THE PROBLEMS THAT LIFE PRESENTS

***'There is great uncertainty, but this is the uncertainty of biological systems'* — Ian Galbally, CSIRO atmospheric scientist**

Life for Australia's climate researchers would be a lot simpler if... well... if life was simpler. Making predictions about climate change would be a comparative breeze if trees didn't grow and drop their leaves, termites stopped eating and cows refrained from belching after dinner. But for the cryptic habits of soil bacteria and marine algae, scientists studying the enhanced greenhouse effect might have the confidence to tell us whether Sydney is going to have the climate of Cairns or the Westgate Bridge will need raising to let the icebergs pass below unheeded.

Uncertainties are never more certain than when atmospheric science tries to take account of the biosphere. As air passes over Earth's surface, it exchanges trace gases such as carbon dioxide and methane with plants, animals and microbes. The quantities involved in the exchange are huge: for example, plants absorb between 50 and 60 billion tonnes of carbon a year (about 10 times the amount released to the atmosphere by the burning of fossil fuels), while micro-organisms in the soil produce about the same amount. Therefore a small change or fluctuation in the rates of these biological processes can have a significant impact on the concentration of CO_2 and other greenhouse gases in the atmosphere.

To complicate things, an increased atmospheric concentration of CO_2 itself can speed up the rate at which plants absorb carbon — a result called the CO_2 fertilisation effect. But we know little about the strength of this effect on a global scale. The release of carbon, too, is anything but straightforward. For example, both the amount and composition of gas produced by the burning of forests and grasslands depend partly on fire intensity, which, on a global scale, is not well documented. To complicate things further, much of the carbon absorbed by plants is stored by the mid-latitude forests — forests that may be reaching the upper limit of their capacity for absorbing carbon dioxide from the air and, consequently, may not be able to store future emissions. The extent to which the forests can continue storing carbon before giving up is — you may have guessed by now — not known.

Carbon dioxide is probably the best understood and most thoroughly studied of the greenhouse gases, and yet the best estimates of the strength of the different biological sources and sinks of CO_2 contain a large element of uncertainty. In the tropics, for instance, modelling studies by CSIRO estimate that additional carbon uptake by plants resulting from higher concentrations of CO_2 (the fertilisation effect) in the early 1980s totalled somewhere between 160 and 560 million tonnes a year. Similar uncertainties apply for the mid to high latitudes: 180 to 510 million tonnes a year in the south, and 360 to more than a billion tonnes a year in the north. Globally, our best estimate of the fertilisation effect could be out by a factor of three.

Other greenhouse gases present an even worse picture: almost all our scientific knowledge on biological sources and sinks comes from spot measurements that may not be representative of the whole. Look, for example, at methane (CH_4), which is responsible for about 13% of Australia's total contribution to global warming. Within one region, the strength of methane fluxes into and out of the Earth's surface can vary by several orders of magnitude, depending on landscape, agricultural use and hydrological factors. (And in the atmosphere itself, the rate of destruction of methane by the hydroxyl radical OH is only known within 25% of its true value.)

Dr Ian Galbally of CSIRO's Division of Atmospheric Research in Melbourne has calculated a budget for methane emissions and absorption in Australia. He estimates that Australia's natural wetlands — which contain methane-generating anaerobic bacteria — produce about 200 000 tonnes of CH_4 a year, 7% of our net total emissions. But, due to lack of knowledge of the extent of short-lived wetlands (such as the 'channel country') and average emissions from wetlands in Australia, the estimate has an 'uncertainty factor' of 5, which puts the true value between 40 000 and 1 million tonnes a year. Comparable margins of uncertainty apply to most of the other sources and sinks for methane.

Carbon monoxide (CO) presents similar problems. Biomass burning in Australia is estimated to release 16·3

Natural non-CO_2 greenhouse gas emissions

best estimates of annual biogenic emissions of some greenhouse gases in Australia ('000 tonnes per year)

	CH_4	CO	N_2O	NO_x
biomass burning	1100	16 000	9	12
natural ecosystems			500	800
crops			38	38
drylands	–2500	600		
natural wetlands	200			
kangaroos	2			
domestic animals	2000			
rice	40			
termites	700		22	
legume pasture			100	2·5

Sources of greenhouse gases are many and varied.

Where does the CO_2 go?

The burning of fossil fuels releases about 5 billion tonnes of carbon each year to the atmosphere. Of this, about 3·5 billion tonnes is accumulating there as carbon dioxide (CO_2), the chief greenhouse gas. The rest is absorbed by the environment.

It has long been assumed that life on land was adding no more carbon to the air than it was taking out, and that the carbon from fossil-fuel burning not retained in the atmosphere is absorbed by the oceans, which contain vast amounts of carbon in the form of carbonate (CO_3) and bicarbonate (HCO_3) ions.

In 1983, however, new studies suggested that land-use changes (such as farming, deforestation and urban development) were releasing another estimated 2 billion tonnes of carbon a year into the atmosphere. Was all of this also going into the oceans? No it wasn't, according to the best models of the global carbon cycle. The search for another carbon 'sink' became known as 'the missing carbon problem'.

Then, in 1990, the problem got bigger. Researchers in the United States suggested that the ocean absorbs far less carbon than the widely accepted estimate — of about 2 billion tonnes a year. Their analysis indicated that the major CO_2 sink lies in the Northern Hemisphere, and is mainly on land. Combining this view with direct measurements of the amount of CO_2 dissolved in northern and tropical waters, they concluded that the ocean globally takes up between 0·5 and 1 billion tonnes of carbon a year.

Their estimate means that — contrary to traditional wisdom — terrestrial life must be a large net sink for CO_2, absorbing 3–3·5 billion tonnes of carbon a year, substantially more than the oceans and significantly more than the best estimate of carbon releases from deforestation and other land-use changes. Many scientists, however, don't think that could be right. For one thing, little firm evidence indicates that the biosphere is currently absorbing more carbon than it releases.

Theoretically, though, this is possible — due to either regrowth of forests after massive deforestation in the 18th and 19th centuries (the so-called pioneer effect) or extra plant growth induced by higher-than-normal concentrations of CO_2 in the atmosphere (the so-called fertilisation effect).

Predictions based on models of how much of the carbon from fossil fuels the oceans and land take up vary by up to 30% due to the poor scientific understanding of the physical and biological processes involved. Direct measurement of carbon uptake is needed, but that's not easy on the land because of the complexity and variety of terrestrial ecosystems. On the ocean side, it is hard to gather data that well represent uptake in all waters (and under all weather conditions). In addition, the amount of carbon stored in the ocean is many times the atmospheric accumulation, making it difficult to measure the relatively small contribution from fossil fuels.

A research team comprising oceanographers at the University of Washington, the CSIRO Division of Oceanography and the Institute of Ocean Sciences in Canada has tried a new tack to eliminate some of the uncertainty shrouding the strength of the oceanic carbon sink.

Carbon dioxide from fossil-fuel and biomass burning contains proportionally less of the heavier carbon isotope ^{13}C than the CO_2 in the atmosphere. This is largely due to plants preferentially absorbing the common carbon isotope ^{12}C during photosynthesis. (According to ice-core measurements, the ratio of ^{13}C to ^{12}C in the atmosphere has fallen over the last 300 years.) Therefore, by measuring proportional changes in ^{13}C and ^{12}C in the ocean over time, the researchers were able to estimate the oceanic uptake of carbon produced by human activities.

Using data collected on a long cruise by a Canadian research ship in the Pacific Ocean in 1970, and comparing them with American cruise data collected in 1989–91, they calculated that the ratio of ^{13}C to ^{12}C in surface waters in the Pacific has dropped in the last 20 years.

But what about all the oceans? In order to derive a global estimate, they looked at seven sites in the Pacific where the radioactive carbon isotope ^{14}C had been measured in the 1970s following atmospheric nuclear tests. Here the scientists found a correlation between the ^{14}C measurements and the $^{13}C/^{12}C$ ratio. By combining that correlation with ^{14}C measurements in all oceans during the 1970s, they were able to estimate how much the ^{13}C to ^{12}C ratio has changed world-wide. From this, they calculated the total net uptake of carbon from human activities at 42 billion tonnes between 1970 and 1990, or about 2 billion tonnes a year. The method of calculation means the estimate is only accurate to within 0·8 billion tonnes.

However, the derived figure of about 2 billion tonnes a year (which has since gained support from other researchers who identified flaws in the calculations by the United States group) shifts the missing carbon problem back to the traditional view that the oceans are the dominant sink for CO_2. The researchers calculate the net absorption of carbon by terrestrial life over the last 20 years to be quite small — about 100 million tonnes a year. If deforestation has been releasing 2 billion tonnes of carbon a year over the same period, then it would appear that the biosphere has been growing by almost the same amount.

That's an important finding because it supports the argument (previously based only on model predictions) that the biosphere has been ameliorating the build-up of CO_2 in the atmosphere to the tune of about 1·5 billion tonnes of carbon a year. The urgent questions remaining are: how, and for how much longer?

Oceanic uptake of fossil fuel CO_2: carbon-13 evidence. P.D. Quay, B. Tilbrook and C.S. Wong. *Science*, 1992, **256**, 74–9.

Calculating future atmospheric CO_2 concentrations. I.G. Enting. *CSIRO Division of Atmospheric Research Technical Paper* No. 22, 1991.

The role of the terrestrial biota in the atmospheric carbon budget. R.J. Francey and I.G. Enting. *Proceedings of the Centre for Mathematical Analysis, Australian National University*, 1990, **25**, 235–44.

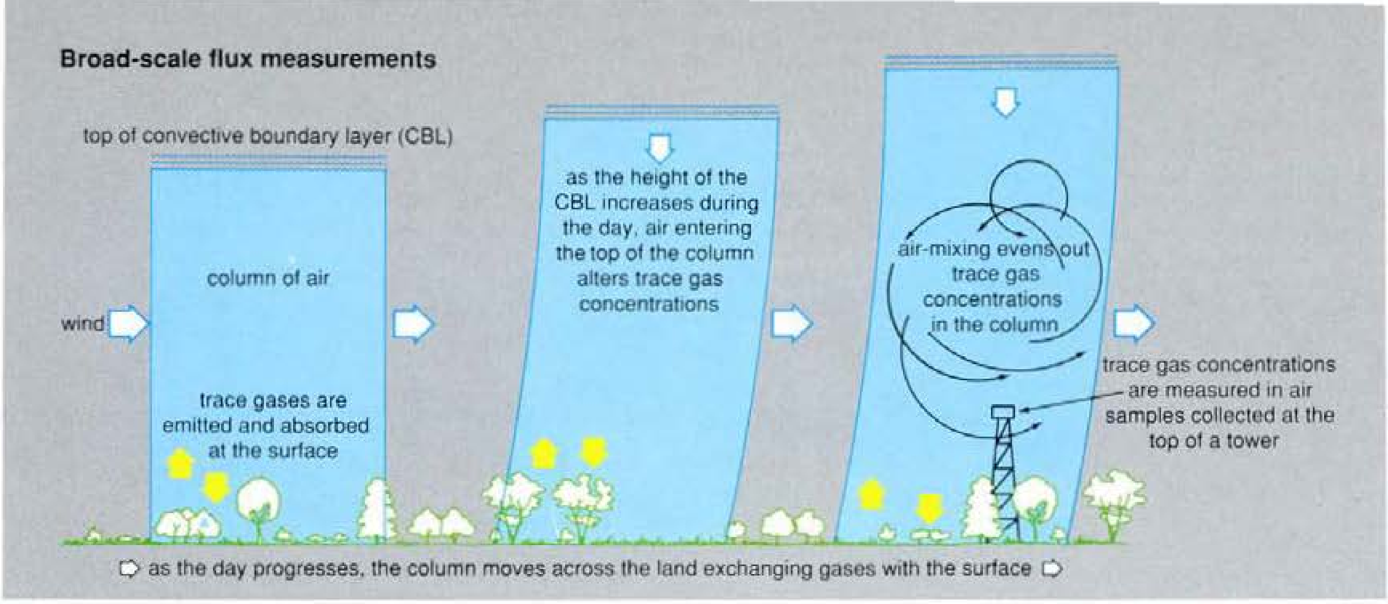
million tonnes of CO a year, but the true figure may be as low as 5·4 million or as high as 49 million tonnes. The amount of CO emitted by a fire, Dr Galbally explains, varies widely, depending on the temperature of the fire (smouldering fires produce the most), the type of fuel and the amount of oxygen available. Estimates for nitrous oxide (N_2O) are also highly variable (see the box on page 23).

The high degree of uncertainty about natural sources and sinks makes it hard in turn to predict what effect human activities are having on gas concentrations in the atmosphere, and therefore the potential for human-induced climate change. Dr Galbally also points out that an improved understanding of natural greenhouse sinks, such as methane-oxidising bacteria in the soil, would raise the prospect of scientists being able to strengthen these sinks for greenhouse abatement.

In order to develop a reliable greenhouse inventory and abatement policy for Australia, he argues for a strong emphasis on research to:

- estimate biomass and the extent of biomass burning in Australia, and the interaction between vegetation cover and frequency of fires
- directly measure and model the land–air exchange of trace gases (CH_4, N_2O, NO_x and CO_2) for forests, farms and natural ecosystems under a variety of management practices
- develop new techniques for measuring trace-gas exchanges

The Division of Atmospheric Research, in collaboration with the Victorian Department of Food and Agriculture and with funding from the Victorian Office of the Environment, recently completed a series of experiments measuring soil–air trace gas fluxes in Victoria's mallee country, about 100 km west of Mildura. Using gas-collection chambers placed at a number of sites, the researchers confirmed that Australian soils absorb and oxidise an amount of methane



Average figures for the greenhouse-gas contributions — positive or negative — made by soil organisms and plants can be determined by the 'convective boundary layer budget' method. The data needed, on trace gas concentrations within and above the convective boundary layer and the height of this layer, are readily gathered.

equivalent to the emissions from the nation's livestock. The experiments also showed that exchange of CO_2 and N_2O between the air and the soil depended heavily on the level of soil moisture and that the world's semi-arid regions may contribute significantly to global N_2O emissions.

Chamber experiments of this type are central to research aimed at estimating Australia's contribution to global greenhouse gas emissions, especially in determining the impact of land-use changes such as clearing for farming. But they cannot provide all the answers; methods that allow regional measurements — on the scale of a farming district, for example — and thereby provide a link between local emission data and the global estimates of sources and sinks of trace gases are also needed.

To this end, scientists in CSIRO are researching the use of satellite data for large-scale estimation of biomass burning, and investigating a number of techniques for measuring trace gas fluxes on scales ranging from hundreds of square metres to many square kilometres.

The most promising of these techniques is a method that, in effect, treats part of the lower atmosphere as a gigantic open chamber. Known as the convective boundary layer (CBL) budget method, it allows the scientist to calculate the average flux of trace gases over a wide area from measurements made at one point downwind.

Development of the CBL budget method for this purpose was initiated by Dr Mike Raupach at the CSIRO Centre for Environmental Mechanics in Canberra. The technique has already proved satisfactory for CO_2, and is expected to be useful for other trace gases.

In order to understand the CBL method, you have to imagine a column of air extending from just above the Earth's surface to the top of the convective boundary layer in the atmosphere, at an altitude of up to 1 km. In the CBL (or planetary boundary layer, as it's also known) the air is in a state of strong turbulence due to the thermal convection generated by the heat of the Earth's surface. During the day, as the surface warms with the heat of the Sun, the CBL steadily grows in height, engulfing the stable layers of air above it.

As the layer grows, the air within the column undergoes vigorous mixing and 'overturning', due to the rising thermals. Typically, the overturning may happen once every 15 minutes, suggesting, the researchers believe, a complete mixing of the air in the column about every four overturnings or possibly once an hour.

On these time-scales, then, we can reasonably assume that the concentration of any trace gas would be about the same at any point within the air column, regardless of height (except in a thin layer near the surface, a few tens of metres deep, where the mixing is weaker). So a single air sample taken at, say, noon at the top of a 50-metre tower would provide an approximation of the trace gas concentration throughout the air column over the previous hour.

Now consider what happened to the column during that hour, as it drifted across the landscape. The concentration of the trace gas would have changed due to three factors: change in the height of the CBL (which would change the volume of the column), incoming or entrained air with a different trace gas concentration from above the column, and the flux (emission and absorption) of trace gases at the surface. In effect the imaginary column of air is being altered by getting higher or lower, and by gases flowing in or out of either or both of its ends. Expressed as an equation, that means:

change in concentration of trace gas with time = [gas flux at the surface] × [influx of trace gas from air above the CBL] ÷ [height of the column].

The term on the left-hand side of the equation, the rate of change of concentration, can be estimated by measuring the concentration at different times within the air column or, in practice, within a succession of air columns (a Parthenon?) under similar wind conditions. On the right-hand side, the height of the CBL at different times can be measured with weather balloons or simply estimated from a model describing growth of the boundary layer.

The rate of entrainment of trace gas from above the column can be calculated from the trace gas concentration of the air above the CBL. This concentration in turn can be determined either by an instrument on an aircraft or — because its value over the sea varies little geographically — from the mean concentration for the Southern Hemisphere, provided the column is within several hundred kilometres of the coast. The research group at the Centre for Environmental Mechanics uses measurements from the Cape Grim Baseline Monitoring Laboratory in Tasmania as a surrogate.

That leaves just one unknown in the equation, the surface flux density, which is the quantity being sought — that is, the average rate of trace gas being emitted or absorbed at the surface over a given area. Given the other quantities, the surface flux of gases such as CO_2, CH_4 and N_2O can be readily calculated. The area in question depends on the wind speed and the tendency for the column to spread laterally as it moves along, but in practice it would comprise a 'footprint' upwind (of the measuring station) about 10 to 100 sq. km in area. The

Researchers used the tethered balloon to probe the depth of the convective boundary layer.

Centre for Environmental Mechanics

method can also be modified to measure the cumulative surface flux, or total amount of trace gas exchanged, over a given period of time.

Field trials have produced encouraging results. Flux data for CO_2 collected over 15 days in a wheat field near Wagga Wagga, N.S.W., show good agreement with the estimated values, except in the early morning and late afternoon. The estimated CO_2 flux was about 20% below the measured values due to the high rate of carbon uptake by the growing wheat, compared with the regional average.

Dr Raupach says the method can be used only for daytime measurements under certain weather conditions (such as little cloud cover), and for relatively unreactive gases. Nor is it suitable for monitoring large point sources such as chemical complexes or power stations. Nevertheless, it presents the possibility of a major advance on existing methods of flux estimation, which require expensive instrumentation or are restricted to much smaller areas. In the case of CO_2, by discriminating between isotopes of carbon the method would enable scientists to estimate the relative importance of plant respiration and photosynthesis in the carbon cycle — and hence gain a better understanding of the fertilisation effect.

'It's early days at this point, but if an accuracy of 20% can be met, it will be an exciting development', Dr Raupach says. He believes that with some refinement of the technique and the use of aircraft measurements, an accuracy of 10% for CO_2 may be possible.

If all goes well, the CBL research is expected to lead to the routine identification of 'hot spots', such as areas of cropland and improved pasture, where trace-gas exchange is relatively high. Combining these measurements with others — especially from chamber studies and Earth-sensing satellites — will provide scientists with the information needed for the preparation of detailed 'greenhouse flux maps' of Australia, showing the relative contributions made to global warming by farming practices, logging and plantations, national parks, coastal development and urban sprawl.

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More about the topic

Greenhouse gas emissions: assessments and control. I.E. Galbally. *Proceedings of the Association for Science Cooperation in Asia, Workshop on Greenhouse Gases and Climate Change, June, 1991.*

'Workshop on Developing Inventories of Greenhouse Gas Emissions for Australia, 22 May 1991.' J. A. Taylor (ed). Centre for Resource and Environmental Studies, ANU. (Australian National University: Canberra 1991.)

Challenges in linking atmospheric CO_2 concentrations to fluxes at local and regional scales. M.R. Raupach, O.T. Denmead and F. X. Dunin. *Australian Journal of Botany*, 1992, **40**, 697–716.

The nitrogen factor

In the climate-change debate, the most mysterious trace gas of note is nitrous oxide (N_2O), a very powerful greenhouse gas that is increasing in concentration for unknown reasons and lasts in the atmosphere for more than a century.

According to the Intergovernmental Panel on Climate Change, N_2O has a direct global warming potential 270 times greater than that of carbon dioxide. It has many sources — soil microbes, plant decay, fertiliser use, cars, termites, fires, landfills and nylon production — and a complicated chemistry. Its atmospheric concentration appears to be rising at a rate of 0·3% a year: currently this stands at 307 parts per billion by volume.

It is responsible for about one-twentieth of the change in the global warming potential of the atmosphere since pre-industrial times, less than the contribution of methane and the halocarbons. However, it has a much longer atmospheric lifetime than methane (at least 132 years compared with 11 years), and most of the halocarbons that contribute to the greenhouse effect also destroy greenhouse gases such as ozone. The net effect of N_2O on other greenhouse gases is not known.

Nitrous oxide accounts for about 11% of the global warming potential of Australian greenhouse emissions. According to scientists at the Division of Atmospheric Research, Australia emits about 660 million kg of nitrogen a year as N_2O, of which nearly 80% comes from natural sources. Most of the natural emissions are generated by micro-organisms in the soil through the processes of nitrification and denitrification. Nitrifying bacteria typically oxidise ammonium ions (NH_4^+) to nitrate (NO_3^-), but also oxidise some ammonium to N_2O. Correspondingly, denitrifying bacteria consume nitrate and nitrite (NO_2^-) ions in the absence of oxygen, reducing them to molecular nitrogen (N_2) and N_2O.

Recent research by the Division has concentrated on establishing the extent to which human activities affect N_2O emissions. Two areas of concern are legume pastures and the impact of land clearance.

Legumes are typically grown to improve the nitrogen content of pasture or to maintain soil fertility when wheat or other crops are grown in rotation with pasture. An experiment by the Division's Dr Ian Galbally and others has found that an unfertilised crop sown into a field previously cropped with lucerne (a leguminous plant) emitted between 20 and 230 billionths of a gram of nitrogen (as N_2O) per sq. metre per second, with a median value of 90. These measurements were much higher than those obtained previously in other experiments, and suggest that Australia's 25 million hectares of legume-improved pasture may be responsible for producing more than 100 000 tonnes of nitrogen as N_2O a year, or about 70% of human-induced emissions in Australia.

Preliminary results from the Division's experiments on soil–air trace gas exchange in the Victorian mallee country suggest that a hectare of wheat-field annually emits about 200 g more nitrogen as N_2O than a hectare of pristine mallee. As some 15 million ha of mallee has been cleared for farming since white settlement, that represents an extra 3000 tonnes annually — more than the estimated total N_2O emissions from motor vehicles. The trace gas measurements were found, however, to be strongly influenced by episodic events such as rainfall, and therefore must be interpreted with caution.