International Collaboration on Data Assimilation in Terrestrial Carbon Cycle Science

CTCD, DARC and CLASSIC

Motivation

The terrestrial carbon (C) cycle plays a major role in the Earth's hydrological and biogeochemical cycles and climate (e.g. Cox *et al.* 2000; Prentice *et al.* 2001; Melillo *et al.* 2002). While the main processes are understood, our quantification remains relatively poor. After more than thirty years of research, the latest IPCC report indicates that we can only apportion the global uptake of excess fossil CO_2 between ocean and land with an uncertainty of ± 1 GtC yr^{-1}. Until recently, approaches to C cycle science have relied either on: (1) detailed bottom-up models of the critical ecological processes (Woodward & Lomas 2004); or (2) top-down constraints on the global cycle, imposed by inversion of global and regional atmospheric data (Gurney *et al.* 2002). While much has been learned from these different approaches, both contain important limiting factors. The bottom-up approach founders when applied globally because of heterogeneity in process and difficulties in regional and global corroboration. The top-down approach uses data so aggregated that it is difficult to generate detailed insights into the ecological processes at finer time and space scales, and thus it cannot improve our prognostic capability.

Recently, it has been realised that the application of two separate approaches for estimating carbon fluxes is an inefficient use of information. Also, no single model or set of observations can quantify the dynamics of terrestrial C exchanges, and describe the critical governing processes. As is the case for all major Earth system cycles, understanding requires integration and synthesis of data and models from a range of disciplines. This has led to a major upsurge of activity in what is known as model-data fusion, or a multiple constraints approach, which attempts to develop a coherent method treating both data and models as sources of information. The core problem is then how to combine and weight the various information sources. In its most highly-developed form, which has become a central element in numerical weather prediction, this is known as data assimilation (DA), and represents a major goal of carbon cycle science (IGCO Report, Ciais et al., 2004). Such an approach to Earth system analysis is at an early stage, except in the NWP and atmospheric communities (Swinbank *et al.* 2003; Kalnay 2003; Scholze 2003; Williams *et al.* 2005).

Historically, the slow penetration of DA into C flux estimates arises from the diffuseness of datasets and the difficulty of direct measurements of the state vector, leading to the design of models that were badly matched to exploit the DA techniques. However, this is changing rapidly, driven by model and data improvements, and an appreciation of the power of the DA concept. Recent satellite launches (Terra/Aqua, Envisat) are generating dramatic improvements in Earth system observations, and planned missions (e.g., the Orbiting Carbon Observatory, to be launched by NASA in 2007) will extend this much further. Coherently linking these global datasets to Earth system models is critical for operational monitoring of the C cycle in the terrestrial biosphere, and for advancing understanding.

In the UK, the use of DA at local scale for terrestrial C flux estimates has been demonstrated in the CTCD by Williams *et al.* (2005). C data assimilation at regional and continental scales is a major research direction for the CTCD, forms part of the CLASSIC programme, and is a central objective of both QUEST and the CAMELS project (part of the EU CARBO-EUROPE project). In addition, DARC has strong current interests in extending its activities into C flux estimation, with a particular

focus towards inverse modelling of atmospheric trace gas data derived from satellites (Struthers *et al.* 2002; Lahoz *et al*. 2005), and on determination of surface fluxes using inverse techniques.

Given the need for improved understanding in terrestrial C cycle research, the availability of new global data sets, the potential for DA techniques to generate novel insights, and the fact that NERC has both major interests and significant capabilities in DA for C flux estimates, the time is right for an international collaboration to bring together the leading researchers in this area. In particular, there are key world-class overseas research groups with whom UK co-operation is likely to yield significant gains in scientific knowledge, as well as ensuring UK participation at the highest level in developing the research area. In this proposal, we identify particularly the Max-Planck-Institute for Biogeochemistry, Germany (Martin Heimann), the Laboratory for Climate Sciences and the Environment, France (Philippe Ciais, Peter Rayner), the Department of Atmospheric Science, Colorado State University, USA (Scott Denning), the Marine Biological Laboratory, USA (Edward Rastetter) and the CSIRO Earth Observation Centre, Australia (Mike Raupach, Damian Barrett and Pep Canadell). Note that the link to CSIRO also puts us in direct contact with the Global Carbon Project (part of the Earth System Partnership), of which Mike Raupach and Pep Canadell are the Chairman and Executive Director, respectively.

Objectives

Our overall objective is to bring together researchers to determine how data assimilation can generate improved insights into the processes underlying the terrestrial C cycle, and thence enhance our prognostic capabilities.

Our particular objectives are (1) to form working links with world-class researchers, in order to accelerate the development of DA in terrestrial C cycle science internationally and in the UK; (2) to bring UK strengths in terrestrial C cycle science (CTCD) and data assimilation (DARC) to the international research community, while benefiting as much as possible from international approaches to the problem; (3) to develop collaborations that will enhance the research capabilities of the UK as a whole and of particularly gifted researchers in the early stages of their career; (4) to develop a global vision and strategy for research, in which the UK can fully participate and take a leading role.

Overarching science question

How can data assimilation contribute to improving the attribution of terrestrial C fluxes, and to reducing errors in estimating the current state of the C cycle?

We identify five subsidiary science questions:

1. What are the relative advantages of different approaches to data assimilation? Various approaches are currently being employed, from ensemble Kalman filters to 4D variational assimilation (Lorenc 2003). What are the advantages and disadvantages of each in terrestrial C cycle science?

2. What computational resources are required for DA in Earth system science? What technical constraints are holding back the science? Can e-Science (GRID) provide the necessary infrastructure?

3. How can we best incorporate remote sensing (especially long time-series for C-cycle re-analyses and CO_2 column content measurements) into DA schemes? Should we concentrate on first order EO products, i.e. radiances? What observation operators are required to map from observations to models? In a more general context, which data have most impact on improving

C flux estimates, and how do we optimise the design of data delivery systems (ground-based, airborne and from satellites)?

4. What is the potential for carbon-water connections in multiple-constraint data assimilation? We believe that data on the water cycle (e.g. runoff) provide powerful constraints on carbon (and vice versa) (Picard et al., 2005). What data streams and model frameworks can benefit from these possibilities?

5. How can we assess errors and their propagation through DA schemes? Error estimation is a critical part of the DA process, but methods for assessing and quantifying errors in models and observation operators are poorly understood.

These five questions may be modified and others may emerge, depending on developments in the early stages of the project (see (2) below).

Description of the proposed activities

We propose a mixture of staff exchanges, workshops, a journal special issue and study leave to accelerate the development and application of DA techniques in terrestrial C science (and more generally in Earth system science), and to bind UK researchers into leading international partnerships. These activities are described more fully below.

1. Enhancing research capabilities by exchanges between participating labs. For exchanging ideas and developing skills we need to bring people together over significant periods of time. We propose exchanging scientific staff for three months between key institutions (CSIRO, MPI, LSCE, CSU, MBL; in the UK, CTCD and DARC are joint leaders on this proposal, but we will also be looking at the needs and opportunities for QUEST, CLASSIC and CEH). The goal of the exchanges is to explore and develop DA methodologies (e.g. ensemble Kalman filter, 4D-var), and to improve and share both datasets and modelling techniques.
We expect to fund the following eight exchange visits:

(a) Reciprocal visits from UK to LSCE (assimilation of satellite data, both radiance and derived products, such as absorbed radiation or leaf area index, into dynamic vegetation models).
(b) Reciprocal visits from UK to CSIRO (assimilation of land cover and tall tower data).
(c) Reciprocal visits from UK to MPI (assimilation of ground and satellite data into atmospheric inversion models).
(d) CTCD visit to Colorado State University (using measurements of atmospheric CO_2 to understand land surface gas exchanges)
(e) Visit from Marine Biological Laboratory, Woods Hole to the UK (scaling effects in data assimilation)

Visitors to the UK will be expected to spend some time at both DARC and CTCD, and we will ensure a programme of visits or joint seminars with other key UK players (CLASSIC, CEH, QUEST and UKMO, together with the ECMWF).

2. Workshops for discussion and demonstration of current capabilities. To boost networking, we need to bring together key people from around the world for intensive workshops in the UK. We will hold one large initial workshop (~50 participants) to bring the leading researchers together early in this collaboration. The workshop would be based around presentations and break-out groups. The presentations would be designed to set out the current state of the science, identify recent progress and critical problems, and share ideas for future research. Break-out groups, of which we envisage five, would discuss critical science questions arising from the plenary sessions, and plan a strategy for resolving them. These break-out groups would also be tasked with

generating ideas for one or two papers, with specific authors, based around the overall and subsidiary science questions. The initial workshop will spawn six smaller workshops (~10 participants each). Five of these will focus on fleshing out and implementing strategies to resolve the identified science questions, and on carrying the journal papers through to completion. A final workshop will be devoted to generating a strategy and vision document (see 4 below). CTCD and DARC have considerable experience in setting up such high-profile summer schools and workshops.

As an associated activity, DARC sees training as central to its mission, and has significant experience in this area through provision of advanced workshops and summer schools. DARC is therefore keen to play a prominent role in developing advanced tutorials and practical classes that both spin off from this project and help to support it.

3. A special issue in a high profile journal focussing on the application of DA to the terrestrial C cycle at regional and global scales. A high-impact output of this collaboration will be scientific papers in peer-reviewed journals. At the initial workshop we will outline key papers and authors for a journal special issue. Authors will then have 5-8 months to produce draft papers that will be presented at the small workshops in 2006-7. These papers will be revised based on the workshop discussions, and combined into a submission to a special issue in a relevant journal. We will talk with the editors of journals such as Global Change Biology or Global Biogeochemical Cycles to carry this forward.

4. A research strategy document detailing a vision for the global community. A final output of this collaboration will be a strategy document for circulation among the funding councils (NERC, NSF, ARC, EU, NASA, ESA, etc.) detailing the future of data assimilation in terrestrial C cycle research and its relation to Earth system and global change research. The strategy document will include recommendations on training, funding, resources and necessary partnerships. One of the smaller workshops in (2) will be tasked with producing this document.

5. A web-page to provide an interactive environment for C cycle research via model-data fusion and data assimilation. The web-page will be based on CTCD/DARC servers, and will be constructed using professional services. The web page will assist communications among the collaborators and in organising the workshops, maintain a library of workshop presentations, provide a repository for model code and manuals and links to key data, and provide a means to share drafts of journal papers. There will also be links to global programmes such as CCDAS and CAMELS (EU), the Global Carbon Project, the Terrestrial Carbon Observations Initiative, the Australian and US Carbon Cycle Science Programmes, GEMS (ECMWF), GMES (EU/ESA) and ELDAS.

Justification for all resources requested

The following costings are gross figures only, but are based on detailed calculations that can be supplied if required.

Administration to organise exchanges, workshops, journal special issue, reports and web-pages	£15.3K
Funding for one 5-day 50-person workshop	£57.1K
Funding for six 10-person workshops, 3 days each	£48.2K

Funding for eight exchanges. Seven are of 3 months duration, costed for T & S only; Dr Rastetter's visit is of 2 months and includes a salary element with reduced T & S.	£80K
Teaching cover for 20 lectures by Dr Williams to enable visit to CSIRO	£1.5K
Total:	£202.1K

The costs for the workshops are full costs based on experience in running major international meetings by CTCD and DARC in the last two years. These may come down if participants provide partial funding or are in the UK for other reasons (such as exchange visits). We will, of course, explore such avenues to reduce the cost to NERC. Particularly useful in this respect may be the links to the Global Carbon Project (GCP) and the Terrestrial Carbon Observations Initiative (TCO). The GCP are keen to be involved in the proposed international workshops and may be able to access supporting funds. The TCO (of which Shaun Quegan is the Chairman) has recently been asked to emphasise model-data fusion and data assimilation by its steering group, the Global Terrestrial Observing Systems Panel. Both cases offer scope for support, which we will pursue as part of our project management.

Note also that the Max-Planck-Institute for Biogeochemistry offers to provide matching funds from in-house resources if required (see covering letter). NERC and the project may benefit greatly from such leverage.

Participants

This proposal is jointly led by the Centre for Terrestrial Carbon Dynamics (CTCD) and the Data Assimilation Research Centre (DARC).

The organisers in CTCD have expertise in Earth observation (S. Quegan) and ecological modelling (M. Williams). Other CTCD members have expertise in global ecosystem models (Ian Woodward), radiative transfer models (P. Lewis) and uncertainty estimation in environmental models (Tony O'Hagan and Clive Anderson). The organisers in DARC have expertise in data assimilation and Earth observation (A. O'Neill and W.A. Lahoz). Applications of data assimilation to C-flux estimation will require a critical examination of options for data assimilation (e.g. whether sequential or variational methods are most suitable); how errors are propagated forward in time; the nature of model errors, including the identification and treatment of model biases, the nature of the observations, their error characteristics and their interface to the data assimilation system. DARC will address these issues by developing simplified representations of the relevant assimilation problem to help design an optimal system based on a sound theoretical understanding of the problem.

The Climate and Land Surface Systems Interaction Centre are associated partners, providing expertise in Earth observation of land surface characteristics (M. Barnsley). All three NERC Centres have strong interests in exploiting data assimilation in their programmes, including the extension of current DA approaches to improve terrestrial carbon cycle calculations.

Other invited participants in the UK will include the QUEST team at Bristol, who have considerable expertise in data assimilation and ecological modelling (C. Prentice, W. Knorr, M. Scholze), the Centre for Ecology and Hydrology, expert in land surface models (P. Cox, C. Huntingford, R. Harding) and the UK Meteorological Office, experts in data assimilation (A. Lorenc).

Our international partners are:

1. CSIRO Land and Water, Australia: **Dr. M.R. Raupach** is Team Leader of the Earth Observation Centre, CSIRO Atmospheric Research, Canberra, Australia with expertise in regional estimates of C fluxes (Leuning *et al.* 2004) and remote sensing of land cover (Lu *et al.* 2003). He is also the Chair of the Global Carbon Project. **Dr. D. Barrett** is Leader of the Terrestrial Remote Sensing in the Environmental Remote Sensing Group, and an expert on using multiple constraints to estimate regional carbon balances (Wang & Barrett 2003). **Dr Pep Canadell** is Executive Director of the Global Carbon Project.

2. Max-Planck-Institute for Biogeochemistry, Germany: **Dr. M. Heimann** is a Director at the MPI-Biogeochemistry, with expertise in biosphere modelling (Knorr & Heimann 2001), inversion of atmospheric data (Gurney *et al.* 2003) and in using satellites to provide extra constraints (Houweling *et al.* 2004).

3. Laboratory for Climate Sciences and the Environment (LSCE), France; **Dr. P. Ciais** and **Dr P. Rayner** are experts in atmospheric inversion modelling (Gurney *et al.* 2002; Rayner *et al.* 2002), use of isotopic data (Ciais *et al.* 1995) and assimilation methods (Kaminski *et al.* 2002).

4. Dept. of Atmospheric Science, Colorado State University, USA: **Dr. A.S. Denning** leads the BioCycle research group, and is focused on linking land surface exchanges to measurements of atmospheric CO_2 (Pielke *et al.* 1998; Denning *et al.* 2003; Nicholls *et al.* 2004).

5. The Ecosystems Centre, Marine Biological Laboratory, Woods Hole, USA.. **Dr. E.B. Rastetter** is a Senior Scientist with expertise in modelling of biogeochemical cycles (Rastetter *et al.* 1997), and in scaling ecological processes across space and time (Rastetter *et al.* 2003).

In generating lists of invitees to the workshops, we will ensure that we build links to CCDAS and CAMELS (EU), ECMWF, the Global Carbon Project, the International Global Carbon Observations Initiative, the Terrestrial Carbon Observations Initiative, the Australian and US Carbon Cycle Science Programmes, GEMS (ECMWF), GMES (EU/ESA), and ELDAS.

Timeline

The collaboration would start in July 2005 and run for 30 months.

1. Website launched September 2005
2. An international workshop (50 attendees), November 2005, UK
3. Five workshops during 2006-7, UK
4. Vision workshop early 2007, UK
5. Workshop reports compiled March 2007
6. Special issue completed June 2007 (and published within 12 months)
7. Vision document completed September 2007

The exchange visits will be spread throughout the project, mainly in 2006-7.

Benefits to NERC and UK

This collaboration links strongly to **NERC** priority areas **Earth's life support systems** and **Climate Change**, through the focus on a detailed global analysis of the terrestrial C cycle and atmospheric CO_2 concentrations. The proposal is also closely tied to the **QUEST Science Plan**, providing "improved qualitative and quantitative understanding of large-scale processes and

interactions in the Earth System". The research objective has strong policy relevance for the Kyoto Protocol, both as regards attribution in its present form and its future directions, and for the preparation of future IPCC reports, to which we expect to contribute. Future international carbon management strategies will rely on global efforts, and by leading the collaboration set out in this proposal the UK will be in an excellent position to play a major role in their development and evolution.

The value added to CTCD by the development of this international dimension is that it will link us into the forefront of what is a global research effort, providing us with opportunities beyond our current capabilities. For instance, groups such as MPI and LSCE have global leadership in atmospheric inversion (top-down) approaches where the UK is weak, whereas CTCD and the UK have strengths in bottom-up approaches. CSU are world leaders in using regional atmospheric data to constrain spatial models of ecosystem processes. The Ecosystems Centre are expert in biogeochemical models, and in solving the problems of scale that are critical in linking field studies to regional datasets. CSIRO have already demonstrated how to use Earth observation data to constrain steady state descriptions of land surface process. The value added to DARC is that they will gain immediate access to the most recent developments in assimilating data relevant to the terrestrial carbon cycle. These connections will save time and circumvent problems that would arise in their intended extension of work to coupled land-ocean-atmosphere carbon cycle DA.

The international dimension will allow UK researchers to tap into DA expertise in other areas of the Earth System (e.g., atmosphere, oceans). By collaborating we will be able to extend our scientific reach – the questions we will be able to address - and provide training opportunities for UK scientists, so that the UK Earth observation and C cycle communities can learn and incorporate international skills. We will also be able to clearly demonstrate UK skills in ecosystem modelling to the global community and build upon these in future international partnerships. International collaboration will provide the UK with access to a broader range of data sources, and insights into different approaches to processing and using Earth observation data.

The benefits to UK science will not be restricted to CTCD and DARC – the collaboration links closely to the goals of QUEST, CLASSIC, CEH and the UKMO. All these organisations will benefit by their involvements with the international partners.

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