GREENHOUSE GASES AND GLOBAL WARMING POTENTIAL VALUES

EXCERPT FROM THE *INVENTORY OF U.S. GREENHOUSE EMISSIONS AND SINKS: 1990-2000*

U.S. Greenhouse Gas Inventory Program
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Introduction

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and removals for the years 1990 through 2000. The estimates are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing. [1,2]

The Intergovenmental Panel on Climate Change (IPCC) has recently updated the specific global warming potentials for most greenhouse gases in their Third Assessment Report (TAR, IPCC 2001). Although the GWPs have been updated, estimates of emissions presented in the U.S. *Inventory* continue to use the GWPs from the Second Assessment Report (SAR). The guidelines under which the *Inventory* is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories[3] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the U.S. *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends.

Additional discussion on emission trends for the United States can be found in the complete Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000.

What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other

elements of the Earth's climate system. Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters, and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33°C lower (IPCC 2001).

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Given that definition, in its Second Assessment Report of the science of climate change, the IPCC concluded that:

> *Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).*

Building on that conclusion, the more recent IPCC Third Assessment Report asserts that "[c]oncentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities" (IPCC 2001).

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[1] See the section below entitled *Global Warming Potentials* for an explanation of GWP values.

[2] See the section below entitled *What is Climate Change?* for an explanation of radiative forcing.

[3] See FCCC/CP/1999/7 at <www.unfccc.de>.

The IPCC went on to report that the global average surface temperature of the Earth has increased by between $0.6 \pm 0.2°C$ over the 20th century (IPCC 2001). This value is about 0.15°C larger than that estimated by the Second Assessment Report, which reported for the period up to 1994, "owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data" (IPCC 2001).

While the Second Assessment Report concluded, "the balance of evidence suggests that there is a discernible human influence on global climate," the Third Assessment Report states the influence of human activities on climate in even starker terms. It concludes that, "[I]n light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (IPCC 2001).

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty; consequently these gases are not included in national greenhouse gas inventories. Some other fluorine containing halogenated substances— hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases— referred to as ambient air pollutants—include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light (sunlight). Aerosols—extremely small particles or liquid droplets—often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants— can affect the absorptive characteristics of the atmosphere. However, the level of scientific understanding of aerosols is still very low (IPCC 2001).

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the

atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly

or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1.

Table 1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6[a]	CF_4[a]
Pre-industrial atmospheric concentration	278	0.700	0.270	0	40
Atmospheric concentration (1998)	365	1.745	0.314	4.2	80
Rate of concentration change[b]	1.5[c]	0.007[c]	0.0008	0.24	1.0
Atmospheric Lifetime	50-200[d]	12[e]	114[e]	3,200	>50,000

Source: IPCC (2001)
[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.
[b] Rate is calculated over the period 1990 to 1999.
[c] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH4 over the period 1990 to 1999.
[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.
[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds,

which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 367 ppmv in 1999, a 31 percent increase (IPCC 2001). The IPCC notes that "[t]his concentration has not been exceeded during the past 420,000 years, and likely not

during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years." The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its second assessment, the IPCC also stated that "[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth's surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane (CH$_4$). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of methane have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use and waste disposal (IPCC 2001).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with Cl in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of methane reduce the concentration of OH, a feedback which may increase methane's atmospheric lifetime (IPCC 2001).

Nitrous Oxide (N$_2$O). Anthropogenic sources of N_2O emissions include agricultural soils, especially the use of synthetic and manure fertilizers; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N_2O) has increased by 16 percent since 1750, from a pre industrial value of about 270 ppb to 314 ppb in 1998, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere.

Ozone (O$_3$). Ozone is present in both the upper stratosphere, where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere, where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds mixing with nitrogen oxides (NO_x) in the presence of sunlight. Ozone, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter are included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF_6). Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride—and bromine—halons, methyl bromide, and hydrobromofluorocarbons (HBFCs)—result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5 countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are not ozone depleting substances, and therefore are not covered under the Montreal Protocol. They are, however, powerful greenhouse gases. HFCs—primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process—currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2001). PFCs and SF_6 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs and SF_6 is also small; however, they have a significant growth rate, extremely long atmospheric lifetimes, and are

strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2001).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. Additionally, NO_x emissions from aircraft are also likely to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning – both natural and anthropogenic fires – fuel combustion, and, in the stratosphere, from the photo-degradation of nitrous oxide (N_2O). Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural

events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. They affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols are typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulphates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols is believed to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere—lasting days to weeks—their concentrations respond rapidly to changes in emissions. Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). "However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result" (IPCC 1996).

The IPCC's Third Assessment Report notes that "the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive" (IPCC 2001). Additionally, current research suggests that another constituent of aerosols, elemental carbon, may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

Global Warming Potentials

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide (CO_2) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg CO}_2 \text{ Eq} = \left(\text{Gg of gas}\right) \times \left(\text{GWP}\right) \times \left(\frac{\text{Tg}}{1,000\,\text{Gg}}\right)$$

where,

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents
Gg = Gigagrams (equivalent to a thousand metric tons)
GWP = Global Warming Potential
Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have

agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table 2).

> *In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons. (FCCC/CP/1996/15/Add.1)*

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and black carbon), however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 2: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory

Gas	Atmospheric Lifetime	100-year GWP[a]	20-year GWP	500-year GWP
Carbon dioxide (CO_2)	50-200	1	1	1
Methane (CH_4)[b]	12±3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF_4	50,000	6,500	4,400	10,000
C_2F_6	10,000	9,200	6,200	14,000
C_4F_{10}	2,600	7,000	4,800	10,100
C_6F_{14}	3,200	7,400	5,000	10,700
SF_6	3,200	23,900	16,300	34,900

Source: IPCC (1996)
[a] GWPs used here are calculated over 100 year time horizon
[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Table 3 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

Table 3: Net 100-year Global Warming Potentials for Select Ozone Depleting Substances*

Gas	Direct	Net$_{min}$	Net$_{max}$
CFC-11	4,600	(600)	3,600
CFC-12	10,600	7,300	9,900
CFC-113	6,000	2,200	5,200
HCFC-22	1,700	1,400	1,700
HCFC-123	120	20	100
HCFC-124	620	480	590
HCFC-141b	700	(5)	570
HCFC-142b	2,400	1,900	2,300
$CHCl_3$	140	(560)	0
CCl_4	1,800	(3,900)	660
CH_3Br	5	(2,600)	(500)
Halon-1211	1,300	(24,000)	(3,600)
Halon-1301	6,900	(76,000)	(9,300)

Source: IPCC (2001)

* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The effects of these compounds on radiative forcing are not addressed here.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within that report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that

resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. The changes are described in the TAR as follows:

New categories of gases include fluorinated organic molecules, many of which are ethers that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to CO_2 using an improved calculation of the CO_2 radiative forcing, the SAR response function for a CO_2 pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.

Table 4 compares the lifetimes and GWPs for the SAR and TAR. As can be seen in Table 4, GWPs changed anywhere from a decrease of 15 percent to an increase of 49 percent.

Table 4: Comparison of GWPs and lifetimes used in the SAR and the TAR

Gas	Lifetime (years)		GWP (100 year)			
	SAR	TAR	SAR	TAR	Difference	
Carbon dioxide (CO_2)	50-200	5-200[a]	1	1	NC	NC
Methane (CH_4)[b]	12±3	8.4/12[c]	21	23	2	10%
Nitrous oxide (N_2O)	120	120/114[c]	310	296	(14)	-5%
Hydrofluorocarbons						
HFC-23	264	260	11,700	12,000	300	3%
HFC-32	5.6	5.0	650	550	(100)	-15%
HFC-41	3.7	2.6	150	97	(53)	-35%
HFC-125	32.6	29	2,800	3,400	600	21%
HFC-134	10.6	9.6	1,000	1,100	100	10%
HFC-134a	14.6	13.8	1,300	1,300	NC	NC
HFC-143	3.8	3.4	300	330	30	10%
HFC-143a	48.3	52	3,800	4,300	500	13%
HFC-152	NA	0.5	NA	43	NA	NA
HFC-152a	1.5	1.4	140	120	(20)	-14%
HFC-161	NA	0.3	NA	12	NA	NA
HFC-227ea	36.5	33.0	2,900	3,500	600	21%
HFC-236cb	NA	13.2	NA	1,300	NA	NA
HFC-236ea	NA	10	NA	1,200	NA	NA
HFC-236fa	209	220	6,300	9,400	3,100	49%
HFC-245ca	6.6	5.9	560	640	80	14%
HFC-245fa	NA	7.2	NA	950	NA	NA
HFC-365mfc	NA	9.9	NA	890	NA	NA
HFC-4310mee	17.1	15	1,300	1,500	200	15%
Iodocarbons						
FIC-1311	<0.005	0.005	<1	1	NC	NC
Fully Fluorinated Species						
SF_6	3,200	3,200	23,900	22,000	(1,900)	-8%
CF_4	50,000	50,000	6,500	5,700	(800)	-12%
C_2F_6	10,000	10,000	9,200	11,900	2,700	29%
C_3F_8	2,600	2,600	7,000	8,600	1,600	23%
C_4F_{10}	2,600	2,600	7,000	8,600	1,600	23%
c-C_4F_8	3,200	3,200	8,700	10,000	1,300	15%
C_5F_{12}	4,100	4,100	7,500	8,900	1,400	19%
C_6F_{14}	3,200	3,200	7,400	9,000	1,600	22%

Table 4: (continued)

Ethers and Halogenated Ethers						
CH_3OCH_3	NA	0.015	NA	1	NA	NA
$(CF_3)_2CFOCH_3$	NA	3.4	NA	330	NA	NA
$(CF_3)CH_2OH$	NA	0.5	NA	57	NA	NA
$CF_3CF_2CH_2OH$	NA	0.4	NA	40	NA	NA
$(CF_3)_2CHOH$	NA	1.8	NA	190	NA	NA
HFE-125	NA	150	NA	14,900	NA	NA
HFE-134	NA	26.2	NA	6,100	NA	NA
HFE-143a	NA	4.4	NA	750	NA	NA
HCFE-235da2	NA	2.6	NA	340	NA	NA
HFE-245cb2	NA	4.3	NA	580	NA	NA
HFE-245fa2	NA	4.4	NA	570	NA	NA
HFE-254cb2	NA	0.22	NA	30	NA	NA
HFE-347mcc3	NA	4.5	NA	480	NA	NA
HFE-356pcf3	NA	3.2	NA	430	NA	NA
HFE-374pcf2	NA	5.0	NA	540	NA	NA
HFE-7100	NA	5.0	NA	390	NA	NA
HFE-7200	NA	0.77	NA	55	NA	NA
H-Galden 1040x	NA	6.3	NA	1,800	NA	NA
HG-10	NA	12.1	NA	2,700	NA	NA
HG-01	NA	6.2	NA	1,500	NA	NA
Others[d]						
NF_3	NA	740	NA	10,800	NA	NA
SF_5CF_3	NA	>1,000	NA	>17,500	NA	NA
$c\text{-}C_3F_6$	NA	>1,000	NA	>16,800	NA	NA
HFE-227ea	NA	11	NA	1,500	NA	NA
HFE-236ea2	NA	5.8	NA	960	NA	NA
HFE-236fa	NA	3.7	NA	470	NA	NA
HFE-245fa1	NA	2.2	NA	280	NA	NA
HFE-263fb2	NA	0.1	NA	11	NA	NA
HFE-329mcc2	NA	6.8	NA	890	NA	NA
HFE-338mcf2	NA	4.3	NA	540	NA	NA
HFE-347-mcf2	NA	2.8	NA	360	NA	NA
HFE-356mec3	NA	0.94	NA	98	NA	NA
HFE-356pcc3	NA	0.93	NA	110	NA	NA
HFE-356pcf2	NA	2.0	NA	260	NA	NA
HFE-365mcf3	NA	0.11	NA	11	NA	NA
$(CF_3)_2CHOCHF_2$	NA	3.1	NA	370	NA	NA
$(CF_3)_2CHOCH_3$	NA	0.25	NA	26	NA	NA
$\text{-}(CF_2)_4CH(OH)\text{-}$	NA	0.85	NA	70	NA	NA

[a] No single lifetime can be determined for carbon dioxide. (See IPCC 2001)

[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).

[d] Gases whose lifetime has been determined only via indirect means of for whom there is uncertainty over the loss process.

Source: IPCC (2001)

NC (No Change)

NA (Not Applicable)

When the GWPs from the TAR are applied to the emission estimates presented in this document, total emissions for the year 2000 are 7,044.3 Tg CO_2 Eq., as compared to 7,001.2 Tg CO_2 Eq. when the GWPs from the SAR are used (0.6% difference). Table 5 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2000, using the GWPs

from the TAR. The adjusted greenhouse gas emissions are shown for each gas in units of Tg CO_2 Eq. in Table 6. The correlating percent change in emissions of each gas is shown in Table 7. The percent change in emissions is equal to the percent change in the GWP, however, in cases where multiple gases are emitted in varying amounts the percent change is variable over the years, such as with substitutes for ozone depleting substances. Table 8 summarizes the emissions and resulting change in emissions using GWPs from the SAR or the TAR for 1990 and 2000.

Table 5: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the TAR GWPs (Tg CO_2 Eq.)

Gas/Source	1990	1995	1996	1997	1998	1999	2000
CO₂	**4,998.5**	**5,305.9**	**5,483.7**	**5,568.0**	**5,575.1**	**5,665.5**	**5,840.0**
Fossil Fuel Combustion	4,779.8	5,085.0	5,266.6	5,339.6	5,356.2	5,448.6	5,623.3
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	6.1
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40.0	41.1
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3
Limestone and Dolomite Use	5.2	7.0	7.4	8.4	8.2	9.1	9.2
Soda Ash Manufacture and Consumption	4.1	4.3	4.2	4.4	4.3	4.2	4.2
Carbon Dioxide Consumption	0.8	1.0	1.1	1.3	1.4	1.6	1.4
Waste Combustion	14.1	18.6	19.6	21.3	20.3	21.8	22.5
Titanium Dioxide Production	1.3	1.7	1.7	1.8	1.8	1.9	2.0
Aluminum Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4
Iron and Steel Production	85.4	74.4	68.3	76.1	67.4	64.4	65.7
Ferroalloys	2.0	1.9	2.0	2.0	2.0	2.0	1.7
Indirect CO₂	30.9	29.5	28.9	28.4	28.2	27.0	26.3
Ammonia Manufacture	18.5	18.9	19.5	19.5	20.1	18.9	18.0
Land-Use Change and Forestry (Sink)[a]	(1,097.7)	(1,110.0)	(1,108.1)	(887.5)	(885.9)	(896.4)	(902.5)
International Bunker Fuels [b]	113.9	101.0	102.3	109.9	112.9	105.3	100.2
CH₄	**713.3**	**720.2**	**705.0**	**693.7**	**686.8**	**679.6**	**673.0**
Stationary Sources	8.6	9.0	9.2	8.2	7.7	8.0	8.2
Mobile Sources	5.4	5.2	5.1	5.0	4.9	4.8	4.8
Coal Mining	95.4	80.5	74.9	74.6	74.4	69.8	66.8
Natural Gas Systems	132.8	137.6	138.7	134.4	133.9	129.9	127.4
Petroleum Systems	28.9	26.5	26.3	26.3	25.6	24.4	23.9
Petrochemical Production	1.3	1.7	1.7	1.8	1.8	1.8	1.8
Silicon Carbide Production	+	+	+	+	+	+	+
Enteric Fermentation	140.1	145.9	141.9	138.8	136.8	136.4	135.7
Manure Management	32.0	38.1	37.5	39.3	41.6	41.1	41.0
Rice Cultivation	7.8	8.3	7.6	8.2	8.7	9.1	8.2
Agricultural Residue Burning	0.7	0.7	0.8	0.8	0.9	0.8	0.9
Landfills	233.7	237.3	231.6	226.0	220.1	222.4	222.9
Wastewater Treatment	26.6	29.3	29.6	30.2	30.5	31.0	31.4
International Bunker Fuels [b]	0.2	0.1	0.1	0.2	0.2	0.1	0.1
N₂O	**369.8**	**400.8**	**411.0**	**410.4**	**407.1**	**404.4**	**406.1**
Stationary Source	12.2	12.9	13.4	13.6	13.7	13.9	14.3
Mobile Sources	48.6	57.7	57.4	57.0	56.5	56.0	55.7
Adipic Acid	14.2	17.1	17.0	11.0	7.4	7.3	7.7
Nitric Acid	17.0	19.0	19.8	20.3	19.9	19.2	18.9
Manure Management	15.3	15.6	16.0	16.3	16.3	16.4	16.7
Agricultural Soil Management	255.0	270.6	279.4	284.1	284.9	282.9	284.1
Agricultural Residue Burning	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Human Sewage	6.7	7.3	7.4	7.6	7.7	8.0	8.1
Waste Combustion	0.3	0.3	0.3	0.2	0.2	0.2	0.2
International Bunker Fuels [b]	0.9	0.8	0.9	0.9	0.9	0.9	0.9

Table 5: (continued)

HFCs, PFCs, and SF_6	91.1		97.8	111.9	117.6	129.8	122.9	125.1
Substitution of Ozone Depleting Substances	0.9		22.6	32.3	39.9	47.4	54.4	61.5
Aluminum Production	16.8		10.9	11.5	10.1	8.3	8.2	7.3
HCFC-22 Production[c]	35.9		27.7	31.9	30.8	41.2	31.2	30.6
Semiconductor Manufacture[d]	3.3		6.8	6.3	7.6	8.4	9.0	8.5
Electrical Transmission and Distribution[e]	29.0		24.6	24.9	22.7	18.7	14.4	13.4
Magnesium Production and Processing[e]	5.1		5.1	5.1	6.4	5.7	5.7	3.7
Total	**6,172.7**		**6,524.8**	**6,711.7**	**6,789.6**	**6,798.8**	**6,872.3**	**7,044.3**

+ Does not exceed 0.05 Tg CO_2 Eq.

[a] Sinks are only included in net emissions total, and are based partially on projected activity data. Parentheses indicate negative values (or sequestration).

[b] Emissions from International Bunker Fuels are not included in totals.

[c] HFC-23 emitted

[d] Emissions from HFC-23, CF_4, C_2F_6, C_3F_8 SF_6, and the addition of NF_3

[e] SF_6 emitted

Note: Totals may not sum due to independent rounding.

Table 6: Change in U.S. Greenhouse Gas Emissions and Sinks Using TAR vs SAR GWPs (Tg CO_2 Eq.)

Gas	1990		1995	1996	1997	1998	1999	2000
CO_2	NC		NC	NC	NC	NC	NC	NC
CH_4	62.0		62.6	61.3	60.3	59.7	59.1	58.5
N_2O	(17.5)		(19.0)	(19.4)	(19.4)	(9.3)	(9.1)	(9.2)
HFCs, PFCs, and SF_6*	(2.6)		(0.7)	0.1	0.6	2.1	2.9	3.8
Total	**42.0**		**42.9**	**41.9**	**41.6**	**42.6**	**42.8**	**43.1**

NC (No change)

*Includes NF_3

Note: Totals may not sum due to independent rounding.

Table 7: Change in U.S. Greenhouse Gas Emissions Using TAR vs SAR GWPs (Percent)

Gas/Source	1990		1995	1996	1997	1998	1999	2000
CO_2	NC		NC	NC	NC	NC	NC	NC
CH_4	9.5		9.5	9.5	9.5	9.5	9.5	9.5
N_2O	(4.5)		(4.5)	(4.5)	(4.5)	(4.5)	(4.5)	(4.5)
HFCs, PFCs, and SF_6	(2.7)		(0.7)	0.1	0.6	1.6	2.4	3.1
Substitution of Ozone Depleting Substances	(3.2)		3.7	5.4	5.1	5.6	6.1	6.5
Aluminum Production[a]	(7.0)		(7.7)	(7.8)	(7.9)	(7.9)	(7.9)	(8.0)
HCFC-22 Production[b]	2.6		2.6	2.6	2.6	2.6	2.6	2.6
Semiconductor Manufacture[c]	15.9		15.9	15.9	15.9	15.9	15.9	15.9
Electrical Transmission and Distribution[d]	(7.1)		(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)
Magnesium Production and Processing[d]	(7.1)		(7.1)	(7.1)	(7.1)	(7.1)	(7.1)	(7.1)
Total	**0.7**		**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**

NC (No change)

[a] PFC emissions from CF_4 and C_2F_6

[b] HFC-23 emitted

[c] Emissions from HFC-23, CF_4, C_2F_6, C_3F_8 SF_6, and the addition of NF_3

[d] SF_6 emitted

Note: Excludes Sinks.

Table 8: Effects on U.S. Greenhouse Gas Emissions Using TAR vs SAR GWPs (Tg CO_2 Eq.)

Gas	Trend from 1990 to 2000		Revisions to Annual Estimates	
	SAR	TAR	1990	2000
CO_2	841.5	841.5	NC	NC
CH_4	(36.8)	(40.3)	62.0	58.5
N_2O	38.0	36.3	(17.5)	(19.2)
HFCs, PFCs, and SF_6*	27.7	34.0	(2.6)	3.8
Total	**870.5**	**871.6**	**42.0**	**43.1**
Percent Change	**14.2%**	**14.1%**	**0.7%**	**0.6%**

NC (No Change)
*Includes NF_3
Note: Totals may not sum due to independent rounding. Excludes Sinks.

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table 6, Table 7, and Table 8. Table 9 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and TAR GWP values. For most sectors, the change in emissions was minimal.

The effect on emissions from waste was by far the greatest (9.1 percent), due the predominance of CH_4 emissions in this sector. Emissions from all other sectors were comprised of mainly CO_2 or a mix of gases, which moderated the effect of the changes.

Table 9: Comparison of Emissions by Sector using IPCC SAR and TAR GWP Values (Tg CO_2 Eq.)

Sector	1990	1995	1996	1997	1998	1999	2000
Energy							
SAR GWP (Used in Inventory)	5,141.9	5,452.4	5,629.9	5,697.9	5,709.5	5,793.9	5,962.6
TAR GWP	5,162.6	5,471.6	5,648.6	5,716.2	5,727.6	5,811.2	5,979.4
Difference (%)	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%
Industrial Processes							
SAR GWP (Used in Inventory)	295.7	301.9	312.3	322.4	322.1	310.8	312.8
TAR GWP	291.8	299.6	310.8	321.7	323.1	312.6	315.5
Difference (%)	-1.3%	-0.8%	-0.5%	-0.2%	0.3%	0.6%	0.8%
Agriculture							
SAR GWP (Used in Inventory)	448.4	476.4	481.3	485.9	487.6	485.0	485.1
TAR GWP	451.3	479.6	483.6	487.9	489.7	487.1	487.1
Difference (%)	0.6%	0.7%	0.5%	0.4%	0.4%	0.4%	0.4%
Land-Use Change and Forestry							
SAR GWP (Used in Inventory)	(1,097.7)	(1,110.0)	(1,108.1)	(887.5)	(885.9)	(896.4)	(902.5)
TAR GWP	(1,097.7)	(1,110.0)	(1,108.1)	(887.5)	(885.9)	(896.4)	(902.5)
Difference (%)	NC	NC	NC	NC	NC	NC	NC
Waste							
SAR GWP (Used in Inventory)	244.7	251.1	246.3	241.9	236.9	239.8	240.6
TAR GWP	267.0	273.9	268.7	263.8	258.3	261.5	262.4
Difference (%)	9.1%	9.1%	9.1%	9.1%	9.0%	9.0%	9.0%
Net Emissions (Sources and Sinks)							
SAR GWP (Used in Inventory)	**5,033.0**	**5,371.8**	**5,561.7**	**5,860.5**	**5,870.3**	**5,933.1**	**6,098.7**
TAR GWP	**5,074.9**	**5,414.7**	**5,603.6**	**5,902.1**	**5,912.9**	**5,975.9**	**6,141.8**
Difference (%)	**0.8%**	**0.8%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**	**0.7%**

NC (No change)
Note: Totals may not sum due to independent rounding.

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