## The greenhouse effect: facts, predictions and uncertainties

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### Introduction

Without the presence of water vapour and carbon dioxide ($CO_2$)in the atmosphere, the earth's surface temperature would be 33 K lower than it is today. For many years the process of retaining heat in the lower atmosphere has been known as the greenhouse effect, and $CO_2$ as one of the key agents which causes this effect, has been known as a greenhouse gas. Indeed, as long ago as 1896 it was suggested that changes in atmospheric carbon dioxide levels might be linked with the temperature changes during recent ice ages (1).

Greenhouse gases such as $CO_2$ and water vapour bring about the greenhouse effect through the property that they absorb strongly in the infrared region of the electromagnetic spectrum. Sunlight, the source of energy for the earth-atmosphere system, is principally in the visible region, where the earth's atmosphere is almost transparent. 0f the total amount of incoming radiation 31% **is reflected** by clouds (21%), by particles in the atmosphere (6%) and by the earth's surface (4%), while the other **69% is absorbed** by ozone in the stratosphere (3%), by water vapour, clouds and aerosols in the troposphere ( 18%) and by the earth's surface (48%).

To maintain total energy balance, long-wave radiation, equivalent to the 69% incoming short-wave radiation which was absorbed, **needs to be emitted to space.** The bulk of this energy comes from the earth's surface which emits black-body radiation (at about 300 K this is infrared radiation). Greenhouse gases and clouds can intercept this radiation, and re-emit it in all directions, thus redirecting a significant amount back down to earth. As a result of these processes the earth's surface emits black-body radiation at a higher temperature until the correct amount of energy is emitted to space. This then is the greenhouse effect (2,3).

### Greenhouse Gases

The current debate about the greenhouse effect is centred on a modification of the process discussed above. In the 1930s, the possibility was again raised (4) that human activities might increase the amount of $CO_2$ in the global atmosphere, and thus alter the earth's radiation balance. Since then the notion that increased levels of atmospheric greenhouse gases would cause the earth's surface temperature to rise in maintaining the same infrared emissions to space has become the common perception of what is meant by the term "greenhouse effect".

0bservations of, and research on the sources and sinks of $CO_2$ commenced in the late 1950's in Hawaii and Antarctica(5), and was later followed by research by scientists in Australia(6) and elsewhere. An important consideration in this respect was that following a rapid development in the field of atmospheric chemistry, it was realised that $CO_2$ was not the only infrared absorbing trace constituent which was accumulating in the global atmosphere. 0ther substances now recognized as greenhouse gases are methane ($CH_4$), chlorofluorocarbons (CFCs), nitrous oxide (N120), and tropospheric ozone (03). Present-day observations of these gases(7), as well as measurements of air trapped in Antarctic ice, which allows $CO_2$, $CH_4$ and $N_20$ concentrations to be traced back for hundreds(8) or even tens of thousands of years (in the case of $CH_4$ and $CO_2$)(9) have by now firmly established that the currently observed rising trends are a relatively recent phenomenon (within the last 200 yrs), closely linked to population growth, land clearing and the industrial revolution. Details are provided in Tables 1 and 2, and Figures 1 and 2.

**Table 1. Greenhouse gases**

| greenhouse gas | concentration pre-indust. (1850) | current (1989) | present trend (% per yr) | possible sources of the increases |
|---|---|---|---|---|
| $CO_2$ | 275 ppmv | 350 ppmv | 0.4 | Fossil fuel combustion, deforestation |
| $CH_4$ | 750 ppbv | 1700 ppbv | 0.8 | Rice paddies, ruminants, biomass burning, gas & coal fields, land fills, tundra |
| CFC-11 | nil | 250 pptv | 4 | Industrial & consumer goods |
| CFC-12 | nil | 450 pptv | 4 | Industrial & consumer goods |
| $N_2O$ | 285 ppbv | 310 ppbv | 0.3 | Biomass burning, agriculture, fossil fuel combustion |
| $O_3$(trop.) | 15-20 ppbv | 20-30 ppbv | 0.5[a] | Urban and industrial pollution |

[a] Estimated to be 1% in the Northern Hemisphere, 0% in the Southern Hemisphere

**Table 2. Warming effect of greenhouse gasses**

| greenhouse gas | radiative forcing[a] ($W\ m^{-2}$) | relative[b] radiative forcing per ppmv increase[a] | atmospheric lifetime (yrs) | long-term relative[b] contribution to global warming per molecule emitted | % of the total radiative forcing to date | % of the radiative forcing due to current increases |
|---|---|---|---|---|---|---|
| $CO_2$ | 1.3 | 1 | 60[c] | 1 | 59 | 55 |
| $CH_4$ | 0.6 | 36 | 10 | 6 | 27 | 20 |
| CFC-11 | 0.06 | 14600 | 75 | 18000 | 3 | 6 |
| CFC-12 | 0.12 | 17000 | 110 | 31000 | 6 | 12 |
| $N_2O$ | 0.05 | 140 | 150 | 350 | 3 | 5 |
| $O_3$(trop.) | 0-0.12 | 430 | 0.2 | 1 | 2 | 2 |

[a] From ref. 3, based on the increases in atmospheric concentrations from pre-industrial times to 1985
[b] Relative to $CO_2$
[c] The turn-over time for atmospheric $CO_2$ is about 6 years, but the time needed to permanently remove $CO_2$ to the deep ocean and the long-lived biosphere is about 60 years

The changes from pre-industrial times have been significant, with $CO_2$ increasing by 25%, $CH_4$ by more than 100%, and the CFCs, being totally man-made, not being present in the atmosphere prior to the 1930s. From the data presented it can also be seen that the actual concentrations of different greenhouse gases vary by up to a factor $10^6$ when comparing $CO_2$ and CFCs. If originally $CO_2$ was seen as the only important greenhouse gas which was increasing as a result of human activity. that perception has now changed for two reasons: firstly, the atmospheric concentrations of the other greenhouse gases are rising more rapidly, and secondly, molecule for molecule these other gases are more effective as greenhouse gases (see Table 2).

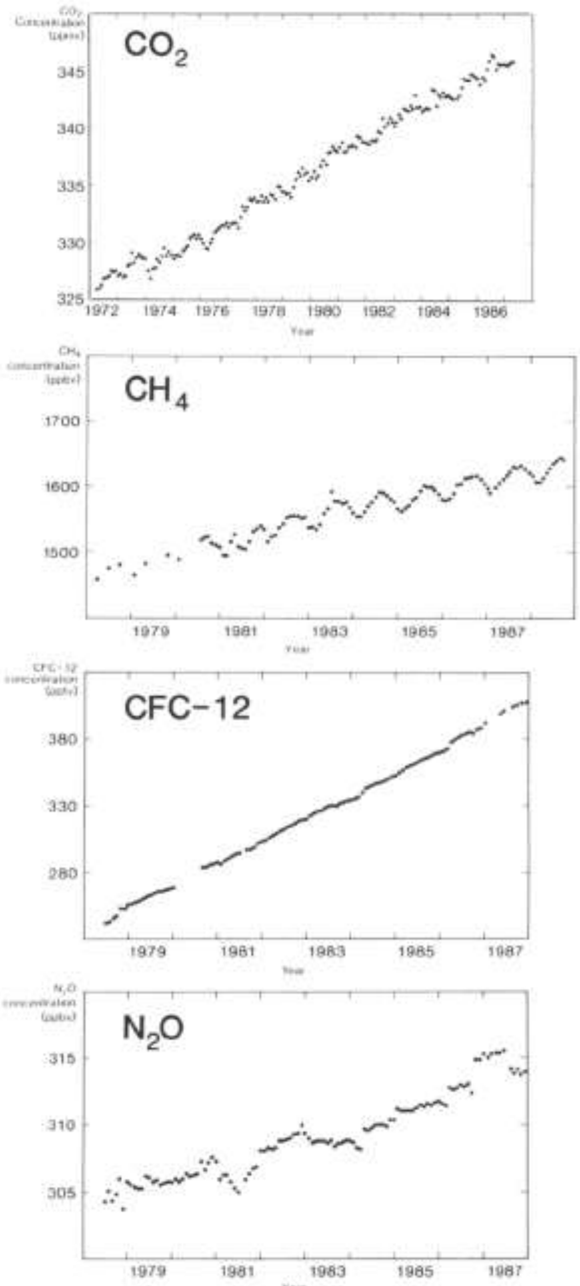


**Figure 1. Atmospheric trace gas concentrations measured over south eastern Australia ($CO_2$) and at the Cape Grim Baseline 0bservatory, north west Tasmania ($CH_4$, CFC- 12 and N20). Note that these Southern Hemisphere observations arc somewhat lower than the global average, while the N20 scale shown here is about 5 ppbv too high.**

Chlorofluorocarbons in particular are very effective because (i) their absorption occurs in a part of the infrared where neither $H_2O$ nor $CO_2$ absorb (the so-called window), (ii) their absorption band strengths are significantly stronger than that of $CO_2$ and (iii) with the small amounts of CFCs in the atmosphere their impact is almost linear with concentration, while $CO_2$ is sufficiently abundant that it is optically thick, and its impact scales logarithmically with concentration(2).

The current and past concentrations of most of the greenhouse gases are now well-known, while research into the sources and sinks of each of these gases is continuing. Although it is currently possible to make rough estimates of the sources, more accurate information is urgently needed in order to enable better estimates of future atmospheric levels to be made, and the impact of possible control strategies to be assessed(7).

A benchmark increase often used in consideration of the greenhouse effect is the doubling of atmospheric $CO_2$ from 300 ppmv to 600 ppmv, an event which is expected by about 2075 AD. If, however, the contributions from anticipated rises in other greenhouse gases are taken into account, an effect **equivalent** to a doubling of $CO_2$ is likely to be reached by 2030 AD( 10,11).

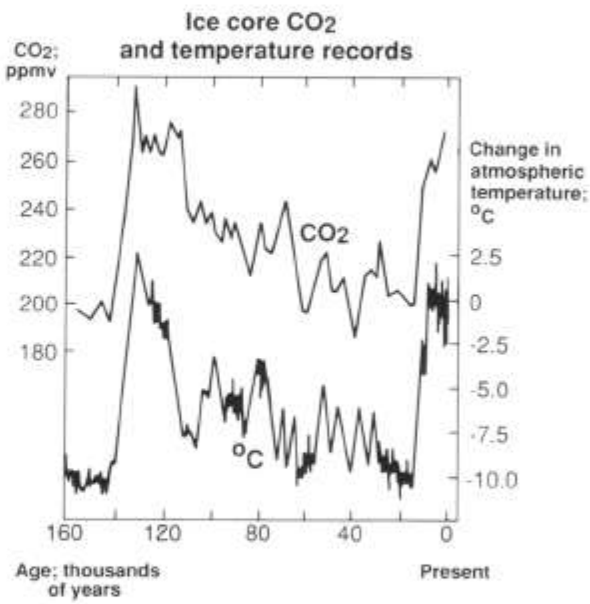


**Figure 2. Analysis of air from the Vostok ice core (Barnola et. al., ref. 9) clearly shows the strong link between atmospheric $CO_2$ and global temperature. It also shows that the CO2 concentration had not been above 290 ppmv for the last 160,000 years. The current value is 350 ppmv, rising at 0.4% per year.**

**Climate modeling predictions**

As explained above, the radiative forcing exerted by the increases in the various greenhouse gases can be calculated, and comes to about 4 W m$^{-}$ for a doubling of $CO_2$. This, in turn is calculated to lead to an equilibrium surface warming of between 1.1 and 4.5 K. These calculations have been carried out using a range of mathematical models describing the global atmosphere, the most sophisticated of which are known as general circulation models (GCMs)(12). The latter predict an equilibrium warming of 4 to 5 K(2).

It is generally agreed that GCMs currently in use need a range of complex changes to increase their accuracy and their regional detail. The representation of soil hydrology, clouds, ocean/atmosphere interaction and a number of other processes needs to be improved. The spacing of the gridpoints around the globe at which key parameters are being calculated is currently too large (500-700 km) to allow detailed descriptions of regional geography and topography to be fed into the model. Nevertheless it is significant that all model calculations to date predict an increase in the global mean temperature(2,10).

Finally, it should be pointed out that the GCM calculations are independent from the research on greenhouse gases. Research on the latter will provide us with estimates of when an effective doubling of $CO_2$ is to be expected. The GCM calculations will tell us what the climatic effect of such a doubling will be. It also needs to be noted that the effective doubling of $CO_2$ is an arbitrary target but not an end point. The increase in greenhouse gas concentrations, and therefore the resulting climatic change, is a continuing process. Lesser changes will occur prior to an effective doubling of $CO_2$, and greater changes after, as long as greenhouse gas concentrations are allowed to continue to increase.

**Climatic change**

Although there are serious limitations to the detail that current GCM calculations can provide, a number of conclusions can be drawn from the results already. The most important general conclusion is that a global warming would not be uniform and would be accompanied by a change in all other parameters which make up global and regional weather and climate. Specifically, the warmer globe will be on average (but not everywhere) more humid and wetter; the warming will be least near the equator and greatest near the edges of the winter ice and snow cover; and as weather systems shift pole-ward, there may be a summer-drying in mid-latitudes(2). Some of this information has recently been used to provide preliminary estimates of regional climate change(13).

**Feedback processes**

Atmospheric scientists are acutely aware that the ultimate outcome of the radiative forcing due to greenhouse gas increases is governed by the way the total climate system will respond. There are many feedback processes which can enhance or ameliorate the primary effect(2).

One such process is due to the extra surface warming leading to more evaporation. As water vapour is a greenhouse gas, this would result in a positive feedback which would increase the surface warming. A second feedback is linked to the observation that a surface warming will lead to reduced snow cover and less sea ice. This would reduce the amount of solar radiation reflected, and thus **increase** the warming at the earth's surface (to a lesser extent than the water vapour feedback, but very significant on a regional basis).

Another important feedback is that due to clouds, which play a major role in the earth's radiation balance, and which reflect a significant amount of the incoming solar radiation. Increased evaporation and increased levels of atmospheric water vapour are likely to lead to increased cloud cover. Low level clouds are known to have a net cooling effect due to their reflection of incoming sunlight, and thus can be expected to decrease any greenhouse warming. But high level cirrus clouds are known to be relatively more efficient in trapping infrared radiation, leading to an increase of the surface warming. At this stage it is not clear which of these two processes would dominate( 14).

One other feedback process involves the oceans: given the heat-capacity of the oceans, the response of tropospheric temperatures will he governed by the response of the ocean surface to the global warming. If the radiative heating were to be sequestered to the deep ocean, the global warming would be significantly delayed.

Yet another feedback involves the role of the stratosphere and stratospheric ozone. The greenhouse warming of the lower atmosphere will be accompanied by a cooling of the stratosphere. This would under normal circumstances enhance the ozone producing processes. But the possible decline of stratospheric ozone due to the presence of CFCs will reduce the amount of incoming solar radiation trapped by the stratosphere, allow this radiation to reach the earth's surface and thus add to any tropospheric warming. The magnitude of this warming would he small compared to the warming due to increases in greenhouse gases in the lower atmosphere.

Finally, it should be noted that there may be a range of other, perhaps minor, feedback processes which at this stage are too poorly understood to be included in climate change considerations. 0ne such process concerns the possibility of the marine production of dimethyl sulfide (DMS) (known to be involved in cloud condensation) being perturbed by climatic change. More DMS might lead to more cloud, and hence act as a negative feedback(15). Feedbacks involving changes in the vegetation cover, and thus the surface reflectivity, roughness and evaporative cooling will almost certainly be of local significance, but may he less important on a global scale, especially in the Southern Hemisphere which is dominated by the oceans.

**Evidence for change**

Model calculations show that the increases of greenhouse gases to date have already committed the planet to an equilibrium surface warming of between 0.6 and 2.4 K(2). A large uncertainty is how much the actual warming will lag behind. The available record of the global average temperature suggests that there has been a warming of about 0.5 K over the last 100 years(l5), but there is no certain way as yet of establishing which of a number of possible causes is responsible for this rise, especially when one looks at the variation in the trend from decade to decade (Figure 3). It is easy to see too, that similar analyses of regional trends would have to be treated with even more caution.

While it is possible that climatic change is already in train. there will be an extended period where all the information on change in temperature, rainfall and extreme events will have to be assessed in the light of natural variability of weather and climate. In the face of this it should be remembered that the evidence of changes in the composition of the atmosphere is firm, irrefutable, and clearly linked to consequent climatic change. It is only a matter of time before it will become evident in the climatic measurements.

**Secondary impacts**

A changing composition of the global atmosphere has a number of secondary impacts which need to be pointed out. Firstly, any global warming will result in some sea-level rise. This is due to two processes. 0ne is the thermal expansion of the surface layers of the oceans which will warm along with the troposphere, the second is the increased melting of temperate ice (glaciers). For a doubling of $CO_2$ it is estimated these effects would raise the global sea level by 20 to 50 cm(17). How much this sea-level rise would lag behind the surface-temperature rise is uncertain. Melting of the Antarctic ice cap is definitely not a risk for hundreds of years(18).

Perhaps less appreciated, but certainly important, is another consequence of atmospheric change: the fact that higher levels of atmospheric $CO_2$ will stimulate plant growth. Carbon dioxide is a known 'fertilizer' which in addition discriminates between different types of plants(19), and this may add a very different aspect to the considerations of the impact of climatic change.

A further outcome of a changing atmosphere and global climate change which almost by definition is impossible to predict is the element of surprise. The mechanisms which govern the sources and the sinks of the atmospheric trace gases such as $CO_2$ and $CH_4$, and the mechanisms of ocean/atmosphere dynamics which determine the global climate are sufficiently complex that scientists cannot rule out the possibility of unforeseen sudden changes. Examples of such events are provided by the recent discovery of stratospheric ozone loss over Antarctica(20, 21) and the observation from geological evidence that the global ocean circulation has in the past shown sudden and dramatic changes (22).

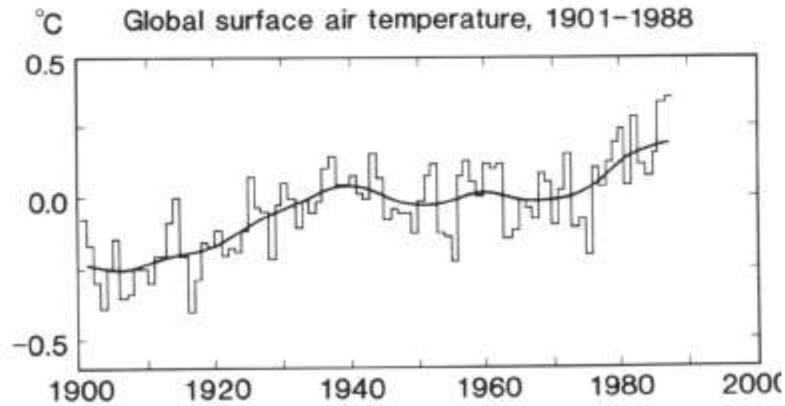


**Figure 3. The global temperature record relative to the 1950-1979 average from Jones et. al., (16) with 1987 and 1988 added.**

**Misconceptions**

A number of misconceptions need to be laid to rest. These are:

- The greenhouse effect is only a theory.
- Incorrect. In its most fundamental form the greenhouse effect is a well established physical process, while the evidence of recent increases in the concentration of so-called greenhouse gases in the atmosphere is incontrovertible.
- The greenhouse effect is based on observed rising temperature and/or sea-level trends. **Incorrect.** The scientific debate is firmly based on the observed changes in atmospheric composition. The observed temperature and sea-level trend, although consistent with the chemical changes, only serve as circumstantial evidence which may or may not he linked to the greenhouse effect.
- The additional $CO_2$ would not trap any extra outgoing infrared radiation, as all of it is already being trapped.
- **Incorrect.** Although the absorption hands of $CO_2$ are almost saturated, increases will still contribute to the greenhouse effect. It is true that $CH_4$ and CFCs are more effective because they absorb in an otherwise clear part of the infrared spectrum - all these properties have been taken into account.
- Cloud feedback might lead to a cooling rather than a warming.
- **Incorrect.** As stated earlier, cloud feedback is certainly one of the aspects ill-described by current GCMs. But as it is a feedback process, one would still need a warming to even start this feedback, and thus in the first instance this process could slow down, but not prevent, far less reversal, a global warming.
- If weather prediction cannot get the forecast reliably beyond a few days, climate prediction would have to be a futile exercise.
- Incorrect. Although both types of effort have the physical description of the atmosphere in common, they deal with very different scientific problems. In weather prediction an instantaneous description of the atmosphere and all its properties is required. Climate modelling, by contrast, deals with statistical averages which are calculated quite differently. We can describe these average properties without necessarily having to describe in detail each individual weather event.

**Concluding remarks**

Considerations of the greenhouse effect have by now moved from the realms of academic curiosity to a position of conviction that global warming is a highly probable expectation for the future. While there are a number of loose ends to be tied up, there is now amongst atmospheric scientists a realisation that the problem has implications and interactions far beyond their restricted domain. The time lag between atmospheric change and climatic change, and between climatic change and sea-level rise, is such that what we do or do not do today has significant repercussions for generations to come. If one accepts this premise, then the need to research what those changes might be, and the need to assess how greenhouse gas emissions might be controlled becomes obvious.

The task of carrying out research aimed at providing more detailed information concerning potential climate change for the Australian region is currently being undertaken by CSIR0 scientists in collaboration with scientists in the Bureau of Meteorology, and in close collaboration with the various Australian States and some colleagues in the Universities.

The task of planning reductions in the various greenhouse gases has only just commenced. CFCs are to he controlled soon, mostly because of their stratospheric ozone depleting properties. Methane and N20 may be difficult to control. Carbon dioxide, being linked so closely to fossil fuel use is amenable to reductions, but many aspects need to be considered. One such aspect is the amount of $CO_2$ emitted for a given fuel source (Table 3). Fuel switching, energy conservation, and a move towards renewable energy will probably all have to be explored to offer any prospect of significant $CO_2$ emission reductions. It is unlikely that there exists a single solution to $CO_2$ emission reduction. Instead there will be a need for a 'package' of changes. Determining what this package should consist of, and what is appropriate for one state or the other, or one country or the other, is a matter for urgent attention. 0bviously any changes in the energy area will have economic consequences, but so too will uncontrolled climatic change and sea level rise.

Tree planting has recently been suggested as a method of countering the greenhouse effect. However, the sheer magnitude of the task at hand needs to be kept in mind. Ten billion trees, occupying 10 million ha, planted today, would take up enough $CO_2$ to reduce the world's annual $CO_2$ emissions from burning fossil fuels by about I%(23). Thus it should he clear that, while planting trees will be good for many other reasons (to stop land degradation, maintain ecosystems, etc.), as a means of countering the build-up of atmospheric $CO_2$ it can have a significant effect, but only if carried out on a large enough scale.

That the atmospheric changes have already committed the earth to a global warming, and that it will he well-nigh impossible to stop any future change should be clear by now. We are left with the task of planning for the change and limiting the ultimate magnitude of the change. How exactly we will tackle these issues remains to be seen.

**Table 3. Carbon emissions from fossil fuels.'**

| Fuel | Energy Content (MJ/kg) | Carbon con tent (%) | Carbon[b] emission (kg/GJ) | $CO_2$ emission (ratio to natural gas) | Australian $CO_2$ emission by source (%) |
|---|---|---|---|---|---|
| Natural gas | 50.0 | 75 | 15.0 | I | 1I |
| Oil | 42.0 | 84 | 20.0 | 1.3 | 35 |
| Black coal | 23.0 | 65 | 28.3 | 1.9 | 40 |
| Brown coal | 7.7 | 24 | 31.2 | 2.1 | 14 |

[a] Adapted from figures provided by the Australian Institute of Petroleum
[b] $CO_2$ emissions are generally measured by their weight as carbon
[c] Data for 1987. Total Australian $CO_2$ emissions are about 1.5% of the global emission of about 5 Gt (measured as carbon).

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