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A GREENHOUSE GAS INDEX FOR COMMUNICATING THE GLOBAL GREENHOUSE GAS BUILDUP

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1. INTRODUCTION

Because of increasing public interest in possible greenhouse-related climate changes, it is often necessary for scientists to explain research findings to decision makers and the public. Some trends, such as the growth of carbon dioxide or another single greenhouse gas, or the general warming of global average temperature since the late 1800s, are relatively easily communicated to the public. However, there is no tool available to concisely display the trend of the composite greenhouse gas content of the air, either observed to date or projected in a scenario, because levels of individual gases are changing at greatly different rates. So, it is difficult to explain to a nonscientist that some of the uncertainty in projected climate changes is caused by the range of future greenhouse gas scenarios. Also, while observed climate changes to date are quite moderate (at least in relation to the higher forecasts of future warming), the public is generally unaware of the magnitude of the growth of greenhouse gases which has already occurred.

2. DEFINITION

An index is often used as a basic indicator of the state of a complex system. Here, a Greenhouse Gas Index (GGI) expresses the global average greenhouse gas content in percent of the preindustrial level. The GGI is modeled on the Consumer Price Index (CPI), which states prices in percent of a reference period to describe inflation. Just as CPI = 200 represents doubled prices (on the average) from the reference, GGI = 200 represents doubled greenhouse gases from the natural level. Unlike the CPI, where the reference is arbitrary (currently in the United States, CPI = 100 refers to average prices from 1982-84), the GGI reference is natural because, without human actions, the GGI would still be very close to 100.

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In the discussion below, most definitions, factors, and scenarios are described in Houghton et al. (2001; hereafter *CC2001*), Nakicenovic and Swart (2000; hereafter *SRES*), and Boden et al. (1994; hereafter *TRENDS93*).

The GGI is a percentage of the preindustrial concentration of well-mixed greenhouse gases, which are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons. Gases are weighted by relative molecular forcing (RMF; Houghton et al. 1990, p. 48 and Table 2.3), which is the ratio of the radiative forcing per unit of volume of a gas (called radiative efficiency in *CC2001*, pp. 386-389) to that of CO_2 (0.01548 W m^{-2} ppm^{-1}).

The GGI is defined as follows, where square brackets are concentrations in parts per million by volume of dry air (ppm), and GGI = 100 is the average preindustrial level of all gases (*CC2001*, Table 6.1), equivalent to 349.0 ppm of CO_2:

$$\text{GGI} = (100 / 349.0\ \text{ppm})\ ([CO_2] + 24\,[CH_4] + 200\,[N_2O] + [\text{halocarbons}]\ \text{weighted by RMF}) \quad (1)$$

Gases called "halocarbons" with scenarios in *CC2001* (pp. 810-813, 816) are CFC-11 (RMF = 16000), CFC-12 (21000), CFC-113 (19000), CFC-114 (20000), CFC-115 (12000), HCFC-22 (13000), HCFC-123 (13000), HCFC-141b (9000), HCFC-142b (13000), HFC-23 (10000), HFC-32 (5800), HFC-125 (15000), HFC-134a (9700), HFC-143a (8400), HFC-152a (5800), HFC-227ea (19000), HFC-245ca (15000), HFC-43-10mee (26000), CH_3CCl_3 (3900), CCl_4 (8400), Halon-1211 (19000), Halon-1301 (21000), SF_6 (34000), CF_4 (5200), and C_2F_6 (17000).

Table 1 lists data sources. Table 2 shows sample GGI values, including three scenarios: IS92a or "business as usual" (*CC2001*, pp. 801-816), a high-emissions scenario called A1FI (*SRES*, p. 437), and a scenario with declining emissions after 2040 called B1 (*SRES*, p. 506). To sample a range of projected CO_2 levels, the B1 scenario uses the low CO_2 case, IS92a uses the reference case, and A1FI uses the high CO_2 case from the ISAM model in *CC2001* (pp. 807-808).

3. OBSERVED AND PROJECTED TRENDS.

Black lines in Figure 1 show GGI components from 1800-2100, using IS92a (*CC2001*, p. 801) from 2000-2100. The thin purple line shows CO_2 alone as a percent of preindustrial. CO_2 growth (32.9 percent by 2001) is less than the composite greenhouse gas growth (42.2 percent). The red and blue lines illustrate very high and low published scenarios.

Figure 2 shows annual percentage GGI changes from 1930-2010. The GGI growth rate (black line) averaged 0.58 percent from 1973-1990 but only 0.42 percent from 1990-2001. No year had 1 percent growth in total greenhouse gas content, but modelers still often use that scenario.

Figure 3a compares annual CO_2 emissions with concentration changes. Industrial emissions (cement production and fossil fuels) are obtained from *TRENDS93* (pp. 505-584). Land use CO_2 emissions (mostly deforestation) are more uncertain (Houghton 1999). In Figure 3b, the CO_2 buildup since 1958 has been 41 percent of human CO_2 emissions. Some studies omit land use CO_2 emissions, and conclude that the buildup averages 55 percent of fossil fuel emissions (e.g., Waple et al. 2002, pp. S14).

Last Glacial Maximum (LGM)	
CO_2	*TRENDS93*, pp. 7-10
CH_4	*TRENDS93*, pp. 229-233
N_2O	*TRENDS93*, pp. 380-384
Preindustrial (including CF_4)	
All gases	*CC2001*, Table 6.1
1800-1850	
CO_2	*TRENDS93*, pp. 11-14
CH_4	*TRENDS93*, pp. 244-249
N_2O	Smooth curve
1850-2001, except halocarbons	
All gases	Hansen et al. (1998)
2010-2100, except halocarbons	
All gases	*CC2001*, pp. 807-810
CFC-11 and CFC-12	
1931-2001	Hansen et al. (1998)
2010-2100	*CC2001*, p. 816
Other halocarbons	
to 1969	Relate to emissions in WMO (1999), pp. 1.23, 2.6
1970-2100	*CC2001*, pp. 810-813, 816

Table 1. Sources of greenhouse gas data. Years outside listed intervals are interpolated if needed. LGM values are ice core averages from 20000-30000 years before present. Projections consider three scenarios as described in the text. If a source is *TRENDS93*, see the listed pages of Boden et al. (1994) for full references.

4. OTHER ISSUES AND ALTERNATIVES

The GGI is a simple index which is linear with concentration, and it includes only well-mixed tropospheric gases. The index was not defined or constructed differently because of reasons such as the following:

4.1 *Why the Index is Weighted by Relative Molecular Forcing Rather than Global Warming Potential*

The Global Warming Potential (GWP) is used most often to compare effects of emissions of different greenhouse gases, but here the gases are weighted by Relative Molecular Forcing (RMF). The RMF is the radiative forcing of a particular volume of a gas, divided by the radiative forcing of the same volume of CO_2. The GWP is the radiative forcing of a particular mass of a gas, divided by the radiative forcing of the same mass of CO_2, over a chosen time horizon.

The first area of difference between the RMF and GWP is that equivalences are computed on the basis of volume or mass. If gas levels are expressed in the correct units, the GGI is unaffected. Published concentrations are stated in parts per million, billion, or trillion, so equivalences based on volume are the most convenient.

The second area of difference is substantial. The GWP assumes a pulse emission of each gas, which is removed from the air according to its profile of decay, and the radiative forcing of each gas is accumulated over a chosen time horizon, such as 100 years. With a long time horizon, a long-lived gas has a higher GWP because the pulse of that gas has decayed less relative to CO_2, while a short-lived gas has a lower GWP because the pulse of that gas has decayed more relative to CO_2. Such distinctions between gas lifetimes are undesirable in defining the GGI. The radiative forcing of each gas is determined without regard to how the level of each gas was attained, and with no implication of future concentrations. RMF values provide a time-independent assessment of the contribution of each gas.

Year or period	Carbon dioxide Ave ppm	Carbon dioxide GGI pts	Methane Ave ppm	Methane Equiv ppm	Methane GGI pts	Nitrous oxide Ave ppm	Nitrous oxide Equiv ppm	Nitrous oxide GGI pts	Halocarbons Ave ppm	Halocarbons Equiv ppm	Halocarbons GGI pts	GREENHOUSE GAS INDEX *Equiv ppm*	GREENHOUSE GAS INDEX **GGI points**
Actual and paleoclimate data				*(LGM is Last Glacial Maximum; Preind. Is Preindustrial average)*									
LGM	197.5	56.6	.396	9.5	2.7	.192	38.4	11.0	.00003	.2	.0	*245.6*	**70.4**
Preind.	278.0	79.7	.700	16.8	4.8	.270	54.0	15.5	.00004	.2	.1	*349.0*	**100.0**
1900	295.5	84.7	.879	21.1	6.0	.280	56.0	16.0	.00005	.2	.1	*372.8*	**106.8**
1950	310.7	89.0	1.147	27.5	7.9	.289	57.8	16.6	.00008	.6	.2	*396.7*	**113.7**
1980	337.9	96.8	1.547	37.1	10.6	.301	60.2	17.3	.00077	11.6	3.3	*446.8*	**128.0**
1990	353.0	101.1	1.676	40.2	11.5	.309	61.7	17.7	.00123	19.1	5.5	*474.1*	**135.8**
2000	368.0	105.4	1.735	41.6	11.9	.316	63.1	18.1	.00134	21.7	6.2	*494.5*	**141.7**
2001	369.5	105.9	1.735	41.6	11.9	.316	63.2	18.1	.00135	21.9	6.3	*496.3*	**142.2**
Scenario B1 - Slow emissions growth (low carbon dioxide model concentrations)													
2000	368.0	105.4	1.760	42.2	12.1	.316	63.2	18.1	.00134	21.7	6.2	*495.2*	**141.9**
2050	455.0	130.4	1.881	45.1	12.9	.357	71.4	20.5	.00129	18.6	5.3	*590.2*	**169.1**
2100	490.0	140.4	1.574	37.8	10.8	.375	75.0	21.5	.00123	15.9	4.6	*618.7*	**177.3**
Scenario IS92a - Business as usual (reference carbon dioxide model concentrations)													
2000	369.0	105.7	1.760	42.2	12.1	.316	63.2	18.1	.00134	21.7	6.2	*496.2*	**142.2**
2050	508.0	145.6	2.497	59.9	17.2	.363	72.6	20.8	.00177	23.6	6.8	*664.1*	**190.3**
2100	723.0	207.2	3.136	75.3	21.6	.403	80.6	23.1	.00238	28.3	8.1	*907.2*	**259.9**
Scenario A1FI - Fast emissions growth (high carbon dioxide model concentrations)													
2000	369.0	105.7	1.760	42.2	12.1	.316	63.2	18.1	.00134	21.7	6.2	*496.2*	**142.2**
2050	597.0	171.1	2.668	64.0	18.3	.378	75.6	21.7	.00166	22.6	6.5	*759.2*	**217.5**
2100	1062.0	304.3	3.413	81.9	23.5	.460	92.0	26.4	.00221	26.3	7.5	*1262.2*	**361.7**

Table 2. Sample Greenhouse Gas Index (GGI) computations, including greenhouse gas concentrations (Ave ppm), equivalent CO_2 concentrations (Equiv ppm), and Greenhouse Gas Index points (GGI pts). Components may not add to totals due to rounding.

4.2 *Why the Index is Not Defined Specifically in Radiative Forcing Terms*

RMF values are assumed constant and are computed from radiative forcings for small changes around recent gas concentrations. Radiative forcing grows less slowly than linearly as concentrations rise because absorbing frequencies gradually become opaque. Nonlinearities can be accounted for by scaling all concentrations in terms of radiative forcing. The Radiative Forcing GGI (RFGGI) is the percentage of the preindustrial concentration of greenhouse gases, with all gases changed by the same percentage, which equals the radiative forcing of an observed (or scenario) combination of gases. The radiative forcing of any combination of greenhouse gases can be computed from factors in Table 6.2 of *CC2001*.

The stated formulation in (1) is a simple linear index of the quantity of gases, which can be explained relatively easily to a nonscientist. The RFGGI would be quite difficult to explain. There are at least three other reasons why the linear form of the index is chosen:

(1) Because the nonlinearities in radiative forcing are not greatly different between an equal increase of gases and the observed unequal increase from preindustrial levels, the RFGGI differs from the linear GGI by no more than 2 points to date. For example, the GGI in 2000 was 141.9 while the RFGGI would have been 143.8 (This means that the observed greenhouse gases in 2000 had the same radiative forcing as an atmosphere with a 43.8 percent increase in each greenhouse gas above the preindustrial level). Future differences between the GGI and RFGGI do not become much larger (in percent of the difference from the base value of 100) in any scenario.

(2) The radiative forcing factors may contain errors as large as 35 percent (*CC2001*, p. 352). The additional precision implied by the RFGGI is not necessarily warranted.

(3) The climate response, or equilibrium warming for a given level of greenhouse gases, is only approximately linear with changes in gas concentrations. The expected amount of global warming (relative to preindustrial) with doubled greenhouse gases should be less than twice as much as with a 50 percent increase in greenhouse gases, whether the change in greenhouse gases is measured by the GGI or RFGGI. The projected amount of warming, or other climate change, must still be determined by modeling.

4.3 *Why Other Forcing Factors Are Excluded*

The GGI excludes many other radiative forcing factors shown in *CC2001*, pp. 392-393. These are tropospheric and stratospheric ozone, sulfate aerosols, carbon aerosols, mineral dust, indirect effects of aerosols on cloud amount and reflectivity, aviation-induced contrails, aviation-induced cirrus, surface albedo effects of land-use changes, and (one natural factor) solar output.

If the magnitude of each factor is expressed as a radiative forcing, it is theoretically possible to compute a Comprehensive Radiative Forcing Index (CRFI), which would be similarly scaled to a preindustrial value of 100. For example, a CRFI of 150 could include the radiative forcing from a 50 percent increase in concentration (from preindustrial levels) of each greenhouse gas in (1) plus tropospheric ozone, sulfate and carbon aerosols, and mineral dust. A percentage increase in any other factor (indirect aerosol effects on clouds, aviation-induced contrails and cirrus, surface albedo changes, and solar output) is not meaningful, so the decision of how to weight each of these factors would be arbitrary. However, if this process is carried out, any combination of forcing factors with that amount of radiative forcing could be assigned a CRFI value of 150.

The error associated with each of these factors is large. As computed from *CC2001* (pp. 392-393), radiative forcing in 2000 from greenhouse gases included in the GGI is centered around 2.43 W m^{-2}, and could range from 2.19 to 2.67 W m^{-2}. Total radiative forcing from all factors is centered around 1.2 W m^{-2} (taking the midpoint of estimates when a most likely forcing is not specified) and could range from -2.35 to 4.23 W m^{-2}. This means that it is felt that the additional factors offset about half of the well-mixed greenhouse gas warming effect, but might compensate for all of that warming, or could reinforce it. The total radiative forcing from all factors might be strong cooling, or more than the radiative forcing from a pure doubling of CO_2 (3.7 W m^{-2}). This extremely large uncertainty makes it impossible to produce a realistic comprehensive index at this time.

Earlier experiments with developing the GGI did include tropospheric ozone. *CC2001* (p. 261) estimates the preindustrial and recent concentration of tropospheric ozone and the radiative forcing fom that increase (including future scenario estimates on p. 822). However, the hypothesized 36 percent increase is not well verified and is not much different from the rise in either CO_2 alone or in the GGI as defined above. With no reliable source of historical global ozone data, the trend can only be included in the index as a smooth curve, and it would change the GGI by less than 1 point to date, so it appears most appropriate to leave it out and define the GGI as strictly an index of the quantity of well-mixed tropospheric greenhouse gases.

The bar chart of forcing factors in *CC2001* (p. 392) omits several factors which may be substantial. These include heat propagating into oceans, heat propagating into land, and radiative forcing from water vapor changes. Only the water vapor factor is discussed below, and it is not feasible to include any of these factors in a GGI at this time.

Models which project a high sensitivity (a large amount of warming for doubled CO_2) assume that the relative humidity does not decrease, so the total water vapor increases by at least the rate implied by Clausius-Clapeyron relationships (about 6 percent per 1° C warming), and the increase in water vapor could double or triple the radiative forcing from the increase in greenhouse gases.

Trends in global water vapor are not known to date. Since water vapor should react very rapidly to any greenhouse warming, any positive or negative water vapor feedback effects should already be operating. Global precipitable water averages should be computable from the radiosonde record back to possibly the early 1960s, if discontinuities caused by radiosonde instrument changes are identified and adjusted for (however, satellite data, available since late 1979, will be required to define trends above the middle troposphere). More speculatively, since the global mass of dry air is almost precisely constant, except for added greenhouse gases (primarily the carbon in CO_2, equivalent to about 0.03 mb since 1900), water vapor changes of a few percent should be detectable over a time scale of a decade or so by computing the global average surface pressure. A 5 percent increase would raise the surface pressure by about 0.12 mb. So, in principle, it will soon be feasible to estimate water vapor radiative forcing for the past few decades and continuing into the future.

4.4 *Why the Index is Not Based on the Definition of "Equivalent Carbon Dioxide"*

Early climate models were often run with doubled CO_2 to estimate the climate sensitivity, or the equilibrium warming with doubled CO_2. As other greenhouse gases were found to be increasing, their increases were expressed as equivalent CO_2 amounts. Equivalent CO_2 is the concentration of CO_2 (with preindustrial amounts of other gases) which would have the same radiative forcing as the observed mixture of gases.

A linear Equivalent CO_2 GGI could be defined by subtracting the preindustrial levels of each gas other than CO_2 (equivalent to 71 ppm of CO_2) from the numerator and denominator of (1). This would produce an Equivalent CO_2 GGI value of 153.0 in 2001, compared to the GGI value of 142.2. Nonlinearity of radiative forcing affects this index more than the basic index, and the radiative forcing of greenhouse gases in 2001 (2.498 W m^{-2} using the formulas in *CC2001*, p. 358) is equivalent to 443.4 ppm of CO_2, an increase of 59.5 percent, giving an index of 159.5.

The equivalent CO_2 concept overstates the composite growth of greenhouse gases, since growth of other gases is converted to growth of CO_2. Doubled equivalent CO_2 would occur if all greenhouse gases increase 71 percent from their preindustrial level. However, the terms "equivalent CO_2" and "climate sensitivity" are useful, so their definitions should not be changed. Climate modelers would need to decide if there should be a term to refer to the expected equilibrium amount of warming with doubled greenhouse gases, or GGI = 200. Assuming the equilibrium temperature changes linearly with the logarithm of the carbon dioxide concentration, this warming would be about 29 percent more than the climate sensitivity (and the equilibrium warming from the level of greenhouse gases in 2001 would be about 66 percent of the climate sensitivity).

5. HOW AN ANALOGOUS GREENHOUSE GAS EMISSIONS INDEX COULD BE DEVELOPED

Because greenhouse gas control efforts focus on emissions, it is desirable to explore the usefulness of a general-purpose Greenhouse Gas Emissions Index (GGEI). Many efforts to derive equivalent emissions of different gases have taken place. The term "Greenhouse Gas Emissions Index" is used by Ellington and Meo (1990) and O'Neill (2000), but their indices were specialized.

There are more difficulties with developing an emissions index than a concentration index (GGI), so a GGEI is only sketched out here.

First, a GGEI unit and a GGI unit of CO_2 should be the same. Since the preindustrial GGI value of 100 is equivalent to 349 ppm of CO_2, a GGI unit of CO_2 is 3.49 ppm, which has a mass of 27.14 gigatons (Gt) of CO_2 or 7.408 Gt of carbon (GtC). The calculation of mass is based on a global mass of dry air of 5,119,500 Gt, excluding 12,500 Gt of water vapor (Trenberth and Guillemot 1994), and molecular weights of 44.0098 for CO_2, 12.011 for carbon, and 28.97 for dry air. A pulse emission of 7.408 GtC in the form of CO_2 would instantly raise the GGI by 1 point.

The second issue is to develop the equivalence of emissions of other gases to CO_2 emissions. A GGEI unit is the amount of a gas with the same integrated radiative forcing over a time horizon as the forcing of a GGEI unit of CO_2. The GWP, as discussed in 4.1 above, expresses this equivalence (*CC2001*, pp. 386-389). Here, a 100-year time horizon is used, so a GGEI unit of a gas is 27.143 Gt divided by its 100-year GWP. For CH_4, with a 100-year GWP of 23, a GGEI unit is 27.143 / 23 = 1.18 Gt of CH_4 or 0.416 ppm. The International Energy Agency (IEA) states United States greenhouse gas emissions as equivalent CO_2 (IEA 2001, Tables ES1 and ES2), which is very similar to the GGEI, but omits land-use CO_2 emissions.

The GGEI is defined as follows, where emissions are expressed in Gt (If CO_2 emissions are in GtC, they must be converted to Gt of CO_2):

$$\begin{aligned} \text{GGEI} = [\,100 / 27.143\ \text{Gt}\,]\ &[\,(CO_2\ \text{emissions}) \\ &+ 23\ (CH_4\ \text{emissions}) \\ &+ 296\ (N_2O\ \text{emissions}) \\ &+ (\text{halocarbons weighted by GWP})\,] \end{aligned} \qquad (2)$$

There are at least four major difficulties that make the GGEI less useful than the GGI:

(1) For all gases except CO_2 and halocarbons, historical (and sometimes even current) emissions are not known accurately.

(2) Indirect anthropogenic emissions are not well defined. For example, CO_2 "emissions" from land-use change (primarily conversion of forests to crop land) include CO_2 which is not absorbed

because trees are no longer growing on that land.

(3) Because gas emissions occur over time rather than as a pulse, 1 GGEI unit of emissions would not be expected to raise the GGI by 1 unit.

(4) A constant 100-year time horizon is not always appropriate for either political or scientific uses, so the GGEI is not necessarily suitable for specific tradeoff decisions. For example, it may be politically desirable to reduce CH_4 emissions to quickly reduce CH_4 levels, while the GGEI may decrease a larger amount by reducing emissions of a long-lived greenhouse gas.

6. RECOMMENDATIONS AND CAUTIONS.

The GGI can be used in the following ways to help put climate findings and projections into the context of the trend of atmospheric changes:

(1) In a model study, display the GGI time series along with the scenario. In a steady state run, such as with "doubled CO_2," state the implied GGI value. If a model run simulates from the past into the future, compare the simulation with historical data and explain differences if possible.

(2) While the GGI is not "owned" by any organization, agencies which maintain scenarios should also maintain (or refer to a source of) historical estimates of greenhouse gases, so scenarios mesh smoothly with the past trend.

(3) If a model computes greenhouse gas concentrations from emissions, compute the model GGI and compare it with the observed GGI.

(4) The GGI should not substitute for any climate research procedures and should not be used to "prove" the climate sensitivity, or forecast the rate of warming or any other climate change.

7. SUMMARY.

The GGI concisely describes observed and possible future greenhouse gas trends to a nontechnical audience. It can clarify facts and projections such as the following:

(1) The greenhouse gas content of the air rose about 42 percent from preindustrial times to 2001.

(2) Human modifications to the air are as large (in percentage) as the natural change from the last ice age to preindustrial times.

(3) Greenhouse gases have grown about 0.5 percent per year in the last few decades but growth slowed from exponential to nearly linear.

(4) In 2100, the highest scenario has over twice the greenhouse gas level of the lowest.

Without the GGI, it is difficult to quantitatively explain greenhouse gas trends to nonscientists. With this index, it is easier to relate these changes to observed and projected climate trends and to clarify expected effects of proposed actions.

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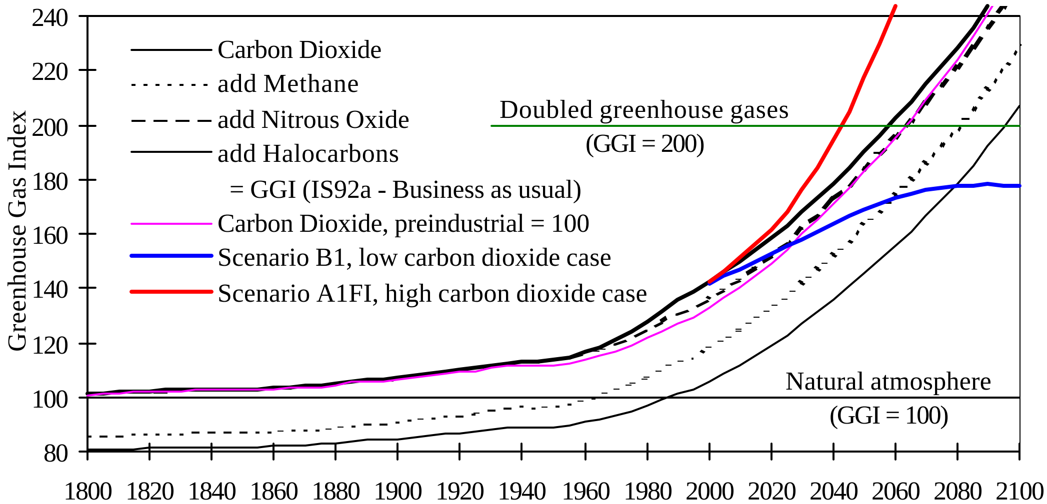

FIG. 1. Black lines show GGI components from 1800 to 2100, with projections using scenario IS92a ("business as usual") after 2000. Thick black line shows total GGI. Purple line shows carbon dioxide alone in percent of preindustrial. Red and blue lines show high and low concentration scenarios.

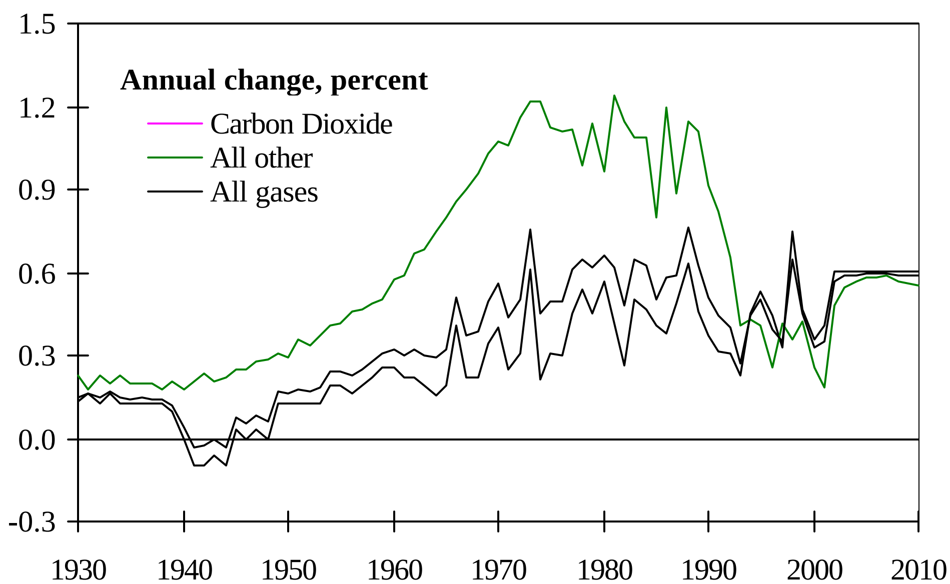

FIG. 2. Annual percent change in GGI from previous year for 1930-2010, using a smooth trend between latest data and IS92a projections from 2002-2010, for CO_2, all other gases, and total GGI.

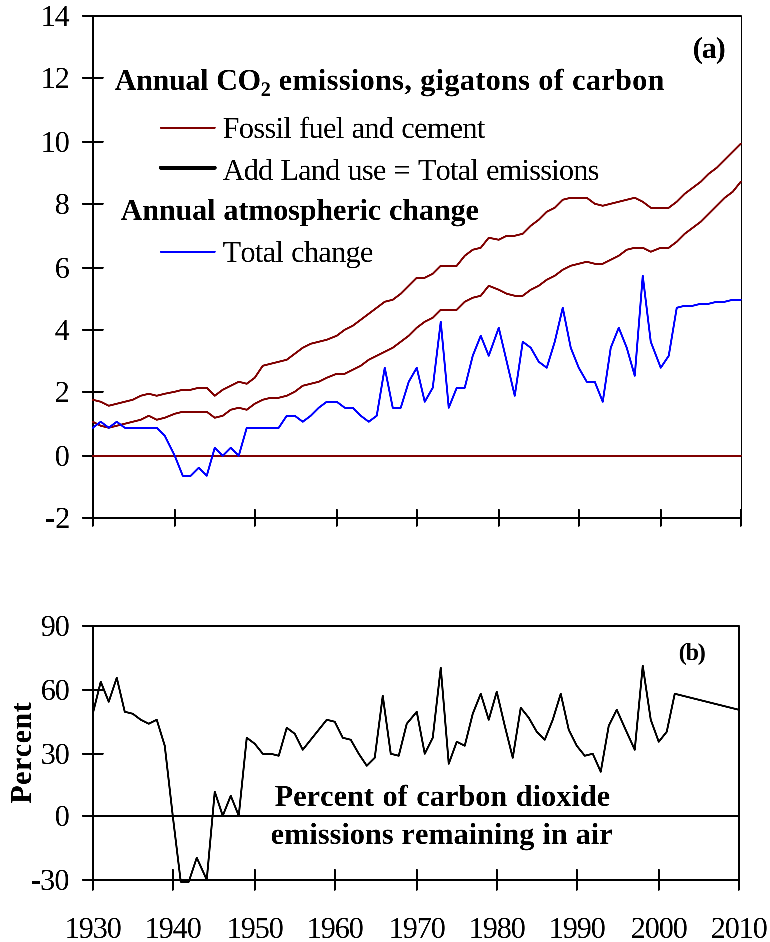

FIG. 3. (a) Annual CO_2 emissions compared with atmospheric CO_2 concentration change from previous year, gigatons of carbon. Brown line shows industrial emissions and thick line shows total emissions. (b) Change of CO_2 in air as a percent of total emissions.