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TELLUS

The role of carbon dioxide in climate forcing from 1979 to 2004: introduction of the Annual Greenhouse Gas Index

By D. J. HOFMANN*, J. H. BUTLER, E. J. DLUGOKENCKY, J. W. ELKINS, K. MASARIE, S. A. MONTZKA and P. TANS, *NOAA Earth System Research Laboratory, Global Monitoring Division, Boulder, CO 80305, USA*

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ABSTRACT

High-precision measurements of CO_2, CH_4, N_2O, CFC-12, CFC-11 (major greenhouse gases) and 10 minor halogenated gases from a globally distributed network of air sampling sites are used to calculate changes in radiative climate forcing since the pre-industrial era (1750) for the period of measurement, 1979–2004. The five major greenhouse gases account for about 97% of the direct radiative forcing by long-lived gases. The fraction of the sum of radiative forcings by all long-lived gases that is due to CO_2 has grown from 60% to 63% over this time. Though the long-term increase in this sum is due primarily to increased anthropogenic emissions of these radiatively important gases, interannual variations in the growth rate of radiative forcing due to CO_2 are large and likely related to natural phenomena such as volcanic eruptions and ENSO events. The annual value of the total global radiative forcing of the long-lived gases is used to define an Annual Greenhouse Gas Index (AGGI). The AGGI is normalized to 1990, the Kyoto Protocol baseline year.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC, 2001) defines radiative forcing of climate change as an externally imposed perturbation in the radiative energy budget of the Earth climate system, for example, through changes in solar radiation, changes in the Earth albedo or changes in atmospheric gases and aerosol particles. Radiative forcing is calculated using a radiative transfer model using the spectral properties and global abundance of a parameter of interest, and it gives a useful estimate of global mean response of a potential climate perturbation. Calculation of radiative forcing does not rely on climate feedbacks (e.g., changes in albedo or atmospheric water vapour content), and computationally intensive climate models are not needed. The perturbations used in radiative forcing calculations are considered from the pre-industrial era (taken as 1750 by IPCC) to the present (e.g., the factor of 2.5 increase in the atmospheric burden of CH_4). The largest and least-uncertain perturbation to Earth's radiation budget is that due to increases in the abundances of the long-lived and well-mixed greenhouse gases, in particular carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocompounds (mainly CFCs). Here, we use high-precision measurements of global, long-lived greenhouse gases to calculate changes in radiative forcing since 1750 for the period 1979–2004. This change in global radiative forcing caused by increase in the atmospheric abundances of long-lived greenhouse gases is used to define the Annual Greenhouse Gas Index (AGGI).

2. Observations

Air samples are collected approximately weekly at sites in the NOAA/ESRL global network including a cooperative program for the carbon gases which provides samples from about 30 fixed-position background sites and at 5 degree latitude intervals from a ship route in the Pacific Ocean (see Fig. 1). Although the current network is considerably larger, these sites have data records extending back to 1979.

Weekly measurements from each site are smoothed in time and latitude, to calculate global averages (see e.g., Dlugokencky et al., 1998; Montzka et al., 1999). Global averages of the major long-lived greenhouse gases are plotted in Fig. 2. The growth rate of CO_2 has averaged about 1.6 ppm yr^{-1} over the past 26 yr. The growth rate of CH_4 has declined substantially since measurements started in 1983. This is, in part, because total global emissions have been relatively constant and the atmospheric burden

*Corresponding author.
e-mail: David.J.Hofmann@noaa.gov
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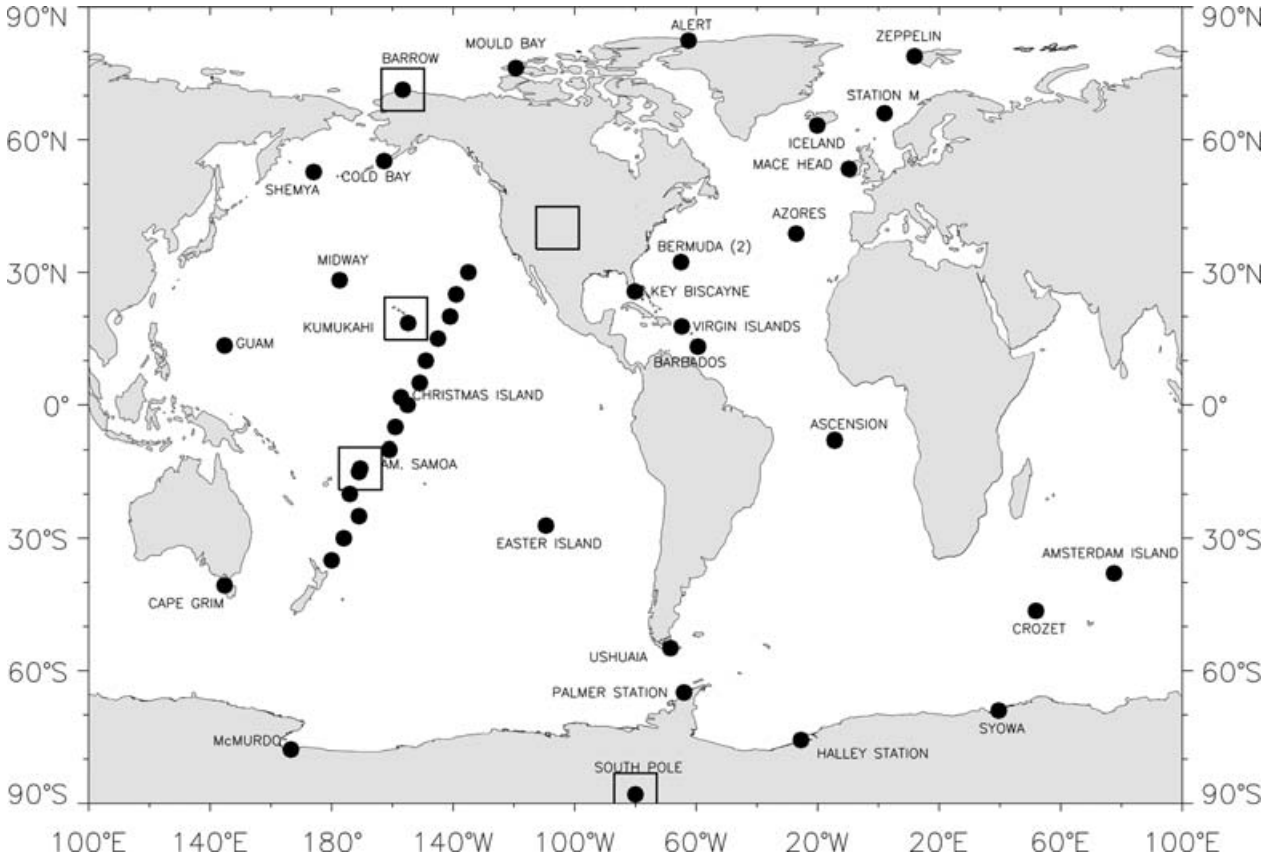

Fig. 1. The NOAA Earth System Research Laboratory global cooperative air sampling network used to determine the AGGI. Closed circles are weekly flask sampling sites and open squares are continuous measurement sites.

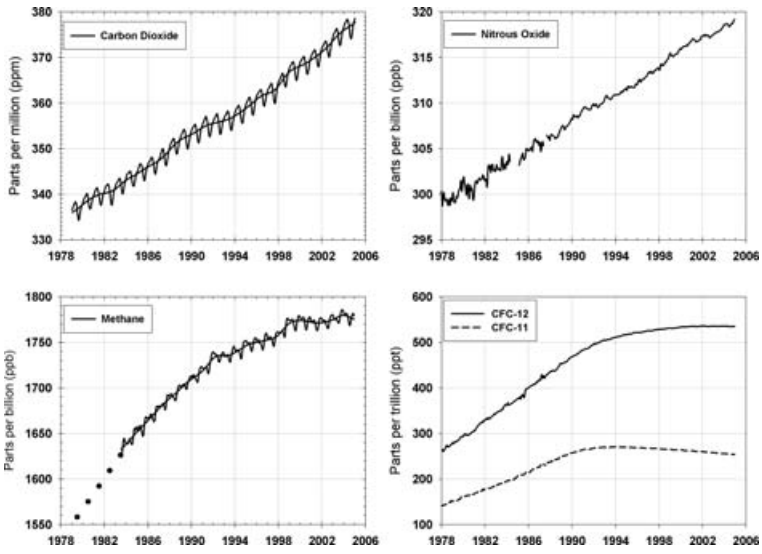

Fig. 2. Monthly averages of the abundances of the major long-lived greenhouse gases responsible for about 97% of the total radiative climate forcing due to long-lived gases. CH_4 data prior to 1983 are annual averages from Etheridge et al. (1998).

is approaching steady state on the timescale of its lifetime of 8–9 yr (Dlugokencky et al., 1998). Approach to steady state may have accelerated after 1992 because of the economic collapse of the former Soviet Union (Dlugokencky et al., 2003). Methane data from 1979 to 1983 used in this work are from Etheridge et al. (1998), adjusted to the NOAA04 scale (Dlugokencky et al., 2005) using a factor of 1.0124. Nitrous oxide continues to increase with a relatively uniform growth rate while the CFCs have ceased the increase observed before about 1992 and have either levelled off or are in decline (Montzka et al., 1999). The

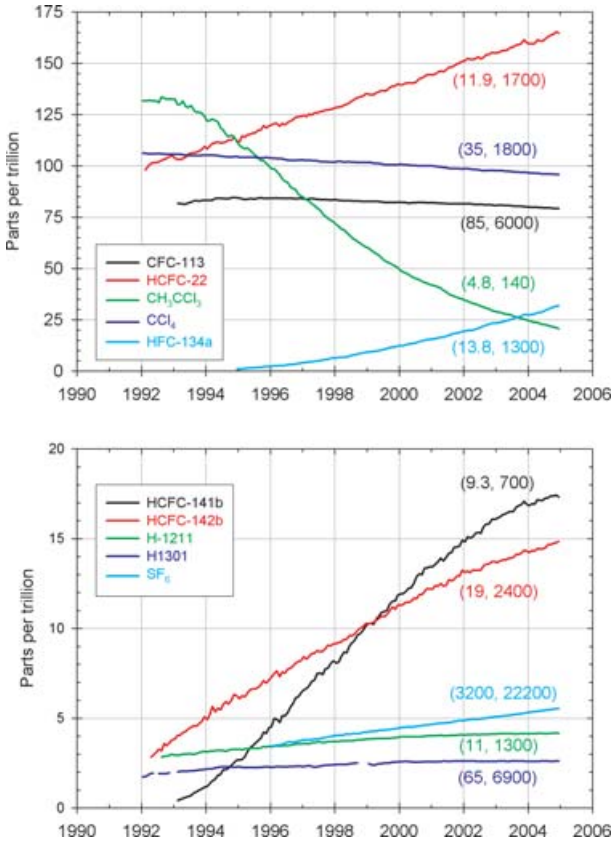

Fig. 3. Monthly global averages of the concentrations of the minor long-lived greenhouse gases monitored by NOAA/ESRL and used in determination of the AGGI. These 10 gases make up about 3% of the total radiative climate forcing due to long-lived gases. Shown in parenthesis for each gas are the lifetime in years and the Global Warming Potential, relative to 1 for CO_2 (IPCC 2001).

latter is a response to decreased emissions related to the Montreal Protocol on Substances that Deplete the Ozone Layer.

Ten minor halogen gases, which have been monitored since the early 1990s because of their implications for stratospheric ozone depletion, are also used in this analysis to include most of the human-produced, long-lived gases that cause radiative forcing of climate. The time variations of these gases are shown in Fig. 3 and include CFC-113, CCl_4, CH_3CCl_3, HCFCs 22, 141b and 142b, HFC134a, SF_6, and halons 1211 and 1301. Further discussion of these data is given by Montzka et al. (1999, 2003).

3. Radiative forcing calculations

To calculate the radiative forcing due to changes in the atmospheric abundances of greenhouse gases since 1750, we used IPCC (2001) recommended expressions for the direct radiative forcing (see Table 1). Model-dependent feedbacks, for example, due to water vapour and ozone depletion, have not been included. Contrary to climate model calculations, these results are based

Table 1. Expressions for calculating radiative climate forcing[a]

Trace gas	Simplified expression for radiative forcing, F (W m^{-2})	Constant
CO_2	$F = a\,[\ln(C/C_o)]$	$a = 5.35$
CH_4	$F = b\,(M^{1/2} - M_o{}^{1/2}) - [f(M,N_o) - f(M_o,N_o)]$	$b = 0.036$
N_2O	$F = c\,(N^{1/2} - N_o{}^{1/2}) - [f(M_o,N) - f(M_o,N_o)]$	$c = 0.12$
CFC-11	$F = d\,(X - X_o)$	$d = 0.25$
CFC-12	$F = e(X - X_o)$	$e = 0.32$

[a]IPCC, 2001.
C is CO_2 in ppm, M is CH_4 in ppb, N is N_2O in ppb, X is CFC in ppb.
The subscript o denotes unperturbed (1750) values:
$C_o = 278$ ppm, $M_o = 700$ ppb, $N_o = 270$ ppb, $X_o = 0$
$f(M,N) = 0.47 \ln[1 + 2.01 \times 10^{-5}\,(MN)^{0.75} + 5.31 \times 10^{-15}\,M\,(MN)^{1.52}]$.

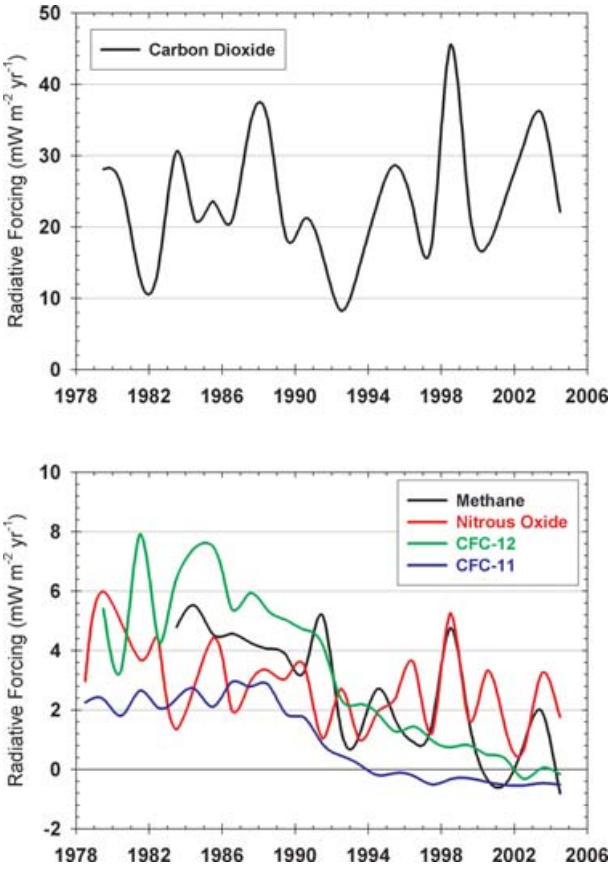

Fig. 4. Trends in radiative forcing growth rates of the five major greenhouse gases.

mainly on measurements and have relatively small uncertainties compared to other forcing agents such as aerosols and short-lived gases. The empirical expressions in Table 1 are generally within 5% of high-spectral resolution radiative transfer calculations,

Table 2. Data used to calculate the AGGI

	Global radiative forcing 1979–2004 (W m^{-2})								
Year	CO_2	CH_4	N_2O	CFC-12	CFC-11	10 Minor	Total	AGGI 1990 = 1	Annual change (%)
1979	1.026	0.412	0.101	0.091	0.039	0.029	1.699	0.783	
1980	1.056	0.418	0.102	0.096	0.041	0.032	1.745	0.804	2.76
1981	1.075	0.425	0.106	0.102	0.043	0.034	1.785	0.822	2.27
1982	1.086	0.432	0.109	0.108	0.045	0.036	1.816	0.837	1.73
1983	1.112	0.438	0.111	0.113	0.048	0.039	1.860	0.857	2.44
1984	1.137	0.446	0.113	0.117	0.050	0.041	1.903	0.877	2.31
1985	1.160	0.451	0.114	0.124	0.053	0.044	1.945	0.896	2.21
1986	1.182	0.456	0.118	0.131	0.055	0.048	1.990	0.917	2.30
1987	1.208	0.460	0.119	0.136	0.058	0.051	2.033	0.937	2.18
1988	1.247	0.464	0.122	0.141	0.061	0.055	2.090	0.963	2.78
1989	1.272	0.469	0.125	0.147	0.063	0.059	2.135	0.984	2.14
1990	1.290	0.472	0.129	0.152	0.065	0.062	2.170	1.000	1.67
1991	1.311	0.476	0.132	0.156	0.066	0.064	2.206	1.016	1.63
1992	1.321	0.480	0.133	0.160	0.067	0.069	2.230	1.028	1.12
1993	1.332	0.481	0.135	0.162	0.067	0.071	2.249	1.036	0.81
1994	1.354	0.483	0.137	0.165	0.067	0.072	2.277	1.049	1.28
1995	1.381	0.485	0.139	0.166	0.067	0.073	2.311	1.065	1.50
1996	1.407	0.486	0.142	0.167	0.067	0.075	2.344	1.080	1.40
1997	1.423	0.487	0.144	0.169	0.067	0.076	2.366	1.090	0.96
1998	1.463	0.491	0.147	0.170	0.066	0.077	2.415	1.113	2.05
1999	1.494	0.494	0.151	0.170	0.066	0.078	2.453	1.130	1.57
2000	1.512	0.494	0.153	0.171	0.066	0.079	2.475	1.140	0.91
2001	1.535	0.494	0.155	0.171	0.065	0.081	2.501	1.152	1.05
2002	1.564	0.494	0.157	0.171	0.065	0.082	2.533	1.167	1.29
2003	1.600	0.496	0.159	0.171	0.064	0.084	2.574	1.186	1.62
2004	1.626	0.496	0.161	0.171	0.064	0.085	2.603	1.199	1.11

with the latter having an uncertainty of about 10% for the radiative forcing due to all the well-mixed greenhouse gases and less than 10% for CO_2 alone (IPCC, 2001). The uncertainties in the global average concentrations of the long-lived greenhouse gases are much smaller than those involved in calculating the radiative forcing.

We tabulate in Table 2 radiative climate forcing for 1979–2004. Figure 4 shows the deseasonalized radiative forcing growth rates for the major gases. Only CO_2 and N_2O have maintained a relatively constant growth rate as opposed to the general decline in CH_4 and the CFCs.

Figure 5 shows the time history of the radiative forcing by the 10 minor halogen gases. Their total forcing lies between that of CFC-12 and CFC-11. Figure 6 shows the trend in total radiative climate forcing of the major long-lived gases and the 10 minor long-lived halogenated gases for the 1979–2004 period. CO_2 dominates the total forcing with CH_4 and the CFCs becoming relatively smaller contributors to the total forcing overtime. The five major greenhouse gases account for about 97% of the direct radiative climate forcing by long-lived greenhouse gas increases since 1750. The remaining 3% is contributed by the 10 minor halogen gases, mainly HCFC-22, CFC-113 and CCl_4.

4. Discussion

Since 1979, the instantaneous radiative forcing by CO_2 has increased from about 60% to 63% of the total forcing calculated for long-lived greenhouse gases. Of the five major long-lived gases that contribute to radiative climate forcing, CO_2 and N_2O are the only gases for which the atmospheric concentrations continue to rise. The lifetimes of the latter species are long, so that continuing emissions will cause a tendency for further accumulation in the atmosphere. The contribution to radiative forcing of climate by CH_4 and CFCs has been nearly constant or declining, respectively, in recent years.

An AGGI has been defined as the ratio of the total radiative climate forcing in any year for which measurements exist to that determined for 1990. This index, shown in Table 2 and on the right-hand axis of Fig. 6, reflects the interannual changes in CO_2 emission and uptake, and the balance between emissions and sinks for CH_4, N_2O, the CFCs and other minor gases. Most of the increase in the AGGI is related to CO_2. For 2004, the AGGI was 1.20 (representing an increase in radiative climate forcing of 20% from 1990 to 2004, relative to the increase noted from 1750 to 1990).

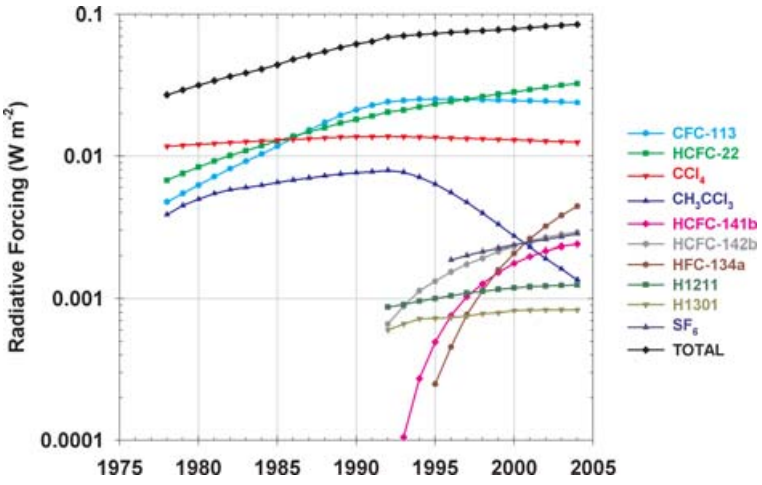

Fig. 5. Radiative forcing by 10 minor long-lived, halogenated gases relative to 1750.

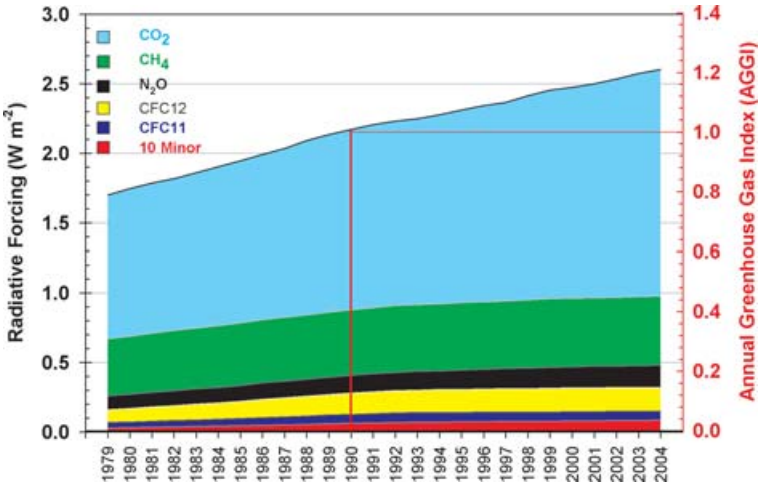

Fig. 6. Sum of annual radiative climate forcings by long-lived greenhouse gases relative to 1750. The AGGI (right vertical axis) is indexed to 1 in 1990.

Figure 7 shows the interannual change in rate of increase in radiative forcing (mWm^{-2} yr^{-1}) by the five major and the group of 10 minor long-lived greenhouse gases. This figure shows how the decline in some of the gases has decreased the net effect of the increase in radiative climate forcing due to CO_2.

Interannual changes in CO_2 can be put into two categories: emissions due to the combustion of fossil fuels, and natural variations in sources and sinks of carbon due to variations in climate and fires. The former provides the main reason why CO_2 mixing ratios have increased since 1750. The latter modulate the annual increase in CO_2, but have always been smaller than the former since direct atmospheric measurements began at the Mauna Loa Observatory in 1958. A statistical correlation between the CO_2 growth rate and the Southern Oscillation Index was first discovered by Bacastow (1976).

The slowdown in CO_2 growth rate for 2 yr after the Pinatubo eruption in 1991 has been attributed to colder temperatures on the Northern Hemisphere land masses, slowing respiration, as

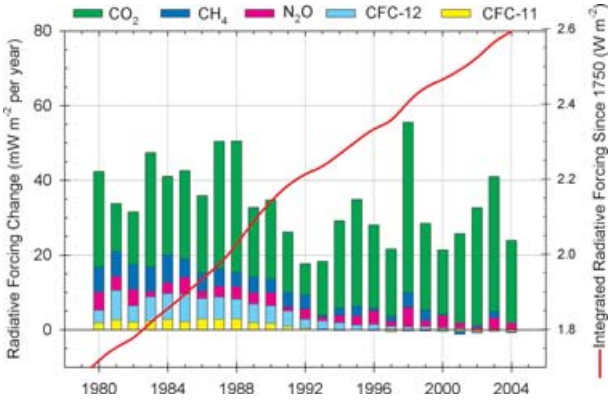

Fig. 7. Annual growth rate in radiative forcing from 1980 to 2004 by long-lived greenhouse gases. The total integrated radiative forcing is also shown (red curve, right axis). CH_4 data prior to 1983 are from Etheridge et al. (1998).

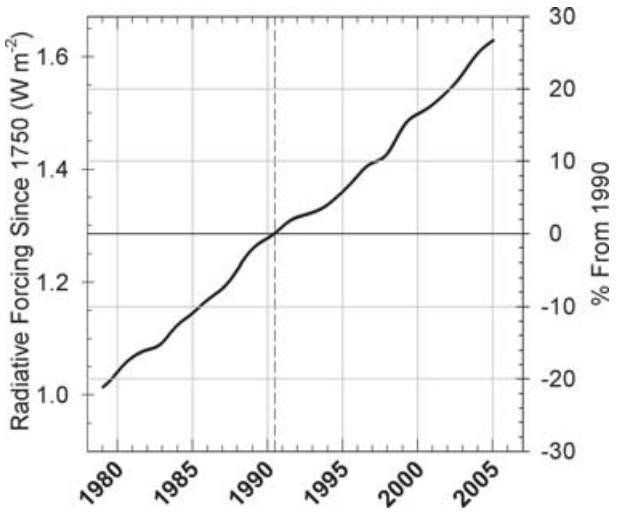

Fig. 8. Radiative forcing by CO_2 from 1979 to 2004 (left axis). The per cent difference in radiative forcing between each year and 1990 is also shown (right axis).

well as to an increase of the diffuse solar radiation component due to increased aerosol loading, increasing photosynthesis (Gu et al., 2003).

Biomass burning received considerable attention after the massive fires in Southeast Asia in 1997 (e.g., Page et al., 2002). The CO_2 growth rate anomalies offer an opportunity to study the behaviour of the carbon cycle on annual timescales. Short of a quantitative understanding, the statistical relationships with environmental variables can be used to better quantify underlying long-term trends of the rate of CO_2 increase and its associated climate forcing.

In Fig. 8, the radiative forcing of climate versus time since 1979 for CO_2 alone is plotted. As can be seen, the forcing in 2004 was about 26% greater than in 1990. Comparing this with the change in the AGGI from 1990 to 2004 (20%), one can see that the slowdown in the CH_4 growth rate and the decline in the CFCs have slowed the increase in total radiative forcing by a measurable amount.

4. Conclusions

Analysis of the global average radiative forcing of all the long-lived atmospheric greenhouse gases and combining them into a single annual forcing value has provided an easy to follow, precise parameter related to how anthropogenic greenhouse gases are accumulating in the atmosphere and influencing its radiative balance. By indexing this radiative forcing to 1 in 1990, an AGGI was created which indicates the increase above the Kyoto Protocol baseline year. The AGGI is not a measure of all the forcing agents of climate change but of the ones that are best known and likely to be the most important. In this application it is similar to economic indicators which use major components which control the economy. The AGGI will be useful in enhancing the connection between science and society by providing a normalized standard that can be easily understood and followed. The contribution of long-lived greenhouse gases to climate forcing is well understood by scientists and has been reported through international assessments. Nevertheless, the language of scientists (for example, W m^{-2} yr^{-1}) often eludes policy makers, educators and the general public. This index is designed to help bridge that gap. It has already seen application, for example, in the World Meteorological Organization's new Greenhouse Gas Bulletin (2006).

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