Quantifying and Understanding the Earth System (QUEST): Science Plan

Published 22 June 2004

Executive Summary

QUEST aims to achieve improved qualitative and quantitative understanding of large-scale processes and interactions in the Earth System, especially the interactions among biological, physical and chemical processes in the atmosphere, ocean and land and their implications for human activities. Thus, QUEST intends to contribute to the solution of major outstanding problems in Earth System Science. QUEST will pursue this ambition by promoting integrative, interdisciplinary activities with a strong focus on theoretical analysis, quantitative modelling, and the systematic deployment of observational and experimental data to evaluate and improve Earth System models.

QUEST is highly topical because of well-founded concerns in society about changes in climate and their consequences for ecosystem goods and services, energy production and other human activities. At the same time, Earth System Science poses interdisciplinary intellectual challenges of a fundamental scientific nature. This dual aspect provides both a challenge and an opportunity for scientists to work across disciplinary and institutional boundaries.

The objectives of QUEST require the consideration of a range of time scales. Geological time scales (especially the past 100,000 to 1 million years covered by continuous ice core and sedimentary records) will be considered, in so far as the geological record can help us to understand the "baseline" natural behaviour of the Earth System under a wide range of conditions, and its reaction to changes in the Earth's environment. The recent (10-100 years) period provides the strongest evidence for a global fingerprint of human activities; a wide variety of ground- and space-based observations developed over recent decades provides the most detailed means to evaluate and improve models of terrestrial, marine and atmospheric processes. The next 100+ years are the focus for concerns about the consequences of large-scale human activities for sustainable resource use and human development. These concerns provide a motivation to deploy Earth System models in a prognostic way and to try to represent the interactions between human activities and environmental change at a global scale.

The research programme of QUEST will have three main components focusing on: (1) the contemporary carbon cycle and its interactions with climate and atmospheric chemistry; (2) the natural regulation of atmospheric composition on glacial-interglacial and longer time scales; and (3) the implications of global environmental changes for the sustainable use of resources. Global models of various levels of complexity, and global data sets on key variables describing both the natural world and the characteristics and activities of its human population, are central to the success of the programme; hence QUEST will develop cross-cutting, strategic activities in these fields (Earth System Modelling and Earth System Atlas). The Earth System Atlas will also provide a means of outreach to a wider public.

QUEST will make extensive use of international workshops and other integrative and community-building mechanisms, and links to the Earth System Science Partnership programmes, to help set up new and lasting interdisciplinary collaborations within and beyond the UK and to ensure a high level of connection between QUEST and other scientifically leading individuals and institutions worldwide. QUEST will also establish links with UK stakeholders within and outside government, and thereby build effective channels of communication between UK policy makers and scientists engaged in Earth System Science.

Objectives

The primary objective of QUEST is ***to achieve a better qualitative and quantitative understanding of large-scale processes and interactions in the Earth System, especially the interactions among biological,***

physical and chemical processes in the atmosphere, ocean and land and their implications for human activities. This objective encompasses various time scales:

- geological time scales, especially but not exclusively the past 100,000 to 1 million years, in so far as palaeoenvironmental observations can help us to understand the natural Earth System dynamics on which current anthropogenic perturbations are superimposed and the complex response of the Earth System to change in its external environment;

- the contemporary era (the present and the past 10-100 years), during which human influences on the Earth System at a global scale have become apparent through direct observations and high-resolution reconstructions;

- the future (the next 100+ years), including consideration of the human dimensions of response to and mitigation of anthropogenic changes in the environment in a global perspective.

QUEST is to be implemented through integrative, interdisciplinary activities, with a strong focus on theoretical analysis, quantitative modelling, and the systematic deployment of observational and experimental data to evaluate and improve Earth System models.

With a view to the potential policy relevance of QUEST research, QUEST will also establish links with UK stakeholders within and outside government. Thus, in achieving its main objective, QUEST additionally aims to:

- build new and lasting collaborations among UK researchers and institutions (especially but not exclusively those with NERC funding) engaged in different disciplines that contribute to Earth System Science, including international links as appropriate;

- build effective channels of communication between UK policy makers and scientists engaged in Earth System Science.

Deliverables

QUEST deliverables will include the following products:

- Improved global process-based dynamic models of terrestrial and marine ecosystems and their interactions with the physics and chemistry of the atmosphere and ocean, including “benchmark” evaluations of models against a wide range of *in situ* and remotely sensed observations and the results of pertinent field experiments on land and at sea;

- A traceable hierarchy of Earth System Models of differing complexity, including physical, biological and chemical components, representations of human land and ocean resource use and the means to interface with models of human processes, such as land use and trade in agricultural and forest products;

- An Earth System Atlas (in collaboration with international partners) offering researchers “one-stop shopping” for high-quality, peer-reviewed and properly documented global data sets of important Earth System variables, including palaeoenvironmental observations and socio-economic variables, and offering well-synthesized information for a wider audience.

QUEST will also deliver improved understanding and knowledge leading to influential international publications on Earth System Science topics including, but not limited to, the following:

- The pattern, mechanisms and prognosis for land and ocean uptake of anthropogenic carbon dioxide;

- The causes of glacial-interglacial cycles of greenhouse gases as recorded in Antarctic ice cores;

- The potential implications of global environmental changes for the sustainability of terrestrial and marine ecosystem goods and services.

Based on an ongoing synthesis of existing and new science addressing these and related questions, QUEST will deliver:

- information for policy makers concerning the likely human environmental consequences of different scenarios of greenhouse gas emissions during the 21st century.

Background

Towards the end of the 19th century, the Swedish chemist Svante Arrhenius proposed that industrial combustion of fossil fuels would produce a build-up of carbon dioxide in the Earth's atmosphere, which would in turn cause global warming. He also suggested that the ice-age cycles might have been associated with changes in the carbon dioxide concentration of the atmosphere. But these ideas were then untestable. Carbon dioxide concentration could not be measured to sufficient precision; climate records existed only for a few places; and the idea that we might one day analyse ancient gas bubbles, trapped in ice, could hardly be dreamed of.

It took time. Only in the late 1950s did Charles David Keeling first show unequivocally that atmospheric carbon dioxide concentrations were rising year on year. Discovery of glacial-interglacial variations in atmospheric composition came in the late 1970s, and it was as recently as 2001 that the Intergovernmental Panel for Climate Change (IPCC) could finally obtain agreement from scientific representatives of all nations that "There is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities".

In the meantime, scientific interest in these questions has been growing continuously. This development has been fuelled in part by political concern. Most policy makers, especially in hot countries, would not share Arrhenius' view that global warming will make the world a more pleasant place to live in! On the other hand, the realization that the Earth's atmosphere can change so rapidly in composition, and that changes can occur due to transfers of carbon and other elements between the atmospheric, oceanic, terrestrial and geological reservoirs, has generated enormous scientific interest and indeed has revolutionized our view of the role of the biosphere in the physical and chemical state of the Earth.

For many scientists, this development has taken an unexpected course. Individuals scientists have been crossing the boundaries among scientific disciplines to an unprecedented extent, and programmes, institutes and scientific journals have been founded with previously unfamiliar names such as "Biogeochemistry", "Global Biogeochemical Cycles" and "Earth Interactions". There has been a major turnaround in the way scientists think about ecosystems, since global principles are required to understand the way in which biological processes control the exchange of carbon dioxide between the atmosphere, which holds a relatively small (albeit growing) store of carbon dioxide, and the larger reservoirs of carbon in the soil and the deep ocean. The chemistry involved has proved to be far more complex than once thought as the roles of methane, ozone, sulphate aerosols, dust and many other atmospheric constituents of partly or wholly biospheric origin have been established. The physics of climate has proved to be more complex too, as terrestrial ecosystem processes have been shown to be fundamentally important in controlling the exchanges of energy, water and momentum between the atmosphere and the land.

Ice-core records have played a further role in alerting scientists to the complex interactions among physical, chemical and biological components of the Earth System. Ice cores from Antarctica and Greenland have delivered exquisitely precise and detailed records of glacial-interglacial variations in a host of atmospheric constituents and other chemical or isotopic indicators preserved in polar ice, while huge efforts by Quaternary scientists worldwide have established a global fingerprint of climate change from studies of terrestrial and marine sediments. Yet although it has been known since the late 1960s that the

"Milankovitch" orbital changes are the pacemaker for glacial-interglacial cycles, we still do not understand in any depth how the atmospheric composition has been controlled under "natural" conditions over thousands of years. Solving this problem is widely recognized as a top priority, if we are to have confidence in model projections of the future.

Perhaps the most startling development of all, for natural scientists, has been the dawning awareness that projections of the future consequences of growing fossil-fuel use, however well founded, do not translate directly into political action to mitigate climate change. The potential impacts of climate change on human activities are complex (and not universally negative), they are highly variable among regions (challenging our still-limited ability to model atmospheric circulation changes in detail), and strongly mediated by social and economic drivers at local, national and international levels. Changes in the human environment cannot realistically be studied without reference to the social and economic context, just as policies cannot usefully be proposed without reference to the political decision-making process. Thus, at a minimum, to develop a sufficient understanding of global environmental changes *and what they mean for human activities* is now understood to require insights from physics, chemistry, biology, the geographical and Earth sciences, and the social and political sciences.

It follows from the above that effective and sustained collaboration across disciplinary boundaries will be a requirement for the solution of major outstanding problems in Earth System Science. From an interdisciplinary perspective, many examples could be given of sub-fields where progress has been frustratingly slow because scientists working in one discipline have not been sufficiently aware of new developments in another, or because scientists working with different tools (such as observations versus models) have not worked effectively together because of differences in methodology and scientific culture. This situation represents an opportunity, however, because it should be possible to make rapid advances through a programme explicitly built around interdisciplinary goals and synergistic, collaborative efforts. This is the essential logic of QUEST. It is not a new idea – it builds on over a decade of experience in international "global change" programmes sponsored by organizations such as the Earth System Science Partnership programmes (that is: the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme, (WCRP) the International Human Dimensions Programme (IHDP) and DIVERSITAS) and the International Institute for Applied Systems Analysis (IIASA) – but it is a new concept for a funded programme within the UK. The UK has major strengths in most of the component fields of Earth System Science, but has lacked co-ordination mechanisms to promote goal-oriented, collaborative research.

A blueprint for QUEST was developed by a cross-section of the UK environmental science community at a Town Meeting which NERC organized in London in December 2002. Despite the diversity of interests represented, this meeting revealed a remarkably strong consensus on many aspects of the content and the implementation of QUEST. As regards scientific content, speakers and discussants broadly agreed on several key points:

- that QUEST should promote a better understanding of the global carbon cycle and its interactions with climate

- that the focus of QUEST should not exclusively be on the carbon cycle, given the importance of other atmospheric constituents and the central roles of the cycles of water and nutrient elements for the function of the biosphere and human activities

- that the challenges posed by the ice-core record, especially the challenge of understanding glacial-interglacial cycles and rapid changes in atmospheric composition, must be addressed

- that analysis of future environmental changes should include a more explicit consideration of the human dimensions of the problem than has usually been the case.

There was also agreement on the following operational principles:

- that QUEST should not be exclusively a modelling programme, but should aim to bring models into closer connection with observational data and experimental results

- that the success of QUEST would depend in part on the extensive use of workshops, research visits and other unconventional instruments to actively encourage scientists of different backgrounds to work together on common problems.

Research Programme

Based in part on the findings of the Town Meeting, the QUEST research programme has been planned to consist primarily of multi-institutional collaborative research projects, centred on three themes corresponding to different temporal perspectives. The topics listed under each theme below are illustrative rather than exhaustive, but they include some of the most important outstanding problem areas in each category.

In all cases, the most effective attack on the problem is likely to involve both modelling and analysis of observational and/or experimental data. New data collection within QUEST should be strictly focused, justifiable within a global analysis and modelling context, and synergistic existing observational projects or programmes. Model analyses in QUEST should be strongly oriented towards the evaluation and improvement of models by bringing them into better correspondence with empirical data and process understanding. Data assimilation techniques are likely to play a role, especially in the analysis of sources and sinks for anthropogenic atmospheric constituents.

Theme 1: The contemporary carbon cycle and its interactions with climate and atmospheric chemistry. QUEST will aim to improve our understanding of the feedbacks among physical, chemical, and biological processes that have contributed to determining the atmospheric greenhouse gas content today and its possible evolution over the 21st century. Candidate issues to be addressed include:

- *The spatial location, temporal variation and causes of carbon dioxide sources and sinks on land and at sea.*

- *The likelihood, magnitude and timing of a transition in the terrestrial biosphere from being a global carbon sink to a source.*

- *The role of the biogeochemical nitrogen cycle in modifying the response of terrestrial and marine carbon cycling processes to changing carbon dioxide concentration and climate.*

- *The controls on the atmospheric content of the next most important greenhouse gases (methane, tropospheric ozone, nitrous oxide) and the interaction of natural and anthropogenic processes in controlling the abundances of these gases.*

- *The roles of terrestrial and marine ecosystem processes in altering the sources and sinks of reactive trace compounds that influence the aerosol content and the oxidizing capacity of the atmosphere.*

Theme 2: The natural regulation of atmospheric composition on glacial-interglacial and longer time scales. The ice-core records present a major challenge to understand the causes of large and sometimes abrupt changes in atmospheric composition associated with the glacial-interglacial cycles of the past 0.5 to 1 million years, and there is evidence for even larger natural changes in the more distant geological past. Major issues in this field, which could usefully be addressed by QUEST, include:

- *The causes of the glacial-interglacial cycle of atmospheric carbon dioxide.*

- *The pattern and controls of variations in processes affecting atmospheric trace gas composition on glacial-interglacial time scales, such as wetland formation, fire frequencies, and changes in terrestrial and marine biotic community composition.*

- *The consequences of changes in the global dust cycle for marine and terrestrial biological productivity, the carbon cycle and climate.*

- *The role of biophysical feedbacks from terrestrial and marine ecosystems in climate change.*

- *Interactions of geochemical and biological mechanisms in determining the long-term habitability of the Earth.*

Theme 3: The implications of global environmental changes for the sustainable use of resources. Human activities depend on marketed and non-marketed "services" provided by the terrestrial and marine biosphere. There is an urgent need to understand the responses of ecosystem services to a changing environment and to quantify the implications of such changes for human activities in a globally consistent way. Typical issues for QUEST therefore include:

- *The consequences of a changing climate for global patterns of freshwater availability, taking into account potential changes in demand.*

- *The consequences of a changing environment for global patterns of agriculture and forestry, taking into account economic drivers and their response to changes in supply.*

- *The degree of threat posed to global biodiversity by a rapidly changing climate, and the potential effectiveness of strategies to mitigate the loss of biodiversity due to changes in climate and land use.*

- *The potential efficacy and cost-effectiveness of measures designed to mitigate global climate change through terrestrial and marine ecosystem management.*

In addition to clusters of collaborative research projects based on these three themes, QUEST will include focused strategic activities under the following headings.

Earth System Modelling. Modelling is a necessary part of Earth System Science research, whether the focus of research is on understanding the past, present or future. Confidence in models used to project alternative futures rests on demonstrating the ability to make correct predictions about the present and past. A strategic activity in QUEST will develop the next generation of Earth System Models, which will include representations of ocean and land biosphere processes and their physical and chemical interactions with the ocean and atmosphere, building on research in Theme 1 projects. The modelling framework will also allow for interfacing with socio-economic models, building on research in Theme 3 projects. The socio-economic interface will include representations of land and ocean resource use processes and associated activities such as trade in food and wood products.

This activity will develop new "community models" of terrestrial and ocean biosphere processes and their interactions with the physical and chemical environment, based in part on the work of Theme 1 projects, and will incorporate them in a hierarchical coupled modelling framework. Standard "benchmarks" will be developed against which to evaluate terrestrial and ocean biosphere models, both as stand-alone models and as components of coupled models in full interaction with ocean circulation and climate. The benchmarks will include a wide range of *in situ* and remotely sensed observations and also the results of pertinent field experiments.

Coupled model development will focus not only on designing models at high spatial and temporal resolution based on ocean-atmosphere general circulation models (although this is an important goal), but also on creating a hierarchy of models of decreasing complexity and resolution for a variety of applications that will require the ability to perform long simulations and/or multiple sensitivity experiments. Key to the design of this hierarchy will be the concept of "traceability", i.e. as far as possible, the underlying principles of models at different levels should be the same and the simplifications made in going from one level to the next should be explicit and transparent. This activity will have a strong "e-science" component, and it is particularly important that it is conducted in a strategic way with due attention to issues of compatibility, modularity and transparency in programming.

Earth System Atlas. Analytical and modelling activities in Earth System Science rely heavily on the availability of high-quality global data sets, yet access to and knowledge of data sources and their reliability and limitations is frequently a major stumbling block for scientists trying to work across disciplinary boundaries. The need for an Earth System Atlas has been identified by the IGBP, which has developed a blueprint for the Atlas as both a key resource for scientists and a tool for communication and outreach. The Earth System Atlas should provide scientists with "one-stop shopping" for high-quality, peer-reviewed global data sets of important Earth System variables, including palaeoenvironmental observations and socio-economic variables (where the problem is especially acute) as well as variables of general importance relating to e.g. physiography, ecosystems, and climate. Developing the Atlas will be of paramount importance for QUEST as well as for the international community of Earth System scientists.

QUEST will accordingly play a central role in initiating and implementing the Earth System Atlas. Like Earth System Modelling, the Atlas has a strong potential e-science dimension. The Atlas also needs to be developed in a strategic manner, with community-wide steering, and due attention to defining and maintaining standards of data integrity, documentation and access.

Finally, ***integrative activities*** will be especially important to QUEST because of the many linkages that must be made among projects and the need for Earth Systems research to be given focus and direction through a collective process involving scientists with different backgrounds and expertise. QUEST will make extensive use of mechanisms such as international interdisciplinary workshops ("working" workshops with clearly defined goals and follow-up activities, involving the relevant individuals from QUEST projects and carefully selected overseas participants), research visits, and "all hands" science meetings.

Training

The QUEST projects will provide opportunities for postgraduate and postdoctoral training through tied studentships and PDRA positions. By participating in QUEST projects the individuals concerned will have exceptionally good possibilities for learning from scientists in other institutions and disciplines, and for international contacts. In addition, QUEST may organize an annual summer school aimed at advanced postgraduate and postdoctoral levels.

The communities involved

QUEST is predicated on the existence of competence and "critical mass" (or in some fields, several subcritical masses that could usefully be brought together) in the UK in most of the component disciplines. The following is a non-exhaustive and non-ranked list of strong scientific communities that are potentially well placed to contribute to QUEST objectives.

- Marine sciences, especially marine biogeochemistry, phytoplankton physiology, atmosphere-ocean trace gas exchange, remote sensing, fisheries research, ocean circulation analysis and modelling, regional and global ecosystem modelling.

- Terrestrial sciences, especially land-surface hydrology, wetland research, convective boundary layer processes, carbon exchange flux measurements, atmosphere-land trace gas exchange, remote sensing, biodiversity research, forestry and agricultural crop research, biosphere modelling.

- Climate modelling in the broadest sense, including coupled modelling of climate, carbon cycle, aerosols and atmospheric chemistry, seasonal forecasting, data assimilation.

- Antarctic science, especially ice-core research, cryosphere-atmosphere trace gas exchange, Southern Ocean biogeochemistry.

- Atmospheric trace-gas measurements and atmospheric chemistry modelling.

- Palaeoclimate modelling, palaeoclimate data synthesis and analysis, Quaternary palaeoecology of the tropics and northern latitudes.

- Earth sciences and physical geography, especially biogeochemical processes, isotope geochemistry, palaeobotany, palaeoceanography.

- Energy research, including renewable energy technology.

- “Sustainability science” in the broad sense, including climate impacts analysis, integrated assessment, environmental economics, environmental law, international politics, development studies, social anthropology, economic geography, land-use and adaptation research.

- Environmental e-science, including distributed data access, grid-based computation, Earth System modelling.

The timely application of QUEST findings in a policy context also rests on the existence of particularly good communications between the environmental science community and the relevant government departments.

Collaboration and links with other programmes

The interdisciplinary and integrative nature of QUEST suggests a large number of potentially productive collaborations within and beyond the UK. There are obvious linkages to be established with existing programmes in the NERC Research Centres, the NERC Collaborative Centres (including the Earth Observation Centres, the NERC Centres for Atmospheric Science and the marine science centres), the Tyndall Centre and the Hadley Centre as well as other, complementary NERC directed programmes including RAPID and UKSOLAS, and university-sponsored organizations such as the Environmental Change Institute.

At the international level, QUEST is well positioned to contribute to the programmes constituting the Earth System Science Partnership, and especially to integrative activities within the such as the IGBP Task Force on Global Analysis, Integration and Modelling (GAIM: currently co-chaired by Prof. Colin Prentice, Leader of QUEST and by Prof. John Schellnhuber, Research Director of the Tyndall Centre) and its successor, and the Earth System Science Partnership joint programmes on carbon (GCP), food (GECAFS) and Water (GWSP).

QUEST will also, as appropriate, explore possible bilateral collaborations with specific agencies and/or programmes in other countries, wherever such co-ordination would help to achieve substantial economies of scale and critical mass. Certain existing programmes are particularly relevant as potential collaboration partners, e.g. the Earth System Modelling programmes of the Institut Pierre-Simon Laplace (IPSL), Paris and the National Center for Atmospheric Research (NCAR), Boulder, USA; the US National Science Foundation programme TERACC which uniquely aims to bring together terrestrial modellers and ecosystem scientists engaged in field experiments.

Resources

QUEST has been allocated £13 million over a three-year period. Subject to a mid-term review for the fourth and fifth years, this is to be extended to make a grand total of £23 million over a five-year period. In addition, £2-4 million have been allocated to QUEST for e -science activities.

Programme management

QUEST is directed by a Leader (Prof. I. Colin Prentice, University of Bristol) who reports directly to the NERC Chief Executive. The Leader will be guided by the NERC Science and Innovation Board (SISB). The NERC Superintending Officer for QUEST is Dr. Phil Newton.

The Leader will be assisted by a core team based in Bristol. Effective mechanisms of liaison with the scientific and user community will be developed, taking account of the programme's wide-ranging remit and policy relevance, both of which create a need for extensive liaison activities. It is anticipated that these mechanisms will include the formation of an independent, international Advisory Board and a group of UK stakeholders, to be appointed with advice from NERC.

Data management

In accordance with NERC policy, a data management strategy will be developed in order to allow timely utilization of data collected or synthesized (including model outputs as appropriate) both within and outside QUEST. The data management strategy will also help to ensure that such data can be maintained by NERC for community use beyond the lifetime of the programme.