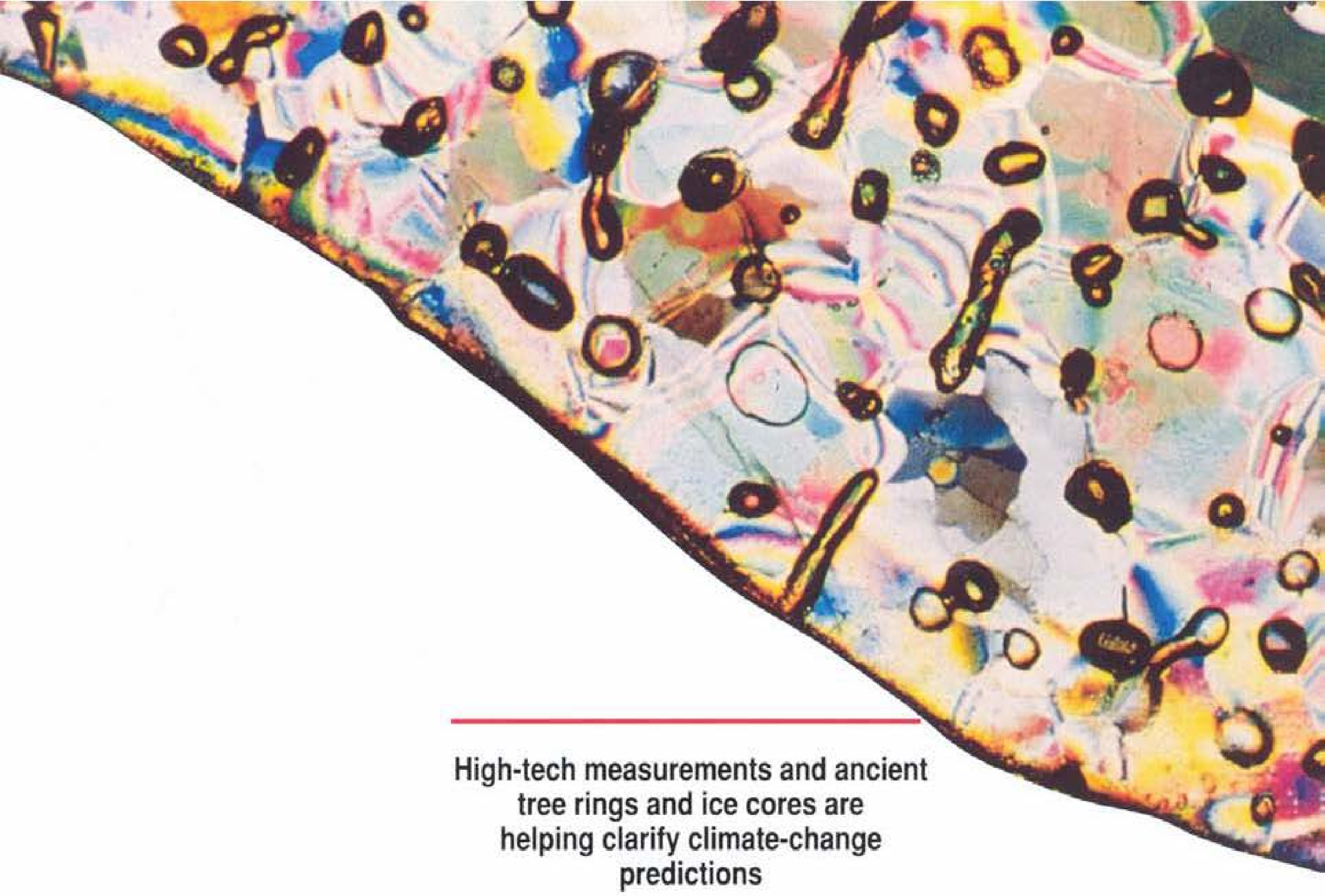


High-tech measurements and ancient tree rings and ice cores are helping clarify climate-change predictions

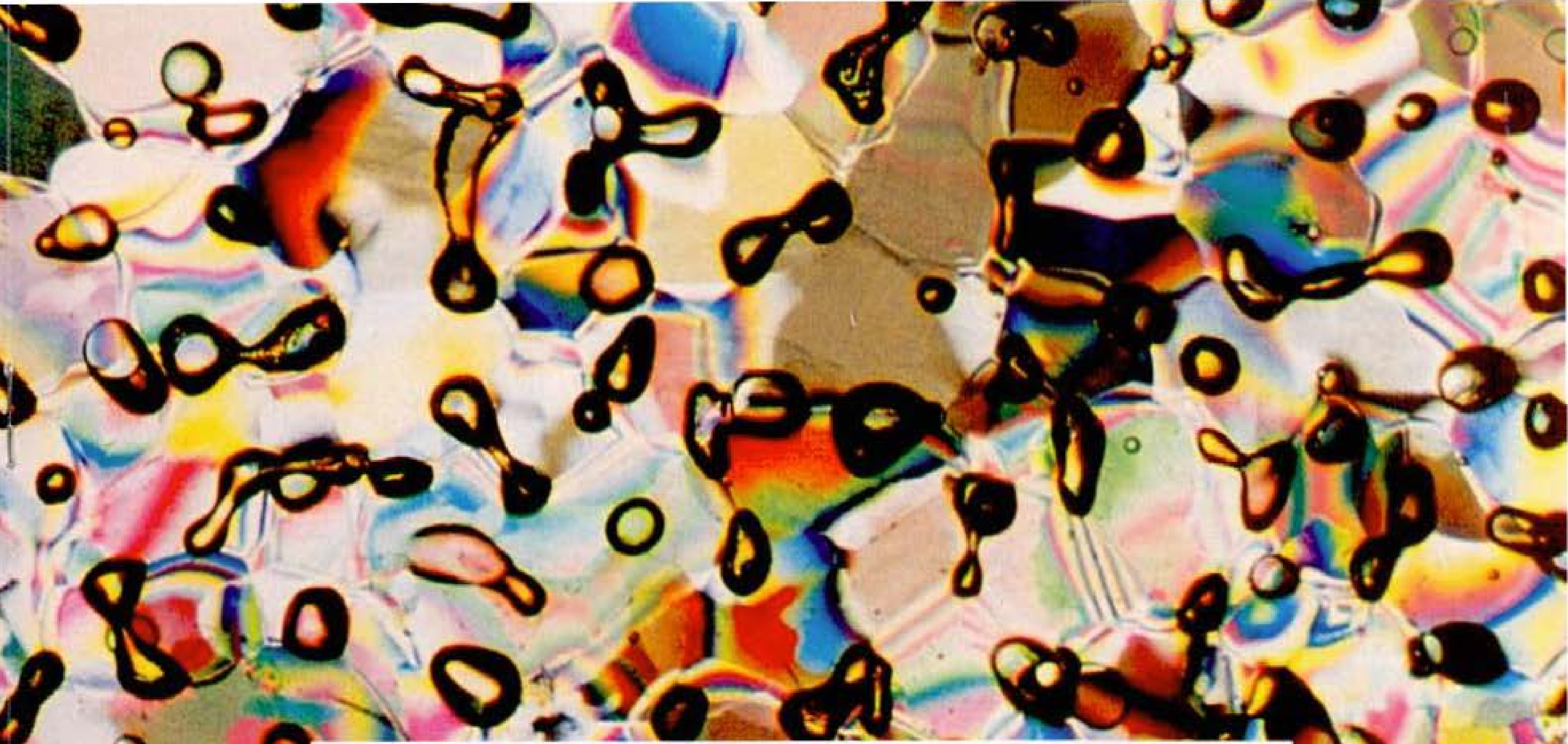
TRACKING CLIMATE CHANGE — AIR UNDER THE MICROSCOPE

Politicians and treasurers aren't the only people worried about balancing budgets: scientists studying the greenhouse effect are putting increasing effort into investigating the pattern of withdrawals from and deposits to the global atmosphere trace-gas budget. Without a better understanding of the cycles involved, predicting future climate change will remain an uncertain exercise.

Researchers are striving to learn more about how our atmosphere is changing by upgrading conventional approaches — as in GASLAB, described below — and are also looking at less conventional avenues such as tree rings studies, which not only have much to tell us about the past but also provide hints of how the past affects the present and the future.

Most trees lay down annual growth rings, and for some species and in some regions there's a clear relationship between climate and the width of rings. Interest in tree-ring studies, as an indicator of climate change, focuses on trees whose rings are reliable indicators of annual growth: eucalypts in arid Australia, for example, aren't suitable because they produce growth rings in response to rainfall more than to seasonal changes in temperature.

The most suitable species for tree-ring dating (dendrochronological) studies are forest trees from temperate and boreal (cold) regions, where low winter temperatures ensure minimum growth followed by strong summer growth… and thus well-defined growth



Photographed under polarised light, a thin slice from an Antarctic ice core reveals tiny bubbles of air.

David Whillas

Roger Francey

A remote mountain lake in western Tasmania, site of recent tree-ring climate studies on sub-alpine Huon pine.

rings. Temperate and boreal trees also exhibit marked variation, or 'sensitivity', in ring widths from year to year, so it is easier to recognise distinctive ring width patterns and common 'signatures' that, presumably, represent a common response to climate change (or dendroclimatology).

Measurement of ring widths among a large number of trees in one area provides a 'site chronology', a record of ring behaviour that smooths out the skewing effect of shading, nutrient depletion or insect attack on individual trees. However, the regional effects of large-scale insect infestation, pollution, changes in land-use or even variations in flowering and fruiting cycles are harder to eliminate from calculations, so researchers look for the right kinds of trees (long-lived species with well-defined annual-growth ring patterns) in the right kinds of areas (where trees experience some environmental stress) to measure the impact of climate on tree growth.

The trees of Tasmania's cool rainforests may provide the best opportunity yet to study past climate change, since several species suitable for ring-width dating grow side by side there; Huon pine (*Lagarostrobus franklinii*), King Billy pine (*Athrotaxis selaginoides*), celery-top pine (*Phyllocladus aspleniifolius*), pencil pine (*Athrotaxis cupressoides*), a hybrid King Billy–pencil pine (*Athrotaxis laxifolia*) and *Dyselma archeri*.

Not only do these species show differences in their responses to climate change, allowing scientists to separate physiological effects from climatic ones, but they are also found in a variety of environments, from low-altitude high-rainfall river flats to exposed sub-alpine plateaux. And, even better, at least four of them live for 1000 years or more. Such long chronologies are very important: researchers can trace the effects of age more easily in long-lived species, follow slow changes in the environment and assess the impact of human influence during the past 100–200 years against a much longer period of equilibrium.

Ice cores also provide records of past climate change, but tree rings have the advantage of being easier to collect and can provide more accurately dated information. Snow may take decades to compress into ice, so the air (which scientists use to study changes in isotopes over long periods) that is trapped by this process may be many years younger than the ice surrounding it, while the cellulose in each tree ring reflects the composition of the atmosphere during the year in which it was laid down.

And, because tree-ring material can be dated to a particular year, climatologists can study precisely periodic phenomena such as the El Niño effect over thousand-year time scales and can compare tree-ring evidence for even longer-period changes, such as changes associated with ocean circulations, with data from other sources.

The study of Tasmanian tree rings, as well as satisfying scientific interest in ancient climates, also has much to tell us about more immediate concerns, such as the greenhouse effect.

Curiously, one of the most important tools for examining recent changes in the atmosphere is also used to look at the distant past — radiocarbon dating, which measures the gradual decay of the carbon-14 (^{14}C) isotope.

An 8000-year-long continuous sequence of tree rings and partially fossilised ('sub-fossil') logs in the Northern Hemisphere has been used to calibrate the radiocarbon 'calendar' that is extrapolated to date organic material formed over the past 40 000 years or so. But the Southern Hemisphere has a quite different history of climate and carbon exchange between organic material and the atmosphere, so the discovery of 1000-year-old living Tasmanian pines and of sub-fossil logs up to 13 000 years old offers an exciting opportunity to verify the Northern Hemisphere calendar and to extend it beyond 8000 years to the most recent ice age, some 12 000 years ago — a period during which the planet underwent rapid changes on a scale similar to those threatening us today.

Tasmanian tree-ring research has involved CSIRO scientists on several occasions during the past decade. Early Tasmanian exploratory work was carried out by Dr John Ogden of the Australian National University and by Dr Don Adamson of Macquarie University, with extensive Southern Hemisphere tree-ring sampling by the late Dr Val LaMarche of the University of Arizona Tree Ring Research Laboratory in the 1970s. Climatologist Dr Barrie Pittock of the Division of Atmospheric Research worked with Dr LaMarche in Tucson, Arizona, to construct a chronology of summer temperatures in Tasmania since 1780, having discovered that growth rings in several Tasmanian species of pine show a response to changes in summer temperatures.

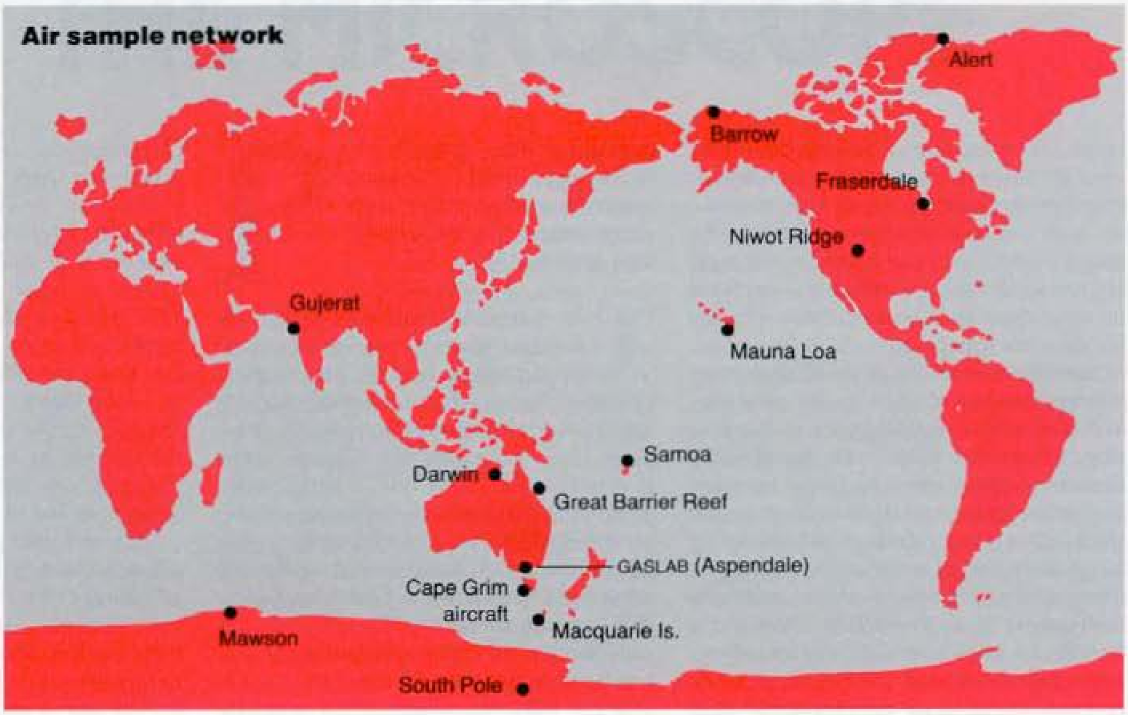
In 1979, Division of Atmospheric Research scientist Dr Roger Francey obtained a grant from the National Energy Research Development and Demonstration Council (NERDDC) to investigate whether the isotopic composition of cellulose in Tasmanian tree rings could be used to chart changes in atmospheric carbon dioxide (CO_2) levels as a result of fossil fuel combustion. Since CO_2 from the burning of fossil fuels is depleted in ^{13}C, and since trees obtain all their CO_2 from the atmosphere, the tree rings should show this change.

Dr Francey and his colleagues (including Mr Trevor Bird of the CSIRO Division of Forestry, Dr Mike Barbetti of the University of Sydney, Dr Gerald Nanson of the University of Wollongong, Dr Roger Gifford of the CSIRO Division of Plant Industry and Dr Graham Farquhar from the Australian National University) conducted field work at Stanley River in north-western Tasmania each summer from 1979 to 1982.

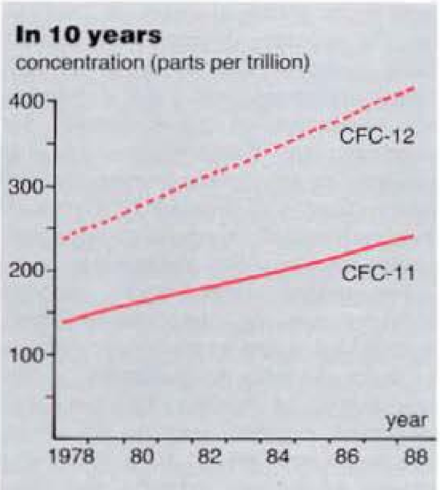
Dr Francey found that the stable isotopes trapped in tree rings did not just record the composition of atmospheric CO_2, they also indicated that trees had adjusted to increased levels of this gas in the atmosphere. In fact, his results suggested that trees increased their assimilation of CO_2 by 10% between 1870 and 1970. At the same time, Dr Barbetti began the huge task of constructing a fossil tree-ring chronology back to the most recent ice age.

In 1989 Mr Mike Peterson of the Tasmanian Forestry Commission discovered stands of sub-alpine Huon pine (this species was previously thought to be restricted to river plains and margins). These high-altitude trees demonstrated a much more marked sensitivity to temperature — presumably due to the harshness of their mountain-top environment — than the Stanley River material.

Prompted by Trevor Bird, Dr Ed Cook of the Lamont–Doherty Laboratory for Climatic Research, New York, spent 2 weeks in 1990 conducting dendroclimatological studies of Tasmanian



Monthly samples of air collected around the world come to GASLAB for analysis.



Concentrations of the chlorofluorocarbons CFC-11 and CFC-12 rose by about 5% per year in the 1980s. Measurements are from Tasmania's Cape Grim 'baseline' monitoring station.

tree-ring samples: Dr Cook returned to Tasmania last summer and, assisted by Mr Bird, Mike Peterson, Mike Barbetti and Roger Francey (with logistical support from the Tasmanian Forestry Commission, CSIRO, the Hydro-Electric Commission and Tasminco), collected living tree cores and sub-fossil wood.

Among the striking results of his preliminary study of sub-alpine material is that ring widths are larger today than at any time in the past 1000 years, most likely as a result of the greenhouse effect. This finding is consistent with Dr Francey's earlier observations. Tasmania's pines are providing an opportunity to tackle two of the most vexing questions in the whole mystery of the global carbon balance — the response of vegetation to changing atmospheric composition over long periods and the stability of ocean air–sea exchange over centuries.

Despite its association with such volatile phenomena as fire and rust, oxygen is a remarkably stable element — so stable, in fact, that the oxygen isotopes trapped by growing Tasmanian pines 1000 years ago represent a 'time capsule' replete with information about the climate of that era. Scientists studying global climate change can compare this information with similar time capsules of oxygen from the ice of Greenland, Scandinavia, North America and Antarctica, and with samples of air from these and other locations. They need such a broad range of collection sites because land masses and oceans — and hence biomass — are so unevenly distributed.

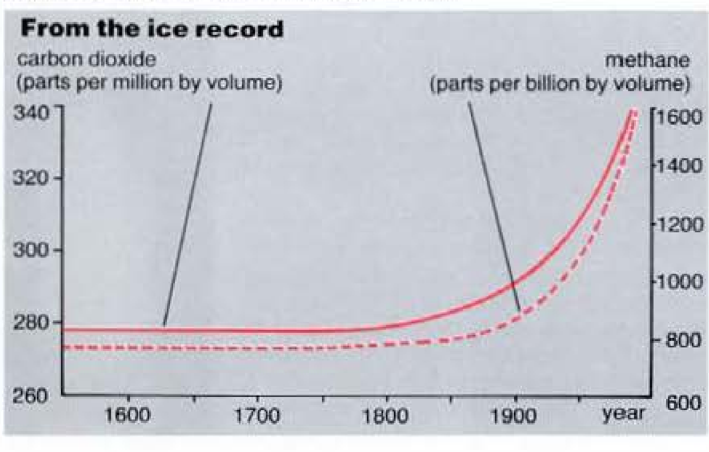
The bulk of humanity lives in the Northern Hemisphere, which is where most greenhouse gases are emitted; but the great oceans of the Southern Hemisphere also drive climate change. Researchers have therefore set up a world-wide sampling network to trace the paths of atmospheric gases through time and space, in an effort to learn more about the forces that shape the world's climate.

For measuring greenhouse and ozone-depleting gases, GASLAB (Global Atmospheric Sampling LABoratory) is the newest 'star' on the world stage. It was officially opened by CSIRO Chief Executive Dr John Stocker late last year at the Division of Atmospheric Research's Aspendale headquarters, Melbourne. This major laboratory facility is devoted to the most precise and efficient measurement of atmospheric gases whose names have become household terms as concern for the health of Earth and its atmosphere has grown.

Its leadership in the measurement of greenhouse-effect and stratospheric ozone-depleting gases stems from the combination of the state-of-the-art specially modified instruments for all of the major gas 'species' involved that have been installed.

- The Finnigan-MAT252 stable isotope ratio mass spectrometer was released in Germany last year, and GASLAB houses only the second such instrument manufactured. Its specifications exceed those of any previous, similar instrument: GASLAB's MAT252 has an attachment especially modified by Dr Francey that enables the automatic extraction and analysis of CO_2 in air, making it the most powerful facility for atmospheric CO_2 isotope studies in the world. It will be further enhanced this year, in association with scientists in New Zealand, to permit precise measurement of the stable isotopes of methane (CH_4) and carbon monoxide (CO) in air.
- A Carle S-Series gas chromatograph (GC) is optimised for the high-precision determination of atmospheric methane concentrations; a second (borrowed) Carle GC is currently optimised for the analysis of CO_2 in very small samples, such as those obtained from ice cores.
- A trace-analytical GC analyses carbon monoxide and hydrogen (H_2) concentrations in air. While neither species plays a direct role in the greenhouse effect or in stratospheric ozone depletion, CO is an important precursor for CO_2 in tropical regions; and both CO and H_2 are intimately involved in the chemistry of the atmosphere and help determine the destruction rates of other, important gases such as CH_4.
- A Shimadzu GC measures nitrous oxide (N_2O), which is responsible for about 3% of greenhouse warming; this instrument was specially modified by an American colleague, Dr Jim Elkins, to optimise its efficiency and precision for clean air measurements. A Shimadzu dual-column GC (also modified by Dr Elkins) measures the chlorofluorocarbons CFC-11, CFC-12, CFC-113 and other halocarbons, chloroform, methyl chloroform and carbon tetrachloride. These are greenhouse gases, but they also include the main culprits in the destruction of stratospheric ozone.
- A further GASLAB feature involves the development of automated, multi-sample carousels. Data from all

Antarctic ice-core measurements show how concentrations of the two main contributors to greenhouse warming have shot up this century. Methane levels have risen by more than 100% since the increase began, and carbon dioxide levels by about 25%.



instruments are stored in a centralised computer, which also controls measurement sequences, makes decisions on data quality and assists with processing and analysis.

The Division has appointed Dr Paul Steele to play a central role in the upgrading of GASLAB's instruments and the use of its facilities to unravel many of the trace-gas uncertainties that hamper accurate forecasts of future atmospheric conditions. Following groundwork by Dr Paul Fraser of the Division of Atmospheric Research, Australian-born Dr Steele established, developed and operated the United States National Oceanic and Atmospheric Administration CH_4-monitoring network.

How does GASLAB use this formidable array of instruments? Division of

David Whillas

Dr Colin Allison with GASLAB's new high-precision mass spectrometer, used to study isotopes of greenhouse gases.

Atmospheric Research scientists have two basic strategies to put the laboratory's facilities to the best possible use.

The first involves collecting a series of precise and comprehensive 'snapshots' of the world's atmosphere, with the aim of understanding in detail the sources, sinks and exchange mechanisms of its principal gases. In particular, the accurate definition of regular daily, seasonal and 4- to 5-year (El Niño) variations will help determine net exchanges of gases forced, for example, by temperature and/or biology, or by ocean mixing. In the future they will extend this sort of 'biogeochemical' modelling approach to decades as records accumulate.

The second measurement strategy involves (usually less-precise) information that spans much longer periods — from decades to millennia — by examination of 'archived' air or clues in preserved material such as ice cores, tree rings and so on. Identifying the impact of human activity and predicting future levels of key gases are easier if measurements cover hundreds of years or more, making the enhanced sensitivity of GASLAB's instruments

'Defrosting' the climate of the past from Antarctic ice

Polar ice sheets provide a natural archive of past atmospheric records; they sample the global 'background' atmosphere unperturbed by cities or forests. A range of information is recorded together in the same medium — ancient air in the bubbles, temperature-related isotopes in the ice and trace substances that relate to atmospheric circulation, volcanic eruptions, nuclear weapons 'events' and solar activity — and, of course, ice cores can be dated from such information. Natural ice is generally a good storage material for gas species, in some cases even better than man-made containers.

Law Dome, 100 km from Australia's Casey Station, is an ideal site for collecting ice cores. Its simple flow pattern and relatively high annual snowfall allow ice layers to build up undisturbed and unmelted for most of its 1200-m thickness. Ice cores with excellent age resolution can be drilled, from recent times (containing air from the 1970s, which can be compared with measurements from baseline stations in other locations) back to pre-industrial times and even to the last ice age, about 12 000 years ago.

To obtain core samples from depths of less than 500 metres, AAD glaciologists use thermal drills. An electrically heated metal head melts its way through the ice at about 2 m per hour, taking cores 100–200 mm in diameter in sections about 2 m long.

Below 500 m the borehole closes during drilling if not filled with a fluid, because of the overburden pressure of the ice. Glaciologists use mechanical drills consisting of a motor-driven rotary cutting head at the end of the drill, itself suspended on a cable some kilometres long (monitoring the borehole's distortion itself provides information on the flow dynamics of the Antarctic ice sheet, which in some locations is more than 4 km thick). The glaciologists conduct initial core analysis and sampling at the drill site, then package and ship the remainder of the cores to Australia in refrigerated containers.

Back in Melbourne, AAD glaciologists determine the ice chronology by counting annual layers: these are seldom visible, but are revealed by analysis of species that vary seasonally, such as the isotopic concentration of ^{18}O (which is temperature-dependent) or hydrogen peroxide (produced in the atmosphere by sunlight). They then check this kind of dating by identifying signals in trace substances that are attributed to specific events — for example, the sulfuric acid peak from the eruption of Tambora, Indonesia, in 1815 A.D.

The air enclosed in bubbles, however, is younger than the surrounding ice. Snow only becomes dense enough to seal air into bubbles at depths of 70 m or so: but Law Dome accumulates snow quickly enough — in some places, the equivalent of 1·2 m of water each year — to enclose air that can be dated to within several years, an obvious advantage for studies of the atmosphere over the past century or two.

At the Division of Atmospheric Research, researchers extract air from the ice at ICELAB, where they place carefully prepared samples (cooled to −80° to reduce the water vapour pressure and to make the ice more brittle) in a crushing flask. They evacuate the flask and crush the ice, which contains about 120 mL of air per kilogram, then vacuum-dry the liberated air and condense it in traps at −269° before taking the traps to GASLAB and measuring the gases mentioned above.

The results show that significant changes have occurred in many trace gases. Prior to 1800 A.D., CO_2 concentrations appear to have fluctuated around an average of about 285 parts per million (p.p.m.), but have since increased to 345 p.p.m. — a rise closely associated with the CO_2 released from fossil-fuel consumption. Methane concentrations began to rise about 50 years earlier than CO_2, possibly due to agriculture, and have since doubled. Nitrous oxide has increased by about 8%, mostly during this century.

Australian Antarctic Division

A glaciologist retrieves an ice core from a depth of 300 m in Law Dome, Antarctica. Air extracted from the ice at ICELAB is measured in GASLAB to study past changes in the composition of the atmosphere.

even more relevant: the MAT252 system, for example, requires air samples less than 1/500th as large as used by the Division's previous instruments.

Either way, GASLAB has particularly good access to samples for both kinds of measurement. In 1984, with funding from NERDDC, Division scientists Roger Francey, Paul Fraser and Dr Graeme Pearman set up a pilot global network of six stations focusing primarily on the isotopes of CO_2, but also providing GC analyses of CO_2, CH_4, CO and, on occasions, CFCs. The program's results were so valuable that it was continued and expanded to the present world-wide network (see the map on page 20).

Monthly samples of clean air in 5-L glass flasks come to Aspendale from the Arctic (Alert, Canada, and Point Barrow on Alaska's northern coast), North America (Fraserdale, Canada; Cheeka Peak, Washington; and Niwot Ridge, Colorado); Asia (the province of Gujerat, in north-western India); the Pacific (Mauna Loa, at 4169 m Hawaii's second-highest peak; and Samoa); Australia (Darwin–Jabiru; the Great Barrier Reef; Cape Grim, Tas.; and aircraft sample-collection over Bass Strait and the Great Australian Bight by commercial Australian Airlines flights and by CSIRO aircraft); New Zealand (aircraft sample-collection by that country's Meteorological Service); and Antarctica.

As well, the CSIRO research vessel *Franklin* and Australian Antarctic Division (AAD) re-supply ships collect samples at sea; AAD also supports regular sampling at Macquarie Island and at Mawson Station. Recently, German scientists have provided Northern Hemisphere stratospheric samples from high-altitude balloon flights launched from Sweden.

David Whillas

Dr Roger Francey with cylinders of air collected at Cape Grim, Tasmania, since 1978, which have been 'archived' for future analysis.

The 'anchor' of the sample network is the Cape Grim Baseline Air Pollution Station in north-western Tasmania. Operated by the Bureau of Meteorology in co-operation with the Division of Atmospheric Research, Cape Grim is closely integrated with GASLAB.

For examining change over longer periods, GASLAB is focusing on archived samples held in stainless steel cylinders and on Antarctic ice cores with unparalleled time resolution. With considerable foresight, almost 20 years ago Paul Fraser initiated a program to store Cape Grim air 'for a rainy day'. In anticipation of changing atmospheric composition and improved instrumentation (now provided by GASLAB), systematic collections of air one to four times a year began at Cape Grim in 1978, under conditions of strong south-westerly Southern Ocean winds.

Air is collected in oxygen tanks made of stainless steel (from World War II aircraft) and in specially prepared aluminium gas cylinders. These are all but submerged in a container of liquid nitrogen, which lowers the internal temperature of the flasks to about –180° and creates a partial vacuum. When the top of the flask is opened, air rushes in (with the help of a small pump) and liquefies. On thawing, the cylinder pressure reaches a level of about 30 atmospheres.

As well as collecting atmospheric gas samples at Mawson and the South Pole, AAD also provides Antarctic ice cores for GASLAB analysis. Air is removed from bubbles within the cores by ICELAB (Ice Core Extraction LABoratory), an annexe to GASLAB.

As part of the Division's ICELAB initiative, Mr David Etheridge was recruited from AAD to design and implement improved methods for air extraction from ice cores and to play a central role in collaborative ice core studies.

Ice cores from polar ice sheets and glaciers provide layers of atmospheric and climatic information up to thousands of years old... layers that in many ways resemble the growth rings of trees. Field teams from AAD collect cores from Law Dome, Antarctica, and transport them to cold storage in Melbourne, where annual layers are dated and past temperatures are calculated from the relative numbers of ^{18}O isotopes in each sample (see the box on page 22).

For measurement of trace gases, ice core samples are crushed under vacuum and the air released from the bubbles is collected in traps immersed in liquid helium at –260°. These traps are transported to GASLAB, where analysts check for a range of gas species, in particular for CO_2, CH_4, N_2O and halocarbons by gas chromatography, and for CO_2 and CH_4 carbon isotopes by mass spectrometry. Graeme Pearman is developing a new instrument to measure the very small decrease in oxygen expected to accompany fossil-fuel combustion, while Mr Ian Galbally is designing an O_3 detector to look for possible changes in tropospheric chemistry over the industrial period.

The GASLAB–ICELAB complex, which represents the integration and substantial upgrading of several relatively independent research efforts, was

Roger Francey

Trevor Bird (left) and Dr Ed Cook remove core samples from fire-killed Huon pines.

The gases GASLAB measures

OXYGEN (O_2)
Photosynthesis and respiration, the key processes of life, keep oxygen — the second-most abundant gas in the atmosphere — circulating. As human populations have expanded, the combustion of fuels and the destruction of forests have not only increased carbon dioxide levels, but may also have caused a very small but potentially measurable depletion of atmospheric oxygen.

Because O_2 is essentially insoluble in the oceans (unlike CO_2), the effects of the human impact on global O_2 should be reflected directly in atmospheric measurements. A small-volume, high-precision oxygen analyser will measure historical changes in atmospheric O_2 using air trapped in Antarctic ice, while GASLAB's MAT252 mass spectrometer traces changes in isotope ratios.

CARBON DIOXIDE (CO_2)
Levels of atmospheric CO_2 have risen by about 25% since 1800 due largely to the burning of fossil fuels, deforestation, agriculture and cement production. CO_2 is the main contributor to enhanced greenhouse warming. The GASLAB Carle gas chromatograph provides precise measurements of it from samples as small as 10 mL. The scientists hope their research will add to our knowledge of the roles of oceans and plants in absorbing excess CO_2.

NITROUS OXIDE (N_2O)
N_2O contributes about 3% of the enhanced greenhouse warming and atmospheric levels have risen since the industrial revolution by about 9%. Sources of atmospheric N_2O include the oceans, soil disturbance, biomass burning, fertilisers and fossil fuel combustion. Since N_2O and CO_2 have the same molecular mass and are not distinguished by the mass spectrometer, GASLAB uses N_2O data to correct isotopic measurements of CO_2 in air samples. N_2O levels are measured by the gas chromatograph.

METHANE (CH_4), CARBON MONOXIDE (CO) AND HYDROGEN (H_2)
Levels of CH_4, the second-largest contributor to the greenhouse effect, have risen by some 125% since 1800, mainly as a result of fossil-fuel combustion, biomass burning and emissions from livestock, rice fields and landfills. Changes in CO and H_2 (as well as CH_4) reflect atmospheric levels of hydroxyl radical (OH°), a major 'scavenger' of atmospheric pollutants. Motor vehicles are an important source of the increase in CO levels, which, like CH_4, are measured by gas chromatograph.

CHLOROFLUOROCARBONS
Chlorofluorocarbons (CFCs) have contributed an estimated 11% of the enhanced greenhouse warming since their wide-scale use began in the 1950s, and are the most rapidly increasing greenhouse gases (around 5% per year). The chlorine from CFCs is also suspected of being the major contributor to depletion of the ozone layer in the stratosphere, especially over Antarctica; GASLAB uses a dual-column gas chromatograph to measure CFCs.

David Whillas

A fish-eye view of the Cape Grim station.

conceived and implemented by Roger Francey as leader of the 'radiatively active gases' projects of the Division's Global Atmospheric Change Program. In many ways, GASLAB is a tribute to Division Assistant Chief and program leader Graeme Pearman, who marshalled the public and political awareness that precipitated support for the laboratory's creation.

Seeding grants from the Department of Arts, Sport, the Environment, Tourism and Territories' Climate Change Initiative and a CSIRO major equipment-upgrade initiative enabled the setting up of GASLAB; support came from NERDDC (a part of the federal Department of Primary Industries and Energy) and other government and commercial organisations with an interest in atmospheric research.

Carson Creagh

More about the topic

Tasmanian tree rings: a treasure trove for globally significant palaeoenvironment reconstructions? R. Francey. *Climate Change Newsletter*, **2** (2), 1990.

Greenhouse studies: assessing uncertainties versus debunking hype. I. G. Enting. *Australian Physicist*, 1990, **27** (8), 167–70.

'GASLAB: Global Atmospheric Sampling.' P. Holper. (CSIRO Division of Atmospheric Research: Melbourne 1990.)

'ICELAB: Ice Core Extraction.' P. Holper. (CSIRO Division of Atmospheric Research: Melbourne 1990.)

King Billy pines and the world's carbon dioxide. *Ecos* No. 12, 1977, 24–26.

What air bubbles trapped in Antarctic ice tell us. *Ecos* No. 47, 1986, 23–26.