Projects involved

Quaternary QUEST; Dynamics of the Earth System and the Ice Core Record (DESIRE); Advanced Fellowship; Quantifying Ecosystem Roles in the Carbon Cycle (QUERCC); Climate-carbon modelling, assimilation and prediction (CCMAP); QUEST Earth System Model (QESM); Feedbacks QUEST; the QUEST Core Team. Working Groups on: Climate prediction for robust policy paking; Wetlands; Palaeo Carbon Modelling Intercomparison Project (PCMIP); international Land-Atmosphere Model Benchmarking project (i-LAMB). International collaborative benchmark development took place with the European ENSEMBLES project, CEH and the Met Office collaborations.

Publications

A full listing of QUEST research publications is constantly being updated by the QUEST synthesis team at the University of Bristol. Contact quest-info@bristol.ac.uk for more information.

De Boer AM, Watson AJ, Edwards NR, Oliver KIC (2010) A comprehensive, multi-process box-model approach to glacial-interglacial carbon cycling. *Climates of the Past Discussions* 6: 867-903.

Friedlingstein P, Prentice IC (2010) Carbon-climate feedbacks: a review of model and observation based estimates. *Current Opinion in Environmental Sustainability* 2: 251-257.

Goodwin P, Lenton TM (2009) Quantifying the feedback between ocean heating and CO_2 solubility as an equivalent carbon emission. *Geophysical Research Letters* 36,15609.

House JI, Huntingford C, Knorr W, Cornell SE, Cox PM, Harris GR, Jones CD, Lowe JA, Prentice IC (2008) What do recent advances in quantifying climate and carbon cycle uncertainties mean for climate policy? *Environmental Research Letters* 3: 044002.

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster P, Friedlingstein P, Gurney K, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento JL, Schuster U, Sitch, S, Takahashi T, Viovy N, van der Werf GR, and Woodward FI (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2: 831-836.

Knorr W, Prentice IC, House JI and Holland EA (2005) Long-term sensitivity of soil carbon turnover to warming. *Nature* 433: 298-301.

Thompson RL, Gloor M, et al. (2008) Variability in atmospheric O_2 and CO_2 concentrations in the southern Pacific Ocean and their comparison with model estimates. *Journal of Geophysical Research-Biogeosciences* 113(G2).

Prentice IC and Harrison SP (2009) Ecosystem effects of CO_2 concentration: evidence from past climates. *Climates of the Past* 5: 297-307.

Scholze M, Knorr W, Arnell N and Prentice, IC (2006) A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences* 103 (35): 13116-13120

Quantifying and Understanding the Earth System

NATURAL ENVIRONMENT RESEARCH COUNCIL

Carbon Cycle Feedbacks

Land and ocean sinks take up about 60% of CO_2 emissions from the atmosphere but these sinks are affected by climate change. For example, warming causes reduced ocean uptake of CO_2 and greater carbon loss from soils, these both increase atmospheric CO_2 concentration, which leads to further warming (a positive feedback). Increasing atmospheric concentrations of CO_2 have a fertilising effect on land plants, which enhances CO_2 uptake (a negative feedback), but leads to ocean acidification and a reduction in the ocean biological sink (a positive feedback).

Carbon cycle feedbacks (positive and negative) have played a major role in past climate changes (Fig. 1) and will continue to do so in the future. Evidence suggests that feedbacks in the carbon cycle will enhance climate warming over the next century. This is a highly robust conclusion based on multiple lines of evidence from both recent and palaeo observations, experiments and modelling. Stabilisation of CO_2 concentrations will require a continuous reduction of emissions throughout the next century, towards an ultimate target of only a small percentage of current emissions, regardless of the magnitude of the feedback.

Highlights

QUEST has worked on many fronts to improve the quantification of interactions between the carbon cycle and climate. Some of the broad areas covered are highlighted below:

- A new observational programme of ultraprecise measurements of changes in atmospheric CO_2 and O_2.
- Data synthesis of natural changes in climate, CO_2 and related data over glacial-interglacial cycles and Earth system modelling to narrow down the causes of these past changes.
- Advanced representation of feedbacks in the QUEST Earth System Model, including nitrogen limits on plant carbon uptake.
- Tools for data assimilation and data-model comparison to narrow uncertainty on the climate-carbon cycle feedback.
- Model analysis of the implications of climate-carbon cycle feedbacks for climate policy and CO_2 stabilisation.

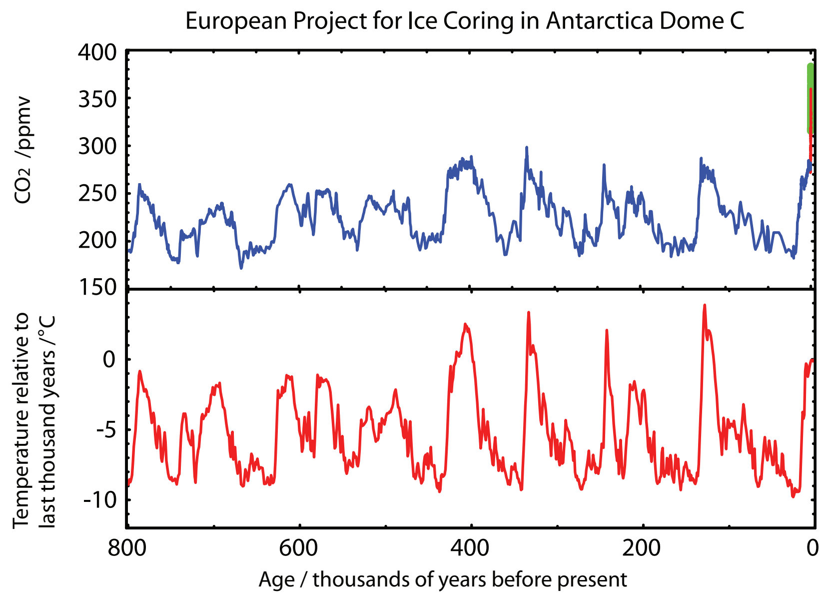
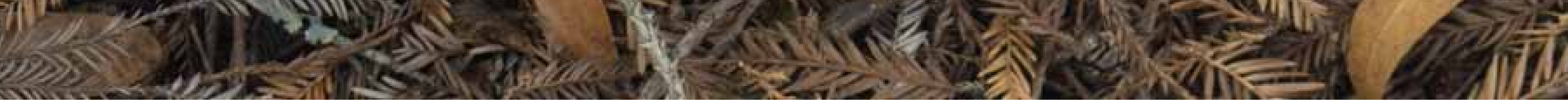
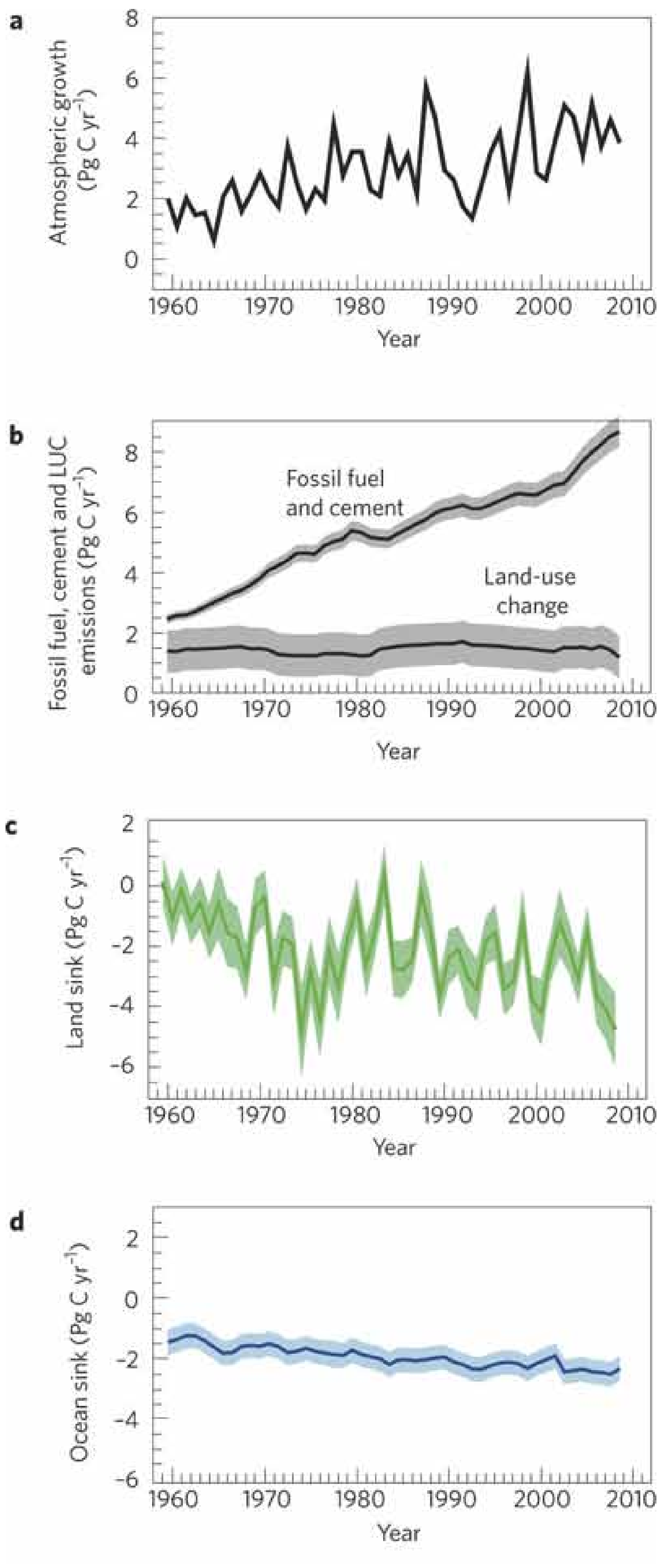


Figure 1. Temperature estimated from deuterium measurements on the EPICA Dome C ice core (Antarctica) over the last 800,000 years, along with CO_2 from Antarctic ice cores and (for the last 50 years) atmospheric measurements. In the top panel the blue is the compilation of Dome C and Vostok ice core CO_2 data, the red is the Law Dome data (as in the last 1000 years) and the green is the measured data from Mauna Loa since 1958. These results indicate important links between carbon cycling and climate over the past 800,000 years.





Selected highlights

- QUEST has established a new UK capability for high-precision oxygen and trace gas measurement and monitoring (Figure 3). These enable a more robust identification of the land and marine sinks for CO_2, including improved quantification of carbon stores in the Atlantic Ocean.
- Identifying the causes of glacial-interglacial CO_2 change is an abiding problem in Earth system science. Using data synthesis of long terms records of marine, terrestrial and ice-core proxies, and by developing models of different complexity, QUEST has improved our understanding of the mechanisms involved. QUEST made the first simulation of a complete glacial-interglacial cycle with a full 3D climate model, and of multiple glacial cycles with a reduced-complexity model. We now have a better understanding of the ocean processes that could have lowered CO_2 concentrations in the last ice ages.
- The ice-core CO_2 record of the past millennium establishes unequivocally that the *net* climate-carbon cycle feedback has a positive sign. However, reconstructed increases in terrestrial productivity, forest cover and carbon storage after the last glacial cannot be accounted for without considering the effects of CO_2 on plant growth, which provides a negative feedback.
- New metrics have been developed to quantify the land and ocean contributions of future emissions of CO_2. The release of carbon due to ocean warming has produced an equivalent emission that has recently increased to 0.2 Pg C per year (Figure 2).
- Peatlands, which act as a terrestrial store of carbon, accumulate faster under warm conditions, and northern peatland growth slowed during the Little Ice Age—opposite to the sign of the global feed-back.

Figure 2. (a), The atmospheric CO_2 growth rate. (b) CO_2 emissions from fossil fuel combustion and cement production, and from land use change (LUC). (c), Land CO_2 sink (negative values correspond to land uptake). (d), Ocean CO_2 sink (negative values correspond to ocean uptake). The land and ocean sinks (c,d) are shown as an average of several models normalised to the observed mean land and ocean sinks for 1990–2000. The shaded area is the uncertainty associated with each component (Le Quéré et al 2009)

- Satellite data on vegetation greenness have been combined with global measurements of CO_2 concentrations and a terrestrial biosphere model, bringing modelled CO_2 fluxes in line with observations and improving predictive ability for CO_2.
- The QUEST Earth System Model's land nitrogen model is the first of its kind to use resource optimization analysis of the costs of nitrogen uptake by plants. The modelled nitrogen cycle constraints on growth result in 50 Pg C less global biomass per year than when these constraints are not considered.
- The apparent "acclimation" of soil decomposition to temperature increases is an artefact of soil warming experiments. In fact it is possible that the slowly decomposing components of soil may be more sensitive to temperature than previously thought.

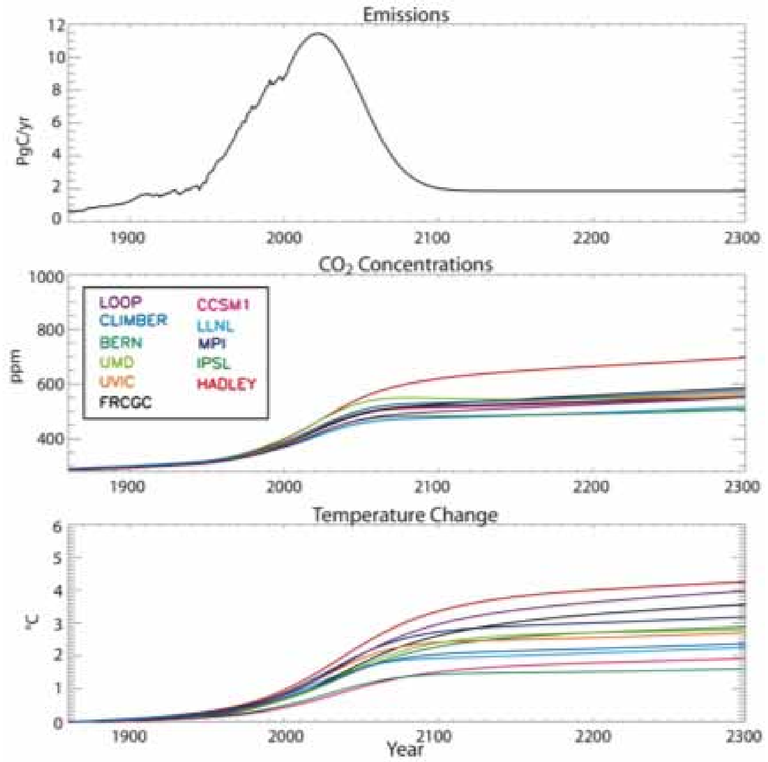


Figure 4. Effect of climate-carbon cycle feedbacks on meeting policy targets to avoid dangerous climate change.
The top panel shows historical emissions combined with projected emissions associated with the "Stern scenario", in which future emissions are cut to a target of 25% reductions by 2050, and to 80% thereafter. The middle and bottom panels show the resulting changes in CO_2 concentrations and temperature respectively, produced using a simple model tuned to the eleven C4MIP coupled climate–carbon cycle models. Temperature in 2100 approaches stabilisation between 1.6 and 4.2˚C. (House et al 2008)

Figure 3. A 300m tall tower in central Siberia used for continuous measurements of biogeochemical trace gas and O_2 concentrations

- QUEST science was embedded in the Global Carbon Project 's assessment of the global CO_2 budget and trends. Fossil fuel emissions increased by 29% between 2000 and 2008, while emissions from land-use changes were nearly constant. There was a slight reduction in the effectiveness of carbon sinks, as predicted from our understanding of carbon feedbacks.
- A working group with DECC, the UK Climate Change Committee and the Met Office aimed to provide information on how to achieve stabilisation targets (Figure 4). The Stern Review proposed reducing emissions by 25% by 2050 and continuing down to 80% reductions to achieve stabilisation of temperatures at 2 °C. When these proposed reductions were modelled they showed temperatures almost stabilised between 1.6 and 4.2 °C. If the emission reduction is much more rapid (50% by 2050), all models project a temperature change of less than 2°C in 2100. Continuing emissions reductions are absolutely necessary for CO_2 stabilisation.