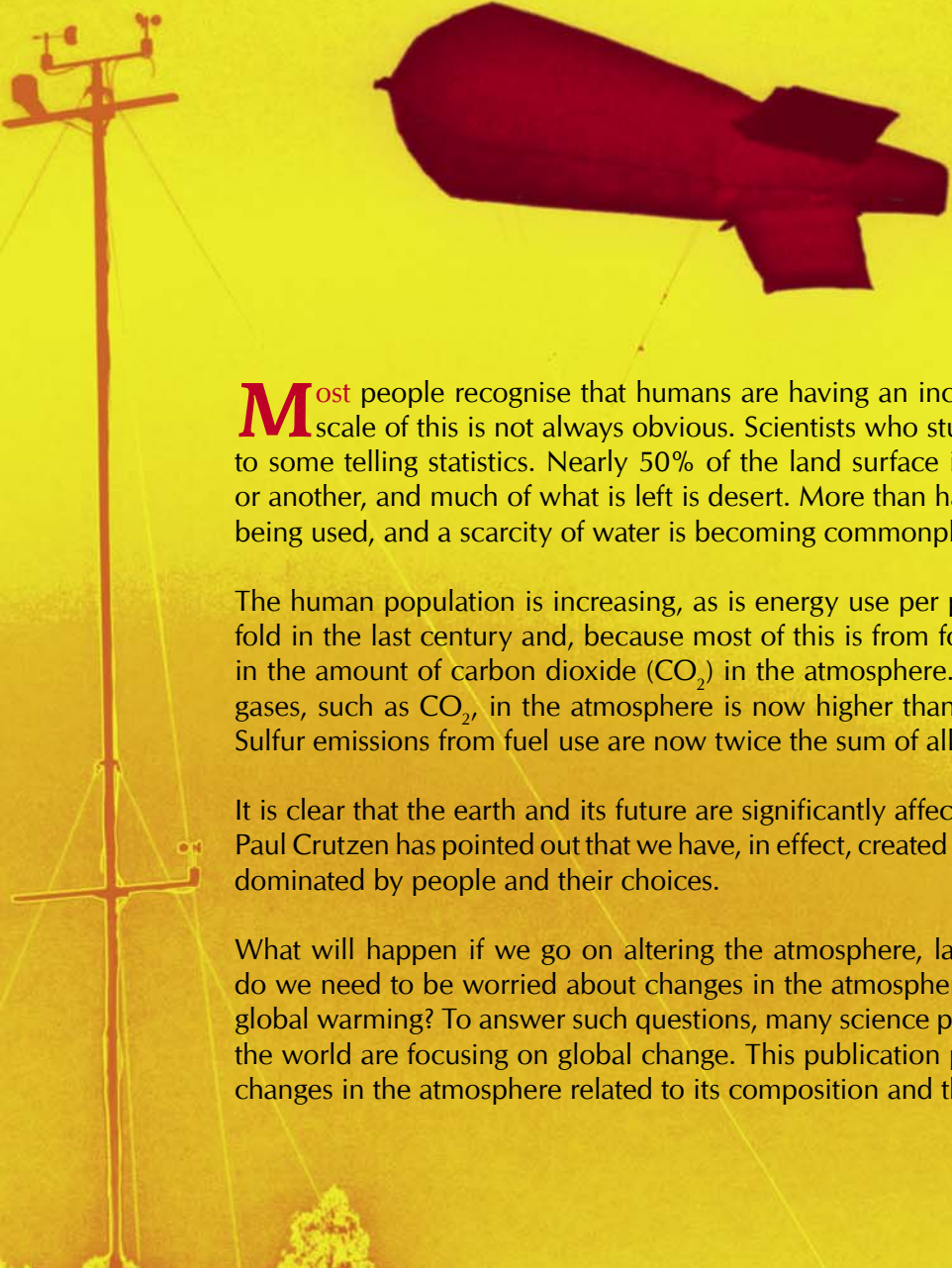


# The Greenhouse Effect

*a New Zealand perspective on climate change*



**M**ost people recognise that humans are having an increasing impact on planet Earth, but the scale of this is not always obvious. Scientists who study the global environment have access to some telling statistics. Nearly 50% of the land surface is now modified by people in one way or another, and much of what is left is desert. More than half of all accessible freshwater is already being used, and a scarcity of water is becoming commonplace, even in the richest countries.

The human population is increasing, as is energy use per person. Total energy use has grown 16-fold in the last century and, because most of this is from fossil fuels, has led to dramatic increases in the amount of carbon dioxide (CO<sub>2</sub>) in the atmosphere. We know that the level of greenhouse gases, such as CO<sub>2</sub>, in the atmosphere is now higher than at any time in the last 400 000 years. Sulfur emissions from fuel use are now twice the sum of all natural sulfur emissions.

It is clear that the earth and its future are significantly affected by human activities. Nobel laureate Paul Crutzen has pointed out that we have, in effect, created a new geological era, the Anthropocene, dominated by people and their choices.

What will happen if we go on altering the atmosphere, land, rivers, and oceans? To what extent do we need to be worried about changes in the atmosphere that are linked to climate change and global warming? To answer such questions, many science programmes in New Zealand and around the world are focusing on global change. This publication presents a summary of NIWA's work on changes in the atmosphere related to its composition and the possible effects on climate.

# The Greenhouse Effect

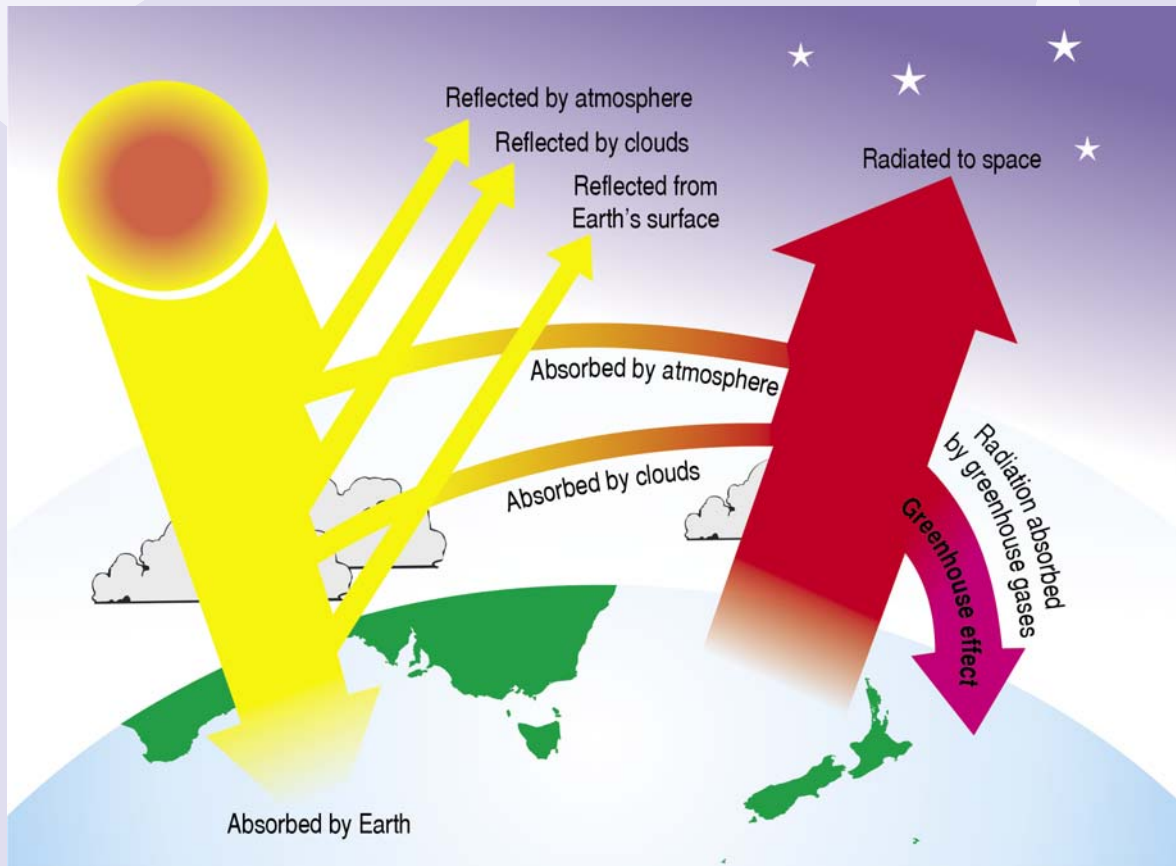


Figure 1: The sun's energy enters the earth's atmosphere. Not all of this energy reaches the earth's surface because a small proportion is reflected by the atmosphere, by clouds, and by the earth's surface. Some energy is also absorbed by the atmosphere and by clouds. Finally, the radiation that does reach the earth's surface is absorbed. During this absorption process the original energy changes in nature to infrared radiation. The earth's surface then re-radiates this infrared energy back to space, but the greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, are able to absorb it, trapping the energy in our lower atmosphere and causing this region to warm up. As levels of the greenhouse gases increase, their ability to trap energy also increases, giving rise to the "greenhouse effect".

The earth is kept warm by the sun. Energy arrives from the sun as visible light and most is absorbed at the surface. However, energy has to be conserved, and so there is a balancing, outgoing stream of what was called "dark light" in the 19th century, which we now refer to as infrared radiation. The amount of outgoing infrared radiation increases with the earth's average surface temperature, so that temperature adjusts until there is a balance between incoming and outgoing energy.

If there were no atmosphere, then the earth's average surface temperature would be about  $-18\text{ }^{\circ}\text{C}$ , too cold to sustain life. However, the atmosphere acts as a blanket that absorbs most of the infrared radiation emitted from the surface. This warms the air above us, which then re-radiates energy both upwards and downwards. The extra downward radiation received back at the surface raises the average surface temperature to a much more comfortable  $+15\text{ }^{\circ}\text{C}$  (Figure 1).

Infrared radiation is absorbed not by the principal gases, such as nitrogen and oxygen, but by less than 0.1% of the gases in the atmosphere, the greenhouse gases,  $\text{CO}_2$ , methane, nitrous oxide, water vapour, and others. Information on past temperature and atmospheric composition obtained from ice-cores from the Antarctic and Greenland show that during the last 400 000 years, when greenhouse gas levels were high, so was temperature; when greenhouse gases were low, so was temperature.

The degree to which each greenhouse gas affects the earth's energy balance and surface temperature depends on its specific properties. To compare the effect on climate of releasing different greenhouse gases to the atmosphere, several factors must be taken into account.

For example, each extra molecule of methane absorbs about 30 times as much infrared radiation as an extra

molecule of  $\text{CO}_2$ , but a pulse of methane into the atmosphere lasts on average for about 12 years whereas  $\text{CO}_2$  lasts for centuries. Methane also has effects on other greenhouse gases, such as ozone and water vapour. Combining these factors leads to the concept of a Global Warming Potential (GWP), which estimates

the climatic effect of an emission of a gas relative to the same amount of  $\text{CO}_2$ , typically averaged over 100 years following the emission. The GWP of methane is 23, which means that the emission of 1 tonne of methane is estimated to have the same climatic effect over 100 years as an emission of 23 tonnes of  $\text{CO}_2$ .

## The major greenhouse gases

**N**IWA makes high precision measurements of the three main greenhouse gases ( $\text{CO}_2$ , methane, and nitrous oxide) at the Baring Head Atmospheric Research Station near Wellington, at Scott Base (Antarctica), and from ships and aircraft in the Pacific Ocean and Southern Ocean. From these measurements we are able to study changes in atmospheric composition over a large part of the extra-tropical southern hemisphere.



Baring Head Atmospheric Research Station and nearby Baring Head lighthouse.

What we see is a steady rise in greenhouse gas levels (Figure 2). Open circles are the actual measurements, the green line is a fitted line, showing the seasonal cycle, and the red line gives a seasonally detrended fit.

A mixing ratio for a particular gas describes the ratio of the number of molecules of that gas to the number of air molecules, in a fixed volume. The units are; parts per million (ppm) or parts per billion (ppb). For example 325 ppm of  $\text{CO}_2$ , means that within one million molecules of dry air, there are 325 molecules of  $\text{CO}_2$ .

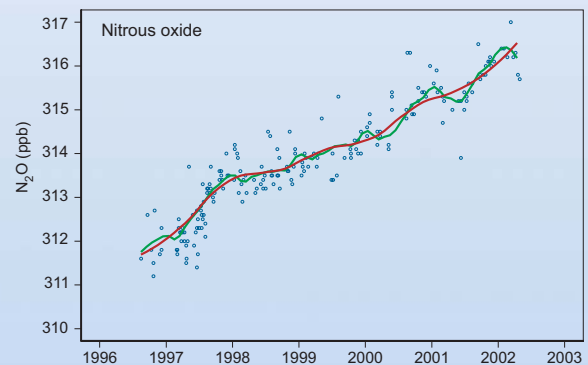
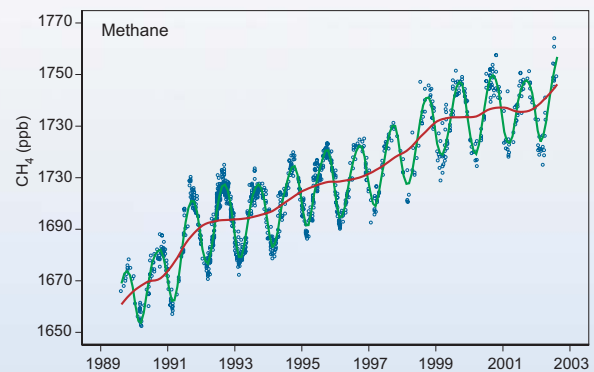
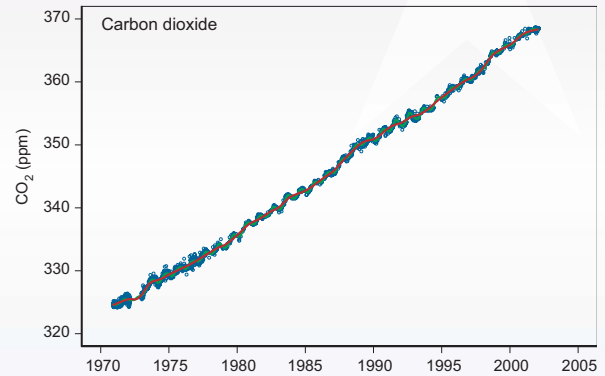


Figure 2: Mixing ratios of the three major greenhouse gases, ( $\text{CO}_2$ , methane, and nitrous oxide) at Baring Head, New Zealand.



# Carbon dioxide (CO<sub>2</sub>)

Carbon dioxide is a naturally occurring greenhouse gas, as well as being a fundamental part of the life cycles of plants and animals. Plants absorb CO<sub>2</sub> in photosynthesis, use the carbon to form sugars and substrates, and then release carbon back to the atmosphere, mainly as CO<sub>2</sub>, when they decay or are consumed. In this way nearly 16% of the CO<sub>2</sub> in the atmosphere is cycled through the biosphere each year.

CO<sub>2</sub> is weakly soluble in seawater, and being more soluble in cold water is taken up from the atmosphere, mainly in the cold oceans near the poles. A slow overturning of the world's oceans transports this carbon-enriched water to depths of 2 km or more, where it flows towards the tropics. There it wells up towards the surface, expelling some of the CO<sub>2</sub> back into the atmosphere, returning the rest via near-surface flows to the polar regions. The effect is continuous removal of CO<sub>2</sub> by oceans near the poles and resupply to the atmosphere near the equator. Such processes cause about 12% of the CO<sub>2</sub> in the atmosphere to be cycled through the oceans each year.

We know that the amount of CO<sub>2</sub> in the atmosphere changed by less than 5% in the 10 000 years from the end of the last ice age to the 18th century, so these natural biospheric and oceanic cycles of carbon were in balance. Since the 18th century this balance has been altered by burning carbon in the form of fossil fuels that were created over millions of years through geological burial of plant material.

Clearing forests and replacing them with crops or pasture also adds CO<sub>2</sub> to the atmosphere. Some of this extra CO<sub>2</sub> is taken up by plant growth and some by the oceans, but these natural removal processes do not keep up with emissions, and each year the total CO<sub>2</sub> in the atmosphere increases by about half of the amount emitted that year.

Plant growth and decay and ocean uptake of CO<sub>2</sub> are affected by year-to-year climate variations, particularly in temperature and rainfall. Thus we expect to see year-to-year changes in the amount of CO<sub>2</sub> removed from the atmosphere by natural processes. The CO<sub>2</sub> growth rate has varied about a mean of 1.5 ppm per year for the last 30 years, but has tended to increase as the temperature has increased by 0.5 °C over the same period.

Higher growth rates in atmospheric CO<sub>2</sub> levels occur when the planet is warmer than usual. This is expected because, when temperatures are higher, respiration and decay of plant carbon back to the atmosphere are faster and less CO<sub>2</sub> is taken up by warmer surface oceans. So, natural removal processes are slowed down during warm periods but the use of fossil fuels and emissions of CO<sub>2</sub> by human activities is not, and we see a more rapid increase in the CO<sub>2</sub> level in the atmosphere.

## THE ACTIVE CARBON CYCLE



# Methane (CH<sub>4</sub>)

**M**ethane, also known as marsh gas, is another naturally occurring greenhouse gas. It is produced mainly by biological breakdown of organic substances in anaerobic (oxygen-deficient) conditions, such as the digestive system of ruminant animals and the decay of plant material in swamps.

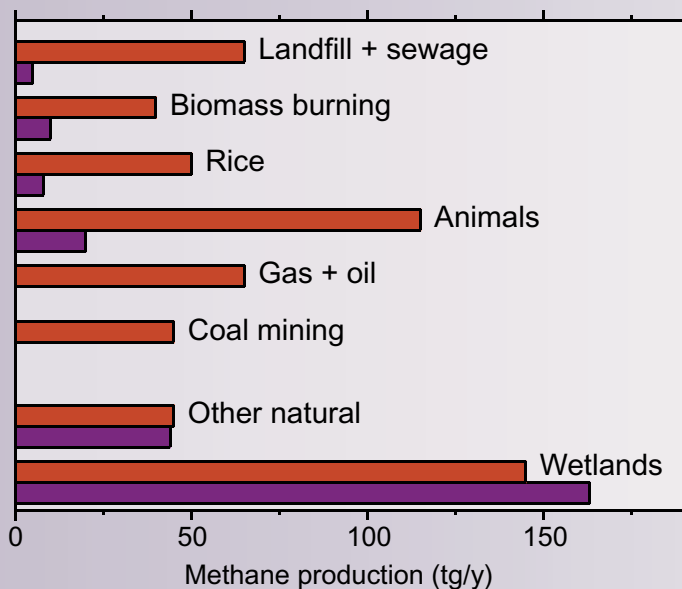


Figure 3: Horizontal bars show recent estimates of the amounts of methane produced from various sources. Purple bars denote values for natural sources in the pre-industrial era and the red bars values for both natural and human-induced sources in the 1990s. (1 teragram (tg) is 1 million tonnes.)

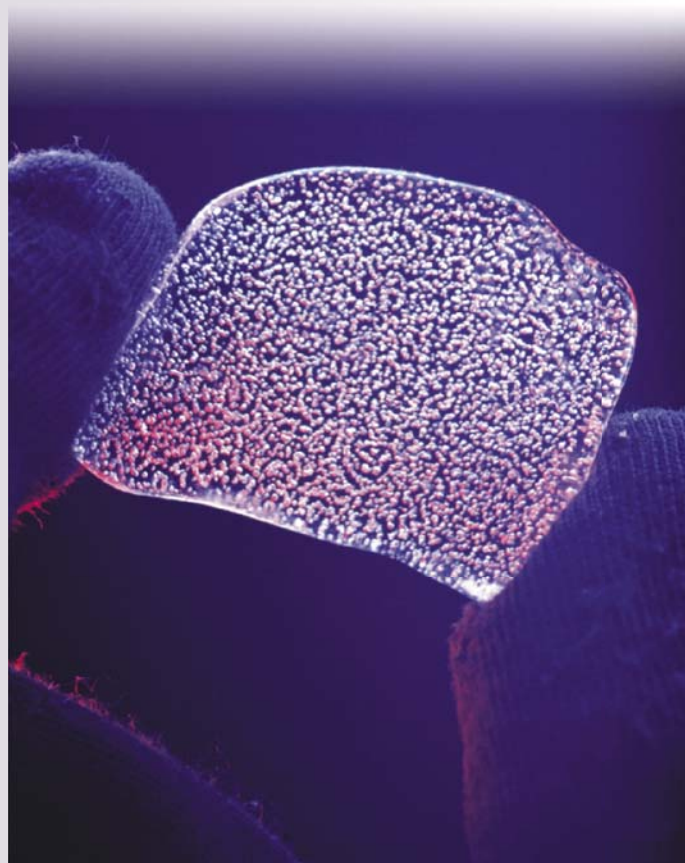
Release of methane to the atmosphere has increased from natural levels of about 250 million tonnes per year to a current value of about 600 million tonnes per year due to human activities. Figure 3 shows estimates of how different sources of methane have changed. Each year about 12% of the methane in the atmosphere is removed by oxidation triggered by sunlight, and a small amount is consumed by soil bacteria. The emission of 1 tonne of methane to the atmosphere has the same effect on the climate system over 100 years as the emission of 23 tonnes of CO<sub>2</sub>.

NIWA has measured the background levels of atmospheric methane in the New Zealand region since August 1989. Most of the data are from clean air samples collected at Baring Head (Figure 4). These measurements have been complemented by data from Whananaki (Northland), Scott Base (Antarctica), Suva (Fiji), and container ships sailing from Auckland.

Our measurements show an increasing trend in the concentration of methane, with a growth rate that

appears to be slowing and becoming more variable. In 1991–92 and 1998–99 the growth rate exceeded 0.5% per year. The growth rate in 2001 has been negative (i.e., methane decreasing), but recent data suggest a return to positive growth.

There is evidence that the high growth rates in 1991 were associated with changes in atmospheric chemistry after the eruption of Mount Pinatubo. High growth rates in 1998 have been attributed to global warming effects of wetlands, particularly in Canada and Siberia. The overall decline in growth rate is consistent with the atmosphere coming into equilibrium with a global source that has not increased in the last decade.



**Air bubbles trapped in Antarctic ice**  
(photo: David Etheridge).

Important insights into changes in greenhouse gases and climate can be gained by analysing air trapped in bubbles deep in Antarctic ice. This analysis has shown that levels of atmospheric methane have more than doubled over the last 150 years. Recently we have begun work with CSIRO Atmospheric Research, Australia, to examine subtle changes in heavy and light fractions of methane gas trapped in snow, and in the abundance of naturally occurring radioactive carbon, as a way of identifying past changes in the different sources of methane.

The measurement of the isotopes of carbon ( $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{14}\text{C}$ ) in methane provides additional information to that obtained by measuring the concentration of methane in the atmosphere. Each source of methane, such as plants or fossil fuels, has different amounts of  $^{13}\text{C}$  and  $^{12}\text{C}$ , giving "signature" ratios of these two isotopes. Oxidation of methane by the hydroxyl radical (OH; see "Atmospheric Chemistry" below) or by chlorine atoms also leads to different carbon isotope ratios in the atmosphere. Modelling the emission, transport, and destruction of methane, including isotope effects, has explained important features of observed methane seasonal cycles in the southern hemisphere.

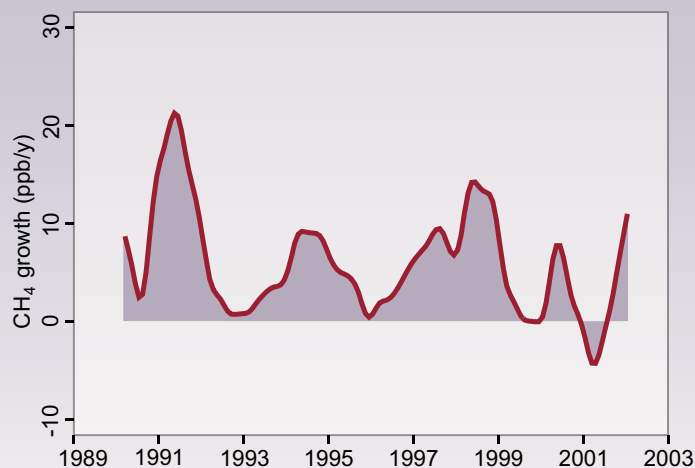


Figure 4: The growth rate of methane at Baring Head, Wellington, from 1989 to 2002 in parts per billion (ppb) per year.

Radioactive  $^{14}\text{C}$  is used as a tracer to follow the transport of methane and  $\text{CO}_2$  through the atmosphere and oceans. It is also being used to estimate the transport and oxidation of carbon monoxide, and so allows changes in levels of the "detergent" OH to be inferred (see "Atmospheric Chemistry" below).

## Nitrous oxide ( $\text{N}_2\text{O}$ )

Nitrous oxide is another naturally occurring greenhouse gas that has increased in concentration in the atmosphere since the pre-industrial era. It is released to the atmosphere as a byproduct of bacterial processing of nitrogen in soils, but has some industrial sources as well. Current estimates are that global releases of nitrous oxide have increased by about 60% due to human activities, mainly through large increases in the use of nitrogen fertilisers in agriculture.

Nitrous oxide is broken down very slowly by sunlight in the stratosphere and has an average lifetime of about 120 years. This means that current emissions will play a long-lasting role in the enhanced greenhouse effect. Nitrous oxide is also very effective at absorbing infrared radiation and the emission of 1 tonne of nitrous oxide to the atmosphere has the same effect on the climate system over 100 years as the emission of 296 tonnes of  $\text{CO}_2$ .

Measurements of baseline levels of nitrous oxide have been made at Baring Head since 1996. During that time the concentration in the atmosphere rose from about 312 ppb to about 316 ppb by mid 2001, with a steady increase of about 0.8 ppb per year. Superimposed on this long-term trend are annual cycles of about 0.4 ppb peak to peak showing maxima in December-January and minima in April-May. We also see irregular short-term variations that are probably caused by event-based release from soils (for example, after rainfall).

Because atmospheric baseline levels of nitrous oxide are low and seasonal cycles are small, the measurements are technically difficult and precise calibration is critical. We are currently using a suite of calibration gases supplied by Scripps Institution of Oceanography in the USA that has allowed us to link our New Zealand data to measurements made elsewhere.

Gas emissions are estimated by combining measurements of concentration and turbulence in the field.

# New Zealand's greenhouse gas emissions

**N**ew Zealand, as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), reports annually on the quantity of greenhouse gases emitted as a result of human activities (anthropogenic emissions). This “inventory” involves measuring emissions and determining their source. Unlike most developed countries, New Zealand has significant non-CO<sub>2</sub> greenhouse gas emissions (Figure 5). New Zealand's biggest greenhouse gas emission is methane, because we have a large population of farmed livestock yet relatively low usage of fossil fuels for electricity generation. All ruminant livestock (such as cows and sheep) produce methane by belching (not from the nether end as most people like to think!) as a result of digestion.

Nitrous oxide is also important in New Zealand's emission inventory. It is produced through breakdown of animal excreta and nitrogenous fertilisers applied to agricultural soils.

Agriculture is responsible for a much larger share of greenhouse gas emissions in New Zealand than in other developed countries. Because of this, we are considering ways of cutting back emissions from pastoral agriculture through various mitigation strategies. That raises some difficult problems of measurement and on-going monitoring because these emissions are variable or the sources are mobile.

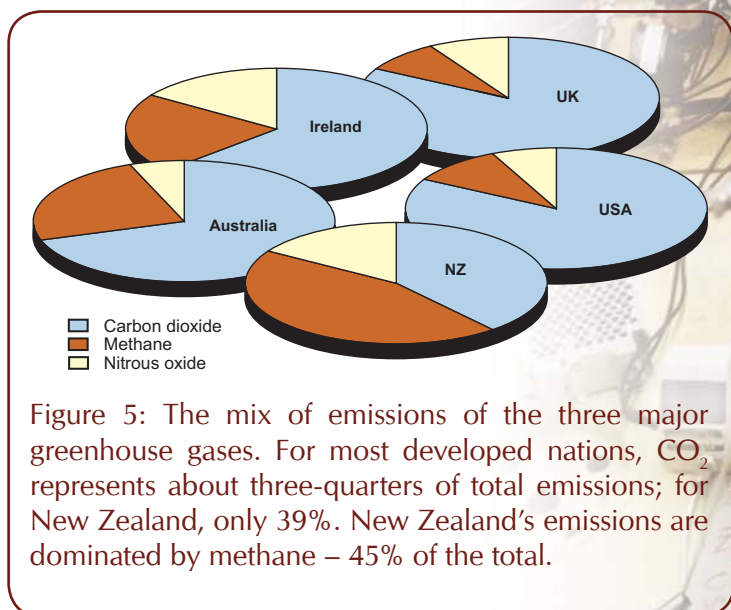


Figure 5: The mix of emissions of the three major greenhouse gases. For most developed nations, CO<sub>2</sub> represents about three-quarters of total emissions; for New Zealand, only 39%. New Zealand's emissions are dominated by methane – 45% of the total.

Rona Thompson in NIWA's Wellington laboratory developing equipment for greenhouse gas analyses.

# Ruminant methane emissions

About 90% of New Zealand's anthropogenic methane emissions are from farmed ruminant livestock: sheep, cattle, deer, and goats. The remaining 10% comes mainly from organic material degrading in landfills. It is estimated that about 1.5 million tonnes of methane are emitted annually by New Zealand's livestock. This is equivalent to more than one-third of the methane taken from New Zealand's natural gas fields every year.

NIWA has introduced (with AgResearch) a tracer technique for measuring daily methane production from individual animals while grazing. The technique involves continuous but unobtrusive sampling of the animal's breath, which is then analysed back in the laboratory for methane.



Sheep with breath collecting equipment.

This technique is sophisticated and expensive. We are now investigating complementary technologies to measure per-animal emissions that are cheaper and easier to use, even if they are less precise. Since 1995, the NIWA-AgResearch collaboration has made over 2500 analyses of daily animal breath samples. A typical dairy cow belches about 370 litres of methane in a day; a typical sheep up to 60 litres a day. If the methane produced by a dairy herd was collected and used as fuel, it could power a medium-sized car for about 4 km a day for every cow in the herd.

As an independent way of assessing these methane emissions, we also make direct measurements of methane in the rural atmosphere. We measure the changes in methane concentration vertically, upwind, and downwind of a region supporting grazing stock.



Launching a tethered kytoon to carry aloft instruments to measure wind speed and direction, temperature, and dew point and tubing for collecting samples.

The downwind sample has passed over the herd, collecting their methane emissions. By comparing the downwind measurement with the background upwind measurement we can determine how much the herd contributed and how much the animals must have emitted.



Tony Bromley and Paul Wilson with equipment to measure CO<sub>2</sub> fluxes from the soil surface.

# Nitrous oxide emissions from agricultural soils

**W**e know little about New Zealand's emissions of nitrous oxide and current estimates have about 60% uncertainty. This is largely because these emissions are very dependent on environmental conditions, such as soil moisture and climate, and are related to microbial processing. More than 95% of New Zealand's anthropogenic nitrous oxide emission comes from agricultural soils, the largest component coming from the excreta of grazing animals. To improve understanding and determine the emission factors (the amount of nitrous oxide emitted for a given amount of applied nitrogen) a group called N<sub>2</sub>O<sub>Net</sub> has been set up to coordinate research and progress.

Experiments to determine emission factors have used small chambers or soil covers (typically 0.5 m or less in diameter and about 10 cm high) to trap the emitted nitrous oxide before analysis. The difficulty with this approach on the farm is that emission fluxes are very variable. NIWA has to make measurements at many different sites and in different seasons to achieve useful estimates of mean annual emissions. This variability in emissions is due to the patchy nature of excreta deposition and high sensitivity to environmental conditions, especially to soil moisture levels.

NIWA has been developing (with Landcare Research) non-intrusive large-scale (paddock and larger) measurement methods that are able to give area-average emission estimates for nitrous oxide. However, measurements at the paddock scale are very challenging, even with sensitive instrumentation with a precision of 0.1%, because nitrous oxide fluxes are usually too small to provide measurable deviation of nitrous oxide levels in the lower atmosphere. Our initial approach has been to look at emissions under stable night-time conditions when vertical diffusion is significantly reduced. Under these conditions, we have the measurement precision to easily detect nitrous oxide in the lower atmosphere.



# Atmospheric chemistry

In addition to changing the physical (warming) properties of the atmosphere, greenhouse gases change the chemistry, altering the balance of natural chemical reactions. The best example of human changes to atmospheric chemistry is ozone depletion. The first major challenge was to determine the role of chlorofluorocarbons (CFCs) in the destruction of stratospheric ozone. Ozone in the stratosphere is important because it screens the earth from some harmful UV radiation. CFCs are artificial compounds that were used primarily for refrigeration and propellants, but once released into the atmosphere were slowly broken down to form chlorine radicals. In the very low temperatures of the stratosphere, the chlorine destroyed ozone. The Montreal Protocol established management of CFCs and led to their replacement with other substances, in the hope that the ozone layer would recover.

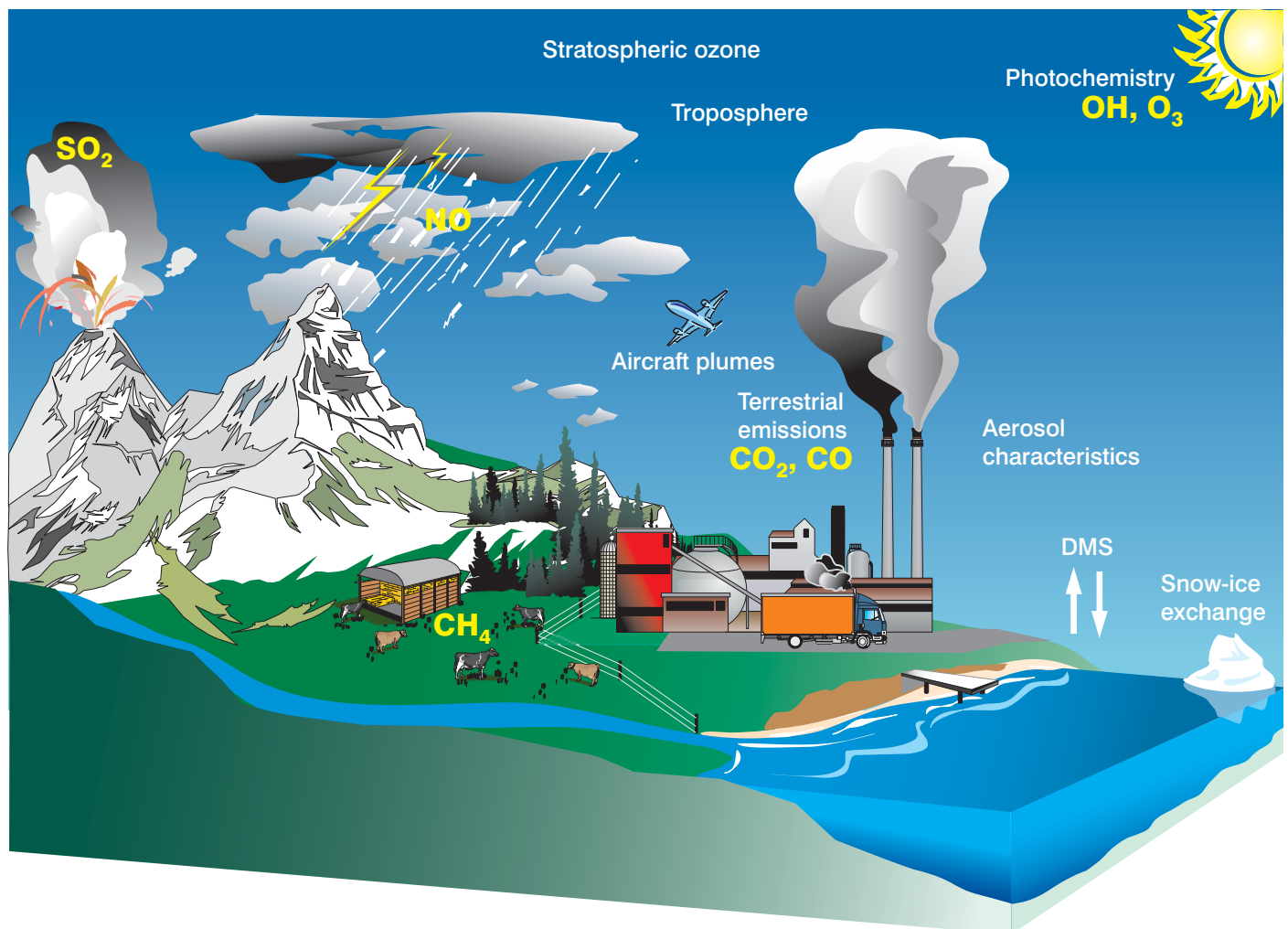
There are many gases in the atmosphere, but the “greenhouse gases” make up less than 0.1%. Despite this, they have a major effect on the chemistry and energy balance of the atmosphere and on climate.

The hydroxyl radical (OH) plays a very important role in the atmosphere. It has been called the “detergent” of

the atmosphere because it reacts with some greenhouse gases, removing them from the atmosphere. Because of its very short residence time in the atmosphere (only a few seconds), concentrations of OH are very difficult to measure. However, changes in the concentrations of many trace gases affect OH concentration and the extent to which it can cleanse other pollutants from the atmosphere. Lower OH concentrations would increase both the lifetimes and concentrations of many greenhouse gases.

Carbon monoxide (CO) is not a greenhouse gas but it plays an important role in atmospheric chemistry, affecting the seasonal cycles and global distributions of several greenhouse gases. It is short-lived (2–3 months) and its reaction with OH is the main removal process for both species in the atmosphere, so the levels of CO in the atmosphere provide an estimate for the levels of OH.

NIWA’s field sites in New Zealand and Antarctica provide a unique opportunity to study CO in clean air. Global studies have shown that the higher southern latitudes have the lowest concentrations of CO. These low concentrations correspond to higher OH levels and hence higher removal rates of methane.



# Clouds and climate change

**O**n a bright sunny day it feels cooler when a cloud covers the sun because clouds act as a barrier and prevent some of the sun's energy from reaching us. Clouds can also trap heat that is re-radiated from the earth's surface. Frosty nights are usually clear and free of clouds, allowing the stored heat in the earth's surface to escape. The nights are much warmer when there is a "blanket" of clouds.



Clouds block some of the sun's energy.

So clouds can have both a warming and a cooling effect and make it difficult to predict how climate change might affect us. If we had more highly reflective clouds (clouds with a higher albedo) in the lower atmosphere, we could expect that far less of the sun's energy would be trapped in our atmosphere and this could offset the effect of the greenhouse gases.

We already know that in the northern hemisphere the increased burning of fossil fuels has resulted in an increase in the number of tiny sulfate particles in the atmosphere. These "aerosols" act directly to reflect the incoming energy from the sun, so the temperature increase in the northern hemisphere is estimated to be about 1 °C less than if these additional aerosols were not present. This is known as the "direct aerosol effect".

There is also an "indirect aerosol effect" by which these tiny particles alter the reflective properties and the lifetime or persistence of clouds. In the direct aerosol effect incoming radiation is reflected by these tiny particles; in the "indirect aerosol effect" the particles initiate the formation of clouds. Clouds are made of condensed water, and to allow water to condense (change from a gas to liquid) aerosols are needed. These tiny particles are called cloud condensation nuclei (CCN). Water vapour is transparent, and we wouldn't see steam or clouds if the water didn't condense on a particle first. The contrails produced by aircraft high in the atmosphere are clouds that are the result of water vapour in the atmosphere condensing on the particles emitted by jet engines.

The ability of a cloud to reflect incoming radiation is dependent on the chemistry of the nuclei that formed it. These nuclei can be the result of our activities, such as the burning of fossil fuels, or the activities of other living things, such as oceanic plankton, as described in the "CLAW" hypothesis (Figure 6).

It has been calculated that a 30% increase in the number of nuclei leads to a cooling that would offset 40% of the warming due to greenhouse gases.

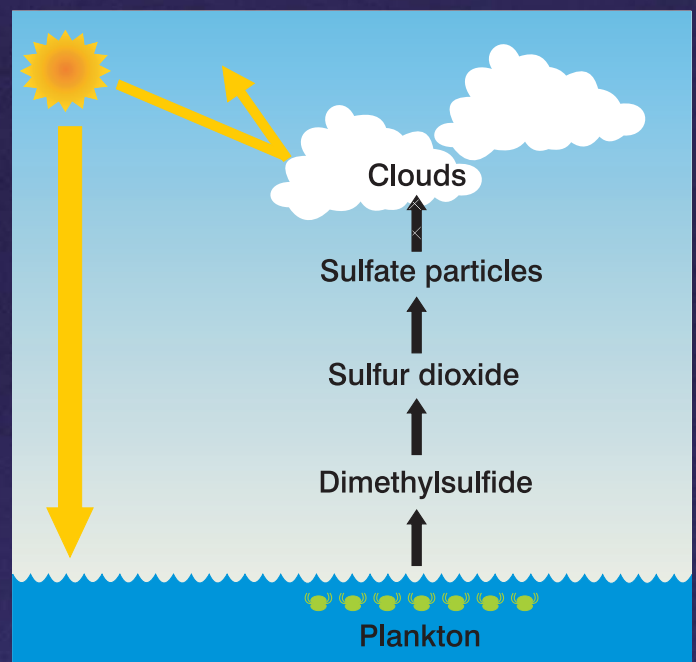


Figure 6: Diagram illustrating the "CLAW" hypothesis, named using the initial letters of each of the authors (Charlson, Lovelock, Andreae, and Warren). This hypothesis states that plankton in the world's oceans emit sulfur gases that are released into the atmosphere. After processing in the atmosphere the gas is converted to particles, which then allow clouds to form. These clouds affect the amount of sun's radiation reaching the ocean surface. As the temperature increases due to climate change, the ocean warms, possibly prompting the plankton to produce more of the sulfur gases and resulting in greater numbers of particles, hence reducing the warming effect due to greenhouse gases. This results in a closed feedback loop, allowing these tiny creatures to modify the global climate.

# Options for the future

Clearly, humans are affecting the earth's atmosphere and hence climate, and we will need to change our behaviour if we are to ensure that the climate can stabilise. One of the major challenges is going to be coping with the significant environmental changes that inevitably will occur over the next 50 or so years. Measures adopted now will generally take many decades to have their full effect. Returning the atmosphere to its pre-industrial state is not a realistic option, and this means that we will need to adapt to the changes.

As part of the international effort to manage global greenhouse gas emissions, many groups have developed various "scenarios" for the future. The most complete scenarios come from an international study, coordinated by the United Nations Intergovernmental Panel on Climate Change (IPCC), which considered ranges of various parameters such as expected population growth, expected or required growth in Gross Domestic Product (GDP), and energy technology and use. These parameters, plus various assumptions for social and economic factors, are used to estimate a range of future greenhouse gas emissions and consequent changes in temperature and sea level.

The IPCC scenarios fall into four families. For example, the A1 scenarios are based on a world that tends to value material things, does not give a high priority to environmental values, and adopts global approaches to trade and technology rather than regional ones. The B1 scenarios cover a world that places a higher value on environment and whose economies tend to have a higher proportion of service and information-based industries. All scenarios considered have real growth in GDP per person in all regions of the world, but significant differences emerge. For example, the B1 scenarios lead to a lower temperature rise than the A1 scenarios for the same population.

A major issue in all scenarios is how we obtain the energy we need. Most countries use fossil fuels as the dominant energy source (for cars, electricity generation, industry, etc). Significant reductions in the projected temperature rise can be achieved by choosing to obtain energy from non-fossil fuel sources, such as solar and wind power, electric cars, more public transport, etc.

Figure 7 shows two of the three A1 scenarios. Each A1 scenario has essentially identical population and GDP growth, but with very different choices for energy sources. A1T (technically advanced) scenario has a strong dependence on renewable energy sources and is estimated to result in a mean rise in temperature of +2.5 °C by 2100. The A1B (balanced, not shown)

scenario has a balanced mix of energy sources and would result in a 3 °C rise over the same period, while the A1FI (fossil intensive) scenario has a heavy reliance on fossil fuels and would result in a 4.5 °C temperature rise.

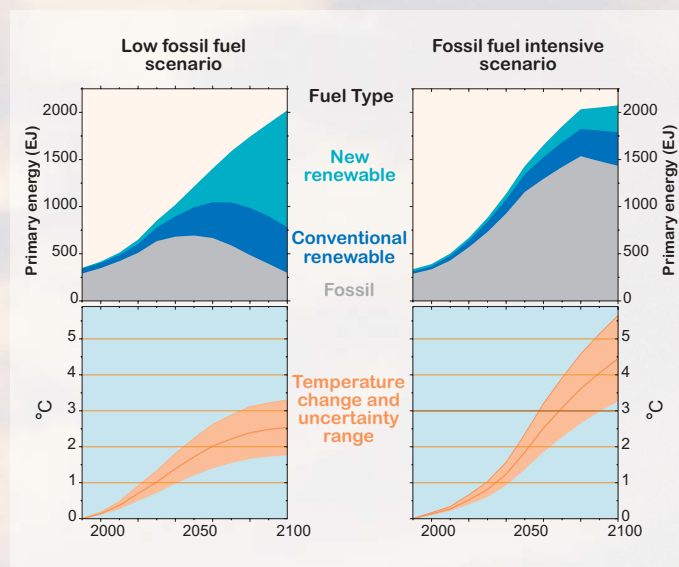


Figure 7: Comparison of the A1 Scenarios. The top panel shows energy supplied by various sources, and the lower panel shows the resulting mean temperature change and range for each mix of energy. The A1T scenario shows the lowest temperature increase of 2.5 °C, and the A1FI scenario shows the highest temperature increase of 4.5 °C.

Such studies show that we can have long-term growth in GDP while limiting the magnitude of climate change. Addressing climate change is not necessarily the end of doing good business and it could be seen as a positive business opportunity.

New Zealand is well placed to consider further development of renewable energy because we have large potential resources in wind, wave, and solar power and an economy that could adapt quickly to the use of hydrogen fuel cells. In a world concerned about fossil fuel emissions, such flexibility implies economic opportunity. NIWA is providing information on this emerging challenge through its new Centre for Climate-Energy Solutions and its quarterly newsletter *Climate-Energy Matters*.

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