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UKESM1 science configuration complete and CMIP6 simulations started

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In April 2018 we completed the scientific and technical development of UKESM1 and started a number of baseline simulations as part of the 6th Coupled Model Intercomparison Project (CMIP6). This newsletter outlines early results from UKESM1 covering the CMIP6 DECK and a number of historical simulations (Eyring et al. 2016), as well as a range of more targeted experiments used to characterize the model's fundamental behaviour. Specifically, one article describes the overall coupled behaviour of UKESM1, followed by a set of papers that look more closely at the model's representation of atmospheric, marine and terrestrial processes and the global carbon cycle. The newsletter concludes with an article outlining plans for the release of UKESM1 to the UK research community in the coming months.

UKESM1 is now being actively run in the first set of simulations in CMIP6, known as the DECK (Eyring et al. 2016). This is a set of baseline experiments designed to characterize the unforced behaviour of a coupled Earth system model and its sensitivity to increased/increasing atmospheric CO_2 concentrations. The DECK consists of:

(i)   A pre-industrial (PI) control simulation (natural emissions only), termed *piControl*, which is run for a minimum of 500 years started from a spun up PI model state.

(ii)   A simulation forced by a 1%yr^{-1} increase in atmospheric CO_2 concentrations from PI values (referred to *1pctCO₂*) and run for 150 years.

(iii)   A simulation where atmospheric CO_2 concentrations are abruptly increased to 4 times pre-industrial values, referred to as *abrupt-4xCO₂* and run for 150 years.

(iv)   An atmosphere-land only simulation, using prescribed, observation-based fields of sea surface temperatures (SST) and sea ice concentration (SIC), referred to as *amip* and run for the period 1979 to 2015.

In addition to the DECK, CMIP6 also include an historical simulation, spanning the period of scientific observations (1850 to present). These experiments, referred to as *historical,* use observed estimates of atmospheric CO_2 concentrations over the historical past, as well as estimates of anthropogenic emissions of aerosol and aerosol-precursors, human-induced land use change and emissions of other important trace gases. The historical simulations provide an important opportunity to evaluate UKESM1 against a range of observations. The historical simulations also provide a stepping-stone for using UKESM1 to make Earth system projections for the coming century. These projection use a range of plausible future greenhouse gas and aerosol emission pathways, combined with different assumptions about future land use. Future projections all start from the end state of a UKESM1 historical simulation and are organized within the scenarioMIP activity in CMIP6 (O'Neill et al. 2017).

The UKESM1 DECK and an ensemble of historical simulations are presently running and we aim to start a first set of scenarioMIP projections in the time-window October to December 2018. UKESM1 will also be extensively used over the coming months in a range of Model Intercomparison Projects (MIPs), addressing different aspects of climate and Earth system science. For more details on individual MIPs see Eyring et al (2016) and accompanying, MIP-specific papers, in the same special issue.

Some top level performance metrics from the UKESM1 piControl

As a brief introduction to the scientific performance of UKESM1, we present a few high-level, global mean metrics from the piControl simulation that are important indicators of whether a coupled model has attained a stable and realistic pre-industrial climate, with the caveat that observational constraints on model PI performance are limited. Figure 1 plots the global mean, annual mean top of atmosphere (TOA) net radiation balance from the UKESM1 piControl, which has now run slightly more than 300 simulated years. For a stable PI control climate a long-term net TOA radiation balance of $0Wm^{-2}$ is required. Figure 1 shows this has been realized with UKESM1. While there is interannual variability of ~+/-$0.5Wm^{-2}$ the long-term mean of the TOA radiation budget is essentially zero meaning that long-term thermal drift in the model's piControl climate is likely to be minimal.
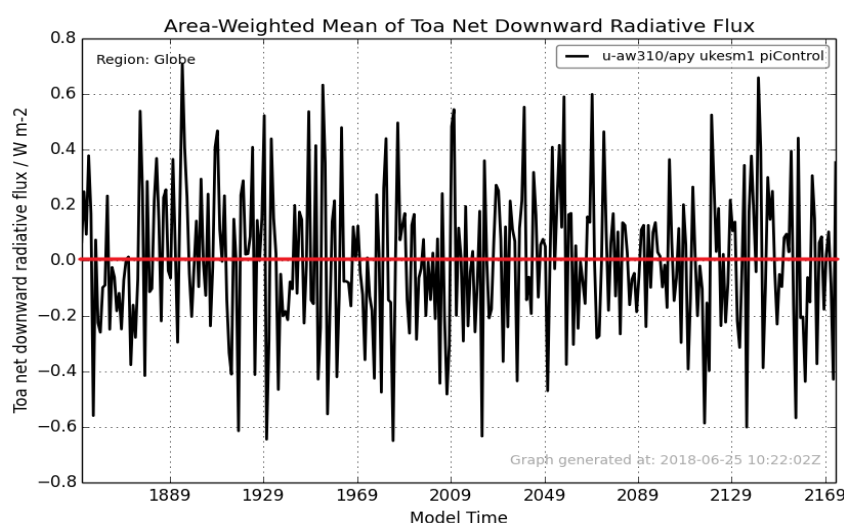

Figure 1: Global mean, annual mean TOA net radiation UKESM1 piControl. While the piControl started with a date of Jan 1st 1850, for such a simulation model dates bear no similarity to the real calendar.

In figure 2 we show the global mean, annual mean surface temperature from the UKESM1 piControl covering the same period as the TOA net radiation figure. While a $0Wm^{-2}$ TOA net radiation balance will, eventually, lead to a coupled climate in long-term thermal equilibrium, due to the ocean's overturning circulation there will be periods when the global mean surface temperature is colder or warmer than the long-term average. For a significant period of the UKESM1 spin-up the model exhibited such variability in surface temperature, on timescales of ~70-120 years. This was linked to periodic overturning of the ocean column off Antarctica, bringing relatively warm deep waters to the surface resulting in significant heat loss from the ocean. Such phenomena have been observed in the real climate, most notably associated with the Weddell Sea polynya of 1974-1977 (Gordon and Comiso 1988).
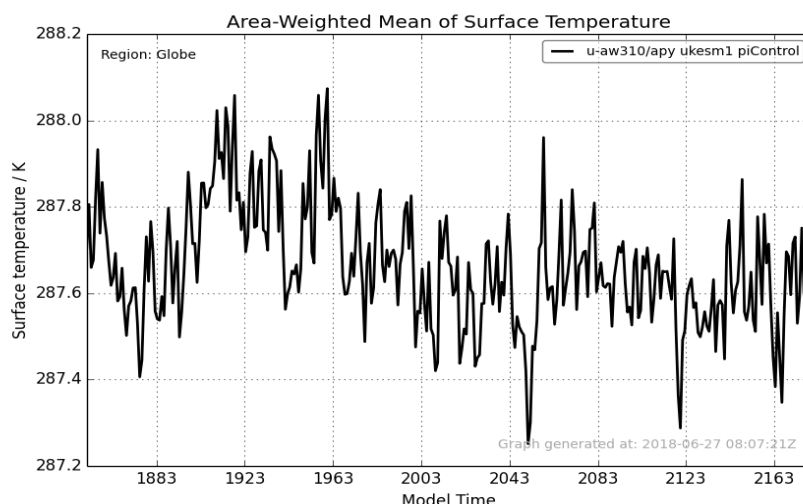
Figure 2: Global mean, annual mean surface temperature from the UKESM1 piControl.

After some variability in surface temperature over the first ~150 years of the piControl, the last ~170 years show a rather stable global mean surface temperature of around 287.6K (~14.5°C), with some short period deviations, most of which are associated with periodic changes in ocean circulation in the North Atlantic.

As a final measure of the piControl being well equilibrated, figure 3 shows the global mean, annual mean net CO_2 flux between the ocean and land reservoirs and the atmosphere. Positive values indicate a flux of CO_2 into the atmosphere. Again, over a sufficiently long averaging period we should expect a PI climate, with no external emissions of CO_2, to reach an equilibrium in exchange between the 3 connected carbon reservoirs, land, ocean and atmosphere. This is clearly the case for the UKESM1 piControl, with interannual variability, driven by both the land and marine fluxes, oscillating around the zero flux value.
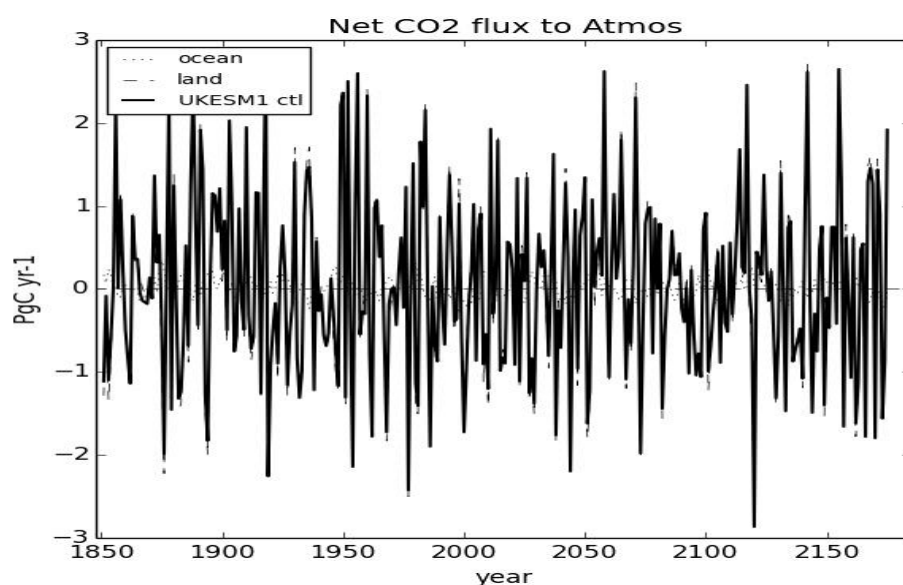

Figure 3: Global mean, annual mean net CO_2 flux into the atmosphere in the UKESM1 piControl. The full black line shows ocean and terrestrial fluxes combined.

From this brief analysis we conclude that the piControl climate simulated by UKESM1 is in radiative, thermal and carbon equilibrium and is therefore a suitable reference for the numerous experiments planned with UKESM1 in CMIP6, in particular the historical and future projection experiments targeted for completion in 2018.

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First results from the CMIP6 DECK and historical runs

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The UKESM1 DECK and historical runs are nearing completion and we (the UKESM core group and collaborators) have begun an initial analysis of first results. Early indications are that the model performs well, with a number of interesting features, which will keep us, and the UK Earth system science community busy for the next few years. A few preliminary results are outlined below.

Looking first at the pre-industrial control run and the spin-up, which preceded it. This exhibits some striking multi-decadal variability in the Southern Ocean. Figure 1 shows oscillations in the strength of the Antarctic Circumpolar Current (ACC) with a period of between 100 and 180 years. These oscillations are driven by extended periods of S. Ocean deep convection, as evidenced by localised peaks in sea surface temperature in the Weddell Sea (Figure 2) and other regions around Antarctica. This convective mixing brings relatively warm and saline water to the surface, increasing the surface salinity of the S. Ocean in general. The net effect of these convective periods is to increase the density gradient across the ACC, and hence drive an increase in current strength.
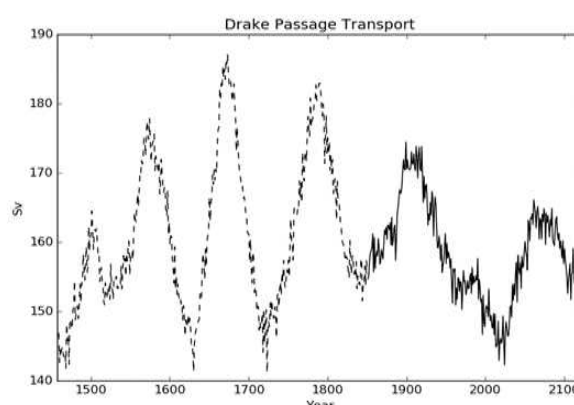

Figure 1: Strength of the ACC circulation, in Sverdrups (10^6 m^{3}s^{-1}), through the Drake Passage. Solid line: pre-industrial control; dashed line: pre-industrial spinup used to initialise the control run. Dates are arbitrary.

Such variability is not seen in the HadGEM3-GC3.1 pre-industrial control run or spin-up, despite sharing the same physical ocean model, so the differing behaviour is intriguing. One hypothesis for the cause is the manner in which UKESM1 was spun up. In order to bring the ocean biogeochemistry, and air-sea CO_2 flux in particular, close to equilibrium, we performed a 5000-year ocean-only spin-up driven by pre-industrial atmospheric forcing derived from an early version of the coupled model. A spin-up of this length would be prohibitively expensive for the fully coupled model. The deep convective episodes may be a result of the coupled model coming into equilibrium with the forcing of the final Earth system model, which underwent further development while the ocean-only spi-nup was running. Indeed there is some indication these oscillations are decreasing in magnitude as the piControl run evolves, though this will become clearer once the run has progressed another few hundred years. The

observational record of the S. Ocean does not allow us to evaluate whether this type of oscillation occurred in the pre-industrial era, but there are indications from observations and other models that the behaviour is plausible (e.g. Latif et al, 2017).
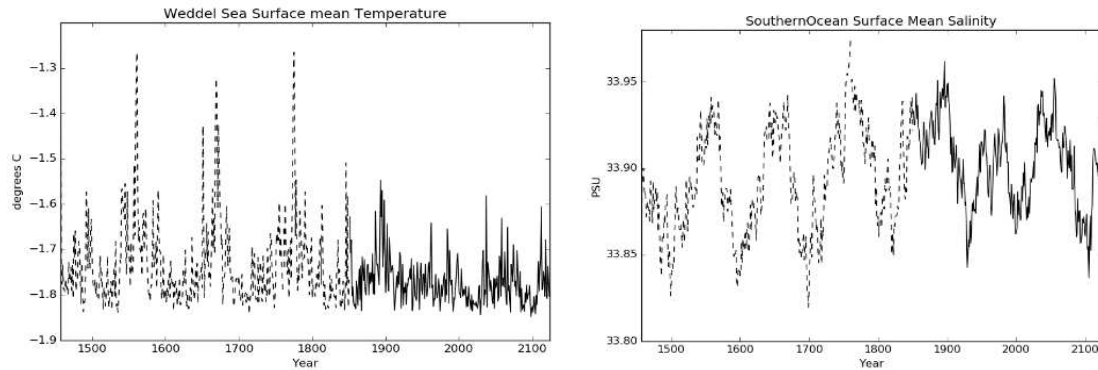

Figure 2: Left: Mean sea surface temperature in the Weddell Sea (80S – 60S, 72.5W - 0E). Right: Mean sea surface salinity in the Southern Ocean (90S - 40S). Lines as in Figure 1.
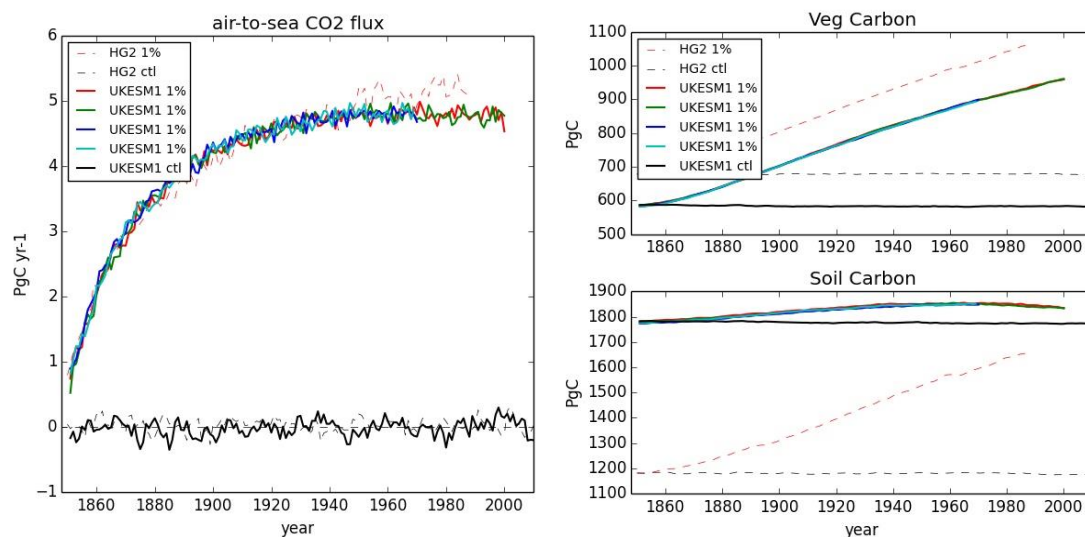

Figure 3: Carbon fluxes and stores in UKESM1 (solid lines) and HadGEM2-ES (dashed lines) 1% CO₂ experiments. Left: CO₂ flux from air to sea (Pg carbon per year). Top right: total vegetation carbon in Pg. Bottom right: total soil carbon in Pg. Black / grey: pre-industrial control; colours: 1% CO₂.

Turning next to the 1% CO_2 experiment, in which increasing CO_2 concentrations are imposed at a compound rate of 1% per year, the key aspect for an Earth system model is carbon uptake by the ocean and land. Figure 3 shows how carbon uptake in UKESM1 compares to its predecessor Earth system model HadGEM2-ES. The CO_2 flux into the ocean is similar to HadGEM2-ES, with some indication of an earlier saturation as concentrations approach 3-4 times pre-industrial levels from 1950 onwards. Uptake by vegetation is also very similar, as shown by the rate of increase of vegetation carbon, albeit from a slightly lower base state than HadGEM2-ES. In contrast to this, the increase in soil carbon in UKESM1 is at least 10 times smaller than HadGEM2-ES. This is a result of the inclusion of nitrogen limitation on

photosynthesis in UKESM1, which makes carbon uptake subject to available mineral nitrogen in the soil. This nitrogen limitation is one of the most significant developments between CMIP5-generation models like HadGEM2-ES and CMIP6 models like UKESM1, and is of critical importance to future projections because it can strongly modulate the amount of carbon taken up by the terrestrial biosphere and thereby influence allowable anthropogenic emissions compatible with specific temperature targets. Temperature-dependence in certain soil processes actually results in a loss of soil carbon toward the end of the UKESM1 simulation and, in contrast to the near-linear uptake in HadGEM2-ES, soil carbon starts to reduce after ~120 years of simulation (1970 in the figure). As a result, terrestrial carbon uptake (by soil and vegetation) reduces to near-zero by the time CO_2 concentrations reach 4 times pre-industrial values (Figure 4).
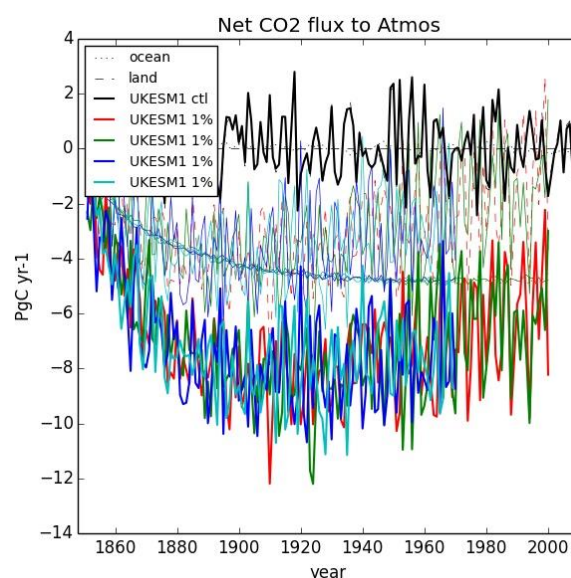

Figure 4: Net CO2 flux from the ocean and land surface to the atmosphere in UKESM1 1% CO_2 experiments (note the opposite sign from the air-to-sea flux in Figure 3). Black: pre-industrial control; colours: 1% CO_2. Dashed lines: flux from land; dotted lines: flux from ocean.

Looking finally at the historical runs, 4 ensemble members are complete and another 3 are underway. These have been initialised from different points in the pre-industrial control simulation, chosen to span the phase-space of key decadal modes of variability: the Pacific decadal oscillation (PDO), Atlantic multi-decadal oscillation (AMO), and the ACC variability noted above in figure 1. Figure 5 shows the surface temperature evolution in these runs compared to the physical model HadGEM3-GC3.1, as global (left) and northern hemisphere extratropical (right) means. Both models show a slight cooling in the mid-to-late 20th Century before warming strongly towards the present day. The mid-century cooling is stronger, and starts earlier, in UKESM1. The size of this cooling is somewhat more realistic in HadGEM3 GC3.1.We are investigating this difference between the models to understand the processes responsible. Initial analysis is focussing on chemical oxidants involved in aerosol formation, which are interactive in UKESM1 but prescribed and time-invariant in HadGEM3-GC3.1, and on land use change, which is implemented differently in the two models because UKESM1 includes dynamic vegetation cover.
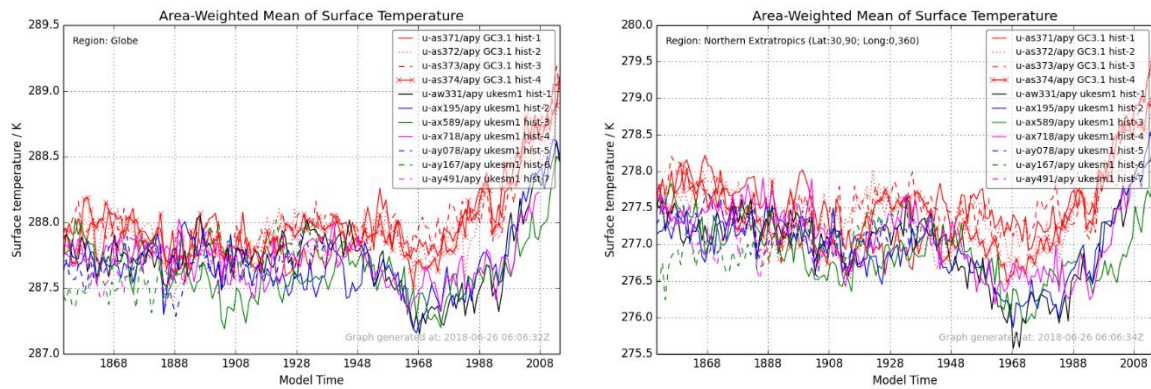
Figure 5: Surface temperature evolution in HadGEM3-GC3.1 (red lines) and UKESM1 (other colours). Left: global mean; Right: northern extratropical mean (30N – 90N).

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A first look at the atmosphere in UKESM1

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The core of the UKESM1 atmosphere is the GA7.1 version of the Unified Model Global Atmosphere (Walters et al. 2018, Mulcahy et al. 2018). In addition to the GA7.1 atmospheric configuration, UKESM1 also includes the UKCA stratosphere-troposphere interactive chemistry scheme, which predicts a number of key atmospheric greenhouse gases (e.g. ozone (O_3), methane (CH_4) and nitrous oxide(N_2O)), as well as the chemical oxidants that lead to the formation of atmospheric aerosol (for example the oxidation of SO_2 to SO_4^{2-} and subsequent formation of H_2SO_4). Furthermore, a number of atmospheric phenomena, which use time-invariant prescribed emission files in the physical model HadGEM3-GC3.1 (GC31 here after) are interactively coupled to other components of UKESM1. This allows for a more complete representation of the full Earth system, in particular allowing the possibility of future feedbacks across components of the Earth system. Such couplings include; (i) marine emissions of dimethlysulfide (DMS) and Primary Marine Organic Aerosol (PMOA) from time evolving fields simulated in the MEDUSA marine biogeochemistry model, (ii) terrestrial emission of Biogenic Volatile Organic Compounds (BVOCs) into the atmosphere are from the time evolving vegetation predicted by the JULES-TRIFFID land surface-vegetation scheme. Similarly, dust emissions into the atmosphere are coupled to the JULES-TRIFFID predicted land surface. Atmospheric dust is also deposited into the ocean, acting as a source of soluble iron for ocean biogeochemistry. Finally, when run in CO_2-emission mode, a full global carbon cycle is activated, with exchanges of CO_2 between the land, ocean and atmospheric components of the model.

In this article we present some initial results from a few important components of the UKESM1 atmosphere, touching on; top of atmosphere (TOA) radiation fluxes, aerosol radiative forcing, the treatment of natural marine aerosols, the representation of mineral dust and some initial results from the prognostic chemistry in UKESM1. A more detailed analysis of UKESM1 performance, both coupled and component models, will appear in the peer reviewed literature. The underpinning coupled physical model of UKESM1 (GC31 at N96 (atmosphere) and 1° (ocean) resolution) has been documented in Kuhlbrodt et al. (2018), while the GA7.1 atmospheric model configuration of GC3.1 and UKESM1 is detailed in Mulcahy et al. (2018).

1. Top of atmosphere radiation fluxes

In the introductory article to this newsletter, we showed that the global mean TOA net radiation balance in UKESM1 is essentially zero when averaged over a sufficiently long time-period. The top panel in figure 1 again shows the UKESM1 piControl TOA net radiation (in black), also shown is the GC31 TOA radiation budget (in red), which is slightly positive at around +0.2Wm[-2]. The second and third panels in figure 1 show the piControl TOA radiation balance averaged over the northern (NH) and southern (SH) hemispheres separately, while the bottom panel shows the North minus South gradient in TOA net radiation. GC31 receives ~1Wm[-2] more energy at the TOA in the SH compared to UKESM1 and as a consequence emits more radiant energy back to space from the NH. As a result, the south to north net TOA meridional

energy gradient is ~1.5Wm^{-2} larger in GC31 than in UKESM1. Recent studies emphasize the importance of the hemispheric gradient of TOA radiation for key aspects of the climate system such as; the location of the Inter Tropical Convergence Zone (ITCZ, Hwang and Frierson 2013) and the strength of the meridional ocean heat transport associated with the Atlantic Meridional Overturning Circulation (AMOC, Marshall et al. 2013).
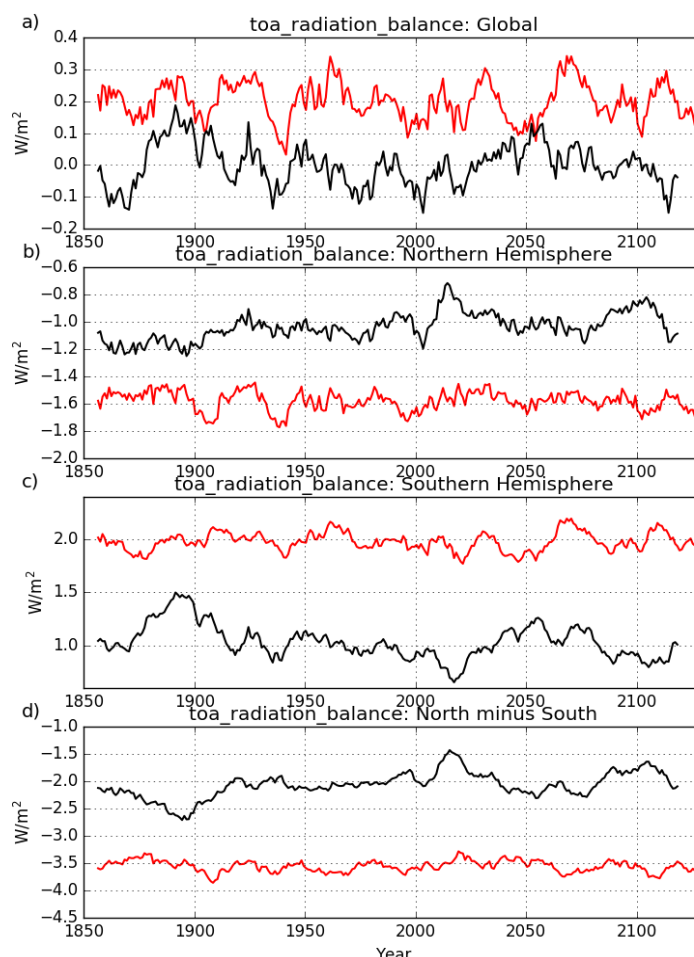

Figure 1 Top: Global mean TOA net radiation, 2nd row: Northern Hemisphere (NH) mean net TOA radiation, 3rd row: Southern Hemisphere (SH) mean net TOA radiation, bottom row: NH minus SH gradient in net TOA radiation. Results are from the UKESM piControl (black) and GC31 piControl (red). Annual values have had an 11 year running mean passed through them.

Figure 2 shows the components of the TOA radiation budget, on the left net shortwave radiation (positive values indicate radiation into the atmosphere) and on the right outgoing longwave radiation (negative values indicate energy leaving the atmosphere). The UKESM1 global atmosphere receives slightly less (~0.5Wm^{-2}) solar energy than GC31. This is equivalent to UKESM1 being is slightly more reflective than GC31 in the global mean. The main difference in reflectivity is seen in the SH, where UKESM1 is ~1.5Wm^{-2} more reflective (receives less net solar energy at TOA) than GC31. The bulk of this difference is in the latitude band ~35°S to 70°S and is associated with a slight increase in cloud fraction and, more importantly for total reflectivity, clouds that are brighter due to having more cloud droplets that are smaller in mean radius than GC31. This change comes about from (i) including marine

PMOA emissions from the ocean into the UKESM1 atmosphere and (ii) linking both the surface flux of PMOA and DMS to the MEDUSA ocean biogeochemistry model. Both these changes lead to more natural aerosol emitted into the UKESM1 atmosphere over the southern ocean and a greater number of cloud droplets are activated. As GC31 is known to have a negative bias in total sky reflectivity for present-day conditions, we consider an increase in reflectivity in UKESM1 relative to GC31 as a performance improvement.
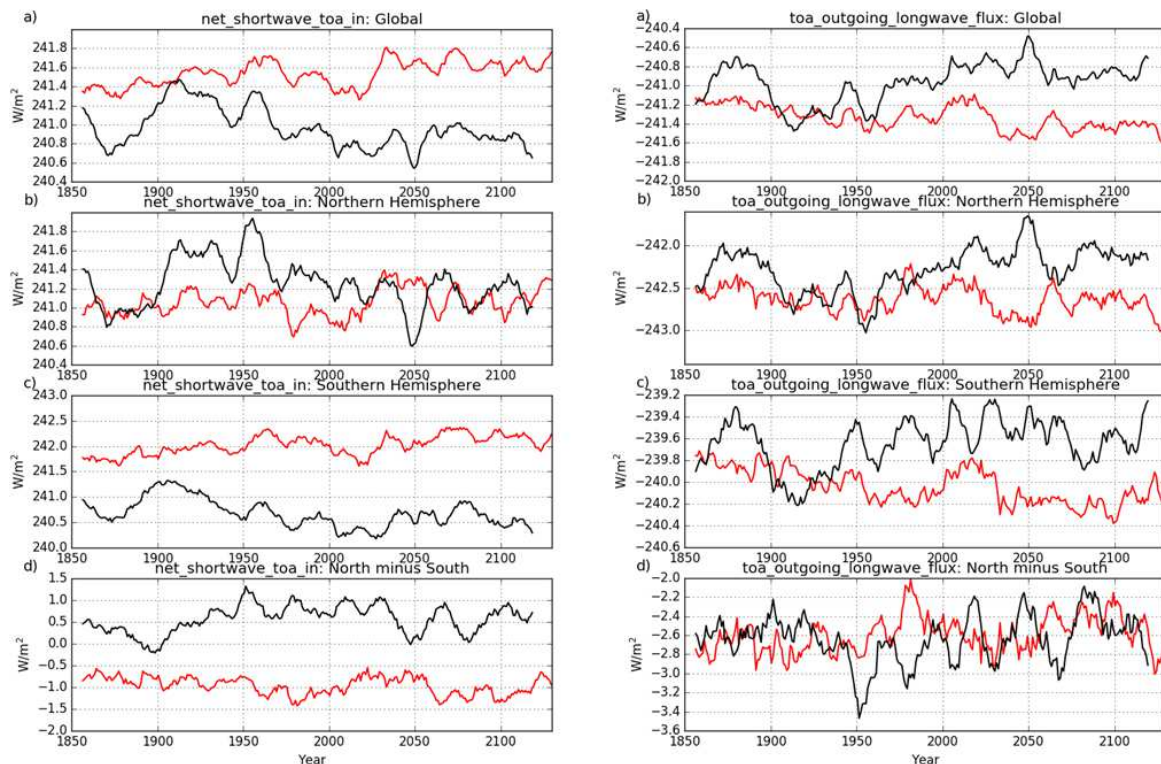

Figure 2: As figure 1 but left panel is net shortwave radiation at TOA and right panel is OLR.

The bottom left panel in figure 2 shows the meridional (NH minus SH) gradient in TOA net solar radiation. UKESM1 has slightly more net solar energy entering the NH than SH, by ~0.5Wm^{-2}, indicating that the SH is more reflective than the NH. GC31 has the converse, with the SH receiving ~1Wm^{-2} more net solar energy than the NH. As these runs are for pre-industrial (PI) conditions it is difficult to apply an observational constraint. Nevertheless, satellite observations (Stephens et al. 2016) for the present-day (PD, ~2000 -2014 period) indicate that the SH and NH receive approximately the same amount of net solar radiation (i.e. an NH minus SH gradient of zero). The primary (although not only) difference in total solar reflectivity going from a PD to a PI climate is the loss of anthropogenic aerosols. These are relatively short-lived species, which primarily influence the northern hemisphere, causing an increase in the PD total sky reflectivity relative to PI conditions. Therefore, going from PD to PI one should expect the real world total reflectivity to decrease as anthropogenic aerosols disappear, with this decrease being primarily in the NH. This implies, if there had been observations of TOA net solar radiation in the pre-industrial period they would likely have seen a planet with a more reflective SH than NH (i.e. the net NH minus SH gradient in TOA solar radiation would have been positive). This thought experiment, combined with the PD

observations and the known southern hemisphere PD biases in GC31, taken together, suggest the UKESM1 TOA net solar radiation field is likely more realistic than GC31.

The right panel of figure 2 shows the TOA outgoing longwave radiation (OLR). Due to the lower amount of incoming solar radiation, the UKESM1 climate system is slightly colder than GC31, which is evident in the lower OLR values in UKESM1 (~0.4Wm^{-2} less than GC31), which is primarily a decrease in the SH OLR. Generally, we believe the UKESM1 piControl TOA radiation budget is slightly more accurate than GC31 in terms of hemispheric structure, although this contention will need to be more thoroughly tested against observations in the latter period of the CMIP6 historical simulations.

2. Aerosol Effective Radiative Forcing and natural aerosols

Mulcahy et al (2018) document the suite of model improvements that took the UM Global Atmosphere configuration (GA7.0) and coupled configuration (GC3.0) to respectively, GA7.1/GC3.1, which constitute the physical model core of UKESM1. These developments were necessary to remedy an excessively large negative aerosol effective radiative forcing (ERF) over the historical period in GA7.0/GC3.0, which was diagnosed to be -2.75Wm^{-2} for year 2000 minus 1850 emissions. Such a large and negative forcing is well outside the IPCC AR5 best estimate and would lead to an historical total radiative forcing close to zero, at odds with the observed warming over the historical past. Figure 3 shows the total historical aerosol ERF from GA7.0 (left column) and GA7.1 (right column). The top row shows the total aerosol ERF, the second row the direct (clear sky) ERF and the bottom the ERF due to both the direct effect and the 1st cloud (indirect) effect (the Twomey effect from increasing cloud droplet number and albedo as aerosol number increases at a fixed liquid water amount). The primary cause of the reduction in aerosol ERF from GA7.0 to GA7.1 is the large decrease in the 1st indirect effect, primarily due to an improved treatment of cloud droplet spectral dispersion in the calculation of droplet effective radius (see Mulcahy et al. 2018). The aerosol direct ERF also decreases, due to a more accurate treatment of black carbon aerosol optical properties. Combined with other components of the total historical radiative forcing (e.g. historical emissions of CO_2, O_3, CH_4 and N_2O and human land use changes) the total historical UKESM1 ERF for year 2000 minus 1850, using CMIP6 emissions is +1.77Wm^{-2}.

A key component of accurately simulating the historical aerosol radiative forcing lies in representing natural aerosols, which define the pre-industrial aerosol climate. In UKESM1, over the ocean, we interactively simulate marine emissions of DMS and Primary Marine Organic Aerosol (PMOA). DMS is oxidized in the atmosphere to form sulfate particles and is known to have a significant impact on cloud droplet number (Kruger and Grassl 2012). DMS and PMOA emissions are associated with biological activity in the ocean (O'Dowd et al. 2004). Hence, to allow for potential future feedbacks involving climate, ocean biology and aerosol emissions, we link the emission of both species to simulated ocean biology from MEDUSA, following the parameterizations of Anderson et al. (2001), for DMS and Gantt et al. (2012) for PMOA. GC31 does not include a formal parameterization of PMOA emissions, to account for this omission in GC31 DMS emissions were multiplied by a factor of1.7. Furthermore, DMS emissions in GC31 are parameterized using an observation-based seawater DMS climatology (Lana et al. 2011). While this provides relative accuracy for present-day conditions, it

precludes the possibility of simulating future changes in ocean biology and their impacts on DMS or PMOA.
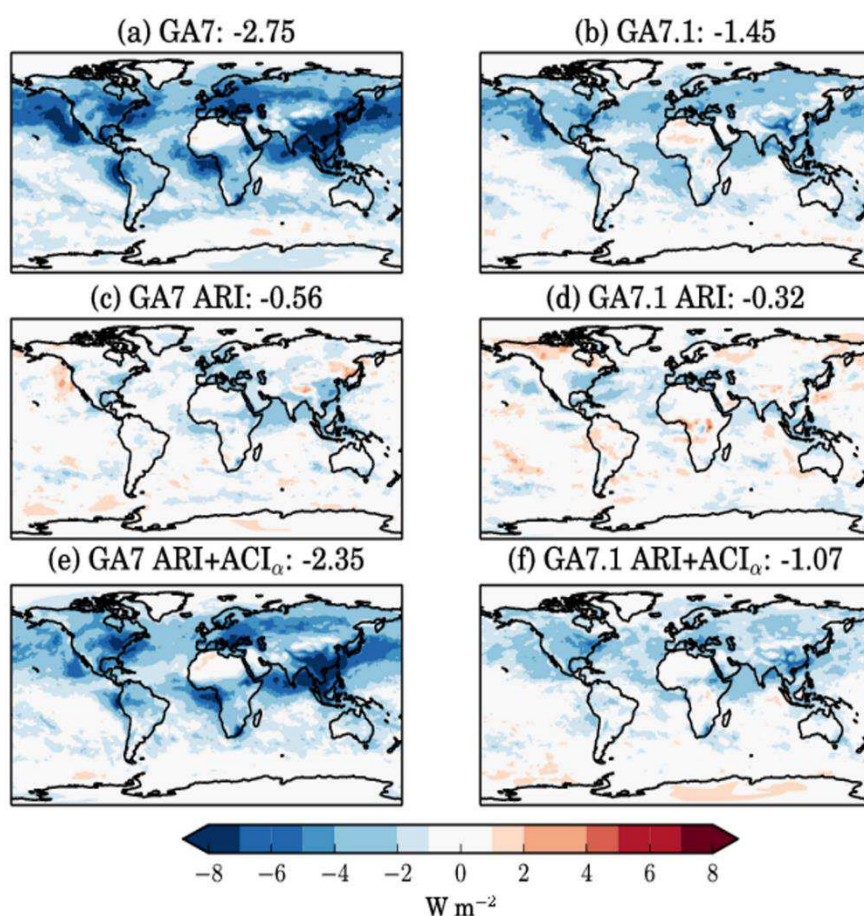

Figure 3. Total historical aerosol ERF (top), direct aerosol ERF (middle) and direct + 1st indirect effect (bottom). GA7.0 is on the left and GA7.1 (atmospheric component of UKESM1) the right.

Figure 4 illustrates the annual cycle of seawater DMS (right) and organic mass concentration (of PMOA, left) simulated by UKESM1. The mean annual cycle of seawater DMS is an average over the Southern Ocean (40°S-65°S) plotted for from UKESM1 (red) and the Lana observations (black). The black vertical lines represent inter-annual variation in the monthly Lana values and the red lines the same statistic from UKESM1. The well-known annual cycle in surface DMS is visible, with maximum values in the austral summer. UKESM1 captures the annual distribution quite well, although the amplitude of the annual cycle is somewhat weaker than observed. The organic mass concentration of marine aerosol (left panel) simulated by UKESM1, (dashed red line) is compared to observations from Amsterdam Island in the Southern Ocean. Again, a clear annual cycle is visible in the observed organic mass concentration, associated with ocean biological activity. This cycle is also well captured by UKESM1, suggesting an interactive treatment of both DMS and PMOA emissions do not degrade the treatment of natural aerosol in the model. In fact, the improved (increased) shortwave reflectivity in UKESM1, compared to GC31, over the Southern Ocean (shown in figure 2) largely arises because of the inclusion of the PMOA emission parameterization in UKESM1 and the linking of both PMOA and DMS emissions to the UKESM1 ocean biology.
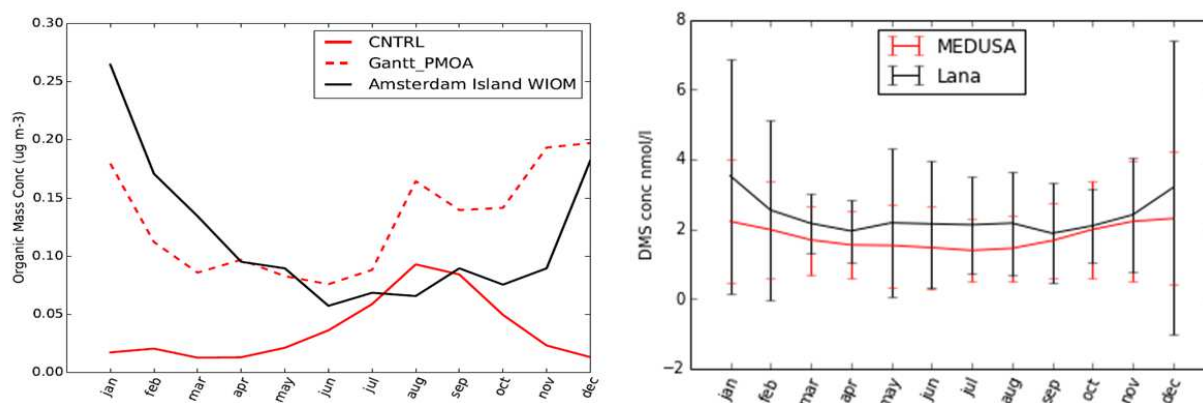
Figure 4: Left panel; Mean annual cycle of organic mass concentration of aerosol particles at the ocean surface observed at Amsterdam Island (black) and simulated for the same grid box location in UKESM1 (red dashed line). Right panel; Southern ocean (40°S-65°S) mean annual cycle of seawater DMS from Lana observations (black) and UKESM1 (red).

In figure 5 we illustrate the importance of natural marine aerosol for the cloud droplet number concentration (CDNC) over the Southern Ocean. For a given cloud liquid water amount, the greater the aerosol number, the greater the number of (smaller) cloud droplets, leading to an increased cloud albedo. The black full line in figure 5 is an estimate of mean annual cycle of CDNC, at 1km altitude, derived from the MODIS satellite instrument. A peak in CDNC is seen in the austral summer (November to February), coincident with maximum surface marine biological activity. The black dashed line in figure 5 (labelled DMSx0) is when the UKESM1 atmosphere is run with only sea-salt emissions active (i.e. non marine biological contribution to aerosol emission). This can be considered as the "background" CDNC over the Southern Ocean. Inclusion of DMS emission, linked to the Lana DMS climatology (labelled DMSx1.0) results in the red dashed line, with a weak summer season maximum in CDNC. The full and dashed blue lines represent maximum and minimum values of CDNC based on the extremes of the quoted uncertainty ranges in the Lana climatology. In GC31 we account for the lack of PMOA emissions by scaling the simulated DMS emissions by x1.7 (Mulcahy et al. 2018), this results in the red full line, with a large annual cycle of CDNC, closer to the observed estimates. Finally, in light blue are two UKESM1 atmosphere simulations where the 1.7 scaling on DMS has been removed and the Gantt et al. (2012) PMOA emission parameterization included. The two lines differ in the scaling applied to the organic mass fraction assumed to be associated with sea salt in the Gantt scheme. Clearly, the amplitude of the CDNC annual cycle increases after addition of the PMOA emission scheme, bringing the summer season CDNC close to the MODIS observations.
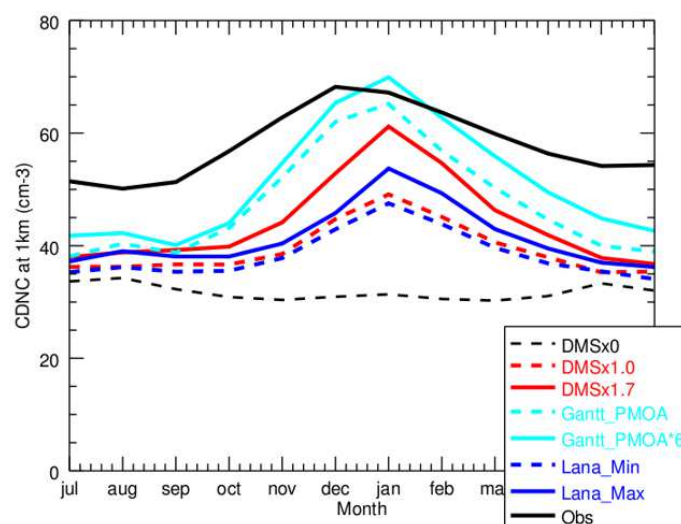
Figure 5. Mean annual cycle of cloud droplet number concentration (CDNC) over the Southern ocean, derived from MODIS observations (full black line) and from various configuration of the UKESM1 atmosphere (see text for details).

3. **Mineral dust in UKESM1**

The representation of mineral dust in UKESM1 is based on the same well-tested scheme used in HadGEM3 (Johnson et al. 2016) and the predecessor UK Earth system model used in CMIP5; HadGEM2-ES (Woodward, 2011). Minimal changes were introduced to UKESM1 compared to the current HadGEM3-GC3.1 configuration. These include; 1) Dust emission from seasonal sources in vegetated areas was switched off, as its inclusion increases the dependence of dust on the interactively simulated vegetation, which had been seen to cause problems in earlier work with HadGEM2-ES; and 2) the dust scheme was retuned for the new model, with the 3 tuneable parameters adjusted empirically to provide the best agreement with observations of dust concentrations, AODs, deposition rates and size distributions. Some tuning of the vegetation scheme was also performed, which improved the representation of bare soil fraction and hence dust source areas. Through this approach, an acceptable dust simulation was achieved without the need for preferential source areas to limit emissions, as required in many models.

A comparison of near-surface dust concentrations and AODs from a UKESM1 historical run (1990-2009) with observations from the University of Miami network and AERONET is shown in figure 6, together with the equivalents from the coupled GC31 and the earlier ESM HadGEM2-ES. In UKESM1 Atlantic dust concentrations are well-simulated, whilst in the Pacific concentration are very slightly high and in the Southern Ocean low. AODs in the Sahel are also slightly low. Overall, however, the agreement with observations is good – certainly considerably better than HadGEM2-ES, and comparable to GC31. This improvement from the earlier model is largely due to improved ESM performance, most directly in the simulation of bare soil fraction. The dust scheme in each model the same apart from the use of preferential source areas in HadGEM2-ES, seasonal sources in GC31, and individual tuning for each.
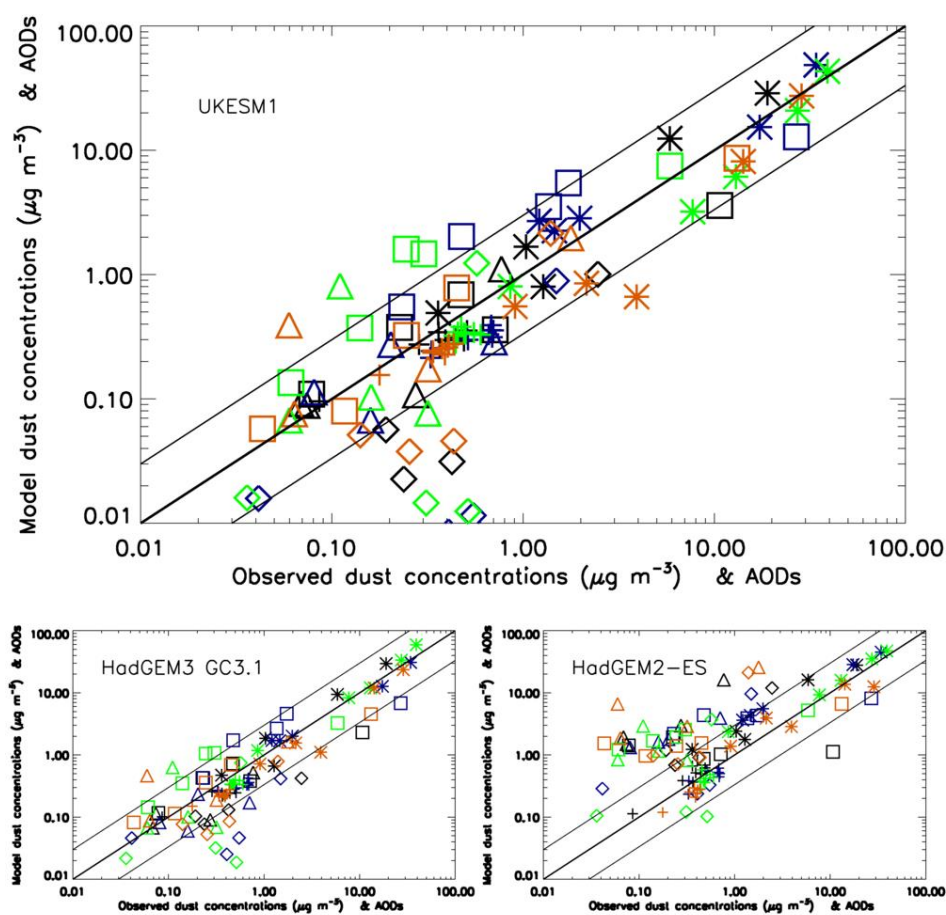
Figure 6. Seasonal mean near-surface dust concentrations and AODs from 20 years of UKESM1 (1990-2009), HadGEM3-GC3.1 (1990-2009) and HadGEM2-ES (1985-2004 - later data not available) plotted versus observations. Concentration data from University of Miami stations in the Atlantic (stars), N Pacific (squares), S Pacific (triangles) and Southern Ocean (diamonds), and AOD data from dust-dominated AERONET stations, mostly in the Sahel (crosses). Colours indicate seasons (djf black, mam blue, jja green, son red).

Tuning of the dust size distribution against observations was introduced for the first time in UKESM1. Normalised volume size distributions for the appropriate location and season were compared with data from the FENNEC campaign of June 2011 (Ryder et al. 2013), chosen as it included flights close to dust sources and measured a wide range of particle sizes, including very coarse sizes. Though dust concentrations and AODs were the primary tuning reference, where two or more combinations of settings gave similar performance against these data, the one which produced the better size distribution was chosen. Figure 7 shows that the size distribution from a UKESM1 historical simulation agrees well with observations across almost the whole modelled range, and is very close to the observational mean for the 4 central size bins. In UKESM1 the concentration of the largest particles in the 20-63 micron diameter bin is just below the mean from the observations, possibly due to the difference between model monthly means and observations taken preferentially during dusty periods, as local dust events give higher concentrations of the largest particles which fall out of the atmosphere very rapidly. The cause of the small low bias of the finest particles is not yet clear: it may be due to a bias in emission size distribution or to underestimated emission flux remotely from the measurement area. Comparison of a climatological mean from the model with data from a

single measurement campaign is not expected to be exact, though it is still indicative and useful in the absence of long-term measurements of such size distributions.

The results of this initial assessment of dust in UKESM1 are encouraging, particularly the level of agreement with observations given that the dust scheme is driven by an earth system model, where the additional processes and feedbacks inevitably complicate the simulation of fields such as bare soil, wind-speed and soil moisture, on which dust emissions strongly depend. A realistic simulated size distribution will help deliver a good simulation of the size-dependent dust processes including, most importantly, the radiative impact.   With the assessment of present-day performance complete, the dust simulation within UKESM1 will be used, both to investigate the behaviour of the mineral dust itself and to assess its impact on climate through radiative and biogeochemical mechanisms within the full earth system.
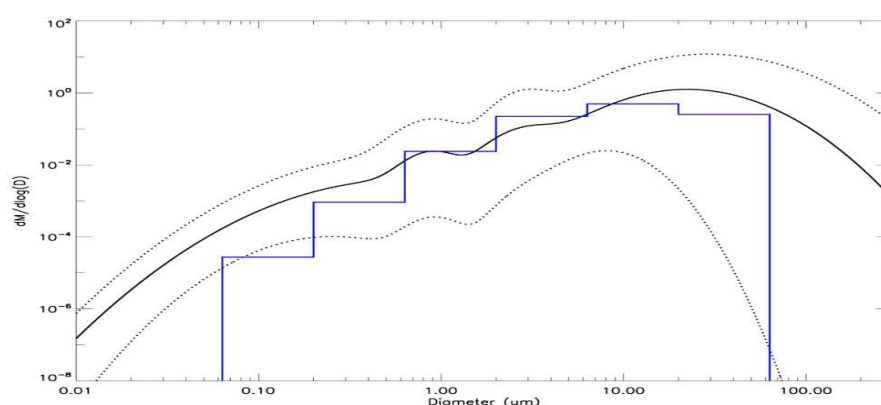

Figure 7. Normalised dust mass size distributions from UKESM1 historical run and lognormal fit to minimum, maximum and mean of FENNEC data (Ryder, 2013). UKESM data is the mean of 20 Junes (1990-2009), from NW Sahara (12-6W, 21-26N), level 2 (approx 50m).

4.   Trace gas atmospheric chemistry in UKESM1

Gas-phase chemistry in UKESM1, is modelled interactively using the United Kingdom Chemistry and Aerosol (UKCA; *http//:www.ukca.ac.uk*) model. UKCA simulates gas-phase chemistry throughout the depth of the atmosphere, combining the stratospheric chemistry from Morgenstern et al. (2009) with the tropospheric "TropIsop" chemistry scheme from O'Connor et al. (2014). Photolysis rates are calculated interactively using Fast-JX (Neu et al. 2007; Telford et al. 2013) and respond to changes in surface albedo, cloud amounts, and overhead ozone column. Further advances in the treatment of gas-phase chemistry and its interactions with other Earth System components in UKESM1 include:

(i)   Interactive terrestrial emissions of isoprene and monoterpenes (Pacifico et al. 2011).
(ii)   Production of secondary organic aerosol precursors (Kelly et al. 2018) for the aerosol component of UKCA; GLOMAP-mode (Mann et al. 2010; Mulcahy et al. 2018).
(iii) Feedbacks onto radiation from whole-atmosphere methane, ozone, nitrous oxide, as well as water vapour from methane oxidation in the stratosphere and lower mesosphere.

Here we present two examples of simulated ozone from one of the UKESM1 historical experiments, comparing the period 2000-2010 from this run against available observations. Figure 8 compares regionally aggregated tropospheric ozone on different pressure levels

against ozone observations. Figure 9 compares vertically resolved ozone against a new observational data set (Bodeker et al. 2013), plotted as a function of latitude and height and as a scatter plot (model against observations) for different latitude bands.
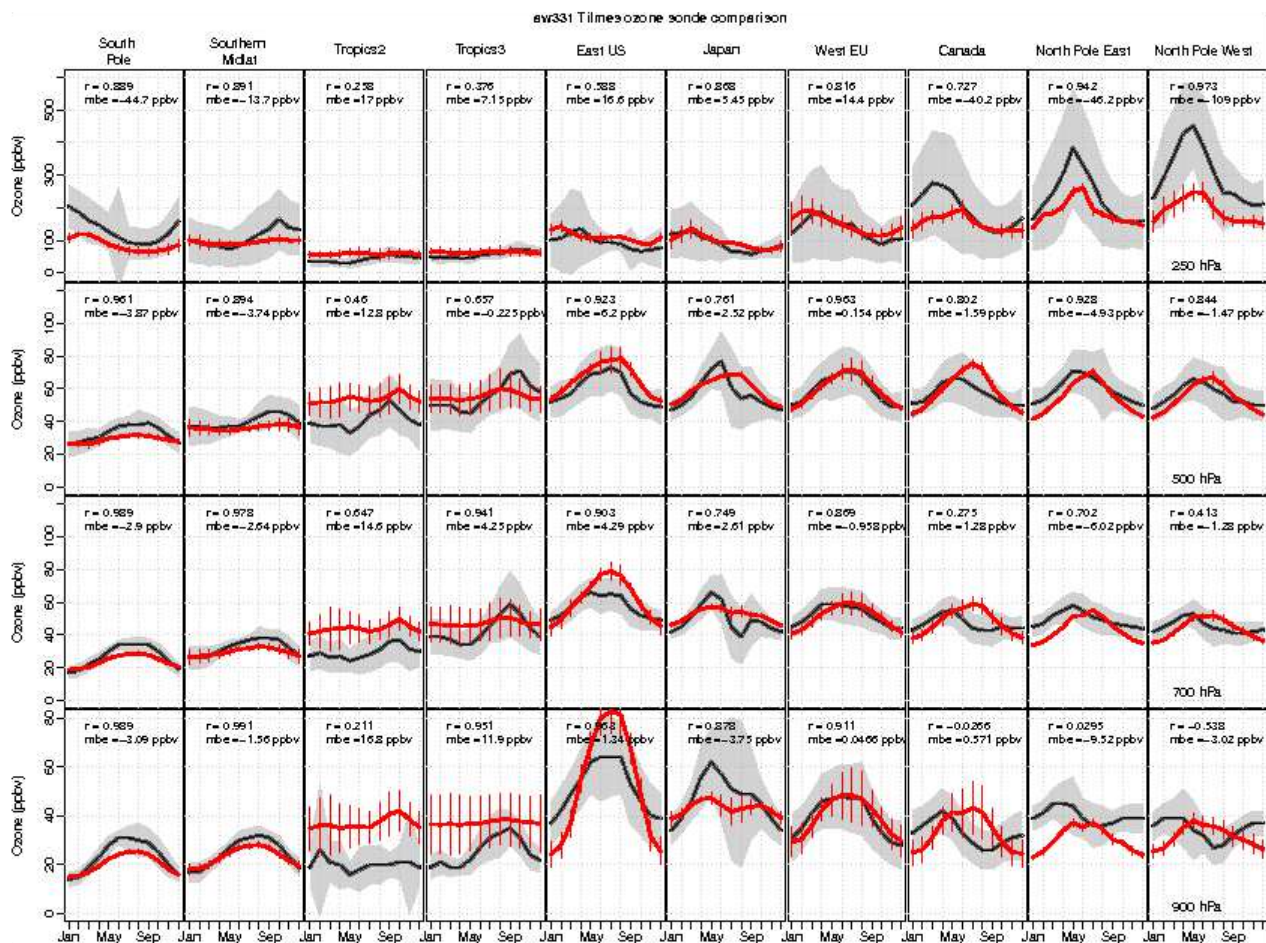

Figure 8: Comparison of the seasonal cycle in modelled ozone for 2000-2010 from one UKESM1 historical simulation against the observational dataset of Tilmes et al., 2012

While there are some discrepancies, on the while both tropospheric and stratospheric ozone appears to be well simulated in UKESM1. The new capability for full atmosphere coupled climate-chemistry interaction provided by UKESM1 represents an excellent tool for community-wide composition-climate studies.
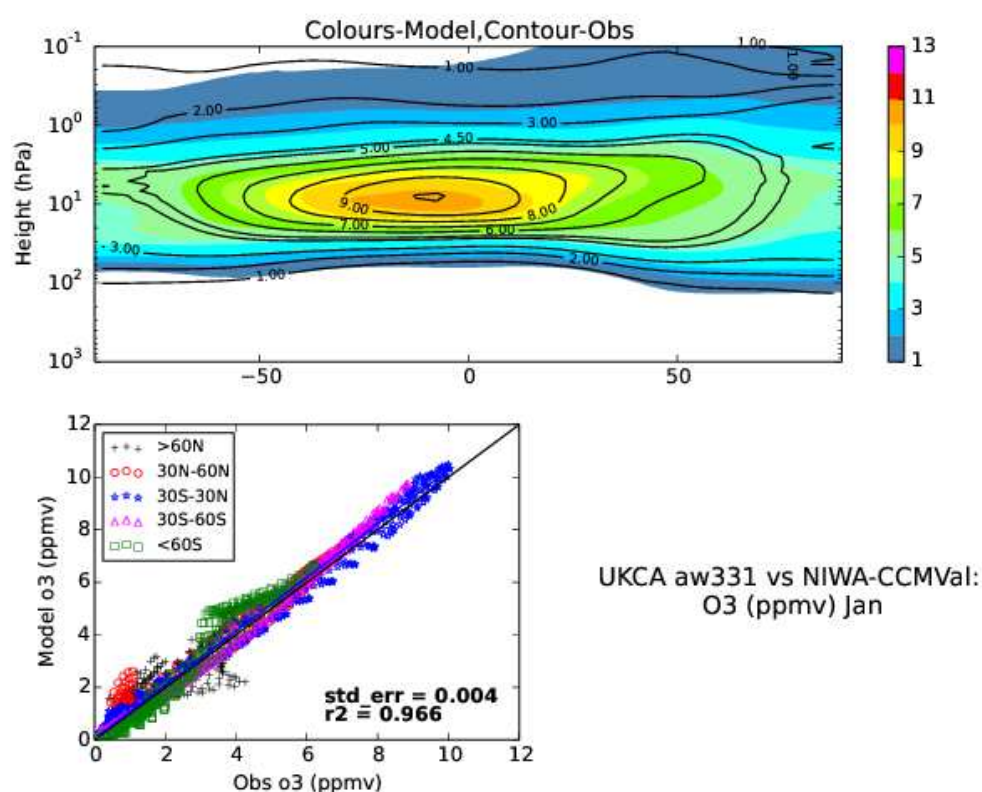
Figure 9: Comparison of vertically resolved modelled ozone in January for 2000-2010 from one of the UKESM1 historical transient simulations against a climatological observational dataset (Bodeker et al., 2013).

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UKESM1 beneath the waves

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As it stores the majority of the excess heat and carbon dioxide (CO_2) associated with climate change (both ongoing and into the future), the World Ocean is a critical component of the Earth system – and therefore UKESM1. Any imbalances in how the ocean interacts with other components of the modelled Earth system can translate into discrepancies between the real climate we see, and the climate we simulate within UKESM1.

The ocean part of UKESM1 is composed of three distinct submodels. NEMO – the Nucleus for European Modelling of the Ocean – is the underpinning ocean general circulation model (OGCM) responsible for the currents, vertical stratification and overturning circulation that govern the ocean and its heat store. CICE – the community sea-ice model – represents the important veneer of sea-ice that seasonally regulates ocean-atmosphere interactions at both poles. Finally, MEDUSA – the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification – simulates both seawater chemistry and the living systems of the ocean, which together play a critical role in the marine carbon cycle.

As reported in a previous issue of the UKESM Newsletter [https://ukesm.ac.uk/portfolio-item/spinning-marine-biogeochemistry-ukesm1/], the process of "spin-up" is important before UKESM1 can formally begin CMIP6 experiments. Put simply, because our understanding of the Earth system – and our models of it – are incomplete, our simulated climates are always slightly different from the real climate. So when we start a model from what we see around us now, its forecast for future change will be biased as it drifts towards its own preferred climate at the same time. To counter this, we bring our models into balance through spin-up such that the future changes we simulate are driven primarily by anthropogenic emissions and activities (and their feedbacks) and not drift.

In the case of UKESM1, our spin-up had a total simulated duration of more than 5000 years, which took more than a year of real time. The majority of the spin-up made use of the model in ocean-only mode. In this, the ocean experienced the atmosphere at its upper surface as a forcing dataset of properties such as temperature, winds and downward fluxes of heat and freshwater. We did this because, relative to the ocean, the atmosphere is highly computationally expensive to run. So while UKESM1 can simulate more than 30 years per day when run ocean-only, it struggles to break 4 years per day when run fully coupled. However, we still used UKESM1's atmosphere to provide the dataset that forces ocean-only mode. And towards the end of our spin-up, we switched to fully-coupled mode for all UKESM1 components to reach a final balance.

Throughout spin-up activity and beyond, UKESM1 performance has been evaluated to ensure realistic behaviour across all of its components. Figures 1-3 illustrate this validation process for the ocean components of UKESM1, from the spin-up itself, through to our use of the pre-industrial initial condition that it provides in CMIP6 experiments. Some of the results here focus on key CMIP6 simulations of the historical period up to the present-day – the period when our best observational data are found, and when anthropogenic change is greatest to date.

Figure 1 presents the time-series of two key metrics of UKESM1 over the last 3000 years of the spin-up period, with different colours denoting phases that differ in forcing / tuning regimes – the first phase ocean-only, and the latter fully-coupled. Figure 1a shows the strength of a major ocean transport, the Atlantic Meridional Overturning Circulation (AMOC), a key indicator of poleward ocean heat transport. Compared to present-day observations (~17 Sv), both ocean-only and coupled, show a strong and stable AMOC close to that observed (~16 Sv), and this agreement is found to improve in our historical simulations up to the present-day. Figure 1b shows the corresponding time-series of air-to-sea flux of CO_2, something that we want to be close to net zero in the pre-industrial equilibrium state. UKESM1 approaches this throughout the spin-up, ultimately being well within our target of 0.1 Pg C y^{-1} (current ocean uptake of anthropogenic CO_2 is ~2.5 Pg C y^{-1}). Overall, both panels show UKESM1's path to equilibrium as well as its strong interannual variability in ocean-only and coupled modes.
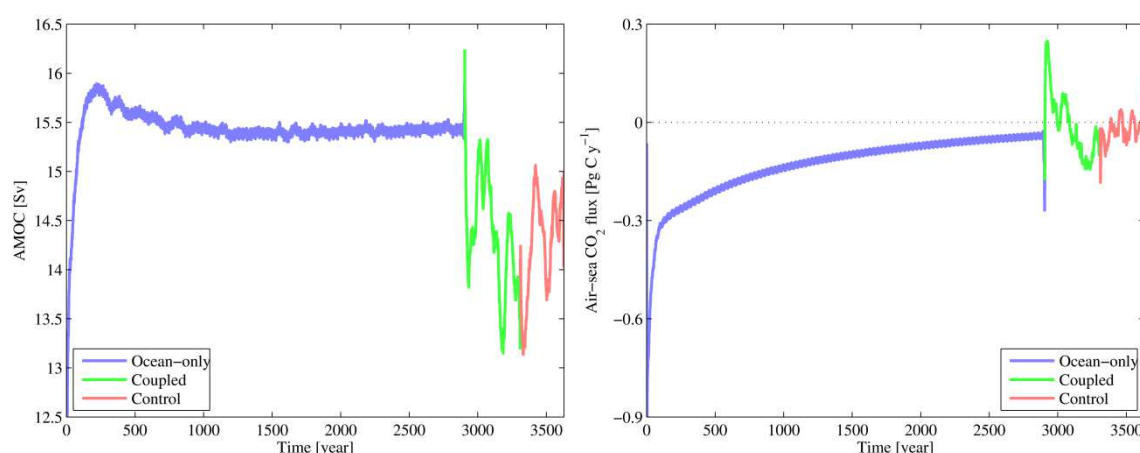

Figure 1: UKESM1 properties during the last 3000+ years of ocean-only (blue) and coupled (green) spin-up, followed by CMIP6 control (red). (a) Atlantic Meridional Overturning Circulation strength at 26˚N, slightly below the observed ~17 Sv. (b) Total air-to-sea flux of CO_2, where a net zero flux would be ideal, but a target of < 0.1 Pg C y^{-1} is sought. Both properties are smoothed to 30-year averages.

Figure 2 shows comparisons of UKESM1's present-day ocean state to observations. In Figure 2a, the model-observations difference in sea surface temperature (SST) is shown, while Figures 2b and 2c shows observational and model distributions of Arctic sea-ice at its seasonal maximum. In both, the simulated ocean and sea-ice properties generally show good agreement with the real Earth system, alongside some discrepancies. For example, a persistent problem with UKESM1 is the so-called "blue spot of death" in North Atlantic SST, where the model has a strongly localised anomaly with respect to observations – this is caused by a poor representation of the Gulf Stream, and is not uncommon in such low resolution models. Generally, UKESM1 is cooler than the observed climate, with more sea-ice as a result. These differences partly reflect biases in UKESM1's representation of the climate, and partly inevitable mismatches due to the chaotic nature of the system.

Finally, Figure 3 focuses on marine biogeochemistry, and the uptake of anthropogenic CO_2 by the ocean during the historical period (1850-2010). The observationally-estimated uptake is shown by the black line, with the shaded area indicating uncertainty. Currently, UKESM1's historical simulation has 7 ensemble members – these are repeated simulations with slightly different initial conditions – and these are shown in different colours here, with not all of them

reaching year 2010 yet. Again, the general agreement is good, with the ensemble tracking the observed estimate.
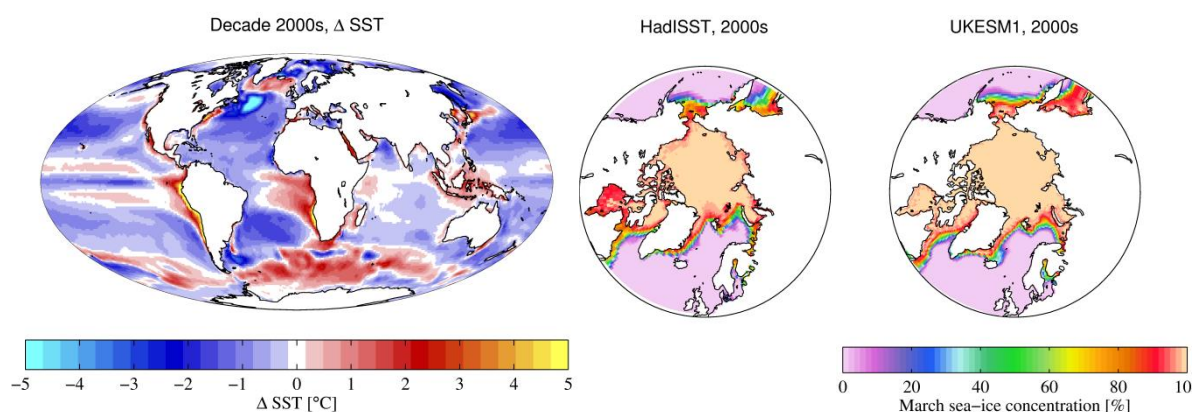

Figure 2: (a) UKESM1 difference with respect to observations (HadISST) for the period 2000-2009; (b) Observational seasonal-maximum sea-ice concentration for the period 2000-2009; (c) UKESM1 seasonal-maximum sea-ice concentration for the period 2000-2009.
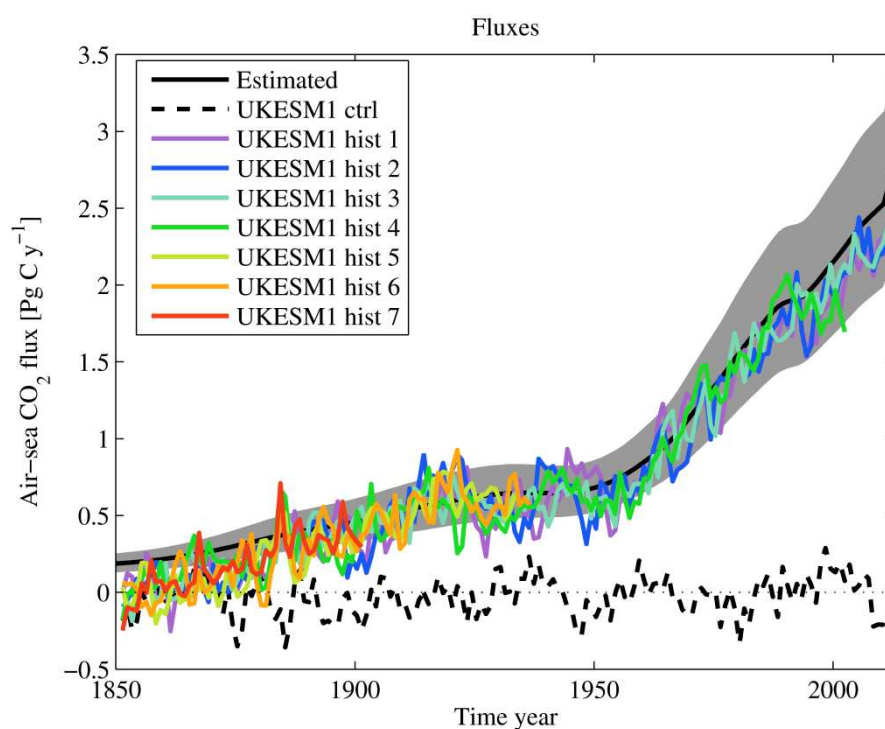

Figure 3: Observationally-estimated (black, with grey shading for uncertainty) and UKESM1 simulated uptake of anthropogenic CO_2 by the ocean over the historical period (1850-2010). UKESM1 output is shown for 7 ensemble members, of which only the first 3 have completed the full period. UKESM1's control simulation is shown as a black dashed line.

In summary, over the ocean system as a whole, UKESM1 performs well. Analysis is continuing and this will finally make use of a broader suite of simulation ensemble members as these become available during CMIP6 work. More details of UKESM1 are currently forthcoming, including full documentation of its spin-up and comprehensive evaluations of its performance.

UKESM1 global carbon cycle and diagnosed historical fossil fuel emissions

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A key aspect of Earth System Models (ESM) that distinguishes them from their Global Climate Model (GCM) counterparts is the representation of biogeochemical processes. The most crucial to understanding climate change is the carbon cycle. Both the land and oceans currently act as sinks for anthropogenic CO_2 from fossil fuel emissions and land use change. In fact, only around 50% of anthropogenic CO_2 remains the atmosphere the rest is taken up by the land and ocean, through plant growth (CO_2 is a plant fertiliser) and dissolution into the oceans (Le Quere et al., 2018; Global Carbon Budget). The ability to accurately capture these processes is crucial for Earth System Models such as UKESM1. UKESM1 includes the state-of-the-art MEDUSA and JULES-ES marine and terrestrial biogeochemical models.

Despite extensive testing and coupling of individual components, this is the first time we are able to look at how these model components combine to represent the full global carbon cycle and it's behaviour over the 20th century. Results are encouraging. **Figure 1** and **Figure 2** show respectively, ocean and land carbon uptake simulated from pre-industrial (1850) to present day, in the context of the CMIP5 multi-model ensemble.

UKESM1 simulates 20th century cumulative carbon uptake by the ocean (**Figure 1**) in agreement with the low end of observational estimates. This is in common with most CMIP5 ESMs and very similar to HadGEM2-ES. A much more stringent test will be analysis at regional and ocean-basin scales, where CMIP5 models diverged more from observations and from each other (Hewitt et al., 2016).
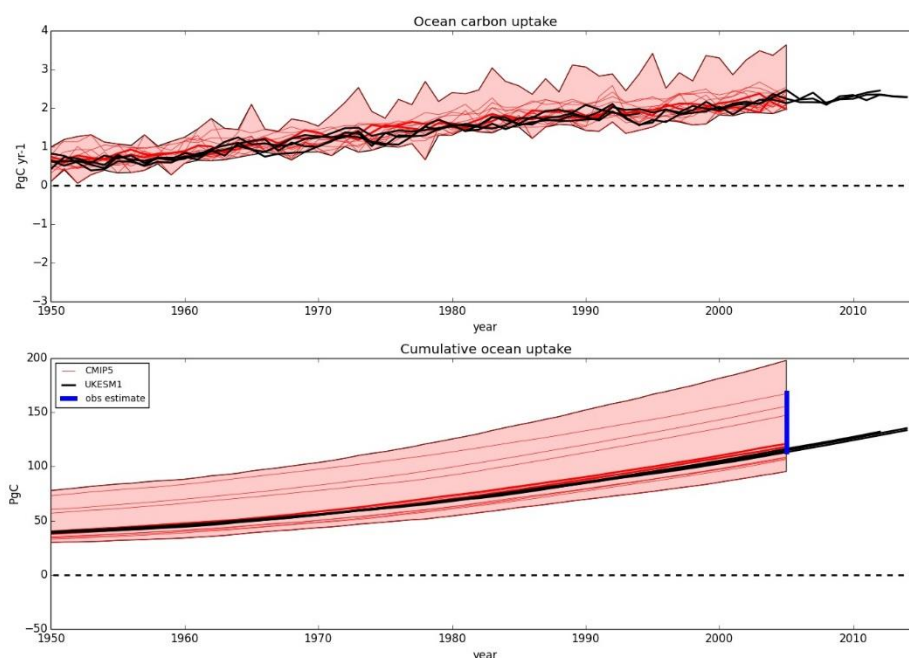

Figure 1. Ocean carbon uptake. (a) year-on-year flux of carbon into the ocean (PgC yr⁻¹) for CMIP5 models (individual models in red lines, of which HadGEM2-ES is thick red line, and multi-model range in pink shading) compared with UKESM1 4 Historical ensemble members (black lines). Panel (b) shows the time integral of the annual fluxes (PgC), with an observational estimate (see Jones et al., 2013) marked in blue for the year 2005.

Similar global-scale analysis of carbon uptake on land also shows agreement with observational estimates (**Figure 2**). Not all CMIP5 models were within the observational estimate, and so it is encouraging that UKESM1 achieves this. More analysis is required to determine if this is being achieved for the correct reasons –although we already know that UKESM1 behaves more differently from HadGEM2-ES than this global total suggests: panels (b) and (c) show that its response of both vegetation and soil carbon is less than in HadGEM2-ES. HadGEM2-ES loses more vegetation carbon than UKESM1 – this is likely due to changes in the way we implement land-use forcing in UKESM1, where "rangeland" used for pasture is not actively deforested. This was not the case in HadGEM2-ES resulting in a greater degree of deforestation and loss of biomass. Conversely, HadGEM2-ES simulated a significant increase in soil organic carbon store – again weaker in UKESM1. Some of this difference may also be related to the change in land-use implementation, but some is also connected to the introduction of a new terrestrial nitrogen cycle scheme.
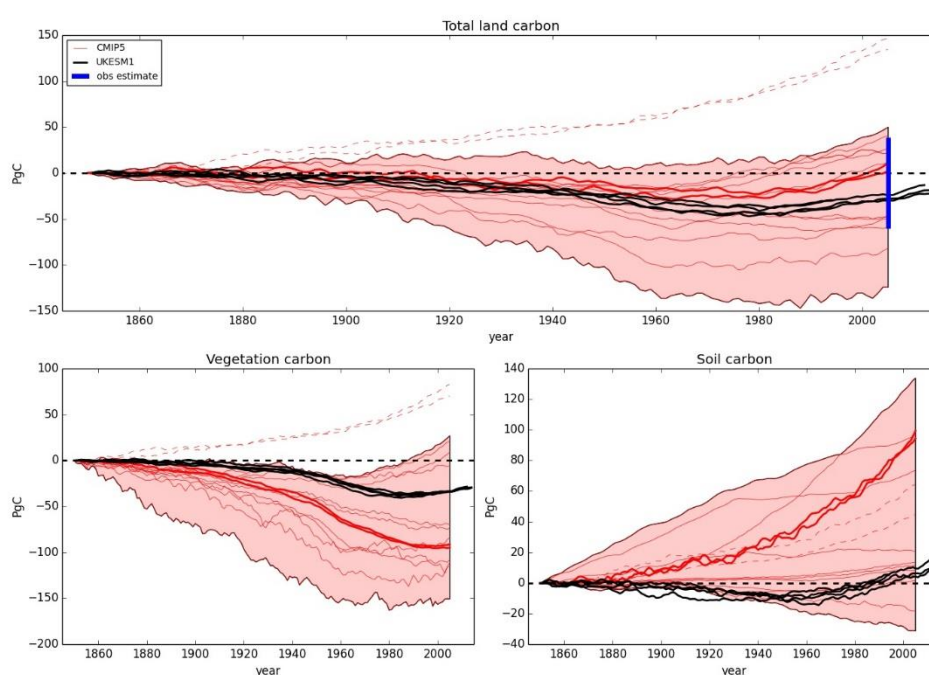

Figure 2. Changes in land carbon pools (PgC): (a) total terrestrial carbon made up of (b) Vegetation carbon (living biomass) and (c) Soil organic matter (including dead litter carbon). Colours, as figure 1, UKESM1 ensemble members in black, CMIP5 models in red with HadGEM2-ES indiciated in thick red. Observational estimate on total change relative to pre-industrial in blue for 2005.

Putting the global ocean and land fluxes together, allows us to diagnose the full global carbon cycle in the form of the anthropogenic fossil fuel emissions diagnosed from the simulations. It is standard practice to use CO_2 concentrations, instead of CO_2 emissions, to drive a model and use the modelled carbon fluxes to diagnose compatible fossil fuel carbon emissions (IPCC AR5, Ciais et al., 2013, Box 6.4). If we want to use the model to provide advice on future carbon budgets to achieve specific climate targets, then it is crucially important UKESM1 does a good job recreating these historical emissions.

Figure 3 compares UKESM1 (solid black) against actual emissions (black dashed) and the CMIP5 model range (red). As can be seen, UKESM1 does a good job capturing these

emissions. This increases our confidence in using UKESM1 to understand future emission pathways.
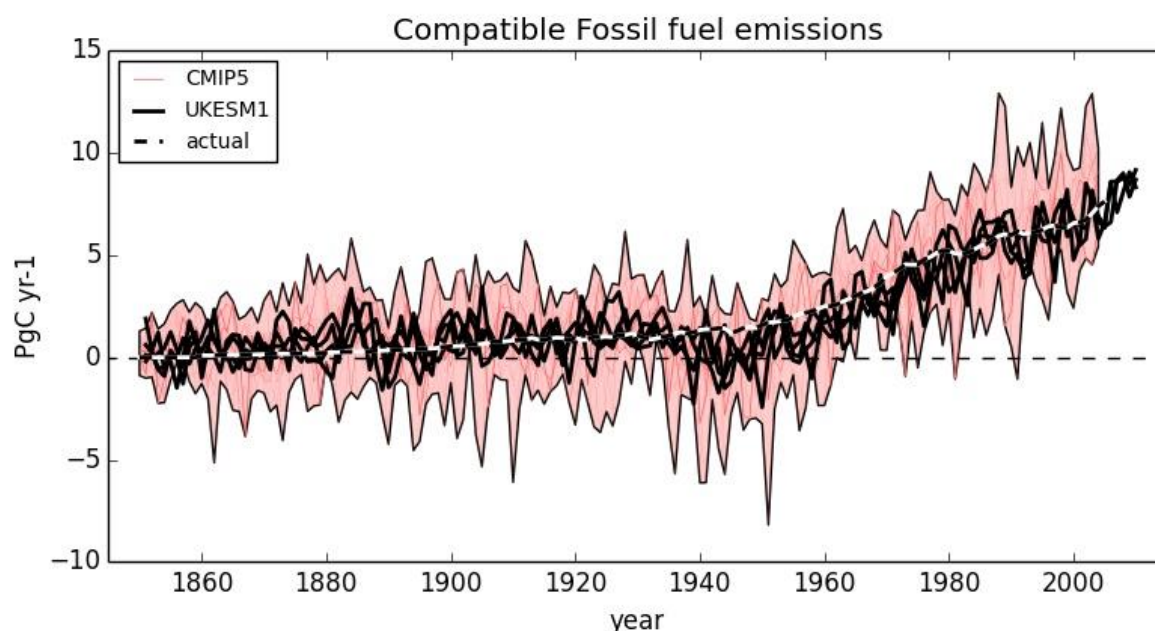

Figure 3. Historical fossil fuel emissions. By inverting the carbon budget in the UKESM1 Historical simulations driven with observed atmospheric CO₂ concentrations it is possible to derive the fossil fuel CO₂ emission (black solid) which can be compared to actual emissions (black dashed) and the CMIP5 multi-model range (pink).

In conclusion, an ensemble of UKESM1 Historical simulations have been analysed for it's global scale carbon fluxes and found to accurately simulate changes in both land and ocean uptake, and therefore reliably recreate the historical record of past fossil fuel emissions. This is an encouraging first result, but extensive further research is required to ensure these answers are correct for the right reasons – both in terms of the driving processes and the geographical location of carbon uptake and stores. This research is ongoing between the Met Office Hadley Centre Climate Programme, the UKESM-LTSM and the EU CRESCENDO project.

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The release and support of UKESM1

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Version 1 of the UK Earth System Model (UKESM1) has been in development for the past five years. Built as a joint venture by the Met Office Hadley Centre and the Natural Environment Research Council (NERC), UKESM1 consists of the HadGEM3 coupled physical climate model (which represents important processes in the atmosphere, ocean, land and sea-ice domains) plus additional components that model key biogeochemical, chemistry, aerosol and vegetation processes (see Figure 1).
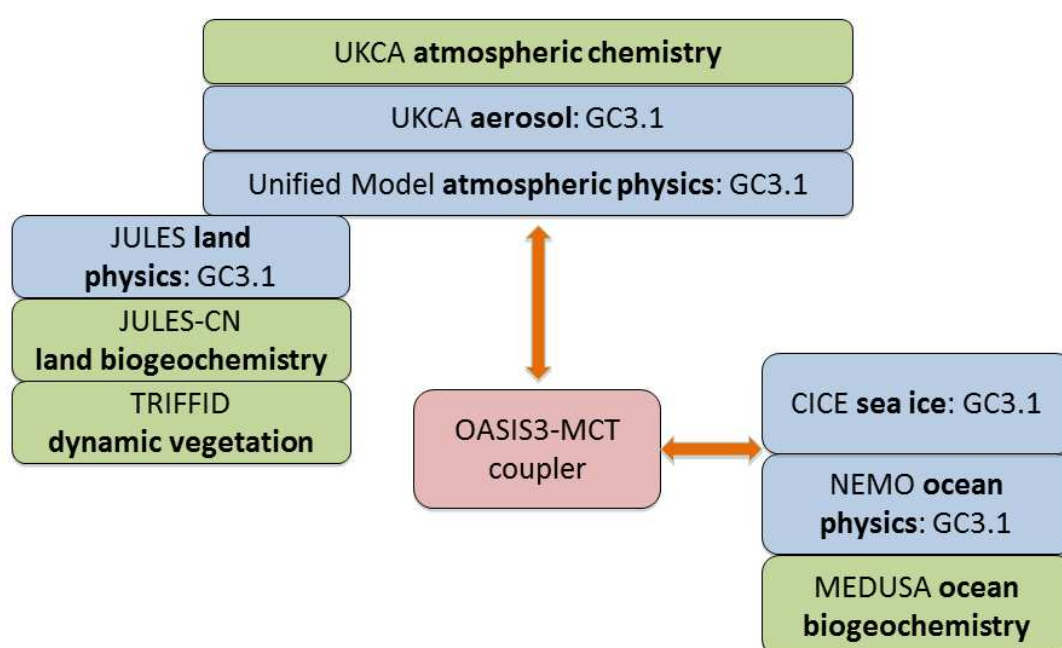

Figure 4. Schematic architecture of UKESM1. Components of the HadGEM3 physical model are coloured blue, additional earth system components are coloured green, and the coupler is coloured pink.

UKESM1 is currently being used as part of the UK contribution to the latest round of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP6). Some preliminary results from one of the so-called CMIP6 DECK experiments using UKESM1 are displayed in Figure 2. In these experiments, each UKESM1 historical run was started from a different coupled initial condition drawn from the UKESM1 pre-industrial control (piControl) simulation. Each historical member is plotted starting from 1850, the date at which anthropogenic emissions are introduced into the model. The large (and relatively short) negative spikes denote major volcanic eruptions in the historical period – Krakatoa (1883), Agung (1963) and Pinatubo (1991) being the three largest events – that cause a temporary global cooling. The gradual increase in positive energy entering the ocean from ~1980 onwards is a result of the

imbalance in the top of atmosphere radiation budget caused by increasing anthropogenic emission of CO_2 and other greenhouse gases.

Plans have been drawn up for the release of UKESM1 to the climate research community. The model has already been ported to the shared MONSooN platform in order to aid collaboration between the Met Office and NERC, and will soon be made available on ARCHER, the UKRI national platform, thanks to our colleagues in the Computational Modelling Services (CMS) unit of the National Centre for Atmospheric Science.   As with other models, CMS will also provide front-line support (in collaboration with the UKESM core group) for UKESM1 after its release later this year.

UKESM1 will be delivered as a Rose suite (see Figure 3 for a snapshot from the control panel for the UKESM1 Rose suite). Rose is the Met Office framework for developing and running meteorological applications. We plan to deliver two configurations of the model:

- a fully coupled configuration, making use of all the components in Figure 1, and

- an atmosphere-only (so-called AMIP) configuration, in which the model atmosphere is forced by observed sea surface temperature and sea ice boundary conditions.

The coupled configuration will be set up to run the CMIP6 historical experiment; switching it to run the pre-industrial control experiment will require only a different set of forcing data.
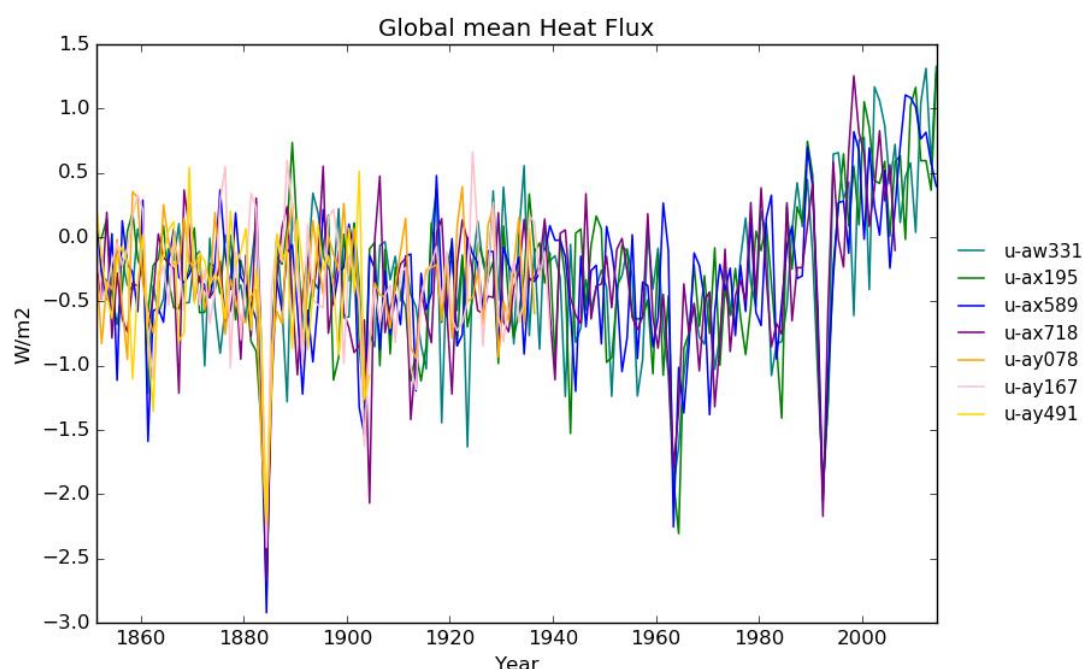

Figure 5. Preliminary results from historical simulations for seven UKESM1 runs showing global mean heat flux into the ocean in watts per square metre (positive values indicate heat entering the ocean).

The model is currently undergoing final scientific testing. Following its port to ARCHER and other platforms (specifically, MONSooN and NEXCS in the UK, plus those used by our overseas collaborators), UKESM1 will be made available as a beta version to a selected group of users, before being released to the climate modeling community later this year. In addition to the full UKESM1 release, we are working on a number of extensions to this first release. These include; (i) A version of UKESM1 (referred to as UKESM1-CN) which retains the full interactive treatment of the global carbon cycle, but runs with prescribed chemical oxidants and ozone rather than interactive atmospheric chemistry. This configuration runs ~50% faster than the full model, and will be useful for experiments not requiring the more complete treatment of atmospheric chemistry available in the UKESM1. (ii) Inclusion of interactive modules for the Greenland and Antarctic ice sheets, referred to as UKESM1-IS. We aim to release these extensions to UKESM1 in late 2018 or early 2019.

For further information, or to be kept informed about the release, please contact Jeremy Walton (jeremy.walton@metoffice.gov.uk).
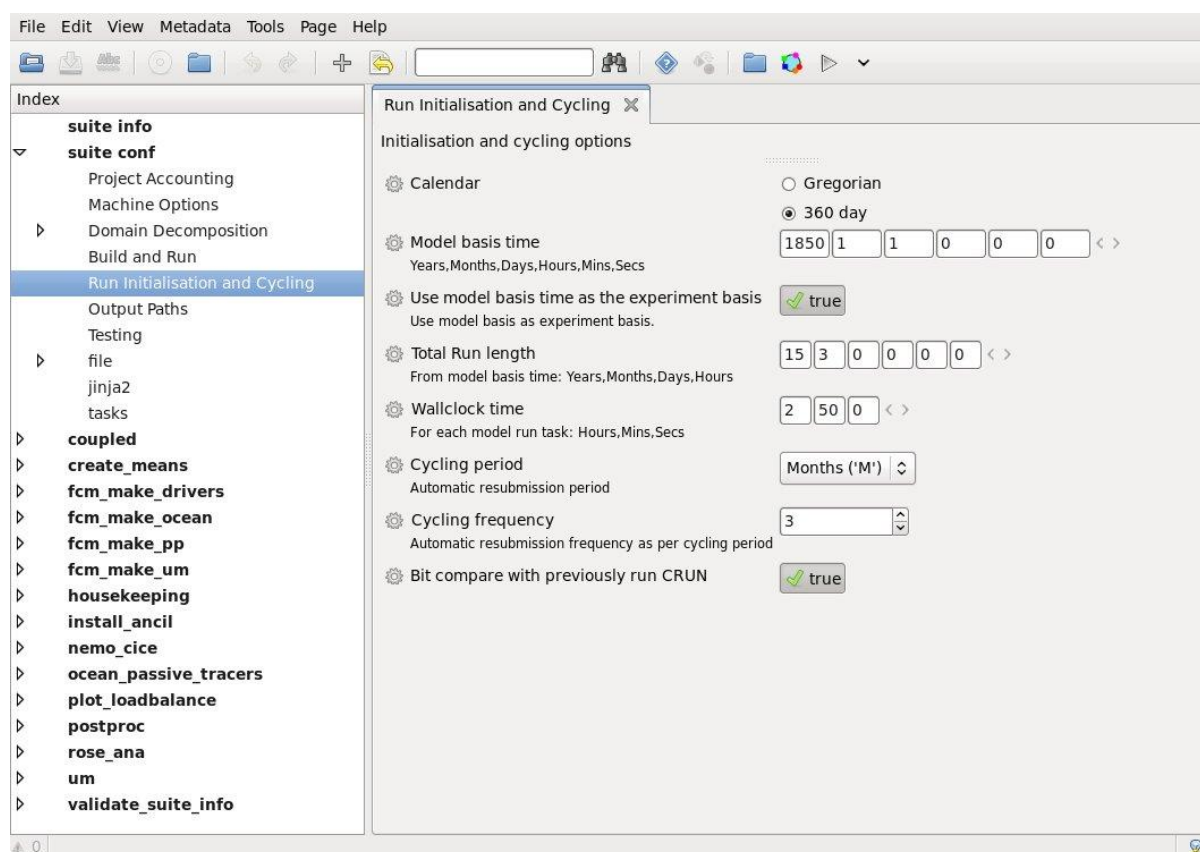

Figure 6. Part of the control panel in the UKESM1 Rose suite. This pane allows the user to set the run duration, wallclock time, job resubmission period and other parameters associated with the run.

Future events

9 -10 July 2018 - UKESM LTSM annual meeting – Met Office, Exeter:

This year, the LTSM project celebrates its annual meeting at the Met Office Headquarters in Exeter. The meeting will run for two full days. Day 1 will include a special session dedicated to the UKESM1 model release, plus a number of presentations on broader research occurring within the UKESM-LTSM, with invited speakers and posters from the contributing NERC centres. Day 2 will be centred around project business, specific break groups future science plans (**download the meeting agenda here**).

Recent past events

26 March 2018 – Data Sciences for Climate and the Environment – The Alan Turing Institute, London:

This one-day workshop was focussed on how new tools being developed in data science can be applied to questions relating to climate and the environment in order to help address the challenges which our society is facing on a rapidly changing planet.

Collectively, we are modelling and monitoring our planet better than ever as a result of sustained efforts from the climate modelling community and space agencies. Climate and weather models can now be run at finer spatial resolutions, enabling more realistic simulations of smaller scale processes (e.g. tropical cyclones in the atmosphere or eddies in the ocean) that can have severe impacts on our planet. At the same time there is a rapid growth in the number of satellites orbiting the Earth, with a significant fraction of these satellites dedicated to Earth Observation using a variety of sensors working at different electromagnetic frequencies. Our ability to store, process and efficiently share the vast amounts of data that are produced by the modelling and remote sensing communities is a pre-requisite for the effective functioning of these large research programmes.

The workshop featured five keynote speakers from the US and the UK who presented on their work on producing, processing, sharing and analysing climate data. They included **Jeremy Walton** from the UKESM core group, who described climate modelling using UKESM1 and the UK efforts to produce, convert and manage climate model data for CMIP6. The workshop concluded with a panel dialogue between the speakers and members of the audience.

More information about the event can be found here. The proceedings were filmed – see here for the videos of the talks, and panel session.

4-8 June 2018 - 4th International Symposium on The Effects of Climate Change on the World's Oceans – Washington, USA:

Team member **Andrew Yool** recently attended the 4th International Symposium on The Effects of Climate Change on the World's Oceans (4-8 June 2018), organised by Pacific ICES. Andrew presented work on size-structured benthic communities, and how these will potentially change into the future using scenarios of change provided by NEMO-MEDUSA (in a slightly earlier form to that used in UKESM1). In summary, these communities are

entirely dependent on food imports from the near-surface plankton, so changes in the activity of the latter (especially in how material is exported downwards from it) are key. The benthic model used in this work is not currently coupled to UKESM1, but there are plans for the inclusion of this submodel as part of ESM LTSM development activities for MEDUSA.

Team News

Recent additions to the UKESM Core Group:

Ranjini Swaminathan, National Centre for Earth Observation (NCEO) - University of Reading: Ranjini joined the UKESM Core Group in April 2018 as part of the NCEO contribution to the UKESM project. She will be involved in the development of science based diagnostics integrating observational data sets for model evaluation. Prior to joining the UKESM team, Ranjini was a research staff member at the Climate Science Centre at Texas Tech University, USA and at the University of Auckland, New Zealand where she developed computational models and machine learning algorithms for various climate science projects. Ranjini has a Ph.D. in Computer Science from The University of Arizona.

Collaboration with European Earth System models: IPSL-ESM:

In May and June 2018, UKESM core group member **Till Kuhlbrodt** spent six weeks in Paris with the team that develops and runs IPSL-ESM. UKESM1 and IPSL-ESM use the same physical ocean model NEMO with the same spatial resolution eORCA1 (approximately 100 km), while all other components (sea-ice, atmosphere, biogeochemistry) are different. While Till has configured and analysed NEMO eORCA1 for UKESM1, the same task for IPSL-ESM is done by Julie Deshayes and Juliette Mignot.
Till, Julie and Juliette have started assessing how the respective ir NEMO eORCA1 configurationsdiffer , and what impact these difference have on the simulatedclimate. In the completed CMIP6 simulations, it appears that in IPSL-CM6 (the physical climate model at the core of IPSL-ESM) the AMOC is weaker and more variable than in the UK models, while the Antarctic circumpolar current shows rather similar strength and variability. Several common publications are planned about the performance of NEMO eORCA1 in European Earth System models and on understanding differences in simulated large-scale ocean variability, and biogeochemistry.
Till's visit at IPSL was funded by the NCAS Visiting Scientist Programme.