Conf-9206130--2

UCRL-JC-110859
PREPRINT

THE ROLE OF REFRIGERANTS IN CLIMATE CHANGE

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This paper was prepared for submittal to
SINTEF/INTERNATIONAL SYMPOSIUM ON
REFRIGERATION, ENERGY AND ENVIRONMENT
TRONDHEIM, NORWAY
JUNE 22-24, 1992

JUNE 1992

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ABSTRACT

The primary chemicals used as refrigerants, chlorofluorocarbons (CFCs), and the compounds being considered as their replacements (HCFCs and HFCs) have been intensely studied because of concerns about chlorine chemistry effects on stratospheric ozone. Increasing attention is being given to the potential effects of these compounds in concerns about global warming. CFCs, HCFCs, and HFCs absorb infrared radiation and thus are greenhouse gases that can influence radiative forcing on climate. The purpose of this paper is to describe the current understanding of the role of refrigerants in affecting climate. Increasing atmospheric concentrations of CFCs have accounted for about 24 % of the direct increase in radiative forcing from greenhouse gases over the last decade. However, observed decreases in stratospheric ozone, thought to be connected to increasing stratospheric chlorine from CFCs, suggests a cooling tendency over the last decade. This cooling tendency has strong latitudinal gradients, but is, when globally averaged, about comparable in magnitude and opposite in sign to the radiative forcing from CFCs over this period. Because of their shorter atmospheric lifetimes, the direct radiative influence on climate from the replacement compounds should generally be much smaller than the CFCs.

1. INTRODUCTION

Chlorofluorocarbons (CFCs) and other halocarbons used as refrigerants have received a great deal of attention and study because of their potential effects on the global environment. The concern about potential environmental effects from man-made CFCs was first raised in 1974 /1/, when it was suggested that the chlorine from these compounds could efficiently destroy stratospheric ozone. Research over the last eighteen years have continued to emphasize the part that these compounds play in affecting the global distribution of ozone. In addition, it has been recognized for some time that these gases also absorb infrared radiation /2/. Over the last decade, CFCs and other halocarbons have been receiving increasing attention because of their potential greenhouse warming effect on climate (/3/, /4/, /5/).

The concern that human activities may be affecting global climate has largely centered around carbon dioxide (CO_2) because of its importance as a greenhouse gas and also because of the rapid rate at which its atmospheric concentration has been increasing. However, research over the last decade has shown that other greenhouse gases are contributing about half of the overall increase in the greenhouse radiative forcing on climate. CFCs and other halocarbons accounted for roughly half of the direct increase in forcing from non-CO_2 greenhouse gases over the last decade. However, a climatic cooling response from decreasing stratospheric ozone concentrations, thought to be primarily related to chlorine from CFCs, may counteract part of the warming effect.

The primary CFCs of concern are $CFCl_3$ (CFC-11) and CF_2Cl_2 (CFC-12). These two CFCs have the largest emissions and largest atmospheric concentrations. The vast majority of domestic refrigeration (refrigerators and freezers) and a number of commercial and industrial refrigeration applications use CFC-12. CFC-12 is also used in automobile air conditioning.

CFC-11 has direct refrigeration applications, but its largest use is as a foam blowing agent for the insulation in refrigeration units. Other CFCs used in refrigeration applications include CF_2ClCF_2Cl (CFC-114) and CF_2ClCF_3 (CFC-115).

International agreements, such as the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer /6/ and its 1990 London Amendments /7/, currently call for the elimination of CFC production by the end of the decade. However, because of the large observed decrease in ozone (/8/, /9/), the phase-out of CFCs is likely to be pushed to as early as 1995. Many countries and some industries have already called for a faster phase-out of the substances than existing mandated reductions. The proposed replacements, primarily hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), retain many of the desirable properties of CFCs; however, as a result of the hydrogen in their molecular structure, they have much shorter lifetimes in the atmosphere. Because they exist for a shorter time in the atmosphere, their effects on ozone and climate are significantly reduced when compared to the compounds they replace. One of these compounds, HCFC-22 ($CHClF_2$) is already used in a number of refrigerant applications. In the U.S, roughly 43 million heat pump plus home air conditioners and industrial air conditioning units use HCFC-22 (American Refrigeration Institute figures provided by M. McFarland, private communication, 1992). HCFC-22 is a potential replacement for CFC-12 in some commercial and industrial applications. Other alternatives being considered in refrigeration applications include HFC-134a (CF_3CH_2F), HFC-152a (CH_3CHF_2), and a blend of HCFC-22, HFC-152a and HCFC-124 (CF_3CHFCl). Replacements for CFC-11 in foam blowing include HCFC-123 (CF_3CHCl_2) and HCFC-141b (CH_3CFCl_2). Although their potential for affecting stratospheric ozone is only a small fraction (2 to 11 % depending on the compound /9/) of the CFCs they replace, the HCFCs still contain chlorine and eventually their production will need to be phased out. In addition, the HCFCs and HFCs are also greenhouse gases.

The purpose of this report is to evaluate the potential effects on climate from the CFCs, HCFCs, and HFCs currently used or projected to be used in refrigeration applications. We begin with a general discussion of climate and the greenhouse effect.

2. THE GREENHOUSE EFFECT

Climate is generally defined as a description of the average (or typical) behavior of the atmosphere. Therefore, climate is the aggregation of the weather; it is usually expressed in terms of mean (or average) conditions and the variations about their means, including the extremes and how often such events occur. One of the fundamental climate variables is the planetary annual average surface temperature. Other variables of interest include averages of regional surface temperatures, the frequency and amount of rainfall, and the extent and frequency of floods and droughts. Concerns about climate change, including those related to the greenhouse gases, therefore relate to the evolution of the mean behavior of such variables.

The "greenhouse effect" is a term that refers to a physical property of the Earth's atmosphere. If the Earth had no atmosphere (but the same reflectivity to solar radiation, or albedo, as it has now), its average surface temperature would be about 255 K rather than the comfortable 288 K found today. The difference in temperature is due to the presence of an atmosphere, in particular, to a suite of gases called greenhouse gases. In its existing state, the Earth-atmosphere system balances absorption of solar radiation by emission of infrared radiation to space. The atmosphere absorbs more infrared energy than it reradiates to space, resulting in a net warming of the Earth-atmosphere system and of surface temperature. This phenomenon is referred to as the greenhouse effect. Note, however, that the greenhouse effect for the atmosphere is somewhat of a misnomer in that the panes of glass in a greenhouse trap solar radiation.

As a means to understanding the greenhouse effect, it is useful to examine the annual and global average radiative energy budget of the combined Earth-atmosphere system. The sun emits most of its energy at wavelengths between 0.2 and 4.0 µm, primarily in the ultraviolet (UV), visible, and near-infrared (near-IR) wavelength regions. A very small fraction of this energy is intercepted by the Earth as it orbits the Sun. The atmosphere absorbs approximately 23 % /3/ of the incoming solar radiation, principally by ozone (O_3) in the UV and visible ranges, and by water vapor in the near-IR.

The Earth re-emits the energy it absorbs back to space in order to maintain an energy balance. Satellite measurements indicate that the incoming and outgoing radiation of the atmosphere is in balance /4/. Because the Earth is much colder than the Sun, the bulk of this emission takes place at longer wavelengths than those for incoming solar radiation. Most of this radiation is emitted in the wavelength range from 4 to 100 µm, which is the region generally referred to as longwave or infrared (IR) radiation (see Figure 1). Although water vapor, carbon dioxide (CO_2), and other greenhouse gases are relatively inefficient absorbers of solar radiation, these gases are strong absorbers of IR radiation. Clouds also play an important role in determining the energy balance (see Figure 2); one of the largest uncertainties in determining the climate change expected from greenhouse gases is the current limitation in understanding cloud processes (/4/, /5/, /10/).

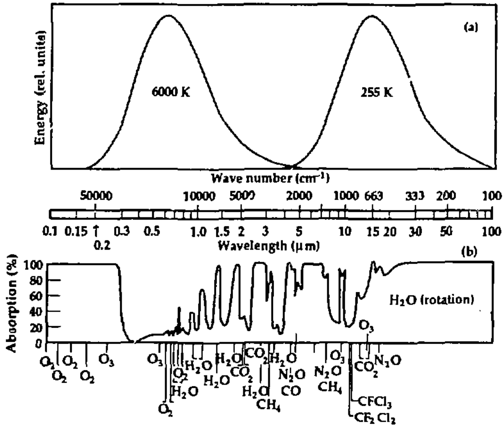


Figure 1 (a) Blackbody curves showing the variation of emitted energy with wavelength for temperatures typical of the Sun and Earth, respectively, and (b) percentage of atmospheric absorption for radiation passing from the top of the atmosphere to the surface. Note the comparatively weak absorption of the solar spectrum and the region from 7 to 13 µm in the longwave spectrum, referred to as the window region. CFCs, HCFCs, and HFCs absorb in the window region.

The greenhouse gases (and clouds) re-emit the absorbed longwave radiation based on their local atmospheric temperature, which tends to be cooler than the Earth's surface temperature. Some of this radiation reaches space. Some of the radiation, however, is emitted downwards, leading to a net trapping of longwave radiation and a warming of the surface. As the concentrations of greenhouse gases increase, this net trapping of IR radiation is enhanced, resulting in increased radiative forcing on climate, and the resulting current concerns about global warming.

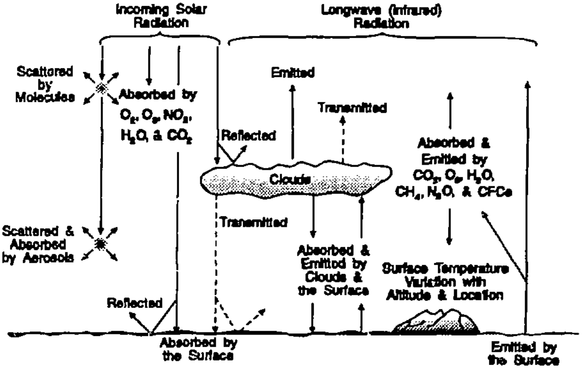


Figure 2. Schematic diagram of the important processes determining radiative processes in the atmosphere.

The CFCs, HCFCs, and HFCs are all greenhouse gases. Because of their molecular structure, they all have strong absorption features in the so-called "window" region of the infrared. The window region is the wavelength region from about 7 to 13 μm, where absorption by the primary absorbers, CO_2 and H_2O, is weak. Absorption in the window region allows gases with much smaller atmospheric concentrations than CO_2 and H_2O to have significant effects in influencing radiative forcing on climate. Infrared absorption for each of the refrigerants and possible refrigerants discussed above have absorption that increases linearly with their concentration. In contrast, CO_2, because of its large atmospheric concentration, already absorbs essentially all of the radiation in the central cores of its absorption lines and will increase the net trapping of infrared radiation logarithmically rather than linearly with concentration.

The net result of these varying radiative characteristics is that comparable increases in concentration of different greenhouse gases have vastly different effects on radiative forcing. The instantaneous radiative forcing of the surface-troposphere system is the change in the net radiative flux at the tropopause; equivalently, it can be defined as the surface temperature change with zero climate feedbacks. Table I shows the radiative forcing for the refrigerants and potential refrigerants relative to current concentrations of CO_2 and of CFC-11; these relative radiative forcings are shown on a per molecule change and a per unit mass change basis (/4/, /11/, /12/). An additional atmospheric molecule or kilogram of any of these compounds is thousands times more effective at affecting radiative forcing than an additional molecule or kilogram of carbon dioxide. However, the compounds being considered as replacement refrigerants are within a factor of two of the radiative forcing of the CFCs they would replace. As discussed later, it is the much shorter atmospheric lifetimes (and thus the smaller achievable atmospheric concentrations for the same emissions) of the HCFCs and HFCs that result in their generally having a much smaller effect on global warming than the direct radiative effect of the CFCs.

Table I. Radiative forcing (ΔF) of a number of CFCs, HCFCs, and HFCs relative to CO_2 and to CFC-11 on a per unit molecule change and a per unit mass change basis. Based on present concentrations of CO_2 (/4/, /11/, /12/).

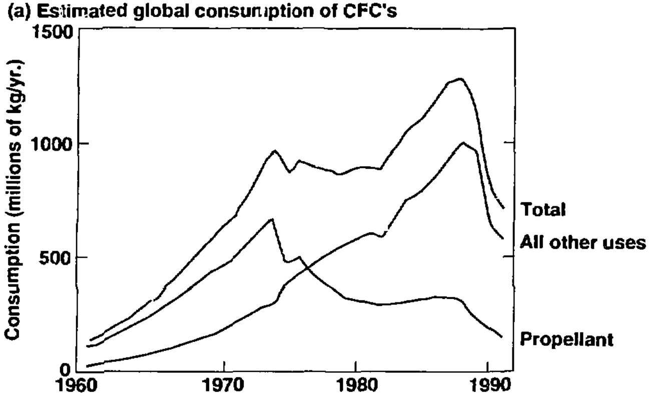
	Relative to CO_2		Relative to CFC-11	
Trace Gas	ΔF, per molecule	ΔF, per unit mass	ΔF, per molecule	ΔF, per unit mass
CO_2	1	1		
CFC-11	12400	3970	1	1
CFC-12	15800	5750	1.27	1.45
CFC-114	18300	4710	1.47	1.18
CFC-115	14500	4130	1.17	1.04
HCFC-22	10700	5440	0.86	1.36
HCFC-123	9940	2860	0.80	0.72
HCFC-124	10800	3480	0.87	0.88
HCFC-141b	9570	4130	0.77	1.04
HFC-134a	6590	4390	0.53	1.10
HFC-152a	7710	2900	0.62	0.73

3. ATMOSPHERIC CONCENTRATIONS AND TRENDS

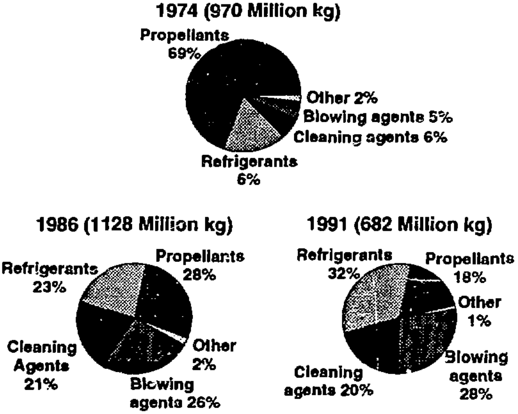
Estimated worldwide consumption of CFCs since 1960 is shown in Figure 3, along with a corresponding estimated consumption of CFCs by application for 1974, 1986, and 1991 /13/. Total consumption of CFCs has dropped dramatically since the peak in the late 1980s, to about 680 million kilograms in 1991. Meanwhile, the percentage consumption of CFCs going into refrigeration has increased from 18 % in 1974 to 32 % in 1991 (this does not include foam blowing for insulation in refrigeration applications). The use of CFCs as refrigerants increased by about 85 million kg from 1974 to 1986, but decreased by over 40 million kilograms from 1986 to 1991.

As a response to their use and eventual emission, atmospheric concentrations of the CFCs have increased substantially since atmospheric measurements began in the late 1970s. Figure 4 gives the measured changes in concentrations for several important halocarbons, including CFC-11 and CFC-12, made at the ALE-GAGE measurement network site in Tasmania (/15/, /9/). Other measurement stations throughout the world show similar increases. Until recently concentrations of CFC-11 and CFC-12 have still been increasing at about 4 % per year, despite the significant decrease in emissions over the last few years (see Table II). However, recent measurements indicate that the CFC concentration increases is slowing down. The large trend results from the continued imbalance between the sources and sinks of the CFCs in the atmosphere. Measured tropospheric concentrations of CFC-11 and

CFC-12 were 0.28 and 0.47 ppbv, respectively, in 1990. Global averaged concentrations of HCFC-22 were 0.116 ppbv (116 pptv) in 1990, while concentrations are continuing to increase at about 6 % per year.



(a) Estimated global consumption of CFC's



(b) Estimated consumption of CFC's by application

Figure 3. (a) Estimated global consumption of CFCs and (b) estimated consumption of CFCs by application /13/.

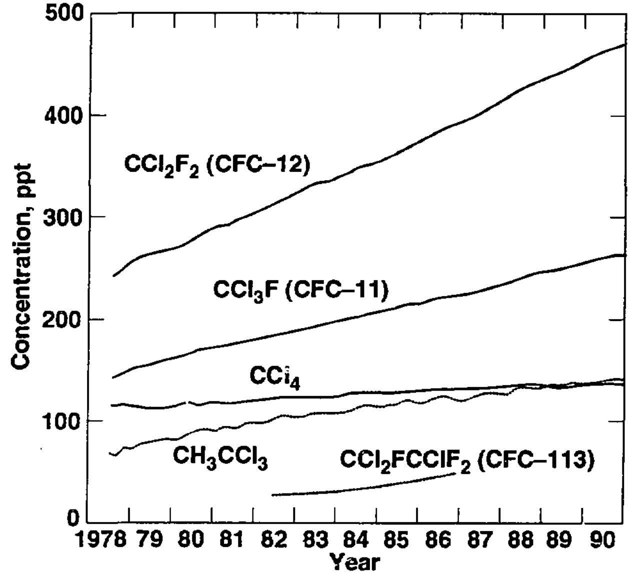


Figure 4. Observed concentrations of CFCs and other halocarbons since 1978 at the Tasmanian station of the ALE/ GAGE network. Qualitatively similar trends are found at the other stations in this global network (/4/, /5/, /9/, /15/).

CFC-11 and CFC-12 account for roughly half of the organic chlorine loading of the current atmosphere /9/. All of the CFCs (-11, -12, -113, -114, and -115) plus carbon tetrachloride (CCl_4) account for about 70 % of the total organic chloride loading. Measured ground levels of total organic chlorine (total of approximately 3.6 ppbv in 1990), when lagged by a five year delay for transport to the upper stratosphere, are consistent with measured concentrations of total inorganic chlorine in the upper stratosphere (/9/, /13/, /14/). Only about 0.6 ppbv (parts per billion by volume) of the approximately 3.3 ppbv of total chlorine in the stratosphere is due to the only known significant natural source of stratospheric chlorine, CH_3Cl.

All of the fully halogenated CFCs have long atmospheric lifetimes. The atmospheric lifetime of CFC-11 emitted into the atmosphere is about 55 years, while the lifetime of CFC-12 is about 116 years. The long atmospheric lifetimes contribute to the sustained increasing concentrations of these gases. The CFCs are essentially inert in the troposphere, but dissociate in the stratosphere, where they are the major sources of reactive chlorine. On the other hand, sea salt and other chlorine containing surface emissions that are water soluble are rapidly removed from the atmosphere by rainout processes and never reach the stratosphere.

Table II. Estimated atmospheric lifetimes, tropospheric concentrations (for 1989) and observed global trends in concentrations for CFCs, HCFCs, and HFCs (/5/, /9/). The atmospheric lifetimes are based on atmospheric models and, where appropriate, constraints from atmospheric observations.

Trace Gas	Estimated atmospheric lifetime (years)	Tropospheric concentration (1990, pptv)[1]	Trend, %/yr
CFC-11	55	270	3.2–3.8
CFC-12	116	470	3.7–4.0
CFC-114	220	20	~6
CFC-115	550	~5	~6
HCFC-22	15.8	115	6–7
HCFC-123	1.7	—	
HCFC-124	6.9	—	
HCFC-141b	10.8	—	
HFC-134a	15.6	—	
HFC-152a	1.8	—	

[1] pptv = parts (molecules) per trillion (molecules of air) by volume

The atmospheric lifetimes of HCFCs and HFCs tend to be much shorter than CFCs as a result of their reactivity in the troposphere with nydroxyl (OH). The atmospheric lifetime of HCFC-22 is about 15-16 years while the lifetime of HCFC-123 is about 1.7 years /9/. Because of their shorter atmospheric lifetimes, the atmospheric concentrations of HCFCs and HFCs used as replacements for CFCs will be much lower for the next several decades than would be the increase in concentrations of CFCs for the same emissions. However, continued use and persistent growth in the emission rates of HCFCs and HFCs would eventually result in atmospheric concentrations that could be radiatively important.

4. RADIATIVE FORCING ON CLIMATE

Increasing concentrations of CFCs are thought to be a significant fraction of the increase in radiative forcing from greenhouse gases over the last two centuries. The Intergovernmental Panel on Climate Change (IPCC) /4/ calculated that the direct radiative effect of the increase in CFCs since the mid-1700s has accounted for an increase in radiative forcing of 0.29 Wm^{-2} (climate models indicate that the 4 Wm^{-2} associated with a doubling of CO_2 from 300 to 600 ppmv would give approximately a 1.5 to 4.5 K increase in surface temperature). This is about 12 % of the total change in radiative due to CO_2 and other greenhouse gases over this time period. Carbon dioxide accounts for 61 % of the 2.45 Wm^{-2} increase in radiative forcing from greenhouse gases determined by IPCC for 1765 to 1990.

With most of the increase in atmospheric concentrations of CFCs occurring over the last few decades, CFCs are a higher proportion of the change in radiative forcing over this period. Of the 0.54 Wm^{-2} increase in radiative forcing from greenhouse gases for 1980 to 1990 (/4/), CFC-11 and CFC-12 together account for 17 % of the increase, while the sum of all CFCs account for about 24 % of the increase in radiative forcing (see Figure 5). Ramaswamy et al. /16/ determined a somewhat smaller increase in total radiative forcing, 0.45 Wm^{-2}, for 1979 to 1990, with CFCs accounting for 22 % of the forcing. As shown in Figure 6, the largest increase in radiative forcing from CFCs and from the sum of all greenhouse gases occurs in the tropics and gradually decreases with latitude (/5/, /16/). None of these studies considered the effect of changes in ozone (see next section) or changes in atmospheric aerosol loading over these periods.

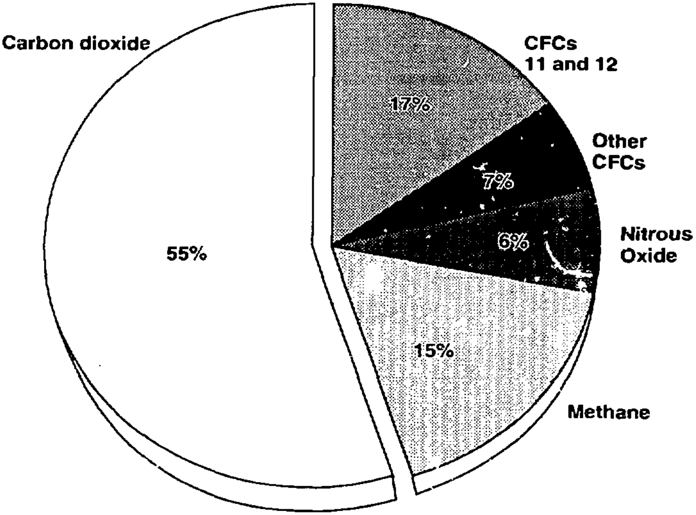


Figure 5. Relative effects of various greenhouse gases on the increase in climatic forcing from 1980 to 1990 /4/.

Future changes in radiative forcing from refrigerants is dependent on the actual atmospheric concentrations reached and, thus, is closely linked to the actual emissions that occur. Radiative-convective climate model calculations indicate that a 1 ppbv increase in the atmospheric concentration of CFC-11, CFC-12, and HCFC-22 would increase surface temperature by 0.18, 0.15, and 0.05, respectively (assuming a climatic sensitivity of 2 K increase in surface temperature for a doubling of CO_2) (/17/, /18/). This is an extremely large increase in concentration for CFCs, but the climatic effect would be linear with the change in concentration. The radiative forcing from the CFCs should gradually decrease over the next century as atmospheric concentrations gradually decrease. Radiative forcing from HCFCs and HFCs should increase, but at a slower rate than a corresponding emission of CFCs. If use of these compounds is large enough, they could become significant contributors to climatic forcing (/4/, /5/). Emissions scenarios analyzed by IPCC suggest that an increase of over 0.5 Wm^{-2} in radiative forcing is possible from extensive use and emission of HCFC-22 and other HCFCs and HFCs (/4/, /5/).

5. CHEMICAL INTERACTIONS AND THEIR EFFECTS ON CLIMATE

In addition to their direct radiative forcing effect on climate, greenhouse gases can also affect climate indirectly through chemical interactions affecting other greenhouse gases. An important indirect effect on climate from CFCs and HCFCS is due to their chemical effects on stratospheric ozone.

5.1 The importance of ozone

Ozone has several important effects on climate. Although the direct radiative effect of CO_2 and other greenhouse gases largely depend on their concentration in the troposphere, the climatic effect of ozone depends on its distribution throughout the troposphere and stratosphere. Ozone is the primary absorber of ultraviolet and visible radiation in the atmosphere, and its concentrations determine the amount of ultraviolet radiation reaching the Earth's surface. It is the absorption of solar radiation by ozone that explains the increase in temperature with altitude in the stratosphere. However, ozone is also a greenhouse gas, with a large infrared absorption band at 9.6 µm. It is the balance between these radiative processes that determines the net effect of ozone on climate /19/.

Increases in ozone above about 30 km tend to decrease the surface temperature as a result of the increased absorption of solar radiation, effectively decreasing the solar energy that would otherwise warm the Earth's surface. Below 30 km, increases in ozone tend to increase the surface temperature. The infrared greenhouse effect dominates in this region. Changes in ozone in the upper troposphere and lower stratosphere are particularly effective in affecting climate forcing. This is because the greenhouse effect produced by ozone is directly proportional to the temperature contrast between the radiation absorbed and the radiation re-emitted. This contrast is greatest near the tropopause where temperatures are at a minimum compared to the surface temperature.

Although ozone is a major component of photochemical smog in urban areas, this ozone contributes very little to the global ozone budget. Ozone is produced in the atmosphere by the rapid reaction of an oxygen atom with an oxygen molecule in the presence of any third molecule. However, the means by which the oxygen atom is primarily generated differs greatly between the troposphere and the stratosphere.

Approximately 90 % of the ozone in the atmosphere is contained in the stratosphere. In the stratosphere, the production of ozone begins with the photodissociation of O_2 at ultraviolet wavelengths less than 242 nm. This reaction produces two ground-state oxygen atoms that can react with O_2 to produce ozone. Since an oxygen atom usually creates an ozone, it is common to refer to the sum of the concentrations of O_3 and oxygen atoms (O) as odd-oxygen. The primary destruction of odd-oxygen in the stratosphere comes from catalytic mechanisms involving various free radical species. Nitrogen oxides, chlorine oxides, and hydrogen oxides participate in catalytic reactions that destroy odd-oxygen. Until recently, the odd-nitrogen (nitrogen oxides) cycle above was believed to be responsible for about 70% of the total odd-oxygen destruction /20/. Recent measurements suggest that as a result of reactions on particles, nitrogen oxides are much less important in destroying lower stratospheric ozone than previously thought /9/.

The chlorine catalytic mechanism is particularly efficient at destroying ozone. Because of the growing levels of reactive chlorine in the stratosphere resulting from emissions of $CFCl_3$, CF_2Cl_2 and other halocarbons, this mechanism has been the subject of much concern due to the potential effects on concentrations of stratospheric ozone. The chlorine catalytic cycle can occur thousands of times before the catalyst is converted to a less reactive form. Because of this cycling, relatively small concentrations of reactive chlorine can have a significant impact on the amount and distribution of ozone in the stratosphere. In the lower stratosphere, atmospheric and laboratory measurements indicate that heterogeneous chemistry on particles are leading to enhanced effects on ozone from chlorine (/9/, /20/, /21/).

Measurements of ozone from ground-based stations and from satellites indicate that concentrations of ozone in the stratosphere are decreasing. Significant decreases in total ozone are found in both the northern and southern hemisphere at middle and high latitudes, with no statistically significant change in the tropics. Surface measurements indicate that the total ozone column at midlatitudes in the Northern Hemisphere has decreased by 1.3 % in the summer months and 2.7 % in the winter months since 1969 /9/. Much larger decreases in total ozone are found in the analyses of satellite and ground-based measurements if the data from 1979 to 1991 is used (/8/, /9/). TOMS satellite data indicates a 2.9 % decrease in total ozone during the summer and a 5.6 % decrease in ozone during the winter at midlatitudes in the Northern Hemisphere since 1979.

Ozone at 40 km altitude is decreasing globally by 3-4 % per decade, generally in agreement with the model calculations of the expected effects from CFCs and other trace gas emissions (/9/, /20/, /22/). Satellite and ozonesonde data sets indicate that ozone in the lower stratosphere is decreasing at a faster rate than the upper stratosphere, and account for a major fraction of the trend in total ozone. Part of the lower stratospheric ozone decrease can be explained by the Antarctic ozone hole (to be discussed below) and the dilution of its effects to midlatitudes after its late springtime breakup. There are indications of similar effects from chlorine chemistry in the arctic polar vortex /9/. Heterogeneous chemistry allowing chlorine to be in a reactive state in the lower stratosphere (instead of being largely tied up in reservoir species such as HCl) is now thought to be a major factor in explaining the overall global decrease in lower stratospheric ozone /9/.

Beginning in the late 1970s, a special phenomena began to occur in the springtime over Antarctica, referred to as the Antarctic ozone "hole". A large decrease in total ozone is occurring over Antarctica beginning in early spring. Decreases in total ozone column of more than 50% as compared to historical values have been observed by both ground-based and satellite techniques. Measurements made in 1987 indicated that more than 95% of the ozone over Antarctica at altitudes from 15 to 20 km had disappeared during September and October (/20/, /21/). Four out of the last five years have had very substantial springtime ozone decreases over Antarctica; the one exception, 1988, still had a significant decrease in ozone (about 25 % less than 1979 satellite measurements) /9/.

Measurements also indicate that the unique meteorology during the winter and spring over Antarctica sets up special conditions producing a relatively isolated air mass (the polar vortex). Polar stratospheric clouds form if the temperatures are cold enough in the lower stratosphere, a situation which often occurs within the vortex over Antarctica. Heterogeneous reactions can occur between atmospheric gases and the particles composing these clouds. Measurements indicate that reactions of HCl and $ClONO_2$ on these particles can release reactive chlorine once the sun appears in early spring. Thus, the reactions on the cloud particles allow chlorine to be in a very reactive state with respect to ozone. The ozone hole ends in late spring with the breakup of the vortex. Scientists have generally concluded that the weight of scientific evidence strongly indicates that man-made chlorinated (i.e.., CFCs) and brominated chemicals (Halons) are primarily responsible for the substantial decreases of stratospheric ozone over Antarctica in springtime (/9/, /20/, /21/).

5.2 Climate forcing from stratospheric ozone loss

The observed global ozone losses occurring in the lower stratosphere over the last decade have a significant impact on calculated climatic forcing (/5/, /16/). Figure 6 compares the calculated annual averaged changes in radiative forcing due to the observed ozone decreases with the direct radiative forcing from CFCs and from all greenhouse gases (note that the radiative forcing for all greenhouse gases does not include the response due to changes in ozone). There are still significant uncertainties associated with the existing analysis of the ozone effects. The published calculations assume that all of the observed decrease in total ozone occurred in the lower stratosphere. As discussed above, most of the change is in the lower stratosphere, but there is also ozone decrease in the upper stratosphere. In addition, the calculations only crudely considered the variations with altitude in the lower stratospheric ozone loss. Nonetheless, the current analyses imply that the decreases in ozone since 1979 have caused a cooling tendency at middle to high latitudes. There is a significant reduction in net radiative forcing at these latitudes when this calculated forcing from ozone is compared to the direct effect of other greenhouse gases. This implies that the greenhouse warming expected from greenhouse gases at these latitudes may be significantly affected by the changes occurring in ozone.

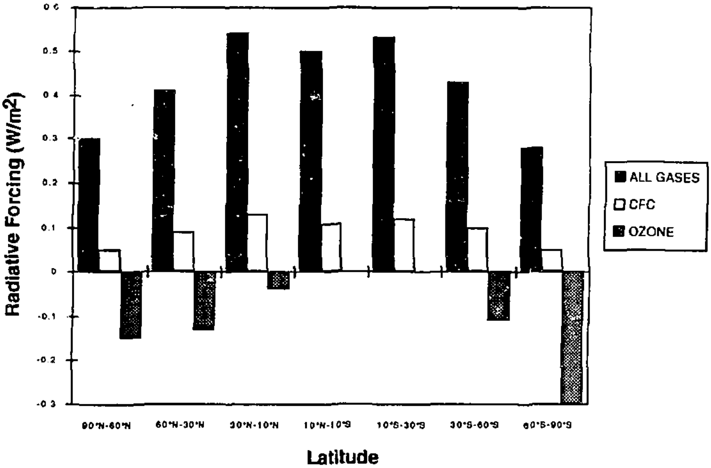


Figure 6. Comparison of the annual averaged changes in radiative forcing due to the observed total ozone decreases with the direct radiative forcing from CFCs and from all greenhouse gases (/5/, /16/).

Since the weight of the evidence suggest that CFCs and to a lesser extent, Halons, appear to be implicated in the observed ozone decrease, the results in Figure 6 suggest that the net radiative forcing from CFCs is greatly influenced by the ozone decrease. When averaged globally over the last decade, the radiative forcing from the ozone change is about the same magnitude and opposite in sign to the enhanced radiative forcing from increased CFCs. However, because of the strong variations in net radiative forcing with latitude, the increase in CFCs can still affect climate despite this globally averaged cancellation.

Emissions of HCFCs, with their shorter atmospheric lifetimes and smaller potential effects on ozone (based on their Ozone Depletion Potentials, ODPs), may have some offset in their radiative forcing from resulting effects on ozone. Such an offset would be roughly in proportion to their ODPs. For HFCs, with no expected effect on ozone, there would be no offset.

6. THE POTENTIAL RESPONSE OF CLIMATE

6.1 Trends in surface temperature

The past record of climate indicates that global temperatures have varied considerably. In fact, it is the general nature of climate to be continually changing. Global average surface temperature was about 4 to 6 K cooler during the maximum of past ice ages than at present; temperatures during interglacial periods have been up to several degrees warmer than currently /4/. The Earth emerged from the last ice age 10, 000 to 15, 000 years ago. Over the vast majority of historical times, humans have had little impact on climate; they had to adapt to any changes in climate.

The concern about the increases in atmospheric greenhouse gas concentrations is that global temperatures may reach levels over the next century that have not been experienced on Earth in the previous 120,000 years. Scenarios for assumed future emissions of greenhouse gases evaluated by the Intergovernmental Panel on Climate Change suggest that the global mean temperature could increase by as much as 3 K before the end of the next century (/4/, /5/). Figure 7 shows the predicted change in surface temperature calculated for the baseline scenario used in the recent IPCC international assessment /5/; the three curves shown reflect the climatic sensitivity to uncertainties in climate feedbacks. Numerical models of climate processes suggest that uncertainties in climate sensitivity from a doubling of carbon dioxide concentrations could lead to an increase in global average temperature of 1.5 to 4.5 K (with 2.5 K as the current best estimated effect), once the oceans warmed and a new equilibrium climate was established (/3/, /4/, /5/). Such a rapid temperature change would require adaptation unprecedented within human history.

Surface temperature records until about 100 years ago were too incomplete to determine the trend in global temperatures. Over the last 100 years, global temperatures have increased by about 0.5 K (range of 0.4 to 0.6 K). This is shown in Figure 8, based on the compilation and analysis of temperature records by P. D. Jones /4/. The size of this warming is near the lower limit, but is broadly consistent with the predictions of the climate models being used to study the potential for future climate change. Temperature changes over the last century are also still within the range of natural climatic variability. Consideration of the cooling effects from decreasing stratospheric ozone (as discussed above) and from increasing concentrations in sulfate particles (/23/, /24/) could also bring theory and measured temperature changes into better agreement.

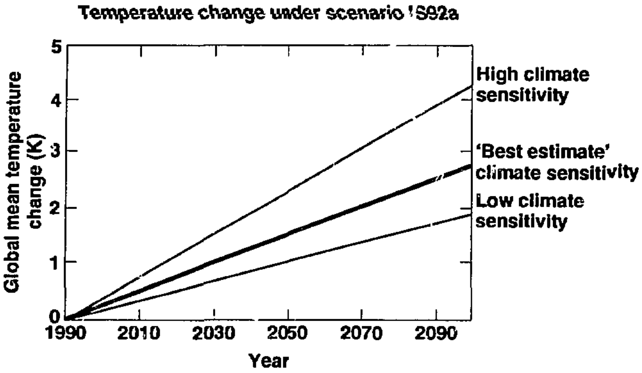


Figure 7. Predicted change in surface temperature calculated for the baseline scenario used in the recent IPCC international assessment /5/; the three curves shown reflect the climatic sensitivity to uncertainties in climate feedbacks.

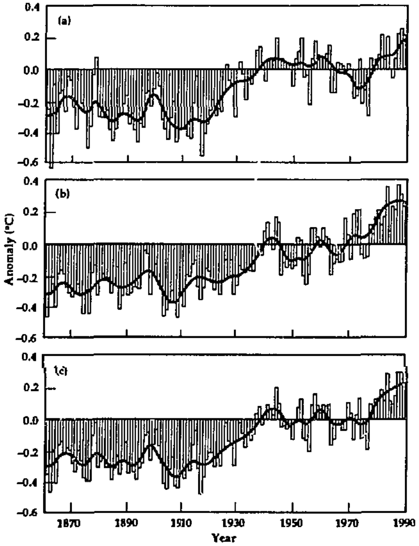


Figure 8. Combined land-air and sea surface temperatures, 1861 to 1989, relative to the average for 1951 to 1980 for (a) Northern Hemisphere, (b) Southern Hemisphere, and (c) global mean /4/.

6.2 The importance of climate feedbacks

There are many uncertainties remaining about the extent of processes acting to amplify (through positive feedbacks) or reduce (through negative feedbacks) the expected warming. Some of the most important feedbacks that have been identified include:

> H_2O greenhouse feedback: As the lower atmosphere (the troposphere) warms, it can hold more water vapor. The enhanced water vapor traps more IR radiation and amplifies the greenhouse effect. Ramanathan /10/ indicates that, based on studies with one-dimensional climate models, this feedback amplifies the air temperature by a factor of about 1.5 and the surface warming by a factor of about 3. The IPCC determined a surface temperature amplification factor of 1.6 for water vapor feedback /4/.
>
> Ice-albedo feedbacks: Warming induced by the global greenhouse effect melts sea ice and snow cover. Whether it is ocean or land, the underlying surface is much darker (i.e., it has a lower albedo) than the ice or snow; therefore, it absorbs more solar radiation, thus amplifying the initial warming. According to Ramanathan, ice-albedo feedback amplifies the global warming by 10 to 20 %, with larger effects near sea-ice margins and in polar oceans /10/.
>
> Cloud feedback: Cloud feedback mechanisms are extremely complex and are still poorly understood. Changes in cloud type, amount, altitude, and water content can all affect the extent of the climatic feedback. The sign of the feedback is also not understood, although current climate models generally find this to be a positive feedback. Since clouds are still treated rather crudely in existing three-dimensional climate models (general circulation models or GCMs), it is premature to attempt reliable conclusions about the magnitude of cloud feedback processes.
>
> Ocean-atmosphere interactions: The oceans influence the climate in two fundamentally important ways. First, because of the importance of the water vapor greenhouse feedback, the air and land temperature response is affected by the warming of the ocean surface. If the oceans do not respond to the greenhouse heating, the H_2O feedback would be turned off, because increased evaporation from the warmer ocean is the primary source of increasing atmospheric water vapor. Second, oceans can sequester the radiative heating into the deeper layers, which, because of their enormous heat capacity, can significantly delay the overall global warming effect over land surfaces. Current climate models suggest this delaying effect may cause a lag in the expected temperature response of at least a few decades, with the best estimate being about 50 years /25/.

Other feedbacks exist, such as changes in albedo related to changes in land features and biomass, but many of these feedbacks are not well understood. It is the combined effect of the many uncertainties in feedback processes that has resulted in the factor of 3 (1.4^o to 4.5^oC) difference in the amount of equilibrium warming estimated for a radiative equivalent doubling of CO_2 concentrations that was mentioned earlier.

6.3 Potential significance of climate change

Many questions about how the changing composition of the atmosphere will affect climate remain unanswered. Nonetheless, a number of research studies are attempting to determine what sorts of impacts on our environment may result from global warming. This section attempts to highlight existing understanding of the concerns regarding the consequences of climate change (/4/, /5/, /26/, /27/)

At this point, there is much less certainty about the climate changes expected in local regions compared to the expected overall global warming. Computer models of the atmosphere and climate generally agree that an overall global warming will occur because of increasing concentrations of greenhouse gases, but they are much less certain in their representation of the spatial distribution of this warming. There is even less certainty about regional changes in precipitation.

Some of the potential impacts of climate change are as follows:

Sea level rise: Sea levels are expected to rise as a response to global warming, but the rate and timing remain uncertain. Over the last century, the global-mean sea level has risen about 10 to 20 cm. Over the next century, current models project a further increase in global-mean sea level of 60±30 cm /4/. Even if further increases in greenhouse forcing were halted by 2030, sea level would continue to rise from 2030 to 2100, by as much again as from 1990 to 2030. Most of the contribution to sea level rise is expected to derive from thermal expansion of the oceans and the increased melting of mountain glaciers. The prospect of such an increase in the rate of sea level rise is of concern to low-lying coasts. The most severe effects of the sea level rise may result from extreme events (e.g., storm surges), the incidence of which may also be affected by climatic change.

Effects on human health: Direct effects on human health of the emitted greenhouse gases are believed to be small. Other links between climate change and human health have not been well established, although modest effects could result. For example, temperature increases could stress human health (e.g., heat stress), but in cold areas they could reduce stress; some diseases and pests could be more prevalent. However, good predictions of effects on health cannot be made without good predictive data on changes in local temperatures, humidities, and levels of precipitation. Stratospheric O_3 depletion could affect health because of the corresponding increase in UV radiation.

Agriculture and food supplies: Increased atmospheric CO_2 could potentially enhance growth of some food crops as well as increase water use efficiency. However, changing climatic patterns could require changes in cropping patterns and consequently in infrastructures and costs, perhaps bringing benefits to some regions while negatively impacting others. According to the DOE Multi-Laboratory Climate Change Committee /26/, it appears likely that the future rate of growth in the worldwide demand for food and fiber can be met assuming typical projections of climate change. However, rapid changes in climate or more severe climate change could make adaptation more difficult.

Ecosystems: Ecosystem structure and species distribution are particularly sensitive to the rate of change of climate. Ecosystems will respond to local changes in temperature, precipitation, soil moisture and also to the occurrence of extreme events. Increasing concentrations of CO_2 increase plant growth. However, rapid changes in climate threaten a reduction in biodiversity /26/. Some existing species of plants and animals might be unable to adapt, being insufficiently mobile to migrate at the rate required for survival. Many uncertainties about the adaptability of natural ecosystems to climate change still remain.

The present state of knowledge of tools for analyzing the consequences of climate change is such that, even if climate change could be forecast with certainty, the relationship between climate change and societal damage or benefit could not be well determined. There is an acute need to systematically expand our understanding of the consequences of climate change.

7. POLICY ANALYSES AND GLOBAL WARMING POTENTIALS

For assessments of regional, national, and sectoral emissions, a set of special tools is required by policymakers. One of the primary tools currently being used is based on the concept of Global Warming Potentials (GWPs) developed for the IPCC (/4/,/5/, /9/, /11/). Since different gases have different lifetimes, different direct effects on the radiative balance of the Earth, and different effects on the overall composition of the atmosphere, a measure of relative importance is needed in order to compare the release of different amounts of each gas into the atmosphere. There is no unambiguously correct method for approaching this problem. However, the concept developed for IPCC is currently being used in many policy related studies.

In determining GWPs, models of the atmosphere and energy are used to simulate the effect on radiative forcing of the release of a kilogram of CO_2, in each year, over a period of time into the future, relative to a standard reference scenario. The change in radiative forcing is then added over a specific period of time, e.g., 20 years, 100 years, 500 years. The experiment is then run for other gases. The cumulative effect of each gas on radiative forcing is then compared to the cumulative effect of CO_2 on radiative forcing. Important factors in determining GWPs include the way different gases are treated with regard to their residence time in the atmosphere after emission, their solar and infrared radiative absorption properties, and the indirect climatic effects resulting from chemical interactions with other greenhouse gases. The IPCC /4/ conventions for GWP coefficients is being used as a standard set of weights for evaluating emissions of radiatively important gases. The updated values for GWPs /5/ for relevant CFCs, HCFCs, and HFCs appear in Table III. These GWPs were evaluated for time-integration periods of 20, 100, and 500 years, reflecting the concern by policy makers that global warming effects should be considered over a range of time periods. The shortest time horizon is more indicative of the initial climatic response after emission. The 500 year integration provides a measure of the cumulative chronic effects on climate. The 100 year period generally provides a balanced representation of the various time horizons for climate response. The indirect radiative effects on ozone due to CFCs has not been included in the GWPs currently available.

One of the applications of GWPs to policy analyses is the examination of the energy and global warming effects of possible CFC replacements in refrigeration (and other) applications (/28/, /29/). These studies indicate the importance of examining entire systems in evaluating the impacts of alternative technologies. Initial findings indicate that the climatic forcing of carbon dioxide being emitted as a result of energy use in refrigeration systems is generally much larger than the direct CFC effect from these systems and that there is little energy use differences between CFCs and the replacements under consideration.

8. CONCLUSIONS

Current use and emissions of CFCs are having a significant influence on the radiative forcing of climate. However, observed decreases in stratospheric ozone, thought to be connected to increasing stratospheric chlorine from CFCs, suggests a cooling tendency over the last decade. This cooling tendency has strong latitudinal gradients, but is, when globally averaged, about comparable in magnitude and opposite in sign to the radiative forcing from CFCs over this period. The effects of the changes in stratospheric ozone on radiative forcing is indicative of the strong coupling between atmospheric chemistry and climate. Because of their shorter atmospheric lifetimes, the direct radiative influence on climate from the replacement compounds should generally be much smaller than the CFCs.

Table III. Global Warming Potentials for relevant CFCs, HCFCs, and HFCs (/5/, /9/). Only direct radiative effects are included; however, the sign of expected indirect effects due to chemical interaction is also shown.

	Global Warming Potentials Time Horizon		
Trace Gas	20 years	100 years	500 years
CO_2	1	1	1
CFC-11	4500	3400	1400
CFC-12	7100	7100	4100
CFC-114	6100	7000	5800
CFC-115	5500	7000	8500
HCFC-22	4200	1600	540
HCFC-123	330	90	30
HCFC-124	1500	440	150
HCFC-141b	1800	580	200
HFC-134a	3100	1200	400
HFC-152a	530	150	49

9. ACKNOWLEDGMENT

Work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48 and was supported in part by the Department of Energy Office of Environmental Analysis, and the Office of Health and Environmental Research's Environmental Sciences Division.

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Tables

Table I. Radiative forcing (ΔF) of a number of CFCs, HCFCs, and HFCs relative to CO_2 and to CFC-11 on a per unit molecule change and a per unit mass change basis. Based on present concentrations of CO_2 (/4/, /11/, /12/).

Table II. Estimated atmospheric lifetimes, tropospheric concentrations (for 1989) and observed global trends in concentrations for CFCs, HCFCs, and HFCs (/5/, /9/). The atmospheric lifetimes are based on atmospheric models and, where appropriate, constraints from atmospheric observations.

Table III. Global Warming Potentials for relevant CFCs, HCFCs, and HFCs (/5/, /9/). Only direct radiative effects are included.

Figures

Figure 1. (a) Blackbody curves showing the variation of emitted energy with wavelength for temperatures typical of the Sun and Earth, respectively, and (b) percentage of atmospheric absorption for radiation passing from the top of the atmosphere to the surface. Note the comparatively weak absorption of the solar spectrum and the region from 7 to 13 μm in the longwave spectrum, referred to as the window region. CFCs, HCFCs, and HFCs absorb in the window region.

Figure 2. Schematic diagram of the important processes determining radiative processes in the atmosphere.

Figure 3. (a) Estimated global consumption of CFCs and (b) estimated consumption of CFCs by application /13/.

Figure 4. Observed concentrations of CFCs and other halocarbons since 1978 at the Tasmanian station of the ALE/ GAGE network. Qualitatively similar trends are found at the other stations in this global network (/4/, /5/, /9/, /15/).

Figure 5. Relative effects of various greenhouse gases on the increase in climatic forcing from 1980 to 1990 /4/.

Figure 6. Comparison of the annual averaged changes in radiative forcing due to the observed total ozone decreases with the direct radiative forcing from CFCs and from all greenhouse gases (/5/, /16/).

Figure 7. Predicted change in surface temperature calculated for the baseline scenario used in the recent IPCC international assessment /5/; the three curves shown reflect the climatic sensitivity to uncertainties in climate feedbacks.

Figure 8. Combined land-air and sea surface temperatures, 1861 to 1989, relative to the average for 1951 to 1980 for (a) Northern Hemisphere, (b) Southern Hemisphere, and (c) global mean /4/.