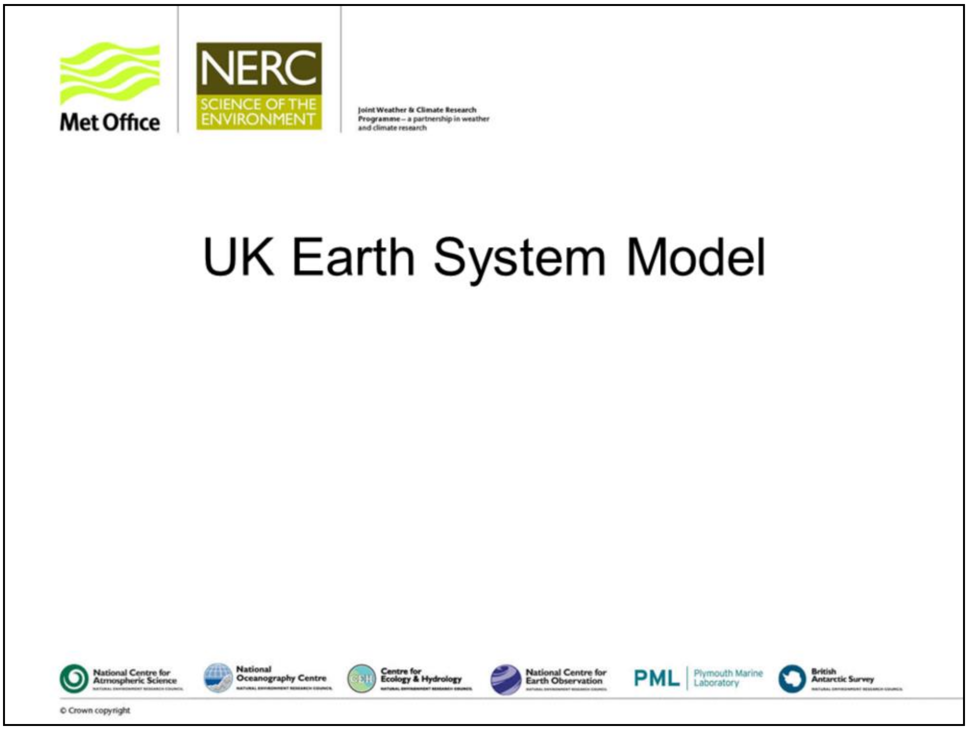
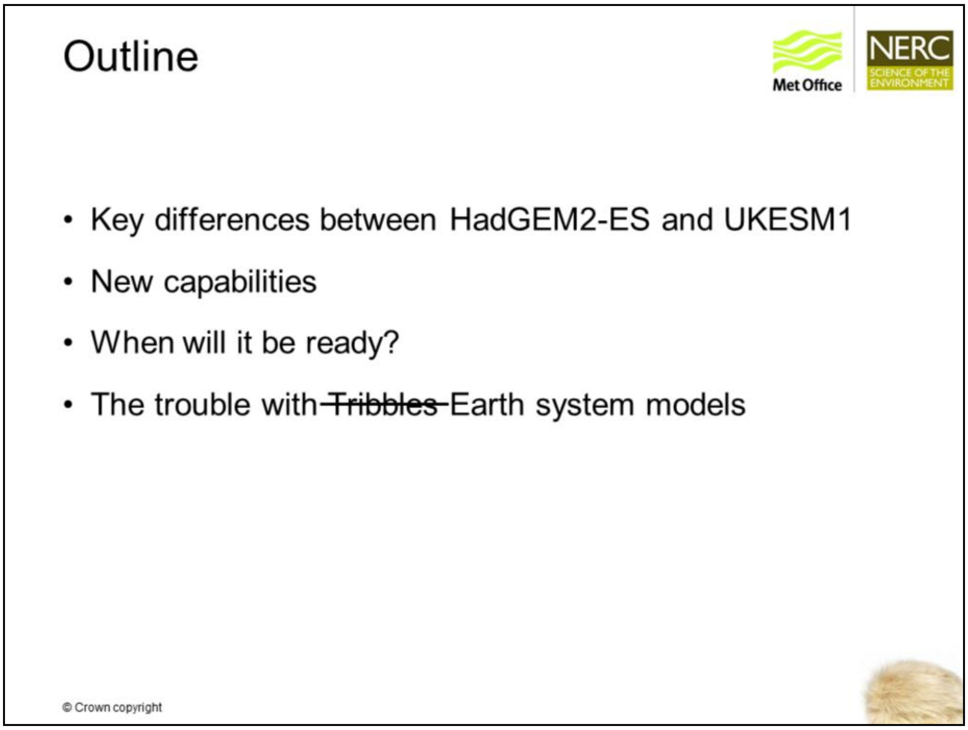


In the last presentation, Fiona has just given us a great overview of Earth system modelling and I don’t need to cover foundations anymore.

We have also heard details about our current flagship science tool HadGEM2-ES.

Over the next 45 minutes or so I will introduce to you the next generation ESM and successor to HadGEM2-ES for the UK community – aptly but boringly called the UK Earth System Model.

This is an ongoing effort and UKCA will be a central component in this new science tool again.



In this presentation I will cover four different topics:

First, I will outline the main differences between the current science tool of choice, namely HadGEM-2 and the future community tool UKESM1.

Then I will outline the new capabilities that are planned for UKESM1.

I will discuss the timeline of development and launch and finally

I will discuss a few of the main issues that Earth system modelling presents to the developer and user.

ESM Core Group: who are we?

JWCRP – a partnership in weather and climate research

1. Head: Colin Jones (NERC/NCAS) *
2. Science Manager (MO) Alistair Sellar*
3. Aerosol-clouds-radiation (MO): Jane Mulcahy*
4. Dust-radiation-vegetation (MO): Steph Woodward*
5. Land/veg JULES expertise (CEH): Rich Ellis
6. Ocean Biogeochemistry (NOC): Julien Palmieri
7. Ice Sheet expertise (NCAS): Robin Smith
8. Atmospheric chemistry-aerosols (MO):Colin Johnson*
9. Atmospheric chemistry coupling to ocean/land (NCAS): Steve Rumbold*
10. UKESM-LO Configuration manager (NCAS): Till Kuhlbrodt
11. UKESM-HI Configuration manager (MO): Yongming Tang*
12. Technical Manager (MO): Jeremy Walton*
13. Common data & Evaluation tools (NCAS): Simon Read
14. Coupling and Optimization (MO): Richard Hill*
15. Coupling and Optimization (NCAS): Marc Stringer*
16. Responsible for ROSE suites for UKESM (MO): Yet to be appointed*

•Indicates based at MOHC in Exeter, otherwise people based at NCAS-Reading, NOC & CEH

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This slide is an overview of the people who are responsible for the UKESM development.

I just included this slide for the handouts to provide a who-is-who of the team.

HadGEM3 and UKESM1

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	Physical climate model	Earth system model
CMIP5	HadGEM2-AO	HadGEM2-ES
CMIP6	HadGEM3-GC3 HadGEM3-GC4 Developed by UK Met Office (with input from UM partners and UK universities)	UKESM1 Jointly developed by UK Met Office and UK universities Physical core = HadGEM3-GC3 UKESM-HI = N216/ORCA025 UKESM-LO = N96/ORCA1 (or lower)

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Lets start with working out the main differences between the current and the next generation ESM.

At the very top level the two ESMs can be distinguished by their physical core and the selection of ES-components.

As Fiona just showed HadGEM2-AO (the atmosphere-ocean configuration) was used as the physical climate model in the last Coupled Model Intercomparison Project Phase 5.

The Earth system model configuration including a land surface component, an ocean biology component, a chemistry component and aerosol component and was build on top of HadGEM2-AO.

The next generation ESM is based on HadGEM3-GC3 where “GC3” refers to a specific version in time of the “global coupled” physical model configuration.

Importantly, there will be a high-resolution and a low-resolution model configuration available.

Key differences from HadGEM2-ES

- Firstly: it's not (only) a Met Office model:
  - UKESM is being developed jointly by the NERC and the Met Office,
  - using shared community models (UKCA, JULES, NEMO),
  - led by a joint NERC-Met Office "ESM core group" of 16 modelling scientists and software scientists.
- ESM core group includes staff from Met Office, NCAS, CEH and NOC,
  - based in Exeter, Reading, Wallingford and Southampton.

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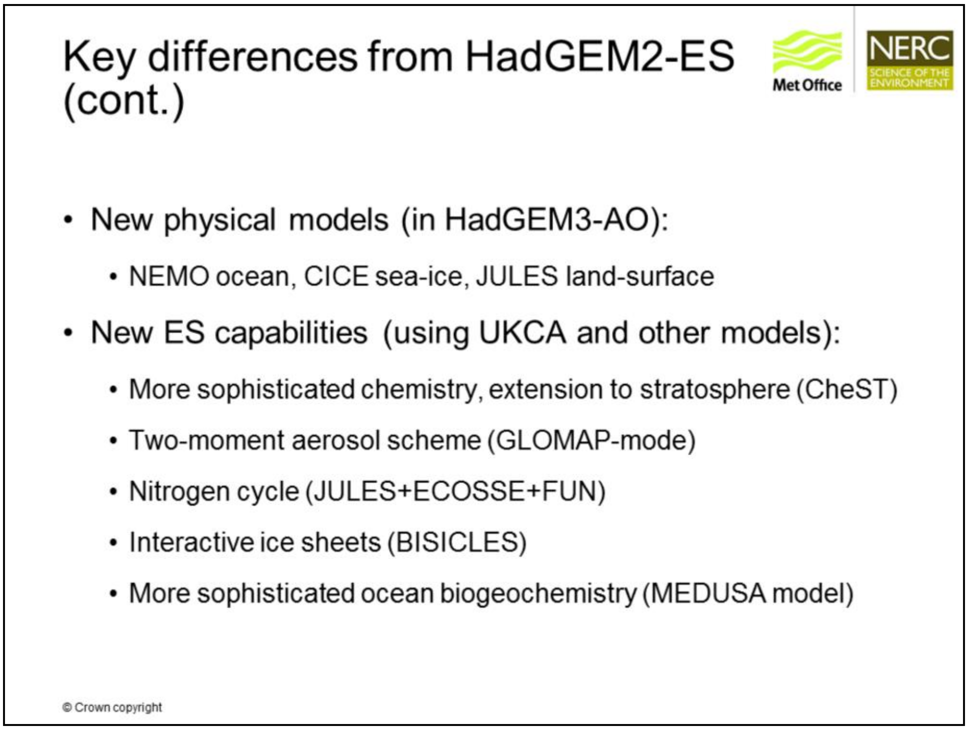
Looking at the main differences between HadGEM2-ES and UKESM1 in more detail there are differences in terms of components and the model development process.

UKESM1 is a "community model" which means that it is being built jointly between the NERC community and the Met Office.

UKESM1 is developed using community models – NEMO, JULES and UKCA as the atmospheric chemistry and aerosol component.

The development of UKESM1 is led by a core group of Met Office and NERC scientists that are predominantly based in Exeter to facilitate collaboration.

Note: NOC is the "National Oceanography Centre".



UKESM1 represents the next generation ESM and, thus, features a number of new capabilities.

There have been changes on the physical side – the ocean model, the new land surface scheme, the sea ice model.

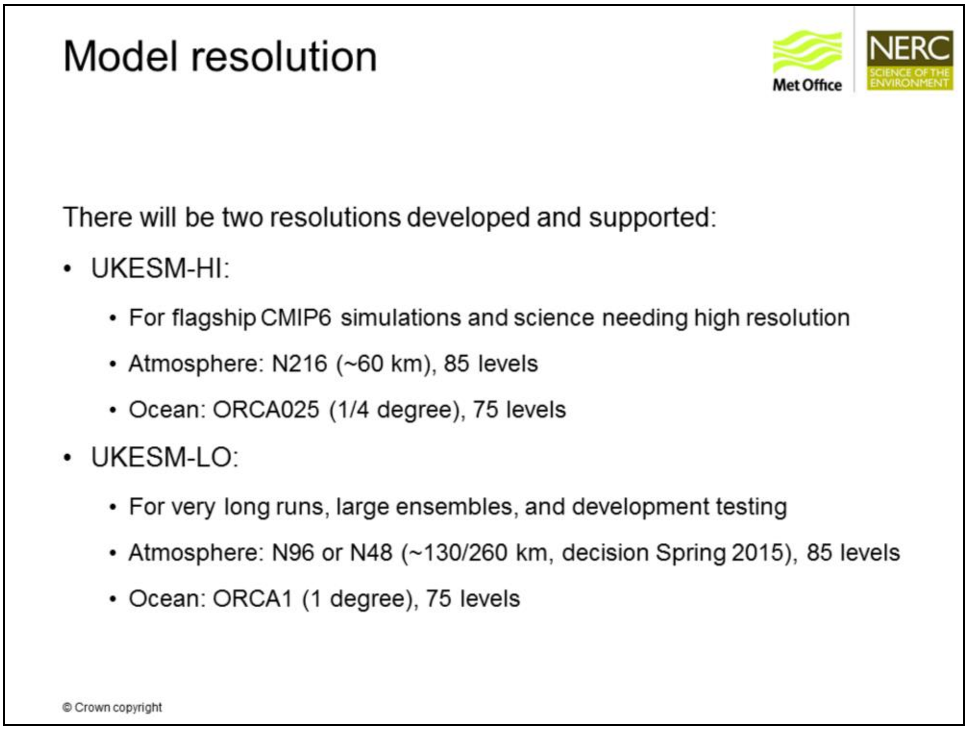
But the main changes and upgrades relate to the ES-components.

UKESM1 will see major changes to UKCA with the introduction of a whole-atmosphere chemistry.

We will also switch to GLOMAP-mode as the new aerosol scheme which links chemistry and aerosols much closer together.

UKESM1 will also include an interactive nitrogen cycle in the land surface scheme rendering plant physiology much more realistic.

The interactive ice sheet model BISICLES and a more sophisticated ocean biogeochemistry model will also be included.



UKESM1 also represents a substantial step forward with regards to model resolution.

There will be two versions available – a high resolution version of UKESM1 with ~60km resolution at the equator and 85 altitude levels extending to the mesopause (up 85km).

Note that these level are not equally stacked – there are more levels per km altitude nearer to the surface.

UKESM-HI will be used in CMIP6 as the flagship model.

A lower resolution version – UKESM-Lo – will also be created with the same number of level and vertical extension as UKESM-HI but a reduced horizontal resolution.

UKESM-LO is aimed at very long integrations, large ensembles and to provide a more efficient tool for development and testing of new processes and science.

The final decision on the horizontal resolution of UKESM-Lo will be made in Spring this year.

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Joint Weather & Climate Research Programme – a partnership in weather and climate research

New capabilities

Motivation and examples

National Centre for Atmospheric Science · National Oceanography Centre · Centre for Ecology & Hydrology · National Centre for Earth Observation · PML Plymouth Marine Laboratory · British Antarctic Survey

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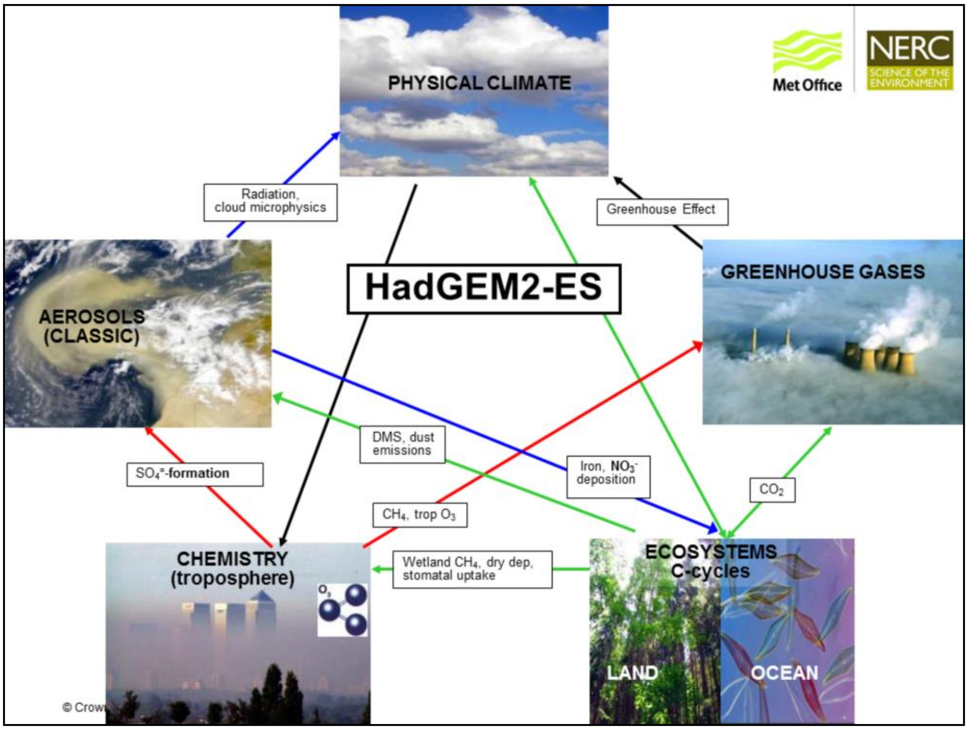
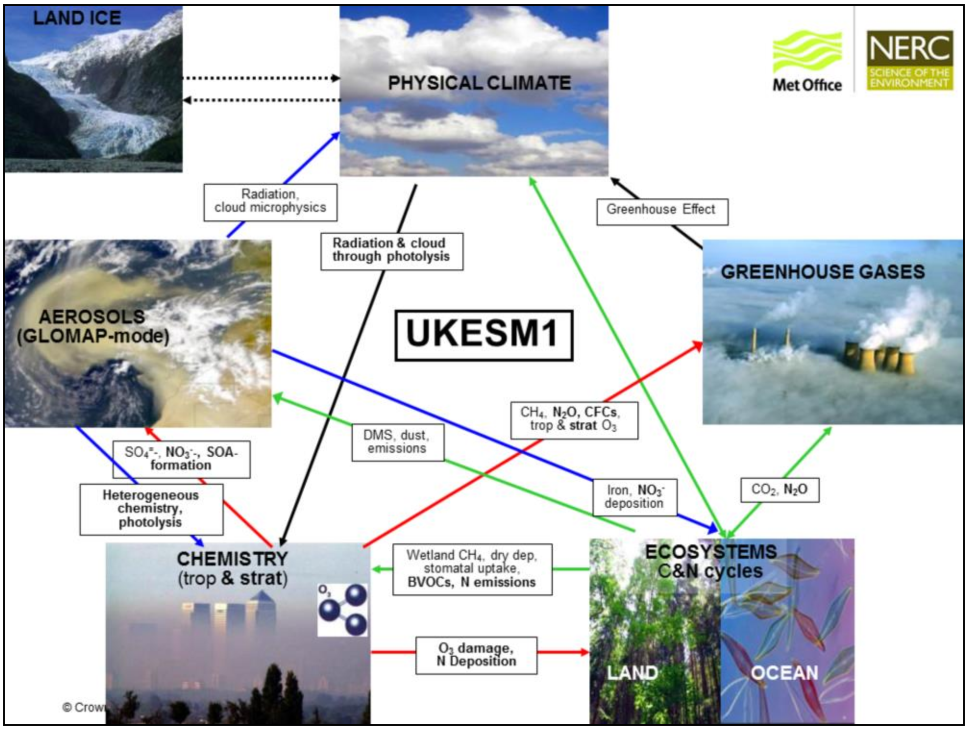


(Basic set of couplings, present in centennial timescale version)

We have seen this diagram already in Fiona's presentation but I want to use it here to work out the differences between HadGEM2-ES and UKESM1.

The schematic shows how the main components in HadGEM2-ES are linked and what is exchanged.

So what are the main changes and upgrades in UKESM1?



(Basic set of couplings, present in centennial timescale version)

In UKESM1 the chemistry will be substantially upgraded to include the stratosphere.

In addition photolysis and heterogeneous chemistry will be interactive, too.

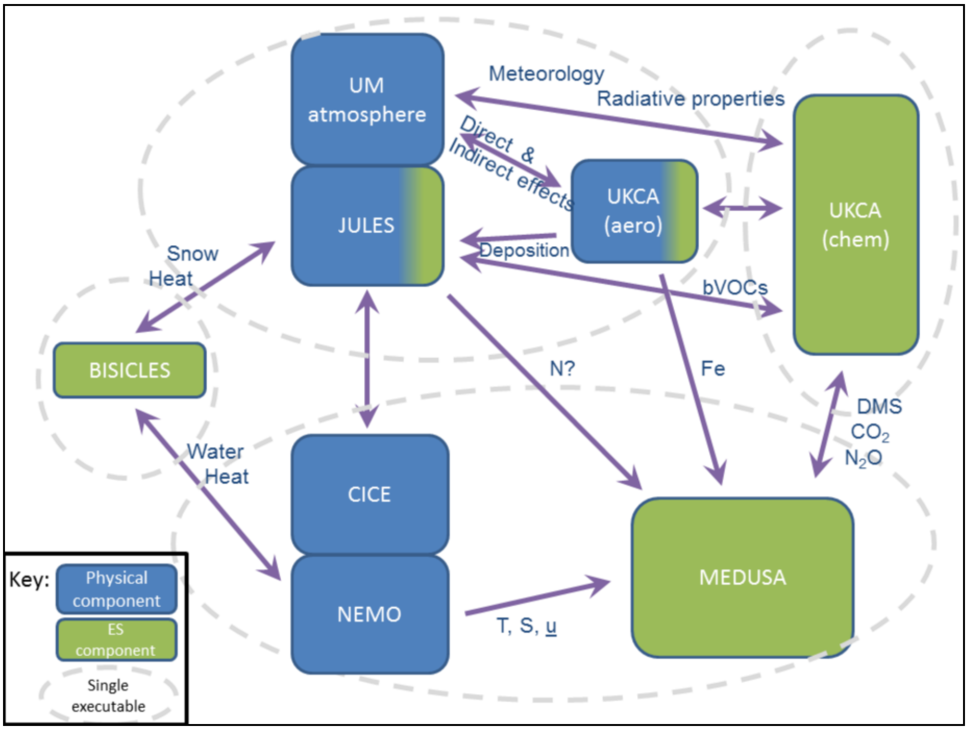
More species will feed from the chemistry into the aerosol component which provides prognostics for both mass and number of aerosols (I'll discuss this later again).

Other capabilities added include a nitrogen cycle in the land surface scheme which can also provide interactive nitrous oxide fluxes and that is important because N_2O is a major greenhouse gas and also plays an important role in stratospheric chemistry.

We now have interactive emissions of biogenic VOC to the atmosphere and we take into account the impact of surface ozone on ecosystems.

Physical climate and chemistry are now closer linked through interactive photolysis which “sees” instantaneous changes in clear-sky radiation and also cloudiness.

I think this concludes the major upgrades but there is of course a lot more detail to all of this than can be included here.



This diagram further separates the model components in “physical” and “Earth system”.

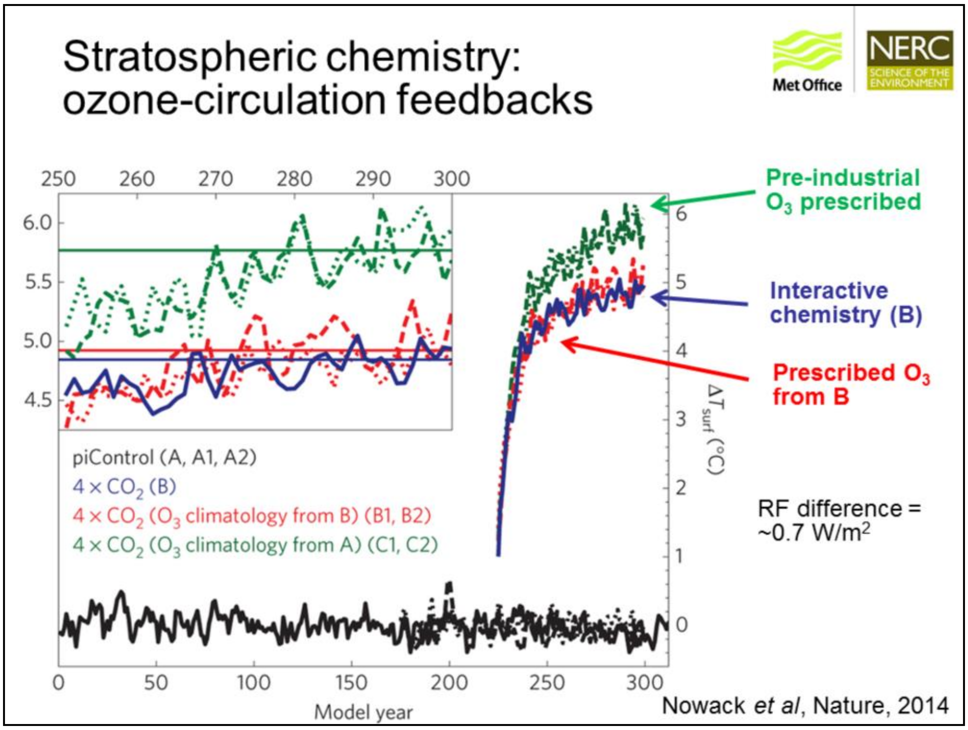
To repeat the definition again: “physical” means part of the climate model, the HadGEM3-GC configuration, the “global coupled” model.

“Earth system” on the other hand refers to components that go beyond the physical climate and include essentially biogeochemical processes and the land-ice model.

The dashed borders mark “single executables”, i.e., these modules could be run in standalone mode.

JULES is an example of a standalone component.

The diagram isn’t entirely correct in where the lines are drawn but are just intended to give a rough idea of where individual processes sit in the grand scheme of things.



In the following slides I am going to provide some motivation for including more processes in the Earth system model.

The first example shows how important the inclusion of stratospheric ozone chemistry can be to correctly projecting future climate.

The plot summarizes a number of different experiments applying an abrupt 4x-CO_2 perturbation 225 years into a 300-year PI control simulation (in black).

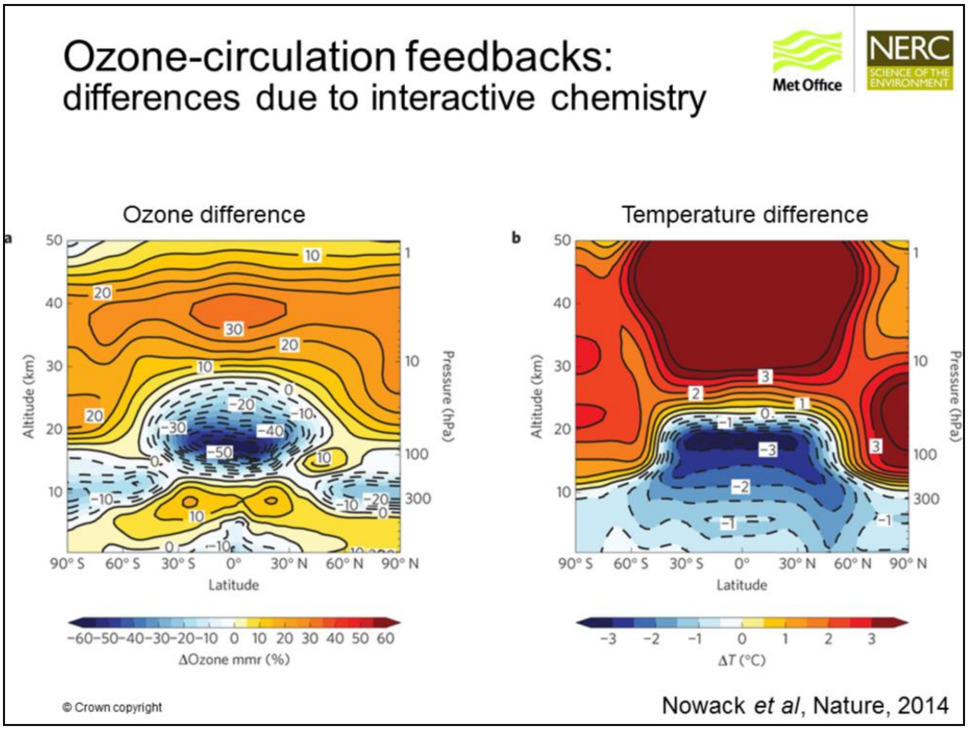
The main difference lies in how stratospheric ozone is treated – interactively or prescribed.

The surface temperature anomalies with respect to the control run are analysed over the final 50 years of the experiments.

In the experiments shown in green an abrupt 4x-CO2 perturbation is applied but stratospheric ozone does not respond to this abrupt change in the radiation budget.

In contrast, the experiment shown in blue includes a fully interactive stratospheric ozone chemistry and the surface temperatures evolution is substantially different.

At the end of the 300-year simulation the surface temperature differs by about one Kelvin between the two experiments due to the ozone-circulation feedback.

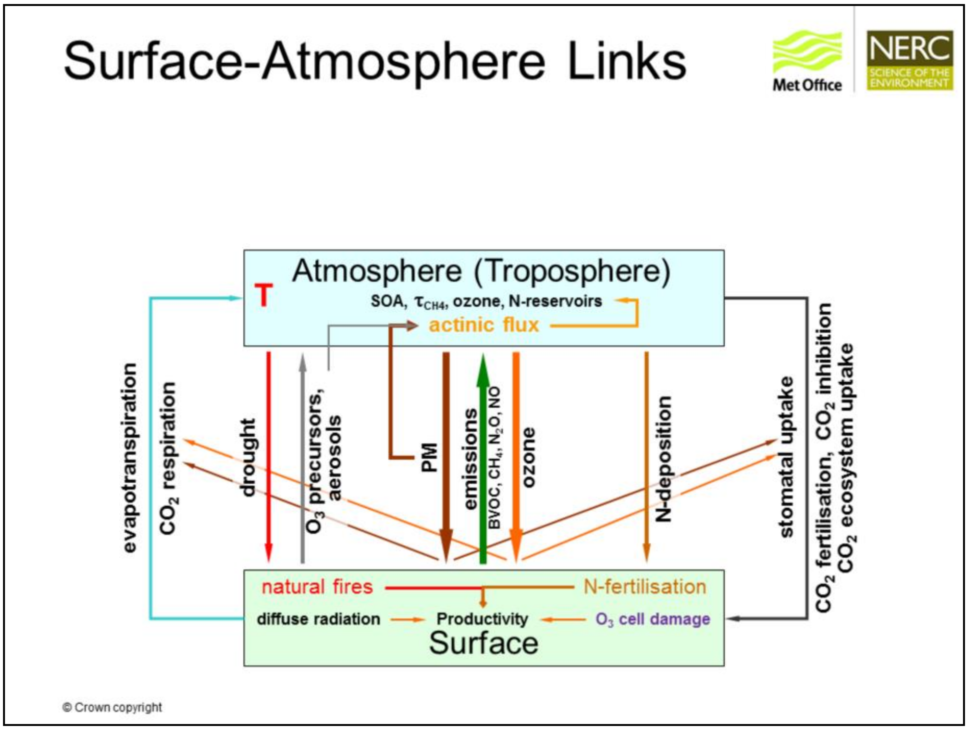


The difference can be attributed primarily to changes in long-wave radiative feedbacks.

These are associated with decreases in tropical lower stratospheric ozone that are driven by changes in circulation.

Other factors include related changes in stratospheric water vapour and changes in cirrus clouds

The result is a stratospheric warming and tropospheric cooling compared to the uncoupled 4x-CO_2 simulations (Nowack et al)



Another example are the numerous that exist between the land surface and the atmosphere.

There are multiple links in both directions that couple the atmosphere and the surface together.

We can see that surface emissions produce not just ozone but also aerosols and other key chemical species.

They affect the lifetime of important greenhouse gases.

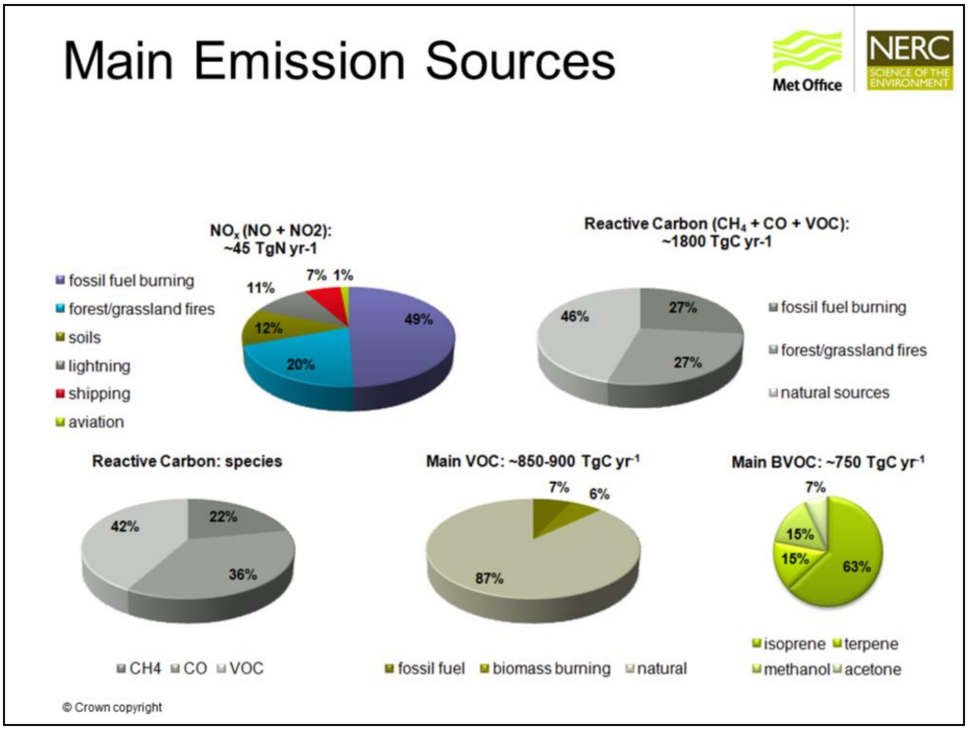
But there are also links in the other direction.

Ozone and CO_2 both affect stomatal uptake thereby modulate ecosystem productivity.

This in turn changes the flux of other gases into and out of plants, most crucially water vapour exchange with the environment.

This has implications for the climate on the local and regional scale through evapo-transpiration and consequently sensible and latent heat fluxes.

I could go on for a while but I am sure you get the idea.



This slide shows an overview of the major emission sources for NO_x and ROCs.

Roughly two thirds of all NO_x emissions at present day are coming from anthropogenic sources.

In contrast to this, up to two thirds of all the reactive carbon emitted comes from natural sources if we split forest and grassland fires in half between natural and man-made sources.

VOCs make up the bulk of reactive carbon species followed by carbon monoxide and methane.

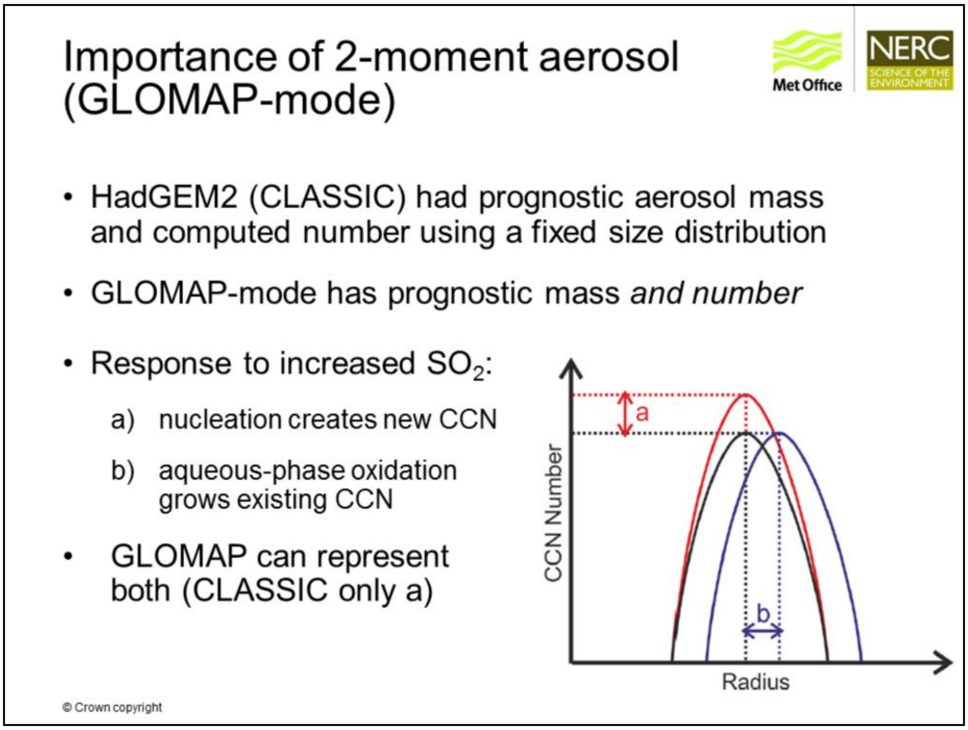
However, almost 90% of the predominant VOC species are of natural origin. In fact, they are emitted by terrestrial ecosystems.

Of those 90% or so natural VOCs almost two thirds are emitted in the form of isoprene alone.

Only four species make up the vast majority of all the natural VOC – roughly 75%.

UKESM1 interactively simulates these natural sources of methane and VOC.

Moreover, the new Earth system model also takes into account the impact of changes in atmospheric composition on ecosystem productivity, such as ozone plant damage.

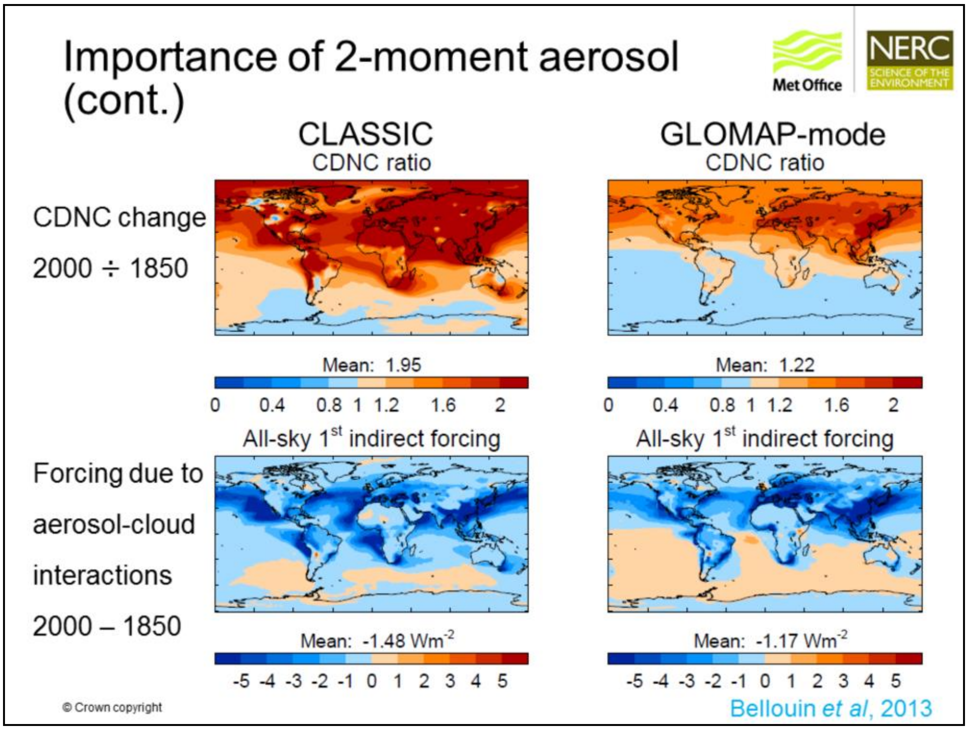


The way aerosols are treated in the model has also markedly changed.

In HadGEM2-ES the CLASSIC aerosol scheme had prognostic aerosol mass but diagnostic number which in addition was based on a fixed size distribution.

The new GLOMAP-mode scheme in UKCA treats both mass and number prognostically.

This means that aerosols can respond to emissions, chemistry and microphysics by either changing the number at a given size or they can change their size independently.



This slide shows the impact of the new aerosol scheme on cloud droplet number concentration in comparison to a simulation using CLASSIC.

The only difference between the two simulations is the aerosol model.

The plots in the upper row show the CDNC-ratio between PI and PD for CLASSIC on the left and GLOMAP-mode on the right.

Similarly, the lower row shows the change in the all-sky 1st indirect forcing between PI and PD for CLASSIC on the left and GLOMAP-mode on the right.

The differences are immediately obvious in both cases.

Nitrogen limitation of carbon uptake by plants

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- HadGEM2-ES (and most CMIP5 ESMs) effectively assumed that plants have limitless nitrogen available for growth
- Thus enhanced CO_2 stimulates more growth (carbon uptake) than if nitrogen was limited
- For UKESM1 we will represent the nitrogen cycle in plants and soil using the FUN and ECOSSE models in JULES

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I want to show you two more examples that outline the importance of the new developments that will be available in UKESM1.

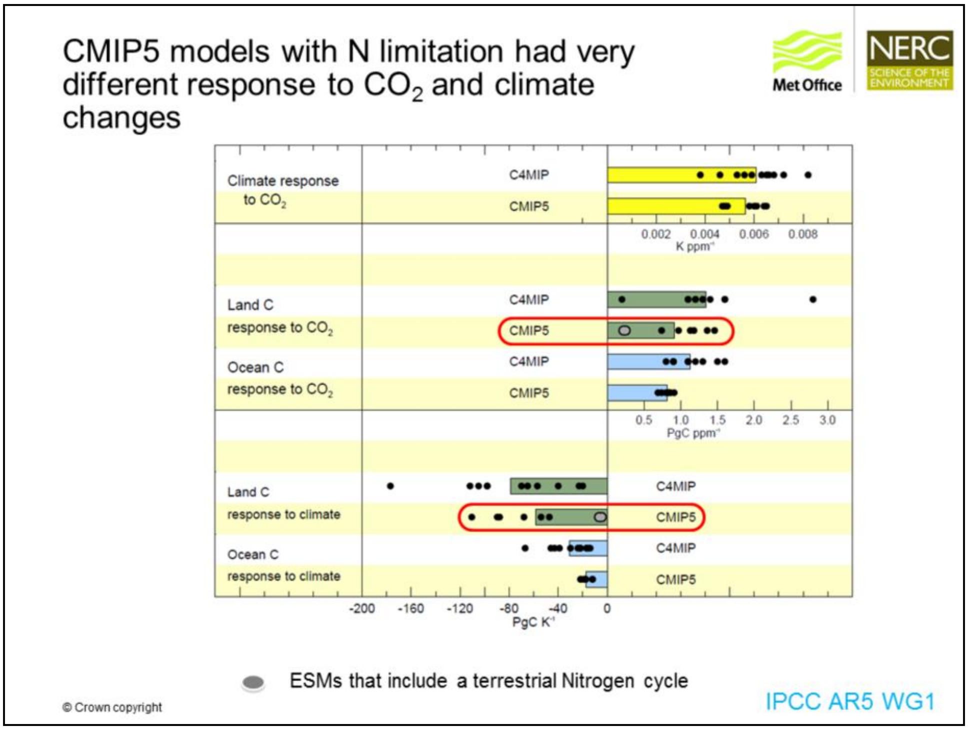
The first is the inclusion of an interactive nitrogen cycle.

Plants need nitrogen mainly to produce the enzymes that drive photosynthesis.

In the current generation of ESMs most models assume an unlimited supply of nitrogen in the plants.

This means they can make use of almost any additional amount of CO2 stimulating more growth than if the nitrogen supply was limited.

In UKESM1 the nitrogen cycle will be represented in the plants and in the soil.



This analysis from the last IPCC report demonstrates why this is important.

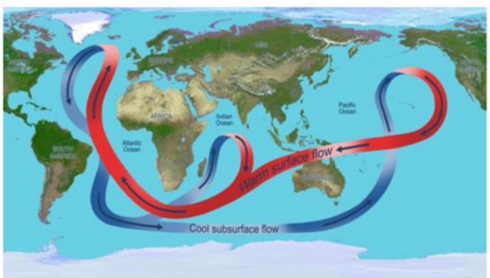
In this plot the climate and land surface responses to a CO2 increase are summarized.

Only two models contributing to this report included a nitrogen cycle.

The results demonstrate that assuming an unlimited nitrogen supply likely leads to an overestimation of the response in the land surface to a change in the climate and the available CO2.

Ice sheet-ocean interactions

- Ice sheets supply most of the freshwater input to the Southern Ocean (more than precipitation)
- If the Southern Ocean warms enough or the circulation changes this could increase melt of marine-terminating ice shelves and change freshwater supply, feeding back on circulation



- It could also trigger collapse of marine-based ice sheets, leading to large increases in global mean sea level (several metres over hundreds of years)

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My final example is related to the coupling between ice sheets and the oceans.

To make that clear this is NOT looking at sea level rise primarily but at fresh water input a to the ocean and salinity.

Salt water is denser and heavier and sinks to the ocean floor.

Fresh water is less dense and lighter and stays at the surface.

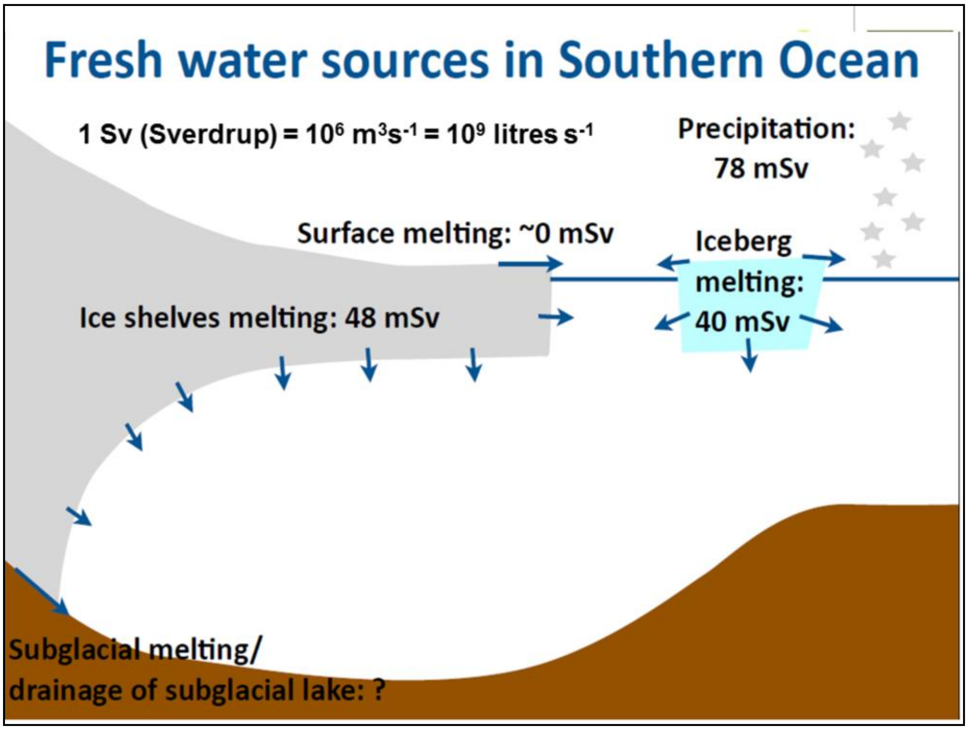
The global ocean currents are driven by these subduction and upwelling processes.

Vast amounts of heat are thus transported.

This is especially important for Europe since this mechanism creates our relatively mild climate.

Warming can lead to an increased fresh water input and a change in the ocean currents.

Ultimately, the collapse of marine-based ice sheets is a possibility with a substantial increase in the sea level.



Ice sheets have a continental base and stretch into the ocean.

Freshwater influx into the ocean occurs along the entire interface.

The volume transport flux of water in the ocean is measured in Sverdrup.

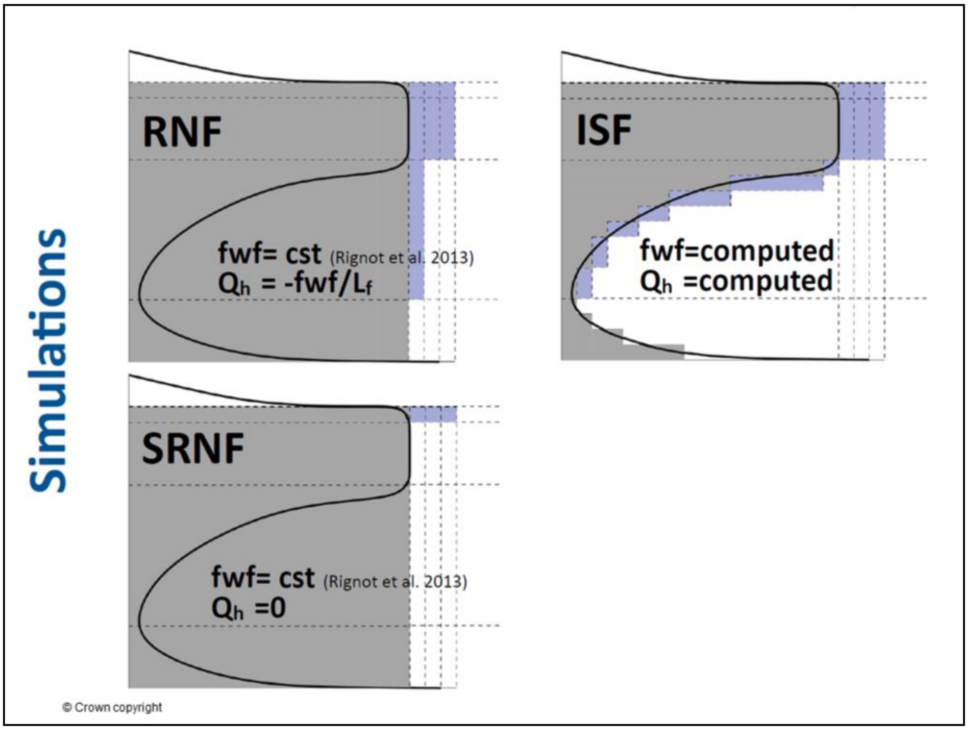
One Sverdrup is 1,000,000 cubic metres or 1,000,000,000 litres of water per second.

Consequently, One milli-Sverdrup is 1000 cubic metres or 1,000,000 litres of water per second.

Fresh water influxes are thus of the order of 40 to 80 million litres a second.

An Olympic-size swimming pool for comparisons hold 2,500 m3 or 2.5 106 litres of water.

The fluxes are then equivalent to 15 to 30 Olympic-size swimming pools every second over the whole of the Southern Ocean admittedly.

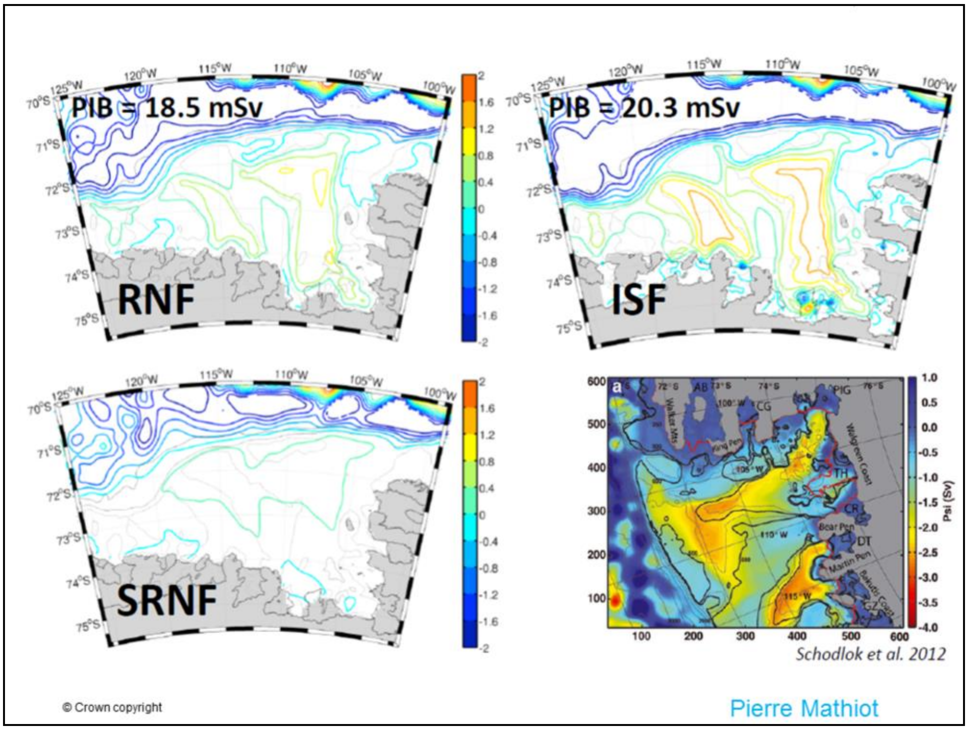


I am not going to go into too much details here.

I just wanted to point out that current sea ice models do not represent the necessary details.

Here are plots from a study that has compared the impact of fresh water fluxes in models of different complexity.

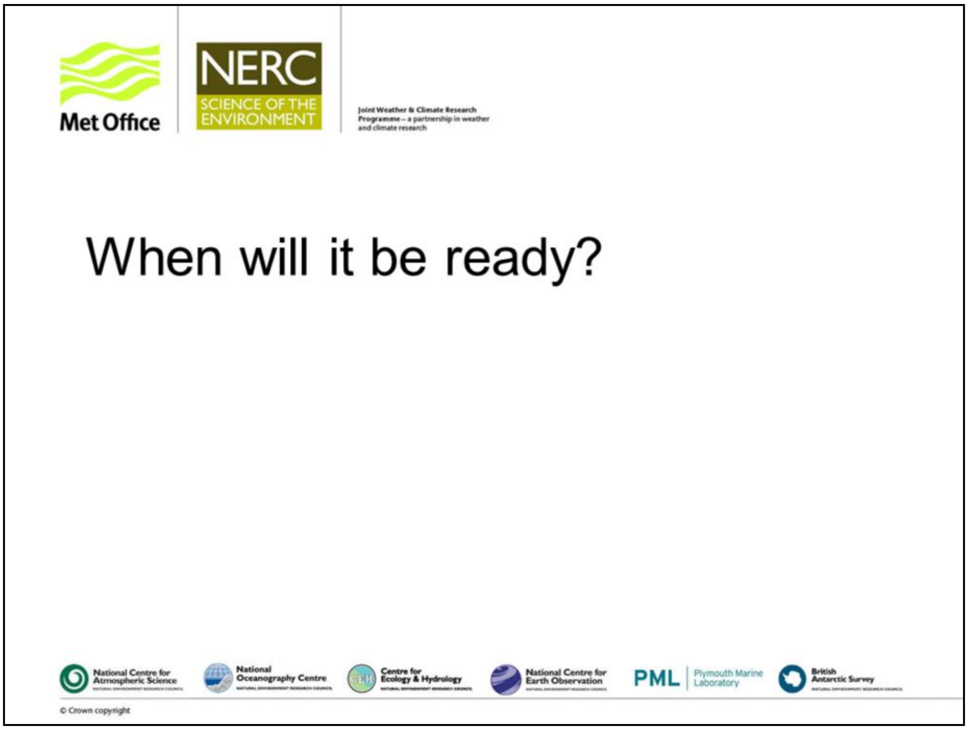
From the simplest approach where the entire flux occurs at the surface to the most realistic setup.



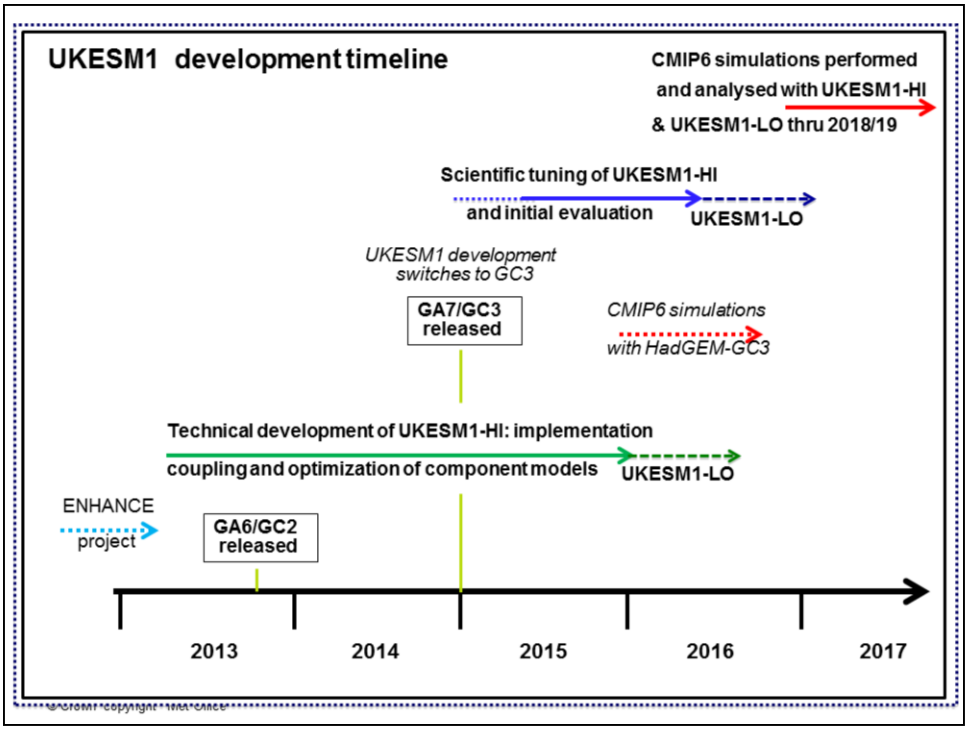
These figures show modelled fresh water fluxes based on those different setups.

The most realistic setup also shows the best agreement overall with the observations shown in the lower right corner.

This is just to demonstrate that UKESM1 will make an effort to improve also in this area.



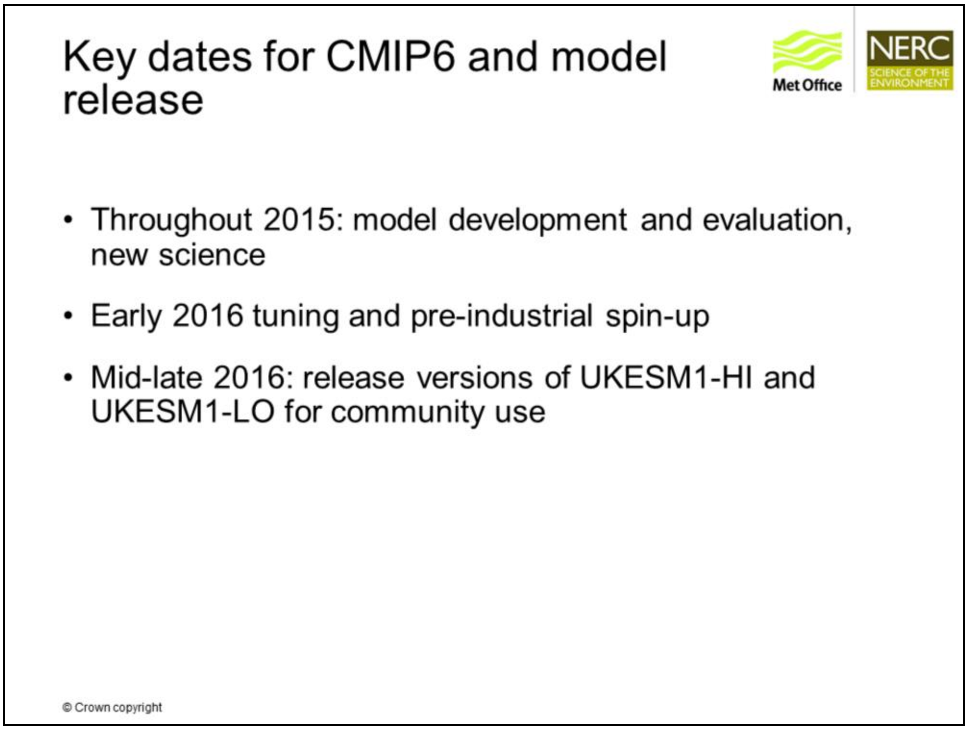
Well, now that I have outlined some of the new capabilities that are planned for UKESM1 you all want to know WHEN is this going to be available.



The development process for UKESM1 has been going on for a while now.

It is expected that the first usable prototype of the new Earth system model will become available sometime in mid-2016.

The development and release is of course constraint by our commitment to CMIP6.

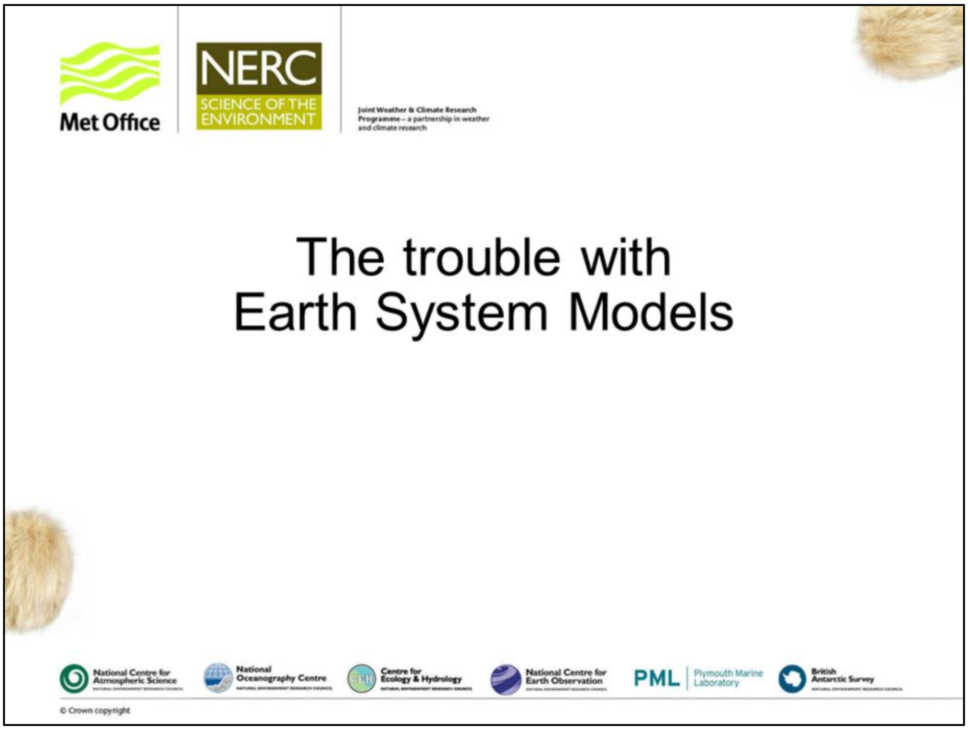


Here are some key dates to remember:

Throughout this year model development, testing and evaluation will take place.

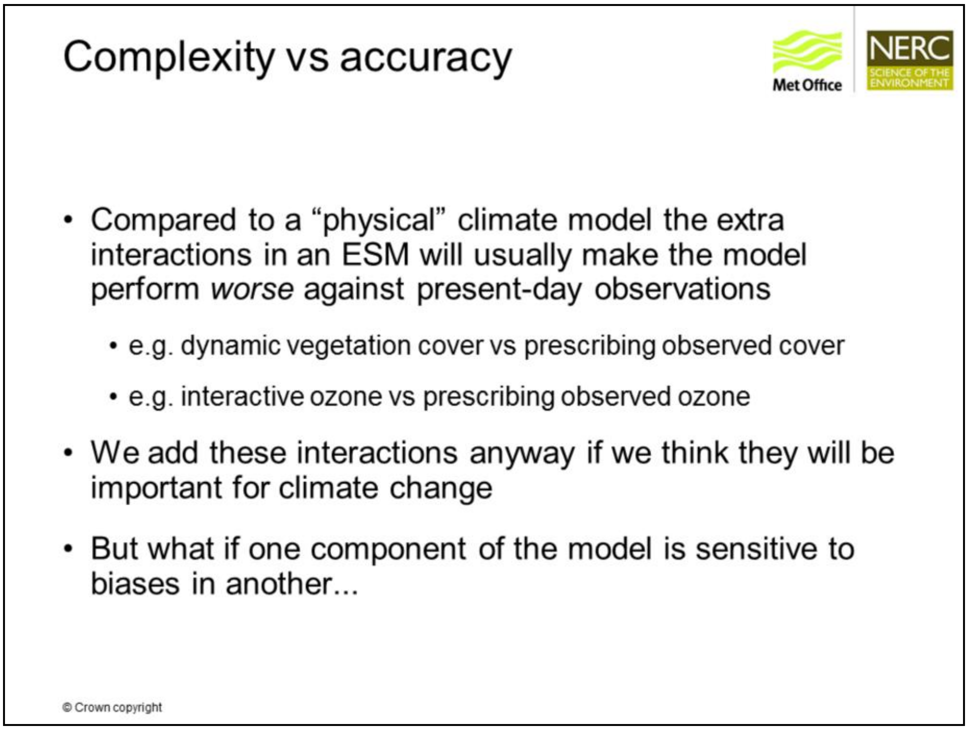
Most of the first half of 2016 will be devoted to model tuning and conducting the pre-industrial spin-up.

As already mentioned, releases of the high- and low-resolution versions of UKESM1 will become available to the community.



In the final section I want to spend some of the time that's left to discussing typical problems that can arise in connection with ESMs.

This has to do with complexity, the usually substantial number of free parameters and degrees of freedom in these models.



The most obvious and controversial aspect of any Earth system model is its increased complexity.

ESMs aim to include substantially more process representations than typically found in physical climate models.

For example, in a physical climate model the ozone distribution in the atmosphere could be prescribed from observations while ozone is simulated interactively in ESMs.

In the latter case one aims to include enough science so that the model is able to produce a realistic distribution on its own, so to say.

However, "more complex" does not necessarily mean "more accurate".

The paradox situation here is that model performance may degrade upon inclusion of new processes.

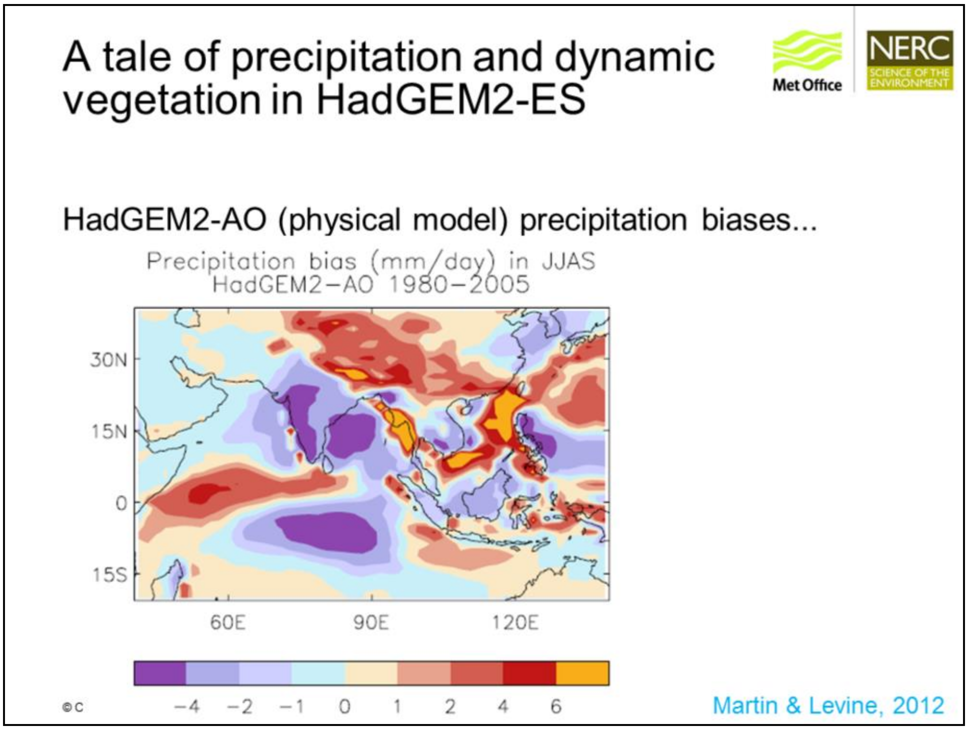
This has many reasons.

It has to do with “double counting” because the missing process may have been “tuned into” the model before.

It may have to do with incomplete process understanding or with unforeseen feedbacks.

It may be worthwhile including the despite nevertheless the loss in performance because without it and related feedbacks a realistic projection of future climate will always be unrealistic.

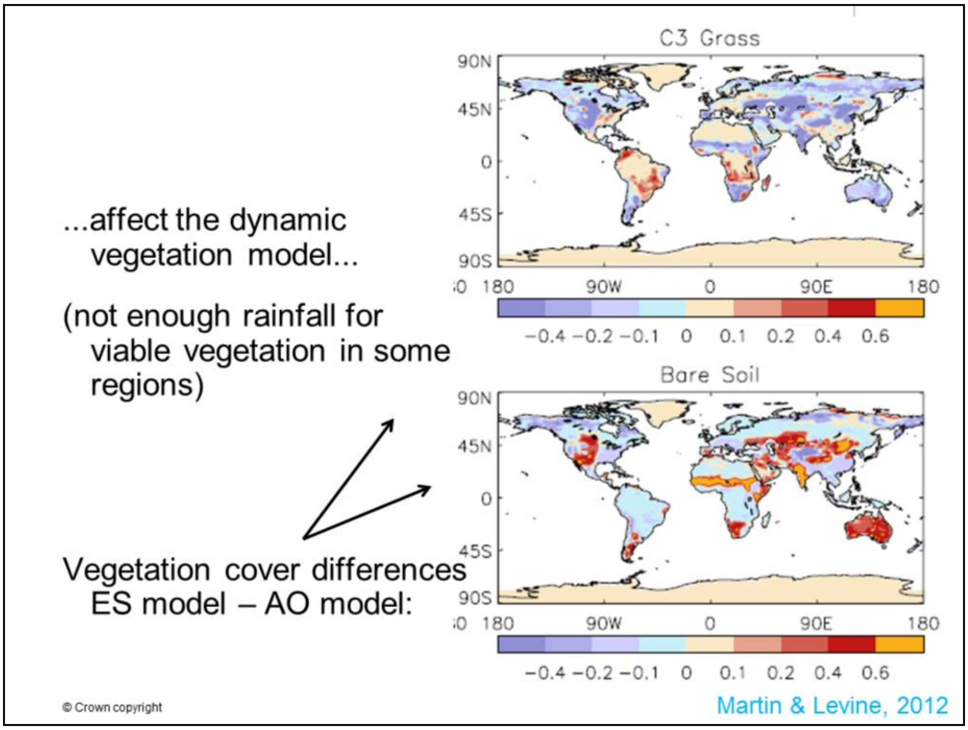
In the following slides I want to demonstrate what happens if one ES-component is sensitive to biases in another.



This example looks at precipitation and vegetation dynamics in the current ESM HadGEM2-ES.

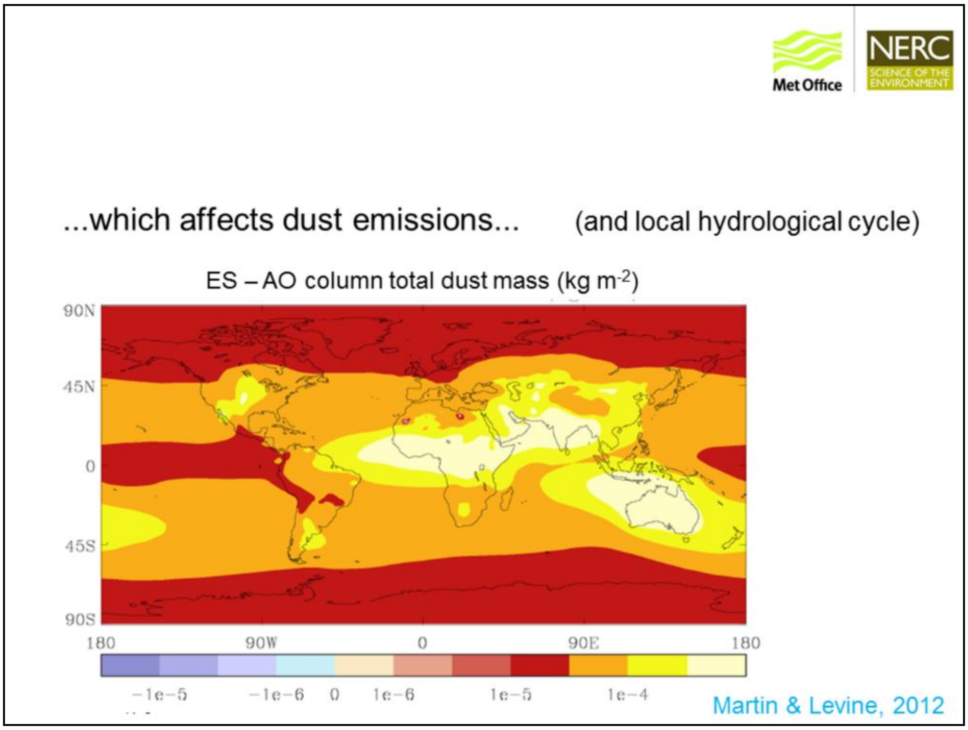
In the corresponding physical version HadGEM2-AO there is a known precipitation bias.

However, vegetation depends strongly on precipitation for productivity and growth.



The precipitation bias that is also in HadGEM2-ES affects the vegetation distribution leading to drought conditions in some areas.

Since vegetation is prescribed in the physical climate model HadGEM2-AO but not in the ESM HadGEM2-ES the bias leads to differences in the vegetation distribution between the two models.

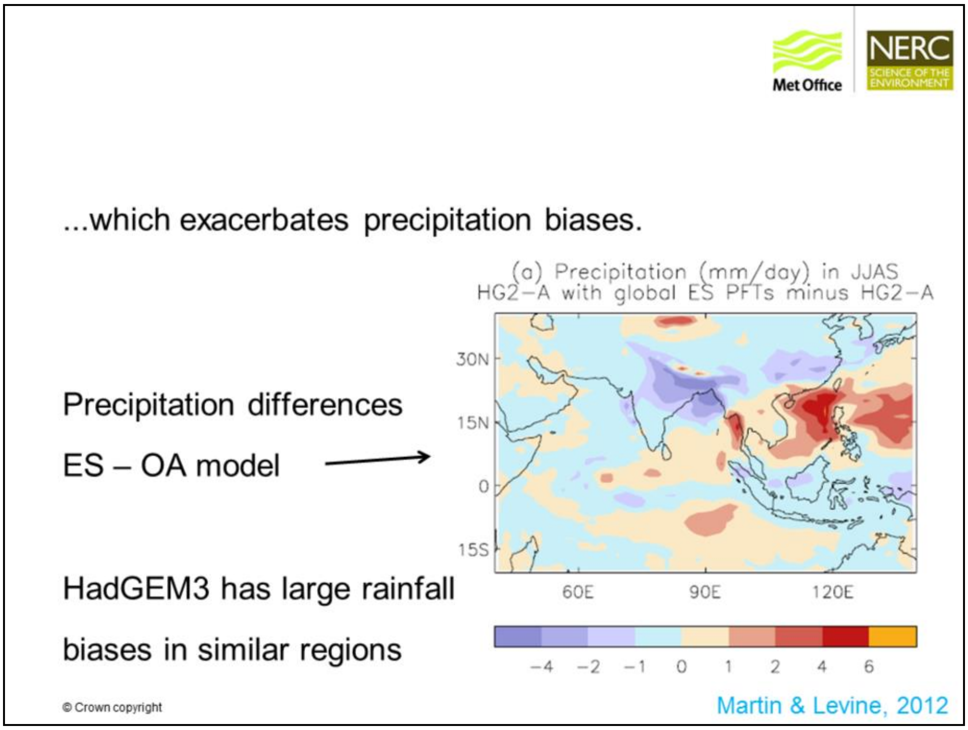


This difference has consequences for other components, too.

One example is dust.

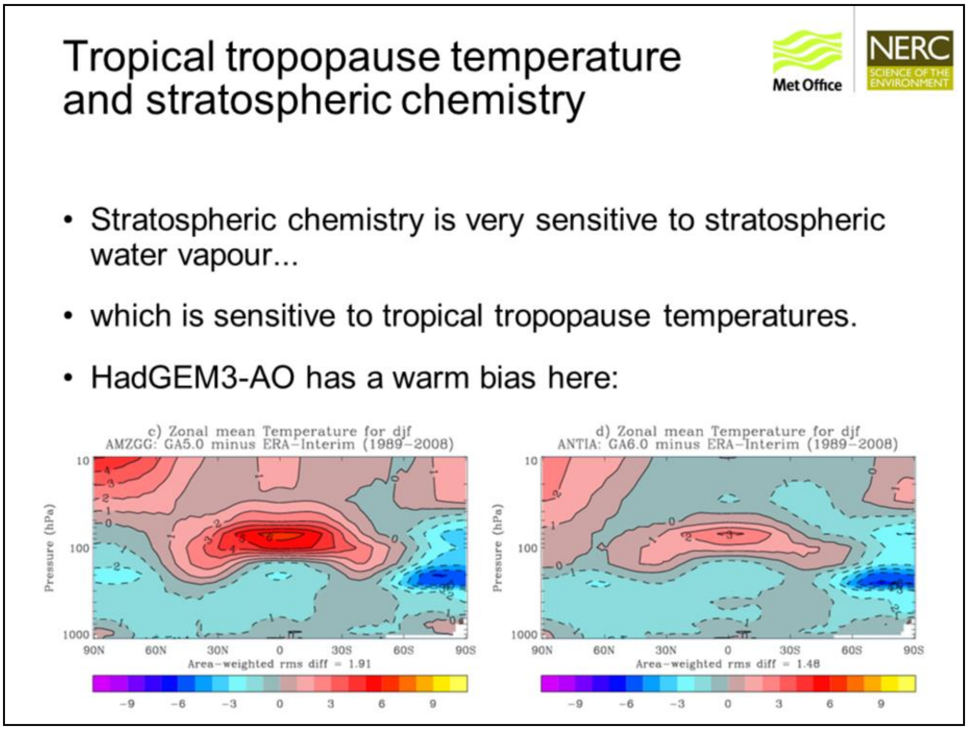
Dust is emitted from regions that exhibit bare soil.

The difference in vegetation and thus bare soil distribution also leads to a difference in the distribution of dust between the two model.



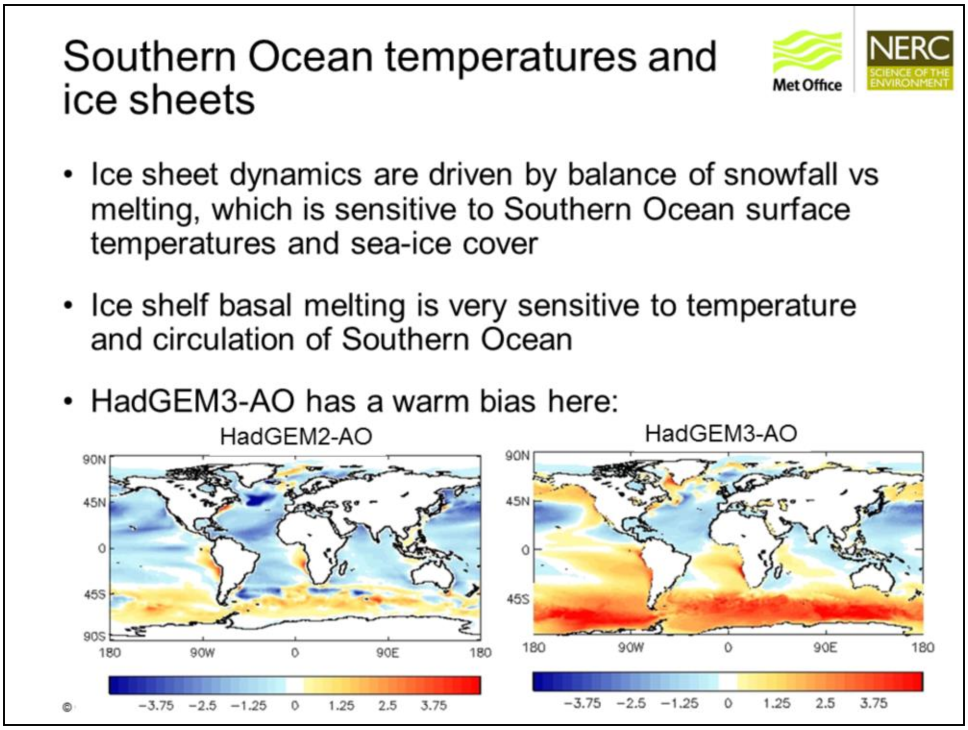
Dust eventually has an effect on precipitation and thus the original bias in the precipitation is exacerbated and the cycle starts again until the model reaches a new equilibrium state.

Similar biases also exist in HadGEM3 and will need to be addressed during the testing and tuning phases.



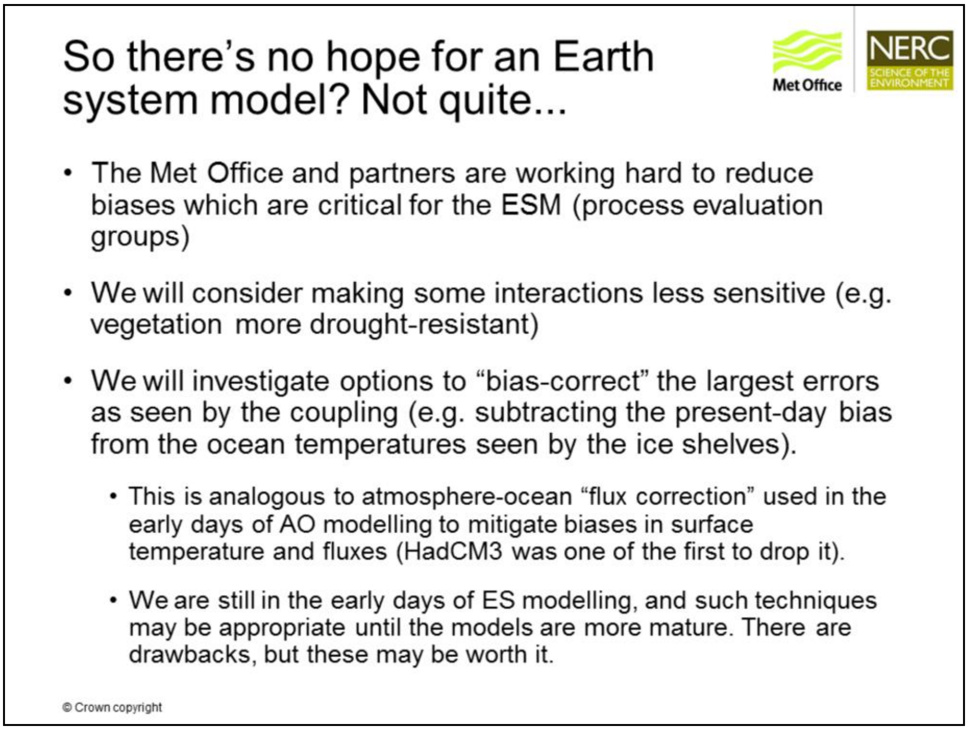
Similar biases exist in other areas.

One example is stratospheric chemistry that is highly sensitive to temperature.



Another example where biases are known to exist is Southern Ocean temperatures.

This will affect the ice sheets in the new model.



Does this mean that Earth system modelling is a lost cause?

Certainly not!

In the end these problems can be mitigated through better understanding of processes and a rigorous testing and evaluation process.

In some cases it will be unavoidable to introduce bias-corrections during the early stages of the new model.

Over time it is anticipated that the need for these corrections will disappear with the emergence of new science.

And that is where all of you come in.

Use the model, improve the model.

Thanks.