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.

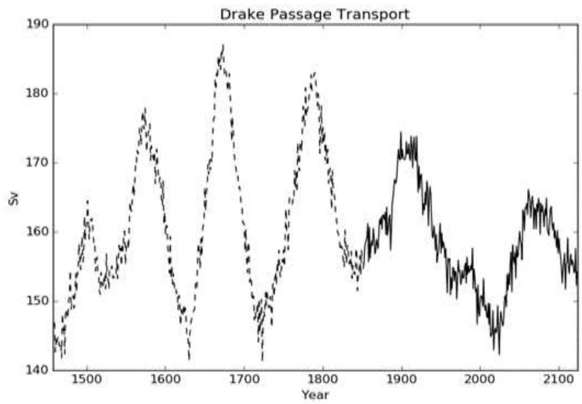

Figure 1: Strength of the ACC circulation, in Sverdrups (10^6 m^3s^{-1}), through the Drake Passage. Solid line: pre-industrial control; dashed line: pre-industrial spinup used to initialise the control run. Dates are arbitrary.

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).

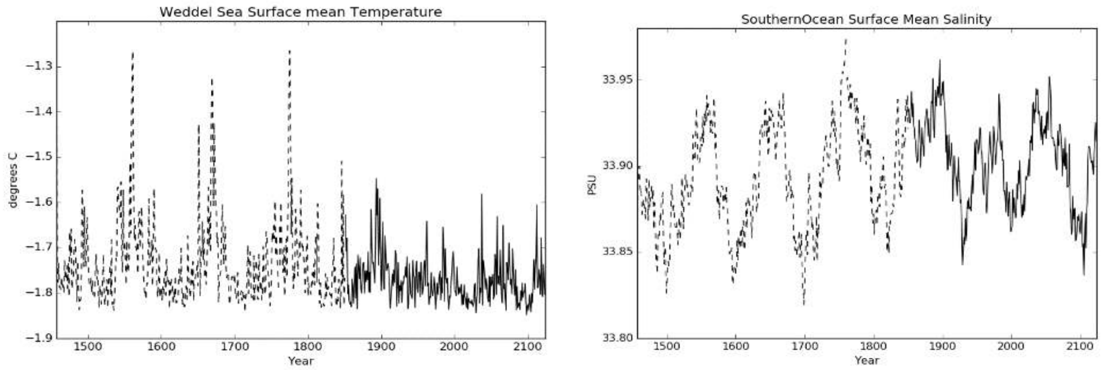

Figure 2: Left: Mean sea surface temperature in the Weddell Sea (80S – 60S, 72.5W - 0E). Right: Mean sea surface salinity in the Southern Ocean (90S - 40S). Lines as in Figure 1.

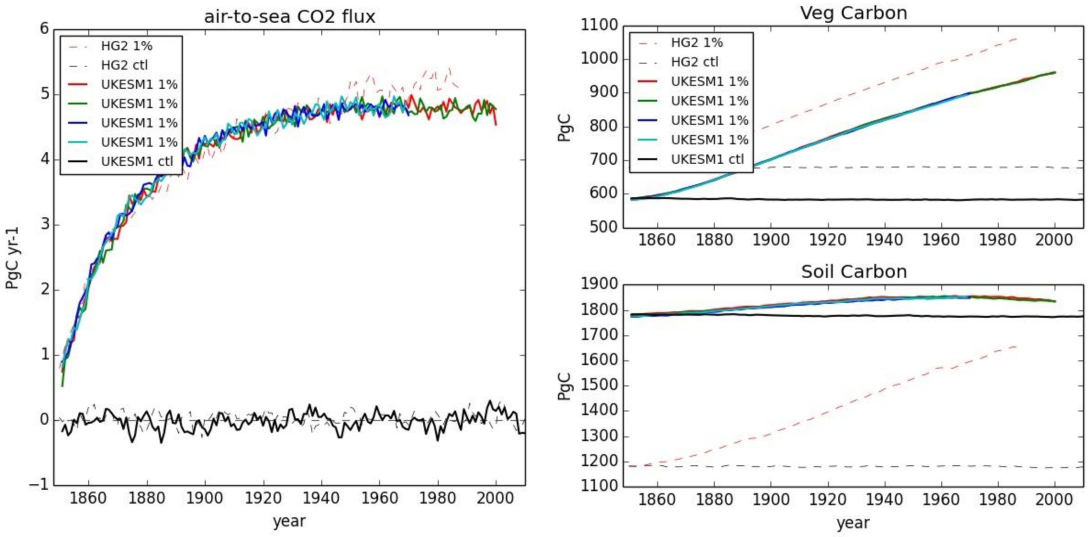

Figure 3: Carbon fluxes and stores in UKESM1 (solid lines) and HadGEM2-ES (dashed lines) 1% CO_2 experiments. Left: CO_2 flux from air to sea (Pg carbon per year). Top right: total vegetation carbon in Pg. Bottom right: total soil carbon in Pg. Black / grey: pre-industrial control; colours: 1% CO_2.

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).

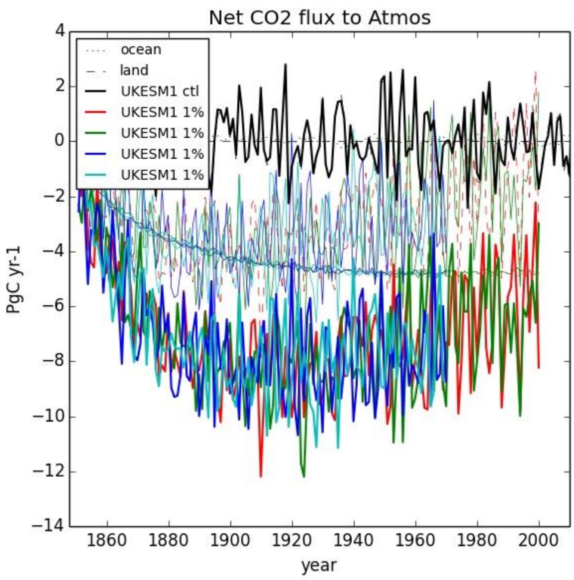

Figure 4: Net CO2 flux from the ocean and land surface to the atmosphere in UKESM1 1% CO_2 experiments (note the opposite sign from the air-to-sea flux in Figure 3). Black: pre-industrial control; colours: 1% CO_2. Dashed lines: flux from land; dotted lines: flux from ocean.

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.

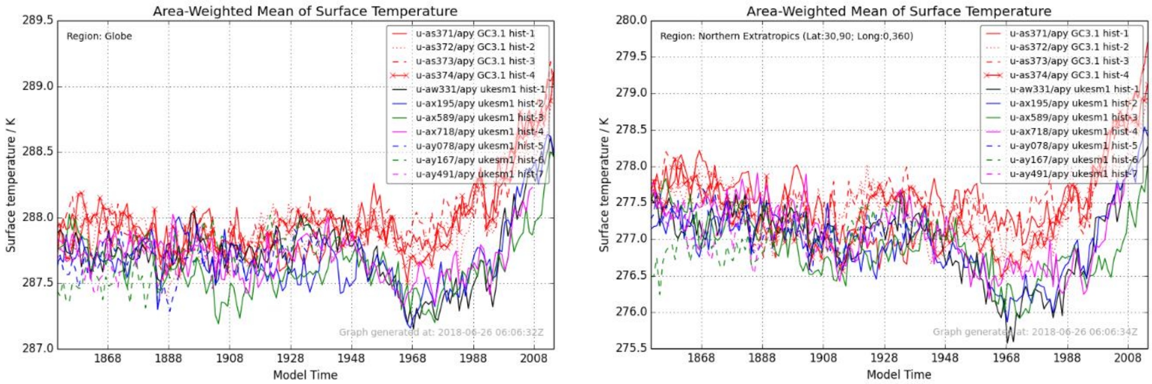

Figure 5: Surface temperature evolution in HadGEM3-GC3.1 (red lines) and UKESM1 (other colours). Left: global mean; Right: northern extratropical mean (30N – 90N).

REFERENCES

- Mojib Latif, Torge Martin, Annika Reintges, Wonsun Park. Southern Ocean Decadal Variability And Predictability. *Current Climate Change Reports*, 2017; 3 (3): 163 DOI: 10.1007/S40641-017-0068-8