A UK Roadmap for GHG Science Activities

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A community-led strategy document with contributions by:

Grant Allen, Gilad Antler, Tim Arnold, Yuri Artioli, Dorothee Bakker, Eleanor Blyth, Hartmut Boesch, Peter Brown, Martyn Chipperfield, Edward Comyn-Platt, Douglas Finch, Grant Forster, Tom Gardiner, Emanuel Gloor, Rob Goddard, Heather Graven, Paul Halloran, Neil Harris, Carole Helfter, Jo House, Jan Kaiser, Ben Keane, Natascha Kljun, Stefan Krause, Peter Levy, Alastair Lewis, Mark Lunt, Rob MacKenzie, Andrew Manning, Alistair Manning, Stephan Matthiesen, Joe McNorton, James Morison, Phil Nightingale, Euan Nisbet, Simon O'Doherty, Marcel van Oijen, Paul Palmer, Penelope Pickers, Dave Reay, Andy Rees, Matt Rigby, Richard Sanders, Ute Skiba, Kieran Stanley, William Sturges, Parvadha Suntharalingam, Amanda Thomson, Jessica Thorn, Sylvia Toet, Tobia Tudino, Sami Ullah, Andrew Watson, Damien Weidmann, Mathew Williams, Chris Wilson, Sirwan Yamulki, Dickon Young.

Edited by Stephan Matthiesen

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Overview

The main objective of this document is to develop a community-led roadmap to underpin future greenhouse gas (GHG) science in the UK on a decadal timescale.

The document is the result of a two-day community workshop held at the University of Leeds, 10-11 January 2017. The purpose of the workshop was to collect information from the GHG science community about the primary research foci for the UK research community in the next 10-20 years. Some of the document contents were later presented at the NERC GHG programme final science meeting at the Royal Society, 8-9 March 2017.

The foci presented here represent a balance between curiosity-led science and applied research that will help enable the UK to play a substantive leadership role in evaluating progress and impacts, at both the national and global scale, of the 2015 UNFCCC Paris agreement.

First, we describe the background and motivation for support of GHG science, formulate the science questions and priorities, and highlight some recommendations for integrated projects that cut across environment disciplines, e.g. atmospheric science, physical and biological oceanography, vegetation and landscape ecology, land use management, remote sensing etc.

This roadmap document is intended to summarise community knowledge and expertise with a focus of suggesting future research rather than an authoritative review of current knowledge. Consequently, we decided not to use references in this document.

Background and Motivation

Human-driven emissions of CO_2, CH_4, N_2O, and other[1] GHGs to the Earth's atmosphere perturb the balance between net incoming solar radiation and outgoing terrestrial radiation. These emissions, primarily from the use of fossil fuels, industrial activities, agriculture, biomass burning, animal husbandry and changes in patterns of land-usage, are the dominant cause of the warming trend observed in the climate system since the 1950s. Countries worldwide are committed to stringent reductions in emissions in order to stabilize atmospheric GHG concentrations and minimize the associated global mean temperature increase.

Achieving this stabilization requires that we have accurate knowledge of human-driven emissions and that we can accurately predict how the land and ocean will respond to climate change and GHG enrichment. Recent NERC investments have improved our knowledge but also highlighted the need for more targeted

1 While much of the text is focused on CO_2, CH_4, and N_2O, the activities are also relevant to other GHGs, i.e. chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydroflurocarbons (HFCs), perflurocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3)

investigation where current data or models meet neither requirement, which this roadmap will describe.

Minimizing the multiple impacts of increasing atmospheric concentrations of GHGs demands a structured timetable of emission reductions leading to zero or negative net emissions by 2100. At the 2015 Paris Conference of the Parties (COP), 195 countries agreed to achieve net zero emissions later this century. Achieving this demands accurate understanding and precise knowledge of natural and anthropogenic GHG emissions and sinks, their drivers and their interactions with simultaneously occurring environmental changes such as land use changes and air pollution, leading to improved representation of GHG fluxes in process based models. This will increase the accuracy of GHG budgets at landscape, regional, national, sub-continental and larger scales, which is urgently needed to design effective strategies to mitigate climate change.

The UK science community is well placed to make substantial improvements to our understanding of GHG emissions and sinks. In particular, building on the integrated UK GHG programme, the UK can play a leading science role in GHG observing systems (e.g. the European Integrated Carbon Observing System, ICOS) via a coherent programme of measurements, data analysis and modelling activities to improve understanding, reduce uncertainties, and motivate, validate and underpin policy decisions. The UK community is ideally placed, through bringing together observational and modelling-focused scientists, to push forward our ability to predict CO_2 emissions compatible with given climate pathways. Experience gained from integrating the land, ocean, and atmospheric communities to quantify the UK GHG budget, and the Atlantic CO_2 sink can be applied to other geographical regions, where the measurement infrastructure and process understanding is poorer, or in some cases non-existent. This is particularly relevant to schemes such as REDD (reducing emissions from deforestation and forest degradation) focused on reducing deforestation of tropical humid forests, or CO_2 observation “deserts” of the Southern Hemisphere oceans[2].

Together with EU colleagues, the UK community aims to use ICOS and related networks (including space-borne assets) to deliver the first big-data driven GHG budget for Europe and on the global scale to ensure that key processes are appropriately represented in Earth System models with well verified capabilities to simulate change in the marine CO_2 sinks which set the boundary conditions for the regional uptake. We will address key questions regarding the drivers of regional variability in emissions and uptake, their likely durability and stability under future changes, potential unexpected behaviour of marine sinks, appropriate measurement and modelling strategies, and the methods and infrastructure required for national Monitoring, Reporting and Verifying (MRV) support to inform on future mitigation strategies.

2 This is also one of the objectives of the NERC RoSES (Role of Southern Ocean in the Earth System) programme aimed at improved assessment of the Southern Ocean carbon sink.

Interlinked Science Challenges

The overarching challenge is to provide a holistic understanding of GHG fluxes, interactions and feedbacks across terrestrial and aquatic ecosystems.

During our community workshops we have identified four key GHG science challenges, which centre on the quantification and understanding of:

1. the variability and trend of GHG fluxes between open ocean and atmosphere,

2. GHG fluxes, drivers and stores of carbon and nitrogen from natural and managed land ecosystems,

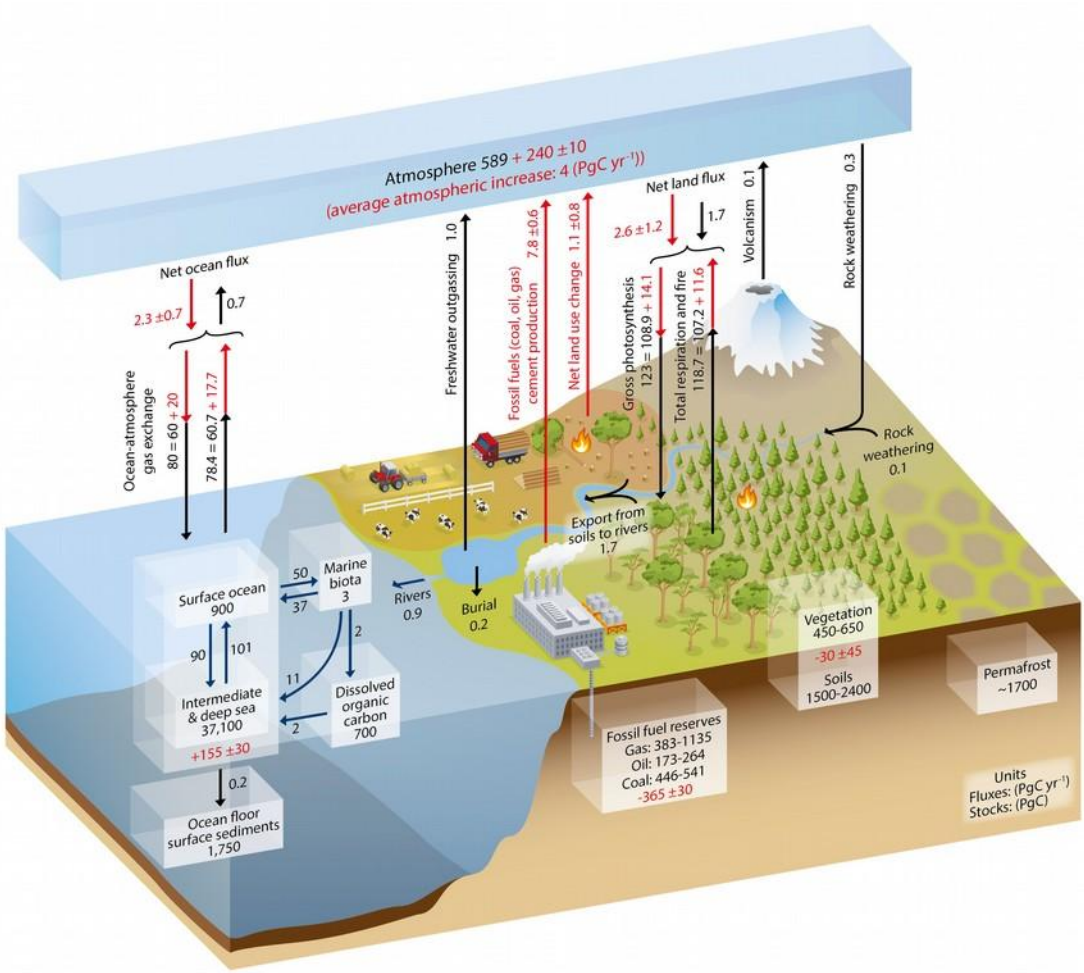
3. GHG fluxes in coastal zones and inland waters, and

4. fluxes and inventories of GHGs associated with the urban environment and industrialised landscapes.

These science challenges underpin the policy needs of separating anthropogenic from natural sources to enable accurate monitoring and reporting, in line with national and international mitigation commitments.

For all four challenges we are interested in quantifying fluxes, stores, and inventories using measurements and atmospheric chemistry transport models; understanding the underlying physical, chemical, and biological processes so that these can be integrated into numerical process models; and using these models to help understand the evolution of GHG fluxes and potential feedbacks to climate as we move into the future.

Broadly speaking, these four challenges are interlinked by coupled physical, biological, and chemical processes; the figure (page 5) illustrates some of these processes, although it does not reflect the full complexity.



Simplified schematic of the global carbon cycle to illustrate some of the key processes that underly the challenges discussed in this roadmap paper.
Source: IPCC (2013): Climate Change 2013: The Physical Science Basis, Fifth Assessment Report (AR5), Fig. 6-01.

Consequently, addressing these science challenges requires coordination not only between measurement and modelling groups, but also between sub-disciplines within environmental science.

In the next sections we expand on each of the challenges.

Open Ocean Processes

The global oceans are a net sink of approximately 25% of anthropogenic emissions of CO_2. There are indications that this percentage is not constant in time: before the mid-20th century it was higher, and it is also expected to be higher in the long-term future because ultimately, in the steady state, the deep ocean will be the repository for most of the CO_2 we emit.

Open oceans are a significant source of natural N_2O and CH_4 production and contribute around one third to the total global N_2O emissions and 11% of CH_4 fluxes.

Oceanic N_2O is produced by microbial activity in the sub-surface ocean. Over the past century the natural cycle of ocean N_2O has been perturbed by inputs of anthropogenically derived nutrients (e.g., via atmospheric deposition and riverine input), and by the impacts of ocean acidification and climate change. Marine N_2O cycling processes are also influenced by local oxygen level, with significantly increased yields in low oxygen zones. Recent studies have suggested that the possible expansion of oceanic oxygen minimum zones (OMZs) in a warming climate could lead to significant changes in N_2O production and fluxes from these regions.

While most of the surface ocean is close to equilibrium with respect to atmospheric N_2O, large emissions from a few regional “hotspots” ensure that the oceans contribute around 30% of the global N_2O source to the atmosphere. While future climate change is likely to increase the magnitudes of these “hotspots”, the resulting N_2O air-sea fluxes are not easy to predict. The relative contributions of different microbial N_2O production mechanisms (denitrification and nitrification) to oceanic N_2O are unclear. Novel isotopic tools such as intramolecular site-preference and oxygen triple isotope measurements would provide important constraints for process models.

The oceans contribute up to 10 % of global atmospheric CH_4, and are thus thought to play a relatively small role in the present-day CH_4 budget of the global atmosphere. Marine CH_4 sources are, however, not well constrained owing to a paucity of observations. Coastal environments including estuaries could account for ~75% of the marine source, and particularly coastal upwelling areas are strong sources (see also the section “Inland Waters and Coastal Zone Processes” below). While there is ample evidence for subsurface CH_4 sources in anoxic environments or zooplankton guts, much of this gas is thought to be oxidized before it reaches the surface. In contrast, the mechanistic understanding of CH_4 sources nearer the surface, which are relevant for atmospheric emissions, is under debate.

There is considerable spatial and temporal variability in N_2O and CH_4 emissions, arising from upwelling. Emission patterns are likely to change due to increased atmospheric N deposition rates and increased CO_2 concentrations.

To improve our understanding of ocean GHG emissions, a holistic approach needs to be adopted and the complexity of feedbacks between atmosphere, oceans and terrestrial carbon, nitrogen and phosphorus cycles needs to be investigated.

The Present State of the Art

Open ocean fluxes of GHGs can be potentially observed at large spatial scales more readily than is the case on the land surface (see below). While hotspots of GHG fluxes, in particular for N_2O, are important, large areas of the open ocean are less heterogeneous on small and medium spatial scales than typical land surfaces and less variable on daily to weekly timescales. This means, in principle, that open ocean fluxes can be characterized by relatively less dense observations than the land surface fluxes. For GHGs such as N_2O with heterogeneous surface flux distributions, we must improve characterization of the regions of intense production and emission, both via more comprehensive observational sampling and improved representation in models.

Global oceans therefore represent an opportunity to make rapid progress in building a component of a global observing system to quantify the response of the Earth system to present and future change. Quantifying ocean fluxes can, through budget considerations in combination with global atmospheric measurements, also help to constrain the more spatially and temporally heterogeneous terrestrial fluxes.

In the North and Equatorial Atlantic and Pacific Oceans, regions that are well traversed by commercial ships, ship-borne instruments are now being used to routinely observe atmospheric CO_2 and sea surface $p(CO_2)$. The $p(CO_2)$ data, integrated with remote-sensing measurements, are being used to construct distributions of atmosphere-ocean CO_2 fluxes. These efforts begin to allow us to interpret observed variations in ocean-atmosphere fluxes of CO_2. While the technology associated with autonomous $p(CO_2)$ measurements is readily adaptable to the measurement of N_2O and CH_4, to date there has been comparatively little coordination for these two GHGs. Nevertheless, advances made during the UK GHG programme and elsewhere mean that opportunities (including isotopic measurements) may arise in the near future.

Ocean CH_4 fluxes remain poorly constrained, with improved monitoring being vital in terms of assessing the extent of methane clathrate loss due to warming. Likewise, estuarine and oceanic N_2O fluxes are highly uncertain in many regions, with increasing reactive N inputs to some coastal areas having the potential to greatly enhance emissions.

Microbial nitrification and denitrification pathways, and possibly some other microbial pathways yet to be identified, are the dominant source of N_2O. Emission rates depend on the supply of N via biological N fixation and atmospheric N deposition. The influence of the different reactive nitrogen pools on N_2O emission rates is not sufficiently well understood.

Main methane sources in oceans are gas leaks from gas and oil mining, methane hydrates and possibly the decomposition of dissolved organic matter. The impact of climate warming and changes in photosynthesis rates on ocean methane emission hotspots require better understanding.

It is only by observing the global oceans to the level which we are now achieving in the North Atlantic that we can begin to assess whether the simplistic assumptions that make up our carbon cycle models – those that underpin our emissions targets – hold up in reality, and in the North Atlantic we find that those assumptions are not adequate.

Key Science Questions

1) What is the net CO_2 balance of major oceans on the basin scale?

Major regions of the world ocean, such as the Southern Ocean, South Pacific, Indian and Arctic Oceans are active as sources and sinks for CO_2 but cannot be observed by commercial ships of opportunities or fixed buoys because they are too remote and consequently not well sampled. New technologies are required to observe CO_2 fluxes in these regions, for example, mounting CO_2 sensors on biogeochemical ARGO floats, gliders and autonomous surface vehicles. GO-SHIP is a program that maps hydrographic sections of the interior ocean every 10 years. Including biogeochemical measurements to the mapping exercise would greatly improve our understanding of ocean GHG fluxes. An example for this approach is the Southern Ocean Carbon and Climate Observation and Modelling (SOCCOM) project[3].

2) What is the net CH_4 and N_2O balance of open oceans?

Observations of CH_4 and N_2O are much sparser than for CO_2, and consequently unable to reliably resolve variations in the oceanic sources of these gases. More observations using automated measurement systems are therefore required. These could, at least initially, have a regional focus, targeting important sources. For example, upwelling zones are known to be large sources of N_2O, while continental shelves (see section “coastal zones” below) and Arctic regions may be significant sources of CH_4 as it is uncertain to which extent methane clathrates will decompose with rising water temperatures. In contrast, some regions such as subtropical gyres and polar regions may be net sinks of N_2O. Changes in the Oxygen Minimum Zones (OMZs) in a warming world may impact N_2O fluxes.

Improved representation of key oceanic source and sink regions in ocean biogeochemical models is required for more robust quantification of present-day oceanic GHG fluxes.

3 https://soccom.princeton.edu/

3) How will oceanic fluxes of the major GHGs change in response to climate change, elevated CO_2 and multiple anthropogenic influences?

Anthropogenic activities are currently adding 10 PgC per year to the atmosphere as CO_2, which is affecting marine ecosystems both directly and indirectly. These effects include warming, ocean acidification (OA), increased stratification and changes to the extent and intensity of oxygen minima with implications for biogeochemical cycling and the ocean-atmosphere exchange of GHGs. Further alterations can be driven by direct anthropogenic influences like inputs of anthropogenically derived nutrients from rivers or atmosphere. Critically, it is highly unlikely that these effects will act in isolation. Because the impact of these multiple stressors on marine ecosystems and biogeochemistry are currently uncharacterised, they are not integrated into existing ocean models.

4) How will our understanding of the net GHG balance of open oceans be affected by revised air-sea exchange parameterizations?

Air-sea gas exchange rates are routinely derived from the product of the air-sea gas concentration difference (derived from measured gas distributions in surface waters) and an appropriate value of the gas transfer velocity (k_w), which cannot be routinely measured. Instead, k_w is usually parameterized as a function of wind speed, although additional controls of surface turbulence such as wind fetch, wave properties, bubbles and surface films are also important in defining k_w; but not all these factors are well understood due to sample bias (e.g. fewer observations in rough seas). Parameterizations accounting for these additional controls need to be developed and applied as appropriate. Eddy correlation (EC) techniques are now available to measure atmosphere-ocean fluxes more accurately than previously possible, as well as improvements using more directly satellite remote sensing and ship-observable products such as mean squared wave slope that provide more direct physical links than wind speed. These need to be employed much more widely to both expand the observational coverage and enable the verification of existing and proposed new air-sea exchange parameterizations.

5) What is the importance of changes in ocean circulation on the ocean GHG balance?

Climate change is expected to have substantial effects on ocean circulation, which will undoubtedly impact the sources and sinks of GHGs but in ways that are poorly understood. For example, models predict that the Atlantic meridional overturning circulation (AMOC) will slow with global warming, and observations of the RAPID array across the Atlantic have documented a decrease in the AMOC over the period since 2004. We might expect this to lead to a decrease in the rate of uptake of atmospheric CO_2. Changes in wind strength in the Southern Ocean may also affect the meridional overturning circulation (MOC) there. Increased ocean stratification and ocean deoxygenation associated with ocean warming has implications for GHG cycling in hypoxic and suboxic zones (N_2O and CH_4). There is a need for coupled atmosphere-ocean and biogeochemical models to be

improved to describe these changes, and for observations to be put in place that can evaluate them.

6) What is the role of marine biology on the open ocean balance of GHGs?

The biological influence on the distribution of marine carbon, and the corresponding influence on fluxes of CO_2 and other GHGs at the surface and in the ocean interior, remains poorly understood. Consequently, models are insufficient to reliably predict future change. A renewed modelling effort coupled with targeted process investigations is required to describe the flux and evolution of biologically-produced material in the ocean interior and to elucidate the specific processes driving marine GHG sources. The biological mechanisms responsible for CH_4 and N_2O air-sea fluxes are under debate. A better mechanistic understanding of the relative contributions of nitrification and denitrification to N_2O in the surface ocean, or CH_4 precursors such as DMS, methylphosphonates, and amines, would provide important constraints for biogeochemical modelling efforts.

Land Surface Processes

The land component of the global carbon cycle is currently estimated to be responsible for absorbing approximately 25% of the CO_2 emitted into the atmosphere. This estimate is highly uncertain with the global value determined as the residual of a mass balance between atmospheric increase and ocean uptake, so that inter-annual variations can be large, driven by regional climate variations such as those during El Nino events. Land management for agriculture and forestry has a key role in the GHG balance, through land use change (e.g. deforestation, afforestation, grassland cultivation) and soil management affecting the carbon and nutrient cycles, and particularly for CH_4 (wetland drainage, wetland crops, ruminant animal production) and N_2O through N-fertiliser use and atmospheric N deposition.

While terrestrial and oceanic CO_2 fluxes to and from the atmosphere are of comparable magnitude, the vast majority of CH_4 net flux to the atmosphere is terrestrial (with small inputs <10% thought to be from relatively stable coastal zone hydrate stores and geological seeps), and 67% of the N_2O fluxes are terrestrial. Current thinking suggests that up to 70% of terrestrial CH_4 emission is biogenic in origin with much of this component accounted for by land-based natural sources (e.g. tropical and high latitude wetlands). These latter sources are the most sensitive to future climate and land use change with the potential for positive feedback and the realization of enormous carbon stores in previously locked reservoirs (e.g. Arctic permafrosts). The precise quantification of the relative proportions of terrestrial (natural) biogenic and anthropogenic CH_4 sources, linked by Earth system modelling to surface processes, is necessary to understand (and predict) the global methane concentration trend; and to better target mitigation policy. Equally, N_2O flux, typically associated with agriculture and inappropriate over-use of fertilizer (particularly in the developing world), needs to be urgently assessed to mitigate further build-up of this extremely long-lived (~1000 years) greenhouse gas.

Despite ongoing research efforts, there are still large uncertainties about where the global carbon is being absorbed terrestrially, and consequently we have little idea of how it is stored, its resilience (e.g. how C stocks might change with land use change and climate change) and the (potential) size of this storage capacity. N_2O and CH_4 emissions carry large spatial and temporal variabilities, driven by complex biogeochemical interactions at the microsite scale, which are difficult to represent in process-based models, and difficult to upscale to units that are meaningful for policy purposes. Land management has enormous implications for terrestrial GHG exchanges that remain poorly understood and quantified. These knowledge gaps limit our ability to project future behaviour of GHG sinks.

The Present State of the Art

Our current understanding of the drivers and magnitude of terrestrial GHG fluxes has greatly improved in the last decade due to technological advancements in measurement and modelling capabilities. The result is a network of sub-hourly

field-scale flux measurements of CO_2, CH_4, and N_2O implemented through ICOS across Europe, and building on previous EU and national programs (e.g. GREENGRASS, Carbomont, NITROEUROPE, CARBOEUROPE, ELUM, GAUGE, GREENHOUSE and others). We now have a European and global network of GHG flux sites on ecosystem/field/forest scales, some with longer data sets that can look at change and interannual variation. These provide good data for CO_2 fluxes, but CH_4 measurements have been added only recently, while N_2O is still expensive and uncommon.

As food and energy demand increases globally, there is an urgent need for improved measurement of CH_4 and N_2O fluxes in developing world nations and for emerging land uses (e.g. conversion to bioenergy cropping). Changes in C stocks held in soils and plant biomass need to be monitored for evaluation against flux data. There are now maps of biomass stocks across the globe developed from a mix of remote sensing datasets. However, repeated mapping is not yet possible for biomass. Global soil C stocks have been mapped from in-situ studies collected over numerous years, but again we lack any robust monitoring changes for in soil C.

The continental land masses comprise the dominant emission sources for CH_4, but emissions are highly heterogeneous over space and time. The major terms for recent atmospheric growth have been found from wetlands, agriculture and fossil fuel burning, with the balance between these highly uncertain. Atmospheric monitoring is an exclusive source of information for understanding the balance between these sources. Further, the mechanisms of anthropogenic CH_4 emissions are numerous and complex, while anthropogenic CO_2 emissions are better understood, driven by fossil fuel combustion data. N_2O emissions are likewise poorly quantified at regional scales – limited by sensor technology and upscaling methods. IPCC guidelines to estimate emissions from fertilizer applications are imprecise and require local, management specific calibrations.

Measurements of the isotopic composition in addition to the mole fraction would provide important constraints for global CH_4 and N_2O budgets. Different emission and removal processes can impart distinctive isotopic signatures in these GHGs, so that stable isotopes as well as radioactive ^{3}H and ^{14}C can serve as quantitative tracers of various processes involving CH_4 and N_2O in the environment. While carbon ($^{13}C/^{12}C$) isotope ratios are starting to become included in monitoring programmes, the additional information is often not sufficient to distinguish between different source and sink scenarios. Hydrogen ($^{2}H/^{1}H$), clumped-isotope CH_4 (i.e. doubly-labelled $^{13}CDH_3$ and $^{12}CD_2H_2$), as well as site-specific intramolecular ^{15}N, ^{18}O and ^{17}O isotope measurements would provide much stronger constraints. Recent developments in instrumental techniques, e.g. mass spectroscopy and laser spectroscopy, now allow these measurements to be made in situ rather than requiring laborious flask sampling and transport to central laboratory facilities, and they allow probing of the more minor isotopologues and provide further detail for source-sink identification.

Key Science Questions

The terrestrial science questions can be split between curiosity-led research and those that are more aligned with measurement, reporting and verification (MRV) activities. Although we acknowledge these activities are not necessarily mutually exclusive, we have in this document separated these questions.

Curiosity-led questions

Curiosity-led research questions are generally much broader than MRV questions, reflecting the uncertainties in current knowledge. They range from the leaf and molecular scale to the ecosystem and global scales. MRV research questions tend to be more technical.

1) What are the current natural carbon stocks (above and below ground) at the global and regional scale and how are they likely to change?

This is a measurement challenge above all. How do we harness all the information (e.g. Earth Observation, GHG concentration and flux networks) that we have and what other data are required to fill in the knowledge gaps? How do we measure long-term carbon changes in organic peat, hydrate stores, and mineral soils, above-ground biomass and below-ground biomass carbon stocks, particularly in the moist tropics? How can strategies for maintaining and storing increasing C in soil and biomass be linked to broader UN sustainable development goals (e.g. food security, economic development)?

2) How do we observe long-term biosphere response to environmental change?

How can we measure spatial patterns in plant stress and/or vegetation trait changes and other ecosystem responses, with sufficient resolution to allow for upscaling to regional and even global scales? How do specific ecosystems contribute to the global and regional GHG budgets and what if any are their key determinants? Particularly critical ecosystems (with the research challenges noted in parentheses) include grasslands (C4 plants), peatlands and wetlands (methanogens), savannas (fire), tundra (permafrost thaw), mangroves (sea level changes, riverine inputs) and agricultural lands (management).

3) What is the role of natural and anthropogenic terrestrial sources and sinks of N_2O and CH_4 in determining global and regional GHG budgets?

How are sources and sinks distributed at present as well as in future climates and across ecosystems and climate zones? What drives sources and sink observed spatial and temporal variation? How will these sources and sinks respond to climate change, air pollution, land use change and management interventions? What maximum levels should we expect these two greenhouse gases to reach and why?

4) To what extend can earth observation deliver the key physical, chemical and biological drivers required to model GHG fluxes more accurately?

Integrating routine hourly flux measurement of GHGs with continuous soil moisture, temperature and isotopologues of e.g. N_2O can help establish robust relationships between fluxes, responsible processes and their controls. Emerging spatio-temporally extensive soil moisture and temperature technology linked to earth observation (soil moisture, canopy phenology) and continuous tall tower monitoring (e.g. online spectroscopic N_2O concentration analyser) can help to generate robust data for assimilation into models.

5) Why and for how long will the global net terrestrial sink continue to increase?

Addressing this question requires better understanding of how we use ecosystem CO_2 exchange measurements to quantify photosynthesis and respiration, how they respond to climate change, and the links to nutrient cycles. We need to determine stress-related (temperature, humidity, water availability, light levels/cloud cover) thresholds to sustainable photosynthesis and plant metabolism, and if these are detectable.

A particular challenge here is how land degradation, ecosystem disturbance from physical mechanisms (storms, floods) and biotic mechanisms (e.g. pests), and fire affect global and regional GHG budgets. We need to quantify the role of humans in terms of emissions and land use change, including mitigation actions, at the global and regional scale. Fully answering this question on C cycling will require clear links to N cycling; for instance, how will increasing atmospheric N deposition alter soil C cycling?

6) How can we improve the way we use data to confront and develop process-based models (e.g. trends, variability, seasonality)?

Numerical models are key to relating small-scale measurements to large-scale climate variations and land management at landscape scale. Important methodological problems, partly exacerbated by the increasing data available for modelling, need to be addressed. Each model is defined for a specific spatiotemporal scale (grid cell size and time step), and the scale determines which processes and feedbacks are implemented. Likewise, data vary from small scale (e.g. leaf measurements) to large scale (e.g. satellite observations). To allow data use for probabilistic inference, we need to develop a multi-scale modelling framework that quantifies how large-scale feedbacks constrain small-scale processes, and vice versa.

In addition, a flexible approach to handling prior uncertainties commonly used in process models is needed to account for e.g. the high precision and transferability of global reference stations and networks (e.g. GAW, ICOS, DECC), versus e.g. the lower accuracy of satellite retrievals. Analogues with assimilation of data in numerical weather prediction models such as 4DVar assimilation could be scoped to optimize the utility of measurements and priors to improve an

appropriate and accurate characterisation of scale-varying uncertainties when such data are used in process models.

We need to predict future risks from both localized extreme weather and large-scale persistent climate change. The combination of a rich modelling framework and multi-scale data sets will inevitably increase computational demands for inference of parameter values. We therefore need to develop model emulators (stochastic approximators) that preserve model behaviour while being computationally fast at the cost of adding structural uncertainty. To quantify and limit structural uncertainty, the framework should be able to use and evaluate model ensembles at every scale. Uncertainty quantification for model structure, parameter values and climate itself will together allow for the first time a comprehensive uncertainty analysis of GHG fluxes.

Measurement, reporting and verification (MRV) research questions

MRV research questions relate the quantification of GHGs in relation to (inter)national climate policy. As noted above, there is often overlap between these questions and those focused on curiosity-led research. For instance, quantifying the national GHG budget demands an understanding of terrestrial and coastal ocean ecosystems that are embedded within national boundaries.

1) How do we attribute observed variations of atmospheric GHGs to anthropogenic (gas leaks, land-fill, agriculture, forestry) and natural (wild fire, wetlands, natural ecosystem) sources and sinks?

This is a major challenge that is common to the urban environment activity. Broadly speaking, there are five approaches:

1. geographical separations of different sources where possible,
2. isotopic measurements,
3. proxy tracer:GHG relationships (e.g. ethane) plus modelling,
4. bottom-up emission inventories, and
5. manipulation experiments.

None of these approaches have been shown to be robust in all environments and all countries, although the third option has not been fully explored as yet. A system that can ingest all available atmosphere and land-based data sets is likely to achieve the best results, but this requires substantial model technology to be developed. It still depends on globally distributed datasets, which are available via surface networks and Earth Observation satellites. A further refinement into emissions from sectors is discussed in the Urban Environment section.

2) How do we quantify land-use change, land management and disturbance and their impacts on GHG emissions?

How do we improve inventories and accounting? There is a need to assess appropriate emission factors, including effects of land use management. In particular, how do we improve data on N_2O for country-level inventories and to improve the partitioning of N_2O fluxes between land and ocean?

Coastal Zone and Inland Water Processes

The coastal zone, defined here broadly as the region between the point where rivers start to become saline and the edge of the continental shelf, plays a key role in global GHG cycling with fluxes comparable to other GHG fluxes in the Earth system. Processes in the coastal zone are separate from but closely linked to processes in inland waters, in particular river systems.

Freshwater GHG emissions are rather uncertain but the amount of carbon vented annually from rivers and lakes may be around 2 Gt as CO_2 and up to 0.1 Gt as CH_4. River N_2O emissions may be around 1 Mt/a, equivalent to around 10% of the total anthropogenic source. These emissions are usually omitted from global budgets. Rivers entering the coastal zone are GHG-supersaturated but they also transport around 1 Gt organic and inorganic carbon per year and around 0.4 Gt nitrogen per year. The microbial processing of these inputs in coastal environments gives rise to substantial production of all three GHGs, at variable rates controlled by a range of factors including C and N composition, temperature, pH and oxygen status, nutrient remineralization rates and other constraints imposed by the physical environment. GHG concentrations and seasonal variability thus reflect a biological-hydrodynamic balance. The result is variable local emissions to air and substantial GHG export to the continental shelves. Coastal regions such as estuaries are major components of the marine cycles of both CH_4 and N_2O but the inherent variability complicates quantifying their magnitude.

On the shelves themselves, tidal exchange, stratification and the interaction of coastal waters with tidal currents and wind stress give rise to strong spatial and temporal heterogeneity. For example, the North Sea varies from near atmospheric CO_2 equilibrium during winter to being a strong CO_2 sink in spring-summer.

The Present State of the Art

Thermal stratification enhances the accumulation of CO_2 below the thermocline via respiration and the CO_2-enriched deep water is exported to the deep ocean. This process is known as the continental shelf pump and its effects are recorded in terrestrial biomarkers in the deep oceans. The continental shelf pump has been quantified in several regions (North Sea, Hebridean shelf, South China Sea, polar systems). Estimates of its magnitude range up to 1 Gt C/a. In a warming climate, to which shelf seas are particularly sensitive, biological production and the carrying capacity are expected to change. Shifts in water temperature, in the strength and timing of water column stratification, in seawater pH, and in nutrient fluxes mediated by vertical and/or horizontal turbulent exchange could all alter the degree of GHG exchange with the atmosphere.

The biological pathways responsible for N_2O and CH_4 production are controlled by a number of factors which include the delivery of nutrients, oxygen status, remineralization of organic nutrients in addition to the constraints offered by the

physical environment. The concentrations of dissolved GHGs and their seasonal variability reflect the biological and hydrodynamical contribution to their source and sink characteristics.

Significant burial of carbon also occurs in shelf, coastal and estuarine systems via saltmarsh and mangrove creation ("blue carbon" phenomena). Changes in land use patterns (see the section "Land Surface Processes") have the potential to significantly perturb natural fluxes in coastal waters. Our understanding of how these regions cycle CH_4 and N_2O is less mature but it is reasonable to assume that there is a dynamic cycle of these gases occurring in them. Studies suggest increases in N_2O fluxes from estuarine and coastal zones, especially associated with increased anthropogenic nutrient loading from rivers, however these fluxes are not well quantified due to insufficient data and limited process understanding.

The key challenge involved in understanding the role of the coastal zone in global GHG fluxes is the heterogeneity of the system in both time and space. The aggregated functioning of multiple individual systems is responsible for the impact of such systems on global GHG fluxes. The system contains riverine, estuarine, potentially deltaic and shelf environments, all of which interact with the atmosphere and solid earth. Inputs of freshwater, momentum via wind forcing and the sunlight required to drive photosynthesis to these systems can be highly variable.

Science Questions

As with other components of GHG science there is a demand for an observing system that is focused on the manifold spatial and temporal scales associated with inland waters and with the coastal zone, and the infrastructure to robustly upscale to larger scales and to confront predictive models. A complicating issue is how to account for "indirect emissions" when organic material is transported by large river systems from inland ecosystems into the ocean, leading to GHGs emissions spatially separated from C and N stocks.

1) What is the role of groundwater discharge in controlling GHG fluxes?

Groundwater is implicated in a number of GHG-relevant processes that are currently not well understood. For example, changes in the groundwater table impact the thawing of cryosoils. Transport of organic carbon in groundwater, even in low concentrations, can lead to the phenomenon of priming, where small amounts of labile carbon trigger the decay of previously unreactive dissolved organic matter (DOM). Priming has been widely observed in soils, but its role in freshwater ecosystems is unclear.

2) What is the role of the very near shore zone between the estuaries and the shelf sea?

The complex dynamics and patchiness of the near shore coastal areas makes it challenging to estimates the net contribution of these to GHG budgets and

understanding the drivers of such variability is crucial to predict how the role can change in the future.

CO_2 and CH_4 dynamics are heavily influenced by the cycling of particulate carbon that depends on a complex interaction of physical (e.g. flocculation, sedimentation, burial wind/flood driven resuspension) and biogeochemical processes (remineralisation, bioturbation of sediments, priming of DOM). N_2O production and consumption is also extremely variable in the near shore and strongly intertwined with the carbon dynamics given its dependency on the redox state of the pelagic and benthic environment. Given the shallow nature of the areas, understanding the role of benthic processes and benthic-pelagic dynamics is crucial (e.g. bioturbation, advective sediments, epibenthic communities, intertidal dynamics).

3) How are we affecting the continental shelf pump as system including inland water discharge, estuarine waters, and the shelf sea?

Coastal areas are experiencing a dramatic increase of human pressures that, in combination with global changes like climate change and ocean acidification, will significantly alter the cycling of GHG. While progress in understanding some of the impacts on GHG emission has been made, much is still unknown, particularly about the combined effect of such drivers of changes. What is the impact of ocean (and freshwater) acidification and changes in rainwater pH on key processes? How this will change due to concurrent changes in temperature and oxygen? How the reduction of riverine nutrient inputs into the coastal areas are affecting the cycling of GHG? Which local/regional management policy can mitigate local hotspot of GHG emission?

4) How will the effects of a changing climate impact and an evolving human pressure on coastal flux of GHGs?

Changing patterns of rainfall, land-use and river management in an environment which is gradually warming will all impact on the biogeochemical and physical processes that control the flux of GHGs between water and air. Changes in the absolute amounts and the stoichiometric balance between nutrients may alter biogenic processes, whereas a decrease in dissolved O_2 is highly likely to favour the release of N_2O and CH_4.

5) Which ecosystem are the major potential sinks?

What is the role of salt marshes and mangroves - the so-called “blue carbon” storage of coastal systems? How will their storage capacity and key drivers change in the future?

6) How can we represent coastal-zone cycling in global GHG budgets and models?

Models at present lack the spatial and temporal resolution required to simulate coastal processes: estuaries and embayments are rarely included and intertidal

areas almost entirely neglected. Similarly, the description of the biogeochemical cycle of GHG is simplified to include only the processes that have influence on large temporal and spatial scales, while processes characterised by high patchiness or frequency (e.g. linked to diel or tidal cycles) are disregarded.

Urban Environment and Industrial Landscapes

Over 3.5 billion people now live in urban areas, with more than 20% of the global population living in cities of over 1 million inhabitants. The UN suggests that cities are already responsible for 70% of global GHG (CO_2-equivalent) emissions. By 2030, the UN projects that more than 5 billion people will live in urban areas. Cities progressively represent large point sources that can already be sensed from space. UN projections also suggest that the global population will grow disproportionately in lower latitude countries, where competing demands on economic growth may not necessarily mesh with the simultaneous mitigation of GHG emissions.

The urban landscape includes a mosaic of natural and anthropogenic GHG sources and sinks. City parks and other green spaces (e.g. parks, woods, golf courses, gardens), are mixed with offices, commercial properties, industrial estates, housing, transport infrastructure, often surrounded by ring roads and greenbelt land. Emissions come from a variety of different types of sources, mainly combustion of different fuels (petrol, gas, coal and – particularly in developing countries – wood and biomass) under different conditions, but also from freshwater and tidal river sections, and from waste disposal and livestock (the latter mostly in developing countries).

Cities are often linked to surrounding industrial landscapes without clearly defined boundaries. Therefore, areas dominated by intense human activity are intricately interconnected with less intensely used areas at all spatial scales, giving the urban landscape fractal characteristics.

Understanding the contributions of different urban source and sinks to GHG balances, upscaling and including the spatial and temporal variation within cities and urban areas is a huge challenge, only recently being tackled. The 3-dimensionality of city landscapes will remain a challenge for transport models for the next decades. As city populations grow, so will the size and number of GHG sources.

Mark Carney, Governor of the Bank of England, announced in 2015 that the Financial Stability Board is “considering recommending to the G20 summit that more be done to develop consistent, comparable, reliable and clear disclosure around the carbon intensity of different assets”[4]. So MRV activities at the small scale are being seriously considered by at least the UK government.

Quantifying (and predicting) GHG sources from such a rapidly changing landscape, driven by human interactions and responsive to ever-evolving policy, technology, and economics, is extremely opaque, and can only be parameterized at the interface between the social sciences and Earth system scientists, informed by both atmospheric and socio-economic measurement and modelling.

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4 Breaking the tragedy of the horizon - climate change and financial stability - speech by Mark Carney at Lloyd's of London, 29 September 2015
http://www.bankofengland.co.uk/publications/Pages/speeches/2015/844.aspx

The Present State of the Art

Bottom-up quantification of urban emissions has been the focus of much recent work in the USA. The VULCAN database estimated emissions across the entire country at 1 km resolution. Subsequently to this, the Hestia project estimated emissions down to the level of individual households in a small number of cities (Indianapolis, Los Angeles, Salt Lake City, Baltimore). From a top-down perspective, a number of cities have begun setting up urban greenhouse gas monitoring networks. The interpretation of these urban measurements remains challenging due to the inhomogeneity and complex meteorology of urban environments. Progress is being made in estimating emissions from industrial sources, through stack measurements, down-wind monitoring and remote sensing.

Currently, there are several emerging techniques and methodologies for quantifying fossil fuel CO_2 emissions at the city scale. One of these techniques is the deployment of many low-cost, small CO_2 sensors across an urban area at high spatial resolution, as has been trialled in several cities including London, Zürich, Oakland in California, and Vancouver amongst others. Although these small CO_2 sensors are not typically precise or accurate enough to be used in the high-precision atmospheric network, by deploying many them, some of the biases in the data cancel out and can be small compared to the magnitude of urban CO_2 signals. Low-cost sensors, however, can be unduly influenced by local emissions if they are placed too close to individual sources. Low-cost sensor networks typically require little maintenance to run, although the data volumes produced can be very large and complex to interpret. Although low-cost sensor networks can be effective in areas of hotspot and high density anthropogenic emissions, they mostly measure total CO_2 only, and cannot distinguish between anthropogenic and natural CO_2 emissions.

An alternative methodology is to deploy a few well-placed, high precision measurement systems that monitor CO_2 mole fraction as well as one or more additional tracers that can be used to separate natural from anthropogenic CO_2 emissions. In contrast to the low-cost small sensors, these very precise measurement systems typically require regular maintenance, which can be costly and time consuming, and they can take many months to build, test and deploy.

Radiocarbon ($^{14}CO_2$) is the current “gold-standard” measurement for separating natural and anthropogenic CO_2 emissions and is currently being sampled across many US and European cities including Los Angeles, Paris and Heidelberg amongst others, however, the measurements are expensive, non-continuous, and can be significantly biased in the UK by $^{14}CO_2$ emissions from gas-cooled nuclear power plants. Additional fossil fuel tracers that can be used continuously and are less expensive than $^{14}CO_2$ include carbon monoxide (CO), nitrogen oxides (NO_x), carbon-13 isotope of CO_2 ($^{13}CO_2$) and oxygen (O_2), although CO and NO_x usually require “calibration” using $^{14}CO_2$ measurements owing to highly variable and poorly constrained CO:CO_2 and NO_x:CO_2 emission ratios, and $^{13}CO_2$ is very sensitive to traffic emissions, and therefore is mostly unable to detect emissions from other fossil fuel sources. O_2 does not require calibration using $^{14}CO_2$ and can

detect most types of fossil fuel emissions. However, O_2 measurements are very challenging, and thus this method is currently limited by a lack of current O_2 measurements in urban areas and a limited number of laboratories with the expertise and facilities to make precise O_2 measurements.

Satellite measurements are another state-of-the-art technology for monitoring urban CO_2 emissions, although the resolution and noise of current satellite data products is only currently sufficient to detect CO_2 emissions of whole cities and large hotspots (for example, high-emitting power plants and industrial areas). However, with improved instrumentation, such as those on the Sentinel 7 satellite, satellite data resolution and noise are expected to improve. Current satellite data products are not as precise as ground-based measurements, and are also prone to systematic and non-systematic biases that can make it difficult to resolve differences between satellite and ground-based emissions estimates, but the spatial information provided by satellites is very valuable. As with low-cost sensor networks, satellite instrumentation currently monitors only total CO_2 and cannot separate natural from anthropogenic emissions, however, plans to deploy instrumentation that measures co-emitted species on future satellites will help to facilitate this capability, and existing data products, such as night light maps, can be used to spatially separate anthropogenic and natural CO_2 emissions to some extent.

All of the current methodologies mentioned above rely on atmospheric transport modelling in order to calculate urban anthropogenic CO_2 emissions from CO_2 concentrations (or in the case of satellite measurements, from total column CO_2). Urban measurements also need to take into account background CO_2 concentrations, either using modelling or using up-wind measurements. Background concentrations can be difficult to define, and are dependent on the city characteristics and prevailing meteorological conditions.

Science Questions

1) What is the role of large cities on UK and other national GHG budgets?

This is the broadest scale question. The population density of some London boroughs is over 15,000 people/km^2. Outside of Greater London the density falls off rapidly with the other major cities typically having less than 5,000 people/km^2. Energy demands and associated GHG emissions per unit area can be crudely scaled with population density, but the relationship is not simple, as some sectors like transport or heating can be more efficient in dense urban areas. A complementary measurement strategy to quantify the nationwide GHG budget would be to target the largest urban areas with a view to wider parameterization.

2) How do we best use activity data to improve bottom-up inventories?

A complementary approach to quantifying GHG emission is to further improve bottom-up emission inventories. There is a growing need to use social and economic activity data to better describe bottom-up emission inventories of GHGs on the city scale down to individual streets. Ongoing work in the US has

used a number of cities as a test bed. Much of the necessary data to build these inventories for the UK already exist, but integrating these data is nontrivial. Such an advance would make future top-down comparisons more meaningful when attempting to deconvolve sources of discrepancy.

In addition to reporting the emissions themselves, it is also crucial to report the uncertainty of the emissions. While the UK inventory reports emission uncertainty at the country level on a per annum basis, there is currently no reporting of the emissions uncertainty at higher temporal and spatial scales.

3) How to best use existing and emerging sensor technology and infrastructure to quantify urban GHG budgets?

As noted above, the cityscape is a mosaic of large point sources at different heights (e.g. industry, household heating, transportation), fugitive emissions (gas leaks), and diffuse sources and sinks (e.g. parks, woodlands, rivers and lakes). To maximize the efficiency of current and future investment we should consider taking advantage of existing measurement sites (e.g. air quality monitoring) and government-owned land and facilities to deconvolve sources at the scales of emission by source-type, while testing their summative quantitative (city-wide) flux capability using snapshot measurement and modelling case studies using less frequent but intensive and targeted unmanned aerial vehicles (UAVs), aircraft and satellite methods downwind of sources and sinks to constrain uncertainty statistics.

Questions that need to be addressed include: What combination of large-scale installations and small-scale sensor technology is appropriate? How do we ensure the small-scale sensors are inter-calibrated and inter-comparable among themselves but also with the larger-scale instruments? How do we ensure that the measurements collected from the resulting sensor network are representative of emissions from the bulk urban landscape? How can we resolve discrepancies between top-down and bottom-up emissions estimates? Can new satellite measurements and products be used to constrain fossil fuel emissions at the city scale?

4) How to separate observed variations of GHG concentrations into sectors (e.g. food production, energy, and transport)?

This represents a further refinement of the source attribution challenge outlined above. Developing verifiable nationwide mitigation strategies relies on understanding the magnitude of GHG sources from individual sectors. Within an urban environment there is arguably a bigger challenge associated with the interpretation of observed variations of GHG from a spatially dense set of different GHG sources and sinks. On the other hand, within a city there will be other atmospheric measurements that can be used to help attribute the influence of individual sources, e.g. carbon monoxide, particulate matter, wood burning tracers, and a range of hydrocarbons.

5) What are the impacts of upwind sources on the urban landscape?

Isolating the influence of a city requires that we understand the composition of air coming into the city. Previous studies have focused on cities that are reasonably well contained and could be isolated using a ring of sensors. This measurement strategy has worked less well for cities such as Paris because of urban sprawl and the heterogeneity of sources. Cities within the UK are likely to impact each other via atmospheric transport.

Atmospheric Modelling Technology

Atmospheric modelling has a key role in translating atmospheric measurements to associated GHG fluxes.

Modelling in all domains (atmospheric modelling, ocean modelling, land surface modelling and various process models) also faces specific challenges, in particular the question which key processes need to be re-evaluated and improved. In this roadmap paper, these more specific issues are included in the relevant topical challenges above, while this section focusses on atmospheric modelling that transcends these areas and links to policy-relevant questions.

The Present State of the Art

Recent studies have been able to quantify GHG fluxes at the national scale using in-situ networks (e.g. using the DECC/GAUGE network in the UK) and remote sensing (e.g. using GOSAT observations over India and the USA). If there is a distinct spatial and/or temporal separation between source sectors, then some level of disaggregation of different sources has been demonstrated (e.g. the isolation of rice emissions from India). However, in general, the problem of attributing national scale fluxes to individual processes remains difficult.

The resolution and accuracy of the current generation of chemical transport models also makes the inference of emissions at sub-national scales less robust than national totals. Furthermore, a significant fraction of the observations at many observation sites cannot be explained by even the highest resolution (~1km) chemical transport models. Finally, inter-comparisons between chemical transport models at regional and global scales reveal major differences between models, particularly for processes such as boundary layer turbulence and stratosphere-troposphere exchange. These findings suggest that further work is needed to resolve small-scale processes, and to improve model parametrisations in general.

Uncertainty quantification in inverse modelling studies has been the subject of much recent debate. Progress has been made in reducing the impact of relatively subjective choices about the random uncertainties in inversions. However, only preliminary work has been carried out in quantifying the impact of systematic/parametric uncertainties, which are likely to dominate the overall uncertainty budget.

Science Questions

1) What do we need to measure?

A major challenge to model atmospheric GHGs is the associated model error. Small errors in the description of atmospheric transport will compromise the estimation of robust flux estimates. In most cases the atmospheric transport model is the weakest link in the flux estimation. One approach may be to

supplement GHG measurements with auxiliary meteorological data such as boundary layer height that help test the model. Another is to measure and simulate complementary tracers that may shed light on some of the key model uncertainties (e.g. radon).

2) How do we evaluate atmospheric models at progressively higher resolution?

Models to represent urban fluxes and industrialised landscapes will need to be resolved at a spatial resolution of the urban street canyon, i.e. 100 m or smaller. Ignoring for the moment the technical challenges of running such a model, how do we evaluate model performance at this resolution? Models within the next decade will only be statistically representative of such complex environments. What are the requirements for city sensor networks to be equally representative, in order to test the models?

3) What is the appropriate computational technology to run high-resolution model simulations of GHGs?

Development of efficient algorithms to describe atmospheric transport and data assimilation is crucial. Given finite resources, some level of national coordination is needed to make meaningful progress in a reasonable timeframe. Do these efficiencies arise from new algorithms or new technology that allows greater parallelization? Is it more efficient to run these models on cloud-computing services or conventional machines?

4) How can we more fully account for uncertainties in our parameter estimation frameworks that combine models and observations?

At present, models are known to be the weakest link in our estimates of several key quantities (e.g. GHG surface flux), but systematic errors in models are routinely ignored in flux uncertainty budgets, primarily because of the technical challenge associated with their exploration. Advances have been made in several areas of statistics that urgently need to be adopted by the GHG community if we are to improve the accuracy of our uncertainty estimates.

5) How can we separate inverse estimates of individual source sectors?

Improvements in the resolution and parametrization of chemical transport models may allow increasingly accurate separation of individual source/sink processes in inverse estimates of national budgets (information which is of significant interest to inventory compilers). However, some GHG sources are likely to remain too closely located to infer using traditional observations. New tracer measurements will be required (e.g. isotopologues, air quality gases, etc.), to separate individual sources in inverse modelling studies, and new inverse frameworks will be needed to maximise the GHG emissions information content of these new measurements.

Recommendations

Given the long list of challenges and science questions outlined above, it is critical that we prioritise so that essential progress can be made. After consultation of the UK science community, some priorities for the future were identified.

General Recommendation: Integration and Capacity-Building

A general recommendation is to integrate the UK activities into a GHG measurement facility or centre. This will be the topic of a separate position paper.

The UK GHG research community is truly world-class, with leading experts in all aspects of GHG flux science, climate change mitigation, projection and adaptation. To date, the extent to which our community has enabled capacity-building in other nations has largely been limited to specific, fixed-term collaborative research projects. In line with the Paris Agreement, and the UK Government's priorities on building capacity in the developing world, we now need to ensure that GHG expertise, training, equipment, and MRV best practice is more effectively shared with partners around the world, and especially in the Global South. One already-successful mechanism to enable such capacity-building has been the development of online resources (e.g. MOOCs) that, when combined with in-country advice and communication, can greatly improve understanding, skills and reporting at scale.

Open Ocean Processes

We identified as a priority to extend the sampling in the Southern Ocean, with the aim of reaching a similar coverage as the North Atlantic. Sampling should be all year, as we currently miss key seasons. Autonomous vehicles can be deployed to fill some of these gaps.

We identify the following priorities for oceanic GHG fluxes, towards improved quantification, process understanding, and assessment of feedbacks to climate.

1. Improved integration of existing laboratory (e.g., process studies) and field measurements to improve model GHG process parametrizations and support model validation.

2. Improved biogeochemical and marine ecosystem model parametrizations to account for the integrated influences of multiple-external stressors (e.g., warming, changes in circulation, deoxygenation, ocean acidification, external nutrient inputs).

Targeted observational strategies for long-term and intensive sampling of regions of high magnitude and high variability GHG fluxes (e.g., North Atlantic, Southern Ocean, oxygen minimum zones and upwelling regions) should be developed.

Land Surface Processes

Sustained measurement systems

The UK community has built up a comprehensive measurement network which needs to be supported long-term. It is essential to have a sustained measurement programme independent of short-term, hypothesis-driven research projects. We also have to continue efforts to include other existing UK observations and data collections so that all available information is accessible, as well as establish new sites.

Tropics

It was also agreed that the Tropics contribute the largest but least well documented contribution to the global GHG budgets. Although the Amazon has been studied extensively, a similar investment in Africa and SE Asia should be a priority. It was recommended that a Pan-Tropical Land programme, should become a focus of scientific research of the UK GHG community. This would include a case study in Africa that could support a tall tower as well as mobile flux towers for land use sampling and a TCCON site to provide both bottom up and top down measurements of GHG fluxes. Any plans should include a legacy element involving capacity building and government partnerships. In addition, the programme of work should include a social science component which would address human land use and management, food security, peoples' livelihood, that impact on GHG balances through socio-economic processes.

Coastal Zone and Inland Water Processes

The priority for the coastal zone is the identification of a set of sites (both within the UK and Internationally) where it is feasible to intensively sample (in both space and time) the whole system including the key science areas identified above areas over long periods so as to distinguish change in system functioning from natural variability. This likely demands the cooperation of a number of different laboratories, funding agencies, NGOs and HEIs. Initially, river mouths in the North Sea and the Channel can be a focus of intense sampling, as they are easily accessible from the UK and often have dense traffic of ships of opportunities (commercial ships that can carry scientific instruments, eg. ferries or fishing vessels) and buoys.

It is also necessary to identify ways in which these site-specific data can be upscaled readily and the key insights incorporated into numerical models of adequate resolution.

The UK academic community has delivered significant insights into system functioning and modelling in the recent past based on diverse funding streams including several NERC strategic programmes (Macronutrient Cycles, Shelf Seas Biogeochemistry, Greenhouse Gases). Further NERC programmes are underway (LOCATE) or under consideration (Blue Carbon) with some EU coordination actions also funded (Ringo). The major challenge is to work out how to align

disparate funding streams so as to maximize their collective output and to guarantee continuity to such effort.

Urban Environment and Industrial Landscapes

In urban areas, the main priority is to develop techniques and observation networks that allow us to separate anthropogenic emissions from natural sources and sinks (e.g. parks and green belt areas).

This will require the design of new urban networks, such as microsensors that can be deployed in large quantities and measurements of atmospheric species that are co-emitted with CO_2 from fossil fuel combustion, with the aim of creating inventories of higher spatial and also temporal resolution (e.g. months, to capture annual cycles), with well-defined uncertainty estimates.

Urban monitoring of GHGs should be combined with air quality monitoring in "supersites" that link various aspects of the urban environment, also engaging with relevant local communities.

On a global perspective, improvements are needed and should be supported by the UK community in developing regions, where inventories are missing or of poor quality.

Atmospheric Modelling Technology

The development of the next generation of chemical transport models is urgently needed for the accurate interpretation of GHG observations. This will involve:

1. meteorological services, who are often responsible for model development, and provide the underlying meteorology that the models rely on;

2. the GHG measurement community, who can provide observations against which model parametrizations can be tested;

3. new developments in computing hardware and software, which can be exploited to maximise model resolution and efficiency;

4. statistical methods, which should be more fully utilised for the accurate calibration of models, and the assessment of remaining systematic model uncertainties.