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Greenhouse Effect of Chlorofluorocarbons and Other Trace Gases

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We compare the radiative (greenhouse) forcing of the climate system due to changes of atmospheric chlorofluorocarbons and other trace gases. We find that CFCs, defined to include chlorofluorocarbons, chlorocarbons, and fluorocarbons, now provide about one-quarter of current annual increases in anthropogenic greenhouse climate forcing. If the growth rates of CFC production in the early 1970s had continued to the present, current annual growth of climate forcing due to CFCs would exceed that due to CO₂.

1. INTRODUCTION

It has been realized for more than a century [Tyndall, 1861] that if it were not for the presence of infrared-absorbing (greenhouse) gases in the Earth's atmosphere, mainly H₂O and CO₂, the Earth's surface would be several tens of degrees Celsius colder than it is. The possibility of global climate change due to anthropogenic and natural variations of CO₂ has been debated increasingly during the past century. Ramanathan [1975] fundamentally altered the greenhouse issue when he showed that CFCs, entirely man-made, also cause a significant greenhouse effect. Wang et al. [1976] argued that a broad range of other trace gases, including CH₄ and N₂O, are also contributing to greenhouse changes. Lacis et al. [1981] showed that the combined measured changes of CFCs, CH₄ and N₂O in the period 1970–1980 caused a greenhouse climate forcing in the range 50–100% of that for the CO₂ change in the same period. Ramanathan et al. [1985] argued that during the next several decades the net greenhouse forcing for projected changes of trace gases other than CO₂ would exceed the greenhouse forcing due to projected CO₂ growth.

We calculate the contribution of CFCs to the increase in greenhouse climate forcing over the decade of the 1980s, comparing it with the greenhouse forcing by CO₂ and other trace gases. The result shows that CFCs have grown to be a large fraction of current increases in greenhouse climate forcing. But this comparison also points out the importance of the sharp reduction in the growth of CFC production that occurred in 1974, illustrating the great impact that a combination of an environmentally aroused public, government action, and worldwide economics can have on the greenhouse forcing of climate. Of course this break in production trends occurred mainly because of concern that CFCs may destroy stratospheric ozone, not because of the greenhouse issue.

2. CALCULATIONS FOR CFCs

Estimated growth rates and abundances of CFCs are listed in Table 1, based mainly on the observed trends reported by the International Ozone Trends Panel [Watson et al. 1988] and by Ramanathan et al. [1985]. We calculate the climate forcing, ΔT₀, due to the changes of each of the gases. Here, ΔT₀ is the surface temperature change at equilibrium (T→∞) with no climate feedbacks included (i.e., the surface albedo, absolute water vapor amount, atmospheric lapse rate, and all other parameters are held fixed), computed with a one-dimensional radiative-convective climate model [Lacis et al., 1981]. Spectral intervals for the thermal infrared region are of the width 50 cm⁻¹. Overlapping absorption by different gases within each spectral interval is approximated as uncorrelated, i.e., the net transmission is based on the sum of all products of individual (k-distribution) transmissions. Absorption by CFCs is assumed to be optically thin, so that CFC absorption can be combined linearly with the k-distribution of the other atmospheric gases and cloud particles.

The full climate response at equilibrium is 2–4 times larger than ΔT₀, if global climate sensitivity for doubled CO₂ is in the range 2.5°C to 5°C, as estimated with current global climate models (GCMs). The time required to approach the equilibrium response is estimated to be at least several decades because of the large thermal inertia of the global ocean [Dickinson, 1986; Wigley and Schlesinger, 1985; Hansen et al., 1985].

Uncertainties in the decadal changes of trace gas abundances are typically less than or of the order of 10% for the major species. Additional error in the net CFC climate forcing is due to uncertainties in infrared absorption data. Band strength measurements for the two principal CFC greenhouse gases, CFC-11 and CFC-12, appear to be reproducible within about 10%. But band strengths of other CFCs, most importantly CFC-22 and CFC-113, are more uncertain. Recent measurements (D. Fisher, private communication, 1989) show band strengths for CFC-22 that are a factor of 2.5 larger than the unpublished values used by Ramanathan et al. [1985] and for CFC-113 35% smaller than the band strengths of Rogers and Stephens [1988]. The uncertainty in the total CFC climate forcing due to inaccuracies of the absorption coefficient data thus is at least of the order of 10%. Because the uncertainties for individual gases are so large, we have included in Table 1 the band strengths which we used for each gas. This allows our results to be scaled as more accurate absorption data become available, because the absorption bands are generally weak and thus in a linear regime.

Figure 1 summarizes the results for the radiative forcing of the climate system due to increases of atmospheric CFCs in the 1980s. CFC-12 and CFC-11 account for two-thirds of the CFC climate forcing added in the 1980s. However, CFC-113 and CFC-22, which are growing more rapidly (Table 1), are approaching the magnitude of the CFC-12 and CFC-11 climate forcings. The climate forcings by the other CFCs are individually an order of magnitude smaller (Table 1), but their combined effect is not negligible (Figure 1).
TABLE 1. Global Mean Radiative Forcing of the Climate System ($\Delta T_o$) due to Estimated Changes of Several Trace Gases During the 1980's. *

<table>
<thead>
<tr>
<th>Trace Gas</th>
<th>Growth Rate, %/yr</th>
<th>Estimated Abundance, pptv</th>
<th>Band Strength, cm$^2$ atm$^{-1}$ stp</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CCl_2F_2$ (CFC-12)</td>
<td>0.0143</td>
<td>4.6</td>
<td>297</td>
<td>468</td>
</tr>
<tr>
<td>$CCl_3F$ (CFC-11)</td>
<td>0.0067</td>
<td>4.7</td>
<td>173</td>
<td>275</td>
</tr>
<tr>
<td>$CClFCClF_2$ (CFC-113)</td>
<td>0.0057</td>
<td>13.3</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>$CHClF_2$ (CFC-22)</td>
<td>0.0034</td>
<td>8.2</td>
<td>50</td>
<td>110</td>
</tr>
<tr>
<td>$CF_4$ (CFC-14)</td>
<td>0.0009</td>
<td>2.5</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>$CCl_4$</td>
<td>0.0007</td>
<td>1.5</td>
<td>100</td>
<td>115</td>
</tr>
<tr>
<td>$CCl_2FCClF_2$ (CFC-114)</td>
<td>0.0004</td>
<td>5.8</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>$CF_3Cl$ (CFC-13)</td>
<td>0.0004</td>
<td>4.7</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>$CF_2CPF_2Cl$ (CFC-115)</td>
<td>0.0003</td>
<td>9.0</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>$CH_4$</td>
<td>0.0002</td>
<td>4.4</td>
<td>110</td>
<td>170</td>
</tr>
<tr>
<td>$CH_2Cl_2$</td>
<td>0.0002</td>
<td>3.9</td>
<td>30</td>
<td>44</td>
</tr>
<tr>
<td>$CH_2ClCH_2Cl$</td>
<td>0.0002</td>
<td>2.4</td>
<td>30</td>
<td>38</td>
</tr>
<tr>
<td>$CF_3Br$</td>
<td>0.0002</td>
<td>18.2</td>
<td>0.6</td>
<td>3.2</td>
</tr>
<tr>
<td>$CCl_2F_3$ (CFC-116)</td>
<td>0.0001</td>
<td>3.2</td>
<td>4</td>
<td>5.5</td>
</tr>
<tr>
<td>$CHCl_3$</td>
<td>0.0001</td>
<td>2.2</td>
<td>10</td>
<td>12.5</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* CFC growth rates are based on (a) data of the International Ozone Trends Panel as summarized by Watson et al. [1988] and (b) on Ramanathan et al. [1985] estimates. Abundances are in parts per trillion by volume. Absorption data used to compute $\Delta T_o$ were obtained from the following sources or assumptions indicated under the Remarks column: S [Smith et al., 1985], R [Rogers and Stephens, 1988], F (D. Fisher, private communication, 1989), P [Pugh and Rao, 1976], X (assumed to absorb like CFC-113), Y (scaled from Hummel and Reck [1981]), Z (assumed to absorb like CH$_3$CCl$_3$).

...
TABLE 2. Trace Gas Abundances Used for Calculations Illustrated in Figures 2, 3, and 4, and the Computed Global Radiative Forcings ($\Delta T_o$ in °C) for the Four Time Intervals Between the Five Indicated Dates.*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T_o$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ (ppm)</td>
<td>285</td>
<td>0.180</td>
<td>316.7</td>
<td>0.044</td>
<td>324.8</td>
</tr>
<tr>
<td>CH$_4$ (ppb)</td>
<td>800</td>
<td>0.070</td>
<td>1300</td>
<td>0.016</td>
<td>1400</td>
</tr>
<tr>
<td>N$_2$O (ppb)</td>
<td>285</td>
<td>0.005</td>
<td>289</td>
<td>0.007</td>
<td>295</td>
</tr>
<tr>
<td>CCl$_2$F$_2$</td>
<td>0</td>
<td>0.003</td>
<td>33</td>
<td>0.007</td>
<td>121</td>
</tr>
<tr>
<td>CCl$_3$F</td>
<td>0</td>
<td>0.011</td>
<td>11</td>
<td>0.003</td>
<td>60</td>
</tr>
<tr>
<td>Other CFCs</td>
<td>0</td>
<td>0.001</td>
<td>(mixed)</td>
<td>0.002</td>
<td>(mixed)</td>
</tr>
<tr>
<td>Total</td>
<td>0.260</td>
<td>0.079</td>
<td>0.121</td>
<td>0.139</td>
<td></td>
</tr>
</tbody>
</table>

*Abundances of other CFCs are given in Table 1 for 1970 and 1980.

forcing for the period 1850–1990 has been added during the last 30 years.

The increase of CFC forcing in the 1980s represents about one-quarter of the total growth in radiative forcing by trace gases (Figure 3). Indeed the CFC contribution to growth of the greenhouse forcing now clearly exceeds that of CH$_4$ and N$_2$O combined. The CFC component of the greenhouse forcing has continued to increase, despite slowdowns for CFC–11 and CFC–12, because of rapid growth of other CFCs, as shown in Figure 3.

We note that there are at least two other changing greenhouse gases: ozone and stratospheric water vapor. Increases of tropospheric ozone and decreases of stratospheric ozone would both cause surface warming [Lacis et al., 1989]. However, the meager available observational data suggest that the dominant O$_3$ change, for greenhouse purposes, is a decrease in the upper troposphere and lower stratosphere [Lacis et al., 1989], especially at high latitudes in both hemispheres. Such an O$_3$ change would cause a negative radiative forcing (cooling) which would partially offset the warming by other greenhouse gases, at these latitudes.

Water vapor is the dominant greenhouse gas in the Earth’s atmosphere. Change of tropospheric water vapor is considered to be a climate feedback, rather than a climate forcing, because the water vapor amount is determined by the climate, especially by the temperature. But stratospheric water vapor may be increasing as a result of the increasing abundance of atmospheric methane [Ehhalt, 1986]. This could cause a significant greenhouse warming; for example, a doubling of stratospheric water vapor from 3 to 6 ppm at altitudes between

**Fig. 2.** Global mean radiative forcing of the climate system due to estimated decadal changes of several trace gases. See Figure 1 for definition of $\Delta T_o$. 

**DECADAL INCREMENTS OF GREENHOUSE FORCING**

**DECADES**

1850-1960 (per decade) 1960's 1970's 1980's

CO$_2$ 8.2 ppm 12.8 ppm 16.6 ppm
N$_2$O 2.8 ppm
CH$_4$
would now exceed that for CO$_2$ (Figure 4b). Of course, some slowdown in CFC growth probably would have occurred due to economic forces, even without environmental concerns. But it appears that CFC greenhouse forcing would now be much greater than it is, at least comparable in magnitude to that for CO$_2$, if there had been no public concern about possible adverse effects of continued CFC growth.

5. DISCUSSION

These results illustrate that CFCs are a large fraction, about one quarter, of current additions to greenhouse climate forcing. Thus, if the rate of release of CFCs to the atmosphere can be reduced, there is the potential for a major reduction in the rate of increase of the greenhouse effect. It should be noted that many of the proposed halocarbon substitutes for CFCs contain only fluorine, and, while posing no threat to the ozone layer, they may still contribute to an increased greenhouse effect. Assessment of the greenhouse impact of possible constraints on CFC emissions requires better data for the infrared absorption coefficients of various CFCs. These data are needed especially for compounds, such as CFC–22, which may be substituted for other CFCs.

If the growth of CFC production in the early 1970s had continued to date, the CFCs would now cause a much larger greenhouse effect, greater than that for CO$_2$. This illustrates that growth trends of greenhouse forcing are not inevitable; in this example decisions of consumers and legislators had a major impact on global climate forcing. This example also shows that, even if emissions are not eliminated, there is eventually a great difference between the greenhouse forcing with continued rapid growth of emissions and the greenhouse forcing with more constant emission rates. Of course, this conclusion applies for CO$_2$ emissions as well as CFCs. Trace gas scenarios that reach a greenhouse forcing equivalent to a doubling of atmospheric CO$_2$ in about 40 years, such as those of Ramanathan et al. [1985] and scenario A of Hansen et al. [1988], are based on an assumption of continued exponential growth. If rapid growth of emissions can be avoided, the
actual climate forcing may be much less than in these "business as usual" scenarios.

Finally, we emphasize that full analysis of greenhouse climate forcing requires better measurements of other atmospheric constituents. The biggest uncertainties appear to arise from the lack of adequate monitoring of ozone in the upper troposphere and lower stratosphere, and of water vapor in the stratosphere.

REFERENCES


