day.

Folberth et al., Urban Climate (2012)

Megacities: HadGEM2-ES with ExtTC (2)

Species	2005 DRF ($mW\ m^{-2}$)	2050 DRF ($mW\ m^{-2}$)
DRF from megacity emission of long-live greenhouse gases		
CO_2 (tot AMTOA)	+120.0	+254.0
CH_4 (tot AMTOA)	+28.4	+59.8
N_2O (tot AMTOA)	+3.3	+8.8
Total forcing long-lived (AMTOA)	+151.7	+322.6
DRF from megacity emissions of short-lived climate forcers		
CH_4 (tot AMTOA)	−1.9 ± 0.04	−0.7 ± 0.02
O_3 (tot AMTOA)	+5.7 ± 0.02	+2.8 ± 0.02
SW_{as} (tot AMTOA)	−6.1 ± 0.21	−2.2 ± 0.10
LW_{cs} (tot AMTOA)	+1.5 ± 0.01	+0.6 ± 0.01
Total forcing short-lived (AMTOA)	−0.8 ± 0.24	+0.5 ± 0.09
Combined direct radiative forcing		
Total forcing (AMTOA)	150.9 ± 0.24	323.1 ± 0.09

With $\lambda \sim 1.0\ K/(Wm^{-2})$ it follows:

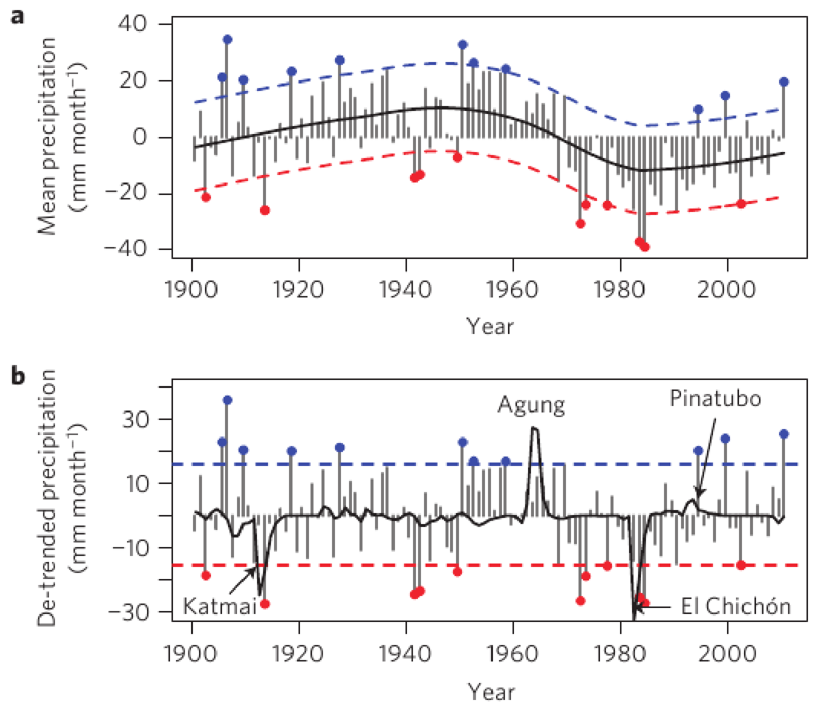
- in 2005: $\Delta T_{sfc}^{equil} \approx 151$ mK
- in 2050: $\Delta T_{sfc}^{equil} \approx 323$ mK

$\Rightarrow \Delta T_{sfc}^{equil,(2005\text{-}2050)} \approx 172$ mK

+800 mK global surface warming since the pre-industrial.

Folberth et al., Urban Climate (2012)

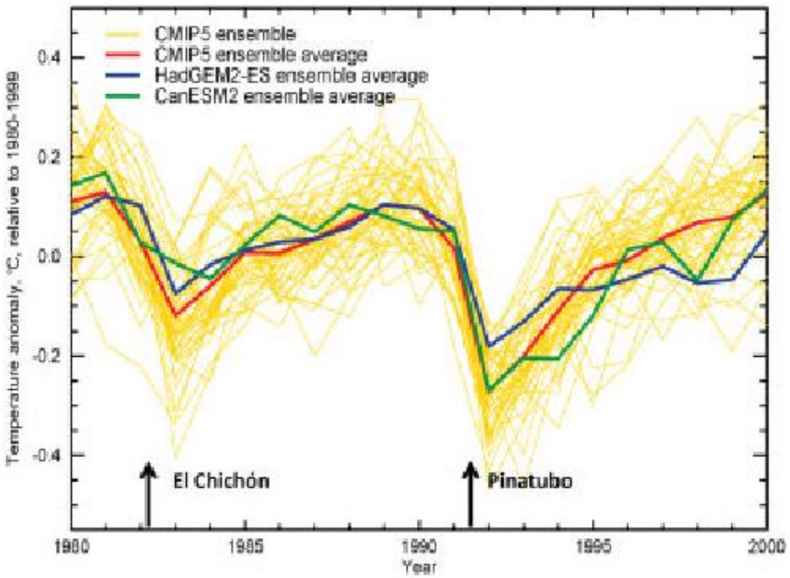
Volcanic Eruptions: Sahel Rainfall

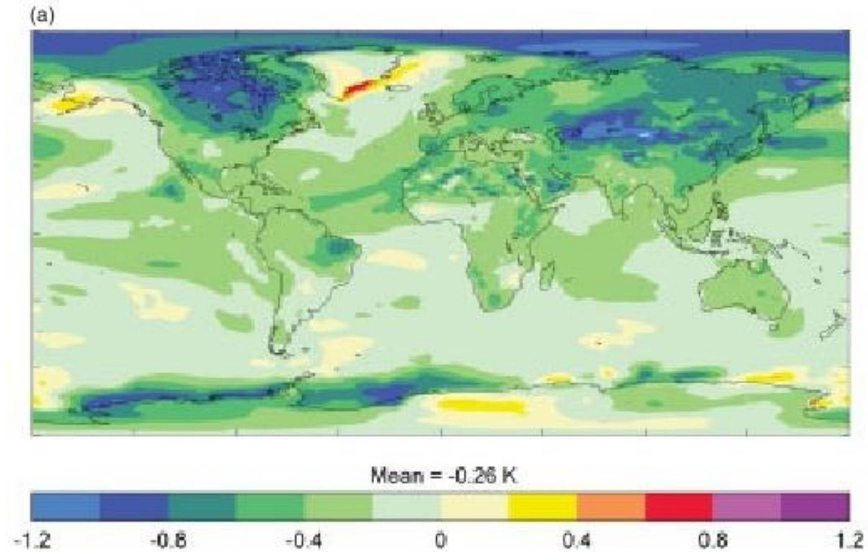


Three of the four driest Sahelian summers were preceded by substantial Northern Hemisphere volcanic eruptions

Haywood et al. (2013)

Volcanic Eruptions: Role in Global Warming Hiatus?



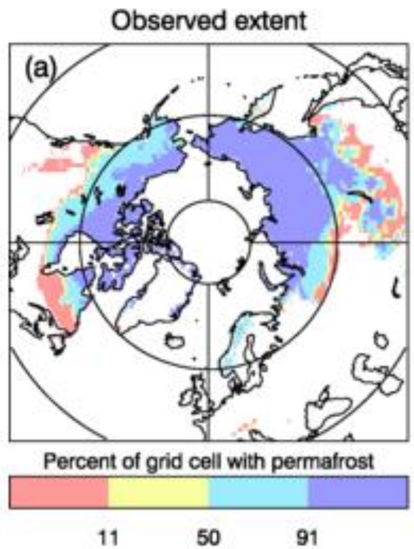


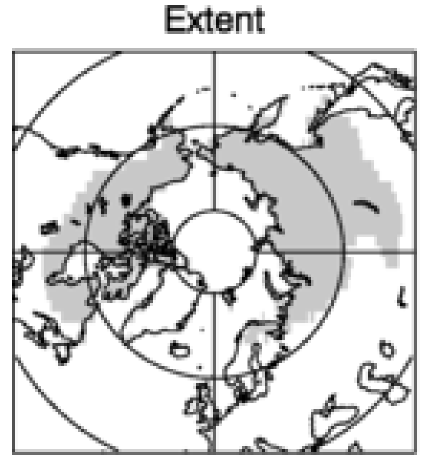
Modest volcanic eruptions since 2000 give rise to a global mean cooling of around −0.02 to −0.03 K over the period 2008–2012. They do not appear to be the primary cause of the recent global warming hiatus.

Haywood et al. (2014)

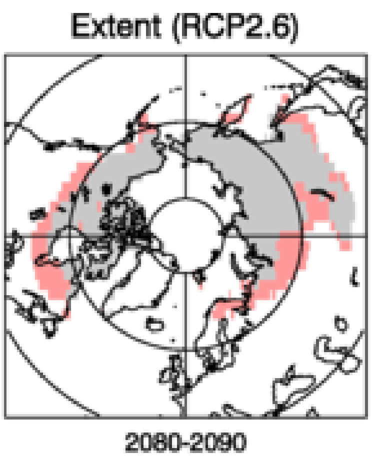
Permafrost Climate Feedback (1)

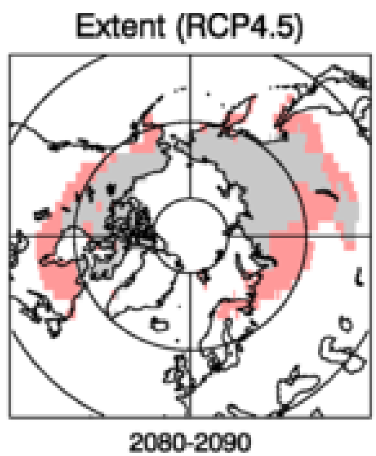
Observed

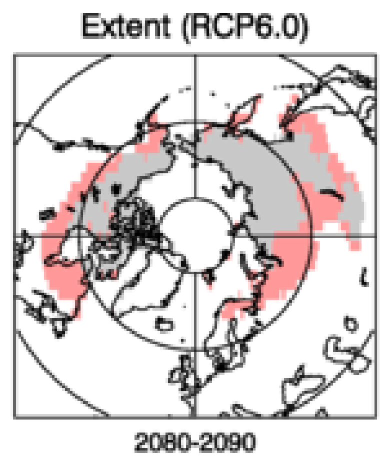


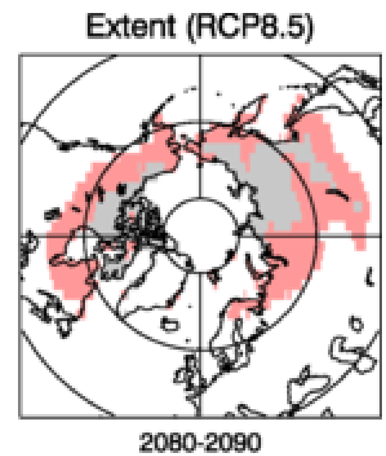


HadGEM2-ES present day



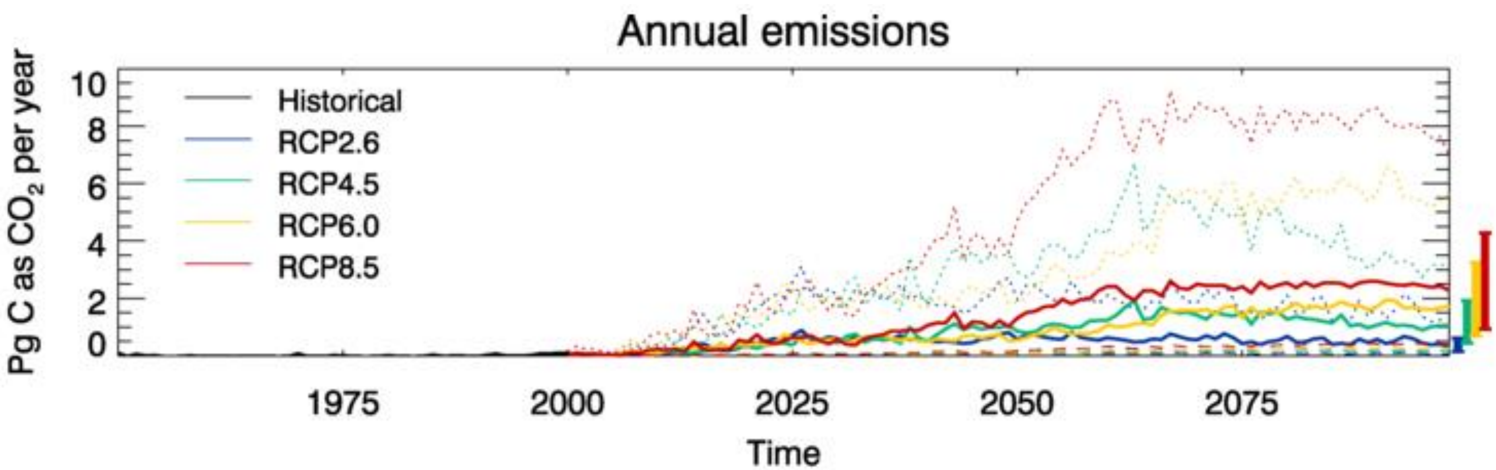




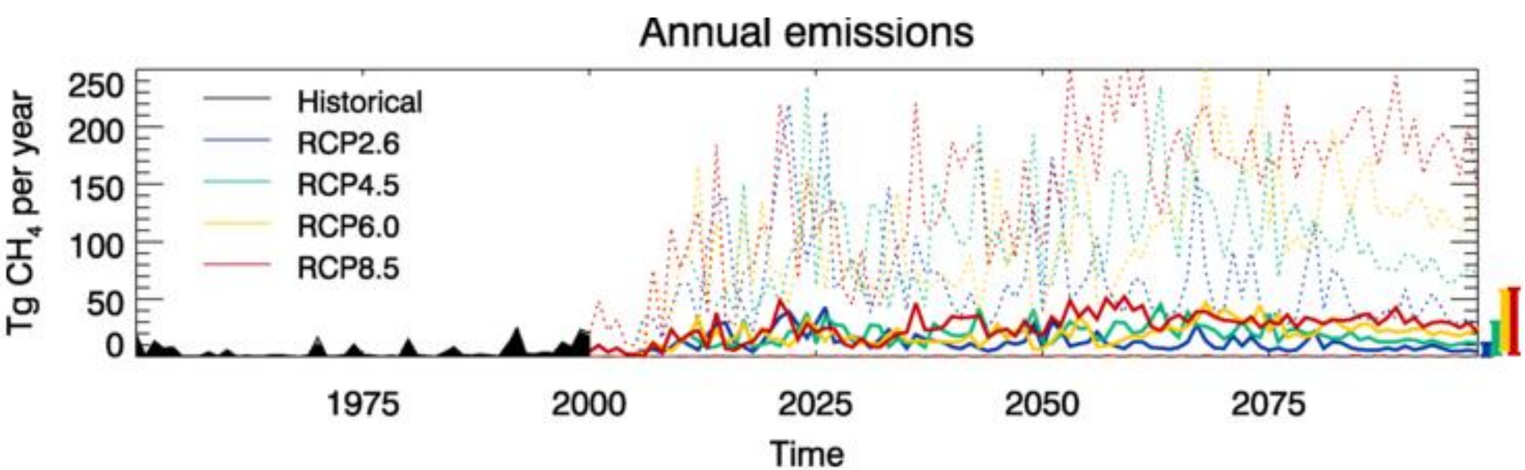


HadGEM2-ES projections for the 2080's. Pink shows areas where permafrost is lost.

Permafrost Climate Feedback (2)



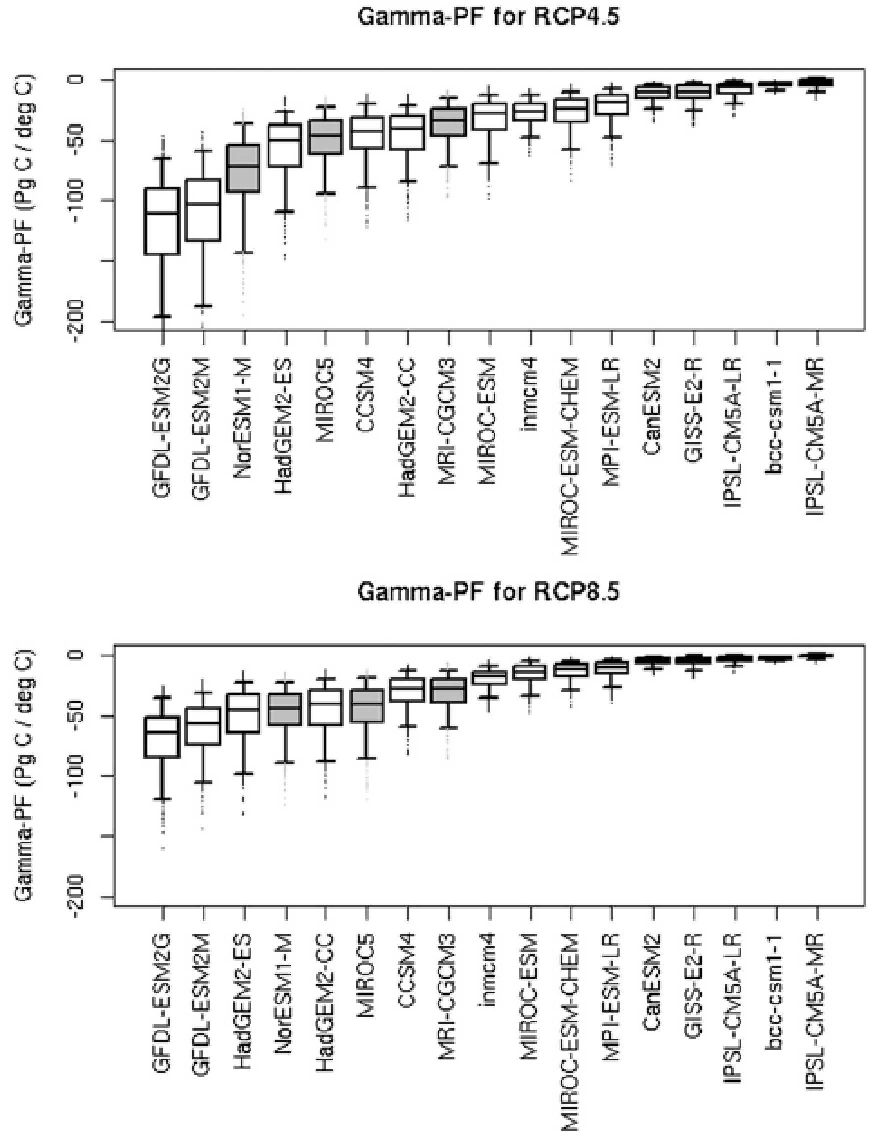
CO_2 emissions in Pg carbon per year



CH_4 emissions in Tg CH4 per year

Burke et al., Cryosphere, 2012

Permafrost Climate Feedback (3)

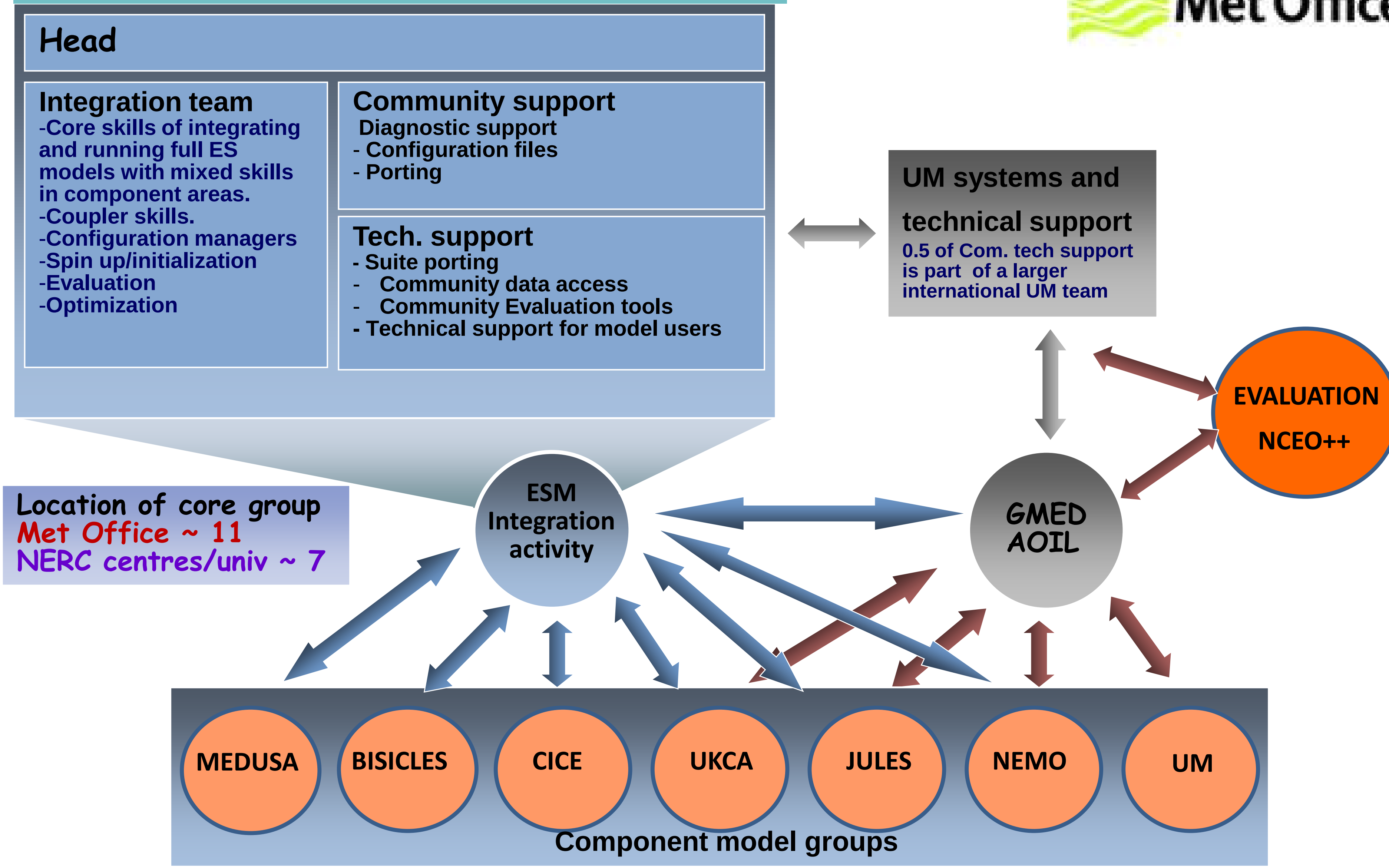


Permafrost-carbon climate response (γ_{PF}) from CMIP5 models

Burke et al., J. Climate, 2013

Next Generation ESM: UKESM1

UKESM Core Group



The core group integrates component developments into a full ESM

Planned development versions

- UKESM0.4: HadGEM3-GC3 + major ESM capabilities
  - UKCA: StratTrop chem, GLOMAP-mode with modal dust
  - JULES-C: + nitrogen cycle, BVOC emissions, 9 PFTs, dynamic vegetation (TRIFFID), diagnostic fires
  - MEDUSA ocean biogeochemistry: CO_2 & DMS coupling to UKCA
  - Aiming for completion Dec 2015, building now.
- UKESM0.5: Last window for **planned** science changes
  - Nitrate aerosol *(may now come post-UKESM1),* remaining couplings, other (minor) sci/tech developments
  - Aiming for completion Feb 2016, to allow 6-8 months for tuning / "reactive development".
- UKESM1.0: Ready for CMIP6 production Autumn 2016
- UKESM1.0-IS: BISICLES ice sheet model included early 2017

Low-resolution UKESM1-lr

The resolution for UKESM1-lr has been selected as:

Atmosphere: N96 (~130km)

Ocean: 1 degree

N96 atmosphere is more expensive than we would like.
N48 was investigated but performance was not acceptable

Can get ~5 simulation years / day with UKESM1-lr using O(1000 cores)

We plan to develop a UKESM1-lr-fast once UKESM1-lr is released.

“Fast” will come from; e.g. *longer dynamical and radiation time steps, reduced call frequency of UKCA and MEDUSA, simplified processes (e.g. grouped tracer advection).* A number of these are being actively worked on now.

“UKESM1-LR-Fast” performance will be judged against UKESM1-lr

UKESM1-hybrid

Full complexity UKESM1 is expensive at N216/ORCA0.25. A hybrid resolution UKESM is under development: GC3 physical model core at N216/ORCA0.25, UKCA-GLOMAP and MEDUSA interactively coupled and run at ~N96/1.0°

- Two versions of UM atmosphere component
  - Junior N96: low-resolution – UM and UKCA-GLOMAP
  - Senior N216: high-resolution – UM only and coupled to ocean, sea-ice,
- Senior and Junior UMs coupled by exchanging 3D fields
  - Senior sends aggregated physical atmospheric state to Junior every time step, constraining Junior's climate to follow Senior
  - Junior runs UKCA using this *Senior-locked climate* and sends trace gas and aerosols back to Senior every hour for use in radiation and clouds
- Separation of versions allows for better scaling (separate UM executables)
- In principle applicable to any (supported) resolution combination

Conclusions

Concluding Remarks

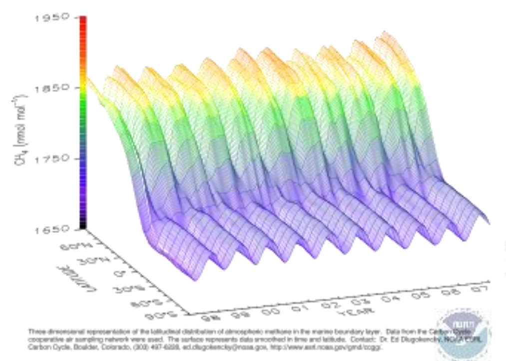
- The Earth System and Climate Change Mitigation
- Motivation behind studying Earth System Science
- Development of Climate Models into Earth System Models
- The HadGEM2-ES Earth System Model
- Science Highlights involving HadGEM2-ES
- Brief overview of the next generation ESM: UKESM1

Thank you for listening!
Any questions?

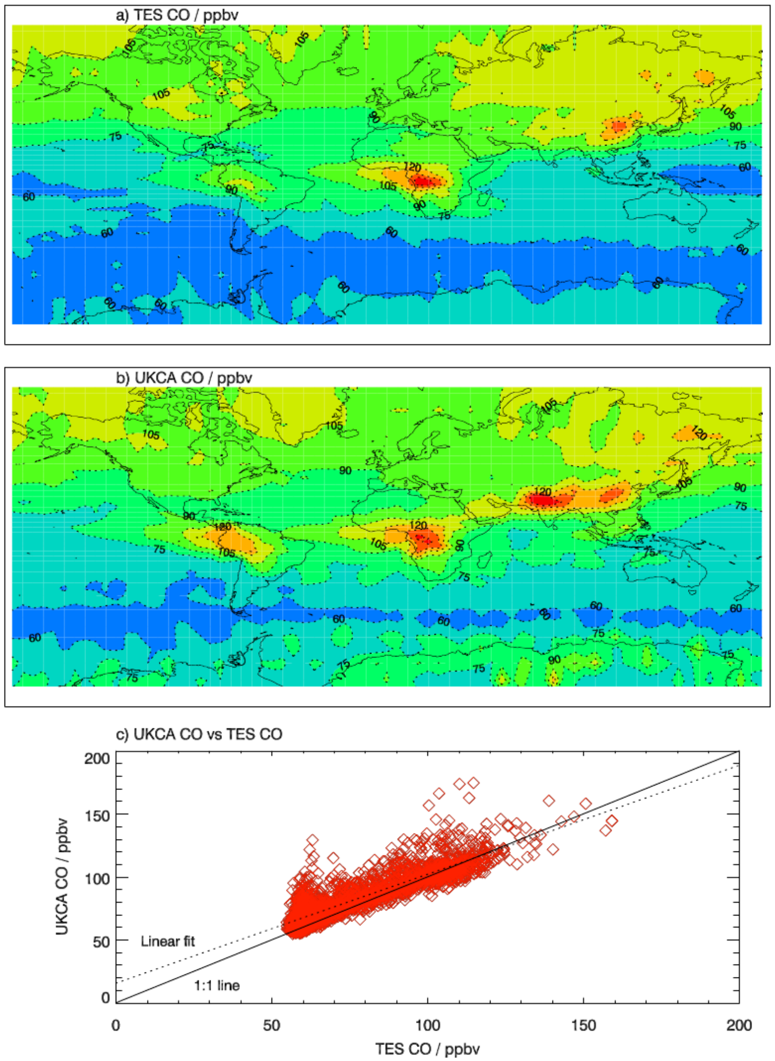
Extra slides

Tools (7): Observations

- Surface measurements
- Aircraft/Balloon measurements
- Ship measurements
- Remote sensing



Use of Observations: Model Evaluation



Example of using satellite observations to evaluate the performance of the UKCA model

O'Connor et al. (2014)