IEAGHG Information Paper: 2016-IP12; Annual Greenhouse Gas Index for 2015

The National Oceanic and Atmospheric Administration of the US has recently published it Annual Greenhouse Gas Index (AGGI). The AGGI is a measure of the warming influence of greenhouse gases and how that influence is changing year by year. It is important to note that the AGGI is not based on modelled data but based upon actual atmospheric data from monitoring stations based around the world, such as the one at Mauna Loa in Hawaii[1].

An Annual Greenhouse Gas Index (AGGI) has been defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990. 1990 was chosen because it is the baseline year for the Kyoto Protocol. This index, is a measure of the inter-annual changes in conditions that affect carbon dioxide emission and uptake, methane and nitrous oxide sources and sinks, the decline in the atmospheric abundance of ozone-depleting chemicals related to the Montreal Protocol, and the increase in their substitutes (HCFCs and HFCs). Most of this increase is related to CO2. For 2015, the AGGI was 1.37 (representing an increase in total direct radiative forcing of 37% since 1990). See Figure 1 below

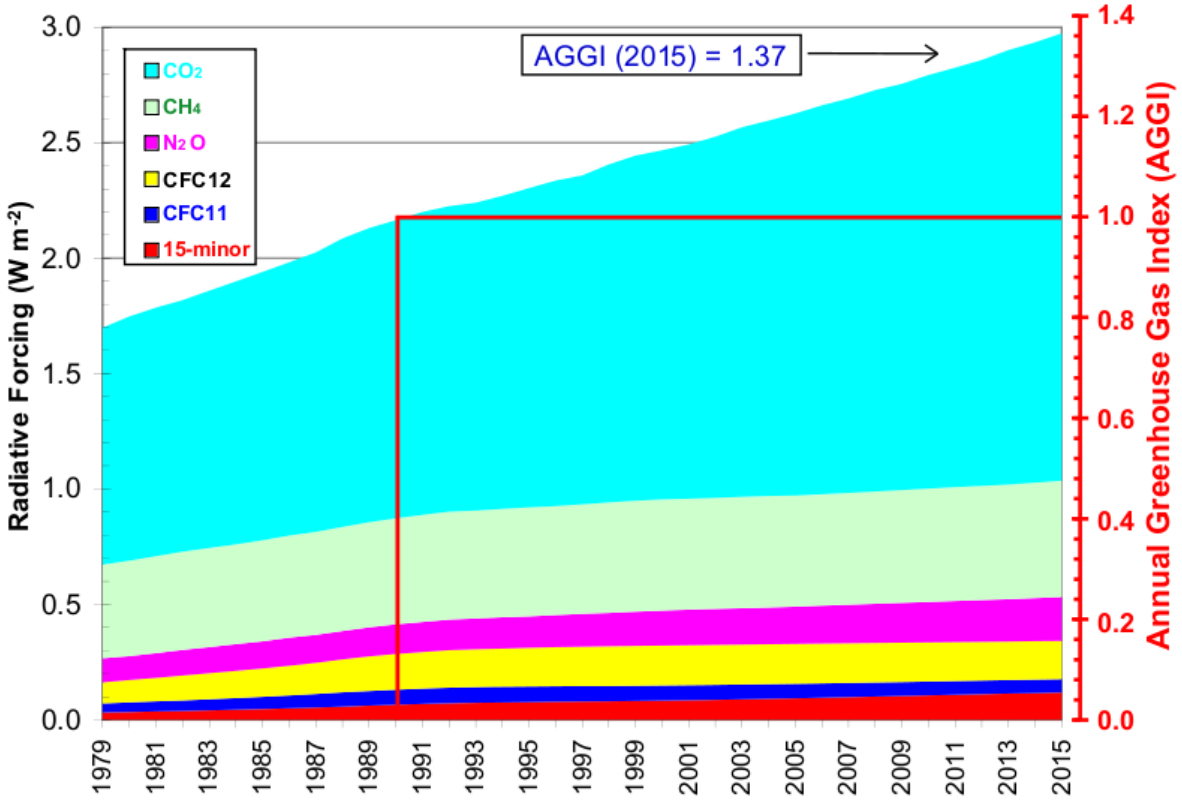

Figure 1. Radiative forcing, relative to 1750, of all the long-lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis.

[1] See: Record annual increase of carbon dioxide observed at Mauna Loa for 2015 at: http://www.noaa.gov/record-annual-increase-carbon-dioxide-observed-mauna-loa-2015

The key messages from the 10th Annual AGGI which was published in spring 2016 are:

- Human activity has increased the direct warming effect of carbon dioxide in the atmosphere by 50 percent above pre-industrial levels during the past 25 years.
- Emissions of all greenhouse gases have amplified the warming impact on the planet by more than one third since 1990.
- In 2015, the global average CO_2 concentration reached 399 ppm, increasing by a record amount of almost 3 ppm in that year. Note: From the end of the Ice Age to the beginning of the industrial era, atmospheric carbon dioxide remained remarkably stable at 278 ppm.
- From 2014 to 2015, atmospheric levels of methane increased substantially faster than from 2007 to 2013.
- Nitrous oxide atmospheric levels, have increased at faster rates recently.
- Chlorofluorocarbons, the ozone depleting gases banned by the Montreal Protocol, are declining. However, atmospheric levels of two replacement chemicals (HCFC22 and HFC134a) are increasing. Both these species have high global warming potentials but are not ozone depleting agents.
- The warming impact of gases other than CO_2 is equivalent to an additional 85 ppm of carbon dioxide. Due to the other GHG's the atmosphere is warming as if it contained 21 percent more carbon dioxide than it does today due to the increased concentration of other GHG's.

The full AGGI report is attached to this Information Paper for those that want to read the full details. The AGGIC report can also be found on line at: http://esrl.noaa.gov/gmd/aggi/aggi.html

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THE NOAA ANNUAL GREENHOUSE GAS INDEX (AGGI)

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Introduction

The AGGI is a measure of the warming influence of long-lived trace gases and how that influence is changing each year. The index was designed to enhance the connection between scientists and society by providing a normalized standard that can be easily understood and followed. The warming influence of long-lived greenhouse gases is well understood by scientists and has been reported by NOAA through a range of national and international assessments. Nevertheless, the language of scientists often eludes policy makers, educators, and the general public. This index is designed to help bridge that gap. The AGGI provides a way for this warming influence to be presented as a simple index.

Increases in the abundance of atmospheric greenhouse gases since the industrial revolution are mainly the result of human activity and are largely responsible for the observed increases in global temperature *[IPCC 2013]*. However, climate projections have model uncertainties that overwhelm the uncertainties in greenhouse gas measurements. We present here an index that is directly proportional to the direct warming influence (also know as climate forcing) supplied from these gases. Because it is based on the observed amounts of long-lived greenhouse gases in the atmosphere, this index contains relatively little uncertainty.

The Intergovernmental Panel on Climate Change (IPCC) defines climate forcing as "An externally imposed perturbation in the radiative energy budget of the Earth climate system, e.g. through changes in solar radiation, changes in the Earth albedo, or changes in atmospheric gases and aerosol particles." Thus climate forcing is a "change" in the status quo. IPCC takes the pre-industrial era (chosen as the year 1750) as the baseline. The perturbation to direct climate forcing (also termed "radiative forcing") that has the largest magnitude and the least scientific uncertainty is the forcing related to changes in long-lived, well mixed greenhouse gases, in particular carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halogenated compounds (mainly CFCs).

Atmospheric global greenhouse gas abundances are used to calculate changes in radiative forcing beginning in 1979 when NOAA's global air sampling network expanded significantly. The change in annual average total radiative forcing by all the long-lived greenhouse gases since the pre-industrial era (1750) is also used to define the NOAA Annual Greenhouse Gas Index (AGGI), which was introduced in 2004 *[Hofmann et al., 2006a]* and has been updated annually since.

Observations

The NOAA monitoring program provides high-precision measurements of the global abundance and distribution of long-lived greenhouse gases that are used to calculate changes in radiative climate forcing.

Air samples are collected through the NOAA/ESRL global air sampling network, including a cooperative program for the carbon gases which provides samples from ~80 global background air sites, including measurements at 5 degree latitude intervals from ship routes (see Figure 1 overleaf).

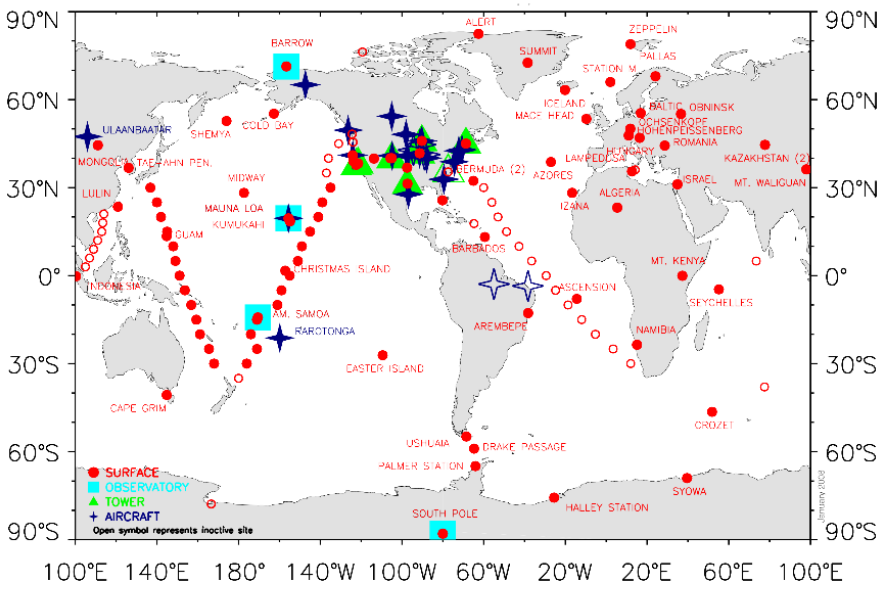

Figure 1. *The NOAA Earth System Research Laboratory cooperative global air sampling network used to determine the AGGI.*

Weekly data are used to create a smoothed north-south latitude profile from which a global average is calculated (Figure 2). The atmospheric abundance of CO_2 has increased by an average of 1.76 ppm per year over the past 37 years (1979-2015). The CO_2increase is accelerating: it averaged about 1.5 ppm per year in the 1980s and 1990s, and it was 2.0 ppm per year during the last decade (2006-2015). The annual CO_2 increase during the past year was nearly 3 ppm for only the second time since 1979. The increase observed for global atmospheric CO_2 has resulted in a 50% increase in its direct warming influence on climate since 1990 (Figure 3).

The growth rate of methane declined from 1983 until 1999, consistent with an approach to steady-state. Superimposed on this decline is significant interannual variability in growth rates *[Dlugokencky et al., 1998, 2003]*. From 1999 to 2006, the atmospheric CH_4 burden was about constant, but since 2007, globally averaged CH_4 has been increasing again. Causes for the increase during 2007-2008 included warm temperatures in the Arctic in 2007 and increased precipitation in the tropics in 2007 and 2008*[Dlugokencky et al., 2009]*. From 2014 to 2015 global methane increased substantially faster (11.5 ppb/yr) than it had from 2007 to 2013 (5.7 ± 1.2 ppb^{-1}). Similarly, the atmospheric burden of nitrous oxide has increased at faster rates in recent years. Radiative forcing from the sum of observed CFC changes ceased increasing in about 2000 and is now declining *[Montzka et al., 2011]*. The latter is a response to decreased emissions related to the fully adjusted and amended Montreal Protocol on Substances that Deplete the Ozone Layer.

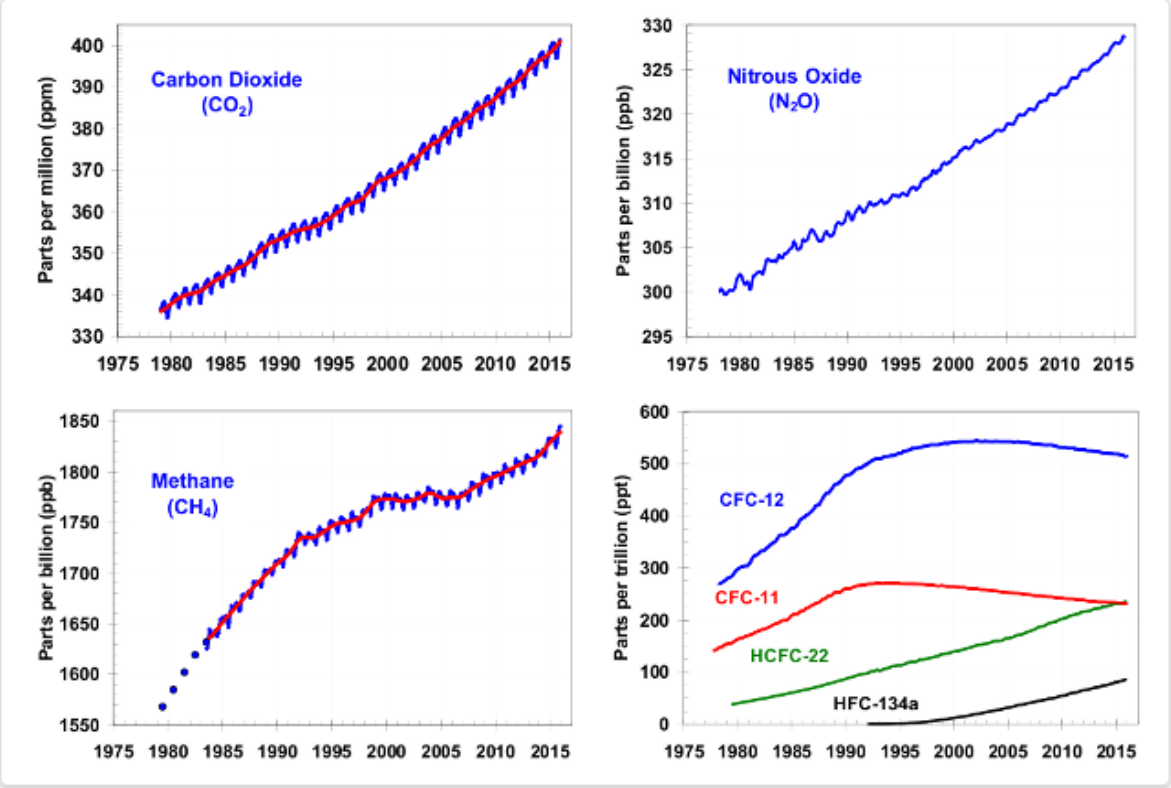

Figure 2. *Global average abundances of the major, well-mixed, long-lived greenhouse gases - carbon dioxide, methane, nitrous oxide, CFC-12 and CFC-11 - from the NOAA global air sampling network are plotted since the beginning of 1979. These five gases account for about 96% of the direct radiative forcing by long-lived greenhouse gases since 1750. The remaining 4% is contributed by an assortment of 15 minor halogenated gases including HCFC-22 and HFC-134a, for which NOAA observations are also shown in the figure (see text). Methane data before 1983 are annual averages from D. Etheridge [Etheridge et al., 1998], adjusted to the NOAA calibration scale [Dlugokencky et al., 2005].*

Radiative Forcing Calculations

To determine the total radiative forcing of the greenhouse gases, we have used IPCC *[Ramaswamy et al., 2001]* recommended expressions to convert greenhouse gas changes, relative to 1750, to instantaneous radiative forcing (see Table 1). These empirical expressions are derived from atmospheric radiative transfer models and generally have an uncertainty of about 10%. The uncertainties in the global average abundances of the long-lived greenhouse gases are much smaller (<1%).

Table 1. Expressions for Calculating Radiative Forcing*

Trace Gas	Simplified Expression Radiative Forcing, ΔF (Wm^{-2})	Constant
CO_2	$\Delta F = \alpha \ln(C/C_o)$	$\alpha = 5.35$
CH_4	$\Delta F = \beta(M^{½} - M_o^{½}) - [f(M,N_o) - f(M_o,N_o)]$	$\beta = 0.036$
N_2O	$\Delta F = \varepsilon(N^{½} - N_o^{½}) - [f(M_o,N) - f(M_o,N_o)]$	$\varepsilon = 0.12$
CFC-11	$\Delta F = \lambda(X - X_o)$	$\lambda = 0.25$
CFC-12	$\Delta F = \omega(X - X_o)$	$\omega = 0.32$

*IPCC (2001)

The subscript "o" denotes the unperturbed (1750) abundance

$f(M,N) = 0.47\ln[1 + 2.01\times10^{-5}(MN)^{0.75} + 5.31\times10^{-15}M(MN)^{1.52}]$

C is CO_2 in ppm, M is CH_4 in ppb
N is N_2O in ppb, X is CFC in ppb

C_o = 278 ppm, M_o = 722 ppb, N_o = 270 ppb, X_o = 0

Because we seek an index that is accurate, only direct forcing from these gases has been included. Model-dependent feedbacks, for example, due to water vapor and ozone depletion, are not included. Other spatially heterogeneous, short-lived, climate forcing agents, such as aerosols and tropospheric ozone, have uncertain global magnitudes and also are not included here to maintain accuracy. Figure 3 shows the results for carbon dioxide global monthly averages for 1979-2015. An index based on the total of these contributions to radiative forcing would be similar to the Consumer Price Index, for example. It would include all the important components but not all the components of climate forcing. In contrast to climate model calculations, the results reported here are based mainly on measurements of long-lived, well mixed gases and have small uncertainties.

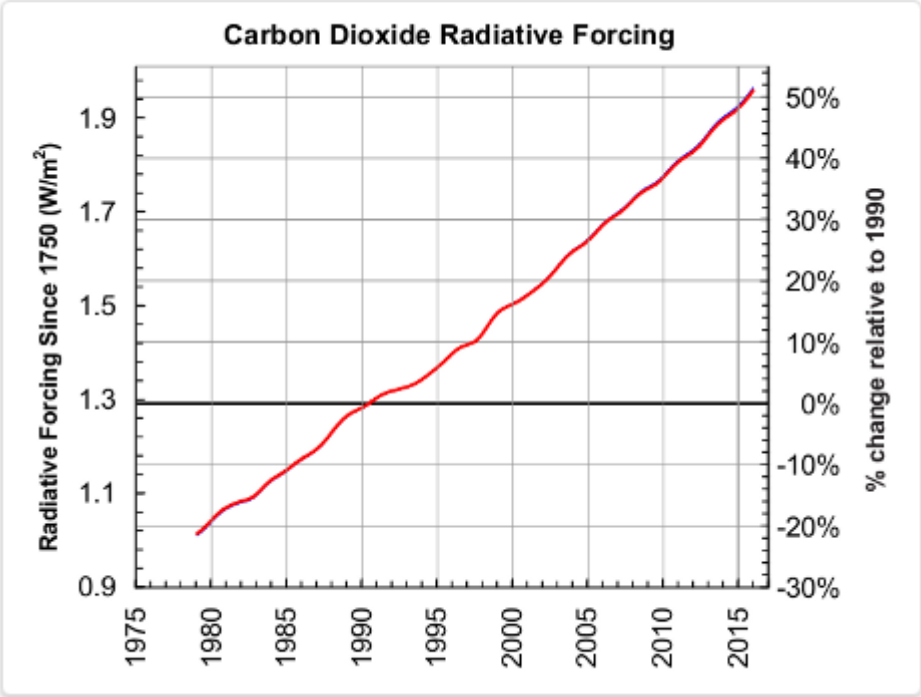

Figure 3. *Radiative forcing, relative to 1750, due to carbon dioxide alone since 1979. The percent change from January 1, 1990 is shown on the right axis and shows how the direct warming influence of CO_2 on climate has increased by about 50% since 1990.*

2015 Results

Figure 4 shows radiative forcing for the major gases and a set of 15 minor long-lived halogenated gases (CFC-113, CCl_4, CH_3CCl_3, HCFCs 22, 141b and 142b, HFCs 134a, 152a, 23, 143a, and 125, SF_6, and halons 1211, 1301 and 2402). Except for the HFCs and SF_6, which do not contain chlorine or bromine, these gases are also ozone-depleting gases and are regulated by the Montreal Protocol. As expected, CO_2 dominates the total forcing with methane and the CFCs becoming relatively smaller contributors to the total forcing over time. The five major greenhouse gases account for about 96% of the direct radiative forcing by long-lived greenhouse gas increases since 1750. The remaining 4% is contributed by the 15 minor halogenated gases.

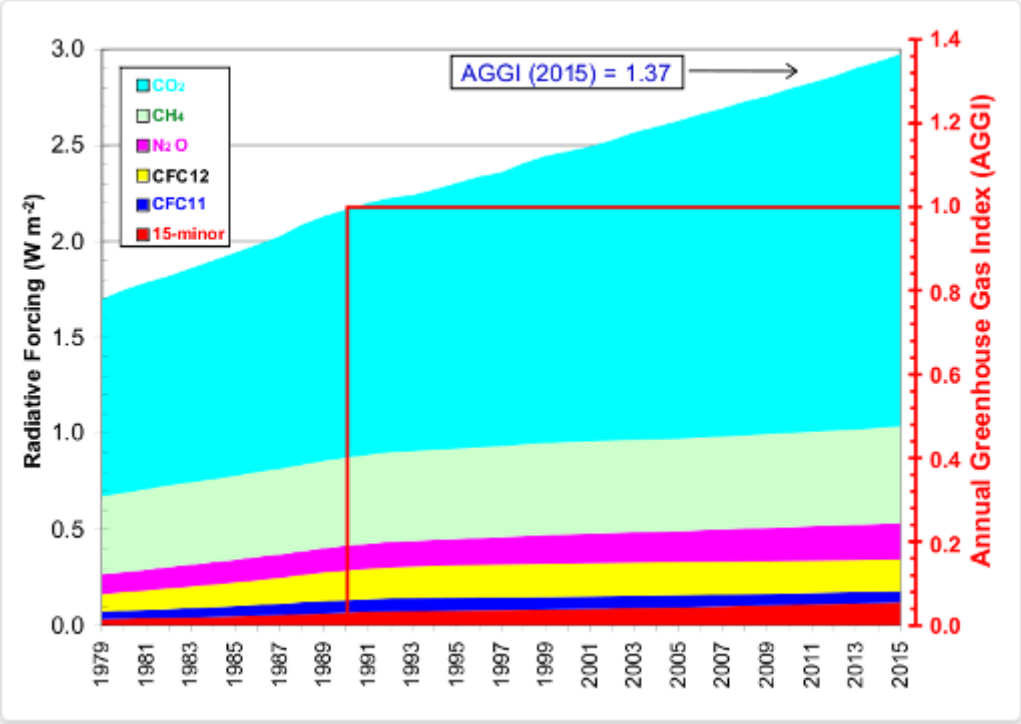

Figure 4. *Radiative forcing, relative to 1750, of all the long-lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis.*

Of the five long-lived greenhouse gases that contribute 96% to radiative climate forcing, CO_2 and N_2O are the only ones that continue to increase at a regular rate; increases in radiative forcing from CH_4 vary substantially from year to year. Radiative forcing from CH_4 increased from 2007 to 2015 after remaining nearly constant from 1999 to 2006. While the radiative forcing of the long-lived, well-mixed greenhouse gases increased 37% from 1990 to 2015 (by ~0.81 watts m^{-2}), CO_2 has accounted for nearly 80% of this increase (~0.65 watts m^{-2}). Had the ozone-depleting gases not been regulated by the Montreal Protocol and its amendments, it is estimated that climate forcing would have been as much as 0.3 watt m^{-2} greater in 2010 *[Velders et al., 2007]*, or more than half of the increase in radiative forcing due to CO_2 alone since 1990. Of the ozone-depleting gases and their substitutes, the largest contributors to direct warming in 2015 were CFC-12, followed by CFC-11, HCFC-22, CFC-113 and HCFC-134a. Although the concentration of HCFC-22 in the remote atmosphere surpassed that of CFC-11 by the end of 2015 (Figure 2), the radiative forcing arising from HCFC-22 is only 80% of that from CFC-11 because CFC-11 is more efficient at trapping infrared radiation on a per molecule basis.

An Annual Greenhouse Gas Index (AGGI) has been defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year for which adequate global measurements exist to that which was present in 1990. 1990 was chosen because it is the baseline year for the Kyoto Protocol. This index, shown with the direct radiative forcing values in Table 2 and on the right-hand axis of Figure 4, is a measure of the interannual changes in conditions that affect carbon dioxide emission and uptake, methane and nitrous oxide sources and sinks, the decline in the atmospheric abundance of ozone-depleting chemicals related to the Montreal Protocol, and the increase in their substitutes (HCFCs and HFCs). Most of this increase is related to CO_2. For 2015, the AGGI was **1.37** (representing an increase in total direct radiative forcing of 37% since 1990). The increase in CO_2 forcing alone since 1990 was about 50% (see Fig. 3). The decline in the CFCs has tempered the increase in net radiative forcing considerably. The AGGI is updated each spring when air samples collected during the previous year from all over the globe have been obtained and analyzed.

Changes in radiative forcing before 1978 are derived from atmospheric measurements of CO_2, started by C.D. Keeling *[Keeling et al., 1958]*, and from measurements of CO_2 and other greenhouse gases in air trapped in snow and ice in Antarctica and Greenland *[Etheridge et al., 1996; Butler et al,, 1999]*. These results define atmospheric composition changes going back to 1750 and radiative forcing changes since preindustrial times (Figure 4). This longer-term view shows how increases in greenhouse gas concentrations over the past 60 years (since 1950) have accounted for three-fourths (75%) of the total increase in the AGGI over the past 260 years. Changes in

radiative forcing before 1978 are derived from atmospheric measurements of CO_2, started by C.D. Keeling *[Keeling et al., 1958]*, and from measurements of CO_2 and other greenhouse gases in air trapped in snow and ice in Antarctica and Greenland *[Etheridge et al., 1996, 1998; Butler et al,, 1999]*. These results define atmospheric composition changes going back to 1750 and radiative forcing changes since preindustrial times (Figure 5). This longer-term view shows how increases in greenhouse gas concentrations over the past 60 years (since 1950) have accounted for three-fourths (75%) of the total increase in the AGGI over the past 260 years.

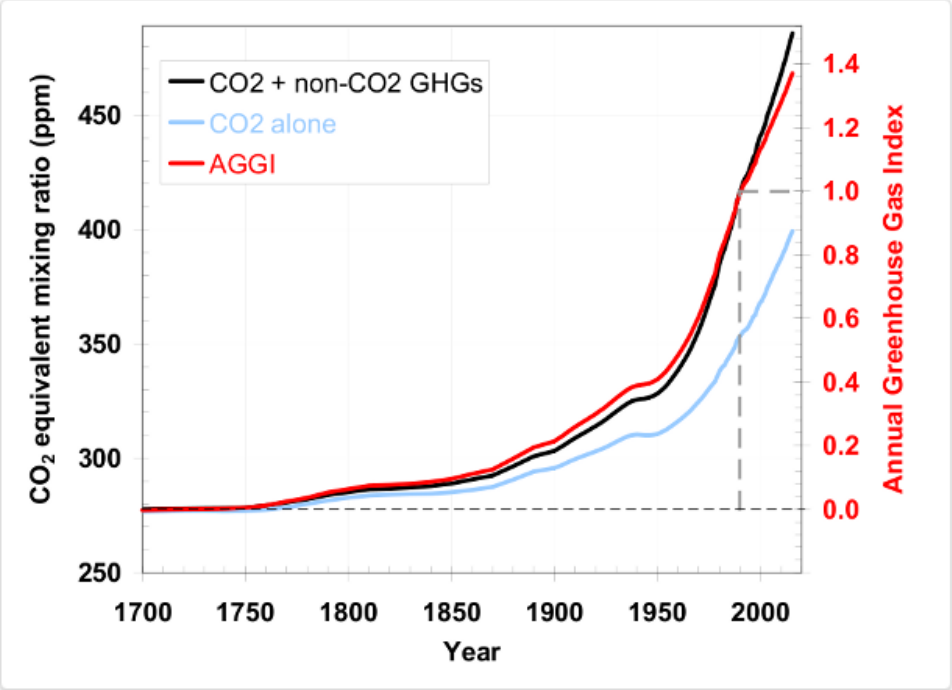

Figure 5. *Pre-1978 changes in the CO_2-equivalent concentration and AGGI based on the ongoing measurements of all greenhouse gases reported here, measurements of CO_2 going back to the 1950s from C.D. Keeling [Keeling et al., 1958], and atmospheric changes derived from air trapped in ice and snow above glaciers [Machida et al., 1995, Battle et al., 1996, Etheridge, et al., 1996; Butler, et al., 1999]. Equivalent CO_2atmospheric amounts (in ppm) are derived with the relationship (Table 1) between CO_2 concentrations and radiative forcing from all long-lived greenhouse gases.*

Table 2. Global Radiative Forcing, CO_2-equivalent mixing ratio, and the AGGI 1979-2013

Global Radiative Forcing ($W\ m^{-2}$)								CO_2-eq (ppm)	AGGI	
Year	CO_2	CH_4	N_2O	CFC12	CFC11	15-minor	Total	Total	1990 = 1	% change
1979	1.027	0.406	0.104	0.092	0.039	0.031	1.699	382	0.785	
1980	1.058	0.413	0.104	0.097	0.042	0.034	1.747	385	0.807	2.2
1981	1.077	0.420	0.107	0.102	0.044	0.036	1.786	388	0.825	1.8
1982	1.089	0.426	0.111	0.107	0.046	0.038	1.818	390	0.840	1.5
1983	1.115	0.429	0.113	0.113	0.048	0.041	1.859	394	0.859	1.9
1984	1.140	0.432	0.116	0.118	0.050	0.044	1.899	396	0.877	1.9
1985	1.162	0.437	0.118	0.123	0.053	0.047	1.940	400	0.896	1.9
1986	1.184	0.442	0.122	0.129	0.056	0.049	1.982	403	0.916	1.9
1987	1.211	0.447	0.120	0.136	0.059	0.053	2.025	406	0.935	2.0
1988	1.250	0.451	0.122	0.143	0.062	0.057	2.085	411	0.963	2.8
1989	1.274	0.455	0.126	0.149	0.064	0.061	2.130	414	0.984	2.1
1990	1.292	0.459	0.129	0.154	0.065	0.065	2.165	417	1.000	1.6
1991	1.312	0.463	0.131	0.158	0.067	0.069	2.200	419	1.016	1.6
1992	1.323	0.467	0.133	0.162	0.067	0.072	2.225	421	1.028	1.2
1993	1.334	0.467	0.133	0.164	0.068	0.074	2.240	423	1.035	0.7
1994	1.356	0.469	0.135	0.165	0.068	0.076	2.270	425	1.048	1.4
1995	1.383	0.472	0.137	0.168	0.067	0.077	2.303	428	1.064	1.6
1996	1.410	0.473	0.139	0.170	0.067	0.078	2.336	430	1.079	1.5
1997	1.426	0.474	0.142	0.171	0.067	0.079	2.359	432	1.090	1.1
1998	1.464	0.478	0.145	0.172	0.067	0.080	2.406	436	1.111	2.2
1999	1.495	0.481	0.148	0.173	0.066	0.082	2.444	439	1.129	1.8
2000	1.512	0.481	0.151	0.173	0.066	0.083	2.467	441	1.140	1.1
2001	1.535	0.480	0.153	0.174	0.065	0.085	2.492	443	1.151	1.2
2002	1.564	0.481	0.155	0.174	0.065	0.087	2.526	446	1.167	1.5
2003	1.600	0.483	0.157	0.174	0.064	0.088	2.567	449	1.186	1.9
2004	1.627	0.483	0.159	0.174	0.063	0.090	2.596	452	1.199	1.4
2005	1.655	0.481	0.162	0.173	0.063	0.092	2.627	454	1.213	1.4
2006	1.685	0.482	0.165	0.173	0.062	0.095	2.662	457	1.229	1.6
2007	1.709	0.484	0.167	0.172	0.062	0.097	2.692	460	1.243	1.4
2008	1.739	0.486	0.170	0.171	0.061	0.100	2.728	463	1.260	1.7
2009	1.760	0.489	0.172	0.171	0.061	0.103	2.755	465	1.273	1.2
2010	1.791	0.491	0.175	0.170	0.060	0.106	2.793	469	1.290	1.7
2011	1.817	0.492	0.178	0.169	0.060	0.109	2.825	471	1.305	1.5
2012	1.845	0.494	0.181	0.168	0.059	0.111	2.858	474	1.320	1.5
2013	1.882	0.496	0.184	0.167	0.059	0.114	2.901	478	1.340	2.0
2014	1.908	0.499	0.187	0.166	0.058	0.116	2.935	481	1.356	1.6
2015	1.939	0.504	0.190	0.165	0.058	0.118	2.974	485	1.374	1.8

** annual change (in %) is calculated relative to 1990*

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