ATMOSPHERIC SCIENCE: CO_2 Is Not the Only Gas
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sediment that moves seaward within the subglacial conveyer belt is deposited in wedges of sedimentary material known as grounding-line wedges. Several such wedges have been identified and mapped in broad valleys on the Antarctic continental shelf with detailed images of the sea floor and high-resolution seismic data (see the second figure, top panel) (*10*). Ice streams excavated these valleys when the ice sheet advanced onto these continental shelves. The wedges were formed at locations where the grounding lines stabilized for a while during retreat.

Anandakrishnan *et al*. now provide the first documentation of a grounding-line wedge beneath a modern ice stream, the Whillans Ice Stream. The wedge is likely to have formed during a pause in the overall retreat of the ice sheet. Alley *et al*. describe the wedge in relation to the current ice stream configuration and behavior, and model the response of the ice stream to sea-level rise. The combined results show that the modern grounding line is situated over the crest of the wedge and that the ice thickness increases appreciably upstream of the grounding line (see the second figure, bottom panel). The model results indicate that the ice sheet is thick enough at that point to remain grounded, even with a sea-level rise of several meters. At the current rate of sea-level rise, it would take several thousand years to float the ice sheet off the bed.

The two reports discuss a single ice stream, but relict grounding-zone wedges are common features on the continental shelf, including the Ross Sea shelf (*3*, *10*). In addition, all ice streams of the Siple Coast have an anomalous elevation and stop at the grounding line (*11*). Thus, this mechanism for stabilization of the grounding line is likely to be widespread.

The ice sheets have changed in the past and are changing today. Yet Anandakrishnan *et al*. and Alley *et al*. demonstrate that grounding-line deposition serves to stabilize ice streams, suggesting a decreased role for sea level in explaining these changes. Future research should focus on other ice streams, especially those that currently display signs of instability, to get at the causes of this instability.

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ATMOSPHERIC SCIENCE

CO_2 Is Not the Only Gas

About 40% of the heat trapped by anthropogenic greenhouse gases is due to gases other than carbon dioxide, primarily methane.

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In 1971, one of the first international assessments of the role of humankind in climate change concluded that "because methane has no direct effects on climate…it is considered of no importance" [(*1*), p. 242]. How times change. By the mid-1980s (*2*), methane and a host of other non-CO_2 gases were together recognized to be contributing to climate change by an amount comparable to that of CO_2.

An increase in the concentration of a greenhouse gas causes a change in Earth's energy balance. This change, or radiative forcing, is a simple indicator of the climate change impact. The largest single contributor to radiative forcing is CO_2, with an estimated value of 1.66 W m^{-2} since preindustrial times—enough, on its own, to eventually raise global average surface temperatures by about 1.4°C. The non-CO_2 greenhouse gases contribute an additional 1 W m^{-2} (*3*, *4*).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change recognizes the importance of non-CO_2 greenhouse gases. Emission targets for signatories to the Convention are given in terms of CO_2-equivalent emissions; the signatories can choose to control emissions of several gases—CO_2, methane, nitrous oxide, sulfur hexafluoride (SF_6), the hydrofluorocarbons, and the perfluorocarbons—to meet their targets. There remain issues concerning what emissions are included and excluded in the Kyoto Protocol and the method by which emissions of different gases are placed on a common "carbon-equivalent" scale (*5*). Nevertheless, it is clear that controlling non-CO_2 greenhouse gas emissions can play a very important role in attempts to limit future climate change (*6*, *7*).

The contribution of a given non-CO_2 greenhouse gas to radiative forcing depends on its ability to absorb infrared radiation emitted by Earth's surface and atmosphere. This ability is determined by fundamental spectroscopic properties of the molecule; to be really effective, the molecule must absorb at wavelengths where the atmosphere is not already strongly absorbing. The contribution also depends on the change in the atmospheric concentration of the gas; this change is determined by the size of its emissions and by its atmospheric lifetime. The lifetimes of non-CO_2 greenhouse gases vary from less than a year to thousands of years.

On a per-molecule basis, many non-CO_2 greenhouse gases are far more effective than CO_2 at contributing to radiative forcing. For example, the absorption strength of heavily fluorinated molecules can be 10,000 times that of CO_2. CO_2 has a dominant radiative forcing only because the increase in its atmospheric concentration has been so large—around 100 parts per million (ppm) since preindustrial times. Methane, by contrast, has increased by only 1 ppm; other important non-CO_2 greenhouse gases have increased by parts per billion or even parts per trillion (ppt), yet still contribute appreciably to radiative forcing (*3*, *8*–*10*).

Determining the past and present growth of non-CO_2 greenhouse gases in the atmosphere is not trivial. A global network of surface measurements has only become available since the late 1970s (*8*–*10*). Unraveling earlier histories requires measurements of "firn air" pumped out of deep snow in polar regions, or analysis of tiny bubbles trapped in ice cores. Glacial records of the more abundant gases,

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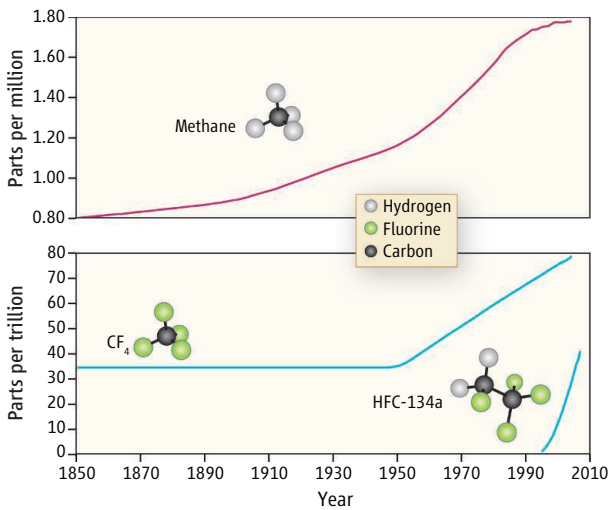
CO_2 and methane, are well established, but more complete histories of a wider range of greenhouse gases have only recently become available (*11*–*14*). Some, such as methane, have natural backgrounds due to emissions from, for example, wetlands, soils, and the ocean; methane concentrations have increased dramatically in the 20th century as a result of human activities, including fossil fuel use and agriculture. Other greenhouse gases have been found to be entirely human-made.

Methane poses the biggest challenge to current understanding. Its concentration has increased by a factor of 2.5 since 1800, giving a radiative forcing of almost 0.5 W m^{-2} (*3*, *9*, *10*). Complications arise because methane is chemically reactive, leading to a number of additional effects. For example, rising methane concentrations can cause increases in ozone and stratospheric water vapor concentrations. A recent emissions-based view of methane's radiative forcing that included these additional effects estimated that methane's true contribution was nearer 0.9 W m^{-2} (*15*), equivalent to more than half the radiative forcing caused by CO_2.



Time histories for the abundances of three non-CO_2 greenhouse gases. Data for methane are from (*6*, *20*) and for the hydrofluorocarbon HFC-134a from (*9*, *10*). The curve for CF_4 is based on a model fit to firn air (*13*) and ice core (*19*) measurements.

The steady rise in methane levels since the mid-19th century has slowed markedly in the past decade (see the figure). There are many possible explanations for this; for example, methane emissions may no longer be increasing, the concentration of oxidizing radicals may have increased because of other emissions, or climate change itself may have hastened methane destruction (via increased temperatures or a greater abundance of oxidizing radicals) (*8*, *9*, *16*). Until this slowdown is properly understood, confidence in projections of future methane changes remains tentative. Questions also persist about the natural emissions of methane; a recent study suggests that plants may constitute a much larger source than hitherto believed (*17*).

Two other major classes of non-CO_2 greenhouse gases are the chlorofluorocarbons and hydrofluorocarbons. Chlorofluorocarbons were widely used in, for example, refrigeration and air conditioning, but have largely been phased out as a result of the Montreal Protocol on Substances that Deplete the Ozone Layer. The concentrations of the most abundant chlorofluorocarbons are nevertheless still high and declining only slowly because of their long lifetimes (*8*). The hydrofluorocarbons have replaced many of the uses of the chlorofluorocarbons; they are benign to stratospheric ozone but are strong greenhouse gases. The concentration of the most abundant of these, HFC-134a, more than doubled every year in the mid-1990s and is still increasing by more than 10% per year; it is now at 40 ppt (see the figure) (*9*, *10*). Its radiative forcing is currently small (about 0.005 W m^{-2}), but if its growth rate is sustained, it will become a significant contributor.

Fully fluorinated gases, including SF_6 and perfluorocarbons such as CF_4, form another distinct group of greenhouse gases. Their sources include aluminum and magnesium smelting, high-voltage dielectrics, and computer chip production. Some, such as SF_5CF_3 (*18*), have origins that remain obscure. These gases have very long lifetimes, in some cases more than 10,000 years (*8*). Once emitted, these "super–greenhouse gases" impart an essentially permanent, although currently very small, change to the atmosphere's ability to absorb infrared radiation. Nearly all are human-made, but CF_4 has a small natural source. It took many millennia for the atmosphere to accumulate 35 ppt of CF_4, and less than 50 years of industrial activity to double it (see the figure) (*8*, *13*, *19*).

It is crucial that researchers continue to monitor non-CO_2 greenhouse gas concentrations and investigate their sources, lifetimes, and spectroscopic properties. These data and insights will enable industry and policymakers to make informed decisions on the desirability and impact of allowing or curbing emissions. CO_2 undoubtedly remains the single most important contributor to greenhouse gas radiative forcing, but the non-CO_2 greenhouse gases are important both collectively and individually. It seems unlikely that we have overlooked a major contributor to radiative forcing, but this was probably what was thought in the early 1970s.

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