Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bengaluru

Lecture 16
Global Warming Potential

In the previous lecture, it was discussed that while major greenhouse gases like carbon dioxide (CO_2), water vapor, and methane (CH_4) are critically important, a large number of minor gases also contribute to the Earth's greenhouse effect. These gases often exist in concentrations as low as parts per trillion. Despite their low abundance, their long atmospheric lifetimes make them significant contributors to long-term climate change. Therefore, when assessing temperature changes projected over the next century, it is essential to account for the impact of these minor greenhouse gases.

To enable meaningful comparisons between gases with different atmospheric lifetimes and radiative efficiencies, the Intergovernmental Panel on Climate Change (IPCC) introduced the concept of Global Warming Potential (GWP). GWP is an index that quantifies the cumulative radiative forcing of a greenhouse gas over a specific time horizon (commonly 100 years), taking into account both how effectively a gas absorbs infrared radiation and how long it remains in the atmosphere. This framework allows policymakers to prioritize actions based on the overall warming impact of each gas.

The need for GWP becomes particularly evident in international climate negotiations, where setting emission reduction targets requires prioritizing gases that pose the greatest long-term threat. For example, methane is a potent greenhouse gas with a relatively short atmospheric lifetime of about 10 to 20 years. It eventually oxidizes into carbon dioxide and water vapor. In contrast, chlorofluorocarbons (CFCs), although present in much smaller quantities, are extremely stable and can persist in the atmosphere for hundreds or even thousands of years, leading to substantial long-term warming despite their current radiative forcing being relatively modest.

GWP captures both these aspects of radiative efficiency (a gas's ability to trap heat) and lifetime (how long it remains in the atmosphere). To standardize this comparison, the IPCC uses CO_2 as the reference gas, assigning it a GWP of 1. All other gases are then evaluated relative to CO_2. For instance, over a 100-year time scale, methane has a GWP of about 27–30, meaning one kilogram of methane traps as much heat as 27 to 30 kilograms of CO_2. Therefore, reducing a smaller quantity of methane can have a climate benefit equivalent to a much larger reduction of CO_2.

Similarly, nitrous oxide (N_2O) is approximately 273 times more powerful than CO_2 over a 100-year period. Despite its low atmospheric concentration, its high GWP and long lifetime make it a critical gas to manage in climate mitigation strategies. Methane also influences ozone formation in the atmosphere, and since ozone itself is a greenhouse gas, this adds another layer to methane's warming potential. Overall, GWP provides a crucial tool for evaluating and comparing the long-term climate impact of various greenhouse gases.

The Global Warming Potential (GWP) of a gas is quantitatively defined using an integral that measures and compares the total radiative forcing of a given gas over a specified time horizon to that of carbon dioxide (CO_2), the reference gas. The formula is expressed as:

$$GWP(x) = \frac{\int_0^{TH} a_x * C_x(t)dt}{\int_0^{TH} a_{CO_2} * C_{CO_2}(t)dt}$$

Here:

- a_x is the radiative efficiency (in $W \cdot m^{-2} \cdot kg^{-1}$) of the gas x,
- $C_x(t)$ is the time-dependent concentration of gas x following a pulse emission of 1 kg at time $t = 0$,
- TH is the time horizon, typically 20, 50, or 100 years,
- a_{CO_2} and $C_{CO_2}(t)$ represent the corresponding values for carbon dioxide.

This ratio effectively compares the cumulative impact of 1 kg of a given gas to 1 kg of CO_2 over a chosen time period. The integral accounts for both how strongly a gas traps heat (its radiative efficiency) and how long it remains in the atmosphere (its decay function). CO_2, with its complex and multi-timescale decay, serves as the baseline (GWP = 1), and all other gases are scaled relative to it. This formulation ensures that both short-lived but potent gases (like methane) and long-lived but less potent gases (like some halocarbons) can be evaluated on a common basis when planning climate policy and emission reductions.

The establishment of the Intergovernmental Panel on Climate Change (IPCC) is closely linked to global efforts to address ozone depletion. A key figure in this development was the scientist Bert Bolin, who recognized the necessity of a formal, international body to assess and address the growing concerns surrounding carbon dioxide and other greenhouse gases. His initiative followed the Montreal Protocol of 1987, a highly successful international agreement designed to reduce substances responsible for ozone layer depletion. Seeing the effectiveness of this treaty, Bolin advocated for a similar mechanism focused on climate change, leading to the formation of the IPCC in 1988.

The IPCC was conceived as a body that could scientifically assess climate change, its impacts, and propose realistic response strategies. This was deemed essential to persuade

governments to commit to meaningful CO_2 emission reductions. The panel comprises representatives from 194 countries, ensuring that its findings undergo comprehensive review and reflect a global consensus. The IPCC's work laid the groundwork for later climate agreements such as the Kyoto Protocol.

Notably, historian Paul Edwards observed that IPCC reports are among the most rigorously scrutinized scientific documents in history. This intense review process is driven by the profound implications that climate policy has for economies and societies worldwide. As such, the IPCC's credibility and thoroughness play a vital role in informing global climate policy and shaping international action against climate change.

A critical point to understand about the Intergovernmental Panel on Climate Change (IPCC) is that it does not conduct original scientific research. Rather, it acts as an assessment body, systematically reviewing and synthesizing the existing scientific literature to summarize what is known at a given time about climate change. This information is then used by governments worldwide to guide policy decisions.

The IPCC has evolved significantly since its creation in 1988. Its first report in 1990 cautiously stated that it was not yet possible to detect unequivocally whether the enhanced greenhouse effect was caused by human activities. However, by 1995, in its second assessment, the IPCC noted that "the balance of evidence suggests" a discernible human influence on global climate—still tentative, but stronger than before.

Over the next two decades, the IPCC's conclusions became increasingly confident as more data accumulated. In the 2001 report, it stated that most of the observed warming over the last 50 years was "likely" (meaning a 66% probability) due to human activities. In 2007, this assessment was upgraded to "very likely" (90% probability), and by 2013, the fifth assessment report declared it "extremely likely" (95% probability) that human influence was the dominant cause of global warming since the mid-20th century.

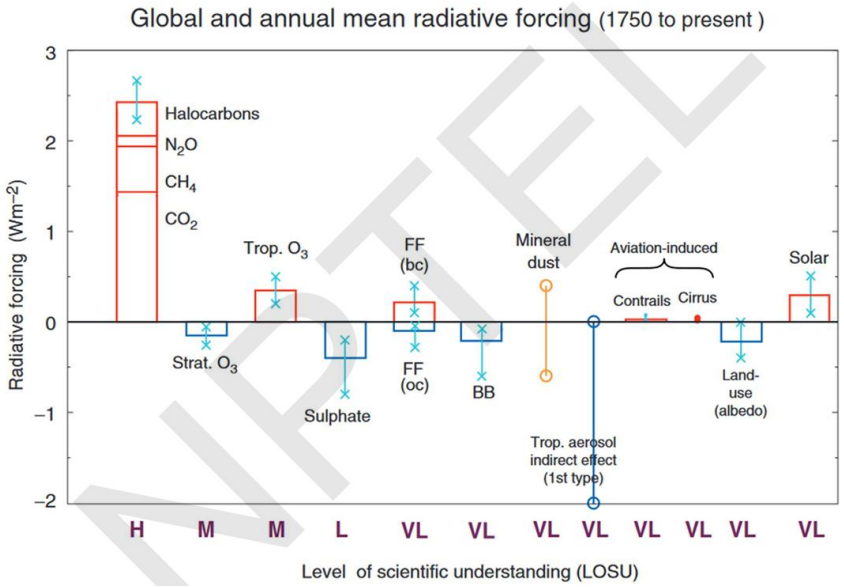
By the 2021 report, the IPCC went further, stating it is virtually certain (99% confidence) that the global upper ocean has warmed due to the greenhouse effect and that human activities are the primary cause. This progression in certainty reflects the cautious, evidence-based approach that the IPCC consistently follows.

Each IPCC report is a massive collaborative effort. A typical assessment involves around 200 lead authors, cites over 14,000 peer-reviewed scientific papers, and receives approximately 78,000 review comments, all of which are addressed in a transparent and traceable manner. The final draft is meticulously reviewed, including line-by-line scrutiny by delegates from around 40 countries. This extensive review process ensures that the IPCC's conclusions are robust, transparent, and reflect the current state of scientific understanding.

The lifetime of non-CO_2 greenhouse gases in the atmosphere is strongly influenced by photochemical processes and chemical reactions that remove them. These mechanisms vary across different gases, leading to differences in how long each remains in the atmosphere. In contrast, carbon dioxide (CO_2) has a more complex and longer removal process that cannot be described using a single exponential decay, making its treatment different from other greenhouse gases. As a result, when analyzing the overall contribution of different gases to the greenhouse effect, it becomes essential to account for each gas's unique atmospheric lifetime.

One of the key complications in comparing the warming effects of different gases lies in the choice of the time horizon for evaluating Global Warming Potential (GWP). The GWP of a gas is not fixed. It changes depending on the time frame over which you evaluate its radiative impact. For example, short-lived gases like methane have a higher GWP over shorter time scales (e.g., 20 years) but a reduced impact over longer periods (e.g., 100 years), due to their quicker removal from the atmosphere. On the other hand, long-lived gases like CO_2 or nitrous oxide show more persistent effects.

Therefore, the selection of the time horizon for GWP calculations - 20, 50, or 100 years - depends entirely on the impact being studied. If the concern is near-term impacts such as heat waves or short-term climate variability, a 20-year time scale may be appropriate. For medium-term issues like infrastructure planning or agricultural shifts, a 50-year horizon might be more relevant. For long-term projections like sea level rise or intergenerational climate policy, a 100-year timeframe is more suitable. This context-dependent nature of GWP introduces complexity in policymaking and climate modeling, as the perceived importance of different greenhouse gases shifts depending on the time scale of interest.



From 1750 to the present, the dominant contributor to radiative forcing—the change in energy balance in the Earth's atmosphere—is carbon dioxide (CO_2). Following CO_2, methane (CH_4) and nitrous oxide (N_2O) also contribute significantly to positive radiative forcing, meaning they enhance warming. Another group of important greenhouse gases is the halocarbons, particularly chlorofluorocarbons (CFCs), which also contribute to warming despite their low concentrations, due to their strong greenhouse effects and long atmospheric lifetimes.

There are also negative forcing agents, primarily aerosols and changes in ozone distribution. For example, the reduction of stratospheric ozone - due to human activity - has led to negative radiative forcing, meaning it causes a cooling effect. However, ozone levels have increased in the troposphere (the lower atmosphere), which contributes positively to warming. Sulphate aerosols are particularly important; they scatter incoming solar radiation and thus cause cooling, especially over regions where they are heavily emitted, such as land areas with industrial activity. Over oceans, where the background reflectivity is low, sulphate aerosols have an even stronger cooling effect due to their high reflectivity.

In contrast, black carbon, a byproduct of incomplete combustion (such as fossil fuels and biomass), has a warming effect because it absorbs solar radiation. Organic carbon, on the other hand, can contribute to cooling by reflecting sunlight when present as atmospheric aerosol. Mineral dust and aerosols in general can have both warming and cooling effects depending on their properties, altitude, and the surface beneath them.

There are also minor but notable contributors such as contrails from aircraft and cirrus cloud modifications, which can alter the Earth’s radiation budget. Additionally, land use changes—such as deforestation—affect surface albedo (reflectivity), generally increasing it and thus producing cooling due to more sunlight being reflected.

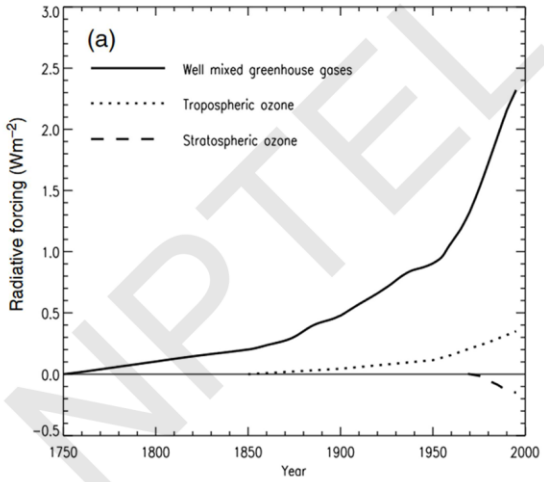
Lastly, solar variability, including the 11-year solar cycle, does influence radiative forcing to a small extent. However, the magnitude of radiative forcing from solar changes is minimal when compared to the dominant contributions from greenhouse gases like CO_2, CH_4, N_2O, and halocarbons. This highlights that anthropogenic greenhouse gases, not natural solar fluctuations, are the primary drivers of modern climate change.

When comparing radiative forcing from various atmospheric constituents, it is clear that well-mixed greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons (CFCs) play the dominant role in warming the Earth's climate.

In contrast, tropospheric ozone, which has been increasing near the surface due to pollution and photochemical reactions, also contributes to positive radiative forcing, but its impact is relatively smaller compared to the major greenhouse gases. Despite being a

short-lived gas, tropospheric ozone is an important secondary greenhouse gas, especially in urban and industrial regions.

On the other hand, stratospheric ozone which naturally exists in the upper atmosphere and protects life by absorbing harmful ultraviolet radiation has experienced depletion due to human activities, particularly from CFC emissions. This ozone depletion leads to negative radiative forcing, meaning it causes a slight cooling effect on the climate.



In summary, while tropospheric ozone contributes somewhat to warming, and stratospheric ozone depletion causes some cooling, the net radiative forcing is overwhelmingly driven by the long-lived, well-mixed greenhouse gases like CO_2, CH_4, and CFCs. This emphasizes the central role of anthropogenic greenhouse gases in driving recent and ongoing climate change.

Table 6.13: Radiative forcings (5-year averages) due to change in well-mixed greenhouse gases (WMGG), stratospheric O_3, tropospheric O_3, direct effect of sulphate aerosols, fossil fuel organic carbon aerosols (FF OC), fossil fuel black carbon aerosols (FF BC), aerosols from biomass burning (organic carbon and black carbon) (BB), stratospheric aerosols of volcanic origin, and changes in Total Solar Irradiance. All values are evaluated with respect to pre-industrial times (1750).

Time period	WMGG	Strat O_3	Trop O_3	Sulphate	FF OC	FF BC	BB	Volcanic	Solar[a]	Solar[b]
1961 to 1965	1.14	0.00	0.17	−0.26	−0.05	0.14	−0.04	−1.00	0.11	−0.07
1966 to 1970	1.27	0.00	0.20	−0.29	−0.06	0.14	−0.04	−0.77	0.11	0.04
1971 to 1975	1.44	−0.01	0.22	−0.33	−0.07	0.15	−0.05	−0.28	0.06	0.03
1976 to 1980	1.64	−0.04	0.25	−0.35	−0.08	0.16	−0.09	−0.15	0.17	0.14
1981 to 1985	1.85	−0.07	0.28	−0.36	−0.09	0.19	−0.16	−0.88	0.17	0.20
1986 to 1990	2.07	−0.11	0.31	−0.40	−0.10	0.20	−0.20	−0.35	0.21	0.19
1991 to 1995	2.26	−0.14	0.34	−0.40	−0.10	0.20	−0.20	−1.42	0.18	0.18

[a] From Lean *et al.* (1995).
[b] From Hoyt and Schatten (1993).

In the above table from an IPCC report, various radiative forcing agents are compared over a five-year period to assess their individual contributions to climate change. The stratospheric ozone shows negative radiative forcing because its concentration has been decreasing, mainly due to chlorofluorocarbon emissions. This depletion reduces its ability to trap outgoing longwave radiation, leading to a slight cooling effect.

On the other hand, tropospheric ozone has been increasing due to pollution and human-induced emissions, particularly from nitrogen oxides and volatile organic compounds. As a result, it contributes to positive radiative forcing, playing a secondary but notable role in warming.

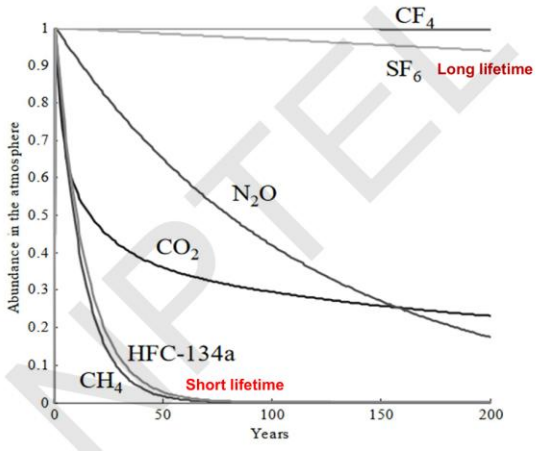
Sulphate aerosols, which are primarily produced from fossil fuel combustion, reflect incoming solar radiation and therefore lead to negative radiative forcing in the shortwave spectrum, exerting a cooling influence on the climate. This is particularly significant over regions where sulfate aerosols are abundant.

Fossil fuel combustion produces both black carbon and organic carbon. Black carbon absorbs sunlight and contributes to positive forcing, while organic carbon, like sulfates, tends to reflect radiation, thereby causing negative forcing. Black carbon from other sources, such as biomass burning, also adds to the warming effect.

Additionally, volcanic eruptions are episodic events that inject aerosols, especially sulfur compounds, into the stratosphere. These aerosols reflect solar radiation and thus cause temporary negative forcing.

Finally, solar radiation varies slightly over the 11-year solar cycle, but its overall radiative forcing is very small compared to anthropogenic greenhouse gases and aerosols. While it plays a role, its impact on climate forcing over recent decades is minimal in comparison to human-induced effects.

This analysis underscores the complexity and diversity of different climate forcing agents, with greenhouse gases as the dominant contributors to recent climate change, modulated by aerosols, ozone changes, and natural factors like volcanic activity and solar variability.

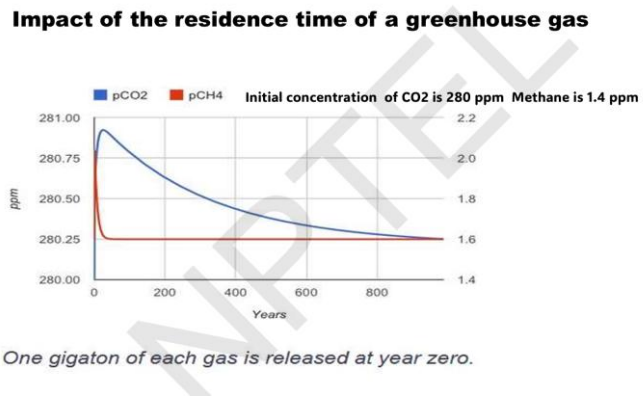


When evaluating the impact of various greenhouse gases on climate, it is essential to consider their atmospheric lifetimes in addition to their radiative efficiency. Gases such as methane (CH_4) and HFC-134a (a type of hydrofluorocarbon) have relatively short

atmospheric lifetimes, typically less than 50 years. This means that although they are potent greenhouse gases with strong radiative forcing in the short term, their impact diminishes over time as they are removed from the atmosphere by chemical reactions or breakdown processes.

In contrast, gases like carbon dioxide (CO_2), nitrous oxide (N_2O), carbon tetrafluoride (CF_4), and sulfur hexafluoride (SF_6) have very long lifetimes ranging from centuries to even millennia. Because they persist in the atmosphere for such extended periods, their cumulative impact on global warming continues to increase over time. These long-lived gases are difficult to remove through natural processes, which makes their contribution to climate change particularly concerning.

Thus, even if a short-lived gas like HFC-134a exerts a strong radiative forcing initially, its effect is transient, while gases with longer lifetimes like CO_2 and SF_6 have a more enduring and growing influence on the Earth's climate system. This distinction is crucial for policy-making and prioritizing emissions reductions, as long-lived gases represent a more persistent and compounding climate risk.



For methane (CH_4), which has a short atmospheric lifetime of about 10-20 years, most of it will be removed from the atmosphere within a few decades. This means that its radiative forcing, although strong, fades relatively quickly. So, its climate impact is short-lived, peaking shortly after emission and then rapidly declining.

In contrast, carbon dioxide (CO_2) behaves very differently. Once emitted, CO_2 persists in the atmosphere for centuries, with portions of it remaining for 600 to 700 years or more. This is due to the complex processes that remove CO_2, involving ocean uptake and geological sequestration, which operate over long time scales. As a result, 1 ton of CO_2 emitted today will continue to affect Earth's climate for many generations, making its cumulative impact far greater than that of an equal mass of methane.

Therefore, while methane has a higher Global Warming Potential (GWP) over short periods (like 20 years), CO_2's long-term presence means it dominates long-term climate

change. This distinction is critical when designing mitigation strategies: short-lived gases affect near-term warming, but long-lived gases lock in long-term climate change.

The Kyoto Protocol, in its Article 5.3, states that the GWPs used to calculate CO_2 equivalents shall be those accepted by the IPCC and agreed upon the Conference of the Parties (COP) at its third session.

The Kyoto Protocol was adopted on 11 December 1997. The Kyoto Protocol commits industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets

The above figure makes a comparison for 100-year period between CO_2, CH_4, N_2O, and PFTBA. Perfluorotributylamine (PFTBA) has a GWP of 7100 over 100-year period as it has a long-life scale.

Table 1: Global Warming Potentials of some key GHGs for time horizons of 20, 100 and 500 years

Gas	GWP for time horizons of		
	20 years	100 years	500 years
CO_2 (reference gas)	1	1	1
CH_4	62	23	7
N_2O	275	296	156
HFC-134a	3 300	1 300	400
CF_4	3 900	5 700	8 900
SF_6	15 100	22 200	32 400

Source: Third Assessment Report of the IPCC.

Table 7-2 Direct global warming potentials of several well-mixed trace gases relative to CO_2. The GWPs of the various non-CO_2 species are calculated for each of five time horizons (20, 50, 100, 200 and 500 years) using, as in IPCC, the carbon cycle model of Siegenthaler (1983). (Note that IPCC contained a typographical error which led to incorrect values for the direct GWP of methane.)

Gas	Lifetime (years)	Time Horizons				
		20 years	50 years	100 years	200 years	500 years
CO_2	#	1	1	1	1	1
CH_4	10.5	35	19	11	7	4
N_2O	132	260	270	270	240	170
CFC-11	55	4500	4100	3400	2400	1400
CFC-12	116	7100	7400	7100	6200	4100
HCFC-22	15.8	4200	2600	1600	970	540
CFC-113	110	4600	4700	4500	3900	2500
CFC-114	220	6100	6700	7000	7000	5800
CFC-115	550	5500	6200	7000	7800	8500
HCFC-123	1.71	330	150	90	55	30
HCFC-124	6.9	1500	760	440	270	150
HFC-125	40.5	5200	4500	3400	2200	1200
HFC-134a	15.6	3100	1900	1200	730	400
HCFC-141b	10.8	1800	980	580	350	200
HCFC-142b	22.4	4000	2800	1800	1100	620
HFC-143a	64.2	4700	4500	3800	2800	1600
HFC-152a	1.8	530	250	150	89	49
CCl_4	47	1800	1600	1300	860	480
CH_3CCl_3	6.1	360	170	100	62	34
CF_3Br	77	5600	5500	4900	3800	2300

#(see Table 2.8, IPCC, 1990)

The Global Warming Potential (GWP) of greenhouse gases varies significantly depending on the time horizon considered. Since carbon dioxide (CO_2) is the reference gas, its GWP is defined as 1 across all time horizons - 20, 100, or 500 years. However, for other gases, especially those with shorter lifetimes, the GWP changes markedly as the time horizon changes.

For example, methane (CH_4) has a high GWP over a 20-year period - about 35 times that of CO_2, due to its strong radiative forcing and short atmospheric lifetime (about 10-20 years). But over 500 years, its GWP drops to around 4 times CO_2, since most of the methane would have decayed long before that time frame. This demonstrates how short-lived gases exert strong but temporary warming.

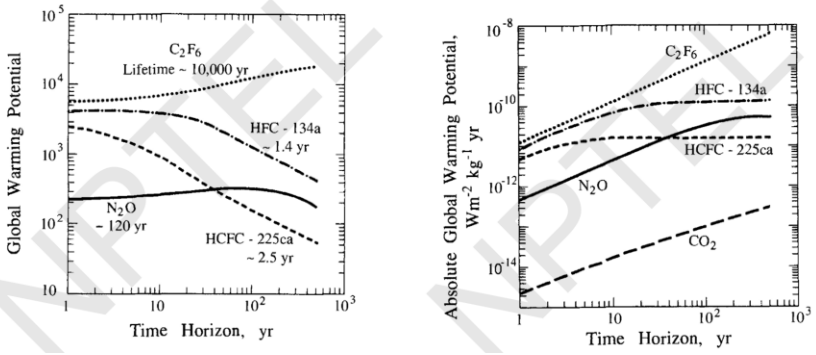
On the other hand, gases like sulfur hexafluoride (SF_6) and CFCs (e.g., CFC-11) have very long atmospheric lifetimes, often exceeding hundreds or even thousands of years. As a result, their GWP values remain high even at the 500-year mark. For instance, SF_6 shows a substantial increase in GWP when comparing 100 years to 500 years, reflecting its persistent presence and long-term impact on the climate system.

A notable case is HCFC-123, which has a very short lifetime (around 1.7 years). Its GWP is high at the 20-year horizon but drops sharply at 100 years and beyond, becoming almost negligible.

These variations highlight the importance of selecting an appropriate time horizon depending on the application or policy goal. For instance:

- 100 years is the standard time frame used by the IPCC, aligned with the goal of limiting global warming by the year 2100.
- 20 years may be more relevant for assessing near-term climate impacts and short-term mitigation strategies.
- 500 years becomes crucial for understanding long-term consequences such as sea level rise or permanent climate shifts.

Thus, the choice of time horizon has a major influence on how different greenhouse gases are prioritized in climate policy and mitigation planning.



The Global Warming Potential (GWP) of a greenhouse gas depends significantly on its atmospheric lifetime and the time horizon over which its impact is assessed. Long-lived gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), and perfluorocarbons (e.g., C_2F_6) exhibit increasing GWP over longer time horizons because they persist in the atmosphere for centuries to millennia. In contrast, short-lived gases like hydrofluorocarbons (e.g., HCFC-225ca) or methane have high GWP over short timeframes due to their strong but temporary radiative forcing. However, their impact diminishes substantially over longer periods as they decay or are removed from the atmosphere.

When comparing gases, the time horizon used - commonly 20, 100, or 500 years - plays a crucial role in determining their relative climate impact. For example, methane is about 35 times more potent than CO_2 over a 20-year period, but only about 4 times more potent over 500 years. Similarly, a gas like HCFC-225ca may seem more damaging than N_2O over a short horizon, but this reverses over longer durations due to its shorter lifetime. Therefore, policy decisions and scientific assessments that use GWP must clearly state the time horizon being considered, as it can dramatically change the interpretation.

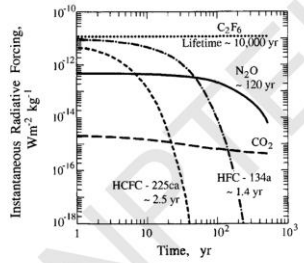


FIGURE 23.13 Radiative forcing ($W m^{-2} kg^{-1}$) versus time after a pulse release for several different greenhouse gases (IPCC 1995).

Furthermore, radiative forcing per unit mass of gas also varies with time depending on the gas's lifetime. Short-lived gases exhibit a steep decline in radiative forcing shortly after their release, while gases like CO_2 decline slowly. Extremely long-lived gases such as C_2F_6 maintain nearly constant radiative forcing over centuries. This emphasizes the need to interpret GWP values in the correct context, especially in documents like IPCC reports, which present multiple time horizons. Careful attention to these details ensures a proper understanding of the comparative impact of different greenhouse gases on climate change.

Table 2: Example for the aggregation and comparison of different GHG emissions via the calculation of CO_2 equivalents using GWPs

	1990			2000		
Gas	Emissions (Gg)	CO_2 equivalents (Gg)	Relative contribution (%)	Emissions (Gg)	CO_2 equivalents (Gg)	Relative contribution (%)
CO_2	3 341 804	3 341 804	79.27	3 324 800	3 324 800	81.74
CH_4	20 310	426 506	10.12	16 275	341 771	8.40
N_2O	1 293	400 948	9.51	1 091	338 111	8.31
HFCs		24 426	0.58		47 285	1.16
PFCs		13 545	0.32		6 846	0.17
SF_6		8 440	0.20		8 955	0.22
Total		**4 215 668**	**100**		**4 067 767**	**100**

Source: UNFCCC Greenhouse Gas Inventory Database, accessible via <http://ghg.unfccc.int>. Shown are data reported to UNFCCC by the European Community for the years 1990 and 2000.

The calculation of Global Warming Potential (GWP) values has evolved over time, becoming increasingly sophisticated as scientific understanding and modeling techniques have improved. Earlier IPCC assessments, such as those from 1990 and 2000, showed small differences in the estimated CO_2-equivalent values for various gases, reflecting refinements in methodology and data. One notable example is methane. Initial GWP estimates for methane were relatively simplistic and did not account for the fact that when methane is oxidized in the atmosphere, it eventually produces carbon dioxide - a gas with a much longer atmospheric lifetime.

While water vapor formed from methane oxidation may condense and be removed relatively quickly, the resultant CO_2 remains in the atmosphere for centuries, contributing to long-term warming. This secondary effect means that methane has a more prolonged climate impact than previously assumed, even after the methane itself has decayed. Updated calculations now factor in these extended impacts, leading to adjustments in methane's GWP across successive IPCC reports. These continual revisions underscore the dynamic nature of climate science and the importance of using the latest available data when interpreting GWP values.

It is important to recognize that all data related to radiative forcing are derived from radiative transfer models. These models simulate how radiation interacts with various gases and particles in the atmosphere, allowing scientists to estimate the forcing contributions of different greenhouse gases and aerosols. However, because these models are built on assumptions, approximations, and varying input parameters, the results can differ depending on the specific model used.

Therefore, when interpreting or comparing radiative forcing values whether for carbon dioxide, methane, aerosols, or any other components, it is crucial to pay close attention to which model produced the data. Different models may incorporate distinct spectral resolutions, atmospheric profiles, or treatment of feedback processes, all of which can influence the calculated radiative forcing. As a result, slight discrepancies in reported values across different studies or reports are not uncommon. This reinforces the need for transparency in climate modeling and the use of standardized methodologies when assessing global warming impacts.

The effect of greenhouse gases varies significantly depending on whether they are located in the troposphere or the stratosphere, primarily due to differences in the atmospheric temperature profile, known as the lapse rate. In the troposphere, temperature decreases with altitude, while in the stratosphere, temperature increases with altitude due to the absorption of ultraviolet radiation by ozone. This contrast alters how radiation is absorbed and emitted by gases in these layers.

For example, ozone behaves differently depending on its location. In the stratosphere, an increase in ozone tends to reduce the greenhouse effect because of the warming with height, which affects how radiation escapes to space. On the other hand, in the troposphere, where temperature decreases with height, an increase in ozone contributes to an enhanced greenhouse effect. Understanding this distinction is critical for interpreting the role of ozone and other gases in radiative forcing accurately. The details of how temperature variation with altitude influences the greenhouse effect will be explored further in the following lecture.

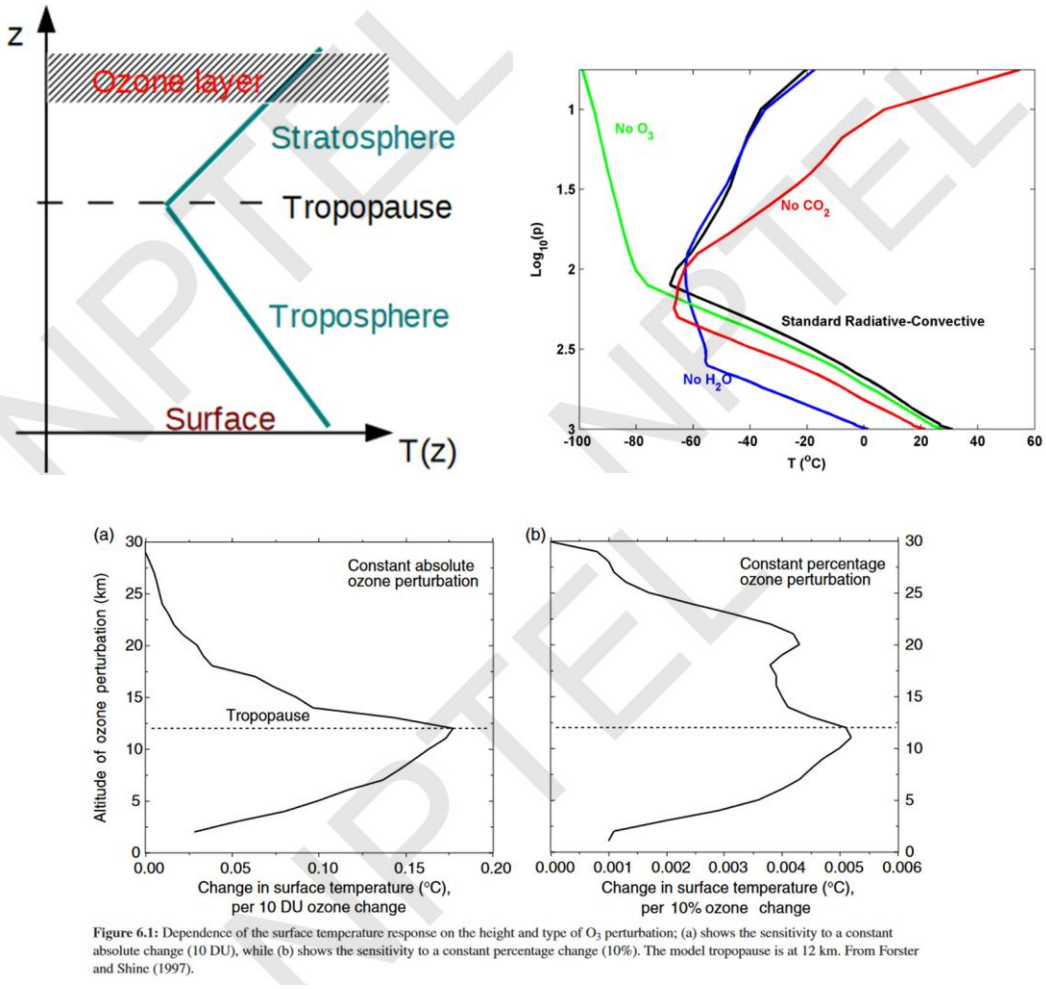


Figure 6.1: Dependence of the surface temperature response on the height and type of O_3 perturbation; (a) shows the sensitivity to a constant absolute change (10 DU), while (b) shows the sensitivity to a constant percentage change (10%). The model tropopause is at 12 km. From Forster and Shine (1997).