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Concerns about Climate Change and Global Warming

1.1 Introduction

Climate is defined as the typical behavior of the atmosphere, the aggregation of the weather, and is generally expressed in terms of averages and variances of temperature, precipitation and other physical properties. The greenhouse effect, the ability of certain gases like carbon dioxide and water vapor to effectively trap some of the reemission of solar energy by the planet, is a necessary component to life on Earth; without the greenhouse effect the planet would be too cold to support life. However, human activities are increasing the concentration of carbon dioxide and several other greenhouse gases, resulting in concerns about warming of the Earth by 1–5°C over the next century (IPCC, 1996a). Recent increases in global averaged temperature over the last decade already appear to be outside the normal variability of temperature changes for the last thousand years. A number of different analyses strongly suggest that this temperature increase is resulting from the increasing atmospheric concentrations of greenhouse gases, thus lending credence to the concerns about much larger changes in climate being predicted for the coming decades. It is this evidence that led the international scientific community through the Intergovernmental Panel on Climate Change (IPCC, 1996a) to conclude, after a discussion of remaining uncertainties, "Nonetheless, the balance of the evidence suggests a human influence on global climate". More recent findings have further strengthened this conclusion. Computer-based models of the complex processes affecting the carbon cycle have implicated the burning of fossil fuels by an ever-increasing world population as a major factor in the past increase in concentrations of carbon dioxide. These models also suggest that, without major policy or technology changes, future concentrations of CO_2 will continue to increase, largely as a result of fossil fuel burning. This chapter briefly reviews the state of the science of the concerns

Table 1.1 *Summary of trends in observed climatic variables (WMO, 1998; Harvey, 2000). Note that NH implies Northern Hemisphere and SH implies Southern Hemisphere*

Variable	Analysis Period	Trend or Change
Surface air temperature and sea surface temperature (SST)	1851–1995	0.65 ± 0.15 °C
Alpine glaciers	Last century	Implies warming of 0.6–1.0 °C in alpine regions
Extent of snowcover in the NH	1972–1992	10% decrease in annual mean
Extent of sea ice in the NH	1973–1994	Downward since 1977
Extent of sea ice in the SH	1973–1994	No change, possible decrease between mid 1950s and early 1970s
Length of the NH growing season	1981–1991	12 ± 4 days longer
Precipitation	1900–1994	Generally increasing outside tropics, decreasing in Sahel
Heavy precipitation	1910–1990	Growing in importance
Antarctic snowfall	Recent decades	5–20% increase
Global mean sea level	Last century	1.8 ± 0.7 mm/year

about climate change that could result from fossil fuels and other human related emissions.

1.2 The Changing Climate

There is an extensive amount of evidence indicating that the Earth's climate has warmed during the past century (see Table 1.1). Foremost among this evidence are compilations of the variation in global mean sea surface temperature and in surface air temperature over land and sea. Supplementing these indicators of surface temperature change is a global network of balloon-based measurements of atmospheric temperature since 1958. As well, there are several indirect or *proxy* indications of temperature change, including satellite observations (since 1979) of microwave emissions from the atmosphere, and records of the width and density of tree rings. The combination of surface-, balloon-, and satellite-based indicators provides a more complete picture than could be obtained from any given indicator alone, while proxy records from tree rings and other indicators allow the temperature record at selected locations to be extended back for a thousand years. Apart from temperature, changes in the

extent of alpine glaciers, sea ice, seasonal snow cover, and the length of the growing season have been documented that are consistent with the evidence that the climate is warming (e.g., IPCC, 1996a; Vaughn and Doake, 1996; Johannessen *et al.*, 1999). Less certain, but also consistent, changes appear to have occurred in precipitation, cloudiness, and interannual temperature and rainfall variability.

As a starting point, paleoclimatic records of past climate changes should be a useful guide as to what one might expect if the climate is warming. During warmer climates in the past, high latitudes have warmed more than lower latitudes (Hoffert and Covey, 1992). Mountain glaciers should retreat. Sea level should rise. The current climate change is showing all of these features (Haeberli, 1990; Diaz and Graham, 1996).

Thermometer-based measurements of air temperature have been systematically recorded at a number of sites in Europe and North America as far back as 1760. However, the set of observing sites did not attain sufficient geographic coverage to permit a rough computation of the global average land temperature until the mid-nineteenth century. Land-based, marine air, and sea surface temperature datasets all require rather involved corrections to account for changing conditions and measurement techniques. Analyses of these records indicates a global mean warming from 1851 to 1995 of about 0.65 ± 0.05°C (Jones *et al.*, 1997a, b).

As shown in Figure 1.1, the increase in temperature has occurred in two distinct periods. The first occurred from roughly 1910–1945, while the second is since 1976. Recent warming has been about 0.2°C per decade. Very large changes have occurred in the last decade, with 1998 being the warmest year in the global temperature record. The highest ten years in global surface temperature have been since 1980, with eight of them occurring in the last eleven years.

In addition to limited sampling of temperature with altitude through balloon-borne instruments, satellite-based sensors, known as microwave sounding units (MSUs), are being used to examine global temperature changes in the middle troposphere (mainly the 850–300 HPa layer), and in the lower stratosphere (~50–100 Hpa). None of the channels sample at the ground. The MSU measurements have been controversial because some earlier versions of the satellite dataset had indicated a cooling in the lower troposphere in contrast to the warming from the ground-based instruments. However, several errors and problems (e.g., due to decay in the orbit of the satellite) with the MSU data have been found, and the latest analyses of MSU corrected for these problems show a warming (about 0.1°C per decade), albeit somewhat smaller than that found at the ground (NRC, 2000). These analyses also suggest that the cooling effect of decreasing ozone in the lower stratosphere (as a result of chlorine and

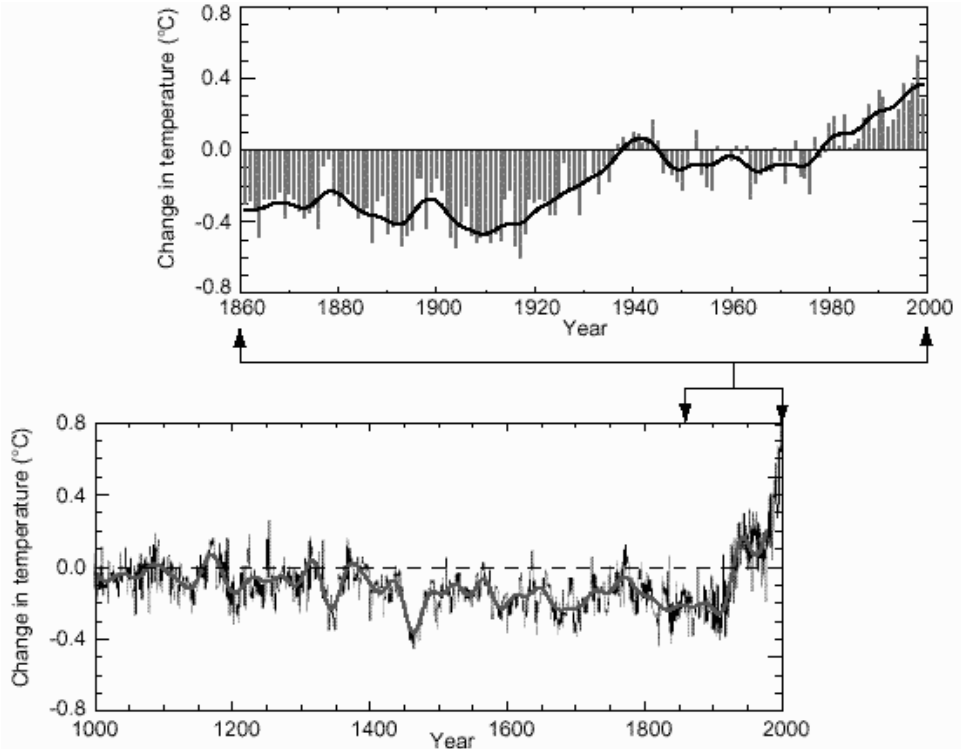

Figure 1.1 Variations of the Earth's surface temperature for the last 1000 years. The top panel shows the combined annual land-surface and sea-surface temperature anomalies for 1861 to 1999, relative to the average of the 1961 to 1990 period. This figure is an update by P. D. Jones of the analysis previously done for IPCC (1996a). The bottom panel shows the Northern Hemispheric temperature reconstruction over the last 1000 years from proxy data in combination with the instrumental data record (Mann *et al.*, 1999).

bromine from human-related emissions of chlorofluorocarbons and other halocarbons) may have led to the difference in upper tropospheric and ground-level temperature trends.

The 1910–1945 warming primarily occurred in the Northern Atlantic. In contrast, the most recent warming has primarily occurred at middle and high latitudes of the Northern Hemisphere continents in winter and spring, while the northwest portion of the Northern Atlantic and the central North Pacific Oceans have shown year-around cooling. Significant regional cooling occurred in the Northern Hemisphere during the period from 1946 to 1975.

Proxy temperature indicators, such as tree ring width and density, the chemical composition and annual growth rate in corals, and characteristics of annual layers in ice cores, are being used at a number of locations to extend

temperature records back as much as a thousand years (Jones *et al.*, 1998; Mann *et al.*, 1999; Bradley, 2000). As seen in Figure 1.1, the reconstruction indicates the decade of the 1990s has been warmer than any time during this millennium and that 1998 was the warmest year in the 1000-year record (Mann *et al.*, 1999). Using a different approach, based on underground temperature measurements from boreholes, Huang *et al.* (2000) found temperature changes over the last 500 years that are very similar to the trend in Mann *et al.* (1999). The basic conclusion is the same, that the late-twentieth century warming is unprecedented in the last 500 to 1000 years.

Recent studies (for example, Boer *et al.*, 2000; Delworth and Knutson, 2000; Wigley, 1999) with state-of-the-art numerical models of the climate system have been able to match the observed temperature record well, but only if they include the effects of greenhouse gases and aerosols. These studies indicate that natural variability of the climate system and solar variations are not sufficient to explain the increasing temperatures in the 1980s and 1990s. However, natural variability and variations in the solar flux are important in fully explaining the increase in temperature in the 1910–1945 period. Emissions from large volcanic eruptions resulting in sulfate aerosols and other aerosols in the lower stratosphere are also important in explaining some of the short-term variations in the climate record.

Levitus *et al.* (2000) have used more than five million measurements of the temperature of the world ocean at various depths and locations to show that the temperatures have increased in the middle depths by an average of about 0.06 °C between the 1950s and the mid-1990s. Watts and Morantine (1991) had previously suggested, based on data of mid-depth Atlantic Ocean temperature changes reported by Roemmich and Wunsch (1984), that much of the global warming temperature signature lay in the deep ocean.

Any changes in climate associated with increasing levels of carbon dioxide would also be expected to result in cooling stratospheric temperatures. The stratosphere indeed is cooling (Angell, 1999). While part of the cooling in the lower stratosphere can be explained by the observed decrease in stratospheric ozone, such changes in ozone can only explain part of the observed temperature change. The increase in CO_2 is also necessary to explain the changes in lower stratospheric temperatures (Miller *et al.*, 1992).

1.3 The Changing Atmospheric Composition

Without human intervention, concentrations of many atmospheric gases would be expected to change slowly. Ice core measurements of the gases trapped in ancient ice bubbles indicate this was the case before the last century.

However, since the beginning of the industrial age, emissions associated with human activities have risen rapidly. Agriculture, industry, waste disposal, deforestation, and especially fossil fuel use have been producing increasing amounts of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and other important gases. Due to increasing emissions, atmospheric levels of these greenhouse gases have been building at an unprecedented rate, raising concerns regarding the impact of these gases on climate. Some of the gases, such as CFCs, are also responsible for large observed depletions in the natural levels of another gas important to climate, ozone. Of these gases, two, carbon dioxide and methane, are of special concern to climate change. These two gases are discussed in some detail in the sections below. Under the international Montreal Protocol and its amendments, emissions of CFCs and other halocarbons are being controlled and their atmospheric concentrations will gradually decline over the next century. Emissions leading to atmospheric concentrations of sulfate and other aerosol particles are also important to climate change and are further discussed below. Unless stated otherwise, most of the discussion below is based on the most recent IPCC and WMO international assessments (IPCC, 1996a; WMO, 1998) of global change, with concentrations and trends updated as much as possible, such as data available from NOAA CMDL (National Oceanic and Atmospheric Administration's Climate Monitoring and Diagnostics Laboratory).

1.3.1 Carbon dioxide

Carbon dioxide has the largest changing concentration of the greenhouse gases. It is also the gas of most concern to analyses of potential human effects on climate. Accurate measurements of atmospheric CO_2 concentration began in 1958. The annually averaged concentration of CO_2 in the atmosphere has risen from 316 ppm (parts per million, molar) in 1959 to 364 ppm in 1997 (Keeling and Whorf, 1998), as shown in Figure 1.2. The CO_2 measurements exhibit a seasonal cycle, which is mainly caused by the seasonal uptake and release of atmospheric CO_2 by terrestrial ecosystems. The average annual rate of increase over the whole time period is about 1.2 ppm or 0.4% per year, with the rate of increase over the last decade being about 1.6 ppm/yr. Measurements of CO_2 concentration in air trapped in ice cores indicate that the pre-industrial concentration of CO_2 was approximately 280 ppm. This data indicates that carbon dioxide concentrations fluctuated by ± 10 ppm around 280 ppm for over a thousand years until the recent increase to the current 360+ ppm, an increase of over 30%.

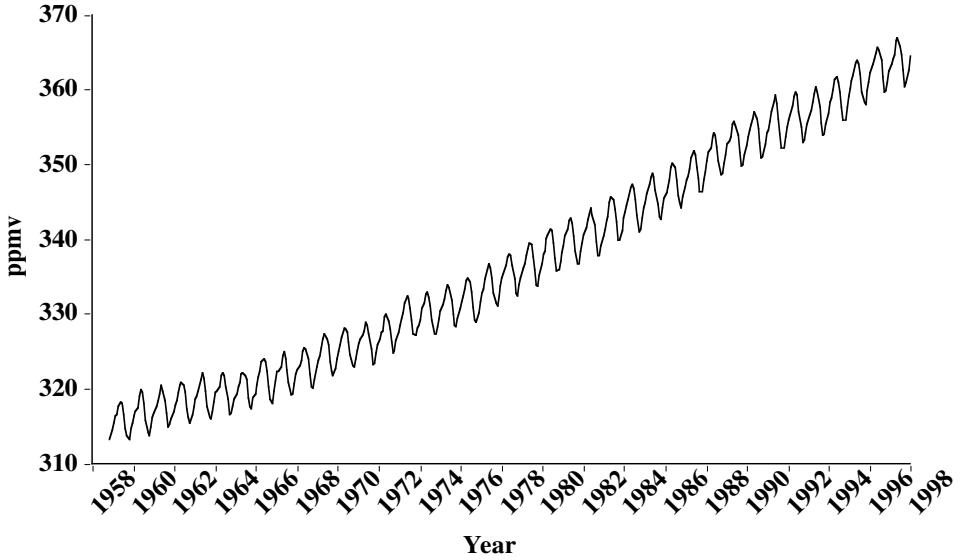

Figure 1.2 Observed monthly average CO_2 concentration (ppmv) from Mauna Loa, Hawaii (Keeling and Whorf, 1998). Seasonal variations are primarily due to the uptake and production of CO_2 by the terrestrial biosphere.

Why has the atmospheric concentration of CO_2 increased so dramatically? Analyses with models of the atmosphere–ocean–biosphere system of the carbon cycle, in coordination with observational analyses of the isotopes of carbon in CO_2, indicate that human activities are primarily responsible for the increase in CO_2. Two types of human activities are primarily responsible for emissions of CO_2: fossil fuel use, which released about 6.0 GtC into the atmosphere in 1990, and land use, including deforestation and biomass burning, which may have contributed about an additional 1.6 ± 1.0 GtC. Evaluations of carbon releases from vegetation and soils based on changes in land use indicate that land use decreased carbon storage in vegetation and soil by about 170 Gt since 1800. The added atmospheric CO_2 resulting from human activities is redistributed within the atmospheric, oceanic, and terrestrial biospheric parts of the global carbon cycle, with the dynamics of this redistribution determining the corresponding rise in atmospheric CO_2 concentration. In the future, as the amount of CO_2 increases in the atmosphere and in the ocean, it is expected that the oceans will take up a smaller percentage of the new emissions. Analyses of the carbon budget previously had implied that a mismatch existed between observed levels of CO_2 and known loss processes. This discrepancy suggested that a missing carbon sink has existed during recent decades. This sink now appears to be largely explained through increased net carbon storage

by the terrestrial biomass stimulated by the CO_2 fertilization effect (increased growth in a higher CO_2 concentration atmosphere) (Kheshgi *et al.*, 1996).

Carbon dioxide is emitted when carbon-containing fossil fuels are oxidized by combustion. Carbon dioxide emissions depend on energy and carbon content, which ranges from 13.6 to 14.0 MtC/EJ for natural gas, 19.0 to 20.3 for oil, and 23.9 to 24.5 for coal. Other energy sources such as hydro, nuclear, wind, and solar have no direct carbon emissions. Biomass energy, however, is a special case. When biomass is used as a fuel, it releases carbon with a carbon-to-energy ratio similar to that of coal. However, the biomass has already absorbed an equal amount of carbon from the atmosphere prior to its emission, so that net emissions of carbon from biomass fuels are zero over its life cycle.

Human-related emissions from fossil fuel use have been estimated as far back as 1751. Before 1863, emissions did not exceed 0.1 GtC/yr. However, by 1995 they had reached 6.5 GtC/yr, giving an average emission growth rate slightly greater than 3 percent per year over the last two and a half centuries. Recent growth rates have been significantly lower, at 1.8 percent per year between 1970 and 1995. Emissions were initially dominated by coal. Since 1985, liquids have been the main source of emissions despite their lower carbon intensity. The regional pattern of emissions has also changed. Once dominated by Europe and North America, developing nations are providing an increasing share of emissions. In 1995, non-Annex I (developing countries; includes China and India) nations accounted for 48 percent of global emissions.

Future CO_2 levels in the atmosphere depend not only on the assumed emission scenarios, but also on the transfer processes between the major carbon reservoirs, such as the oceans (with marine biota and sediments) and the terrestrial ecosystems (with land use changes, soil and forest destruction). Recent work for the new IPCC assessment shows, based on projections of fossil-fuel use and land use changes, that the concentration of CO_2 is expected to increase well above current levels by 2100 (75 to 220% over pre-industrial concentrations). As discussed later, none of these scenarios lead to stabilization of the CO_2 concentration before 2100.

1.3.2 Methane

Although its atmospheric abundance is less than 0.5 percent that of CO_2, on a molecule by molecule basis, a molecule of CH_4 is approximately 50 times more effective as a greenhouse gas in the current atmosphere than CO_2. When this is combined with the large increase in its atmospheric concentration, methane becomes the second most important greenhouse gas of concern to climate change. Based on analyses of ice cores, the concentration of methane has more

than doubled since pre-industrial times. In the year 1997, the globally averaged atmospheric concentration of methane was about 1.73 ppmv (Dlugokencky *et al.*, 1998).

Continuous monitoring of methane trends in ambient air from 1979 to 1989 indicates that concentrations had been increasing at an average of about 16 ppb (~1 percent per year). During much of the 1990s, the rate of increase in methane appeared to be declining. Although the cause of the longer-term global decline in methane growth is still not well understood, it may be that much of the earlier rapid increase in methane emissions from agricultural sources is now slowing down. However, in 1998 the CH_4 growth rate increased to about 10 ppb per year (Figure 1.3b). There are some indications that this increase in the growth rate may be due to a response of emissions from wetlands in the Northern Hemisphere responding to warm temperatures. In 1999, the growth rate decreased to about 5 ppb per year (Dlugokencky, NOAA CMDL, private communication, 2000).

Methane emissions come from a number of different sources, both natural and anthropogenic. One type of human related emission arises from biogenic sources from agriculture and waste disposal, including enteric fermentation, animal and human wastes, rice paddies, biomass burning, and landfills. Emissions also result from fossil fuel-related methane sources such as natural gas loss, coal mining, and the petroleum industry. Methane is emitted naturally by wetlands, termites, other wild ruminants, oceans, and by hydrates. Based on recent estimates, current human-related biogenic and fossil fuel-related sources of methane are approximately 275 and 100 $TgCH_4$/yr while total natural sources are around 160 $TgCH_4$/yr.

1.3.3 Sulfuric and other aerosols

Emissions of sulfur dioxide and other gases can result in the formation of aerosols that can affect climate. Aerosols affect climate directly by absorption and scattering of solar radiation and indirectly by acting as cloud condensation nuclei (CCN). A variety of analyses indicate that human-related emissions of sulfur, and the resulting increased sulfuric acid concentrations in the troposphere, may be cooling the Northern Hemisphere sufficiently to compensate for a sizable fraction of the warming expected from greenhouse gases. As the lifetime in the lower atmosphere of these aerosols is typically only about one week, the large continual emissions of the aerosol precursors largely determines the impact of the aerosols on climate. Large volcanic explosions can influence climate for periods of one to three years through emissions of sulfur dioxide, and the resulting sulfate aerosols, into the lower stratosphere.

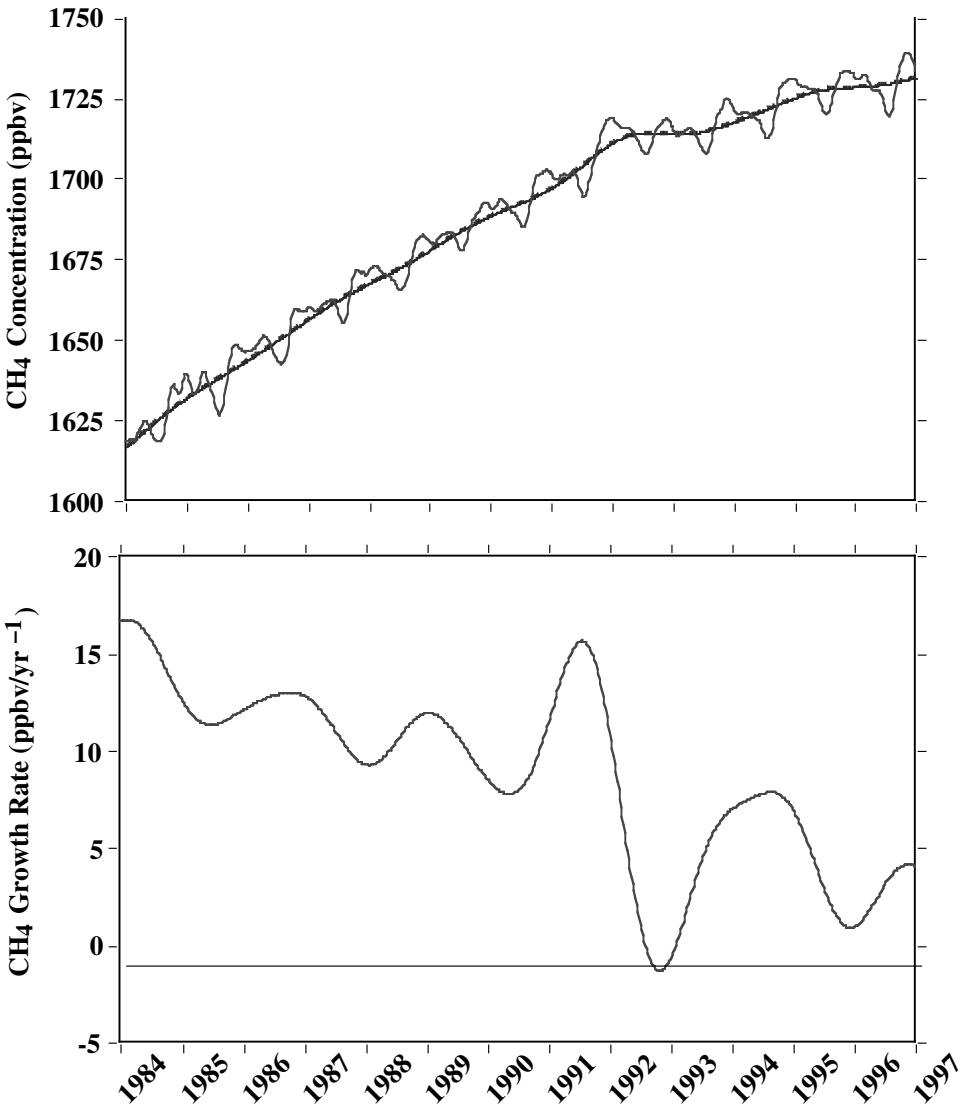

Figure 1.3 Globally averaged atmospheric CH_4 concentrations (ppbv) derived from NOAA Climate Monitoring Diagnostic Laboratory air sampling sites (Dlugokencky *et al.*, 1998). The solid line is a deseasonalized trend curve fitted to the data. The dashed line is a model (that accounts for CH_4 emissions and loss in the atmosphere) estimated calculated trend that is fitted to the globally average values. (b) Atmospheric CH_4 instantaneous growth rate (ppbv/year) which is the derivative with respect to the trend curve shown in (a).