Welcome to UK Earth System Model (UKESM) News from the Joint Weather and Climate Research Programme (JWCRP).

The UK Earth system modelling project is a joint venture between the Met Office and the Natural Environmental Research Council (NERC) to develop and apply a world-leading community Earth System Model.

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Results from the UKESM1 CMIP6 DECK and historical simulations

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The UKESM1 CMIP6 DECK is now largely complete, with the pre-industrial control (*piControl*) having run ~900 years and continuing. Six historical simulations are complete and a further six are running. A number of the historical runs will be extended to 2100, following a range of CMIP6 scenarioMIP emission pathways (O'Neill et al. 2016). A first set of scenarioMIP projections are planned to begin before the end of 2018. We have also completed the two climate change simulations: (i) abrupt 4xCO_2 increase (*abrupt-4xCO2*) and (ii) 1% transient CO_2 increase (*1pctCO2*), which help define the Effective Climate Sensitivity (ECS) and Transient Climate Response (TCR) of models. We are in the process of drafting a series of papers documenting the performance of UKESM1. These will appear in the peer-reviewed literature in 2019. Here we give a brief overview of some headline results from the UKESM1 DECK and historical runs.

UKESM1 science configuration and couplings

As a reminder, UKESM1 is built on the physical model HadGEM3-GC3.1 N96ORCA1 (Kuhlbrodt et al. 2018), extending it through inclusion of; (i) Interactive stratosphere-troposphere chemistry coupled to the GLOMAP-mode aerosol scheme (Mulcahy et al. 2018). (ii) A global carbon cycle, including terrestrial carbon processes with nitrogen limitation on carbon uptake and dynamic vegetation. Marine carbon cycle processes are represented by the MEDUSA2 model, within NEMO-ORCA1. A further configuration of UKESM1 (UKESM1-is) that includes interactive treatment of the Greenland and Antarctic ice sheets is under development, details of which can be found in the article by Smith et al. in this newsletter.

UKESM1 includes a range of couplings, between 'physical' and 'Earth system (ES)' components, as well as across domains of the coupled model (i.e. between the land, ocean and atmosphere). These couplings increase the realism (and degrees of freedom) of the model, enabling an investigation of potential Earth system feedbacks arising from future anthropogenic CO_2 emissions. The primary cross-domain model coupling is CO_2, exchanged between the atmosphere, ocean and land and allowing UKESM1 to run either with prescribed atmospheric CO_2 concentrations or with anthropogenic CO_2 emissions. Other important couplings include; (i) Dust emissions that depend on predicted vegetation cover and climate and influence aerosols and radiation processes in the atmosphere and are a source of soluble iron for the ocean. (ii) Biogenic Volatile Organic Compounds (BVOCs), emitted by vegetation and influencing model cloud-aerosol formation. (iii) Marine dimethyl sulfide (DMS) and Primary Marine Organic Aerosol (PMOA) emissions, coupled to MEDUSA-predicted seawater DMS and chlorophyll and acting as cloud condensation nuclei in the model atmosphere. Finally, concentrations of O_3, CH_4 and N_2O, simulated by the UKESM1 chemistry scheme are active in the model radiation parameterization. This degree of coupling likely makes UKESM1 the most "*Earth system complete*" model in CMIP6.

UKESM1 science performance

Pre-industrial control simulation *(piControl)*

As stressed in earlier newsletter articles, an important requirement of an Earth system model is a temporally stable (and realistic to the degree this can be established) simulation of the (unforced) pre-industrial climate. To this end, figure 1 shows global mean values of; left; top of atmosphere (TOA) net radiation (positive values indicating downward directed radiation), middle; global mean (for land points only) surface temperature and right; global mean surface temperature (for ocean points only). The dashed lines on the figure show values from the CMIP5 model, HadGEM2-ES. The UKESM1 net TOA radiation is centred on $0Wm^{-2}$, accompanied by long-term (i.e. on multi-century timescales) stable surface temperatures. Even though the *piControl* does not have any time varying external forcing, there is still evidence of variability in the simulated surface temperatures, particularly in the ocean, where an oscillation with a timescale of ~100 years is evident, particularly from 500 years into the *piControl*. This variability is most evident in surface temperatures over the Southern ocean around Antarctica and is linked to deep ocean overturning, periodic reduction in sea-ice extent and venting of deep ocean heat to the model atmosphere.

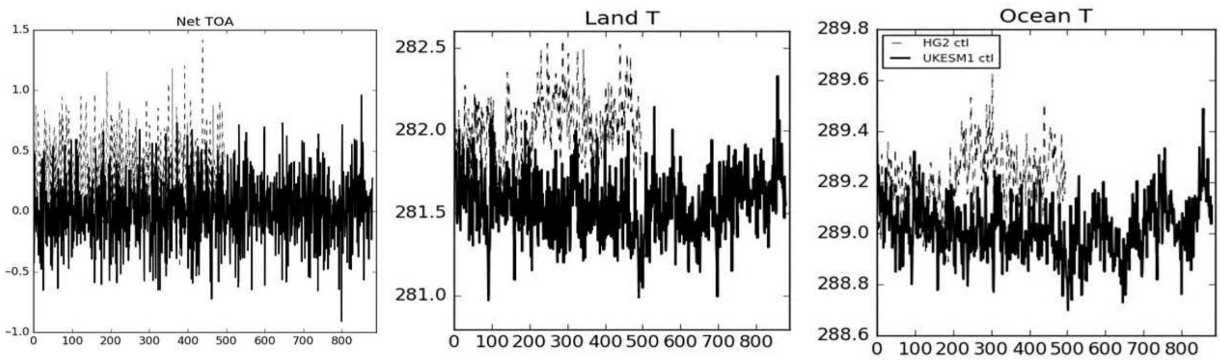

Figure 1: Global mean TOA net radiation (left), surface temperature, land points only (middle) and ocean point only (right) from ~900 years of the UKESM1 piControl (full black lines) and 500 years of the CMIP5 HadGEM2-ES piControl (dashed line).

Figure 2 illustrates the simulated global carbon cycle in the UKESM1 piControl. The left panel shows the global mean flux of carbon from the land to the atmosphere and the right panel the ocean to atmosphere flux. Thin black lines in the figure are a measure of inter-annual variability, while the thick black line is a 50-year running mean of the annual fluxes. Both land and ocean fluxes are essentially zero on long timescales, again with evidence of multi-decadal to centennial variability around the long term mean. The unforced nature of the piControl simulations requires, on sufficiently long averaging timescales, a zero global mean flux of carbon between the atmosphere and the land/ocean reservoirs.

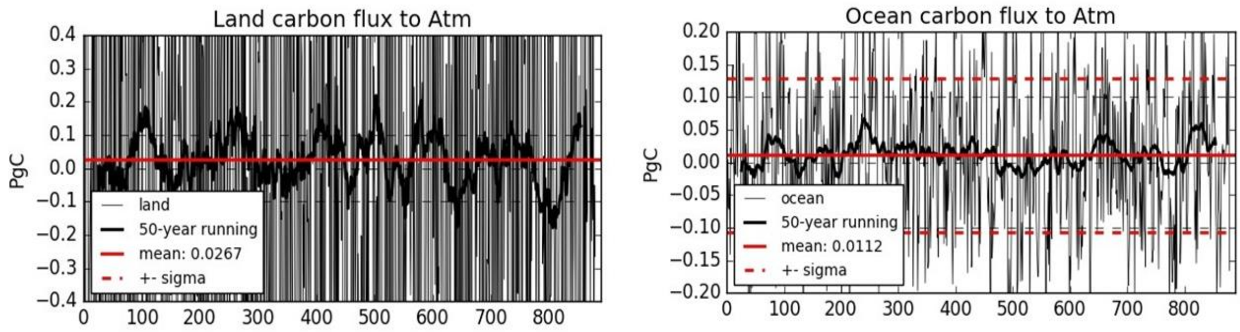

Figure 2: Global mean flux of carbon from land to atmosphere (left) and ocean to atmosphere (right) from the UKESM1 piControl. Thin lines are inter-annually varying fluxes, thick black line is a 50 year running mean flux and the red full line indicates the long term mean flux.

Historical Simulations

Extending the analysis of the UKESM1 carbon cycle, figure 3 shows cumulative global mean land carbon uptake (top panel) in the UKESM1 CMIP6 historical simulations (covering the period 1850-2014) and the cumulative marine carbon uptake (right panel) for 1950 to 2014 of the same simulation. Three UKESM1 members are show by the black lines in figure 3. Observational estimates for both carbon uptakes are shown by the vertical blue lines on the figure, centred on year 2005. The pink plume shows the spread in the CMIP5 multi-model ensemble.

UKESM1 terrestrial uptake sits close to the centre of the observed range for 2005, with the land losing carbon to the atmosphere until ~1980 (the approximate time where the black lines reach a minimum value in the figure), before becoming a sink for atmospheric carbon. The loss of terrestrial carbon is due to land use change (primarily loss of forest cover) while the later terrestrial uptake of carbon is due to the increasing atmospheric concentrations driving an atmosphere to land gradient in carbon and a resulting flux greater in magnitude than the carbon loss from land use change. Simulated ocean uptake is at the lower end of the 2005 observational estimates, but still within the observed range. The ocean has acted as a strong sink for atmospheric carbon from at least 1950 through to present day. Combining these two uptake terms with the atmospheric CO_2 concentrations prescribed in the CMIP6 historical runs, allows us to diagnose the historical (anthropogenic) carbon emissions compatible with the prescribed atmospheric CO_2 concentrations. These are shown in the lower panel of figure 1 (black full lines) and compared with actual historical emissions (dashed line). The UKESM1 compatible emissions track the observed emissions closely, suggesting the global-scale carbon cycle is accurately simulated. This will be important when we run the model in emission-driven mode. Here we do not prescribe atmospheric CO_2 concentrations but rather start the model from pre-industrial (PI) conditions and a PI estimate of atmospheric CO_2 and prescribe anthropogenic historical emissions, allowing the models carbon cycle to determine where this carbon goes between the Earth's reservoirs and on what timescales.

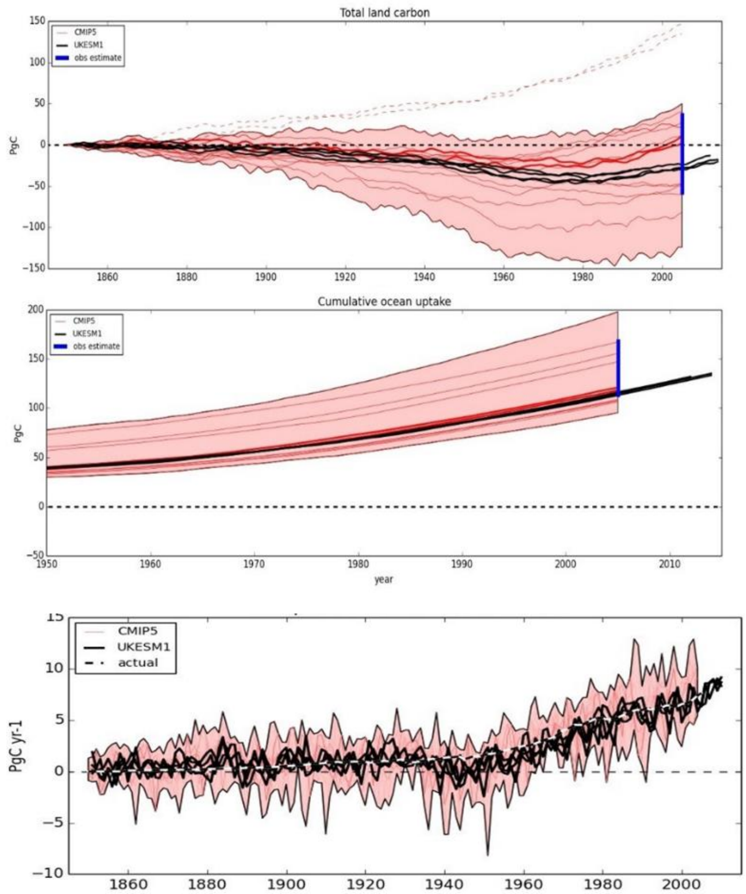

Figure 3: Top: Global mean cumulative terrestrial carbon uptake 1850-2014 from three UKESM1 historical simulations (black lines). The pink plume spans the CMIP5 multi-model ensemble and the blue vertical line is an observed range for 2005. Middle: As top panel but cumulative ocean carbon uptake for 1950-2014. Bottom: Diagnosed UKESM1 (black) carbon emissions compatible with the prescribed atmospheric CO_2 concentrations and simulated carbon uptake from the atmosphere. Observed carbon emissions are shown by the white dashed line and the CMIP5 ensemble by the pink plume.

In figure 4 we show another important performance metric for UKESM1, namely the model's ability to simulate the Antarctic ozone hole. We show the temporal evolution of total column ozone at the South Pole, simulated in two UKESM1 historical runs and from observations, the latter beginning in 1964. Monthly mean column ozone is shown for September, October, January and February through the entire historical simulation period. From the early 1970's both the model and observations depict a decrease in column ozone at the South Pole (indicative of the onset of the stratospheric ozone hole). This decrease reaches a minimum, both in the model and observations, around 2005. The observed annual cycle of the ozone hole shows a rapid decrease through September and October (the Antarctic spring) and subsequent dissipation, as the polar vortex breaks up in the following January and February (the Antarctic summer). Both the annual cycle of the growth and decay of the ozone hole and its overall development, from initiation in the early 1970's to minimum values around 2005, are well simulated. The overall magnitude of the ozone decrease also appears well captured by the model. For example, October column ozone decreases from ~310 Dobson units (DU) in the mid-1960s to a minimum of ~125 DU by ~2005, in line with observations.

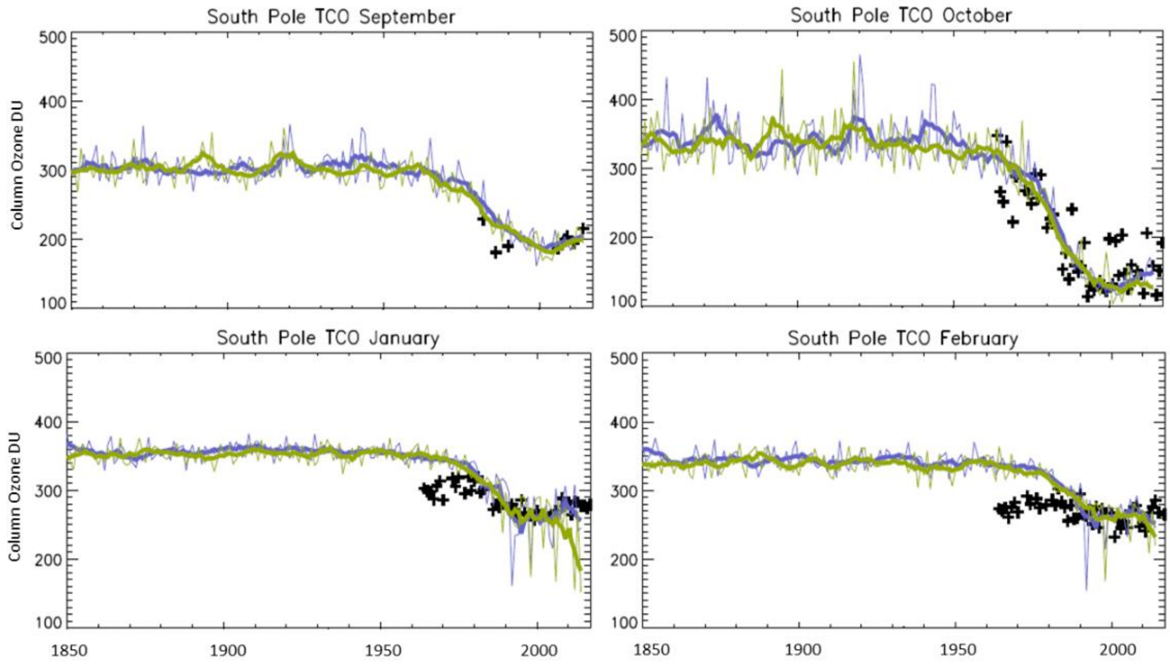

Figure 4: Total column ozone at the South Pole in two UKESM1 CMIP6 historical simulations (green and blue lines) and observed at the South Pole (1964 to present-day, black crosses). Monthly mean ozone values are shown for September, October, January and February.

Idealized climate change experiments (*abrupt-4xCO2 and 1pctCO2)*

In the *abrupt-4xCO2* experiment, we start from a UKESM1 *piControl* model state and instantaneously quadruple the amount of atmospheric CO_2. This results in a large (downward) net radiation imbalance at the TOA, which leads to a warming. After sufficient simulation years, the model will come back to zero TOA net radiation balance, with a warmer climate and an increased emission of longwave radiation at TOA. As this adjustment to the model's equilibrium climate response can potentially take thousands of simulation years, Gregory et al. (2004) developed a method to estimate the *Effective Climate Sensitivity* (ECS) of a model to an external forcing perturbation, such as a quadrupling of CO_2. This method regresses the TOA radiative flux perturbation at the time of CO_2 quadrupling against the global mean surface temperature change. Extrapolating the linear regression (best-fit line) to a zero TOA radiative perturbation provides an estimate of the model ECS to a quadrupling of CO_2. Halving this value gives the more traditional ECS for a doubling of CO_2.

Figure 5 shows the change in global mean surface temperature (dT) in UKESM1 as a function of simulation year (from a nominal start date of 1850) in the *abrupt-4xCO2* experiment. Two UKESM1 realizations are shown (blue and red lines), compared to the HadGEM2-ES response and the range of CMIP5 models. The right panel shows the linear regression between the net TOA radiation imbalance (dN) and the surface temperature change (dT). This gives an estimate of the UKESM1 $2xCO_2$ ECS of ~5.3K. The left panel indicates this response is larger than seen in the CMIP5 multi-model ensemble. There is a strong indication (not yet published) that a number of other CMIP6 models will have ECS values higher than the upper end of the CMIP5 range.

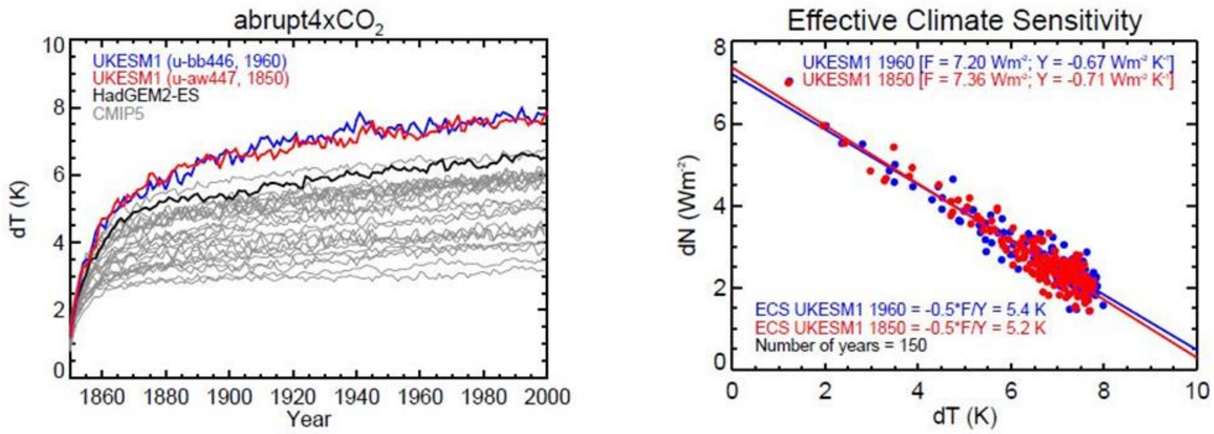

Figure 5: Left: Global mean surface temperature (GMST) response simulated by UKESM1 (red and blue lines) to an instantaneous quadrupling of atmospheric CO_2. HadGEM2-ES is in black and the CMIP5 multi-model ensemble the light grey lines. Right: Linear regression between TOA net radiation perturbation (dN) and the change in GMST (dT) in two UKESM1 abrupt-4xCO2 experiments. ECS is estimated from 150 years of simulation.

Another important measure of a model's sensitivity to increasing CO_2 is the transient climate response (TCR). TCR is defined as the global mean temperature change, averaged over a twenty-year period centred on the time of CO_2 doubling, in a transient simulation with CO_2 increasing at 1% per year from PI values (Randall et al. 2007). Figure 6 shows two UKESM1 *1pctCO2* experiments, again compared to the same simulation using HadGEM2-ES and the CMIP5 multi-model ensemble. The final UKESM1 TCR will be derived from a 4 member ensemble of *1pctCO2* experiments. From these two initial experiments the TCR lies in the approximate range 2.6-2.9K, slightly higher than HadGEM2-ES and at the upper edge of the CMIP5 range. Work is ongoing to understand the various feedbacks leading to the ECS and TCR in UKESM1 and will be reported in the peer-reviewed literature in 2019.

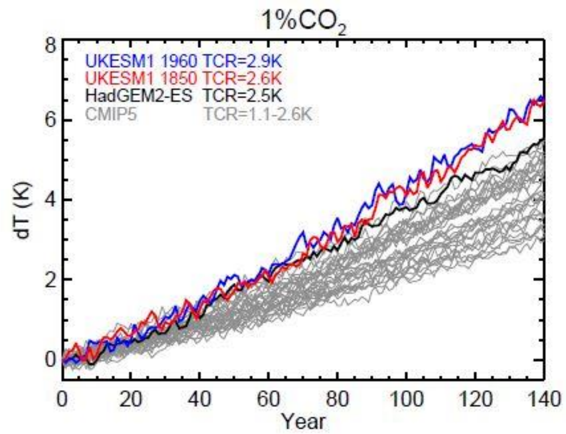

Figure 6: Global mean surface temperature (GMST) response in the UKESM1 1pctCO2 experiment (red and blue lines), compared to HadGEM2-ES (black) and the CMIP5 mutli-model ensemble (grey lines).

Summary

We are nearing completion of the UKESM1 CMIP6 DECK and historical simulation set. Output from these runs will be submitted to the UK Earth System Grid Federation (ESGF) node early in 2019. The UKESM team, along with collaborators at the Met Office, NERC centres and UK universities are actively analysing these simulations and papers documenting the performance of the model will appear in the scientific literature over the coming year.

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The release of UKESM1: update

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Plans for the release and support of UKESM1 were presented in the previous issue of the UKESM newsletter (see https://ukesm.ac.uk/portfolio-item/release-and-support-of-ukesm1/); in this article, we describe recent work on the release, and how those plans have progressed since then.

The model was developed and tested on the internal UK Met Office HPC, with occasional test runs on MONSooN, the shared Met Office/NERC resource (including NEXCS, the NERC-only share of the machine). Following an extensive period of scientific testing, the model was made available to our collaborators for porting to other platforms. These include ARCHER, the UKRI national platform and machines run by some of the international members of the Unified Model Partnership – specifically, the Korea Meteorological Administration (KMA) and New Zealand's National Institute of Weather and Atmospheric Research (NIWA). The port to ARCHER is being performed by our colleagues in the Computational Modelling Services (CMS) unit of the National Centre for Atmospheric Science (NCAS). As with other models, CMS will also provide front-line user support (in collaboration with the UKESM core group) for UKESM1 following its release.

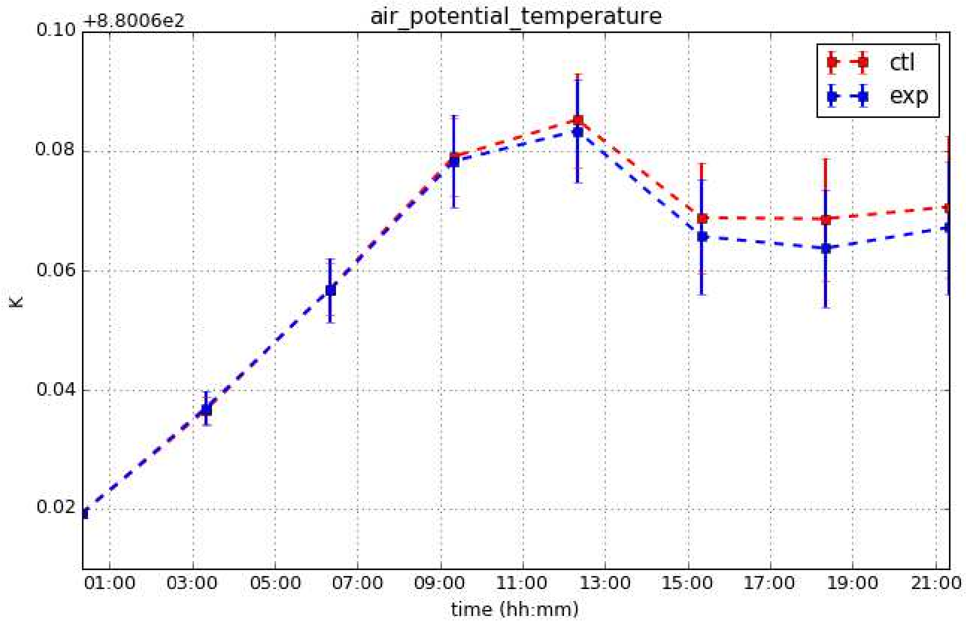

Figure 1: Time evolution of global average potential temperature at model level 65, calculated from two runs of UKESM1 with the same initial conditions performed on the Met Office HPC (red points) and the NIWA HPC (blue points). Error bars represent the spread of results from an ensemble whose (fifty) members were generated by perturbations to the initial conditions; red bars show the spread in the ensemble performed on the Met Office HPC and blue bars the spread of the NIWA ensemble.

We are currently analyzing the results from the ports to other platforms. The achievement of bit-wise identical results on different machines is generally not possible for complex numerical models such as UKESM1, because of the unpredictable way in which minute differences propagate through the model simulation on different platforms, leading to differing results. Instead of asking for identical model behaviour on two different machines, we seek to verify that each model configuration is *scientifically consistent* with the other– that is, could each have been sampled from the same ensemble of results generated on either machine? To check this, we create an ensemble of runs on each machine by perturbing selected variables in their initial conditions, using a perturbation whose numerical value is comparable with the machine's precision. The spread of results (at each point in time and space) on each platform can then be used to determine whether they could have come from a common ensemble. An example comparison for a single variable (drawn from a wide collection of various results and properties) for an ensemble of short runs on the machines at the Met Office and NIWA is shown in Figure 1. Comparisons such as these, and statistical analyses, are used to verify the consistency of the UKESM1 ports to other platforms.

UKESM1 will be delivered as a set of Rose suites (see Figure 2 for a snapshot from the control panel for the UKESM1 Rose suite). Rose is the Met Office framework for developing and running climate and meteorological models. We plan to deliver three configurations of the model:

- two fully coupled configurations which each make use of all model components:
  - one set up to run the CMIP6 pre-industrial control experiment, and
  - one to run the CMIP6 historical experiment, 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.

We note that previously we were planning to offer the historical experiment along with instructions on how to change the forcing data to run the pre-industrial control experiment; we will now make these available as separate suites.

The coupled configurations of UKESM1 have already been used in the CMIP6 DECK experiments, the majority of which are complete. The AMIP configuration was finalized very recently, and the official CMIP6 AMIP experiment is now running.

Following the completion of the port testing, UKESM1 will be openly available for use by the NERC research community. We subsequently plan to offer an update to the model allowing parts of the interactive atmospheric chemistry to be turned off (specifically, chemical oxidants and ozone concentrations will be prescribed, rather than interactively calculated in the model), whilst retaining an interactive treatment of the global carbon cycle. This configuration – referred to as UKESM1-CN – runs faster than the full model, and can be used in experiments which do not require the more complete treatment of atmospheric chemistry available in the full model. Future model developments include the addition of interactive ice sheets for both Greenland and Antarctica (see the article by Smith et al. in this issue of the newsletter).

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

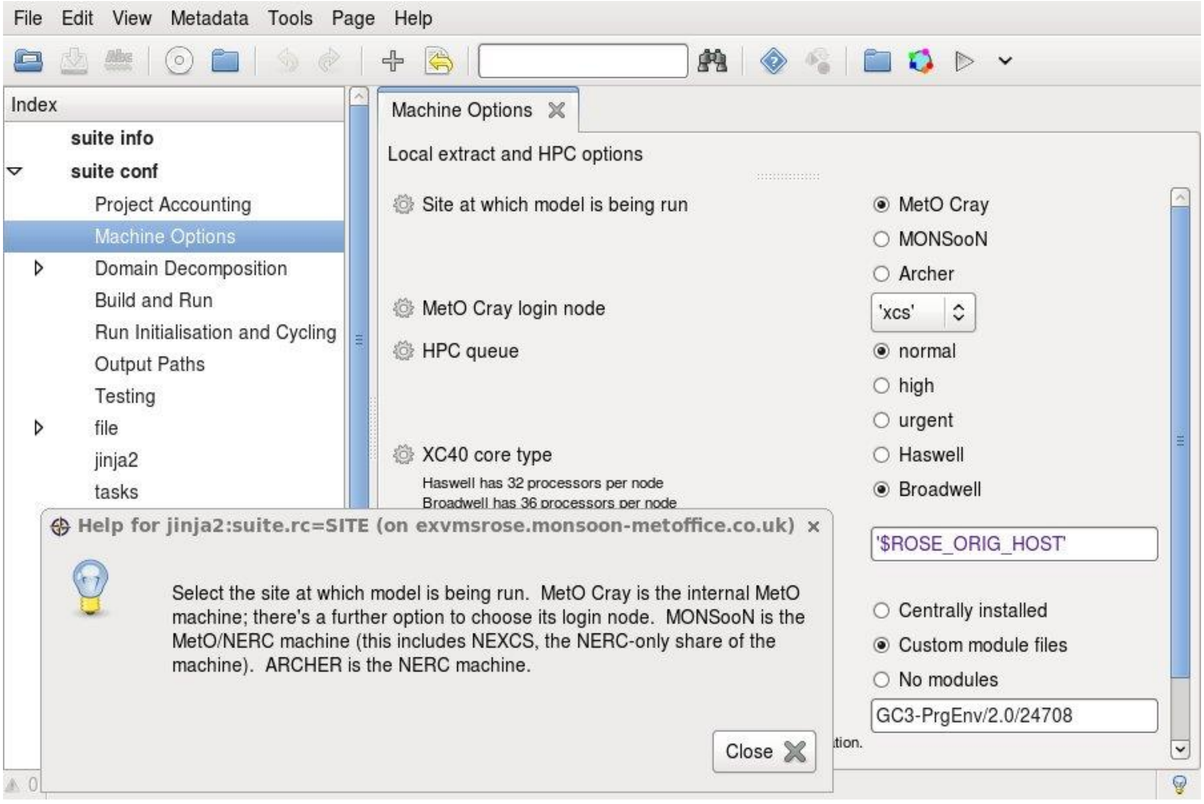

Figure 2: Part of the control panel in one of the UKESM1 Rose suites. This pane allows the user to specify the site at which the model is being run. The popup window provides further help for this option.

UKESM-hybrid: focusing resolution where it's most needed

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An Earth system model contains numerous scientific components. Some, such as the core dynamics and moist parameterizations, are known to benefit from higher model resolution (e.g. Jung et al, 2012, Tao and Chern, 2017). Others, such as aerosols and chemistry, are computationally expensive and there is less evidence they benefit from increased model resolution. In the UKESM hybrid model, there are two atmospheres: one at a higher resolution, for science which either benefits from high resolution or is computational cheap, which we call Senior (Snr); and one at a lower resolution which contains everything, and is referred to as Junior (Jnr). Where there is science overlap, Snr should take precedence over Jnr and we try to lock the temporal evolution of Jnr to follow that of Snr as much as possible, without greatly delaying either model. Any input required in Snr that is not directly simulated in Snr is provided to Snr from Jnr.

The science currently absent from Snr is the calculation of aerosol and chemistry processes, plus the transport and advection of the considerable number of associated 3D fields. In the first UKESM newsletter (https://ukesm.ac.uk/portfolio-item/reduced-resolution-chemistry-aerosols-ukesm1/), when we introduced the concept of running the aerosol and chemistry schemes at a reduced resolution, they slowed the model atmosphere by a factor of around five (i.e. 400% slower). Since then, the computational performance of the aerosol and chemistry has improved greatly, largely due to the introduction of OpenMP into both schemes, work carried out primarily by the UKESM team. Inclusion of aerosols and chemistry now only slows the model atmosphere by a factor of around three (i.e. 200% slower) – a significant improvement but still an important slow down.

Figure 1 shows a schematic of UKESM-hybrid, and shows the three main executables, a Snr Unified Model atmosphere (UM), a Jnr UM and an ocean. The latter consisting of the physical ocean (NEMO-ORCA) and ocean biogeochemistry (MEDUSA). There is an additional fourth executable for an ocean I/O server (XIOS), which is not shown in the figure. The aerosols and the chemistry in the UM are calculated by the UK Chemistry and Aerosol code (UKCA). Crossing out UKCA in the Snr image in figure 1 indicates UKCA is turned off in Snr. The arrows show the direction of coupling and indicate that coupling happens between all three models. The only exchange currently not performed is from Jnr to the ocean, since Snr is used to drive the ocean model. In the earlier newsletter article on UKESM-hybrid the atmosphere was not coupled to the ocean. We recently started working on this coupling as shown in figure 1. This is a new coupling and currently only runs for a few months before Jnr develops an instability and the model fails. We are presently working to understand and remedy this problem.

Thus far the hybrid configuration has consisted of a N216 Snr UM, a N96 Jnr UM and, when an ocean is included, an ORCA025 (0.25° resolution) ocean. This is likely to be the only N216-based UKESM configuration that will be computationally affordable for full (multi-century) CMIP experiments. We are currently also developing a hybrid model with a N96 Snr, a N48 Jnr and an ORCA1 (1°) ocean which should be a faster, but scientifically traceable, alternative to UKESM1 N96 ORCA1.

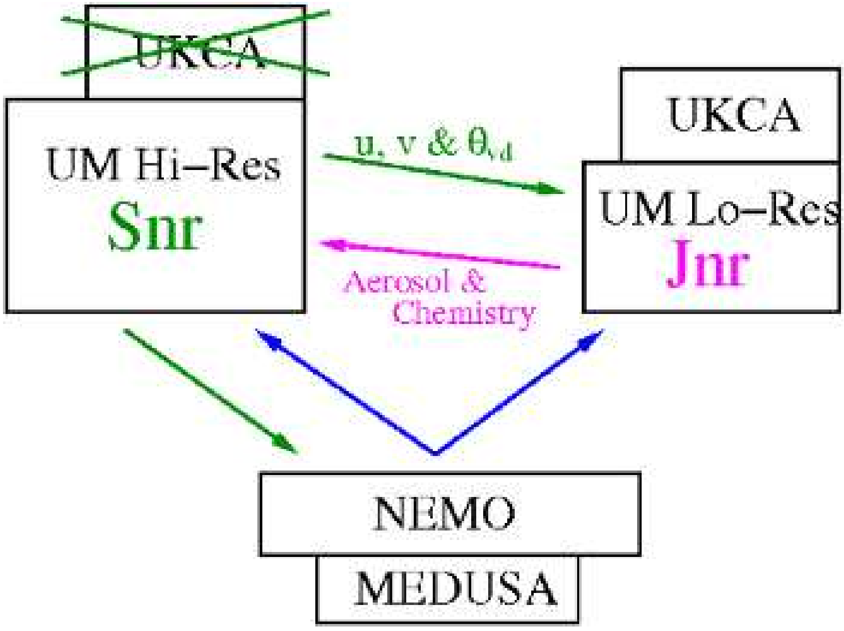

Figure 1: Schematic of UKESM1-hybrid. The Snr UM contains all the UKESM1 science except aerosols and chemistry. Input that Snr requires from UKCA are provided by the Jnr UM. The Jnr UM contains all the UKESM1 science, and is locked to Snr by passing dynamical core fields from Snr. The ocean, which consists of NEMO-ORCA and MEDUSA (biogeochemistry), passes its simulation results to both Snr and Jnr, while it only receives atmospheric forcing from Snr. All coupling is performed by OASIS3-MCT every model hour.

Coupling between all the models components is done through the OASIS3-MCT coupler on the hour, directly after most of the aerosol and chemistry science is calculated in Jnr. This means the 48 3D UKCA fields which Snr requires from Jnr are available for coupling at the earliest opportunity. These fields are re-gridded from the Jnr grid to the higher resolution Snr grid using the coupler. To lock the evolution of the physical atmosphere in Jnr to follow Snr, a number of dynamical core fields are passed from Snr to Jnr, with re-gridding also performed by the coupler. These fields overwrite the same native variables in Jnr. Determining which are the best dynamical core fields to use for the locking is still being evaluated. The green arrow in figure 1 shows locking being done using the horizontal velocity components and dry potential temperature. It is likely these are the minimum required. Additional fields to further constrain Jnr to follow Snr, such as surface and soil variables, are likely also necessary. More work is needed to identify the optimal set.

Performing this locking every timestep would improve how well Jnr is locked to Snr. However, the final timestep of every hour in Jnr is computationally long, as this is when the majority of the aerosol and chemistry science is carried out. The discrepancy in the relative duration of timesteps between those in Snr and those in Jnr means locking at every timestep causes Snr and Jnr to have to wait for one another, slowing the hybrid model. Hence, coupling from Snr to Jnr is only done once every hour. Ocean coupling in a standard UM-NEMO configuration already happens on the hour. The one special thing we do is to simultaneously send output from the ocean to both Snr at N216 and Jnr at N96, where the re-gridding is again performed by the coupler.

Until we can successfully couple the ocean for a long run, our evaluation of the hybrid model is limited to atmosphere only configurations. Jones et al. (2018) found that the hybrid model, with Snr at N216 and Jnr at N96 compared very well against a UM model with all components integrated at N216. That assessment compared an atmosphere with full stratospheric chemistry configuration (known as GA+StratTrop) at both N216 and N96 resolutions with a hybrid configuration with Snr at N216 and Jnr at N96. Figure 2 is typical of the results. It shows annual mean TOA net shortwave solar radiation (SWD), with positive values indicating downward directed flux. The left column shows the absolute SWD values for N216 (top), the hybrid model (middle) and N96 (bottom). On the right is the bias in the annual mean SWD relative to CERES satellite observations (Loeb et al. 2009). The absolute fields on the left column are very similar for all three models. However, looking at the biases against CERES observations, it is evident that the hybrid-simulated fluxes are more similar to those in the N216 model than the N96 model. This is particularly evident from the RMS difference between the models and CERES. For SWD the hybrid model has a RMS value of 8.03, marginally

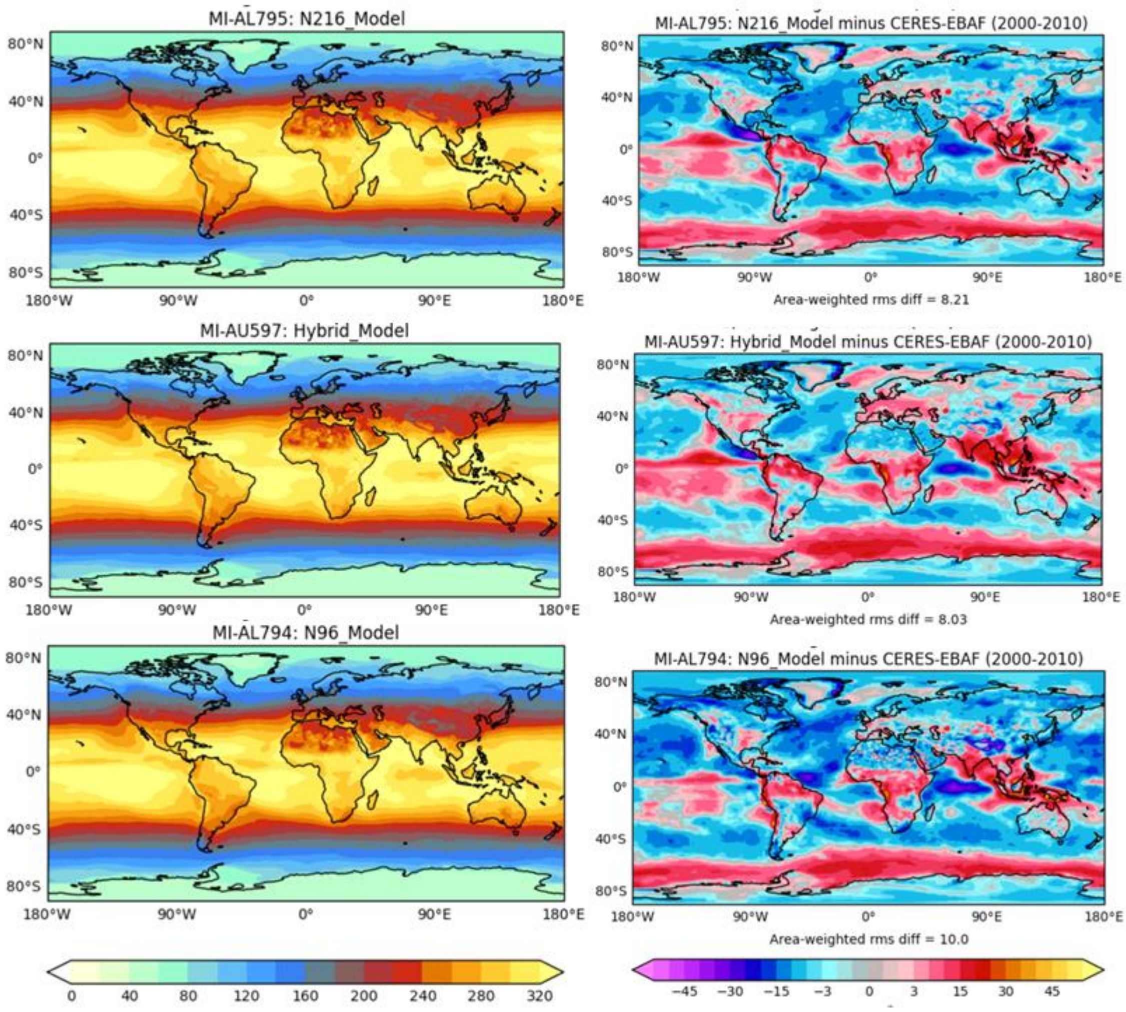

Figure 2: Absolute annual mean TOA net shortwave radiation (left column) and bias in TOA SWD against CERES observations (right column) for N216 (top row), hybrid (middle row) and N96 (bottom row).

smaller than the RMS value of the N216 model, which is 8.21. These are both significantly smaller than the N96 model, which has a RMS difference of 10.0. This result is mirrored for individual seasons and most other variables considered. It was surprising to find the hybrid model apparently outperforming the N216 model, if only slightly.

Degrading the aerosol and chemistry resolution, as we do for the hybrid, is only acceptable if there is a large performance gain. In tables 1 and 2 the hybrid model is compared against the equivalent N216 resolution models. All runs were only for one month – hence the speeds are very approximate – and were done on the Met Office XCS which has 36 cores per node. They show the hybrid model giving between a 45-68% speed-up. We believe there is more science which can fairly easily be moved out of Snr which might increase this up to about 80%.

	On 60 nodes	Top speed on 2 threads
UKESM AMIP N216	1.1 model years/day	2.2 model years/day
UKESM-hybrid AMIP N216 N96	1.8 model years/day	3.7 model years/day
Speed-up of hybrid	64%	68%

Table 1. Approximate speeds of atmosphere only configurations comparing UKESM-AMIP N216 with UKESM-hybrid N216 N96. The hybrid model is listed with two resolutions where the first is the resolution of Snr and the second is the resolution of Jnr.

	On 60 nodes for atmosphere	Top speed on 2 threads
UKESM N216 ORCA025 without MEDUSA	1.1 model years/day	1.7 model years/day
UKESM-hybrid N216 N96 ORCA025 without MEDUSA	1.6 model years/day	2.8 model years/day
Speed-up of hybrid	45%	65%

Table 2.Comparing the approximate speeds of UKESM N216 ORCAO25 without the ocean biogeochemistry (MEDUSA) against UKESM-hybrid N216 N96 ORCA025 without MEDUSA. For the 60 node atmosphere jobs, UKESM N216 ORCA025 used a total of 85 nodes, whereas UKESM-hybrid N216 N96 ORCA025 used a total of 95 nodes. Note also that the 2 (OpenMP) threads for the top speed refer only to the atmosphere as NEMO can currently only be run on one OpenMP thread

It should be noted in table 2 that the ocean biogeochemistry (MEDUSA) has been removed from the configuration. This is because MEDUSA slows the ocean by a factor of about three (200% slower), and the top speeds of any N216 ORCA025 configuration is bound to be limited by how fast the ocean can be run. Hence, increasing the speed of any N216 ORCA025 configuration requires increasing the speed of the ocean, and we have begun the process of applying a similar hybrid approach to the ocean biogeochemistry. This will not be a problem for UKESM-hybrid N96 N48 ORCA1, because our ORCA1 ocean is considerably faster than our N96 atmosphere.

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Progress coupling Greenland and Antarctic ice sheets into UKESM1

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As regular readers of this newsletter will know, the main version of UKESM1, being used for CMIP6 simulations, is not the only version of our Earth system model. Alongside other variations, we are developing versions of UKESM with direct, physical two-way couplings to models of the Greenland and Antarctic ice sheets - see “An overview of the Land Ice in UKESM1” (Newsletter #2, https://ukesm.ac.uk/portfolio-item/overview-land-ice-ukesm1/) and “Progress towards interactive Ice Sheets in UKESM1” (Newsletter #6, https://ukesm.ac.uk/portfolio-item/interactive-ice-sheets-ukesm1/). We now have two separate configurations that have interactive ice sheets: one with only Greenland coupled (referred to as UKESM1-is1), and a prototype model where both Greenland and Antarctica are coupled (referred to as UKESM-is2). Coupling Greenland generally requires only atmosphere-ice coupling at the surface of the ice sheet. Due to Antarctica’s climate and a fringe of floating ice shelves means coupled ocean-ice interactions also need to be simulated.

ISMIP6 (Nowicki et al., 2016) is the project within CMIP6 coordinating projections of ice sheet mass loss under future climate change. Most of the work in ISMIP6 will use standalone ice sheet models, but some coupled climate-ice sheet simulations, with only Greenland coupled, are planned. Results need to be available in 2019 if they are to be considered by IPCC AR6.

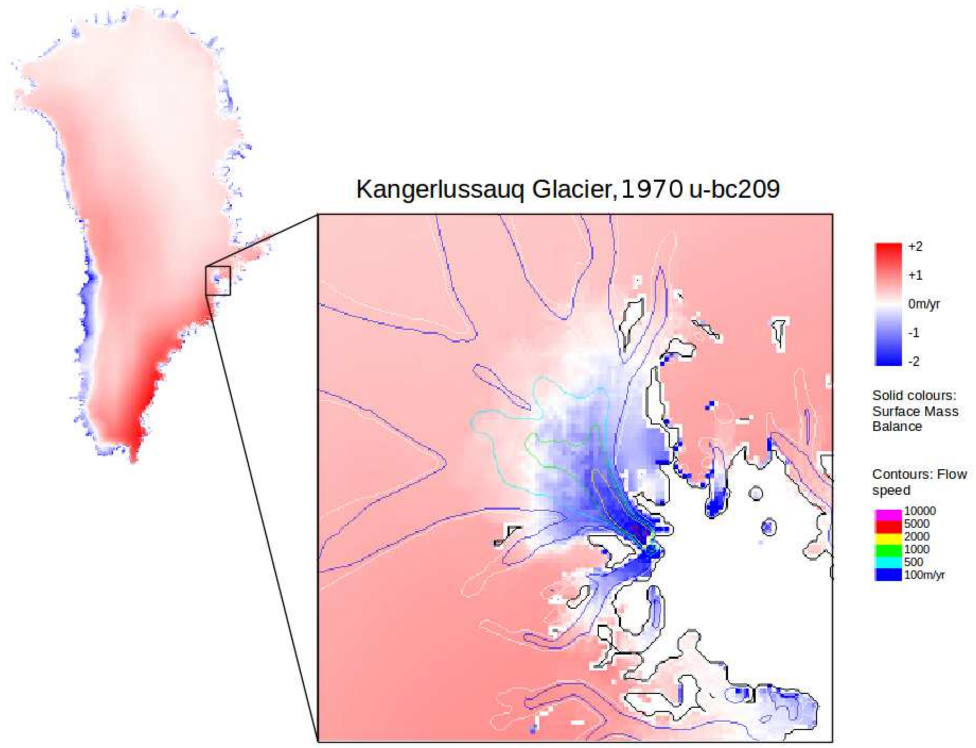

Figure 1: A snapshot of the coupled climate mass balance and glacier flow on Greenland simulated by the UKESM1-is model run for ISMIP6. The flow speeds and climate components all compare well with results from more specialised modelling studies.

We have therefore frozen our most stable, Greenland-only UKESM-is configuration - an N96 atmosphere, ORCA1 ocean coupled to the ice sheet model BISICLES, with mesh refinement down to 1.2km as required to simulate details of the Greenland ice sheet (see figures 1-2). Simulations for ISMIP6 were started at the end of 2018. In keeping with the ISMIP6 design we first concentrate on idealised abrupt 4xCO_2 and 1%/yr CO_2 increase experiments, both relative to a control run representative of recent decades.

There is potential for a significant "coupling shock" to occur when two previously uncoupled models are made to interact with each other and can respond to, and influence, biases in the other model. Directly coupling climate and ice sheet models, as we are doing, is a new and active area of research. Reliable techniques to guarantee a stable and realistic coupled state are therefore not yet available. Nevertheless, the climate and flow fields for Greenland in the component models of UKESM1-is have so far shown themselves to be compatible, and terms contributing to the mass balance of the Greenland ice sheet (e.g. snowfall, melt, runoff and calving) compare well with simulations by more highly-tuned regional models, with little drift apparent in the control simulation (figure 2).

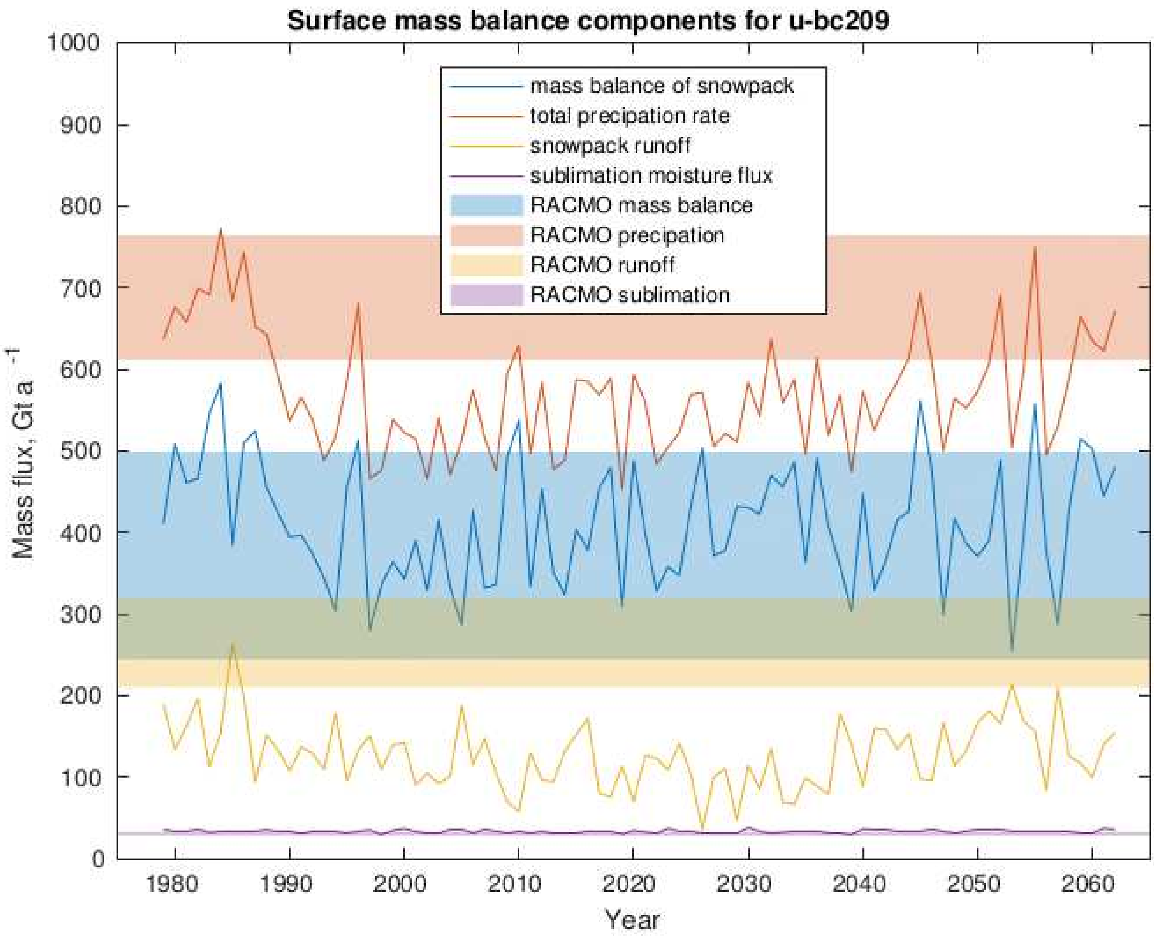

Figure 2: Accumulation and runoff components of the Greenland surface mass balance in a UKESM-is present day control run are stable and compare reasonably with results from a highly tuned regional model, RACMO (van Angelen et al. 2012). There are no observations for these quantities covering the entire ice sheet. The net positive surface mass term is balanced by calving of icebergs at the edges of Greenland.

As noted above, coupling Antarctica, as well as Greenland, is both technically and scientifically more challenging, requiring a good simulation of the ocean circulation under the ice shelves, as well as the of the surface climate of the ice sheet and ice dynamics and the ability for the models to pass information in all directions and update boundary conditions accordingly. We have made enough progress on the technical side of the UKESM ice coupling that we can now run a configuration (UKESM-is2) that has both Greenland and Antarctic ice sheets interactively coupled. As far as we are aware, no other global climate model exists with this capability.

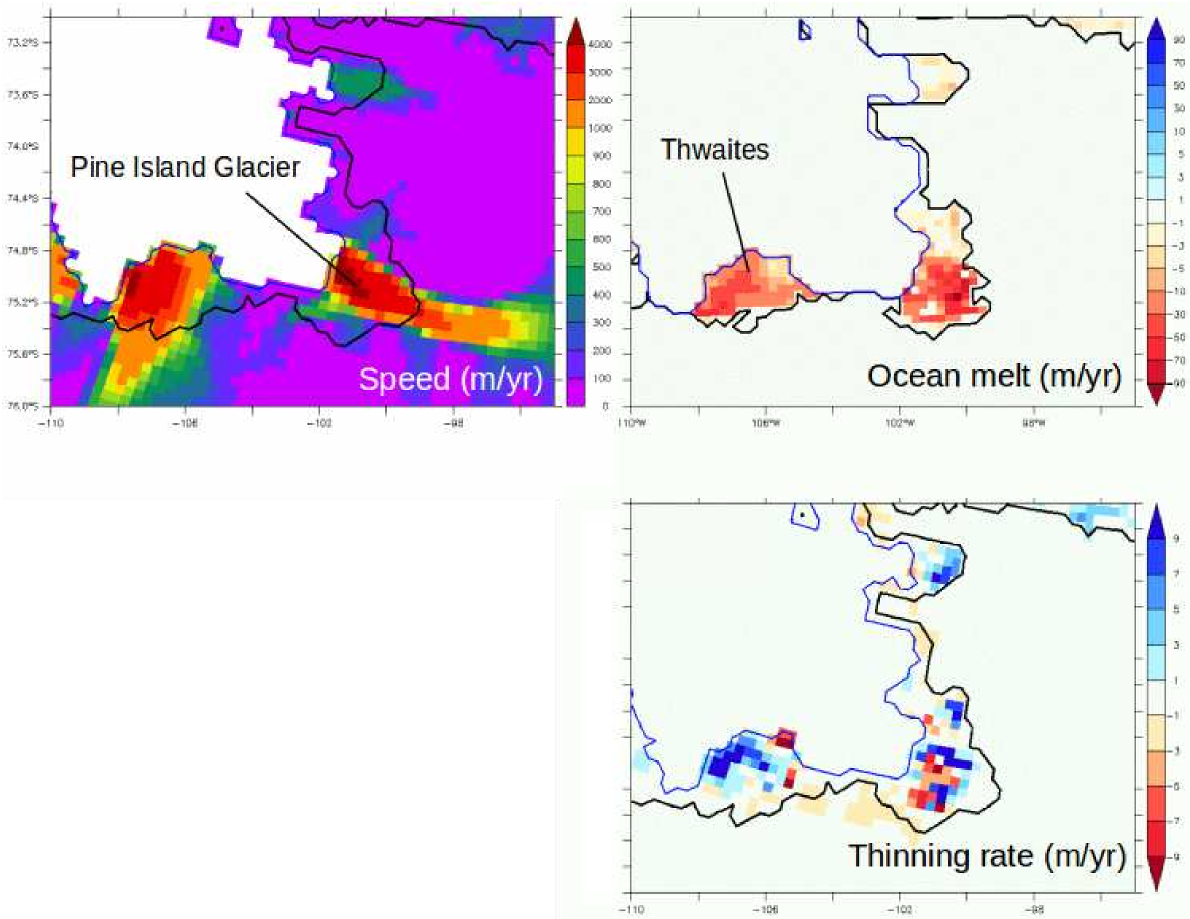

Figure 3: Pine Island Glacier is observed to be thinning and retreating at up to 20 m/yr as the warm ocean melts up to 100m/yr from the underside of the ice shelf (Wingham et al. 2009, Jenkins et al. 2010). Our first simulation achieves reasonable melt rates in the ocean model, but the ice state is not yet compatible with these, and in our first simulation the ice flow from upstream means that thinning is patchy at Pine Island, while the Thwaites shelf thickens. Black lines show the limit of the grounded ice sheet, blue lines the limit of the floating ice. BISICLES data is shown on a coarser grid than actually used in the model.

To resolve the ocean under the ice shelves UKESM-is2 uses a higher resolution ocean model (ORCA025, with ~15km gridboxes at the Antarctic ice-ocean interface) than the Greenland-only UKESM1-is1. We still use the N96-resolution UKESM1 atmosphere to maintain an acceptable computational cost. To achieve a realistic Antarctic ocean-ice simulation, we require the water mass properties under the ice shelves to be reasonably accurate (there is significant regional variation in the waters around Antarctica, and some shelves are characterised as "warm", and some as "cold", e.g. Dinniman et al. (2016). We further require that the temperature and velocity of water below the ice shelves produces accurate melt rates at the ice fronts and, for the location and size of those melt rates to balance where the ice sheet model flows out from the grounded ice upstream. In addition to all this, we need to smoothly and realistically evolve these features as the ocean domain itself grows (or shrinks) as the ice shelves retreat (or advance). The coupling shock, outlined above, has potential to be particularly severe when simulating Antarctic ice as we need to balance the atmosphere, ice sheet and ocean models, all in the presence of positive feedback processes at the retreating ice fronts.

It is an extremely challenging problem, but our results so far are encouraging. Our first simulation with UKESM1-is2 shows a basically correct distribution of warm and cold shelves around Antarctica, and we find the highest melt rates under shelves in the Amundensen Bay, matching observations (figure 3). The ice and ocean are not yet fully compatible here, however, and our melting does not give us the observed rates of shelf retreat as flow from the grounded ice upstream balances the loss of ice to the sea. We do not plan to run a full suite of ISMIP6 climate change runs with UKESM-is+, but we will exploit our unique modelling capability by conducting at least one global ice sheet-climate sensitivity experiment in 2019. Watch this space...

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Recent past events

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

This year, the LTSM project celebrated its annual meeting at the Met Office Headquarters in Exeter. The meeting ran for two full days. Day 1 included 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 was centred around project business, specific break groups and future science plans (**download the meeting agenda with links to presentations here**).

29 Oct - 1 Nov 2018 - 14th IEEE international conference on eScience, Amsterdam:

By Jeremy Walton. This ongoing series of meetings that examines how the adoption of digital technologies is changing the way in which research is performed – initially, in science, but more recently in the humanities as well.

The cross-disciplinary nature of eScience was reflected in the range of presentations at the conference, which discussed work in areas as diverse as using machine learning to automatically decipher handwritten documents, identifying animal calls in the wild, curating and accessing medical images, the coupled modelling of magnetic plasmas and analysing the propagation of news information across media sources. In addition to illustrating the application of techniques from computer simulation, data modelling and machine learning across the research spectrum, the meeting included discussions about the importance of open science – i.e. unfettered access to data, code, models, methodologies, publications and evaluations. The tension between the requirements of open science and current reward and incentive policies in science and research was explored in an interactive session by all conference attendees.

In addition to plenary eScience sessions, the conference included four parallel sessions which were more focussed on specific fields: *Data Handling and Analytics for Health, Advances in eScience for the Humanities and Social Sciences, Exascale computing for High-Energy Physics and Weather & Climate Science in the Digital Era*, which I attended. This included interesting talks on multiscale modelling (resolving clouds in a global atmosphere model), increasing parallelism in climate models via additional component concurrency, using machine learning for weather forecasting (directed at prediction of energy usage) and the enhancement of flood maps using social media reports. I presented our work on the hybrid-resolution version of UKESM, which appeared to generate a positive response, and was complimentary to the discussions of multiscale modelling in other systems.

The keynote talk in this session was from Peter Neilly of The Weather Company (now part of IBM) who described their efforts to make weather forecasts part of probabilistic-based decision-making systems. Other contributions from IBM included the downscaling of results from physical weather models using deep neural networks, and improving the pre-season agricultural yield forecasts using machine learning. Finally, one of the posters in that session came from (I think) ECMWF, and which discussed the problem of transforming climate model output into CMIP6 datasets for submission to the Earth System Grid Federation – an issue which rang a few bells with the present author.

5-6 November 2018 – UKESM core group annual meeting and retreat, Bristol:

The UKESM core group recently met for a day at the annual core team retreat in Bristol. The group analysed, reviewed and discussed the following topics: UKESM1 coupled, atmospheric, terrestrial and marine performance, progress and plans for UKESM-IS, UKESM-hybrid and ESMValTool, and Model release and support, as well as short presentations for core group members plus four sessions with break-out groups to discuss a range of topics: (i) 'What type of observations are we lacking or require for evaluating/analysing UKESM1?'; (ii) What further analysis (leading to) papers etc should we prioritise?; (iii) What developments (scientific, computational etc) should we prioritise for a subsequent UKESM1.x?; (iv) How should we work together in the future?; and (v) What is the potential for using AI/emulators/Big Data?

2-23 November 2018 – OMIP meeting, LOCEAN-IPSL, Paris:

Core group members Julien Palmieri and Andrew Yool (NOC; UKESM1 marine biogeochemistry), together with George Nurser and Andrew Coward (NOC; ocean physics), attended an OMIP workshop on the 22-23 November 2018 at LOCEAN-IPSL in Paris. The workshop was organised by Julie Deshayes (IPSL) and involved European groups using NEMO as the ocean component of their Earth system models, with a view to analyse and discuss preliminary findings of NEMO-OMIP simulations. Modelling groups represented at the meeting included IPSL (France), CNRM (France), CMCC (Italy), EC-Earth (Spain) and UKESM1 (NOC; UK). Day 1 focused on 1-degree NEMO configurations, and results presented by IPSL, CNRM and NOC found diversity both in NEMO configurations and simulation results. A common issue identified across models was the occurrence of extreme polynyas in the sea-ice zone of the Southern Ocean, which had consequences for the physical and biogeochemical realism of simulations. On day 2, IPSL presented a detailed evaluation of a suite of 1/4-degree NEMO configurations, and discussion focused on coordination of OMIP activity across groups using NEMO. This could include common approaches to freshwater balancing, and the use of a consistent set of JRA-55 atmospheric reanalysis forcing.

Team News

Recent additions to the UKESM Core Group:

Catherine Hardacre, Met Office Hadley Centre, Exeter: Catherine joined the UKESM core group in November 2018, transferring from the Atmospheric Dispersion and Air Quality (ADAQ) team in Weather Science. She will be working on UKCA, initially to improve sulfur chemistry, and will also contribute to selected AerChemMIP experiments. In ADAQ Catherine worked with the Air Quality configuration of the UM (AQUM) to produce and develop the UK's air quality forecast, and also with the Numerical Atmospheric-Dispersion Modelling Environment (NAME) to study other aspects of air quality. Prior to joining the Met Office Catherine has worked in postdoctoral roles at the University of Edinburgh and Lancaster University where she used global scale chemistry-transport models to investigate atmospheric composition and how it is affected by interactions with the land surface. Catherine has a Ph.D. in Chemistry from the University of Edinburgh.