Carbon cycle science – Perspectives from the Royal Society Global Environmental Research Committee

This paper is an output of a discussion on carbon cycle science at a Royal Society Global Environment Research Committee (GERC) meeting (see 'context' on page 3). It seeks to highlight science issues of potential interest to researchers, funders and government.

Executive summary

GERC identified four key areas where further research or investment is important and a further two cross-cutting challenges for global carbon cycle science.

Key priorities areas for study or investment are: (1) Improving continuous monitoring of the global carbon cycle; (2) Increasing our understanding of risks of potential saturation or reversal of the global carbon sinks; (3) Developing carbon cycle models of different levels of complexity; and (4) Reducing the global carbon budget imbalance.

Cross-cutting challenges identified include: (1) The need for multi-disciplinary collaboration on the carbon cycle across a wide range of scientific disciplines, from biology to social sciences; (2) The need to support and enhance international collaboration, in particular for carbon cycle observations.

Introduction

The global carbon cycle plays a critical role in controlling the climate system and its response to anthropogenic perturbation. Land and ocean together currently absorb more than half of anthropogenic carbon dioxide (CO_2) emissions. Without these carbon sinks, the present-day atmospheric CO_2 concentration would be almost double pre-industrial level and global warming would already have exceeded 2°C. Atmospheric methane (CH_4) is also partly controlled by land ecosystems, with wetlands and peatlands being large natural sources of CH_4.

Understanding the key processes controlling these sinks and sources of carbon, and how they are changing is essential to understand how carbon concentrations in the atmosphere will evolve. Influences include environmental change (for example temperature rise and CO_2 increase) and direct human pressure (for example deforestation, drainage, and other land use change).

Science issues

The GERC discussion identified four key areas for global carbon cycle research (not in priority order).

1. **Continuous monitoring of the global carbon cycle**: Long-term observations of all components of the carbon cycle are essential to answer critical science questions such as how do carbon concentrations evolve in the atmosphere, terrestrial ecosystems and oceans in a changing climate. This would include atmospheric observations of carbon, measurements of pCO_2 (partial pressure of CO_2) at the ocean surface, measurements of organic/inorganic carbon within the ocean, terrestrial observations of biomass and soil carbon, and proxies of carbon cycle activity (e.g. Leaf Area Index, chlorophyll).

   These observations, when combined with models and improved understanding of processes, will enable earth scientists to further understand the effects of present and future anthropogenic perturbation on the global carbon cycle and its potential impact on planetary health.

2. **Risk of potential saturation or reversal of the global carbon sinks**. There is no guarantee the current land and ocean carbon sinks will continue to operate in the future. Land and ocean carbon sinks may slow down in response to climate change, which would induce a 'positive feedback' on the climate system, worsening climate change. However, our understanding of such positive feedbacks, and potential associated thresholds is still limited and based on relatively simple

models. The development of more complex models would allow us to better understand this risk, by capturing the complexity of biogeochemical processes and their interaction with climate change and other direct drivers like land use change.

For example, specific carbon-rich ecosystems such as permafrost and peatlands have the potential to release significant quantities of carbon in a warming world, but there is a significant lack of quantification of likelihood and associated risks. Further, although there are no indications of a risk of ocean turning from carbon sink to source, there is limited understanding of the risk of disruption of oceanic circulations at large scale (e.g. Atlantic Meridional Overturning Circulation), which is possible in the coming centuries and could have substantial impact.

3. **Development of carbon cycle models of different levels of complexity.** The representation of the carbon cycle in earth system models is still an area for development. In land carbon models, ongoing challenges include the representation of nutrients, water stress, carbon leaching, peatlands and permafrost dynamics, and fires. In ocean models, challenges include the representation of seasonal to semi-decadal variability of carbon dynamics, adequate spatial resolution, biological activity in the surface ocean, and carbon inputs from land into the ocean and transfer of that carbon to the deep ocean.

   Model developments should also include data driven approaches such as machine learning or data assimilation techniques that make use of the growing amount of satellite measurements to provide spatial and temporal information on the dynamics of the carbon cycle. In addition, there is an opportunity to better link the large-scale climate, atmospheric transport and chemistry scientific communities with the process level observation and theoretical scientific communities, particularly around regional systems (e.g. Amazon forest, Arctic permafrost, Southern Ocean).

4. **Reducing the global carbon budget imbalance.** Current models and observations currently don't account for all of the carbon expected to exist within the carbon cycle. The difference between CO_2 emissions, observed atmospheric CO_2 increase and modelled CO_2 land and ocean sinks is not zero, which is why it is referred to as the carbon budget *imbalance*. There are significant interannual to decadal excursions highlighting our limited understanding of the carbon cycle on these time scales.

   Also, while the carbon cycle is better understood at the global scale, we have only an extremely limited understanding of regional sources and sinks, both on land and in the ocean, and their variability and long-term changes. Similarly, the global CH_4 budget is not fully understood. The unexplained recent variations in atmospheric CH_4 growth rate highlight our incomplete understanding of the dynamics of the natural sources and sinks of CH_4.

The GERC discussion also raised a couple of key cross-cutting challenges for global carbon cycle science, which are detailed below.

1. **The need for multi-disciplinary collaboration.** The UK global carbon cycle community is fragmented with very few opportunities to meet (apart for the International Carbon Dioxide Conference (ICDC) happening every 4 years), even though an increasing amount of work on the carbon cycle is being carried out by UK scientists from diverse science disciplines such as biology, biogeochemistry, physics and mathematics. There is a need for cross-UK co-operation on the carbon cycle between these disciplines, and economics and social sciences to fully understand the

impact of anthropogenic activities on the carbon cycle as well as the climate adaptation/mitigation challenges.

One way to better integrate within and across disciplines could be to have a UK-based carbon cycle conference every 4 years (in between 2 ICDC conferences) to promote multi-disciplinary collaboration within the UK, while also strengthening international partnerships.

2. **International co-operation**. Although the UK is amongst the world leaders in carbon cycle science, the global nature of the carbon cycle (atmosphere, land, ocean) and its global climatic and environmental impacts mean that international collaboration is critical. Both carbon cycle observations (such as ICOS[1], SOCCAT[2]) and modelling (such as GCP[3]) cannot be done in isolation with a UK-limited focus. Priorities include the need to be able to lead/contribute to international research activities, and to enhance access to international facilities, especially for observations in key environments (Southern Ocean, Arctic Ocean, tropical forests, peatlands…).

The context for Global Environmental Research Committee reports

The Royal Society's Global Environment Research Committee (GERC) is charged with advising the Royal Society, and interacting with research councils, the environmental science community and other bodies. To do this, it is undertaking a rolling series of reviews of areas of science within its remit. The areas it has identified are (in alphabetical order): air quality, biodiversity, carbon and other biogeochemical cycles, climate, natural resources (including land use) and food, oceans, polar science, and water. In each area, GERC uses its own expertise, and that of a number of invited experts to consider the questions:

1. What are the hot research topics in this area at present?

2. What is the status of UK science within this area?

3. What are the most pressing research needs in the next 5-10 years?

4. Are there specific areas where UK science should be focussed to meet these needs?

5. How should priority topics be incorporated into multidisciplinary (funded across research councils) issues that Future Earth and its UK committee should consider?

This paper results from the discussion on global carbon science, organised by Prof Pierre Friedlingstein and Prof Pete Smith FRS, held in November 2019. In addition to contributions from its regular and co-opted members, the committee was advised in person by **Dr Angela Gallego-Sala (University of Exeter), Prof Simon Lewis (UCL and University of Leeds), Prof Corinne Le Quéré FRS (UEA), Prof Andy Watson FRS (University of Exeter), Prof Colin Prentice FRS (Imperial College) and Prof Paul Palmer (University of Edinburgh)**.

This paper does not seek to represent the views of the Royal Society or to produce a comprehensive overview of carbon cycle science, but instead to highlight some specific areas of potential interest to researchers, funders and government. Exclusion of a topic from this document does not negate its importance, and many areas that are already under intense research are not highlighted here.

Membership of GERC (including co-opted members) at the time this topic was discussed (November 2019) was: **Dr Kirsti Ashworth, Prof Mike Bentley, Prof Harry Bryden FRS, Dr Maria Dornelas, Prof Pierre Friedlingstein, Prof Joanna Haigh FRS, Prof Louise Heathwaite, Prof Gideon Henderson FRS (Chair), Prof Peter Smith FRS, Prof Martin Solan, Prof Alessandro Tagliabue, Dr Sarah Webb**. Hélène Margue acted as Secretary.

[1] Integrated Carbon Observation System https://www.icos-cp.eu/
[2] Surface Ocean CO2 Atlas https://www.socat.info/
[3] The Global Carbon Project https://www.globalcarbonproject.org/