UKESM1 beneath the waves

Andrew Yool[1]*, Julien Palmiéri[1]*, Lee de Mora[2]*, Till Kuhlbrodt[3]* and Colin Jones[3]*

[1] National Oceanography Centre (NOC); [2] Plymouth Marine Laboratory (PML); [3] National Centre for Atmospheric Science (NCAS); * UKESM core group member

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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.

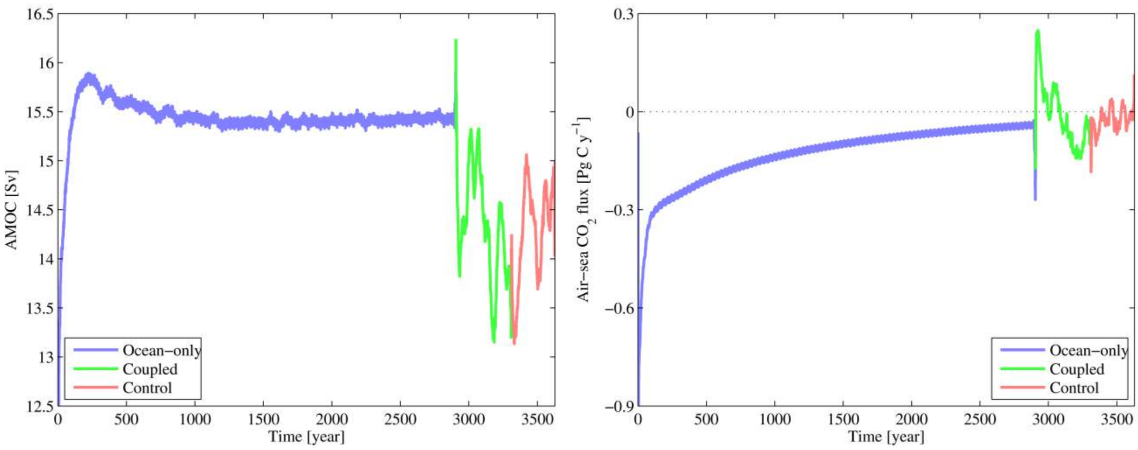

Figure 1: UKESM1 properties during the last 3000+ years of ocean-only (blue) and coupled (green) spin-up, followed by CMIP6 control (red). (a) Atlantic Meridional Overturning Circulation strength at 26˚N, slightly below the observed ~17 Sv. (b) Total air-to-sea flux of CO_2, where a net zero flux would 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.

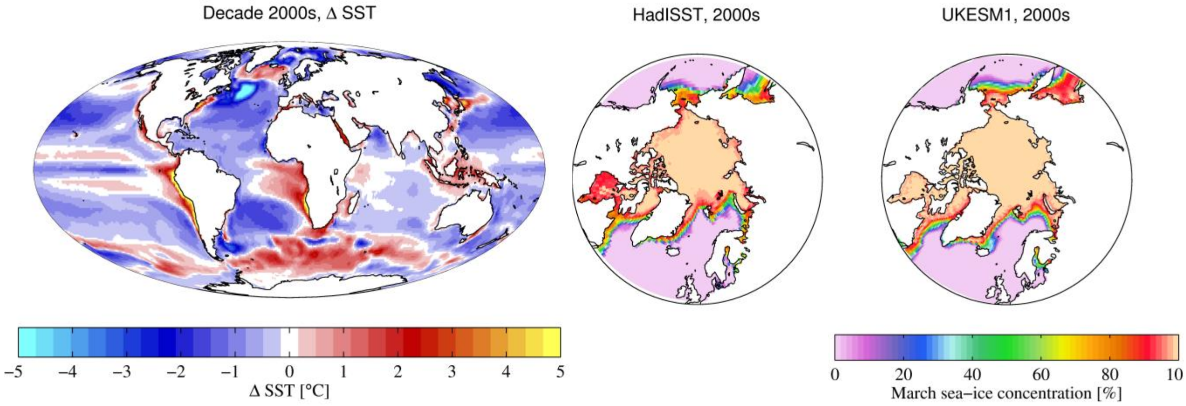

Figure 2: (a) UKESM1 difference with respect to observations (HadISST) for the period 2000-2009; (b) Observational seasonal-maximum sea-ice concentration for the period 2000-2009; (c) UKESM1 seasonal-maximum sea-ice concentration for the period 2000-2009.

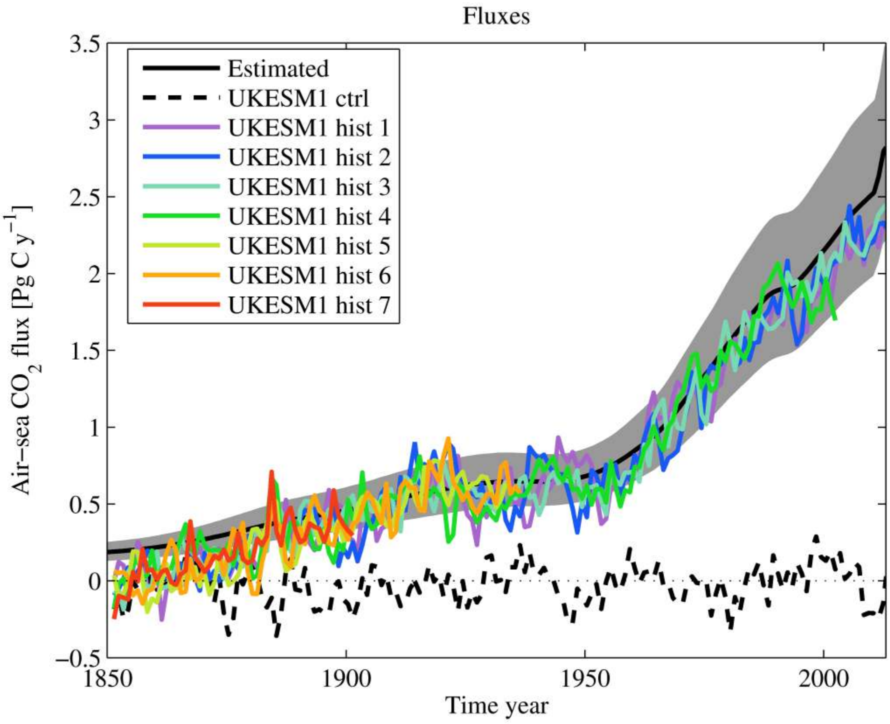

Figure 3: Observationally-estimated (black, with grey shading for uncertainty) and UKESM1 simulated uptake of anthropogenic CO_2 by the ocean over the historical period (1850-2010). UKESM1 output is shown for 7 ensemble members, of which only the first 3 have completed the full period. UKESM1's control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