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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 CO_2.

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 H_2O and CO_2, 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 CO_2 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 CH_4 and N_2O, are also contributing to greenhouse changes. *Lacis et al.* [1981] showed that the combined measured changes of CFCs, CH_4, and N_2O in the period 1970–1980 caused a greenhouse climate forcing in the range 50–100% of that for the CO_2 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 CO_2 would exceed the greenhouse forcing due to projected CO_2 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 CO_2 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, ΔT_o, due to the changes of each of the gases. Here, ΔT_o is the surface temperature change at equilibrium ($T \rightarrow \infty$) 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 ΔT_o if global climate sensitivity for doubled CO_2 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 (ΔT_o) due to Estimated Changes of Several Trace Gases During the 1980's.[*]

	ΔT_o, °C	Growth Rate, %/yr	Estimated Abundance, pptv 1980	Estimated Abundance, pptv 1990	Band Strength, cm^{-2} atm^{-1} stp	Remarks
CCl_2F_2 (CFC-12)	0.0143	4.6	297	468	3642	a, S
CCl_3F (CFC-11)	0.0067	4.7	173	275	2782	a, S
CCl_2FCClF_2 (CFC-113)	0.0057	13.3	20	70	5315	a, R
$CHClF_2$ (CFC-22)	0.0034	8.2	50	110	2627	a, F
CF_4 (CFC-14)	0.0009	2.5	70	90	4640	b, S
CCl_4	0.0007	1.5	100	115	1437	a, P
$CClF_2CClF_2$ (CFC-114)	0.0004	5.8	4	7	6570	a, R
CF_3Cl (CFC-13)	0.0004	4.7	7	11	4452	b, S
CF_3CF_2Cl (CFC-115)	0.0003	9.0	2	5		a, X
CH_3CCl_3	0.0002	4.4	110	170		a, Y
CH_2Cl_2	0.0002	3.9	30	44	583	b, P
CH_2ClCH_2Cl	0.0002	2.4	30	38		b, Z
CF_3Br	0.0002	18.2	0.6	3.2	4144	a, P
C_2F_6 (CFC-116)	0.0001	3.2	4	5.5	4861	b, P
$CHCl_3$	0.0001	2.2	10	12.5	1149	b, P
Sum	**0.0338**					

[*]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 ΔT_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_3CCl_3).

The results tabulated in Table 1 and summarized in Figure 1 are useful in estimating the impact upon future greenhouse forcings of possible controls on CFC emissions. The Montreal Protocol restricts future growth in production of CFCs 11, 12, 113, 114, and 115, but as currently ratified it does not restrict growth in CFC-22 production. Given current growth rates

Fig. 1. Global mean radiative forcing of the climate system due to estimated changes of CFCs in the 1980s; ΔT_o is the equilibrium greenhouse warming computed with no climate feedbacks. The total response of the climate system to this forcing involves many feedback processes, some of which are poorly understood; current global climate models suggest that the global temperature response at equilibrium is about 2–4 times larger than the global radiative forcing.

(Table 1), it seems likely that CFC-22 will become a substantial greenhouse gas in the future, especially if it becomes a major substitute for CFC-12 and CFC-11.

3. COMPARISON OF CFC AND OTHER GREENHOUSE FORCINGS

We compare the radiative forcing due to CFCs and other greenhouse gases, for the past few decades and the preceding century. Estimated abundances for the gases are given in Table 2. The estimates for recent decades are based mainly on atmospheric measurements, while the estimates of CO_2 and CH_4 for 1850 are based on measurements of air bubbles trapped in polar ice as summarized by *Oeschger and Siegenthaler* [1988], *Cicerone and Oremland* [1988], and *Ehhalt* [1988]. The CFC history was estimated from production figures for reporting companies [*Chemical Manufacturers Association*, 1988] and the assumption of simple lifetimes (60 and 120 years for CFC-11 and CFC-12, respectively) with no lag between production and release. The calculated CFC atmospheric amounts are in good agreement with observations over the past several years (perhaps accidentally because failure to include production by nonreporting companies approximately compensates for the time lag between CFC production and release into the atmosphere).

Figure 2 compares the decadal increments of climate forcing due to measured greenhouse gas changes since 1850. CO_2 is the dominant greenhouse gas (62%) for the full period 1850–1990, with CH_4 next at 21%, CFCs at 13%, and N_2O 4%. The rate of increase of greenhouse forcing has accelerated in recent decades. Indeed, more than 50% of the total added
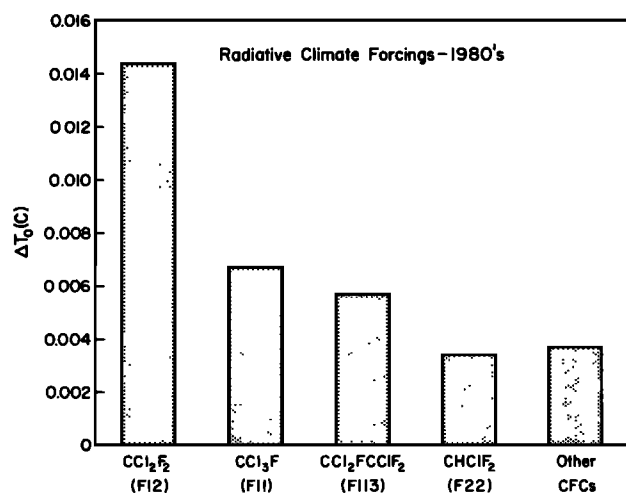
TABLE 2. Trace Gas Abundances Used for Calculations Illustrated in Figures 2, 3, and 4, and the Computed Global Radiative Forcings (ΔT_0 in °C) for the Four Time Intervals Between the Five Indicated Dates.[*]

	1850	ΔT_0	1960	ΔT_0	1970	ΔT_0	1980	ΔT_0	1990
CO_2 (ppm)	285	0.180	316.7	0.044	324.8	0.067	337.6	0.079	353.2
CH_4 (ppb)	800	0.070	1300	0.016	1400	0.018	1555	0.017	1725
N_2O (ppb)	285	0.005	289	0.007	295	0.008	302	0.009	310
CCl_2F_2	0	0.003	33	0.007	121	0.015	297	0.014	468
CCl_3F	0	0.011	11	0.003	60	0.007	173	0.007	275
Other CFCs	0	0.001	(mixed)	0.002	(mixed)	0.006	(mixed)	0.013	(mixed)
Total		0.260		0.079		0.121		0.139	

[*]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_2O 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
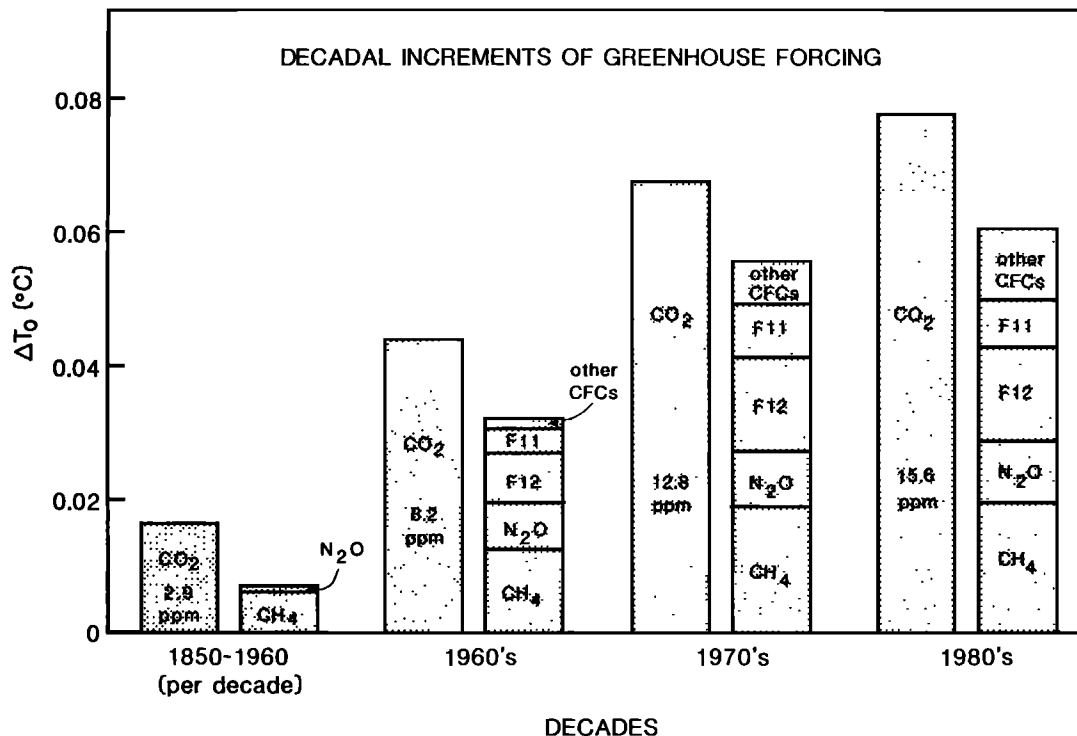

Fig. 2. Global mean radiative forcing of the climate system due to estimated decadal changes of several trace gases. See Figure 1 for definition of ΔT_0.
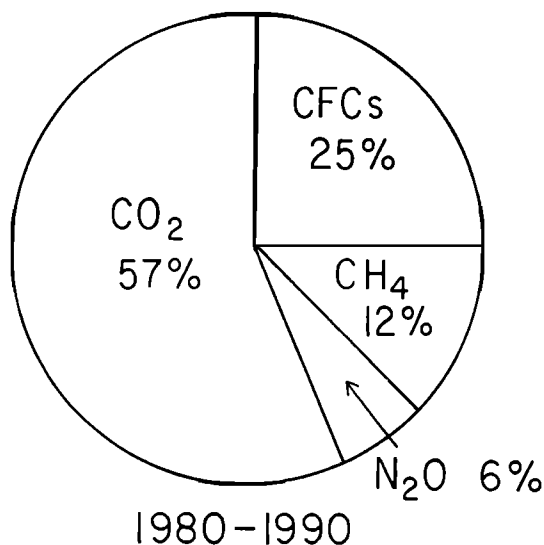
Fig. 3. Relative contributions of different gases to the total estimated greenhouse forcing that was added to the atmosphere during the 1980s.

20 and 50 km would yield ΔT_0 of approximately 0.06°C. Because adequate measurements are not available, we do not include either ozone or stratospheric water vapor changes in our results. Based on the discussion above, it seems likely that these two omissions are partially offsetting.

4. IMPACT OF PRODUCTION CONSTRAINTS IN 1970s

Prior to 1974 the production of CFC–12 and CFC–11 was increasing by about 8–11% per year (Figure 4a). After public concern was raised that CFCs may destroy stratospheric ozone there was a sharp break in the growth of CFC production, initially because consumers voluntarily turned to alternative products and, shortly thereafter, because legislatures in the United States, Canada and a few European countries passed laws restricting certain CFC uses.

If the growth rates of the early 1970s had continued to the present, the annual increments of greenhouse forcing by CFCs

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
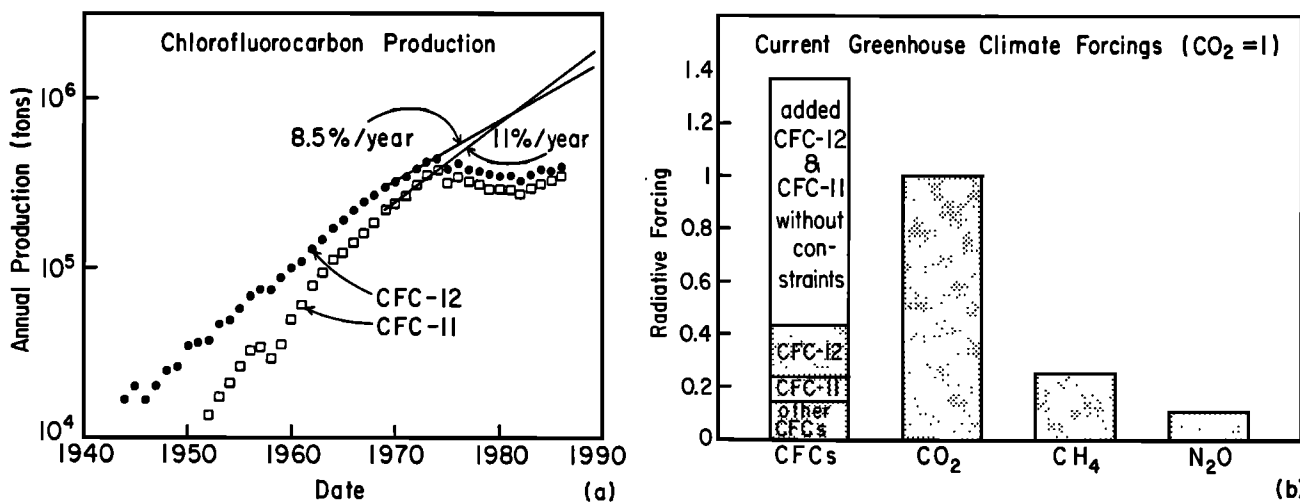

Fig. 4. (a) Annual production of CFC–11 and CFC–12 by reporting companies, as tabulated by the Chemical Manufacturers Association, and extrapolations based on growth rates of the early 1970s. (b) Relative radiative forcing of the climate system (CO_2=1) due to increasing trace gases, including the CFC climate forcing which would have occurred for the extrapolated CFC production in Figure 4a. Calculated radiative forcings are for smoothed current (1989) annual trace gas increments.

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.

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