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).

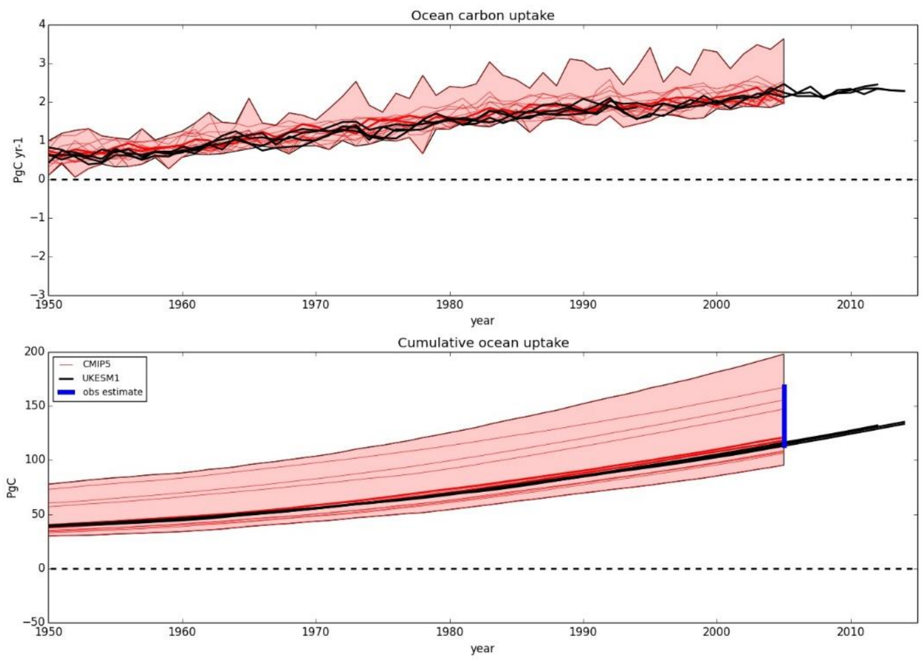

Figure 1. Ocean carbon uptake. (a) year-on-year flux of carbon into the ocean (PgC yr^{-1}) for CMIP5 models (individual models in red lines, of which HadGEM2-ES is thick red line, and multi-model range in pink shading) compared with UKESM1 4 Historical ensemble members (black lines). Panel (b) shows 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.

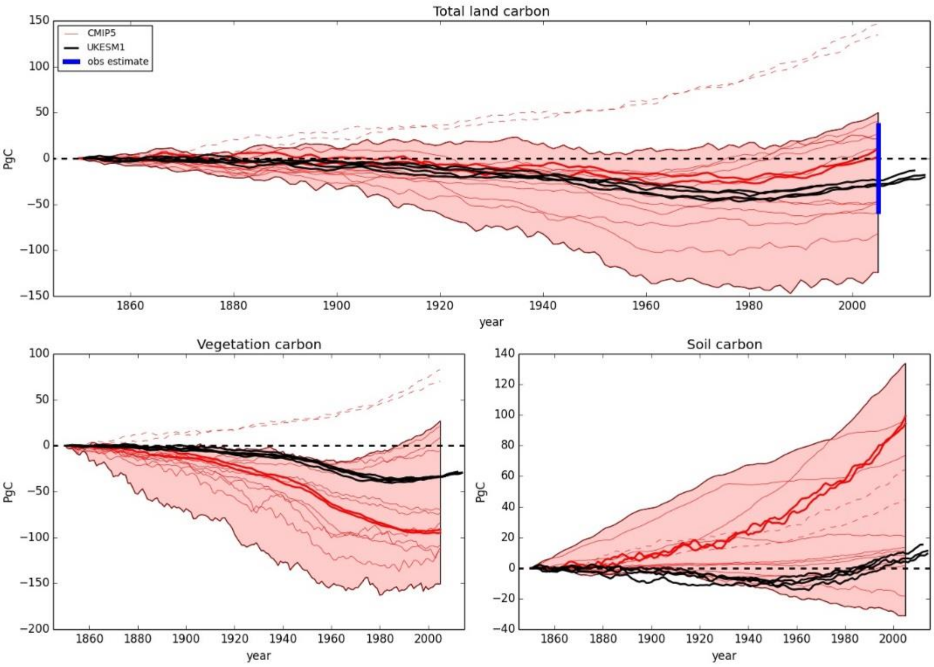

Figure 2. Changes in land carbon pools (PgC): (a) total terrestrial carbon made up of (b) Vegetation carbon (living biomass) and (c) Soil organic matter (including dead litter carbon). Colours, as figure 1, UKESM1 ensemble members in black, CMIP5 models in red with HadGEM2-ES indiciated in thick red.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

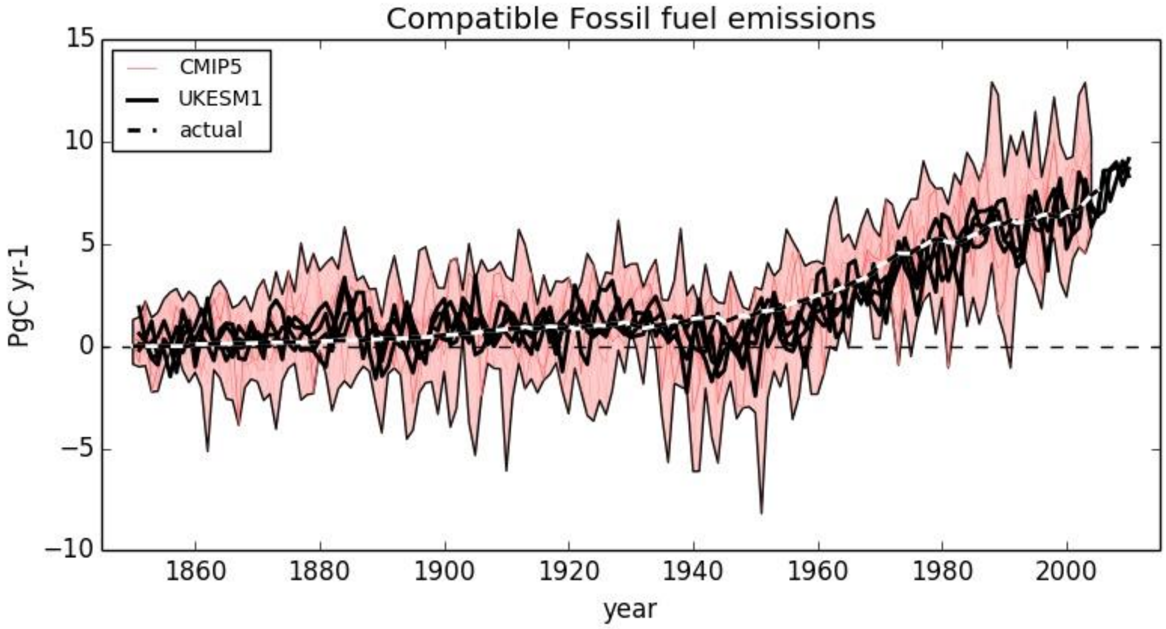

Figure 3. Historical fossil fuel emissions. By inverting the carbon budget in the UKESM1 Historical simulations driven with observed atmospheric CO_2 concentrations it is possible to derive the fossil fuel CO_2 emission (black solid) which can be compared to actual emissions (black dashed) and the CMIP5 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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