Introduction

Greenhouse gases in the Earth system: setting the agenda to 2030

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What do we need to know about greenhouse gases? Over the next 20 years, how should scientists study the role of greenhouse gases in the Earth system and the changes that are taking place? These questions were addressed at a Royal Society scientific Discussion Meeting in London on 22–23 February 2010, with over 300 participants.

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Half a century ago, Charles David Keeling began his measurements of atmospheric greenhouse gases, at the South Pole and high on Mauna Loa volcano in the middle of the Pacific Ocean. Keeling’s measurements led rapidly to remarkable conclusions [1]. He found that the Earth breathes, in and out, as carbon dioxide (CO2) is taken up by leaf growth in spring and summer, and given off again as leaves fall and decompose in autumn and winter. The timing of the CO2 rise and fall between Hawaii and the South Pole showed him that air mixes from pole to pole on an approximately annual time scale. The seasonal dominance of the Northern Hemisphere showed Keeling that land plants largely control the annual cycle of carbon uptake and release. Finally, Keeling found that each year there is more CO2 in the air than the year before. He identified the cause—humanity’s use of fossil fuels.

Surprisingly, the community of scientists who measure greenhouse gases in the air and study their atmospheric distribution to understand their sources and sinks remains relatively small, perhaps only two hundred worldwide. Today, Keeling’s original two stations have been expanded to a global network of almost 120 stations, with figure 1 showing the location of ground-based stations that are measuring atmospheric CO2 and methane (CH4) concentration as of 2011. Many of these stations also monitor other greenhouse gases and related species, such as nitrous oxide (N2O), sulphur hexafluoride (SF6), oxygen (O2) and stable isotopes

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Figure 1. Shows ground-based sampling stations that measure both atmospheric CO₂ and CH₄ concentration (magenta symbols) or CO₂ only (cyan symbols). Measurements made via an in situ continuous analyser, or discrete flask sample collection (usually weekly or fortnightly) followed by analysis in a central laboratory. All stations shown are presently running and collect data at, or close to, the WMO/GAW quality control specifications for these species. Aircraft and shipboard measurements are not shown.

(e.g. δ¹³C-CO₂ and δ¹³C-CH₄). This monitoring network is very small, for example when compared to the several thousand surface temperature monitoring stations, and, as shown in the figure, there are large gaps in many parts of the world such as Africa, Siberia, Asia, South America, and the tropics. These geographic gaps in the measurement network significantly hinder scientific investigation and understanding of the carbon cycle and carbon–climate interactions.

Many national institutions and university research groups carry out the arduous task of continuing the atmospheric time series records of greenhouse gases for the global network. The World Meteorological Organization Global Atmosphere Watch programme (WMO/GAW) acts as the umbrella organisation bringing together these different groups, and provides a publicly accessible database at the World Data Centre for Greenhouse Gases (WDCGG: http://gaw.kishou.go.jp/wdcgg/). In today’s environment where data transparency, particularly in climate-related sciences, is being demanded by both the public and policymakers, the WDCGG performs a vital role.

In the oceans, measurement programmes have developed with good multi-national collaboration such as the former EU ‘CarboOcean’ project (www.carbocean.org) and the new EU ‘CarboChange’ project. Land ecosystem studies have developed to measure carbon fluxes such as the ongoing EU ‘GHG Europe’ project (www.ghg-europe.eu). Both the ‘CarbonTracker’ programme in the USA [2] and the planned EU Integrated Carbon Observing System promise much better regional insights. Aircraft sampling is being carried out to measure the free troposphere. Satellite remote sensing, in the near-infrared, now offers a powerful widescreen vision to complement ground-based in situ studies. The highly accurate in situ measurements are needed to ground-truth the satellite
Figure 2. Three-dimensional representation of the latitudinal distribution of (a) atmospheric CO$_2$ and (b) atmospheric CH$_4$ in the marine boundary layer, from the US NOAA/ESRL/GMD programme. Data from the Carbon Cycle cooperative global air sampling network were used. The surface represents data mathematically smoothed in time and latitude. (CO$_2$: P. Tans, T. Conway and K. Masarie; CH$_4$, E. Dlugokencky; NOAA/ESRL/GMD Carbon Cycle Greenhouse Gases Group, Boulder, CO, USA). Available at: http://www.esrl.noaa.gov/gmd/Photo_Gallery/GMD_Figures/ccgg_figures/).

data; the satellites provide the more general view. Fortunately, the Japanese GOSAT (Greenhouse Gases Observing Satellite) is producing excellent results, and OCO2 is due in 2013.
The US National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Global Monitoring Division (NOAA/ESRL/GMD) maintains a crucial global network, encompassing almost half of the stations shown in figure 1. Their data are also publicly available, on NOAA webpages, as well as being placed in the WDCGG database. Figure 2a integrates their results as a ‘flying carpet’ or ‘rug’ which shows the in-and-out breathing of CO₂, the dominance of the north and the increase over time. This graph is a remarkable illustration of the working of the terrestrial biosphere. In figure 2b, the methane ‘flying carpet’ looks similar, but for very different reasons, as the major sink mechanism is reaction with OH radical, whose concentration correlates with the amount of daylight in each hemisphere.

In parallel with the data gathering, modelling tools have been developed. There are many ways of understanding greenhouse gas emissions. Just as a fox can locate a chicken coop by sniffing, so trajectory models can be used to locate greenhouse gas sources. A single station, for example in Spitsbergen, Norway, can be used to map emissions from a wide area, as the winds bring the gases to the station. Forest fires in Canada can be easily identified in air arriving on the Irish coast, and carbon isotopes have been used in New Zealand to identify grassfire emissions as far away as Africa. The other modelling approach is mathematical inversion using data from an array of stations to work out the emissions. There are many ways in which this can be done, and with methane the technique is already being used to verify national emissions in Europe, though the task is harder with CO₂ as the sinks and sources are more complex.

Challenges remain. The spatial gaps in the network are huge, especially in the tropics, missing the heart of the terrestrial biosphere, and in Siberia, home to the world’s largest forest and where thawing permafrost will result in significant changes to biogeochemical cycling. Isotopic records of carbon gases, potent in identifying sources, are few. The measurement network for oxygen, the biological inverse of CO₂, is in its infancy. Release of nitrous oxide, an easy target for greenhouse reduction, is poorly understood. The oceans are being acidified by the uptake of CO₂ and are losing oxygen from breakdown of organic material, but our observational network, and our understanding, is sparse. Few aircraft sample in the middle troposphere. Better measurement, at all vertical levels from the Earth’s surface to space, should be high on the agenda for the period to 2030.

Under the Kyoto Protocol of the UN Framework Convention on Climate Change, Annex I nations (developed nations and economies in transition) which ratified the treaty are required to declare their greenhouse gas emissions. These emissions are calculated with ‘bottom-up’ accounting techniques (for example, by working out how much oil and coal are burned by a country, and how much methane is emitted by its cows, landfills and gas leaks) and are published in very precise terms. However, evidence from atmospheric measurements show that emissions of many industrial greenhouse gases tend to be greater than reported—sometimes disagreeing with reported ‘bottom-up’ emission measurements by factors of two or more. The implications are significant for activities such as carbon trading and compliance to the Kyoto Protocol, and generally challenge the validity of promises to reduce emissions.

There is some hope here. Verification of emissions by atmospheric measurement is necessary. Verification of emissions by atmospheric measurement is possible and may play a major role in future international agreements on climate change.
The European Commissioner for Research has recognized the need for better top-down verification of emissions, while the US National Research Council’s Committee on Methods for Estimating Greenhouse Gas Emissions published similar recommendations. It is vital that the discussion should be open and transparent, with both data and interpretation robust to external criticism.

The papers in this Discussion Meeting Issue range over the full breadth of research into atmospheric greenhouse gases. Measuring the air, Wofsy et al. [3] report on the highly successful HIPPO (HIAPER Pole-to-Pole Observations) flights around the planet, while Dlugokencky et al. [4] examine the state of methane. Wunch et al. [5] describe the important work being done by the Total Carbon Column Observing Network to ground-truth satellites. Wolff [6] brings a palaeoclimate perspective from the ice core records. Ciais et al. [7] consider Africa’s poorly understood carbon balance, while Mahadevan et al. [8], Gruber [9] and Watson et al. [10] discuss the underappreciated changes taking place in the ocean, including deoxygenation and acidification. Rayner et al. [11] and Keeling et al. [12] discuss the general puzzles of where the carbon is going. How much of the emissions will stay in the air? Can we verify carbon capture and storage? The wider topic of assessing the accuracy of emission declarations is addressed in several papers: Manning [13] tackles the challenge of estimating regional emissions; Levin et al. [14] consider the problems of emissions in polluted areas; Weiss and Prinn [15] discuss the urgent need for reconciling ‘top-down’ (from the air) emission estimates with ‘bottom-up’; and Durant et al. [16] consider the economic value of improved estimates of CO₂ sources and sinks. Finally, Manning & Reisinger [17] reconsider the concept of Global Warming Potentials (GWP) for comparing greenhouse gases, whereas Huntingford et al. [18] take a further step and suggest that impacts of greenhouse gases on ecosystem services need to be considered rather than only radiative forcing.

In sum, we have learnt much about the Earth system. We are able to track the bulk greenhouse gas flows across the planet. In the air, on land and in the oceans, scientists are studying the ways in which greenhouse gases cycle through the Earth system. Large changes are occurring that are likely to have large impacts on climate, but they are poorly understood. Will ocean acidification and deoxygenation cause large swathes of tropical oceans to become ‘marine deserts’? Will plant growth increase as CO₂ rises? What carbon and biogeochemical changes are in store as Arctic warming continues, and how will these changes in turn feed back on climate? Can we reconcile reported emissions with those calculated from atmospheric measurement? This Issue highlights and discusses these questions: in the answers we will learn much about our home, its robustness to change and its fragility.

References

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