PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Review and Synthesis

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Studies of trace gases in the atmosphere, their sources, sinks, and mechanisms of transport, have developed rapidly in the last few decades. This has been driven partly by increasing recognition that particular gases are associated with problems such as acidification, eutrophication, and global warming, but also by the developing enthusiasm for multidisciplinary research in which scientists from many disciplines collaborate to explore biological, geochemical, and atmospheric cycles and to understand how human action disturbs such cycles. Major international programs such as the International Biological Program (IBP) and the International Geosphere–Biosphere Program (IGBP) have been very influential in generating and encouraging this new way of working. To answer these complex environmental research questions, scientists have needed to develop new field instrumentation, or at least to modify instruments normally used in the laboratory. Equally, mathematical simulation models are increasingly being used at scales ranging from cellular to global to allow complex computations that would have been unthinkable even a decade ago. The papers in this proceedings illustrate some of the exciting developments taking place in the study of the exchange of trace gases between the atmosphere and the land. They describe new understanding of the processes in soils, plants and the atmosphere that control gases important in the carbon and nitrogen cycles, they summarize new techniques and instrumentation that allow field studies at scales ranging from soil grains to landscapes, and they present results of mathematical models that allow us to explore consequences of global changes that may yet come.

1. Review

In attempting to review and synthesize material that was presented at the meeting, I will group various papers together to attempt to show common links.

Several papers discussed the chemistry of polluted atmospheres. Derwent described the complex chemistry associated with the oxidizing power of the atmosphere, drawing out the role of nitrogen oxides, hydrocarbons of natural and manmade origins, carbon monoxide, and sunlight. The paper toward the end of the meeting by Pyle linked some of this chemical knowledge to a general circulation model of the atmosphere to explore relationships between methane, carbon monoxide and ozone. Also, on a global scale, Helas summarized our current knowledge of the rates of trace gas release from biomass burning, a process important in many regions for agriculture as well as for domestic energy production. As part of this group of papers, Duyzer described the importance of including corrections for chemical reactions in the atmosphere between trace gases in the interpretation of trace gas fluxes to or from the land surface. Without such corrections, not

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only the magnitude but also the direction of flux may be changed, emphasizing the need for atmospheric scientists to collaborate with atmospheric chemists and to measure more than a single gas when studying trace gas fluxes in polluted atmospheres.

A second set of papers was concerned with processes associated with the soil. Conrad reviewed the role of soil microbiological processes in trace gas exchange, emphasizing that there are very commonly simultaneous production and consumption processes. He also noted that some types of soil microorganisms are concerned with the cycling of more than one trace gas, and he pointed out that the cycling of trace gases differs between wetlands and areas with drier soils. Goulding's talk focused on the importance of soils as a sink for methane. His laboratory and field experiments particularly took advantage of the long series of soil fertilizer treatment experiments that exist at Rothamsted. Smith addressed the important issue of nitrous oxide emissions from soil. He described progress that has been made in developing automated systems that can be used in the field or with soil monoliths maintained under controlled conditions. By using gas analysis with long-path infrared spectrometry, it is possible to overcome small-scale spatial variability that is so often a problem in the measurement of gas fluxes from soils.

On the subject of spatial variability, Clymo reviewed progress in understanding the variation of methane fluxes from peat wetlands, in which differences in water-logging between tussocks and hollows, as well as differences in temperature, rooting of vascular plants, and light can substantially influence the flux. New measurement techniques are allowing profiles of methane to be studied *in situ*, and this may eventually lead to improved models of the transfer of methane between wetlands and the atmosphere.

Two papers described micrometeorological and boundary layer budget methods of obtaining methane fluxes at the landscape scale. Fowler described several micrometeorological techniques that have been used to measure land atmosphere exchange. In particular, the use of new tuned diode laser instruments for detecting very small changes in trace gas concentrations has created a great opportunity for making micrometeorological measurements of fluxes of methane and other trace gases. He also showed that the relaxed eddy accumulation method, which has been known for many years but seldom used, is also a very promising method for the future.

Choularton extended the scale even further in describing measurements of atmospheric profiles of methane collected in an aircraft over a large area of natural wetlands of northern Scotland. By combining the measurements with a model of the diffusion of methane in the boundary layer, he was able to obtain good estimates of average fluxes on the landscape scale. Methods at night using Doppler Sodar and gas concentration profiles collected from tethered balloons also seem very promising.

Two papers included detailed analysis of gas exchange processes associated with leaves and vegetation canopies. Sutton reviewed recent micrometeorological and laboratory measurements of plant–atmosphere exchange of ammonia. Careful analysis confirmed the existence of an ammonia compensation point in leaves, as predicted several years ago by Sinclair and Farquhar. Sutton described how he has extended this analysis to develop a resistance model of gas exchange for plant canopies from which net fluxes may be inferred. It is very clear that there are

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substantial differences between fertilized agricultural crops and natural vegetation in the net exchange of ammonia with the atmosphere.

Baldocchi described a multidisciplinary study on the controls of isoprene emission from a deciduous forest. Isoprene emission is linked to photosynthesis, and consequently emission rates depend on radiation and leaf temperature. He showed how isoprene fluxes can be scaled from the leaf to the canopy by combining knowledge of production processes within the leaf with a canopy micrometeorological model.

Finally, a strong theme at the meeting, represented by several papers, some of which have been mentioned already, was the development of new instrumentation and methodology for the study of trace gas exchanges. Zahniser reviewed one of the most important recent developments for field investigations, the fast-response high-precision tunable diode laser spectrometer. Instruments of this type have already been used, as reported at this meeting, to measure methane and nitrous oxide exchanges, and Zahniser also discussed ways in which they may be used in the future to measure highly surface-reactive gases such as nitric acid and ammonia. Denmead reviewed some novel meteorological methods for trace gas flux measurement. One set of methods makes use of small experimental plots that avoid some of the limitations of small covered chambers and complications of other micrometeorological approaches. The second method uses new theoretical analysis of the transport processes in the atmosphere within crop canopies to provide new approaches for the estimation of the spatial distribution of source and sink strengths. This development may well allow micrometeorologists at last to analyse in-canopy processes for a number of trace gases.

To summarize, the meeting revealed that there has been substantial progress in measuring and interpreting trace gas exchange between the land and the atmosphere. Much of this progress has been made because we have a better understanding of the soil and plant processes associated with trace gas production and destruction, and of the atmospheric chemistry associated with trace gases. There has also been good progress in developing methods for studying gas exchange in the field, ranging from designs of chambers that can be used to study diurnal and seasonal cycles, new micrometeorological methods that can be used above and within crop canopies, and boundary layer studies from aircraft which have great potential for the future.

There was less progress apparent at the meeting in the development of models that can be used to simulate methane and nitrous oxide production in a range of environmental conditions, and it seems important that development of these models should proceed in parallel with the greatly improved ability that we now have to collect appropriate data. There was also relatively little work reported for tropical conditions, although the importance of trace gas fluxes from tropical wetlands and in tropical agriculture is very great. It is hoped that a number of the techniques that have been developed in temperate regions will be applied in the tropics before long. It was unfortunate that the meeting coincided with the major field campaigns of BOREAS, the international multi-agency study of boreal ecosystem–atmosphere exchange processes in northern Canada. This overlap precluded the involvement of a number of groups, although many of the methods and approaches used in BOREAS were included in reviews presented at the meeting. Undoubtedly, results collected in BOREAS, and in other major

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programmes such as the UK NERC TIGER Programme, will advance this topic even more rapidly in the next few years.

Studies of trace gas exchange are at an exciting stage of development. With the benefits of new instrumentation and new approaches to modelling transfer in canopies and in the surface boundary layer, there is the scope to quantify source and sink strengths of many natural and artificial vegetation types. Such studies need to be associated with basic research into the environmental controls of source and sink strength so that robust models can be developed. The next challenge will be to scale up from these single-system studies to estimate transfer over complex topography, regions and eventually the globe. The interpretation of trends and short-term variations in the long records of trace gas concentration from monitoring stations around the world is an important challenge that can be addressed with the understanding that is coming from work described at this meeting.

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