Radiative forcings and global warming potentials of 39 greenhouse gases

Atul K. Jain,¹ Bruce P. Bruegge,² K. Minschwaner,³ and Donald J. Wuebbles¹

Abstract. The radiative forcings and global warming potentials for 39 greenhouse gases are evaluated using narrowband and broadband radiative transfer models. Unlike many previous studies, latitudinal and seasonal variations are considered explicitly, using distributions of major greenhouse gases from a combination of chemical-transport model results and Upper Atmosphere Research Satellite (UARS) measurements and cloud statistics from the International Satellite Cloud Climatology Project. The gases examined include CO₂, CH₄, N₂O, plus a number of chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, hydrobromocarbons, bromocarbons, iodocarbons, and perfluorocarbons (PFCs). The model calculations are performed on a 5° latitude grid from 82.5°S to 82.5°N. The radiative forcings determined by the model are then used to derive global warming potential for each of the compounds, which are compared with prior analyses. In addition, the latitudinal and seasonal dependence of radiative forcing since preindustrial time is calculated. The vertical profiles of the gases are found to be important in determining the radiative forcings; the use of height-independent vertical distributions of greenhouse gases, as used in many previous studies, produce errors of several percent in estimated radiative forcings for gases studied here; the errors for the short-lived compounds are relatively higher. Errors in evaluated radiative forcings caused by neglecting both the seasonal and the latitudinal distributions of greenhouse gases and atmospheres are generally smaller than those due to height-independent vertical distributions. Our total radiative forcing due to increase in major greenhouse gas concentrations for the period 1765-1997 is 2.32 Wm⁻², only 2% higher than other recent estimates; however, the differences for individual gases are as large as 23%.

1. Introduction

Radiative forcing, expressed as the change in radiative energy flux in units of Wm⁻², is a useful measure of the climate change impact expected from changing concentrations of greenhouse gases (CO₂, CH₄, N₂O, H₂O, O₃, and halocarbons) and aerosols. While radiative forcing can be calculated with more confidence than the response of climate in terms of global and regional temperature change, care must be taken where large seasonal and/or regional variations exist in the anthropogenic and natural factors affecting the radiative forcing. Previous estimates of the radiative forcings for several greenhouse gases have been published, with relatively large differences in the results [Hansen et al., 1997, Minschwaner et al., 1998; Good et al., 1998; Myhre and Stordal, 1997; Myhre et al., 1998; Naik et al., 2000; Pinnock et al., 1995; Freckleton et al., 1998, and references therein]. This may be due to the fact that the estimates had been carried out using a range of different types of radiative transfer models and a diverse set of data sources. In the absence of a coherent set of radiative forcing estimates, even the international assessments, such as the Intergovernmental Panel on Climate Change [Schimel et al., 1996] and World Meteorological Organization [Granier et al., 1999], used these diverse results for their assessment of greenhouse warming impact.

The purpose of this paper is to examine the radiative forcings and the global warming potentials (GWP) of a wide range of greenhouse gases using a consistent set of radiative transfer models, in addition to spectroscopic and climate data sets. The gases examined here include the most common greenhouse gases (CO₂, CH₄, and N₂O) as well as a number of halocarbons and perfluorocarbons (SF₆, CF₃). First, we evaluate the radiative forcings due to a single global and annual mean (GAM) profile of temperature, water vapor (H₂O), ozone (O₃), cloudiness, and greenhouse gas concentrations using broadband (BBM) and narrowband (NBM) radiative transfer models. Our motivation here is to examine the sensitivity of greenhouse gas radiative forcings to a number of simplified assumptions widely used in past calculations. Since there are large spatial and temporal variations in climate data, we next calculate the radiative forcings of the greenhouse gases considered in this study as a function of latitude and season using the NBM. Third, we examine the radiative forcings of a number of greenhouse gases since preindustrial times as a function of latitude and season. In the past, simplified expressions relating the radiative forcings to the changes in the greenhouse gas concentrations were used for this type of evaluation [Shine et al., 1990; Schimel et al., 1996]. In contrast, we have estimated the radiative forcing using the NBM as well as using the distributions of major greenhouse gases based on a combination of atmospheric model calculations and UARS measurements. Finally, we evaluate the GWPs for the 39 gases considered here on the basis of our "best estimate" values of radiative forcings.
Section 2 provides a brief description of the method used to calculate radiative forcings using radiative transfer models, along with a discussion of the climate and the spectroscopic data sets used in this study. In section 3 we report the global mean radiative forcing results for various sensitivity tests based on a single GAM atmosphere. Section 4 discusses the radiative forcing results for major greenhouse gases based on latitudinal and seasonal atmospheres since preindustrial times. In section 5 we compare the observation-based and CTM-based (chemical-transport model) radiative forcings. Section 6 compares the NBM-calculated radiative forcings for various greenhouse gases with other recent research studies. The estimated GWPs based on our “best estimates” of radiative forcings are discussed in section 7. Finally, the major findings of this study are summarized in section 8.

2. Method, Models, and Input Data

2.1. Method

The purpose of this paper is to calculate the radiative forcing of a number of greenhouse gases using a consistent set of radiative transfer models and data sets, which are discussed in detail in following sections. Radiative forcing is calculated as the change in net irradiance due to a change in greenhouse gas concentrations at the tropopause after allowing for the adjustment of stratospheric temperatures to radiative equilibrium [Schumel et al., 1996; Granier et al., 1999]. The adjustment of the stratosphere is included because the stratosphere responds in a few months, whereas the surface-troposphere system responds in decades due to the large thermal inertia of the ocean. The radiative forcing that we have calculated here, taking this adjustment into account, is called the adjusted radiative forcing. If the stratospheric adjustment is not accounted for, the derived radiative forcing is called the instantaneous radiative forcing. We explicitly consider the latitudinal and seasonal variations using zonally and seasonally averaged distributions of temperature, H₂O, O₃, trace gases, and clouds.

As discussed by Myhre and Stordal [1997] and Freckleton et al. [1998], the tropopause height and definition (i.e., lapse rate criteria, temperature minimum, and top of convective layer) are crucial in determining the magnitude of radiative forcing. Myhre and Stordal [1997] show that assuming a fixed global-mean tropopause height for each latitude belt can produce errors of up to 10% in the instantaneous global-mean forcing. Moreover, Freckleton et al. [1998] have shown that the choice of tropopause definition can influence the radiative forcing results by up to 9%. In this study we define the tropopause at each latitude as a level where the minima in temperature occurs.

2.2. Distributions of H₂O, O₃, Temperature, and Clouds

The vertical profiles of temperature, H₂O, and O₃ are important parameters in the calculations of radiative forcing. In this study, latitudinal and seasonal variations of temperature, H₂O, O₃, and clouds are based on in situ and satellite data. Here we provide only the brief description of the data used. A detailed description of the data used in this study can be found in the work of Minschwaner et al. [1998].

Distributions of H₂O, O₃, and temperature, along with the cloud fraction and heights assumed in the calculations for the September-October time period, are shown in Plate 1. Zonally averaged distributions of temperature, H₂O, and O₃ in the stratosphere were compiled on the basis of UARS Microwave Limb Sounder measurements [Waters et al., 1993] over 2 month periods covering the equinoxes and solstices. The total time interval extends from March 1992 to January 1993. Temperature profiles in the troposphere were adopted from the National Meteorological Center analysis [McPherson et al., 1979]. O₃ in the troposphere was based on the climatological values from Oltmans [1981] and Levy et al. [1985], while tropospheric H₂O was specified on the basis of standard Air Force Geophysics Laboratory (AFGL) models [Anderson et al., 1986]. We adopted the values for the cloud fractions for low, middle, and high clouds from the International Satellite Cloud Climatology Project (ISCCP) [Rossow and Schiffer, 1991]. Low clouds are assumed to be located between 850 and 750 mb, middle-level clouds are placed in a 100-mbar-thick layer centered near 500 mbar at middle and high latitudes, and near 350 mbar in tropics. High clouds are located in a 20-mbar-thick layer located just below the tropopause. The values for cloud liquid water paths and effective drop radii for the three cloud types assumed in this study were taken from Stephens and Platt [1987], consistent with the values used by Dessler et al. [1996]. Surface emissivity was assumed to be fixed at 0.92, independent of latitude and season. This value represents an estimate of the weighted mean of sea surface, sand, and snow. Calculated forcings were found to be relatively insensitive to the precise choice of surface longwave emissivity.

2.3. Model-Estimated and Observed Concentrations for Trace Gases

To examine the sensitivity of the radiative forcing to vertical, latitudinal, and seasonal greenhouse gas distribution, two changes were considered. (1) uniform changes throughout the atmosphere for all seasons (UCA), and (2) height dependent changes in the vertical profile as well as latitudinal and seasonal changes in vertical profiles (NUCA). The radiative forcings for UCA were estimated for a uniform increase of 5 ppbv for CO₂ (350 to 355 ppmv), 10 ppbv for CH₄ (1714 to 1724 ppbv), and N₂O (311 to 321 ppbv). In order to reduce the error due to nonlinear absorption caused by a weak line limit for halocarbons and perfluorocarbons, the forcings were calculated for a 0.1 ppbv (zero to 0.1 ppbv) change. For the NUCA case the radiative forcings were calculated for an increase in greenhouse gas concentrations from preindustrial times to the present day time period (1992). The latitudinal, seasonal, and vertical distributions of all greenhouse gases, with the exception of CO₂, CFC-13, perfluorocarbons (PFCs), iodocarbons (ICs) and three bromocarbons (CH₃Br, CH₂Br₂, and CHFBr), were calculated using a two-dimensional (latitude and altitude) chemical-transport model (CTM) of the global atmosphere [Naik et al., 2000; Wuebbles et al., 2000; Kotamarthi et al., 1999]. This model has been used extensively in past international ozone assessments to determine lifetimes of halocarbons and other greenhouse gases and their effects on ozone [WMO, 1992, 1995]. The model grid is 5° in latitude from pole to pole and about 1.5 km in altitude from the surface to 85 km. The preindustrial and present-day concentrations were calculated for fixed surface concentration boundary conditions, which were taken from Schumel et al. [1996]. The preindustrial surface concentrations for all halocarbons were assumed to be zero. The current concentrations for all of the HCFCs (except for HCFC-22) and HFCs are also zero. However, to evaluate the sensitivity of radiative forcing to the variation in vertical profile, the 1992 concentrations for these compounds were calculated by assuming the surface concentration of 5 ppbv. Generally, the radiative forcings for halocarbons are reported for a 1 ppbv increase; hence our results for the UCA and NUCA cases were recalculated to reflect the impact of a 1 ppbv change in halocarbon concentrations.
Plate 1. Distributions of (a) temperature (K), (b) cloud fractions (percent), (c) H$_2$O (ppmv), and (d) O$_3$ (ppmv) used in the radiative calculations for the September-October preindustrial and contemporary time periods.
Plate 2. Chemical transport model- (CTM) estimated and observed distribution of CH₄ (ppmv) used in the radiative calculations for the September-October contemporary period. Plate also shows the CTM-estimated CH₄ distributions that were used for the September-October preindustrial time period.
Plate 3. CTM estimated and observed distribution of N₂O (ppbv) used in the radiative calculations for the September-October contemporary period. Plate also shows the CTM-estimated N₂O distributions used for the September-October preindustrial time period.
To validate CTM-based radiative forcings with observation-based forcings, we have estimated the forcings for CH₄, N₂O, and CFC-12 based on the observed measurements [Minschwaner et al., 1998]. Plates 2, 3, and 4 show that CTM distributions of CH₄, N₂O, and CFC-12 for the September-October present-day atmosphere compare well with the observation data. In Plates 2-4 the observed distributions of gases in the stratosphere were derived from vertical profiles measured by the Cryogenic Limb Array Eulon Spectrometer (CLAES) onboard UARS [Minschwaner et al., 1998]. Measurement times were extended from March 1992 to January 1993. Observed concentrations for CH₄ [Tans et al., 1992] and for N₂O, and CFC-12 [Montzka et al., 1992] in the troposphere, assumed to be height independent, were obtained from 1991 to 1992 measurements from a surface network operated by the Climate Monitoring and Diagnostics Laboratory (CMDL). Plates 2-4 show the latitudinal variations for N₂O (less than 1% pole to pole) but is significant for CH₄ (about 9% pole to pole) and CFC-12 (about 6%). In general, the values from the model agree well with the observations. Plates 2 and 3 also show the CTM concentrations of CH₄ and N₂O for preindustrial time, which were used in the model-based and observation-based radiative forcing calculations for the preindustrial time.

2.4. Spectroscopic Data

Line parameters for H₂O, CO₂, O₃, CH₄, N₂O, and SF₆ were based on the HITRAN-1992 database [Rothman et al., 1992]. The HITRAN database does not provide the hot bands for SF₆.

In this study the total radiative forcings for SF₆ were assumed to be 3.4 times the value estimated on the basis of HITRAN-1992 data set [Myhre and Skordal, 1997; Grossman et al.,1993]. A newer version of HITRAN database, HITRAN 1996, has also been released. Pinnock and Shine [1998] have shown that the effects of updated HITRAN database on calculations of radiative forcing for CO₂, CH₄, N₂O, and O₃ is less than 1%. Absorption cross-section data for CFC-11,12,13,113,114,115, HFCFC-22, and CF₃ were taken from McDaniel et al. [1991]. The absorption data for CCl₃ and CH₃CCl₃ were taken from Fisher et al. [1990]. H-1301 absorption data were from Person and Polo [1961], and data for HFC-245fa were made available by H. Magid of Allied Signal Inc. The infrared spectral data for the remainder of the gases were provided by M. Hurley of the Ford Motor Company: detailed information about these spectral data can be found in the work of Pinnock et al. [1995] and Christidès et al. [1997], and comparisons have also been made therein with other published works.

2.5. Description of Radiative Transfer Models

The radiative forcing calculations are performed with a broadband model (BBM) and a narrow band model (NBM). The BBM is based on the longwave band model of Briegleb [1992a]. This is a uniform 100 cm⁻¹ band model that calculates infrared fluxes due to H₂O, CO₂, O₃, CH₄, N₂O, and CFC-11 and -12. The gas transmissions are computed by a modified Malkmus function. Gas overlapping in the same 100 cm⁻¹ interval is approximated by random overlap. Cloud particle scattering is
Figure 1. Comparison of the narrowband model (NBM) top of atmosphere infrared fluxes with the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis estimates for (a) June-July and (b) December-January. Modeled values were calculated using the narrow band radiative transfer model initialized with temperature, greenhouse gas distributions, and clouds as discussed in the text. The NCEP/NCAR estimates are averaged for the period 1957-1996.

3. Radiative Forcing Calculations Based on Single Global and Annual Mean Atmosphere

There are number of published studies that report radiative forcing calculations. However, many problems arise when comparing these studies, mainly because these calculations were carried out for the wide range of assumptions and data sets. For example, in some studies, stratospheric adjustment was not included. In other studies, radiative forcing was calculated for clear-sky conditions. Radiative forcing should be calculated with the stratospheric adjustment and using appropriate temperature, water vapor, ozone, and cloud conditions [Albritton et al., 1995; Granier et al., 1999]. Intercomparison results from these models show that the uncertainties in the radiative forcing for doubling of CO$_2$ could be as large as 10% [Lathier and Fouquart, 1984]. In this section we estimate the sensitivity of greenhouse gas radiative forcing to a number of the assumptions discussed above, including the use of the BBM versus the NBM, clear-sky versus cloudy sky forcing, instantaneous versus adjusted forcing, diffusivity factor based versus angular integration-based forcings, and constant versus realistic profile-based forcings.
Table 1. Global and Annual Mean (GAM) Atmospheric Profile Used for Radiative Forcing Calculations for the Single Atmosphere Profile.

<table>
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<th>Temperature, K</th>
<th>H$_2$O* g/g</th>
<th>O$_3$* g/g</th>
<th>Cl$_4$ N$_2$O_ppbv</th>
<th>Cl$_4$ N$_2$O_ppbv</th>
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The preindustrial and 1992 distributions for all gases except for CO$_2$ were derived on the basis of chemical transport model results. CO$_2$ concentrations were assumed constant throughout the atmosphere at preindustrial and present-day 1992 levels of 278 and 356 ppmv. The concentrations of CFC-11 and CFC-12 during preindustrial times were assumed to be zero. Read 3.99E-06 as 3.99 x 10^{-6}.

* Mass mixing ratio.

Cloudiness (Table 1), which were based on latitudinal and seasonal averaging of the data discussed above.

3.1. Broadband Model Versus Narrowband Model Results for Radiative Forcing

Although line-by-line model (LBLM) calculations are generally considered to provide the most accurate results for radiative forcings, they are too computationally expensive to calculate the cloudy sky radiative forcings. This is particularly true for the adjusted radiative forcing, which requires several radiative transfer calculation for each single atmospheric profile. On the other hand, NBAM calculations are computationally less expensive than LBLM calculations and more accurate than the BBM results and have been shown to produce greenhouse gas forcings within a few percent of that LBLM calculations [Freckleton et al., 1996]. In previous studies, we employed a BBM to calculate the radiative forcings for a number of greenhouse gases [Naik et al., 2000; Li et al., 2000; Good et al., 1998; Minschwaner et al., 1998]. In order to evaluate the accuracy of the BBM results, we compare the cloudy sky instantaneous radiative forcing results of the BBM with the NBAM (Table 2). The major difference between the NBAM (spectral resolution 5-10 cm$^{-1}$) and the BBM has two overlapping effects with the absorption bands of CO$_2$, CH$_4$, N$_2$O, and O$_3$. Table 2 shows that the spectral overlapping of these gases with H$_2$O and other gases is poorly treated in a BBM, since many of the halocarbons have absorption bands much less than 100 cm$^{-1}$ wide. For example, CCl$_4$ has a very localized absorption band centered at 790 cm$^{-1}$, which overlaps with the wing of the 665 cm$^{-1}$ band of CO$_2$. In the case of H-1301, which has a very narrow band centered at 1085 cm$^{-1}$, the overlap occurs mainly...
Table 2. Impact of Overlapping Effects on Instantaneous Cloudy Sky Radiative Forcing Calculated Using the Narrowband Model (NBM) and Broadband Model (BBM).

<table>
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<th>Radiative Forcing</th>
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<th>No O₂⁺</th>
<th>No CO₂⁺</th>
<th>No CH₄⁺</th>
<th>No N₂O⁺</th>
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<tbody>
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<td>BBM</td>
<td>BBM-NRM</td>
<td>NBM</td>
<td>BBM</td>
<td>NBM</td>
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<td>-8</td>
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</table>

Chloroform (CF₃CIF)

| CFC-11    | 0.268 | 0.253 | -3 | 10 | 10 | 1 | 7 | 2 | 2 | 0 | 0 | 0 | 0 |
| CFC-12    | 0.322 | 0.300 | -7 | 9 | 9 | 1 | 5 | 0 | 1 | 1 | 0 | 1 | 1 |
| CFC-13    | 0.280 | 0.280 | -24 | 17 | 17 | 1 | 6 | 0 | 3 | 0 | 6 | 0 | 7 |
| CFC-114   | 0.307 | 0.301 | -2 | 11 | 10 | 7 | 6 | 0 | 1 | 1 | 1 | 1 | 1 |
| CFC-114   | 0.298 | 0.305 | 2 | 12 | 11 | 8 | 6 | 0 | 0 | 2 | 1 | 2 | 2 |
| CFC-115   | 0.216 | 0.202 | -6 | 14 | 17 | 2 | 2 | 0 | 0 | 2 | 5 | 2 | 6 |

Chloroform (CCl₃)

| CCl₄      | 0.148 | 0.106 | -28 | 16 | 11 | 0 | 2 | 6 | 50 | 0 | 0 | 0 | 0 |
| CH₂Cl₂    | 0.079 | 0.077 | -3 | 12 | 11 | 5 | 7 | 49 | 30 | 1 | 0 | 1 | 1 |

Hydrochlorofluorocarbons (HCFCs)

| HCFC-22   | 0.213 | 0.192 | -10 | 13 | 14 | 1 | 4 | 0 | 3 | 1 | 1 | 2 | 1 |
| HCFC-123  | 0.189 | 0.192 | 1 | 17 | 17 | 1 | 1 | 0 | 1 | 5 | 4 | 5 | 4 |
| HCFC-124  | 0.211 | 0.201 | -5 | 18 | 18 | 1 | 3 | 7 | 7 | 4 | 5 | 4 | 6 |
| HCFC-141b | 0.149 | 0.126 | 14 | 12 | 12 | 1 | 4 | 7 | 19 | 1 | 1 | 1 | 1 |
| HCFC-142b | 0.184 | 0.111 | 1 | 15 | 15 | 1 | 2 | 0 | 0 | 1 | 2 | 1 | 3 |
| HCFC-225ca| 0.260 | 0.239 | 8 | 18 | 21 | 7 | 6 | 14 | 14 | 2 | 6 | 2 | 6 |
| HCFC-225cb| 0.271 | 0.264 | -3 | 12 | 12 | 2 | 5 | 8 | 9 | 2 | 1 | 2 | 2 |

Hydrofluorocarbons (HFCs)

| HFC-23    | 0.255 | 0.256 | 0 | 21 | 22 | 2 | 3 | 4 | 3 | 4 | 1 | 4 | 3 |
| HFC-32    | 0.168 | 0.149 | -11 | 18 | 19 | 6 | 19 | 4 | 4 | 1 | 1 | 1 | 1 |
| HFC-125   | 0.256 | 0.226 | -12 | 19 | 23 | 1 | 6 | 5 | 3 | 7 | 3 | 7 | 3 |
| HFC-134   | 0.188 | 0.178 | -5 | 19 | 20 | 2 | 2 | 0 | 1 | 2 | 1 | 2 | 3 |
| HFC-134a  | 0.201 | 0.201 | 5 | 20 | 21 | 2 | 2 | 2 | 2 | 2 | 5 | 4 | 5 |
| HFC-143   | 0.130 | 0.115 | -12 | 13 | 14 | 3 | 16 | 1 | 1 | 1 | 1 | 1 | 2 |
| HFC-143a  | 0.161 | 0.138 | -14 | 24 | 25 | 0 | 0 | 2 | 4 | 4 | 1 | 1 | 1 |
| HFC-157a  | 0.171 | 0.117 | -3 | 21 | 20 | 1 | 7 | 1 | 0 | 1 | 0 | 1 | 2 |
| HFC-161b  | 0.037 | 0.037 | 0 | 20 | 18 | 23 | 27 | 0 | 1 | 0 | 0 | 0 | 0 |
| HFC-227ea | 0.325 | 0.279 | -14 | 24 | 28 | 0 | 0 | 2 | 4 | 4 | 1 | 1 | 11 |
| HFC-236fa | 0.259 | 0.226 | -13 | 31 | 37 | 1 | 1 | 9 | 9 | 4 | 1 | 4 | 9 |
| HFC-245fa | 0.272 | 0.281 | 3 | 27 | 25 | 3 | 8 | 3 | 4 | 4 | 3 | 4 | 4 |

Perfluorocarbons (PFCs)

| SF₆       | 0.148 | 0.148 | 0 | 7 | 7 | 0 | 1 | 3 | 1 | 0 | 0 | 0 | 0 |
| CF₄       | 0.088 | 0.149 | 68 | 40 | 28 | 0 | 0 | 0 | 0 | 36 | 19 | 36 | 17 |

Bromoform (HCl)

| H-1211    | 0.791 | 0.277 | -5 | 11 | 11 | 1 | 7 | ? | 2 | 2 | 1 | 0 | 1 | 1 |
| H-1301    | 0.302 | 0.206 | -32 | 11 | 13 | 1 | 29 | 3 | 4 | 0 | 6 | 0 | 6 |
| CH₃Br     | 0.008 | 0.008 | 0 | 41 | 47 | 3 | 3 | 25 | 39 | 6 | 4 | 6 | 3 |
| CH₃Br₂    | 0.019 | 0.020 | 6 | 18 | 20 | 0 | 1 | 168 | 137 | 2 | 1 | 2 | 3 |
| CH₃Br₃    | 0.182 | 0.181 | 2 | 15 | 16 | 2 | 9 | 19 | 12 | 2 | 1 | 2 | 3 |

Iodoform (NaCl)

| CF₄       | 0.279 | 0.267 | -4 | 13 | 10 | 9 | 24 | 6 | 4 | 2 | 0 | 7 | 1 |
| CF₃CF₃    | 0.290 | 0.257 | -12 | 17 | 20 | 0 | 1 | 15 | 5 | 1 | 5 | 1 | 5 |

Radiative forcings are for an increase of 1 ppb (0.1 ppbv) for halocarbons, 5 ppbv for CO₂ (350-355 ppbv), 10 ppbv for CH₄ (1714-1774 ppbv) and N₂O (311-321 ppbv).

* The values are the increase in the net flux due to overlap reduction for individual gas.

with H₂O. Table 2 shows that the BBM was incapable of taking into account these localized overlapping effects.

3.2. Clear-Sky Versus Cloudy Sky Radiative Forcing

Clouds play an important role in the calculation of greenhouse gas radiative forcings. Table 3 shows that clouds could reduce the adjusted clear-sky radiative forcings by as much as 35%, consistent with the results of Pinnoak et al. [1995] and Myhre and Stordal [1997], due to a smaller upward irradiance during cloudy sky conditions. The clouds have a smaller effect on the radiative forcing of CO₂ than on other greenhouse gases, because the total optical depth is already large due to higher CO₂ concentrations and strong absorption in the 15 μm band. On the other hand, halocarbons absorb in the weak line limit and CH₄ and N₂O between weak and strong line limits, therefore optical depths for non-CO₂ gases are much smaller, and hence the impact of clouds on their radiative forcing is larger (Table 3).
Table 3. Estimated Radiative Forcings Using the Narrowband model (NBM) in Combination With a Global and Annual Mean (GAM) Background Atmosphere.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Lifetime (year)</th>
<th>Radiative Forcing (Wm$^{-2}$)</th>
<th>Clear Sky (%)</th>
<th>Instantaneous (%)</th>
<th>Constant Diffusivity (%)</th>
<th>Model-Derived Vertical Profile (%)</th>
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<tbody>
<tr>
<td>CO$_2$</td>
<td>variable</td>
<td>0.073</td>
<td>14.1</td>
<td>14.8</td>
<td>0.3</td>
<td>-1.4</td>
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<tr>
<td>CH$_4$</td>
<td>12.2</td>
<td>$4.73	imes10^{-1}$</td>
<td>28.5</td>
<td>2.5</td>
<td>1.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>120</td>
<td>$3.37	imes10^{-2}$</td>
<td>24.7</td>
<td>3.6</td>
<td>0.4</td>
<td>-1.9</td>
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<td>CFC-11</td>
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<td>-1.9</td>
<td>-10.2</td>
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<td>CFC-12</td>
<td>100</td>
<td>0.340</td>
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<td>-5.3</td>
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<td>-4.9</td>
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<td>0.227</td>
<td>33.8</td>
<td>-4.7</td>
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<td>-10.5</td>
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<td>4.1</td>
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<td>-5.8</td>
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<td>-15.9</td>
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<td>H-1301</td>
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<td>-5.4</td>
<td>-5.4</td>
</tr>
<tr>
<td>CF$_2$CF$_2$I</td>
<td>0.005</td>
<td>0.306</td>
<td>32.3</td>
<td>-5.2</td>
<td>4.2</td>
<td>-4.2</td>
</tr>
</tbody>
</table>

The reference values listed in column 3 are the cloudy sky adjusted radiative forcing with the angular integration due to a constant concentration change throughout the atmosphere. Columns 4-7 are the calculated percentage changes under the different condition as compared to reference case. Radiative forcings are for an increase of 1 ppbv (0-1 ppbv) for halocarbons, 5 ppmv for CO$_2$ (350-355 ppmv), 10 ppbv for CH$_4$ (1714-1724 ppbv), and N$_2$O (311-321 ppbv).

* Naik et al. (2000).

3.3. Instantaneous Versus Adjusted Radiative Forcing

The sign and the magnitude of the effect of stratospheric adjustment on radiative forcing due to the stratospheric adjustment depends on whether the net effect of both the stratospheric and the tropospheric forcings leads to a heating or a cooling of the stratosphere, with a resultant increase or decrease in thermal infrared emissions from the lower stratosphere to the troposphere, respectively [Schumel et al., 1996]. Halocarbons absorb predominantly in the window region (750-1250 cm$^{-1}$), in the linear line limit; therefore in the stratosphere they absorb the upwellng radiation from the troposphere and increase the heating rate of the stratosphere. When the stratospheric temperature is allowed to reach equilibrium, the stratosphere warms. Stratospheric warming
increases the downward radiative flux into the troposphere, resulting in an increase in the radiative forcing. Table 3 shows that the NBM-estimated instantaneous cloudy sky radiative forcings for halocarbons are up to 6% lower than the adjusted radiative forcing. Increasing the amounts of strongly absorbing gases results in enhanced CO$_2$, CH$_4$, and N$_2$O stratospheric cooling. For this reason, the instantaneous radiative forcings for CO$_2$, CH$_4$, and N$_2$O are 15%, 3%, and 4% higher, respectively, than the adjusted radiative forcings.

### 3.4 Diffusivity Factor-Based Versus Angular Integration-Based Radiative Forcings

In the original version of the radiative transfer model used in this study [Briegleb, 1992a], the angular integration for the radiative calculations was approximated by a band-independent diffusivity factor. For CO$_2$, CH$_4$, N$_2$O, H$_2$O, and O$_3$, a diffusivity factor of 1.66 was assumed, while for chlorofluorocarbons, diffusivity was assumed to be a function of total optical depth [Ramanathan et al., 1985]. Instead of using a diffusivity factor approximation we estimated the angular integration within each spectral interval with a 12-point Gaussian quadrature. The explicit angle integration allowed the use of angle-dependent surface emissivities. A NBM-estimated diffusivity-based and explicit angular-integration-based radiative forcings are compared in Table 3. The inaccuracy in radiative forcing for well-mixed and strongly absorbing greenhouse gases, such as CO$_2$, CH$_4$, and N$_2$O, due to a diffusivity factor approximation is small (1% or less). However, a diffusivity factor approximation employed by Briegleb [1992a] for the weakly absorbing halocarbons underestimates the radiative forcings by as much as 7%.

### 3.5. Constant Vertical Profile-Based Versus Realistic Vertical Profile-Based Radiative Forcings

The greenhouse gases in radiative forcing calculations are often assumed to be evenly distributed throughout the atmosphere and over the globe. Observed vertical profiles of greenhouse gases, however, reveal a decrease in concentrations with height, depending on the lifetime of the gas. Gases with lifetimes of a few years or more are generally well mixed in the troposphere, but in the stratosphere, the vertical transport is much slower. In addition, for many of the greenhouse gases, the photochemical loss rate increases with height above the tropopause. The combined effects of transport and photochemistry cause most greenhouse gas concentrations to decrease with height in the stratosphere. Here we compare the radiative forcing calculated with evenly distributed concentrations with the forcing calculated using 2-D CTEM-estimated vertical changes in greenhouse gas concentrations [see Naik et al., 2000, Figure 1]. Radiative forcing calculations were done for the adjusted and cloudy sky conditions using the NBM discussed in section 2.5. As shown in Table 3, both the uniform mixing ratio profiles and the 2-D CTEM model-estimated profiles with decreasing concentration in height yield about the same radiative forcings for CH$_4$ and N$_2$O; the difference is less than 1%. The reason for this is that the scale heights of the mixing ratios for CH$_4$ and N$_2$O are sufficiently large to yield nearly the same changes in stratospheric concentrations for these gases. However, the global and annual mean radiative forcings estimated using realistic vertical profiles are considerably lower for all CFCs, HCFCs, and HFCs studied here. Table 3 clearly shows that the reduction in the radiative forcing is not the same for all gases. Table 3 also indicates that the total lifetime of a gas itself is not a good indicator to estimate the reduction in radiative forcings, which occurs when using actual vertical profiles. For example, the total lifetimes of HFC-141b and HFC-142b are 10 and 18 years, respectively [Naik et al., 2000]. However, the reductions in radiative forcing due to these gases occurs when using the decreasing vertical profiles are the same for both gases (13%). Moreover, it is the combination of stratospheric and tropospheric lifetimes that determines the vertical profile of a gas and hence the reductions in radiative forcing. If a gas has a tropospheric lifetime of 2-3 years, it will generally be well mixed in the troposphere. For these gases, it is the stratospheric lifetime that is more important in determining the vertical profiles. As shown in Table 3, the percent reductions are quite significant for the gases with a lifetime of 2 years or less, e.g., HFC-161 (39%, 0.3 years), HFC-152a (20%, 2 years), and HCFC-123 (27%, 1.4 years) (in parentheses the first value is a percent reduction in radiative forcing (Table 3), and the second value is a total lifetime of a gas [Naik et al., 2000]). On the other hand, percent reduction in radiative forcing is quite small for long-lived CFCs, HFCs, and HCFCs, for example, CFC-115 (1.5%, 1/100 years), HCFC-22 (2%, 12 years), and HFC-236fa (0.5%, 209 years). These radiative forcing results show the importance of varying vertical profiles of greenhouse gas concentrations when calculating radiative forcings. In section 4 we show that the radiative forcing is sensitive not only to the vertical profile but also to latitudinal and the seasonal variations in greenhouse gas concentrations and atmospheric characteristics.

### 4. Radiative Forcing With Realistic Latitudinal and Seasonal Profiles of Greenhouse Gases and Atmospheres

Radiative forcings presented in section 3 were calculated on the basis of a single GAM atmospheric profile. However, radiative forcing changes with region and season as well, mainly due to spatial and time variations in temperature, H$_2$O, O$_3$, and cloudiness, as well as greenhouse gas distribution. Myhre and Stordal [1997] and Froeke et al. [1998] found that the calculated global mean radiative forcing, based on spatially varying atmospheric profiles, is quite different for some gases than the radiative forcing calculated on the basis of the single GAM atmospheric profile. Specifically, Myhre and Stordal [1997] found that the global and annual mean radiative forcing for several well-mixed greenhouse gases calculated from a single atmospheric profile could be 5-10% in error compared to the calculations using monthly and regional resolution 2.5° x 2.5° atmospheric profiles. However, they found that the error in radiative forcing due to temporal and longitudinal variations in well-mixed greenhouse gases was small (less than 1%). They also concluded that it was the latitudinal variation that must be represented to reduce the majority of the error in radiative forcing. Extending this conclusion, Froeke et al. [1998] show that the error in the radiative forcing for some well-mixed greenhouse gases calculated from the single atmospheric profile could be reduced by an order of magnitude or more by using three atmospheric profiles, one representing the tropics and one representing each of the northern and southern extratropics.

The purpose of this section is to provide global and annual mean radiative forcing calculated from changes in H$_2$O, O$_3$, greenhouse gas concentrations, temperature, and cloud distribution as a function of latitude and season. Of particular importance for our calculations in this section are the latitudinal and seasonal variations in the vertical profiles of greenhouse gases. The latitudinal and seasonal data used for the calculations have already been discussed in sections 2.2 and 2.3 and shown in Plates 1-4 for the September-October time period. The calculations were carried out on a 5° latitude grid from 87.5° S to 87.5° N, for four standard seasons. The latitudinal mean data for the background atmosphere for each season is the
Table 4. NBM-Based Cloudy Sky Adjusted Radiative Forcing in Wm⁻² Due to a Constant Change in Surface Concentrations Calculated With a Narrowband Model Using the CTM-Based latitudinal and Seasonal (LAS) Greenhouse Gas Profiles.

<table>
<thead>
<tr>
<th>Gas</th>
<th>LAS Wm⁻²</th>
<th>GAM-LAS</th>
<th>WMO [Granier et al., 1999]</th>
<th>WMO-LAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>0.075</td>
<td>-2.7</td>
<td>0.076</td>
<td>0.9</td>
</tr>
<tr>
<td>CH₄</td>
<td>4.67x10⁻³</td>
<td>-0.3</td>
<td>3.70x10⁻³</td>
<td>-21.3</td>
</tr>
<tr>
<td>N₂O</td>
<td>3.29x10⁻²</td>
<td>-0.4</td>
<td>3.70x10⁻²</td>
<td>11.3</td>
</tr>
</tbody>
</table>

**Chlorofluorocarbons (CFCs)**

| CFC-11       | 0.240    | 4.9     | 0.25                         | 4.3     |
| CFC-12       | 0.302    | 7.0     | 0.32                         | 6.0     |
| CFC-13       | 0.245    | 6.0     | 0.25                         | 2.0     |
| CFC-113      | 0.284    | 2.1     | 0.30                         | 5.7     |
| CFC-114      | 0.290    | 1.5     | 0.31                         | 7.1     |
| CFC-115      | 0.214    | 4.4     | 0.21 (0.25)⁺                | -2.0 (21) |

**Chlorocarbons (CCs)**

| CCl₃         | 0.125    | 1.3     | 0.10                         | -20.2   |
| CH₂(CCl₂)    | 0.065    | 2.7     | 0.06                         | -8.1    |

**Hydrochlorofluorocarbons (HCFCs)**

| HCFC-22      | 0.205    | 6.4     | 0.22                         | 7.3     |
| HCFC-123     | 0.143    | 1.4     | 0.20                         | 39.5    |
| HCFC-143     | 0.195    | 2.1     | 0.27                         | 17.8    |
| HCFC-141b    | 0.151    | 2.6     | 0.14                         | 7.1     |
| HCFC-142b    | 0.164    | 2.6     | 0.20                         | 22.1    |
| HCFC-225ea   | 0.207    | 1.3     | 0.27                         | 30.3    |
| HCFC-225eb   | 0.245    | 2.3     | 0.32                         | 30.6    |

**Hydrofluorocarbons (HFCs)**

| HFC-23       | 0.248    | 4.5     | 0.20                         | -19.4   |
| HFC-32       | 0.155    | 2.9     | 0.13                         | -16.3   |
| HFC-125      | 0.249    | 3.0     | 0.23                         | -7.5    |
| HFC-134      | 0.176    | 3.3     | 0.18                         | 2.3     |
| HFC-134a     | 0.200    | 2.6     | 0.19                         | -4.9    |
| HFC-143      | 0.115    | 2.6     | 0.13                         | 13.1    |
| HFC-143a     | 0.160    | 3.0     | 0.16                         | 0.3     |
| HFC-152a     | 0.097    | 3.8     | 0.13                         | 33.6    |
| HFC-161      | 0.022    | 2.7     | 0.03                         | 38.9    |
| HFC-227ea    | 0.322    | 4.3     | 0.30                         | -6.6    |
| HFC-236fa    | 0.264    | 3.4     | 0.28                         | 6.2     |
| HFC-245fa    | 0.261    | 2.6     | 0.23                         | -12.0   |

**Perfluorocarbons (PFCs)**

| SF₆         | 0.494⁺   | 7.5     | 0.52                         | 5.3     |
| CF₃         | 0.089⁺   | 2.6     | 0.08                         | -10.1   |

**Bromocarbons (BCs)**

| H-1211       | 0.251    | 2.6     | 0.30                         | 19.7    |
| H-1301       | 0.273    | 5.5     | 0.32                         | 17.1    |
| CH₃Br        | 0.007⁺   | 2.9     | 0.01                         | 31.9    |
| CH₂Br₂       | 0.019⁺   | 3.7     | 0.01                         | 46.5    |
| CHF₂Br       | 0.174⁺   | 4.8     | 0.14                         | -19.4   |

**Iodocarbons (ICs)**

| CF₃I        | 0.268⁺   | 6.3     | 0.23                         | 14.2    |
| CF₂CF₂I     | 0.293⁺   | 4.2     | 0.26                         | -11.5   |

LAS values are also compared with the GAM (global and annual mean) atmosphere-based values as well as with those of recent WMO assessment values [Granier et al., 1999]. Radiative forcings are for an increase of 1 ppbv (0-1 ppbv) for halocarbons, 5 ppbv for CO₂ (550-355 ppmv), 10 ppbv for CH₄ (1714-1724 ppbv) and N₂O (311-321 ppbv).

* Calculated by assuming uniform distribution with height and latitude.

⁺ Based on Schimel et al. [1996]

Note that there was a typographical error in WMO [Granier et al., 1999] reported value for CFC-115; the actual value was 0.21 Wm⁻², whereas reported value was 0.26 Wm⁻².
average of the 2 months of data covering the solstice or equinox. To
calculate the global mean radiative forcings, latitudinal
averaging is done by area weighting. For this set of calculations,
2-D CTM-estimate greenhouse gas distributions were employed.
The CTM was not used to calculate the distributions for CO₂,
CFC-13, perfluorocarbons (PFCs), iodocarbons (ICs) and three
bromocarbons (CH₃Br, CH₂Br₂, and CHF₂Br). Therefore these
gases were assumed to be distributed uniformly in altitude and
latitude for each season. The adjusted radiative forcing
calculations were done for cloudy sky conditions using the
NBM. Table 4 compares the global and annual mean radiative
forcing calculated using latitudinal and seasonal (LAS) mean
greenhouse gas profiles and atmospheric conditions with the
realistic single GAN atmosphere case.
Radiative forcing for most of the greenhouse gases is
noticeably sensitive to the LAS mean greenhouse gas
distributions and atmospheric conditions. Estimated forcings for
CO₂, CH₄, and N₂O based on a single GAN profile were lower
than the LAS case, whereas the single-profile forcings were
higher for halocarbons and perfluorocarbons, consistent with the
findings of Ferek et al. [1998]. This is due to the fact that the
tropopause height in the GAN profile is relatively higher
than the LAS case, and hence the stratospheric adjustment
place at a lower pressure level. Thus the stratospheric
adjustment will be large compared to LAS case, producing a
larger cooling for CO₂, CH₄, N₂O, and smaller warming for
other gases. This results in a difference of up to 7% between
LAS- and GAN-based forcings. The differences were
significantly higher (5-7%) for CFC-11, CFC-12, HFC-22,
HFC-23, and H-1301, mainly because these gases decay much
more rapidly in the stratosphere. Similar results have also been
found by Ferek et al. [1998], who estimated the differences in
radiative forcings between GAN and LAS cases to be about
6-7% for CFC-11 and CFC-12. For other gases with higher
stratospheric lifetimes, the differences are relatively small. Most
of these gases have very small stratospheric sinks, which yield
nearly the same changes in stratospheric concentrations for both
the LAM and the GAN cases. The difference in radiative
forcings due to a constant change in SF₆ is slightly higher than
CFC-11 and CFC-12. This occurs as a result of both the higher
concentrations in the stratosphere, and the differences in
tropopause height between GAN and LAS cases, as discussed
above.
The changes in radiative forcing from preindustrial to
present day times for CO₂, CH₄, N₂O, and for total CFCs as a
function of time and latitude are shown in Plate 5. As evident in
this figure, changes in greenhouse gas radiative forcings vary
with latitude and season. The radiative forcing due to CO₂ was
more homogenous than other gases, as CO₂ overlaps more
strongly with water and is less influenced by clouds. The largest
CO₂ forcing occurs in the subtropical summer, where lower
water vapor amount and comparatively clear-sky are found.
Additionally, during summer the difference between surface
temperature and tropopause is large, leading to further
enhancement of the greenhouse effect. Kiehl and Bruggen
[1993] and Myleire and Stordal [1997] found similar effects in
their three-dimensional simulations.

5. UARS-Based Versus Model-Based Radiative
Forcings
In a recent study, Minschwaner et al. [1998] used Upper
Atmosphere Research Satellite (UARS) data in combination
with a BBM to calculate the radiative forcing for CH₄, CFC-12,
and N₂O. In this study we revise the UARS-based radiative
forcing estimates for CH₄, N₂O, and CFC-12 using a more
accurate approach, namely combining an NBM with
stratospheric UARS observations and surface-based
tropospheric observations. The observational data used for this
set of calculations have already been discussed in detail in
section 2.4. The radiative forcing is calculated for an increase in
trace gas concentrations from preindustrial time (1750) to

Table 5. NBM-Estimated Adjusted Cloudy-Sky Radiative Forcing in Wm⁻² Due to Changes in Greenhouse Gas Concentrations

<table>
<thead>
<tr>
<th>GAS</th>
<th>Preind. (1765)</th>
<th>Current (1992)</th>
<th>Model-Based Gas Concentration Wm⁻² (1)</th>
<th>Observed-Based Gas Concentration Wm⁻² (2)</th>
<th>Difference % (2) - (1)</th>
<th>Wm⁻² (3)</th>
<th>Difference % (3) - (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>278,000</td>
<td>356,000</td>
<td>1.308⁹</td>
<td>1.3083</td>
<td>0</td>
<td>1.322</td>
<td>+1</td>
</tr>
<tr>
<td>CH₄</td>
<td>700</td>
<td>1,714</td>
<td>0.578</td>
<td>0.604</td>
<td>+3</td>
<td>0.500</td>
<td>-13</td>
</tr>
<tr>
<td>N₂O</td>
<td>275</td>
<td>311</td>
<td>0.117</td>
<td>0.121</td>
<td>+3</td>
<td>0.119</td>
<td>+2</td>
</tr>
<tr>
<td>CFC-11</td>
<td>0</td>
<td>0.268</td>
<td>0.064</td>
<td></td>
<td></td>
<td>0.067</td>
<td>+3</td>
</tr>
<tr>
<td>CFC-12</td>
<td>0</td>
<td>0.503</td>
<td>0.152</td>
<td>0.148</td>
<td>2</td>
<td>0.161</td>
<td>+7</td>
</tr>
<tr>
<td>CFC-113</td>
<td>0</td>
<td>0.082</td>
<td>0.023</td>
<td></td>
<td></td>
<td>0.075</td>
<td>+9</td>
</tr>
<tr>
<td>CFC-114</td>
<td>0</td>
<td>0.020</td>
<td>0.006</td>
<td></td>
<td></td>
<td>0.006</td>
<td>0</td>
</tr>
<tr>
<td>CFC-115</td>
<td>0</td>
<td>0.010</td>
<td>0.001</td>
<td></td>
<td></td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>CCl₄</td>
<td>0</td>
<td>0.132</td>
<td>0.017</td>
<td></td>
<td></td>
<td>0.013</td>
<td>-23</td>
</tr>
<tr>
<td>CH₂CCL₃</td>
<td>0</td>
<td>0.135</td>
<td>0.009</td>
<td></td>
<td></td>
<td>0.008</td>
<td>11</td>
</tr>
<tr>
<td>FCFC 22</td>
<td>0</td>
<td>0.100</td>
<td>0.020</td>
<td></td>
<td></td>
<td>0.022</td>
<td>+10</td>
</tr>
<tr>
<td>H-1211</td>
<td>0</td>
<td>0.007</td>
<td>0.002</td>
<td></td>
<td></td>
<td>0.002</td>
<td>0</td>
</tr>
<tr>
<td>H-1301</td>
<td>0</td>
<td>0.003</td>
<td>0.001</td>
<td></td>
<td></td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>SF₆</td>
<td>0</td>
<td>0.032</td>
<td>0.016⁹</td>
<td></td>
<td></td>
<td>0.017</td>
<td>6</td>
</tr>
<tr>
<td>CF₄</td>
<td>0</td>
<td>0.070</td>
<td>0.006⁹</td>
<td></td>
<td></td>
<td>0.006</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2.320</td>
<td></td>
<td></td>
<td>2.27</td>
<td>+2.2</td>
</tr>
</tbody>
</table>

The forcings are calculated using model-based gas distributions. WMO [1999] reported values and the percent difference between WMO
and model-based radiative forcings are also given in columns 7 and 8.
* Schimel et al. [1996].
¹ Calculated by assuming uniform distribution with height and latitude.
Plate 5. Estimated seasonal and latitudinal dependent changes in the radiative forcing (W m$^{-2}$) for the period 1765-1992 for (a) CO$_2$, (b) CH$_4$, (c) N$_2$O, and (d) CFCs.
contemporary time (1992). Since there is no observed data available for the preindustrial time, 2-D CTM distributions of \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) were combined with the observation-based data for these radiative transfer calculations.

Observation-based radiative forcing are 0.60, 0.12, and 0.15 Wm\(^{-2}\) for \( \text{CH}_4 \), \( \text{N}_2\text{O} \), and \( \text{CFC}-12 \), respectively (Table 5). Radiative forcing based on the observed distributions of \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) is 3% higher, and CFC 12 is about 3% lower, compared to the forcing based on CTM distributions. Our NBM radiative forcings results for \( \text{CH}_4 \), \( \text{N}_2\text{O} \) and \( \text{CFC}-12 \) are 9%, 8%, and 12% higher than the \text{Minschwaner et al.} [1998] BBM results, which is likely related to the differences in preindustrial concentrations, width of spectral intervals, and in treatment of angular radiances. \text{Freckleton et al.} [1998] also estimated the radiative forcings for CFC-12 using the UARS observation data, and our estimated forcing results were the same as estimated by \text{Freckleton et al.} [1998].

6. Comparison With Other Research Studies

In this section we compare our NBM adjusted cloudy sky forcings based on the realistic greenhouse gas and atmosphere profiles with other most recent estimates of forcings [\text{Granier et al.,} 1999; \text{Schimel et al.,} 1996; \text{Myhre et al.,} 1998]. Table 4 compares the radiative forcing for a doubling of \( \text{CO}_2 \) and for a change in surface concentrations of 10 ppbv for \( \text{CH}_4 \) and \( \text{N}_2\text{O} \), and 1 ppbv for other greenhouse gases, whereas Table 5 compares the radiative forcings for major greenhouse gases from preindustrial time to date (year 1992).

Although our estimated radiative forcing of 3.7 Wm\(^{-2}\) for a doubling of \( \text{CO}_2 \) compares well with the recent estimates by \text{Myhre et al.} [1998] and \text{Pinnock et al.} [1995], it is about 16 % lower than the value given by \text{Schimel et al.} [1996]. Possible reasons for the differences in forcing are the stratospheric adjustment and shortwave radiative forcings. Both of these forcings are negative and hence lower the net radiative forcing for \( \text{CO}_2 \). As we have shown earlier, GAM atmosphere-based adjusted radiative forcings for \( \text{CO}_2 \) were about 15% lower than the instantaneous forcings. Shortwave absorption by \( \text{CO}_2 \) occurs mostly in the stratosphere, which reduces the shortwave radiation reaching the tropopause. The estimated shortwave forcing is only about 5% of the difference in net flux for \( \text{CO}_2 \) doubling, consistent with the GCMs results [\text{Cess et al.,} 1993]. The estimated radiative forcing for \( \text{CO}_2 \) since preindustrial time was 1.31 Wm\(^{-2}\), about 16% lower than \text{Schimel et al.} [1996] but only 1% lower than the most recent estimates by \text{Myhre et al.} [1997]. We estimate that the uncertainty in our model-derived radiative forcing for \( \text{CO}_2 \) is less than 10%, which is much smaller than for the other gases.

The NBM radiative forcing due to the 2-D CTM-based \( \text{CH}_4 \) concentration change from preindustrial time to the present was 0.58 Wm\(^{-2}\), although this value is consistent with other most recent NBM-based estimates [\text{Freckleton et al.,} 1998; \text{Myhre et al.,} 1998], but 20-23% higher than the \text{Schimel et al.} [1996]. As discussed by \text{Ramanathan et al.} [1987], band model-estimated forcing due to \( \text{CH}_4 \) is generally higher, because they poorly characterize absorption and emissions by \( \text{CH}_4 \) along inhomogeneous paths. The NBM is most accurate for weak-line and strong-line limits; however, the present abundance of \( \text{CH}_4 \) yields absorption between these two limits. \text{Ramanathan et al.} [1987] compared the several model results for \( \text{CH}_4 \) (including the \text{Malkmus} radiation model used in this study) with I.R.I.M. calculations and found that all band models overestimate the \( \text{CH}_4 \) radiative forcing, with the \text{Malkmus} model producing the smallest error of about 11% for the radiative flux at the tropopause. On the basis of \text{Ramanathan et al.} [1987], we conclude that our NBM-estimated \( \text{CH}_4 \) forcing might be in error by 11%.

For \( \text{N}_2\text{O} \) the 2D CTM-based estimated radiative forcing using the NBM over the period 1765-1992 was 0.12 Wm\(^{-2}\) (Table 4). Again, the NBM value is consistent with recent estimates by \text{Myhre et al.} [1998] but 20 % lower than the \text{Schimel et al.} [1996] estimates. We estimate that the uncertainty in \( \text{N}_2\text{O} \) forcing could be as large as 10% based on the spatial and temporal variations and different radiation schemes.

Except for CFCs and a few other halocarbons, the estimated radiative forcings for other halocarbons differ by more than 10% from the values given in recent WMO assessment report [\text{Granier et al.,} 1999], ranging as high as 58% for HCFC-161. The reasons for the large differences from WMO-reported values are unclear. WMO radiative forcings for most of these halocarbons are unchanged from recent IPCC assessment value.

![Figure 2](image-url)  
*Figure 2. Comparison of Integrated Science Assessment Model (ISAM) [\text{Ju"{u}n et al.,} 1995] estimated response to a pulse input of \( \text{CO}_2 \) with that of Bern model [\text{Joos et al.,} 1996].*
Table 6. Estimated Global Warming Potentials (GWP) Based on the Lifetime Given in Table 3 and Radiative Forcings Given in Table 4 for 20, 100, and 500 years time horizons.

<table>
<thead>
<tr>
<th>Gas</th>
<th>20 This Study</th>
<th>100 This Study</th>
<th>WMO [Granier et al., 1999]</th>
<th>% Difference</th>
<th>500 This Study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>This Study</td>
<td>WMO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>72</td>
<td>28</td>
<td>24</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>N₂O</td>
<td>296</td>
<td>340</td>
<td>360</td>
<td>6</td>
<td>188</td>
</tr>
</tbody>
</table>

Chlorofluorocarbons (CFCs)

| CFC-11       | 6100          | 4700           | 4600                        | -2           | 1100           |
| CFC-12       | 9800          | 10600          | 10600                       | 0            | 5200           |
| CFC-13       | 10000         | 14600          | 14000                       | -4           | 17000          |
| CFC-113      | 5800          | 6000           | 6000                        | 0            | 2700           |
| CFC-114      | 7100          | 9700           | 9800                        | 1            | 8700           |
| CFC-115      | 6000          | 9100           | 10300                       | 13           | 12700          |

Chlorocarbons (CCl₃)

| CCl₃         | 2700          | 1800           | 1400                        | -22          | 600            |
| CH₂CCH₂      | 500           | 160            | 140                         | -12          | 50             |

Hydrochlorofluorocarbons (HCFCs)

| HCFC-22      | 4900          | 1900           | 1900                        | 0            | 590            |
| HCFC-123     | 280           | 90             | 120                         | 33           | 28             |
| HCFC-124     | 1800          | 580            | 670                         | 5            | 180            |
| HCFC-114b    | 2000          | 690            | 700                         | 1            | 220            |
| HCFC-142b    | 4300          | 7000           | 7300                        | 15           | 640            |
| HCFC-223ca   | 400           | 140            | 180                         | 28           | 45             |
| HCFC-225cb   | 1600          | 500            | 670                         | 24           | 160            |

Hydrofluorocarbons (HFCs)

| HFC-23       | 15000         | 19600          | 14800                       | -24          | 13900          |
| HFC-32       | 3500          | 1100           | 880                         | -70          | 350            |
| HFC-125      | 6700          | 4300           | 3800                        | -12          | 1400           |
| HFC-134      | 3400          | 1200           | 1200                        | 0            | 390            |
| HFC-134a     | 4400          | 1800           | 1600                        | -11          | 360            |
| HFC-143      | 1100          | 350            | 370                         | 6            | 110            |
| HFC-143a     | 6900          | 3800           | 3400                        | -7           | 2100           |
| HFC-152a     | 480           | 150            | 190                         | 26           | 46             |
| HFC-161      | 25            | 8              | 8                           | -            | 2              |
| HFC-227ea    | 6300          | 4400           | 3800                        | -14          | 1500           |
| HFC-236fa    | 7200          | 9500           | 9400                        | -1           | 7400           |
| HFC-245fa    | 3000          | 1000           | 1000                        | -            | 370            |

Perfluorocarbons (PFCs)

| SF₆          | 14600         | 22500          | 22200                       | -1           | 33200          |
| CF₃          | 4400          | 6800           | 5700                        | -16          | 10600          |

Bromocarbons (BCs)

| H-1211       | 2900          | 1100           | 1300                        | 18           | 340            |
| H-1301       | 6800          | 6300           | 6900                        | 10           | 2500           |
| CH₃Br        | 11            | 4              | 5                           | 25           | 1              |
| CH₂Br         | 10            | 3              | 1                           | -67          | 1              |
| CH₃FBr       | 1200          | 390            | 470                         | 20           | 120            |

Iodocarbons (ICs)

| CHF₃         | 1             | <1             | <1                          | 0            | <1             |
| CF₃CF₃       | 1             | <1             | <1                          | -            | <1             |

The percent difference in GWPs for 100 year time horizon evaluated in this study and those reported by WMO [Granier et al., 1999] is also given.

[Schimel et al., 1996] estimates, except that for forcings have been increased by a factor of 1.1,14 to account for a change in the revised forcing for CFC-11. Note that the IPCC-reported estimates for most of the replacement compounds have not been amended since their first assessment [Shine et al., 1990], and the forcings were reported relative to CFC-11. WMO-reported values for the CFCs, SF₆, and CF₃ were based on revised estimates by Myhre et al. [1998], and our values for these compounds are in good agreement with those of Myhre et al. [1998]. WMO-reported radiative forcings for few HFCs (HFC-134a, HFC-161, and HFC-236fa), bromocarbons (except for H-1301), and iodocarbons were reproduced from Christidis et al. [1997] after a simple scaling to account for the decrease in the stratosphere concentrations. In contrast, our estimates are based on a consistent set of radiative transfer calculations.

The estimated total radiative forcings due to changes in the major greenhouse gases from preindustrial time to the present day is 2.32 Wm⁻², only about 2-3% higher than the most recent estimates [Granier et al., 1999; Myhre et al., 1998; Hansen et al., 1997], however, the differences for the individual gases are as large as 23% (Table 5). The uncertainties in halocarbon radiative forcings could be much higher than the other major...
greenhouse gases. The potential sources of uncertainties are the spectroscopic data and the spatial and vertical distributions of these gases.

7. Global Warming Potentials

Global warming potential (GWP) is an important concept used to compare the relative potential effects on climate from various greenhouse gases. The GWP of a greenhouse gas as defined in IPCC [Shine et al., 1990; Albritton et al., 1995; Schimel et al., 1996] is the time-integrated change in the radiative forcing of a gas, also known as absolute global warming potential (AGWP) of a gas, over a specified time horizon relative to that of CO$_2$. Calculating the GWP for a particular gas requires the radiative forcing and the temporal decay both for the gas of interest and for CO$_2$, the reference gas. In this study we evaluated the GWPs for the greenhouse gases studied here using our NBM-derived radiative forcings shown in Table 4. The temporal decay of a gas of interest was calculated on the basis of lifetimes shown in Table 3, which were taken from recent WMO assessment report [Granier et al., 1999]. The decay for CO$_2$ was estimated on the basis of the carbon cycle component of our Integrated Science Assessment Model (ISAM) described by Jain et al. [1995]. As shown in Figure 2, the estimated decay of CO$_2$ based on the ISAM [Jain et al., 1995] and Bern model [Joos et al., 1996] are nearly the same. Both of these models were used to estimate the atmospheric CO$_2$ concentrations in recent IPCC assessment [Schimel et al., 1996]. Because of the different CO$_2$ response function and CO$_2$ radiative forcings from recent WMO assessment [Granier et al., 1999], the CO$_2$ AGWPs differ from the values used in recent WMO assessment [Granier et al., 1999] by -3, -7, and -8% for the 20-, 100-, and 500-year time horizons, respectively. These lower CO$_2$ AGWPs lead to larger GWPs with other gases as compared to Granier et al. [1999].

The derived GWPs for time horizons of 20, 100, and 500 years are listed in Table 6. In this table we also compare our estimated 100-year GWPs with those reported in recent WMO assessment report [Granier et al., 1999]. Our GWPs for some of the gases differ notably from Granier et al. [1999], mainly because of the significant differences in the radiative forcings (Table 4) and CO$_2$ response function (Figure 2) as discussed above.

8. Conclusions

We have evaluated the radiative forcings and GWPs for a number of greenhouse gases using a consistent set of radiative transfer models, as well as spectroscopic and climate data sets. In addition, we have also evaluated the sensitivity of greenhouse gas radiative forcings to a number of simplified assumptions widely used in the past to calculate these forcings. Since many of the previous studies were not able to account for every detail required for radiative calculations, a sensitivity study would help to interpret the results of other studies.

The main conclusions of the paper can be summarized as follows:

1. The top-of-atmosphere fluxes calculated with the narrowband model (NBM) are in good agreement with the observed data. We also compared our NBM and BGM model results and found that the representation of spectral overlapping in the BGM model was unable to reproduce the NBM results for most of the greenhouse gases studied here. The differences in the instantaneous radiative forcings for two models were as large as 68% (for CF$_4$) for gases that have strong narrow features in their spectra.

2. We also investigated the sensitivity of the radiative forcings to clouds, stratospheric adjustment, and angular radiances. Our model results show that omitting these factors in the radiation schemes could result in forcing errors of several percent. The errors due to omitting these factors are much higher for halocarbons.

3. Our model results show that the vertical profiles of the gases are important in determining the radiative forcings; the use of height-independent vertical distributions of greenhouse gases resulted in errors of up to 39% in estimated radiative forcings for gases studied here; the errors for the short-lived compounds were particularly high. We also find that the errors in evaluated radiative forcings caused by neglecting both the seasonal and the latitudinal distributions of greenhouse gases and atmospheric conditions were much smaller than the errors due to ignoring height-independent vertical distributions.

4. Our results indicate a strong variation of greenhouse gas forcings with season and latitude, with forcing maxima in the summer sub-tropics. The radiative forcing of CO$_2$ was more homogeneous than that of other gases, as CO$_2$ overlaps more strongly with water vapor and is also less influenced by clouds.

5. For most halocarbons, our estimated radiative forcings are significantly different than the most recent estimated values given by WMO [Granier et al., 1999]. These differences might be due to the use of a different model, the inclusion of cloudy conditions, the background atmosphere specified, and type of forcings considered, whether instantaneous or adjusted.

6. Our estimated change in radiative forcing due to increases in major greenhouse gas concentrations for the period 1765-1992 is 2.32 Wm$^{-2}$. This value is only about 2% higher than the recent WMO estimates [Granier et al., 1999]; however, the differences for individual gases were as large as 23%.

7. Radiative forcing based on the UARS-measured distributions of CH$_4$ and N$_2$O are 3% higher, and forcings for CFC-12 is 3% lower as compared to the forcing based on CCM distributions.

8. Finally, the calculated GWPs for most of the greenhouse gases differ significantly from most recent estimated values by WMO [Granier et al., 1999], mainly because of differences in our evaluated radiative forcings.

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