Spinning up marine biogeochemistry in UKESM1

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To a first approximation, much of what happens in the Earth system depends on the dynamics and interactions of the two key geophysical fluids that make it up: the atmosphere and the ocean. As anyone familiar with the UK's weather will attest, the atmosphere is flighty and dynamic, with perturbations in temperature, humidity or chemical composition quickly created and dissipated on timescales of days to weeks or months. The ocean, by contrast, is a much more sedate fluid. While its surface readily exchanges heat and freshwater with the atmosphere, its interior has a vast thermohaline circulation that sluggishly transports water and chemical constituents into the deep and around its basins. Depending upon where it does so, water leaving contact with the atmosphere can take decades to centuries or even millennia before it again comes into contact with the atmosphere.

Consequently, with an average ventilation timescale of more than 2000 years, the ocean component of the Earth system has a long memory – one that can "remember" environmental perturbations far longer than other components such as the atmosphere and land surface. In addition, the ocean serves as the largest reservoir of carbon in the Earth system. Relative to the atmosphere – where the concentration of carbon dioxide (CO_2) has been of long-standing interest – the ocean stores more than 50 times as much. A consequence of this, both for Earth system models and the real Earth system, is that even small imbalances in the air-sea exchange of CO_2 can lead to large changes in atmospheric CO_2. This is a particular concern for fully coupled ESMs where both the climate and CO_2 are free to evolve. Since both our understanding of marine biogeochemistry is far from complete and observations of carbon in the ocean are relatively under-sampled, there is a risk of substantial – and unwelcome – drift in ESM-simulated atmospheric CO_2 towards unrealistic values.

As part of the UK's preparations for CMIP6 – and to specifically address the ocean's carbon cycle – spin-up simulations of the low resolution version of UKESM1 (UKESM-lr) have been planned and now begun. To this end, the marine carbon cycle of UKESM1-lr has been initialised from estimated pre-industrial conditions and has been spinning up in ocean-only mode using atmospheric forcing (including winds, radiation, heat and freshwater fluxes) derived from an atmosphere-land simulation that employed sea surface temperatures (SST), sea-ice (SIC) and atmospheric gases, including CO_2, representative of pre-industrial conditions. To date, almost 700 years have been completed, comprised of more than 20 cycles of the 30-year atmospheric dataset.

The accompanying graphs show representative time-series of ocean circulation, biological activity in the ocean, and – most pertinently – the exchange of CO_2 between the ocean and the atmosphere. While the ocean's circulation is broadly stable, some deficiencies have been detected that will hopefully be remedied as the spin-up progresses. Similarly, ocean productivity is found to equilibriate within the spin-up duration so far, though somewhat at the lower end of that observed. Meanwhile, the air-sea CO_2 flux is behaving as we expect: a long-term transient steadily approaching, but not reaching, zero. However, the aim of spin-up is to decrease drift, rather than eliminating it completely.

The next stage of UKESM1 spin-up will involve the transition of the ocean's simulated state – physical and biogeochemical – to a fully coupled simulation. Because of the much-increased cost of the coupled simulation, after a multi-decadal period of spin-up in this mode, the ocean's end state and the atmosphere's output will be used in a further ocean-only phase. Depending on progress, it is planned that iteration between ocean-only and coupled phases will continue, before a final – and extended – coupled phase will be used to provide an initial condition for CMIP6. It is expected that this will be produced by late-2016 or early-2017.

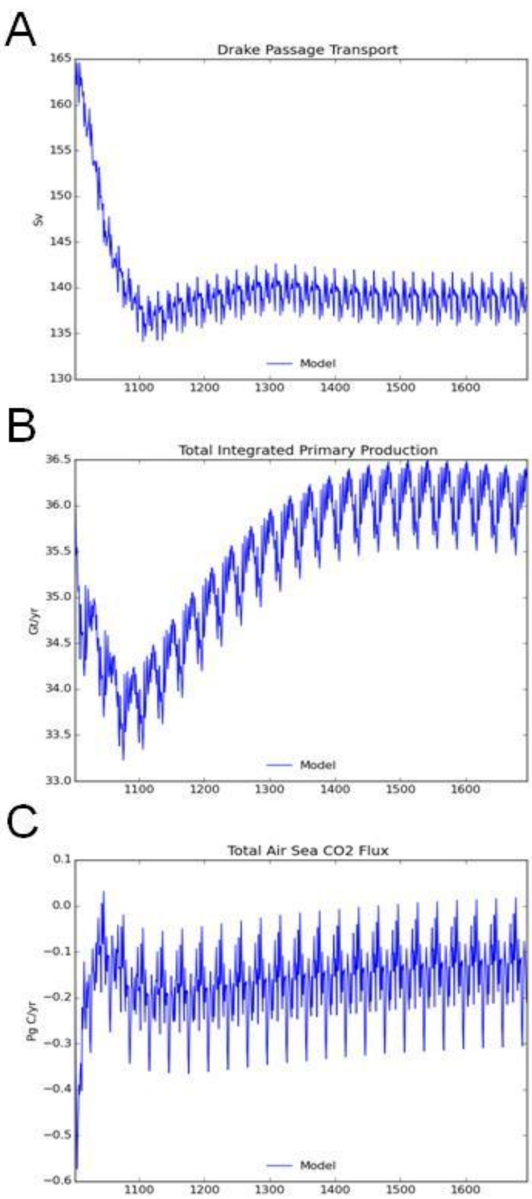

Figure 1:

A) Time evolution of the ocean's circulation is illustrated here via the strength of the Antarctic Circumpolar Current through Drake Passage (the gap between the southern tip of South America and the northern tip of the Antarctic Peninsula). After an initial period of rapid change (100 year duration), the ACC settles down to a steady transport of around 135-140 Sv.

B) A key metric of biological activity in the ocean is integrated primary production. This is the total amount of carbon "fixed" from the ocean by phytoplankton. This serves as the energy supply to rest of the ocean ecosystem, including up the trophic chain, to familiar animals such as fish and whales. In this case, an initial decline in primary production (100 years) shifts to long-term stability (500 years).

C) The total air-sea flux of CO_2 measures the exchange between the atmosphere and ocean. Here, the ocean is generally losing CO_2 to the atmosphere (outgassing) as it comes into equilibrium with its pre-industrial concentration. The trend is *towards* zero, but while the timescale of ocean circulation means that zero net flux is unlikely, the spin-up will serve to decrease drift in UKESM1 simulation made for CMIP6.

Figures here are provided by the Biogeochemistry Evaluation Suite, developed by Lee de Mora (Plymouth Marine Laboratory). This is a Python-based tool operating on the JASMIN facility and producing web-based output accessible to the UKESM1 community.