

**CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY
AIR RESOURCES BOARD**

**TECHNICAL SUPPORT DOCUMENT FOR
STAFF PROPOSAL REGARDING REDUCTION OF GREENHOUSE GAS
EMISSIONS FROM MOTOR VEHICLES**

CLIMATE CHANGE OVERVIEW



This report has been reviewed by the staff of the California Air Resources Board and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

August 6, 2004

Introduction

The earth's climate has always evolved - the extremes of the 100,000-year ice-age cycles in both climate and greenhouse gases over the last half million years is well documented. The last 10,000 years has been a warm and stable period, and the last millennium, over which current societies have developed, has been one of the most stable climates observed. Yet, over the 20th century, we have observed a rapid change in the climate and atmospheric concentration of greenhouse gases that is attributable to human activities. These recent changes in greenhouse gases far exceed the extremes of the ice ages, and the global mean temperature is warming at a rate that cannot be explained by natural causes alone. Human activities are directly altering the chemical composition of the atmosphere through the buildup of greenhouse gases (GHGs), primarily carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Climate research has identified other greenhouse agents that can drive climate change, particularly tropospheric ozone, hydrofluorocarbons, and atmospheric aerosols (particles containing sulfate, black carbon or other carbonaceous compounds). Thus, it appears that an effective response to the threat of climate change ultimately will need to address CO₂, other greenhouse gases, and aerosols.

It is true that levels of natural greenhouse gases have fluctuated in the past. However, there are several reasons for attributing the rise in greenhouse gases to anthropogenic, rather than natural emissions. The first indicator comes from comparing the rate of the current increase with changes that have occurred in the past. At the end of the last ice age, the concentration of CO₂ increased by around 100 ppm (parts per million) over about 8,000 years, or approximately 1.25 ppm per century. Since the start of the industrial revolution, the rate of increase has accelerated markedly. Since 1860, the concentration of CO₂ has increased by around 80 ppm, just over 50 ppm per century. The rate of CO₂ accumulation has continued to increase, and it currently stands at around 150 ppm/century – over 200 times faster than the background rate for the past 15,000 years.

The heat-trapping property of GHGs is undisputed. Although there is uncertainty about exactly how and when the earth's climate will respond to increasing concentrations of GHGs, combining observations with climate models indicates that detectable changes are under way. There most likely are and will continue to be changes beyond just a global mean warming, such as changes in regional temperature extremes, precipitation, soil moisture, and sea level, all of which could have significant adverse effects on many ecological systems, as well as on human health and the economy.

A. Climate Change Causes and Projections

Climate change is a shift in the "average weather" that a given region experiences. This is measured by changes in the features we associate with weather, such as temperature, wind patterns, precipitation, and storms. Global climate change means change in the climate of the Earth as a whole. Global climate change can occur naturally; an ice age is an example of naturally occurring climate change. The Earth's

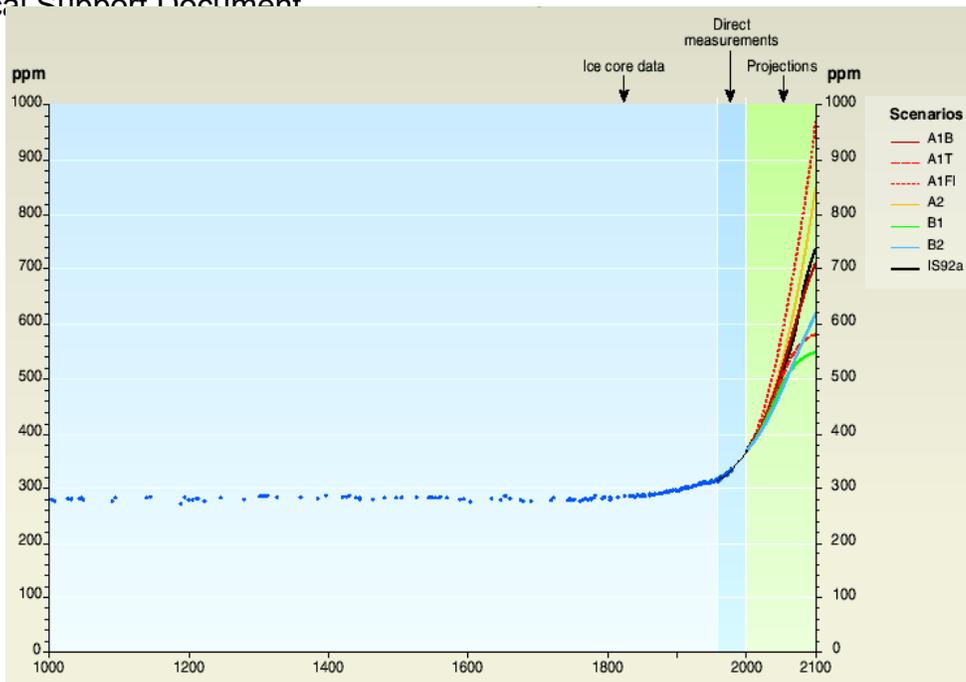
Technical Support Document Climate Change Overview

natural climate has always been, and still is, constantly changing. The climate change we are seeing today, however, differs from previous climate change in both its rate and its magnitude.

The temperature on Earth is regulated by a system commonly known as the "greenhouse effect". Naturally occurring GHGs, primarily water vapor, CO₂, CH₄, and N₂O, absorb heat radiated from the Earth's surface. As the atmosphere warms, it in turn radiates heat back to the surface, to create what is commonly called the "greenhouse effect". The Earth's surface temperature would be about 34°C (61°F) colder than it is now if it were not for the natural heat trapping effect of greenhouse gases like CO₂, CH₄, N₂O, and water vapor. Indeed, water vapor is the most abundant and important of these naturally occurring greenhouse gases. In addition to its direct effect as a greenhouse gas, clouds formed from atmospheric water vapor also affect the heat balance of the Earth by reflecting sunlight (a cooling effect), and trapping infrared radiation (a heating effect).

Human activities are exerting a major and growing influence on some of the key factors that govern climate by changing the composition of the atmosphere and by modifying the land surface. The human impact on these factors is clear. The concentration of CO₂ in the atmosphere has risen about 30 percent since the late 1800s (NAST, 2001). This increase has resulted from the burning of coal, oil, and natural gas, and the destruction of forests around the world to provide space for agriculture and other human activities. Rising concentrations of CO₂ and other GHGs are intensifying Earth's natural greenhouse effect. Global projections of population growth and assumptions about energy use indicate that the CO₂ concentration will continue to rise, likely reaching between two and three times its late-19th-century level by 2100. Figure 1 (Source: IPCC 2001 Synthesis report) shows the atmospheric CO₂ concentration from year 1000 to year 2000 from ice core data and from direct atmospheric measurements over the past few decades. Projections of CO₂ concentrations for the period 2000 to 2100 are based on model predictions. Figure 2 (Source: IPCC 2001 Synthesis report) shows variations of the Earth's surface temperature for years 1000 to 2100. From year 1000 to year 1860 variations in average surface temperature of the Northern Hemisphere are reconstructed from proxy data (tree rings, corals, ice cores, and historical records). The line shows the 50-year average, the gray region the 95% confidence limit in the annual data. For the period 1860 to 2000 the figure shows variations in observations of globally and annually averaged surface temperature from the instrumental record; the line shows the decadal average. For 2000 to 2100 projections of globally averaged surface temperature are shown for several model scenarios using a global climate model.

Figure 1. Past and future CO₂ atmospheric concentrations. (source: IPCC 2001 Synthesis report).



The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC Synthesis Report, 2001) and the National Research Council of the National Academies (NRC, 2001) conclude that the global climate is changing at a rate unmatched in the past one thousand years. The IPCC Assessment cites new and stronger evidence that most of the global warming observed over the last fifty years is attributable to human activities and that anthropogenic climate change will persist for many centuries. Also, the IPCC concludes that the observed changes over the last fifty years and those projected for the future include higher maximum air temperatures, more hot days, fewer cold days, greater extremes of drying and heavy rainfall, and sea level rise (IPCC Synthesis Report, 2001). While the NRC Report generally agrees with the IPCC Assessment, it does not rule out that some significant part of these changes is also a reflection of natural variability.

Many sources of data indicate that the Earth is warming faster than at any time in the previous 1,000 years. The global mean surface temperature has increased by 1.1 °F since the 19th century (IPCC Synthesis Report, 2001). The 10 warmest years of the last century all occurred within the last 15 years. For example, 2002 and 2003 are tied as the second warmest years on record, according to a year-end review of climate data by the National Oceanic and Atmospheric Administration. Satellite data indicate that 2003 was the fourth-warmest year for temperatures centered in the middle troposphere at altitudes from two to six miles. The average temperature in the lower troposphere (surface to about five miles) was the third warmest since satellite measurements began in 1979. Both the IPCC (2001) and the NAST (2001) reports project that warming in the 21st century will be significantly larger than in the 20th century. Scenarios examined in these assessments, which assume no major interventions to reduce continued growth of world GHG emissions, indicate that temperatures in the US will rise by about 5-9°F (3-5°C) on average in the next 100 years, which is more than the projected global average increase. In general the continental regions of the Northern Hemisphere are expected to warm more than the global average. This rise is very likely to be associated

Technical Support Document Climate Change Overview

with more extreme precipitation and faster evaporation of water, leading to greater frequency of both very wet and very dry conditions. Climate change, whether warming or cooling, will impact public health, air quality, water resources, agriculture, ecological resources, and California's economy. As a result, global climate change issues are receiving increasing national and international attention from governments, business and industry, the research community, environmental interests, and the public (IPCC, 2001).

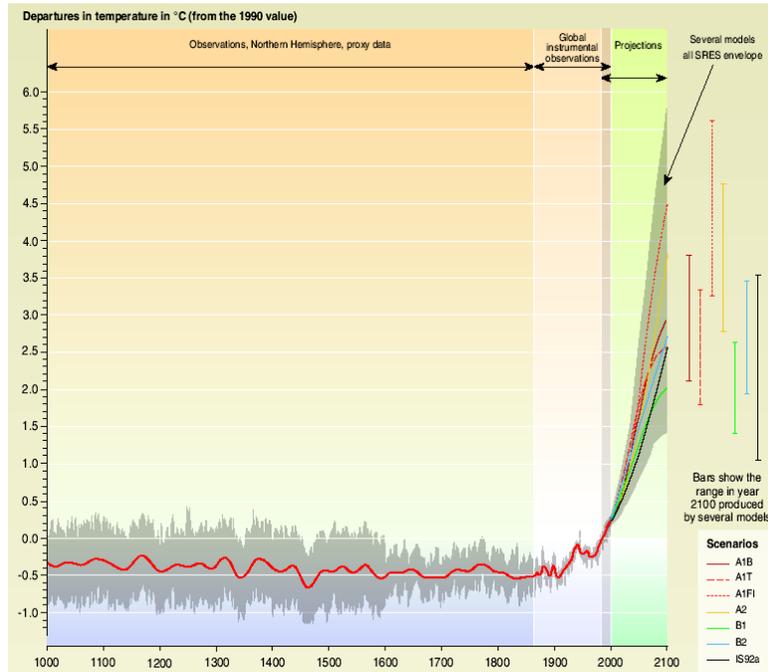


Figure 2. Variations of the Earth's surface temperatures for years 1000 to 2100 (source: IPCC Synthesis Report, 2001)

The relationship between CO₂ concentration, temperature increase, and the risks of adverse impacts from climate change are depicted in Figure 3 (IPCC 2001 Synthesis report). In the upper right of the figure are bars for different atmospheric concentrations of CO₂ (450 ppm to 1000 ppm) showing the range of mean global temperature range predicted from these concentrations using climate models. In the upper left of the figure are five vertical bars, each representing a type of negative impact caused by climate change (e.g., threatened ecosystems, extreme climate events, etc.). In each bar the white area represents neutral or small impacts; yellow indicates low negative impacts, and red means more widespread or greater magnitude of negative impacts. It is possible the high risk, serious impacts represented by the red areas, which is associated with warming above 3.5°C, would be avoided by stabilizing the CO₂ concentrations at or below 1000 ppm. Stabilization of atmospheric CO₂ concentrations at 1,000 ppm or below would require global anthropogenic CO₂ emissions to drop below year 1990 levels, in less than a century, and continue to decrease steadily thereafter to a small fraction of current emissions.

Figure 3 provides a schematic view of the IPCC's assessment of potential climate impacts at varying levels of temperature increase. It reflects the very broad range of impacts—from the local to the global, the environmental to the economic, and the gradual to the sudden. Across this full range, as the IPCC readily acknowledges, there are significant limitations on our ability to project the timing and magnitude of impacts. Even if we were able to accurately forecast future temperature rises, our understanding of the climate responses remains limited, particularly at local and regional scales. Some impacts, particularly those on ecosystems, are quite sensitive not only to the magnitude of local climatic shifts but also to the rate of change. A slow change may allow for adaptation or shifts in the spatial distribution of species, while a quick one may accelerate the rate of extinction or disrupt ecological functions in an irreversible way. However, Figure 2-3 presents general trends in the relationships between increases in temperature and the risks of negative impacts, and the trends are not affected by the uncertainties in specific future impacts.

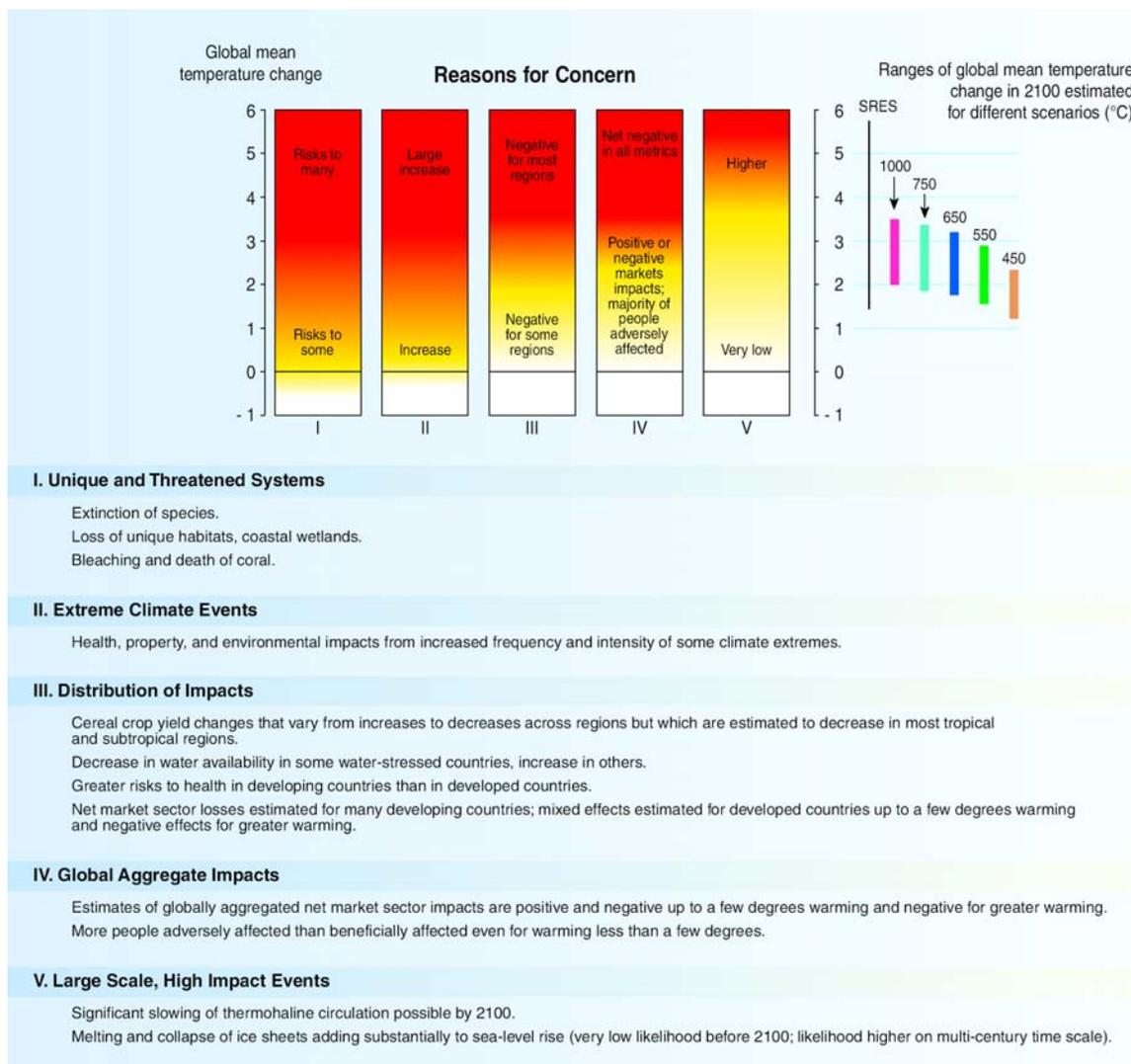


Figure 3. Risks of adverse impacts from climate change (source: IPCC Synthesis Report, 2001).

B. Climate Change Pollutants

Naturally occurring GHGs include water vapor, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and ozone (O₃). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also GHGs, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are substances which deplete stratospheric ozone, they are regulated by the Montreal Protocol on Substances that Deplete the Ozone

Layer. The United Nations Framework Convention on Climate Change (UNFCCC) defers to this earlier international treaty; consequently these gases are not included in national GHG inventories. Other fluorine-containing gases —hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆)—do not deplete stratospheric ozone but are potent GHGs. These latter substances are addressed by the UNFCCC and accounted for in State and national GHG inventories. In addition, there are a number of other pollutants such as carbon monoxide, nitrogen oxides, and aerosols that have direct or indirect effects on terrestrial or solar radiation absorption. They are discussed later in this section.

In September 2000, the California Legislature passed Senate Bill 1771 (SB1771, 2000), requiring the California Energy Commission (CEC), in consultation with other state agencies, to update California's inventory of GHG emissions in January 2002 and every five years thereafter. The CEC (2002) report includes emissions of the four GHGs (CO₂, CH₄, N₂O, and SF₆) and two classes of GHGs (HFCs and PFCs) that are listed in Annex A of the Kyoto Protocol. Although the first three gases are also emitted from natural sources, this report focuses on emissions due to human activities (anthropogenic emissions). The report also concluded that there were major uncertainties associated with input data quality, protocols available to disaggregate data, and inventory methodologies applied to the State. It was recommended that future GHG inventories could be improved by: (1) incorporating improved data and methods; (2) updating emissions estimates to the most recent year; and, (3) presenting a discussion of the uncertainty in emissions estimates from key sources. Individual climate change species are briefly discussed in the following section. Detailed discussions of GHG emissions and sinks are given in the CEC (2002) report.

Carbon Dioxide (CO₂): Carbon is naturally cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. In the atmosphere, carbon generally exists in its oxidized form, as CO₂. Increased CO₂ concentrations in the atmosphere have been primarily linked to increased combustion of fossil fuels. Figure 4 shows the distribution of California's anthropogenic emissions by GHG type. At 84 percent of the total, CO₂ is the largest single contributor to emissions from in-state sources.

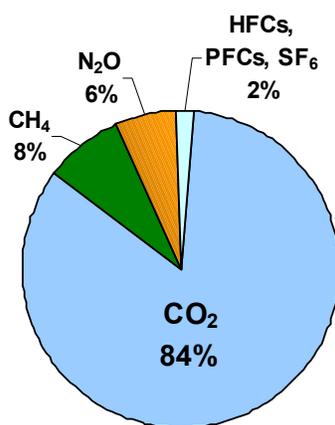


Figure 4. Distribution of California greenhouse gas emissions by gas in 1999, expressed in terms of CO₂ equivalent (adapted from CEC, 2002).

Fossil fuel combustion accounted for 98 percent of gross California CO₂ emissions. Other sources of CO₂ emissions in California include non-energy production processes and waste combustion. Carbon sinks in California brought about by land-use change and forestry practices offset roughly 5 percent of gross State CO₂ emissions.

California's total CO₂ emissions from fossil fuel combustion in 1999 were 356 million metric tons of CO₂ equivalent (MMTCO₂ Eq), which accounts for approximately 7 percent of the U.S. emissions from this source. The transportation sector accounted for the largest portion of emissions, averaging 59 percent of the total CO₂ emissions from fossil fuel combustion in California for the period 1990-1999. Within the transportation sector, gasoline consumption accounted for the greatest portion of emissions.

In-state power plants contribute about 16 percent of the CO₂ emissions from the combustion of fossil fuels. California imports a substantial amount of electricity from out-of-state power plants. It is estimated that the CO₂ emissions associated with the imported electricity is on the order of 67.5 MMTCO₂ Eq. in 1990 and 73.0 MMTCO₂ Eq. in 1999. Out-of-state power plants contribute about 20 percent of the CO₂ emissions from fossil fuels. These emissions are not included for California in compliance with international and national protocols (CEC, 2002). Figure 5 presents the contribution of each sector to CO₂ emissions from fossil fuel combustion in 1999.

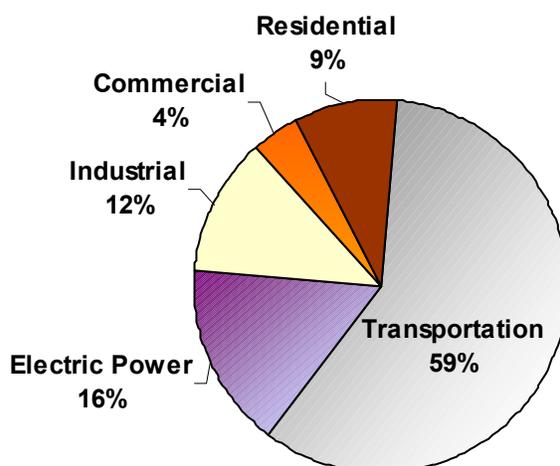


Figure 5. Carbon Dioxide Emissions from the Combustion of Fossil Fuels by Sector for 1999 (adapted from CEC, 2002).

The CEC (2002) report indicates that CO₂ emissions from fossil fuel combustion tracked economic and population growth in the early 1970s. Emissions remained flat through 1986, and then started to grow through the end of the decade. Economic and population growth both outpaced the growth in emissions during this period.

U.S. greenhouse gas emissions generally follow trends in U.S. energy consumption. In 1999, for example, some 82 percent of U.S. greenhouse gas emissions consisted of carbon dioxide released by the combustion of energy fuels—coal, petroleum, and natural gas. Carbon dioxide emissions in the transportation sector, at 496 million metric tons carbon equivalent, were 2.9 percent higher in 1999 than in 1998. Gasoline consumption, which accounted for 60 percent of transportation sector emissions, grew by 2.1 percent.

Methane (CH₄): Methane accounted for more than 7 percent of gross 1999 GHG emissions in California, in terms of equivalent CO₂ emissions. Methane is produced during anaerobic decomposition of organic matter in biological systems. Decomposition occurring in landfills accounts for the majority of anthropogenic CH₄ emissions in California and in the United States as a whole. Agricultural processes such as enteric fermentation, manure management, and rice cultivation are also significant sources of CH₄ in California.

While it is well established that exhaust from vehicles using hydrocarbon fuels contains CH₄, there are few published data concerning the magnitude of CH₄ emissions from the modern, and likely future, vehicle fleet. Metz (2001) concluded that the anthropogenic contribution of road transport to the global CH₄ budget is less than 0.5 percent. Three-way catalyst emission control systems installed on all modern vehicles are effective in removing CH₄ from vehicle exhaust (Nam et al., 2004). It seems highly likely that the future will bring increasingly stringent regulations concerning the effectiveness and

durability of vehicle emission control systems. Hence, it is likely that emissions of CH₄ from gasoline- and diesel-powered vehicles will be reduced from their already low values. A possible exception to this trend would be the increased use of compressed natural gas (CNG) powered vehicles. However, based on the emission measurements reported in Nam et al., (2004) even assuming a substantial fraction of CNG-powered vehicles, the tailpipe CH₄ emissions from such vehicles are likely to have negligible environmental impact. However, refueling losses would be another source of CH₄ emissions from CNG vehicles, and leakage may be significant as well. **Nitrous Oxide (N₂O):** Nitrous oxide emissions accounted for nearly 6 percent of GHG emissions (CO₂ equivalent) in California in 1999. The primary sources of anthropogenic N₂O emissions in California are agricultural soil management and fossil fuel combustion in mobile sources. Nitrous oxide is a product of the reaction that occurs between nitrogen and oxygen during fuel combustion. Both mobile and stationary combustion emit N₂O, and the quantity emitted varies according to the type of fuel, technology, and pollution control device used, as well as maintenance and operating practices. For example, some types of catalytic converters installed to reduce motor vehicle pollution can promote the formation of N₂O. U.S. EPA (2003) estimates suggest that, in 2001, N₂O emissions from mobile combustion were 13 percent of U.S. N₂O emissions, while stationary combustion accounted for 3 percent. From 1990 to 2001, combined N₂O emissions from stationary and mobile combustion increased by 9 percent, primarily due to increased rates of N₂O generation from on-road vehicles.

Behrentz et al., (2004) conducted a pilot study to measure exhaust emissions of N₂O in order to gain information concerning the important variables in catalyst and driving conditions that most affect N₂O emission from motor vehicles. Their results indicate that the average N₂O emissions factor for the 37 vehicles tested was 20 ± 4 mg/km, significantly lower than previous reports of average values of ~35 mg/km (Dasch, 1992; Ballantyne et al., 1994; Barton and Simpson, 1994; Michaels et al., 1998). The difference between the previously reported emission factors and those presented in this pilot study could be related to the introduction of new technologies on some of the vehicles tested since they play a significant role in the amount of N₂O emitted by the vehicles. The differences between this pilot study and those reported previously could also be related to difference in the vehicle fleets studied. This issue will be resolved with ARB's future analysis of a much larger database of N₂O emissions. However, It is generally expected N₂O emission from light-duty vehicles will continue this pattern of decreasing emissions with increasingly stringent control technologies for nitrogen oxides (NO_x).

Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur hexafluoride (SF₆): HFCs, PFCs and SF₆ accounted for the remaining 2 percent of gross 1999 GHG emissions in California. HFCs are primarily used as substitutes for ozone-depleting substances (ODS) regulated under the Montreal Protocol. PFCs and SF₆ are generally emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. There is no aluminum or magnesium production in California; however, the rapid growth in the semiconductor industry leads to greater use of PFCs.

Technical Support Document Climate Change Overview

For vehicular HFC emissions (particularly HFC-134a), four emission sources, all related to air conditioning, should be considered: emissions leaking from the hoses, seals and system components of vehicle air conditioning system, and emissions that are released when the air conditioning system is opened for servicing. HFC emissions can also occur when the vehicle is scrapped at the end of its useful life or due to sudden releases (e.g., traffic accident refrigerant releases). HFC-134a, commercially known as R-134a, is presently the vehicle refrigerant of choice among vehicle manufacturers. The assessment of mobile air conditioning system technology and associated cost analysis are included in later chapter.

Water Vapor: It should be noted that just because water vapor is the most important contributor to the natural greenhouse effect does not mean that human-made greenhouse gases are unimportant. Over the past ten thousand years, the amounts of the various greenhouse gases in the Earth's atmosphere remained relatively stable until a few centuries ago, when the concentrations of many of these gases began to increase due to industrialization, increasing demand for energy, rising population, and changing land use. A simple comparison of the relative greenhouse efficiencies of water vapor and CO₂ quickly becomes problematic because water vapor enters the climate system mostly as a "feedback" gas. The overall impact of water vapor with respect to global climate change is not well understood as it can lead to both warming (absorption of long-wave radiation from Earth) and cooling (cloud formation/reflection of solar radiation).

As the temperature of the atmosphere rises, more water is evaporated from ground storage (oceans, rivers, reservoirs, and soil). Because the air is warmer, the relative humidity can be higher, leading to more water vapor in the atmosphere. As a greenhouse gas, the higher concentration of water vapor is then able to absorb more long-wave radiation radiated from the Earth, thus further warming the atmosphere. This is referred to as a "positive or warming feedback loop." However, as water vapor increases in the atmosphere, more of it will eventually also condense into clouds, which are more able to reflect incoming solar radiation, thus allowing less energy to reach the Earth's surface and heat it up. This is referred to as a "negative or cooling feedback loop."

Large scientific uncertainty exists in defining the extent and importance of the overall water vapor feedback (both positive and negative impacts). The uncertainties in the cloud response are probably the largest contributor to this uncertainty. Climate modeling studies provide circumstantial evidence for water vapor feedbacks. However, as the authors themselves acknowledge, their findings are unable to completely confirm the relationship.

There's an important difference between water vapor and other greenhouse gases. Human activities do not seem to be appreciably changing the atmospheric concentration of water vapor in any direct way on the global average. Nor does water vapor accumulate in the atmosphere over the multi-year periods that other greenhouse gases do. Natural processes (e.g., rain) remove water vapor when it reaches certain

limits. Water stays in the atmosphere for a few days, while other greenhouse gases linger for decades or centuries.

Other Radiatively Important Gases: In addition, there are a number of man-made pollutants, emitted primarily as byproducts of combustion (both of fossil fuels and of biomass), that have indirect effects on terrestrial or solar radiation absorption by influencing the formation or destruction of other GHGs. These include carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), and sulfur dioxide. These compounds, regulated in the US and California pursuant to the Clean Air Act, are often referred to as “criteria pollutants.” The criteria pollutants are reactive compounds, and they tend to remain in the atmosphere for a much shorter time than previously discussed gases. As shown in Table 1, CO₂, N₂O, CH₄, and HFC-134a have atmospheric lifetimes ranging from a century to ten years. Reactive compounds typically last only hours to months. The sequence of reactions that removes CO, NO_x, and NMVOCs from the atmosphere, however, tends to promote the formation of tropospheric O₃. O₃ in the stratosphere protects life on Earth from ultraviolet radiation, but ozone at ground level causes respiratory distress in people and animals and, throughout the troposphere, O₃ is a potent (though short-lived) GHG. The lifetime of criteria pollutants in the atmosphere is short and varies by location and season. The reactions that produce O₃ or alter the losses of CH₄ are strongly affected by the relative concentrations of various pollutants, the ambient temperature, and local weather conditions. At present, there is large scientific uncertainty in estimating their radiative forcing effects.

Molecular hydrogen (H₂) is a trace component of the lower atmosphere. Hydrogen is not radiatively-active and therefore does not have a direct impact on climate; however, it has an indirect impact on climate change as (a) it is involved in the production of tropospheric O₃, and (b) it can modify the concentration of CH₄ through its affect on the concentration of the hydroxyl radical (OH).

Since the 1980s, alternative options for fulfilling the global energy demand have been developed. The widespread use of H₂ produced with renewable energy sources currently appears to be a promising option, in particular for the transportation sector. . Although H₂ fuel cells themselves are a "clean" technology, producing water vapor (a GHG) as exhaust, concurrent changes in emissions of GHGs and ozone precursors associated with the production and distribution of H₂ must be considered as well as the changes in vehicle fleet emissions (Schultz et al., 2003). Furthermore, the release of H₂ may increase because of leakage attributable to the production, transport, storage, and end use of H₂ (Zittel and Altmann, 1996). At present, the average leak rate to be expected in a full-scale hydrogen-driven economy is very uncertain (Schultz et al., 2003).

Sulfur dioxide is emitted largely as a byproduct from the combustion of sulfur-containing fossil fuels, particularly coal. Sulfur dioxide reacts in the air to form sulfate compounds that are very efficient at scattering light. The impact of sulfate on Earth's radiation balance is predominantly negative forcing due to backscatter of incoming solar radiation

, and they are also effective in promoting cloud formation. The clouds, in turn, reflect sunlight back into space, cooling the planet. Sulfur dioxide emissions are regulated in the United States and California under the Clean Air Act, and their concentrations have declined considerably in recent years. This is due to low-sulfur fuels for mobile and stationary sources. California primarily depends on clean-burning natural gas rather than coal or oil, which typically have higher sulfur content, to meet its energy needs.

Aerosols: Aerosols are extremely small particles or liquid droplets found in the atmosphere. Various categories of aerosols exist, including naturally produced aerosols (e.g., soil dust, sea salt, biogenic aerosols, and volcanic aerosols), and anthropogenically aerosols (e.g., sulfates, ammonium nitrate, industrial dust and carbonaceous aerosols including black carbon or organic carbon). Anthropogenic aerosols are derived directly or indirectly from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning. Aerosols affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; indirectly by altering the cloud properties and atmospheric heating rates that in turn modify the formation, precipitation efficiency, and radiative properties of clouds. The effect of aerosols on regional and global climate is complex: in general, sulfate aerosols enhance the reflection of sunlight and cool the Earth, while black carbon aerosols enhance the absorption of sunlight and warm the Earth.

The strongest aerosol particle absorber in the visible spectrum is Black Carbon (BC). The first estimates of forcing by light-absorbing BC particles were almost insignificant ($+0.1 \text{ W/m}^2$, Haywood and Shine, 1995). Radiative forcing is often specified as the net change in energy flux in the atmosphere, and is expressed in watts per square meter (W/m^2) (heat per area of the Earth's surface). Shortly thereafter, three-dimensional models predicted forcing of about $+0.15$ to $+0.2 \text{ W/m}^2$ for BC from fossil fuel combustion (Haywood and Ramaswamy, 1998; Penner et al., 1998). Since that time, higher forcing estimates have resulted from considering the mixing state of BC (Haywood and Ramaswamy, 1998; Jacobson, 2001) and the inclusion of BC from biomass burning in addition to fossil fuel burning (Jacobson, 2001; Chung and Seinfeld, 2002).

Recent modeling and field studies indicate that aerosol light absorption by BC particles is an important component of climate forcing (Jacobson, 2001; Chung and Seinfeld, 2002; Hansen and Nazarenko, 2003,). The global mean radiative forcing of aerosol light absorption may be comparable to that of GHGs. BC is a strong absorber of solar radiation; however, particles containing BC in the atmosphere both scatter and absorb solar radiation. Because BC-containing particles prevent radiation from reaching the Earth's surface, they act to cool the surface, but because they absorb radiation, they warm the atmosphere itself. Previous work has also shown that the overall radiative effect of aerosol BC depends significantly on the manner in which the BC is mixed with non-absorbing aerosols such as sulfate. While the atmospheric warming effect of BC and its surface cooling are well established, the resulting climate forcing from BC has not been clearly established.

Unlike GHGs that exhibit comparatively homogeneous global concentrations, aerosols are very non-uniformly dispersed, and thus the influence of aerosols is stronger regionally than globally. If airborne particles absorb solar radiation, the air warms.

Whether the particles absorb or only scatter, they prevent solar radiation from reaching the surface, cooling the surface and possibly increasing the air's stability. Observations from the Indian Ocean Experiment (INDOEX, Krishnan and Ramanathan, 2002) showed that aerosol-induced changes in regional radiative fluxes can be an order of magnitude larger than the global mean forcing by aerosols or GHGs. The INDOEX field campaign in the North Indian Ocean and South and Southeast Asia had high optical depths, strong absorption by BC, heavy anthropogenic sources, a large reduction in downward surface solar radiation due to the aerosols, and large atmospheric heating rates. Pollution layers during INDOEX, however, generally rose to high altitudes and more clouds were present during INDOEX. INDOEX allowed for studies of the impact of aerosol particles on cloud suppression and other hydrologic-cycle features. To date, several studies have examined the effect of aerosol particles on regional temperature in Asia (Menon et al., 2003; Krishnan and Ramanathan, 2002], but the net effects vary with aerosol loading, absorption properties, and feedbacks. Altered regional stability by atmospheric heating by light-absorbing aerosol alters larger scale circulation and the hydrological cycle, enough so as to account for observed temperature and precipitation changes in China and India, according to a climate modeling study (Menon et al., 2003).

Understanding the role of aerosols in climate change requires inclusion of realistic representations of aerosols and their radiative forcings in climate models. However, compared to long-lived, well-mixed GHGs, the optical properties and temporal and spatial patterns of the many different types of aerosols are heterogeneous. Further, uncertainty in aerosol radiative forcing arises because neither emissions, atmospheric abundance, optical properties, nor indirect effects are fully known. The IPCC (2001) and the NACIP (2002) have identified the total (direct and indirect) radiative forcing due to aerosols, and in particular light absorbing aerosols, as one of the most uncertain components of climate change models. For a more extensive review of aerosol particle impacts on climate change, the reader is referred to Attachment A of this report.

C. Global Warming Potentials: General concept of climate change and definition

The term “radiative forcing” has been employed in the IPCC (2001) assessment to denote an externally imposed perturbation in the radiative energy budget of the Earth’s climate system. Radiative forcing of the surface-troposphere system, resulting, for example, from a change in GHG concentrations, is the change in the balance between radiation coming into the atmosphere and radiation going out. A positive radiative forcing tends, on average, to warm the surface of the Earth, and negative forcing tends, on average, to cool the surface.

The impact of a GHG emission upon the atmosphere is related not only to radiative properties of the gas and its initial abundance, but also to the length of time the GHG remains in the atmosphere. Radiative properties control the absorption of radiation per kilogram of gas present at any instant, but the lifetime of the gas controls how long an emitted kilogram remains in the atmosphere and hence its cumulative impact on the atmosphere's thermal budget. The climate system responds to changes in the thermal budget on time-scales ranging from the order of months to millennia depending upon processes within the atmosphere, ocean, and biosphere.

Gases in the atmosphere can contribute to the greenhouse effect both directly and indirectly. Direct effects occur when the gas itself is a GHG. Indirect radiative forcing occurs when chemical transformations of the original gas produce other GHGs, when a gas influences the atmospheric lifetimes of CH₄, and/or when a gas affects atmospheric processes that alter the radiative balance of the Earth (e.g., affect cloud formation). The concept of a Global Warming Potential (GWP) has been developed in parallel to the concept of ozone depletion potential developed under the Montreal Protocol to compare the ability of each GHG to trap heat in the atmosphere relative to another gas. CO₂, as the primary anthropogenic GHG, has been chosen as the reference gas. GWP is defined as the ratio of the time-integrated radiative forcing from the release of 1 kilogram (Kg) of a trace substance relative to that of 1 kg of a CO₂ (IPCC 2001). While any length of integration can be selected, the 100 year GWPs are recommended by the IPCC and will be employed by the ARB for policy-making and reporting purposes.

GWP values allow a comparison of the impacts of emissions changes (reductions or increases) of different gases. According to the IPCC (2001), GWPs typically have an uncertainty of ±35 percent. In addition to communicating GHG emissions in units of mass, we have also chosen to use GWPs to reflect their inventories in carbon dioxide-equivalent terms because it effectively places all of the GHGs on the same comparative scale. Table 1 lists GWPs for CO₂, CH₄, N₂O, HFC-134a, for the 20, 100, and 500 years time horizons. It should be noted that when the lifetime of the species in question differs substantially from the response time of CO₂ (nominally about 150 years), then the GWP becomes very sensitive to the choice of time horizon. The GWP concept is valid provided emissions of the gas have the same climate impact wherever and whenever they occur. Therefore, short-lived gases and aerosols with varying atmospheric distributions and lifetimes pose a problem in the simple GWP framework.

Table 1. Numerical estimates of global warming potentials compared with carbon dioxide (kilograms of gas per kilogram of carbon dioxide -- adapted from IPCC 2001).

| Climate Pollutants | Lifetime (years) | Global Warming Potential | | |
|--------------------|------------------|--------------------------|------------|-----------|
| | | 20 years | 100 years* | 500 years |
| CO ₂ | ~150 | 1 | 1 | 1 |
| CH ₄ | 12 | 62 | 23 | 7 |
| N ₂ O | 114 | 275 | 296 | 156 |
| HFC-134a | ~14 | 3,300 | 1,300 | 400 |

* Recommended by IPCC (2001) and proposed by ARB staff for AB1493 regulation

As mentioned earlier, some gases can indirectly affect radiative forcing, mainly through chemical processes. For example, tropospheric O₃ provides a significant radiative forcing of the climate system, but its production occurs indirectly, as a result of atmospheric chemistry following emissions of precursors such as NO_x, CO, and NMHCs. Indirect effects will be described below for a number of key gases.

Carbon monoxide: CO is produced when carbon-containing fuels undergo incomplete combustion. As indicated in the IPCC third assessment report (2001), CO does not

absorb terrestrial infrared strongly enough to be counted as a direct GHG. However, it has an indirect radiative forcing effect by elevating concentrations of CH₄ and tropospheric O₃ through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical or OH) that would otherwise assist in destroying CH₄ and tropospheric O₃. It has been proposed that CO emissions should have a GWP because of its effects on the lifetimes of other GHGs (Prather, 1996; Daniel and Solomon, 1998).

The emission of CO perturbs OH, which in turn can then lead to an increase in the CH₄ lifetime. This term involves the same processes whereby CH₄ itself influences its own lifetime and hence GWP value (Prather, 1996) and is subject to similar uncertainty. Emissions of CO can also lead to the production of O₃, with the magnitude of O₃ formation dependent on the amount of NO_x present. As with CH₄, this effect is quite difficult to quantify due to the highly variable and uncertain NO_x distribution (Emmons et al., 1997). Table 2 presents estimates of the CO GWP due to O₃ production and to feedbacks on the CH₄ cycle from two-dimensional model studies along with the box-model estimate for the latter term alone from Daniel and Solomon (1998). Table 2 shows that the 100-year GWP for CO is likely to be 1.0 to 3.0, while that for shorter time horizons is estimated at 2.8 to 10. These estimates are subject to large uncertainties, as discussed further in the IPCC report (2001).

Because of the difficulty in accurately calculating the amount of O₃ produced by CO emissions, an accurate estimate of the entire indirect forcing of CO requires a three-dimensional chemical model. Wild et al (2001) have developed a method for analyzing the response of concentrations of O₃ and CH₄ to changes in the quantity of air pollutant emissions, using a three-dimensional global chemical transport model (CTM) that combines a global climate model with a photochemical reaction model. The results demonstrated that although the production of O₃ is suppressed when only NO_x emissions are reduced, the concentration of CH₄ rises, thereby possibly accelerating global warming in the long-term. When NO_x and CO emissions are reduced simultaneously, however, it has been shown that the build up of methane is abated and that this approach is thus effective in mitigating global warming. They also discussed some clear inadequacies in their modeling results. For example, the treatment of urban emissions in the CTM does not include the effects of non-linearities in small-scale plumes where NO_x concentrations may be sufficiently high to suppress O₃ production or to remove NO_x rapidly. It is not clear in these cases that the OH effect is also proportionally suppressed. Uncertainties such as these can be evaluated by comparing the global CTM with carefully designed high-resolution regional models.

Table 2. Estimated indirect Global Warming Potentials for CO for time horizons of 20, 100, and 500 years (adapted from IPCC third assessment report (2001). Note: United Nations Framework Convention on Climate Change (UNFCCC) has not yet adopted the IPCC reporting of a GWP for CO.

| | Indirect Global Warming Potentials Time horizon | | |
|---|--|-----------|-----------|
| | 20 years | 100 years | 500 years |
| Daniel and Solomon (1998): box model considering CH ₄ feedbacks only | 2.8 | 1.0 | 0.3 |
| Fuglestvedt et al. (1996): two-dimensional model including CH ₄ feedbacks and tropospheric O ₃ production by CO itself | 10 | 3.0 | 1.0 |
| Johnson and Derwent (1996): two-dimensional model including CH ₄ feedbacks and tropospheric O ₃ production by CO itself | ---- | 2.1 | ---- |

NO_x and Non-Methane Hydrocarbons: The short lifetimes and complex non-linear chemistries of NO_x and NMHC make calculation of their indirect GWPs a challenging task subject to very large uncertainties. Through production of tropospheric O₃, emissions of NO_x lead to a positive radiative forcing of climate (warming), but by affecting the concentration of OH they reduce the levels of CH₄, providing a negative forcing (cooling) which partly offsets the O₃ forcing. IPCC (2001) has reported the relative differences in the impacts of NO_x upon O₃ depending on where it is emitted (in particular, surface emissions versus those from aircraft). Higher altitude emissions have greater impacts both because of longer NO_x residence times and more efficient tropospheric O₃ production, as well as enhanced radiative forcing sensitivity. Two-dimensional model studies (Fuglestvedt et al., 1996; Johnson and Derwent, 1996) have presented estimates of the GWPs for NO_x emitted from aircraft on the order of 450 considering a 100-year time horizon, while those for surface emissions are likely to be much smaller, on the order of 5. It should be noted that such numerical values are subject to very large quantitative uncertainties. Similarly, NMHCs have a small direct radiative forcing. As indicated by Johnson and Derwent (1996), the indirect forcing through changes in OH and tropospheric O₃ is also small for each NMHC taken individually but can be significant taken as a family. The indirect forcings of NMHCs are still poorly quantified and require the use of global three-dimensional chemical transport models. Accurate calculations of these effects are a notoriously difficult problem in atmospheric chemistry.

D. Pollutants Included in the Proposed Regulation

Assembly Bill 1493 calls for reductions in GHGs, which are defined in the bill as CO₂, CH₄, N₂O, HFCs, PFCs and SF₆. The same list of GHGs was also included in the 1997 Kyoto protocol, under UNFCCC agreement. The first four of these identified global climate change pollutants are clearly associated with motor vehicle use in California.

Technical Support Document Climate Change Overview

PFCs and SF₆ are not known to be associated with motor vehicle emissions in California and therefore are not addressed further in the staff report.

Black carbon and criteria pollutant emissions from motor vehicles are also known to have climate change impacts. Although these pollutants are not specifically defined as greenhouse gases in AB 1493, the authority to regulate these pollutants currently exists in the Health and Safety Code (Section 39014). AB 1493 does not limit that authority; rather it supports the need to address the impacts of climate change pollutants.

The 2001 IPCC states that in addition to the gases targeted in the Kyoto Protocol, the contribution of tropospheric O₃ to the greenhouse effect is also important. The report further states that in order to curb global warming it is necessary to reduce the emissions of both GHGs and other gases that influence the concentration of GHGs. Air pollutants such as NO_x, CO, and NMVOC generate O₃ and impact tropospheric OH radicals, which in turn alters CH₄ levels. Hence they are called indirect GHGs. However, due to the basic uncertainties regarding the quantitative impact of criteria pollutant emissions on climate, it is impossible at this time to have confidence in any numerical prediction of the climate effect of their emissions from light-duty motor vehicles. Because the uncertainties associated with the impact of criteria pollutants on climate change are large, at this time the ARB has chosen not to consider the potential climate change effects when regulating CO, NO_x, NMVOC or aerosols. However, as more definite scientific evidence becomes available, the ARB will, if appropriate, consider the climate change impacts of these criteria pollutants in its regulatory decisions.

E. Indicators of Climate Change In California

The climate is changing under the influence of human activity. Indicators of climate forcing and actual climate change can be used to illustrate trends, measure the suitability of particular actions in certain areas and encourage public awareness of the climate change impacts. The European Topic Center on Air and Climate Change (ETC/ACC) has recently developed a list of climate change indicators that should reflect, among other things, trends in GHG emissions, atmospheric GHG concentrations, temperature increase and effects on biodiversity, human health, and socio-economic sectors. One goal was that some indicators could show the progress made in meeting climate change policy targets and should identify requirements for adaptation and mitigation measures. Trends in GHG emissions are useful in these areas. Atmospheric CO₂ and other greenhouse gas concentrations are the key indicator for international negotiations on emission reduction. Climate and atmospheric variables such as temperature change and trends in precipitation are obvious parts of assessments, which study climate change impacts. Emphasis up to now has often been on changes in absolute trends. Extreme events and changes in seasonality have also been investigated. Statistical analysis of climate data can be used to describe the interrelationships in changes in the different climate parameters but might not be as understandable to policy makers and the public as temperature or precipitation.

For the indicators that show impacts on human health and on economic sectors, no suitable indicators were identified that could be available in the short-term. However several indicators are expected to be available in the medium-term. In general,

Technical Support Document Climate Change Overview

indicators to describe the impact of climate change on human health are still limited due to lack of data. Climate change can exacerbate heat waves resulting in higher rates of morbidity and mortality. Furthermore, higher temperatures could lead to an increase of water and food related diseases. The identification and evaluation of indicators for climate change impacts on human health is one of the activities of the scientists who are studying potential implications for human health.

In California several potential climate change indicators have been suggested, including anthropogenic GHG emissions, air temperature, annual Sierra Nevada snow melt runoff, and sea level rise in California (EPIC, 2002).

Time series of historical emissions of anthropogenic GHGs have been produced for a number of geographical regions. The GHGs emissions trends illustrate that, although California has been able to moderate its GHG emissions, total GHG emissions are still increasing and continue to remain above 1990 levels. With a relatively temperate climate, California uses less heating and cooling energy than other states. However, California leads the nation in vehicle miles traveled, which leads to a concomitant increase in carbon dioxide emissions in the transportation sector. Tracking California's trends in motor vehicle-related GHGs emissions will allow an assessment of the State's contributions to global GHG emissions.

Figure 6 depicts overall trends in gross GHG emissions in California and the United States. Gross emissions include emissions from all the in-state and United States sources normalized to 1990 levels (i.e., gross emissions in each year are presented as a ratio of gross emissions in 1990) to allow a comparison between emissions in California and the United States. The emissions decline in California in 1991 and 1992 is in large measure the result of the economic recession experienced during those years. In 1994, emissions were relatively high because: 1) a recovering economy resulted in increased industrial activity and 2) low rainfall reduced availability of hydroelectric power, which in turn resulted in increased emissions from fossil-fueled electricity generation. Although moderated by availability of hydroelectric power, emissions from 1995 to 1999 increased from a strong expansion in the economy.

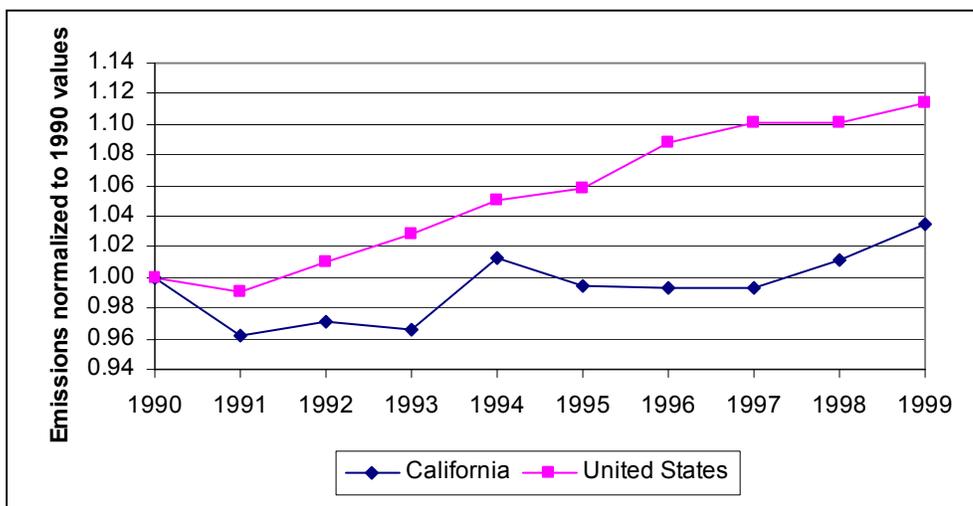


Figure 6: 1990-1999 relative gross greenhouse gas emissions (adapted from CEC, 2002)

Increases in the concentrations of GHG are predicted to change regional and global climate-related parameters such as temperature, precipitation, soil moisture, and sea level. Temperature data have been collected at many weather stations in the State for almost a century. The air temperature indicator can be used to track trends in statewide surface air temperatures and regional variations, allowing for a comparison of temperature changes in California with those occurring globally. Analysis of annual mean air temperature at 93 California stations indicates that air temperature has increased over the past 90 years, more so in large cities than towns. Land use has an impact on temperature and large urban areas are generally warmer than rural areas, and can have temperatures up to 5° F higher, creating their own warm belt (urban heat island). Causes of the "heat island effect" include less vegetation that would provide shade and cool the air and dark surfaces that absorb more heat from the sun. Roads and parking lots are frequently paved with black asphalt concrete and other dark materials that absorb most of the sunlight that falls upon them. The energy of the sunlight is converted into thermal energy and pavements get hot, heating the air around them and contributing greatly to the heat island. The less populated and rural areas, have shown the lowest average rate of temperature increase. For the period 1910 to 2000 these areas have shown a temperature increase of 0.7° F per century that agrees with a global estimated mean surface temperature increase of 0.5 to 1.0 °F since the 19th century (EPIC, 2002).

The warming of global climate could increase evaporation rates, thereby potentially increasing precipitation and storms in the State. The yearly ratio of rain to snow depends on temperature, as does snow level elevations. The warmer the storm temperature, the higher the elevation at which snow falls and accumulates. Higher elevations of the snow line mean reduced snow pack and lower spring water yields. Snowmelt and runoff volume data can be used as a climate change indicator to document changes in runoff patterns. These specific regional changes are related, at least in part, to the climate change associated with the observed global mean warming.

Technical Support Document Climate Change Overview

In California, large accumulations of snow occur in the Sierra Nevada and southern Cascade Mountains from October to March. Each winter, at the high elevations, snow accumulates into a deep pack, preserving much of California's water supply in cold storage. Early spring warming causes snowmelt runoff, mostly during April through July. If the winter temperatures are warm, more of the precipitation falls as rain instead of snow, and water directly flows from watersheds before the spring snowmelt. Thus, there is less buildup of snow pack; as a result, the volume of water from the spring runoff is diminished. Lower water volumes of the spring snowmelt runoff may indicate warmer winter temperatures or unusually warm springtime temperatures. Figure 7 shows that throughout the 20th century, annual April to July spring runoff in the Sierra Nevada has been decreasing. This decreased runoff was especially evident after mid-century, since then the water runoff has declined by about twelve percent (Roos, 2002).

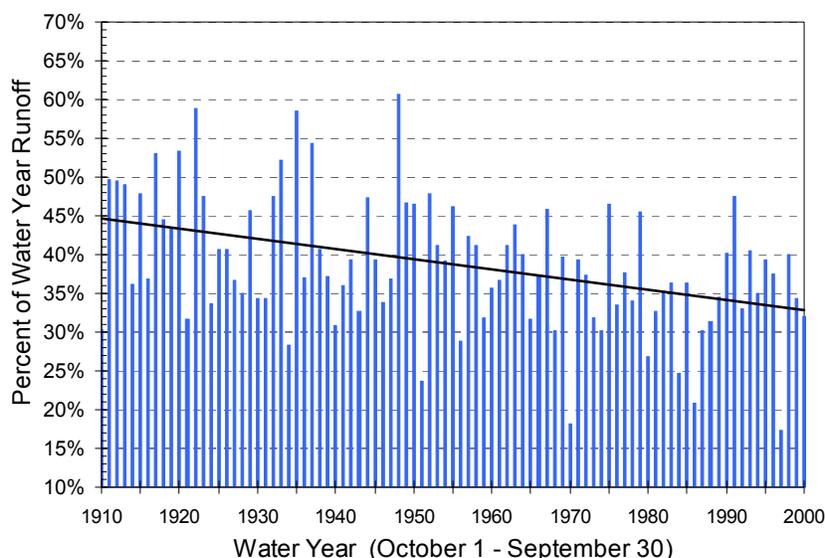
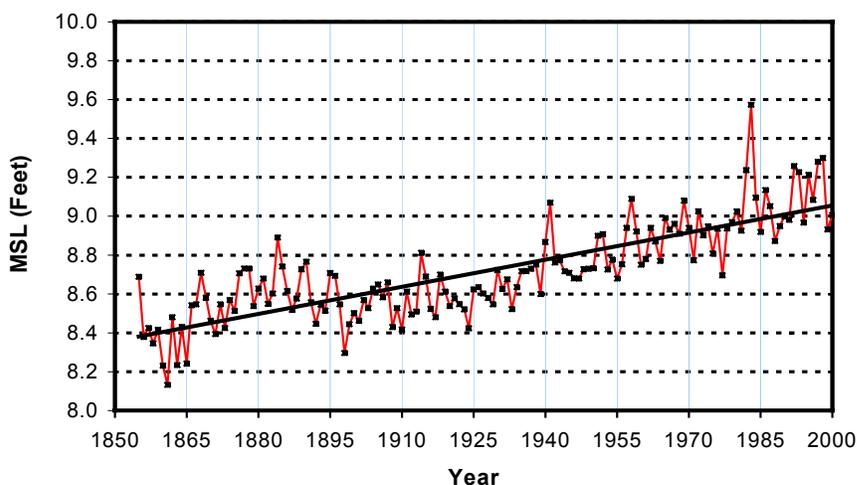


Figure 7. Sacramento river runoff (1910-2000) - April to July as a percent of total runoff (Roos, 2002).

Sea level rise also provides a physical measure of possible oceanic response to climate change. Increasing global mean temperatures will result in the rise of mean sea level. Warming of the ocean water will cause a greater volume of sea water because of thermal expansion. This phenomenon contributes the largest share of sea level rise, followed by melting of mountain glaciers and ice caps (IPCC, 2001). Along California's coast, sea level already has risen by three to eight inches over the last century, consistent with the global mean value of four to eight inches (IPCC, 2001). Long-term data from 10 of 11 California stations show increases in sea level (Figure 8, using San Francisco as an example). Sea level rise is not expected to be uniform globally and is influenced by shifts in weather patterns as well as the long-term motion of the continents.

Figure 8. 1855-2000 San Francisco yearly mean sea level (Roos, 2002).



While the rates of increase vary, sea level is increasing almost everywhere in California (Flick, 1999). Sea level rise and storm surges could lead to flooding of low-lying areas, loss of coastal wetlands such as the San Francisco Bay Delta, erosion of cliffs and beaches, saltwater contamination of groundwater aquifers and drinking water, and damage to roads, causeways, and bridges. California's hundreds of miles of scenic coastline contain ecologically fragile estuaries, expansive urban centers, and fisheries that could be impacted by future changes in sea level elevation. Sea level rise could have serious impacts on the water resources of California.

With sea level rise there would be a serious impact to the California water supply in the Sacramento-San Joaquin River Delta. There would be problems with the levees protecting low-lying land, such as Delta islands, where the land subsidence has resulted in lands well below sea level, and increased salinity intrusion from the ocean, which could degrade fresh water transfer supplies pumped at the southern edge of the delta (Roos, 2000). Many Delta levees are built on peat soil foundations. The impact of sea level rise on these levees depends on the rate. A small rise can probably be tolerated; a major rise could cause significant problems. A substantial rise in sea level over the next century could challenge the continued viability of the 1,100-mile system of Delta levees, and would add greatly to the cost of maintaining these levees.

The climate change indicators described in this report represent key properties of the climate system that are considered sensitive to climate change. Many additional potential indicators remain to be explored. For example, climate change may influence the frequency of extreme weather events, ecosystem structures and processes, and species distribution and survival. It may affect forestry, energy and other industries, insurance and other financial services, and human settlements. In addition, the impacts can vary from one region, ecosystem, species, industry, or community to the next. Research into the regional impacts of climate change is ongoing, and the potential climate change indicators will be updated and be expanded, as new information becomes available.

F. Potential Impacts on California

Technical Support Document Climate Change Overview

Climate is a central factor in Californian life. It is at least partially responsible for the State's rapid population growth in the past 50 years, and largely responsible for the success of industries such as agriculture and tourism. The potential effects of climate change on California have been widely discussed from a variety of perspectives (Lettenmaier and Sheer 1991; Gleick and Chalecki 1999; Wilkinson 2002). The signs of a global warming trend continue to become more evident and much of the scientific debate is now focused on expected rates at which future changes will occur. Rising temperatures and sea levels, and changes in hydrological systems affecting water resources are threats to California's economy, public health, and environment. The following section provides examples of why the State is particularly at risk from an increasingly warmer and more variable climate.

Human Health and Air Pollution: Human health in the California region is likely to be impacted by climate change. Several recent studies have addressed potential implications for human health at the national and international levels (Patz et al., 2000). Greater climate variability and changes in climate patterns would potentially cause both direct and indirect health effects. Direct health impacts due to climate change include extreme events, such as heat waves, droughts, increased fire frequency, and increased storm intensity resulting in flooding and landslides. Secondary or indirect health effects will likely include changes in air pollution and allergen exposure, infectious diseases, particularly waterborne and vectorborne microbes; as well as effects on food productivity and safety. In California, as in much of the world, there is concern that increased heat and moisture will facilitate the spread of emerging infectious diseases, many of which are vector-borne. West Nile virus for example in the US was first documented in New York City during the spring drought and heat wave of 1999, and was confirmed in California in 2002. WEE (western equine encephalitis) increases in cool, wet, El-Nino years while SLE (St. Louis encephalitis) does so in hot, dry, La Nina years (Cayan, Tyree et al. 2003). Both WEE and SLE are caused by arboviruses. The activity of these viruses has increased in CA over the last decade. Other climate-sensitive vectorborne diseases that occur in California are malaria, tickborne diseases, plague and hantavirus.

Air quality impacts such as increases in tropospheric ozone due to higher temperatures may also cause secondary health impacts. The most obvious direct impacts of projected climate change are higher temperatures and increased frequency of heat waves which may increase the number of heat-related deaths and the incidence of heat-related illnesses. Cities such as Los Angeles that experience occasional very hot, dry weather may be especially susceptible. Studies of heat waves in urban areas have shown an association between increases in mortality and increases in heat, measured by maximum or minimum temperature, heat index (a measure of temperature and humidity), or air-mass conditions (Semenza et al., 1996). For example, after a 5-day heat wave in 1995 in which maximum temperatures in Chicago ranged from 93 to 104°F, the number of deaths increased 85 percent over the number recorded during the same period of the preceding year. At least 700 excess deaths (deaths beyond those expected for that period in that population) were recorded, most of which were directly attributed to heat (Semenza et al., 1999).

Technical Support Document Climate Change Overview

Until recently, excess deaths occurring during heat waves have been attributed entirely to heat-induced stress. However, analyses in the Netherlands (Fischer et al., 2004) and the United Kingdom (Stedman, 2004) during the August 2003 heat wave in Europe conclude that a substantial portion of the mortality is actually due to elevated O₃ and aerosols levels. Fischer et al. (2004) estimate 400-600 excess air pollution-related deaths occurred in the Netherlands during June-August 2003 compared to 2000 and 2002. These values are almost half of the 1000-1400 total excess deaths estimated for summer 2003. The UK Office of National Statistics reported an excess of 2045 deaths in England and Wales for August 4-13, 2003 in comparison to the 1998-2002 average for that time of year. Stedman (2004) estimates that 21-38 percent of the total excess deaths are due to the elevated ozone and PM₁₀ levels that occurred during the heat wave. Air quality has a very real and direct effect on the health of many Californians who experience the worst air quality in the nation. Over 90 percent of Californians are living in areas that violate the State ambient air quality standard for ozone and/or particulate matter. In the Los Angeles area, population density, cars, climate, and geography combine to create some of the nation's worst air quality. A study by Kinney and Ozkaynak (1991) of urban air pollution in Los Angeles County found a significant association between daily mortality and ozone levels. Other California cities including Bakersfield and Fresno are also struggling with severe air quality problems as the San Joaquin Valley (SJV) suffers from air pollution from various sources.

Climate change can lead to changes in weather patterns that can influence the frequency of meteorological conditions conducive to the development of high pollutant concentrations. High temperatures, strong sunlight, and stable air masses tend to occur simultaneously and increase the formation of ozone and secondary organic carbon particles – weather conditions associated with warmer temperatures increase smog. Figure 9 shows the relationship between ozone and temperature in the South Coast Air Basin.

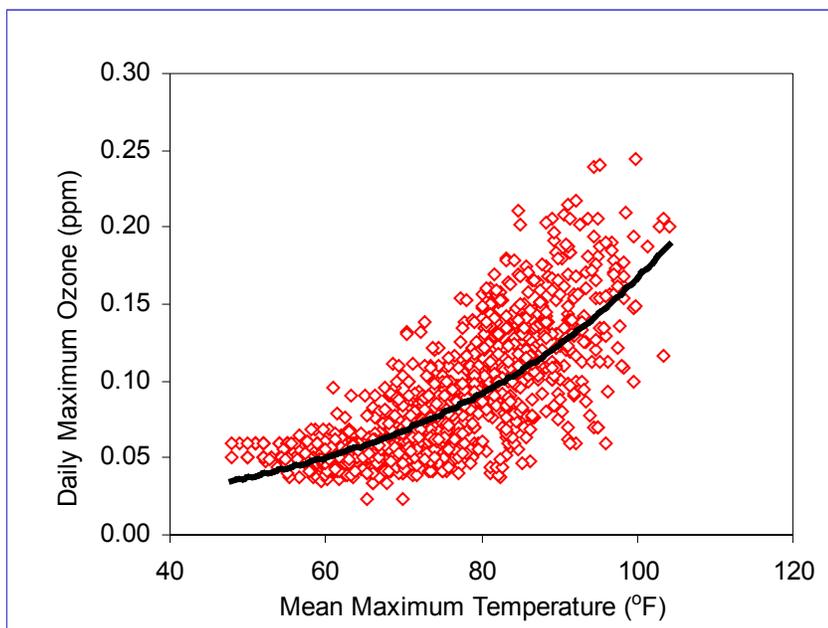


Figure 9. Relationship between ozone and temperature in the South Coast Air Basin, 1996-1998

Air pollution is also made worse by increases in biogenic hydrocarbon emissions and evaporative emissions of fuels and solvents which leads to higher levels of ozone and PM₁₀ during hot weather. During hot summer days in California, air conditioners are used more frequently leading to increasing demands for electric power production and an associated increase in power plant emissions of NO_x, hydrocarbons, and PM.

The interrelation of climate change and air quality has been investigated by several researchers. The premise of several studies (e.g., Sillman and Samson 1995, Taha and Bornstein, 1999; Taha et al., 2000) is that ozone air quality is profoundly affected by changes in climate and meteorology. Temperature, winds, solar radiation, atmospheric moisture, venting and mixing affect both the photochemical production of smog as well as the emissions of ozone precursors (e.g., NO_x and VOC) that are temperature- and solar-radiation-dependent. For example, biogenic hydrocarbon emissions are particularly sensitive to changes in air temperature and solar radiation. In addition, meteorology affects the transport, dispersion, and deposition of pollutants and precursors alike.

The direct effect of temperature variability on ozone and fine PM concentrations in Southern California was investigated by Aw and Kleeman (2003). Results indicate that the concentration of ozone and non-volatile secondary PM will generally increase at higher temperatures due to increased gas-phase reaction rates. The concentration of semi-volatile reaction products also will increase at higher temperatures, but the amount of this material that partitions to the particle-phase may decrease as the thermodynamic equilibrium between nitric acid, ammonia and ammonium nitrate favors the gases under warm, dry conditions. The role of temperature in pollutant emissions was not considered in this study.

Technical Support Document Climate Change Overview

There has been some focus on the potential impacts of changes (e.g., increases) in air temperature on ozone air quality. Air temperature has a direct effect on the photochemical reactions producing ozone, e.g., chemistry of PAN (Sillman et al., 1990) as well as emissions of precursors. But temperature is also an indirect indicator of other mechanisms that can accelerate smog formation. These include stalled high-pressure systems, intensified subsidence, reduced cloud cover, increased atmospheric water vapor, etc. Thus in this sense, high temperature is concurrent with many other exacerbating factors.

Climate change may alter the frequency, timing, intensity, and duration of extreme weather events (i.e., meteorological events that have a significant impact on local communities). Injury and death are the direct health impacts most often associated with natural disasters. Secondary health effects may also occur. These impacts are mediated by changes in ecological systems and public health infrastructures, such as bacterial proliferation and the availability of safe drinking water. Changes in precipitation, temperature, humidity, salinity, and wind have a measurable effect on the quality of water used for drinking, recreational, and commercial use, and as a source of fish and shellfish. Direct weather associations have been documented for waterborne disease agents such as *Vibrio* bacteria (Motes et al., 1998), viruses (Lipp et al., 1999), and harmful algal blooms (Harvell et al., 1999)

From 1945 to 1989, 145 natural disasters caused 14,536 deaths in the United States, an average of 323 deaths/year (Glickman and Silverman, 1992). According to the National Weather Service (NWS) report severe storms caused 600 deaths and 3,799 reported injuries in 1997. Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the United States; the average annual loss of life is estimated to be as high as 146 deaths per year. Brooks and Adger (2003) used data relating to natural disasters for the assessment of recent historical and current risk associated with climatic variability. The data are derived from the Emergency Events Database developed by the US Office of Foreign Disaster Assistance and the Center for Research into the Epidemiology of Disasters at the Université Catholique de Louvain in Brussels, Belgium (<http://www.em.dat.nett>) as well as population data from the World Bank. Their results indicate that the broad trend in recorded disaster occurrence is one of increasing frequency in the latter half of the century (Figure 10). This is likely to be the result of several factors such as increases and improvements in reporting, population growth and increased population in areas subject to climate-related disasters (Berz, 1997). Climate change could have played significantly in increasing the frequency of disasters (Augusti et al., 2001; Frich et al., 2002).

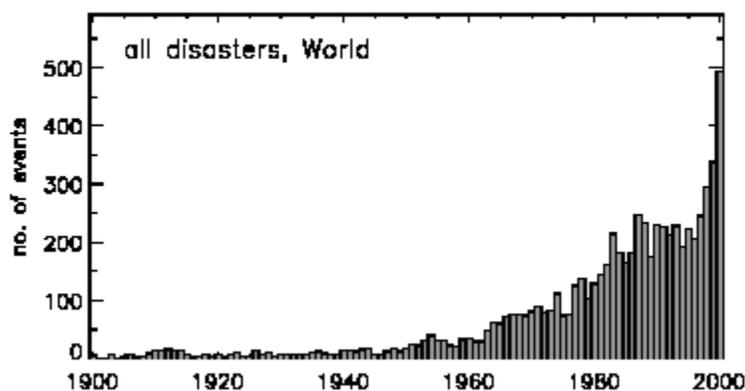


Figure 10 Annual global frequency of recorded climate-related disasters for all disaster types (adapted from Brooks and Adger, 2003).

The cost of extreme weather events have increased in recent decades (IPCC Synthesis report, 2001). Global economic losses from catastrophic events increased ten-fold from 3.9 billion dollars per year in the 1950s to 40 billion in 1990s. The insured portion of these losses rose from negligible level to 9.2 billion during the same period. The cost of weather events have risen rapidly despite significant and increasing efforts at fortifying infrastructure and enhancing disaster preparation.

Indirect health effects of climate change include increases in the potential transmission of vector-borne infectious diseases caused by the extensions of ranges and seasons of some vector organisms and acceleration of the maturation of certain infectious parasites. Diseases transmitted between humans by blood-feeding arthropods (insects, ticks, and mites), such as plague, typhus, malaria, yellow fever, and dengue fever were once common in the United States and in Europe. Many of these diseases are no longer present in the United States, mainly because of changes in land use, agricultural methods, residential patterns, human behavior, and vector control. The ecology and transmission dynamics of these vector-borne infections are complex and the factors that influence transmission are unique to each disease. Most vector-borne diseases exhibit a distinct seasonal pattern which clearly suggests that they are weather sensitive. Rainfall, temperature, and other weather variables affect in many ways both the vectors and the pathogens they transmit. In California, as in much of the world there is concern that increased heat and moisture will facilitate the spread of emerging infectious diseases, many of which are vector-borne. It has also been suggested that climate change will increase exposure to natural allergens. Fungi have adapted to virtually all environments, but fungal growth is often enhanced at increased temperature and/or humidity (Bernard et al., 2001).

In summary, serious effects on human health may result from climate change. It is clear that heat waves and other extreme events pose serious public health concerns. Higher temperatures are also likely to negatively affect health by exacerbating air pollution. The elderly, infirm, and poor are most at risk because heat and poor air quality can exacerbate pre-existing disease. Lack of access to air conditioning increases the risk of

heat-related illness. Secondary or indirect effects of changes in climate such as changes in disease vectors may also pose concerns. Poor and immigrant populations (residence in urban areas where the heat island effect actually increases warming and the consequent effects of heat) are more vulnerable to climate change as they are often without adequate resources to control their environment with appliances such as air conditioners, or to seek medical attention. Thus, these communities are the first to experience negative climate change impacts like heat death and illness, respiratory illness, infectious disease, and economic displacement.

Water Resources: Much of California is semi-arid and, thus, water resources are a key factor in the State's economic and environmental well-being. Water resources are affected by changes in precipitation as well as by temperature, humidity, wind, and sunshine. Water resources in drier climates, such as California, tend to be more sensitive to climate changes. Because evaporation is likely to increase with warmer climate, it could result in lower river flows and lake levels, particularly in the summer. In addition, changes in meteorology could result in more precipitation occurring in intense events, which reduces the ability to capture the water and could increase flooding. If streamflow and lake levels drop, groundwater also could be reduced. The seasonal pattern of runoff into California's reservoirs could be susceptible to climatic warming. Winter runoff most likely would increase, while spring and summer runoff would decrease. This shift could be problematic, because the existing reservoirs are not large enough to store the increased winter flows for the demand in summer. Increased winter flows to San Francisco Bay could increase the risk of flooding (Gleick and Chalecki 1999; Miller, et al., 2001; Roos 2002).

The California Department of Water Resources recognizes that climate change and variability can have important consequences for the State's water resource systems. Warmer temperatures combined with increased variation in the timing and quantity of precipitation can significantly influence the snowpack in the Sierra Nevada Mountains, water runoff patterns, water supply and demand, water temperatures, hydroelectric power production, wildfires, and soil moisture and groundwater levels. Increased severe weather events like the 1996-97 storm in California highlighted the State's vulnerability to climate variability and the need to prepare for the possibility of increases in frequency of extreme weather events.

Population pressures have already strained California's water resources. California is home to about 35 million people. Using the California Department of Finance projections, it is estimated that California's population will grow by an average of 1.4 percent per year over the next 20 years. This projection translates to approximately 10 million more Californians by 2020. The combination of population growth and climate warming could impose serious environmental challenges. Increased water demands and decreased water availability raise substantially the costs of providing water to urban, agricultural, and hydropower users. It is possible that California's water system could adapt to the population growth and climate change impact. However, even with new technologies for water supply, treatment, and water use efficiency, widespread implementation of water transfers and conjunctive use, coordinated operation of reservoirs, improved flow forecasting, and the close cooperation of local, regional, State, and federal government, this adaptation most likely will be costly.

Agriculture: If California's water resource systems face challenges from climate change and variability, so will the State's agricultural sectors. While agricultural production is vulnerable to climate change risks associated with adverse water system impacts, this sector faces other risks that come with increasingly unpredictable variations in both temperature and precipitation. For example, increases in the frequency of extreme weather at inopportune times can cause significant declines in agricultural productivity (Wilkinson, 2002).

California is the leading agricultural state in the U.S. by a considerable margin. The State has the most diverse crop mix of any region in the country. California has produced the highest agricultural crop value in the U.S. for more than 50 consecutive years. 28 million acres in California are involved in some form of agriculture. The impacts of global warming on crop yields and productivity will vary considerably by region. But several studies, including one by the US Department of Agriculture, show that maintaining today's levels of agricultural productivity would be difficult. At best, this would require expensive adaptation strategies. Farmers will likely need to change crops and cultivation methods because warming generally hinders crop yields, although the beneficial effects of elevated CO₂ in fertilizing plant growth may offset other damaging effects. If climate warming is accompanied by increased drought, however, the detrimental effects would be intensified.

In California, 87 percent of the crop area is irrigated, and increased drought could be countered by human management. Yet there are severe constraints on increased irrigation since 100 percent of the surface water is already allocated. Agricultural water users in the Central Valley are the most vulnerable to climate warming. While wetter future climate could increase water availability for these users, the drier climates could significantly reduce agricultural water deliveries in the Central Valley. If the climate shifts toward a severe drought, not only will more irrigation be needed, but also the snow pack at higher elevations will be lacking. This can be disastrous for producers that grow fruit trees and vines that will require years to reestablish production.

Growers of perennial crops, including fruits, nuts, and grapes, cannot shift quickly to new cultivars as conditions change. They are most vulnerable to shifts in climate and to extreme events such as drought or pest outbreaks. The economics of producing and selling crops will depend on the impacts of global climate change on worldwide agricultural markets.

Ecological Impacts: California is an ecologically diverse state, with 134 endangered and threatened species, including the sea otter, the California condor, and the American bald eagle. California's unique ecosystems include 25,000 square miles of desert. California's mountain ecosystems in the Sierra Nevada, including Yosemite National Park, contain alpine wilderness areas with large numbers of sequoia trees. The ranges of many species of plants and animals are restricted and fragmented because of both natural and human causes. Many invading species have colonized large areas and displaced native species in the wake of environmental changes in recent centuries (Wilkinson and Rounds, 1998).

Potential responses of California ecosystems to climate change fall generally into three categories. The response may be geographic; the boundaries between ecosystem

types will move and the character of landscapes will inevitably change along with shifts in climate. The responses may involve changes in the way ecological processes work and in the goods and services that ecosystems supply to human societies (such as purification of air and water, decomposition of wastes, maintenance of soil fertility, control of pests, pollination services, recreational opportunities, plant productivity, the health of fisheries). Finally, the responses may entail changes in the kinds of plants and animals that live in a community, and these necessarily lead to changes in how the ecosystem works. All three types of responses are interrelated (Field et al., 1999). Changes in climate have the potential to affect the geographic location of ecological systems, the mix of species that they contain, and their ability to provide the wide range of benefits on which societies rely for their continued existence. Ecological systems are intrinsically dynamic and are constantly influenced by climate variability. The primary influence of anthropogenic climate change on ecosystems is expected to be through the rate and magnitude of change in climate means and extremes.

Climate change could have an impact on many of California's species and ecosystems. For example, aquatic habitats are likely to be significantly affected by climatic changes. Most fish have evolved to thrive in a specific, narrow temperature range. As temperatures warm, many fish will have to retreat to cooler waters. Species differ significantly in their abilities to disperse and to become established in new locations with more suitable climates. Poorly dispersed species, such as amphibians and oaks, may not be able to survive the predicted rapid climatic changes if they have narrow tolerances for specific environmental conditions. Even for easily dispersed species, such as grasses and birds, other biological interactions (i.e., new predators, missing pollinators, lack of specific food sources) or physical environments (i.e., different soils, roads, lack of suitable intervening habitat) may block the success of migration.

With changes in climate, the extent of forested areas in California could also change. The magnitude of change depends on many factors, including whether soils become drier and, if so, how much. Hotter, drier weather could increase the frequency and intensity of wildfires, threatening both property and forests. Along the Sierras, drier conditions could reduce the range and productivity of conifer and oak forests. Farther north and along the northern coast, drier conditions could reduce growth of the Douglas fir and redwood forests. A significant increase in the extent of grasslands and chaparral throughout the State could result. These changes would affect the character of California forests and the activities that depend on them.

The responses of California forest species to climate change will depend critically on changes in water supply and the availability of mineral nutrients in the soil. In forests, as in other California ecosystems, fires, pests, and pathogens have the potential to greatly affect how ecosystems respond to climate change. Adaptation options for ecosystems are limited, and their effectiveness is uncertain for this reason, and others such as the projected rapid rate of change relative to the rate at which species can reestablish themselves, the isolation and fragmentation of many ecosystems, the existence of multiple stresses (e.g., land-use change, pollution), and limited adaptation options, ecosystems (especially forested systems) are vulnerable to climate change.

Impact on Economy: California produces more than one-eighth of total U.S. economic output, which makes it equivalent to the fifth or sixth largest economy in the world.

Increased climate variability and long-term climate change potentially will affect the state's sectors in important and different ways. Some activities and enterprises will be impacted directly through changes in natural resource and ecosystem services. Water shortages and increased insect perdition of crops due to relatively rapid changes in insect populations, for example, will have direct impacts on the State's diverse agricultural sector. While field crops may be switched perennial crops including vineyards and orchards are long-term investments. The reported damages from the El Niño storms in 1997-98 for agricultural losses was approaching \$100 million. From dairy farmers losing cows to exhaustion as they try to escape the mud and are attacked by diseases, to strawberry growers losing crops to the rain, farmers have experienced significant losses due to strong climate variability (Wilkinson and Rounds, 1998).

Precipitation falling as rain instead of snow will pose major problems for water managers, as the existing capture will become inadequate, and distribution system designed for the current supply and demand areas will develop bottlenecks. Higher summer temperatures will cause more rapid deterioration of asphalt and concrete, impacting the highway and rail systems. The globally averaged sea level is projected by climate models to rise up to three feet over the next century, with consequent implications for coastal erosion, inundation of wetlands, salt water intrusion of coastal and delta aquifers, and impacts on developed areas would clearly be extremely costly to mitigate, and devastating to some ecosystems and urban communities.

The varied impacts of relatively rapid climate change, and increased variability in rainfall and temperatures, will have significant economic impacts upon California's many sectors. Rising costs for infrastructure maintenance, resources, and insurance will reduce California's economic competitiveness. Rapid changes and greater variability are generally more difficult and expensive to adapt to than slower changes and lower variability. Electric and water supply utilities, wastewater treatment systems, and transportation systems are all subject to very significant expenditures in response to challenges imposed by climate variability. Both storms and droughts cause hundreds of millions of dollars in preventive costs and in damages. Pacific Gas and Electric, for example, allocated \$250 million in 1997 for tree trimming to reduce the incidence of power outages in its service area (Wilkinson and Rounds, 1998). Climate change has the potential to affect many aspects of California—the survival of its unique ecosystems, its ability to produce electricity, its supply of water and agricultural products, and the resources that support its economy.

G. Abrupt Climate Change

When most people think about climate change, they imagine gradual increases in temperature and only marginal changes in other climatic conditions, continuing indefinitely or even leveling off at some time in the future. It is assumed that human societies can adapt to gradual climate change. However, recent climate change research has uncovered a disturbing feature of the Earth's climate system: it is capable of sudden, violent shifts. This is a critically important realization. Climate change will not necessarily be gradual, as assumed in most climate change projections, but may instead involve sudden jumps between very different states. A mounting body of evidence suggests that continued GHG emissions may push the oceans past a critical

threshold and into a drastically different future. Abrupt climate change is the subject of reports commissioned by the National Academy of Science (NRC 2002) and the U.S. Department of Defense (Schwartz and Randall, 2003).

Change in any measure of climate or its variability can be abrupt, including a change in the intensity, duration, or frequency of extreme events. For example, single floods, hurricanes, or volcanic eruptions are important for humans and ecosystems, but their effects generally would not be considered abrupt climate changes. However, a rapid, persistent change in the number or strength of floods or hurricanes might be an abrupt climate change. Although more regionally limited, the apparent change in El Niño behavior (Graham, 1994; Trenberth and Hoar, 1996) could also be considered an abrupt change. El Niño is characterized by a large-scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño is notorious worldwide for causing catastrophic disruptions in weather patterns. Floods in California are countered by droughts in Australia.

Abrupt changes in climate are most likely to be significant, from a human perspective, if they persist over years or longer, are larger than typical climate variability, and affect sub-continental or larger regions. The simplest concept for a mechanism causing abrupt climatic change is that of a threshold. A gradual change in external forcing or in an internal climatic parameter continues until a specific threshold value is reached at which point a qualitative change in climate is triggered. Various such critical thresholds are known to exist in the climate system (NRC, 2002). Continental ice sheets may have a stability threshold where they start to surge; the thermohaline ocean circulation has thresholds where deep water formation shuts down or shifts location; and the atmosphere itself may have thresholds where large-scale circulation regimes switch. Bacteria produce methane as they decompose organic matter in the ocean sediments, and in cold, high-pressure environments, methane hydrates will form. This is an ice-like solid that consists of methane surrounded by water molecules in a lattice structure. However, if the temperature warms, or the pressure is reduced (for instance if local sea level decreases), the hydrate will break up and release the methane as gas into the atmosphere.

Researchers first became intrigued by abrupt climate change when they discovered striking evidence of large, abrupt, and widespread changes preserved in paleoclimatic archives. Paleoclimatology is the study of past changes in the climate system. Interpretation of such proxy records of climate, for example, using tree rings to judge occurrence of droughts or gas bubbles in ice cores to study the atmosphere at the time the bubbles were trapped, is a well-established science that has seen much growth in recent years. Recent scientific evidence (NRC, 2002) shows that major and widespread climate changes have occurred with startling speed. For example, roughly half the north Atlantic warming since the last ice age was achieved in only a decade, and it was accompanied by significant climatic changes across most of the globe. It is almost certain that there are nonlinearities in the climate system that could have caused abrupt climatic changes in the past or may do so in the future. Significant anthropogenic warming of the lower atmosphere and ocean surface will almost certainly occur in this century, raising concerns that nonlinear thresholds in the climate system could be exceeded and abrupt changes could be triggered at some point. Processes that have

been mentioned in this context include a collapse of the West Antarctic Ice Sheet, a strongly enhanced greenhouse effect due to melting of permafrost or triggering of methane hydrate deposits at the seafloor, a large-scale wilting of forests when drought tolerance thresholds are exceeded, nonlinear changes in monsoon regimes, and abrupt changes in ocean circulation. The probability of major climatic thresholds being crossed in the coming centuries is difficult to establish and largely unknown. Currently, this possibility lies within the uncertainty range for future climate projections, so the risk cannot be ruled out.

One proposed response to climate change assumes that modern civilization will adapt to whatever weather conditions we face and that the pace of climate change will not overwhelm the adaptive capacity of society, or that our efforts such as those embodied in the Kyoto Protocol will be sufficient to mitigate the impacts. Optimists assert that the benefits from technological innovation will be able to outpace the negative effects of climate change. However, the current complex human society has not faced any climate change comparable to that which has occurred the last 50 years and certainly that which will occur in the next 100 years at any time over the last 1000 years. Thus, in addition to the gradual (albeit accelerated) climate changes projected by current climate models, Californians need to be aware of the possibility of much more sudden climate shifts. These shifts have a scientifically well-founded place among the possible futures facing the State and should be among the possibilities accommodated in planning and adaptation measures.

Summary

Historically, atmospheric gases such as water vapor, CO₂, CH₄, and N₂O have trapped terrestrial radiation in the Earth's atmosphere, which has maintained a temperature and climate hospitable to life over much of the Earth — a condition known as the *greenhouse effect*. It is true that levels of natural greenhouse gases have fluctuated in the past. However, there are several reasons for attributing the rise in greenhouse gases to man made, rather than natural, emissions. The first indicator comes from comparing the current increase with changes that have occurred in the past. At the end of the last ice age, the concentration of CO₂ increased by around 100 ppm (parts per million) over about 8,000 years, or approximately 1.25 ppm per century. Since the start of the industrial revolution, the rate of increase has accelerated markedly. Since 1860, the concentration of CO₂ has increased by around 80 ppm, just over 50 ppm per century. The rate of CO₂ accumulation has continued to increase, and currently stands at around 150 ppm per century – over 200 times faster than the background rate for the past 15,000 years.

There is little doubt that climate change is happening today, that human-caused increases in the atmospheric abundance of greenhouse gases are a large cause of that change, and the 21st century climate change will be greater than that we have experienced in the 20th. Much of that projected climate change is as yet unrealized warming from the greenhouse gases in the atmosphere today. Nevertheless, actions

Technical Support Document
Climate Change Overview

taken to reduce greenhouse gases today can reduce the magnitude and rate of climate change this century.

There is no scientific uncertainty about the fact that human activities have increased the atmospheric abundance of greenhouse gases. The uncertainties start when we try to predict exactly what the climate changes will be in various local areas of the Earth, and what the effects of clouds will be in determining the rate at which the mean temperature will increase. There are also uncertainties associated with the magnitude and timing of other consequences of a warmer planet: sea level rise, spread of certain diseases out of their usual geographic range, the effect on agricultural production, water supply, sustainability of ecosystems, increased strength and frequency of storms, extreme heat events, air pollution episodes, and the consequence of these effects on the economy. Already, some of these effects have been seen in California. Over the last hundred years, average temperatures have increased 0.7 °F, sea levels have risen by three to eight inches, and spring run-off has decreased 12 percent.

California's transportation sector is the single largest contributor of GHGs in the State, producing close to 60% of all such emissions. If current trends in transportation energy consumption continue, the State's inventory of greenhouse gases could mirror the growth in population. Transportation and land-use trends in California will likely continue to increase greenhouse gas production. This proposal will reduce GHG emissions from motor vehicles. The international community recognizes such greenhouse gas emission reduction (mitigation) actions would lessen the pressures on natural and human systems from climate change. Slower rates of increase in global mean temperature and sea level would allow more time for adaptation. Consequently, mitigation actions are expected to delay and reduce damages caused by climate change and thereby generate environmental and socio-economic benefits.

References

Augusti, G., Borri, C., and Niemann, H.J. Is aeolian risk as significant as other environmental risk? *Reliability Engineering and System Safety* 74: 227-237, 2001

Aw, J., Kleeman, M.J. Evaluating the first-order effect of intraannual temperature variability on urban air pollution. *J. Geophys. Res.*, 108: D12, 4365, doi:10.1029/2002JD002688, 2003

Jeremy Aw and Michael J. Kleeman

Ballantyne, V.F., Howes, P., and Stephanson, L. Nitrous oxide emissions from light-duty vehicles. Society of Automotive Engineers (SAE) Paper No. 940304, 1994.

Barton, P., and Simpson, J. The effects of aged catalysts and cold ambient temperatures on nitrous oxide emissions. Mobile sources emissions division (MSED). Environment Canada, MSED Report #94-21, 1994.

Behrentz, E., Ling, R., Rieger, P., and Winer, A.M. Measurements of nitrous oxide emissions from light-duty motor vehicles: a pilot study. Submitted to *Journal of Atmospheric Environment*, April 2004.

Bernard, S.M., Samet, J.M., et al. "The potential impacts of climate variability and change on air pollution-related health effects in the United States." *Environ Health Perspect* 109 Suppl 2: 199-209, 2001.

Berz, G.A. Catastrophes and climate change: Risks and (re-)actions from the viewpoint of an international reinsurer. *Ecologiae Geologicae Helvetiae* 90: 375- 179, 1997.

Brooks, N. and Adger, W.N. Country level risk measures of climate-related natural disasters and implications for adaptation to climate change, Tyndall Centre Working Paper 26, 2003. Available at:
http://www.tyndall.ac.uk/publications/working_papers/wp26.pdf

California Department of Water Resources, Division of Flood Management, California Cooperative Snow Surveys, 1929-present. Posted at: cdec.water.ca.gov/snow.

Cayan, D., M. Tyree, et al.. Climate linkages to female *Culex Cx. tarsalis* abundance in California, California Applications Program (UCSD). 2003.

CEC (California Energy Commission). Inventory of California Greenhouse Gas Emissions and Sinks: 1990-1999 STAFF REPORT Publication Numbers: 600-02-001F & 600-02-001F-ES, November 2002. Available at:
<http://www.energy.ca.gov/reports/600-02-001F>.

Chung, S.H., and Seinfeld, J.H. "Global Distribution and Climate Forcing of Carbonaceous Aerosols," *J. Geophys. Res.*, 107, (D19), 4407, doi: 10.1029/2001JD001397, 2002.

Technical Support Document
Climate Change Overview

Daniel, J.S. and S. Solomon. On the climate forcing of carbon monoxide. *J. Geophys. Res.*, 103, 13249-13260, 1998.

Dasch, J.M. Nitrous oxide emissions from vehicles. *J. Air and Waste Management Association*, 42 (1):63-67, 1992.

Emmons, L.K., M.A. Carroll, D.A. Hauglustaine, G.P. Brasseur, C. Atherton, J. Penner, S. Sillman, H. Levy, F. Rohrer, W.M.F. Wauben, P.F.J. Van Velthoven, Y. Wang, D. Jacob, P. Bakwin, R. Dickerson, B. Doddridge, C. Gerbig, R. Honrath, G. Hübner, D. Jaffe, Y. Kondo, J.W. Munger, A. Torres, and A. Volz-Thomas: Climatologies of NO_x and NO_y: A comparison of data and models. *Atmos. Env.*, 31, 1851-1904, 1997.

EPIC (Environmental Protection Indicators for California). Office of Environmental Health Hazard Assessment. Available at:
<http://oehha.ca.gov/multimedia/epic/index.html>.

Field, C.B., Daily G.C., Davis, F.W., Gaines, S., Matson, P.A., Melack, J., and Miller, N.L. *Confronting Climate Change in California: Ecological Impacts on The Golden State*, Union of Concerned Scientists, Cambridge, MA and Ecological Society of America, Washington, DC, 1999.

Fischer, P.H., Brunekreef, B., and Lebet, E. Air pollution related deaths during the 2003 heat wave in the Netherlands. *Atmospheric Environment* 38: 1083-1085, 2004.

Flick, R.E., Murray, J.F., and Ewing, L.C. Trends in U.S. Tidal Datum Statistics and Tide Range: A Data Report Atlas. SIO Reference Series Report No. 99-20. Center for Coastal Studies, Scripps Institution of Oceanography. La Jolla, CA. 1999.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A.M.G and Peterson, T. Observed coherent changes in climatic extremes during the second half of the twentieth century, *Clim Res* 19: 193-212, 2002.

Fuglestad, J.S., Isaksen, I.S.A., and Wang, W.-C. Estimates of indirect global warming potentials for CH₄, CO, and NO_x. *Clim. Change*, 34: 405-437, 1996.

Gleick, P.H., and Chalecki, E.L. "The Impact of Climatic Changes for Water Resources of the Colorado and Sacramento-San Joaquin River Systems," *Journal of the American Water Resources Association*, Vo. 35, No. 6, pp. 1429-1441, 1999.

Glickman, T.S., Silverman, E.D. Acts of God and Acts of Man. Washington, DC: Center for Risk Management, Resources for the Future, 1992.

Graham, N.E. Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: Observations and model results. *Climate Dynamics* 10:135-162, 1994.

Technical Support Document
Climate Change Overview

Hansen, J., and Nazarenko, L. Soot climate forcing via snow and ice albedos, *Proc. Natl. Acad. Sci.*, 101, 423-428, 2003.

Harvell, C.D., Kim, K., Burkholder, J.M., Colwell, R.R., Epstein, P.R., Grimes, D.J., Hofmann, E.E., Lipp, E.K., Osterhaus, A.D., Overstreet, R.M., et al. Emerging marine diseases--climate links and anthropogenic factors. *Science* 285:1505-1510 (1999).

Haywood, J.M., and K.P. Shine, The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget, *Geophysical Research Letters*, 22 (5), 603-606, 1995.

Haywood, J.M., and V. Ramaswamy, Global sensitivity studies of the direct radiative forcing due to anthropogenic sulfate and black carbon aerosols, *Journal of Geophysical Research*, 103 (D6), 6043-6058, 1998.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J., and Xiaosu, S. *Climate change 2001: the scientific basis*, Cambridge University Press, Cambridge, 2001.

IPCC (Intergovernmental Panel on Climate Change), 2001. *Climate Change 2001: The Scientific Basis*. Working Group I of the IPCC, World Meteorological Organization-U.N. Environment Program, Geneva, Switzerland. Available at: www.ipcc.ch.

Jacobson, M.Z. Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, *Nature*, 409, 695-697, 2001.

Johnson, C.E. and R.G. Derwent: Relative radiative forcing consequences of global emissions of hydrocarbons, carbon monoxide, and NO_x from human activities estimated with a zonally-averaged two-dimensional model. *Clim. Change*, 34: 439-462, 1996.

Kinney, P., and Ozkaynak, H. Associations of daily mortality and air pollution in Los Angeles County. *Environmental Research* 54:99-120, 1991.

Koike, N., and Odaka, M. Methane and Nitrous Oxide (N₂O) Emission Characteristics from Automobiles. *Soc. Automot. Eng.* 1996, No.960061.

Krishnan, R., and Ramanathan, V. Evidence of surface cooling from absorbing aerosols, *Geophys. Res. Lett.*, 29, doi:10.1029/2002GL014687, 2002.

Lettenmaier, D.P. and Sheer, D.P. Climatic Sensitivity of California Water Resources, *Journal of Water Resources Planning and Management*, Vol. 117, No. 1, Jan/Feb, pp. 108-125, 1991.

Lipp, E.K., Rose, J.B., Vincent, R., Kurz, R., and Rodriguez-Palacios, C. Assessment of the Microbiological Water Quality in Charlotte Harbor, FL. Technical Report to the

Technical Support Document
Climate Change Overview

Southwest Florida Water Management District, Surface Water Improvement and Management Plan. Tampa, FL:Southwest Florida Water Management District, 1999.

Menon, S., Hansen, J., Nazarenko, L., and Luo, Y.F. Climate effects of black carbon aerosols in China and India, *Science*, 297, 2250-2253, 2002.

Metz, N. Contribution of Passenger Cars and Trucks to CO₂, CH₄, N₂O, CFC, and HFC Emissions. *Soc. Automot. Eng.* 2001, No. 2001-0103758.

Michaels, H., Fulper, C., Kolowich, B. Nitrous oxide emission factors for mobile sources. Presented at the AWMA emission inventory conference, New Orleans, LA, 1998.

Miller, N. L., Bashford, K. E., and Strem, E. Climate Change Sensitivity Study of California Hydrology. A report to the California Energy Commission, LBNL Technical Report No. 49110, Berkeley, CA, November, 2001.

Motes, M.L., DePaola, A., Cook, D.W., Veazey, J.E., Hunsucker, J.C., Garthright, W.E., Blodgett, R.J, and Chirtel, S.J. Influence of water temperature and salinity on *Vibrio vulnificus* in Northern Gulf and Atlantic Coast Oysters (*Crassostrea virginica*). *Appl Environ Microbiol* 64:1459-1465, 1998.

NACIP, National Aerosol-Climate Interactions Program, <http://www-NACIP.ucsd.edu/NACIPWhitePaperMay2102.pdf>, 2002.

Nam, E. K., Jensen, T. E., and Wallington, T. J. "Methane Emissions from Vehicles". *Environ. Sci. Technol.*; 2004; DOI: 10.1021/es034837g.

NAST. National Assessment Synthesis Team, 2001. *Climate Change Impacts on the United States*. Report for the United States Global Change Research Program. Cambridge University <http://prod.gcrio.org/nationalassessment>

National Research Council, Committee on Abrupt Climate Change, 2002. *Abrupt Climate Change: Inevitable Surprises*, National Academy Press, Washington, DC. <http://www.nap.edu/catalog/10136.html>

NRC (National Research Council of the National Academies), 2001. *Climate Change Science: An Analysis of Some Key Questions*. National Academy Press, Washington, DC, www.nap.edu.

NWS. National Weather Service report Available: <http://www.nws.noaa.gov/om/hazstats.htm>

Pavley, 2002. Assembly Bill No. 1493. Vehicular emissions: greenhouse gases. An act to amend Section 42823 of, and to add Section 43018.5 to, the California Health and Safety Code, relating to air quality.

Technical Support Document
Climate Change Overview

Patz, J.A., McGeehin, M.A., Bernard, S.M., Ebi, K.L., Epstein, P.R., Grambsch, A., Gubler, D.J., Reiter, P., Romieu, I., Rose, J.B., Samet, J.M., and Trtanj, J. The Potential Health Impacts of Climate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment, Environmental Health Perspectives, Volume 108, Number 4, April 2000.
<http://ehis.niehs.nih.gov/topic/global/patzfull.htm>.

Penner JE, Chuang CC, Grant K, Climate forcing by carbonaceous and sulfate aerosols, CLIMATE DYNAMICS 14 (12): 839-851, 1998.

Prather, M.J. Times scales in atmospheric chemistry: theory, GWPs for CH₄ and CO, and runaway growth. Geophys. Res. Lett., 23: 2597-2600, 1996.

Roos, M. Possible effects of global warming on California water or more worriers for the water engineer. Presented at the W. E. F. Water Law and Policy Briefing, July 14, 2000 at San Diego.

Roos, M. *The Effects of Global Climate Change on California Water Resources*, A report to the California Energy Commission's Public Interest Energy Research Program (PIER), Sacramento, September 2002.

SB 1771 (Senator Sher, Chapter 1018, Statues of 2000). Greenhouse gas emission reductions: climate change, 2000.

Schwartz, P. and Randall, D. An Abrupt Climate Change Scenario and Its Implications for United States National Security. A report commissioned by the U.S. Defense Department, October 2003. Available at <http://www.fas.org/irp/agency/dod/schwartz.pdf>

Schultz, M.G., Diehl, T., Brasseur, G.P., and Zittel W. Air pollution and climate-forcing impacts of a global hydrogen economy. Science, Vol 302, 624-627, 2003

Semenza, J.C., Rubin, C.H., and Falter, K.H. Heat-related deaths during the July 1995 heat wave in Chicago. N Engl J Med 335:84-90, 1996; CDC. Heat-related mortality-- Chicago, July 1995. MMWR 44:577-579 (1995).

Semenza, J.C., McCullough, J., Flanders, D.W., McGeehin, M.A., and Lumpkin, J.R. Excess hospital admissions during the 1995 heat wave in Chicago. Am J Prev Med 16:269- 277, 1999.

Sillman, S., Logan, J.A., and Wofsy, S.C. "The sensitivity of ozone to nitrogen oxides and hydrocarbons in regional ozone episodes", Journal of Geophysical Research, Vol. 95, pp. 1837-1851, 1990.

Sillman, S. and Samson, P.J. "Impact of temperature on oxidant photochemistry in urban, polluted rural, and remote environments", Journal of Geophysical Research, Vol. 100, pp. 11497-11508, 1995.

Technical Support Document
Climate Change Overview

Stedman, J.R. The predicted number of air pollution related deaths in the UK during the August 2003 heatwave. *Atmospheric Environment* 38: 1087-1090, 2004.

Taha, H. and Bornstein, R. "Urbanization of meteorological models: Implications on simulated heat islands and air quality", Invited paper, *International Congress of Biometeorology and International Conference on Urban Climatology*, 8-12 November, 1999, Sydney, Australia.

Taha, H., Chang, S.C., and Akbari, H.. "Meteorological and air quality impacts of heat island mitigation measures in three U.S. cities", LBNL Report 44222 (2000), Lawrence Berkeley National Laboratory, Berkeley, California 94720.

Trenberth, K.E., and Hoar, T.J. The 1990-1995 El Niño-Southern Oscillation event: Longest on record. *Geophysical Research Letters* 23:57-60, 1996.

U.S. EPA "Emissions of Greenhouse Gases in the United States 2001". Office of Integrated Analysis and Forecasting U.S. Department of Energy, Washington, DC 20585. DOE/EIA-0573(2001/ES), 2003. Available at: www.eia.doe.gov/oiaf/1605/ggrpt/summary/index.html.

Wild, O., Prather, M.J., and Akimoto, H. Indirect long-term global radiative cooling from NOx emissions. *Geophysical Research Letters*, 28 (9), 1719-1722, 2001.

Wilkinson, R., and Rounds, T. Climate Change and Variability in California; White Paper for the California Regional Assessment. National Center for Ecological Analysis and Synthesis, Santa Barbara, California Research Paper No. 4, 1998. (Available at <http://www.nceas.ucsb.edu/papers/climate.pdf>).

Wilkinson, R. Preparing for a Changing Climate: The potential consequences of climate variability and change – California, A report of the California Regional Assessment Group for the U.S. Global Change Research Program, Santa Barbara, CA, 2002.

Zittel, W., and Altmann, M. in Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, Germany, June 1996 (Scho'n & Wetzler, Frankfurt am Main, Germany, 1996), pp. 71–82.

Attachment A: Aerosol Particles and Climate Change

Atmospheric aerosols refer to solid or liquid phase material suspended into air. Aerosol particles or particulate matter (PM) is not a single pollutant, but rather a mixture of many subclasses of pollutants with each subclass potentially containing many different chemical species. Particles may be either directly emitted into the atmosphere (primary particles) or formed there by chemical reactions of gases (secondary particles) from natural and anthropogenic sources such as sulfur dioxide (SO₂), oxides of nitrogen (NO_x), and certain organic compounds. The relative importance of primary and secondary particles generally depends on the geographical location with precursor emissions, atmospheric chemistry, and meteorology all playing a role. Examples of PM include combustion-generated particles, such as those from automobiles or wood burning; photochemically-produced particles, such as those found in urban haze; salt particles formed from sea spray; and soil-like particles from resuspended dust. Airborne particles have been extensively studied because of the adverse health effects and poor visibility they cause; however, PM also has an effect on climate.

With respect to climate change the initial focus of concern, both scientifically and for managing climate, was on greenhouse gases – carbon dioxide (CO₂), methane (CH₄), etc. – but research over the last two decades has demonstrated that particles, too, have the potential to significantly alter climate processes. Particles impact climate directly by modifying Earth's radiation balance through their interaction with both long wave (infrared) and short wave (visible) light, and indirectly by altering the cloud properties and atmospheric heating rates that in turn modify the formation, precipitation efficiency, and radiative properties of clouds. This effect is termed "radiative forcing." Depending on chemistry, timing, and location, particles may either heat or cool the atmosphere. Positive radiative forcing warms the Earth's surface and lower atmosphere. Conversely, negative radiative forcing has a cooling effect. Natural factors, such as changes in solar output, explosive volcanic activity, atmospheric heating and hydrological cycle can also have radiative forcing effects. The planetary radiation balance is the net sum of all positive and negative forcing occurring together. Thus an effect such as climate warming by positive infrared forcing caused by increasing greenhouse gas concentrations may be offset by negative forcing due to visible light scattering by "white" aerosols (e.g., sulfates) or enhanced by warming due to infrared and visible light absorption by "black carbon" or soot.

The chemical composition and optical properties of aerosols vary with their sources; for example, aerosols emitted into the air as urban industrial pollution influence the climate very differently from windblown desert dust or sea salt or biogenic aerosols. To further complicate this picture, aerosols tend to remain in the air for only a few days to a week or so, resulting in extreme spatial and temporal variability over the surface of the Earth. As a consequence, measuring or describing "typical" properties of aerosols, as well as quantifying their instantaneous radiative impact on global and regional scales, is a daunting task.

Technical Support Document Climate Change Overview

Determining the impact of anthropogenic PM emissions on climate requires properly accounting for all radiative forcing, natural and manmade, then determining the shift in net radiation that would occur if the anthropogenic component were removed, and finally calculating the change in climate that would result from that shift in radiation. While this is simple in concept, it is very difficult to implement because of lack of a proper inventory of all the aerosols in the Earth's atmosphere, knowledge of how much aerosol in the Earth's atmosphere is due to anthropogenic activity, knowledge of ambient aerosol distribution patterns with sufficient temporal and spatial resolution and how to partition secondary aerosol effects, such as cloud formation, between natural and anthropogenic aerosols, and having climate models with sufficient precision to reliably perform the climate effect calculation.

Figure 1 shows estimated worldwide climate forcing from all climate pollutant sources since 1750, measured in watts per square meter. The rectangular bars represent estimates of the contributions of different variables - some of which are positive and thus represent warming, other are negative and represent cooling. The vertical line about the rectangular bars indicates a range of estimates, guided by the spread in the published values of the forcings and physical understanding. Some of the forcings possess a much greater degree of certainty than others. A vertical line without a rectangular bar denotes a forcing for which no best estimate can be given owing to large uncertainties. The overall level of scientific understanding for each forcing varies considerably. For this and other reasons, a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system.

Climate forcing by CO₂ is the largest, but it does not dwarf the others. Forcing by non-CO₂ greenhouse gases approximately equals that of CO₂. Moreover, in comparing forcing due to different activities, it should be noted that fossil fuel combustion is a major source of atmospheric aerosols, especially sulfates, black carbon, and organic aerosols.

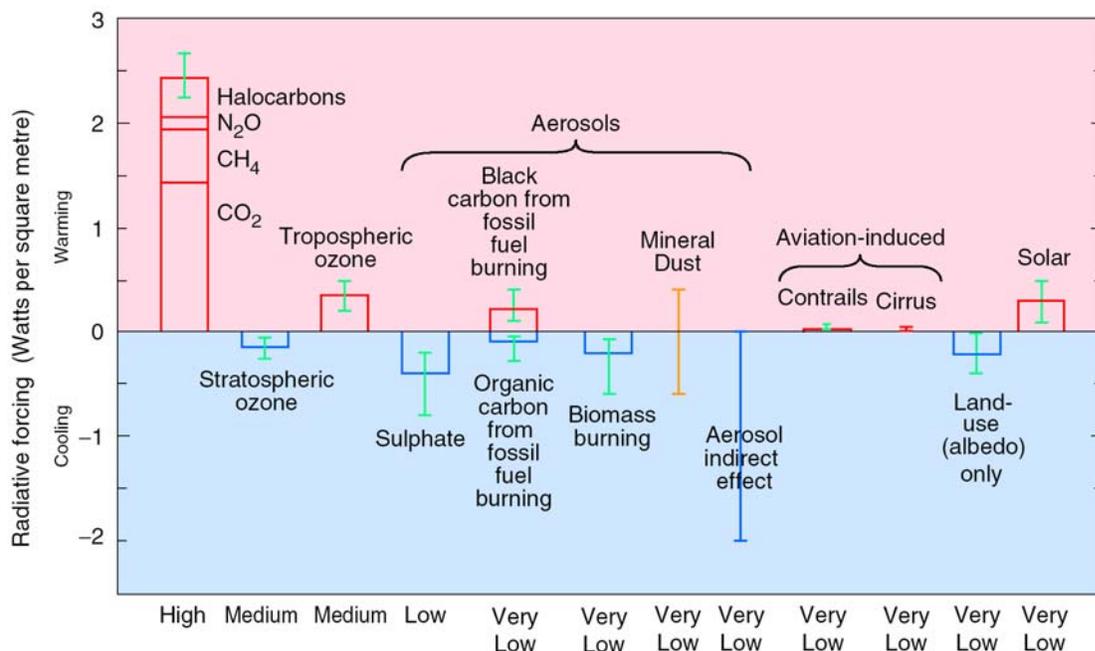


Figure 1. The global annual-mean radiative forcing of the climate system for the year 2000, relative to 1750 (source, IPCC 2001).

Climate forcing by anthropogenic aerosols may be the largest source of uncertainty about future climate change. Climate scientists do not even know the sign of the current impact of aerosol forcing, because such information would require knowledge of the trends of different aerosol compositions. For example, direct aerosol forcing depends on the aerosol's light scattering properties and on the amount of absorbing constituents. Aerosols also alter the formation and precipitation efficiency of liquid water, ice and mixed-phase clouds, thereby causing an indirect radiative forcing associated with these changes in cloud properties. The problem of estimating the indirect climate effect of atmospheric aerosols is a very complex one as many parameters need to be known to quantify it.

In addition to aerosol mass concentration, aerosol properties, such as number distribution and size-dependent composition and shape, exert a strong influence on important aerosol optical properties influencing the scattering and absorption of radiation. Specifically, the light scattering and absorption coefficients and the angular dependence of light scattering depend strongly on the size, shape, and real and imaginary components of index of refraction of the particles comprising the aerosol. Hygroscopic growth of aerosol particles (which itself strongly influences their optical properties) and the ability of particles to nucleate cloud droplets during cloud formation similarly depend on particle composition and size. Consequently, a description of aerosol influences on atmospheric radiation (direct effects), on cloud properties influencing radiation (indirect effects) or precipitation development (with concomitant removal of the aerosol material from the atmosphere) must explicitly or implicitly take

into account the size-dependent composition of the particles comprising the aerosol in addition to mass concentration.

In principle aerosol mass concentration and the pertinent other aerosol properties might be determined by measurement. However such an approach to meeting the needs for representing aerosol influences on climate is a very complicated task for a variety of reasons. Sources of aerosols are very nonuniformly distributed, both in amount and in kind. Mean residence times of aerosols in the troposphere are short (about 1 week) compared to the time required to uniformly distribute material in a given hemisphere (about 1 year), and removal is quite intermittent, governed mainly by precipitation processes. Hence the spatial distribution of aerosol mass concentrations and properties in the atmosphere is quite nonuniform. Likewise, there is high temporal variation in aerosol mass concentration and properties mainly resulting from variability of synoptic scale meteorology which controls transport and removal but also to a considerable extent from variability of emissions. Hence, the measurement of global aerosol properties by in-situ sampling at representative locations, as is done for the long-lived greenhouse gases, is not practical.

Even if it were possible by measurement to characterize the aerosol properties required to represent aerosol radiative influences in radiation transfer models, this information would still be insufficient to meet the requirements of modeling these influences at places and times other than those of the measurements. For example, climate modeling is required for past times, importantly over the last 200 years marking the growth of industrial emissions of CO₂ and other greenhouse gases. To accurately model anthropogenic influences on climate, it is necessary to determine the historical aerosol forcing as a component of the total climate forcing. Likewise it would not be possible on the basis of aerosol measurements alone to represent aerosol forcing in future time for various scenarios of emissions of aerosols and precursor gases.

Aerosol loading and properties necessary to represent aerosol influences in climate models can be calculated by means of chemical transport models incorporating aerosol evolution processes. Although present modeling capability is still fairly rudimentary, this modeling approach, which consists of numerically representing the processes governing the concentration and microphysical properties of these aerosols, appears to be useful tools for obtaining this information. In order to reduce model uncertainty (i.e., to evaluate consistency between the observed data and climate model simulated response) the model as a whole must be tested against measurements such as meteorological, chemical, and radiative field data. The major aerosol classes are briefly described on the following pages.

Sulfate: The vast majority of sulfate aerosols are formed by the oxidation of gaseous sulfur compounds into sulfuric acid, which then combines with a metallic or alkaline ion to form a stable salt (Na₂SO₄, MgSO₄, (NH₄)₂SO₄, etc.). Sulfate aerosols mostly form in heterogeneous (gas, droplet, and particle) atmospheric conversion, which tends to concentrate sulfate in fine aerosols (<2:μm diameter). When both humidity and sulfuric

acid concentrations are high and sufficient neutralizing ions are not present, a liquid phase sulfuric acid aerosol can form.

Due to the hygroscopic nature of both sulfuric acid and sulfate salts, sulfate aerosols are prone to grow by accumulation of water, so that at typical relative humidity their effective optical cross section is enhanced far beyond the actual sulfate mass. Since sulfate aerosols are very efficient at scattering light, their impact on the Earth's radiation balance is predominantly negative forcing (cooling) due to backscatter of incoming solar radiation; this effect may be enhanced if their hygroscopicity contributes to increased daytime clouds or fog, or may be somewhat offset if they increase the presence of nighttime clouds or fog.

Of all the chemical species present as atmospheric aerosol, sulfate is considered to be the largest contributor to anthropogenic direct climate forcing. Direct radiative forcing by sulfate aerosols has received considerable attention over the past decade; estimates of global mean forcing range between -0.29 and -0.95 W/m^2 . Disagreements over the atmospheric sulfate burden and the fraction of that burden that is caused by human activities accounts for some, but not all, of this uncertainty.

The importance of pollutant sulfate in climate change was only fully appreciated in the last decade; inclusion of sulfate cooling helped to reduce the gap between climate change predicted based on GHG calculations and observed secular temperature records (Charleston, et al., 1992). Future reductions in global pollutant sulfur emissions (necessary to manage impacts on public health and prevent "acid rain") may accelerate climate warming as the artificial cooling effect of sulfate is removed (IPCC, 2001).

The precursor sulfur compounds come from both natural and anthropogenic sources. Globally, most natural sulfate comes from biogenic production (primarily in the oceans), with volcanic emissions contributing modestly (e.g., hot springs and fumaroles) on a continuing basis, and occasionally very intensely (large eruptions). The primary role of volcanic sulfur aerosols instead of volcanic ash in causing short-term changes in the world's climate following some eruptions was hypothesized by scientists in the early 1980's. They based their hypothesis on the effects of several explosive eruptions in Indonesia and the world's largest historical effusive eruption in Iceland.

Scientists studied three historical explosive eruptions of different sizes in Indonesia--Tambora (1815), Krakatau (1883), and Agung (1963). They noted that decreases in surface temperatures after the eruptions were of similar magnitude (0.18 - 1.3 °C). The amount of material injected into the stratosphere, however, differed greatly. By comparing the estimated amount of ash vs. sulfur injected into the stratosphere by each eruption, it was suggested that the longer residence time of sulfate aerosols, not the ash particles which fall out within a few months of an eruption, was the paramount controlling factor (Rampino and Self, 1982).

Clearly, these examples suggested that the explosivity of an eruption and the amount of ash injected into the stratosphere are not the main factors in causing a change in

Earth's climate. Instead, scientists concluded that it must be the amount of sulfur in the erupting magma. The eruption of El Chichon, Mexico, in 1982 conclusively demonstrated this experience was correct. The explosive eruption injected at least 8 Mt of sulfur aerosols into the atmosphere, and it was followed by a measurable cooling of parts of the Earth's surface and a warming of the upper atmosphere. A similar-sized eruption at Mount St. Helens in 1980, however, injected only about 1 Mt of sulfur aerosols into the stratosphere. The eruption of Mount St. Helens injected much less sulfur into the atmosphere and it did not result in a noticeable cooling of the Earth's surface. The newly launched TOMS satellite (in 1978) made it possible to measure these differences in the eruption clouds. Such direct measurements of the eruption clouds combined with surface temperatures make it possible to study the correlation between volcanic sulfur aerosols (instead of ash) and temporary changes in the world's climate after some volcanic eruptions.

The most significant impacts from large explosive eruptions come from the conversion of sulfur dioxide (SO_2) to sulfuric acid (H_2SO_4), which condenses rapidly in the stratosphere to form fine sulfate aerosols. Natural sulfate levels in the atmosphere have been estimated from observations and calculation of emissions, and their climatic effect estimated as well (Charleson, 1987).

Anthropogenic sulfate aerosol is generated through the same chemical pathways, but the precursor gases generally come from sulfur bound in fuels used in combustion processes (predominantly coal and petroleum). The potential effects of anthropogenic sulfate are strongest near industrialized regions where large amounts of fossil fuels are burned, thus the cooling effect is strongest over eastern North America, Europe, eastern Asia, and the oceanic and continental areas downwind of these regions (Charleson, 1992; IPCC, 2001).

Nitrate: Analogously to sulfate, nitrate aerosols form from the oxidation of gaseous nitrogen oxides followed by nitrate salt formation. . Aerosol nitrate is closely tied to the relative abundances of ammonium and sulfate. If ammonia is available in excess of the amount required to neutralize sulfuric acid, nitrate can form small, radiatively efficient aerosols. Nitrate aerosol in the form of ammonium nitrate is a locally important aerosol species in terms of aerosol mass in the optically active sub-micron size range and hence the associated radiative forcing. The problems in measuring the concentrations and size distributions of nitrate is due to its semi-volatility. Nitrate salts are unstable and can return to the vapor phase when air temperature rises and humidity drops or the surrounding air's concentration of precursor gases drops.

Atmospheric aerosols contain significant amounts of nitrate in polluted areas. Both nitrate and sulfate are generally neutralized to a substantial degree by ammonia, which exists in the aerosol phase as the ammonium cation. Most importantly, inorganic aerosols are hygroscopic and contain water under nearly all atmospheric conditions. The amount of aerosol nitrate, ammonium, and water influence, with sulfate, affects the optical properties of the aerosol.

Forcing due to nitrate aerosol is particularly important at the regional scale. Observations and model results both show that in regions of elevated NO_x and NH_3 emissions, such as Europe, India, and parts of North America, NH_4NO_3 aerosol concentrations may be quite high and actually exceed those of sulfate. Adams et al. (2001) estimate the present-day anthropogenic direct aerosol forcing to be -0.95 W/m^2 for sulfate and -0.19 W/m^2 for nitrate. Moreover, based on the IPCC (2001) emissions scenario with especially strong increases in NO_x emissions, it is predicted that the nitrate forcing will increase to -1.28 W/m^2 by the end of this century, even while sulfate forcing declines to -0.85 W/m^2 . This result shows that future estimates of aerosol forcing based solely on predicted sulfate concentrations may be misleading and that the potential for significant amounts of ammonium nitrate aerosol needs to be considered in estimates of future climate change.

A key finding is that the calculated direct forcing is extremely sensitive to how the effect of water uptake on aerosol scattering behavior is taken into account. In particular, Adams et al. (2001) find that the large amount of water taken up by the aerosol above 95% RH increases the total forcing by about 60%. This is important because a method commonly used in previous global climate models for parameterizing the effect of water uptake on optical properties has been to assume a low RH scattering coefficient and to correct for that at higher humidities with an empirical factor. In principle, there is nothing wrong with this approach, but in practice, lack of data at high RH has caused investigators to conservatively limit it to values that are unrealistically low.

Mineral Dust: “Mineral dust” is generally derived from soil surfaces, either as a result of natural or anthropogenic activities. Near-source mineral dust is composed of a variety of crystalline materials, including sand, fine rock fragments (“silt”), and clay particles. Sand and silt materials such as silica have high specific densities and generally fracture into compact shapes, thus coarse mineral particles ($>5\mu\text{m}$ diameter) settle rapidly and have very short atmospheric lifetimes (minutes to hours). Conversely, clays, having sheet crystal structures and much smaller particle dimensions, have very large surface to mass ratios and very small settling velocities. Global “background” mineral aerosol is thus finer (mass median diameter near $2\mu\text{m}$) and often chemically distinct from most local-source mineral PM. The lifetime of fine particles in the atmosphere is days or weeks, and they can travel by air thousands of kilometers.

While the precise fraction of mineral dust of anthropogenic origin being extremely difficult to determine, recent studies have suggested that 20% and up to 30 to 50% (Tegen and Fung, 1995) of the total mineral dust in the atmosphere originates from anthropogenic activities. In addition to the short-wave radiative forcing, mineral dust particles may exert a significant long-wave radiative forcing. The global mean short-wave radiative forcing will be negative due to the predominantly scattering nature in the solar spectrum (although partial absorption may lead to a local positive radiative forcing over high surface albedos and clouds) and the global mean long-wave forcing will be positive. Albedo is the fraction of solar energy (shortwave radiation) reflected from the Earth back into space.

Tegen and Fung (1995) performed a three-dimensional global climate modeling study of dust aerosol and estimated that approximately 30 to 50% of the total dust burden is due to changes in land use associated with anthropogenic activity. The radiative forcing using this data was estimated by Tegen et al. (1996) to be -0.25 W/m^2 in the short-wave and $+0.34 \text{ W/m}^2$ in the long-wave, resulting in a net radiative forcing of $+0.09 \text{ W/m}^2$. Updated calculations of the net radiative forcing based on Miller and Tegen (1998) estimate the radiative forcing to be -0.22 W/m^2 in the short-wave and $+0.16 \text{ W/m}^2$ in the long-wave, resulting in a net radiative forcing of -0.06 W/m^2 . Hansen et al. (1998) perform similar calculations and calculate a net radiative forcing of -0.12 W/m^2 by assuming a different vertical distribution, different optical parameters and using a different global model. Jacobson (2001) used a multi-component global aerosol model to estimate the direct radiative forcing to be -0.062 W/m^2 in the short-wave and $+0.05 \text{ W/m}^2$ in the long-wave, resulting in a net radiative forcing of -0.012 W/m^2 . The effects of non-sphericity of the mineral dust are not accounted for in these calculations. Mishchenko et al. (1997) suggest that differences in the optical parameters between model spheroids and actual dust particles do not exceed 10 to 15%, although changes of this magnitude may have a large effect on the radiative forcing.

One problem with modeling the impacts of mineral dust is uncertainty in representative refractive indices and how they vary geographically due to different mineral composition of different source regions. Additional uncertainties lie in modeling the size distributions which, together with the refractive indices, determine the optical parameters. Relating instantaneous observational measurements that do not account for the effects of clouds, diurnal averaging of the radiation, the seasonal signal associated with emissions and the fraction of mineral dust that is anthropogenic to the global mean radiative forcing is very difficult. Because the resultant global mean net radiative forcing is a residual obtained by summing the short-wave and the long-wave radiative forcings which are of roughly comparable magnitudes, the uncertainty in the radiative forcing is large and even the sign is in doubt due to the competing nature of the short-wave and long-wave effects. The studies above suggest, on balance, that the short-wave radiative forcing is likely to be of a larger magnitude than the long-wave radiative forcing, which indicates that the net radiative forcing is likely to be negative, although a net positive radiative forcing cannot be ruled out. Therefore, a tentative range of -0.6 to $+0.4 \text{ W/m}^2$ is adopted; a best estimate cannot be assigned as yet.

Carbonaceous Particles: Carbonaceous particulate matter consists of a complex mixture of chemical compounds. Such particulate matter is usually divided into two fractions, black (or elemental) carbon (BC) and organic carbon (OC). Black carbon is a strong absorber of visible and near-infrared light; therefore, BC concentrations are traditionally determined by light-absorption measurements of particles collected on filters (Lindberg et al., 1999). In contrast, particulate OC represents an aggregate of hundreds of individual compounds with a wide range of chemical and thermodynamic properties, making concentration measurements difficult using any single analytical technique. Instead, aerosol OC content is usually determined from the difference between total carbon and black carbon contents (Turpin et al., 2000).

Organic carbon can be emitted directly into the atmosphere as products of fossil fuel combustion or biomass burning. This is called primary organic aerosol (POA). By contrast, secondary organic aerosol (SOA) is formed in the atmosphere as the oxidation products of certain volatile organic compounds (VOCs) condense on pre-existing aerosols. Aerosol organic carbon, whether primary or secondary in nature, is not a strong absorber of solar radiation. Organic carbon aerosols may absorb visible light weakly, with this absorption usually increasing toward ultraviolet wavelengths.

Black carbon, by contrast, is a strong absorber of solar radiation; particles containing BC in the atmosphere both scatter and absorb solar radiation. Because BC-containing particles prevent radiation from reaching the Earth's surface, they act to cool the surface, but because they absorb radiation, they warm the atmosphere itself. Their heat-trapping ability depends on how they clump together and join with other substances to make larger particles. While the atmospheric warming effect of BC and its surface cooling are well established, the resulting climate forcing from BC has not been established clearly. This uncertainty arises for two basic reasons. First, BC emission inventories are uncertain, and therefore the actual amount of BC in the air is in question. Second, the manner in which BC is mixed with other aerosol material, such as sulfate and organics, is critical to its radiative impact. If the BC is mixed with other aerosol material, which is what most atmospheric measurements show, then its radiative warming effect is considerably enhanced over that of BC existing as separate particles. Previous work has shown that the overall radiative effect of aerosol BC depends significantly on the manner in which that BC is mixed with non-absorbing aerosols such as sulfate (Jacobson, 2000; Chung and Seinfeld, 2002).

Chung and Seinfeld, (2002) compared the predicted direct radiative of BC with those of previous studies. Many of the previous estimated BC radiative forcings are relatively small because they considered only fossil fuel BC and not biomass burning. In Figure 2, predicted BC radiative forcing is shown as a function of the global BC burden for the studies in which the global burdens can be determined. Even when differences in global burdens are taken into account, discrepancies among the different studies still exist. Another important factor affecting radiative forcing is the actual three-dimensional distribution of BC aerosols, which is different for fossil fuel and biomass burning BC. The geographical distribution is important because the radiative forcing is strongly dependent on the surface albedo, the presence of clouds, and the interaction of scattering and absorbing aerosols in the case of an internal mixture (Haywood et al., 1997; Haywood and Ramaswamy, 1998). Finally, uncertainties in the size distribution of the aerosols lead to variabilities in the predictions.

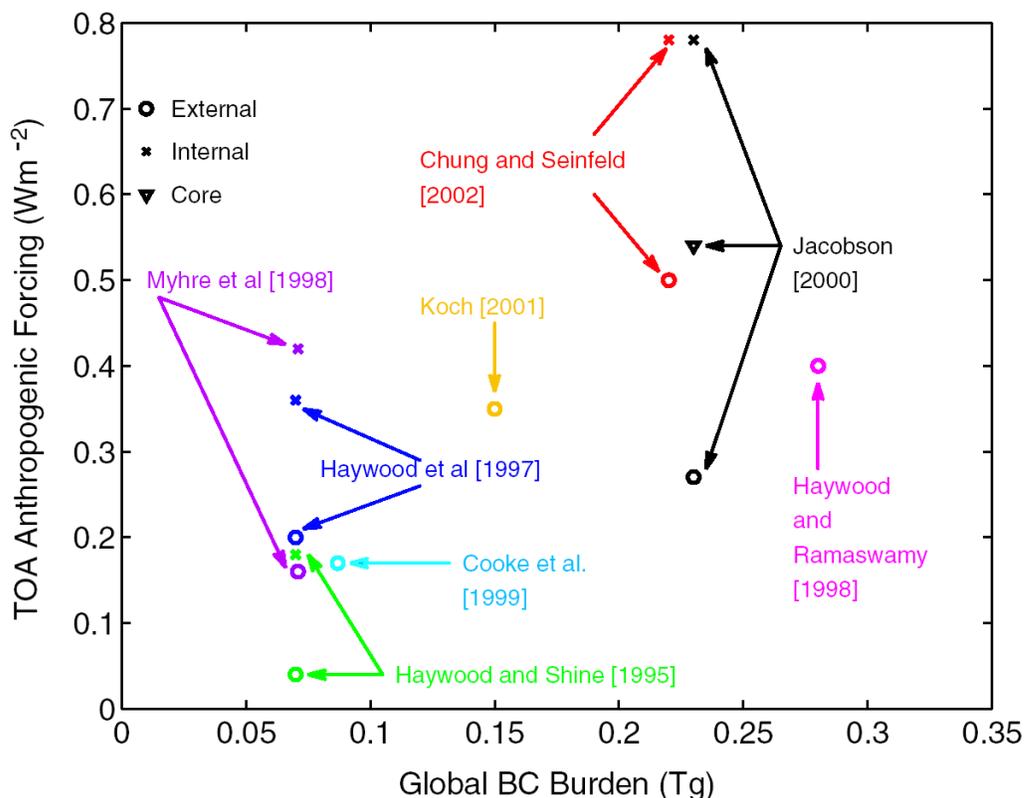


Figure 2. Comparison of BC radiative forcing predictions versus BC global burden by various authors (Chung and Seinfeld, 2000).

Black carbon inventories rely on different assumptions and on data related to emission activities, PM emission factors, and source profiles, all of which apportion PM mass to BC and other chemical constituents. These differences may be a major cause of discrepancies and uncertainties in model predictions. Bond et al. (1998) identifies PM mass emission factors and the BC fraction of emitted PM (i.e., "source profiles") as the most variable. Currie et al. (2002) show more than a factor of seven in the range of BC concentrations for different measurement methods commonly used throughout the world.

Global BC emission inventories are based on international fuel consumption estimates. Regional BC inventories have also been created. Bond et al. (2002) estimated that North American sources are about 6.6 Tg BC/yr (1 teragrams (Tg) = 1×10^9 kilograms). Battye et al. (2002) ranked the major contributors to U.S. BC emissions as: 1) non-road diesel exhaust (21%); 2) on-road diesel exhaust (15%); 3) prescribed forest fires (7.9%); 4) open burning (7.7%); and 5) residential wood combustion (4.8%). Natural wildfires were not considered as manmade sources in Battye's analysis, although 100 years of fire suppression have caused them to be large emitters in recent years. Gasoline engine cold-starts and high emitters, which have been shown to contain substantial BC fractions (Zielinska et al., 1998), were not considered in this analysis.

Technical Support Document Climate Change Overview

Agricultural biomass burning and wildfire activity throughout the world are major sources of BC and other atmospheric aerosols that adversely affect global climate, health, and visibility. The chemical characterization of particles from burning is essential for assessing its contribution in ambient air and, in turn, for predicting the health and environmental effects of prescribed and wildfire burning. Due to emission variation, sampling artifacts, and measurement method differences, fundamental challenges exist in determining the carbon composition of aerosols that accurately represent large-scale vegetative burning.

At present, there is no official BC emissions inventory at the national level. Current emissions models have the ability to estimate BC emissions based on the national emission inventory and default speciation profiles. However, U.S. EPA has recently formed a working group with a two-year schedule to compile improved speciation profiles. Eventually, these speciation profiles will be incorporated into emissions models, such as the Sparse Matrix Operator Kernel Emissions model (SMOKE) to improve BC emissions estimate.

In California, motor vehicles are a significant source of fine carbonaceous particle emissions. Professor Harely's team at UC Berkeley measured gas- and particle-phase pollutant concentrations in the Caldecott Tunnel in the San Francisco Bay Area during the summer of 1996. Fine particle BC and polycyclic aromatic hydrocarbons (PAH) concentrations were normalized to fuel consumption to compute emission factors. Light-duty vehicles emitted 30 ± 2 mg of fine BC particle per kg of fuel burned (about 4.6 mg/mi). Dr. Norbeck of University of California, Riverside, tested PM emissions rates from 10 gasoline-fueled vehicles (MY 1979-1994). On vehicle average, elemental carbon emissions was reported about 1.92 mg/mi.

In 1996, a California Institute of Technology (Caltech) team quantified gas-and particle organic compounds present in the tailpipe emissions from an in-use fleet of gasoline-powered automobiles and light-duty trucks using two-stage dilution source sampling systems. Average elemental carbon emissions was reported at about 1.22 mg/mi. Professor Michael Kleeman of University of California, Davis, recently conducted PM source sampling of light-duty vehicles at the ARB's Haagen-Smit Laboratory in El Monte. Newer vehicles were tested (MY 1999-2002). Preliminary results from source testing of low emission vehicles indicate that PM emissions rates (about 1-3 mg/mi) were significantly lower than previously released data that did not include vehicles newer than model year 1995. A very crude estimate of elemental carbon emissions would be about 10 percent of total PM emissions or about 0.2 mg/mi.

As mentioned above, uncertainties in measurement methods contribute to the large uncertainty in the BC inventory. Methods that measure light absorption in particulate matter assume that BC is the only light absorbing component present; however, some components of OC may also absorb light; in this case, inventories of BC and OC may overlap. The various measurements of light-absorbing carbon are not well related, and consensus on interpretation has not yet been reached for the current suite of available measurement techniques. "Black" carbon is defined optically, by measuring the change

in light transmittance or reflection caused by particles. However, the attenuation of light by particles collected on a filter is usually enhanced over that of suspended particles and cannot be used without adjustment.

Most source-characterization studies do not measure BC, but rather so-called “elemental” carbon (EC) using thermal optical methods rather than absorption technique. This type of measurement is widely used in air-quality and source-characterization applications. Large numbers of OC and EC measurements have been reported by using thermal/optical methods. Results of method comparisons among many laboratories provide ambiguous results owing to subtle differences in the methods applied and the samples included in the comparison. There is a need to evaluate a treatment of the relationship between each measurement method and the quantity of interest—that is, light absorption.

In summary, understanding the role of aerosols in climate change requires inclusion of realistic representations of aerosols and their radiative forcings in climate models. Compared to the long-lived, well mixed GHGs, however, the optical properties and temporal and spatial patterns of the many different types of aerosols are heterogeneous. Further uncertainty in aerosol radiative forcing arises because neither emissions, atmospheric abundance, optical properties, nor indirect effects are fully known. The IPCC (2001) and the NACIP (2002) have identified the total (direct and indirect) radiative forcing due to aerosols, and in particular light absorbing aerosols, as one of the most uncertain components of climate change models.

References

- Adams, P.J., Seinfeld, J.H., Koch, D., Mickley, L., and Jacob, D. General circulation model assessment of direct radiative forcing by the sulfate-nitrate-ammonium-water inorganic aerosol system, *J. Geophys. Res.*, **106**: 1097-1111, 2001.
- Bond, T.C., Charlson, R.J., and Heintzenberg, J. Quantifying the emission of light-absorbing particles: measurements tailored to climate studies, *Geophysical Research Letters*, **25** (3), 337-340, 1998.
- Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M. Woo, J-H., Klimont, Z.. A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion. In press at *Journal of Geophysical Research*, 2004.
- Battye, W., Boyer, K., and Pace, T.G. Methods for Improving Global Inventories of Black Carbon and Organic Carbon Particulates. Report No. 68-D-98-046. Prepared for U.S. Environmental Protection Agency. Research Triangle Park, NC, by EC/R Inc., Chapel Hill NC., 2002.
- Cass, G., Contribution of Vehicle Emissions to Ambient Carbonaceous Particulate Matter: A Review and Synthesis of Available Data in the South Coast Air Basin. PB 98 125172 February 1997.
- Charleson, R., Lovelock, J., Andreae, M., and Warren, S. "Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate," *Nature* **326**: 655-661, 1987.
- Charlson, R.J., Schwartz, S.E., Hales, J.M., Cess, R.D., Coakley Jr., J.A., Hansen, J.E., and Hoffmann, D.J. Climate forcing by anthropogenic aerosols. *Science*, **255**: 423-430, 1992.
- Chung, S.H. and Seinfeld, J.H. "Global Distribution and Climate Forcing of Carbonaceous Aerosols," *J. Geophys. Res.*, **107**: (D19), 4407, doi: 10.1029/2001JD001397, 2002.
- Cooke, W.F., Liousse, C., Cachier, H., and Feichter, J. Construction of a 1°x1° fossil fuel emission data set for carbonaceous aerosol and implementation and radiative impact in the ECHAM4 model, *J. Geophys. Res.*, **104**: 22,137– 22,162, 1999.
- Currie, L.A., Benner, B.A., Cachier, H., Cary, R., Chow, J.C., Druffel, E.R.M., Eglinton, T.I., Gustafsson, O., Hartman, P.C., J.I., Hedges, P.C., Kessler, J.D., Kirchstetter, T.W., Klinedinst, D.B., Klouda, G.A., SKohl, .D., Marlof, J.V., Masiello, C.A., Novakov, T., Pearson, A., Prentice, K.M., Puxbaum, H., Quinn, J.G., Reddy, C.M., Schmid, H., Slater, J.F., and Wise, S.A. A critical evaluation of interlaboratory data on total, elemental and isotopic carbon in the carbonaceous particle reference material, NISTSRM 1649a, *Environmental Science and Technology*, **107**: 279-298, 2002.
- Hansen, J., Sato, M., Lacis, A., Ruedy, R., Tegen, I., and Matthews, E. Climate forcings in the Industrial Era. *Proc. Natl. Acad. Sci.*, **95**: 12753-12758, 1998.

Hansen, J., Sato, M., Ruedy, R., Lacis, A., and Oinas, V. Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci.* **97**: 9875-9880, 2000.

Haywood, J.M., and Shine, K.P. The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget, *Geophys. Res. Lett.*, **22**: 603– 605, 1995.

Haywood, J.M., Roberts, D.L., A. Slingo, A., Edwards, J.M., and Shine, K.P. General circulation model calculations of the direct radiative forcing by anthropogenic sulfate and fossil-fuel soot aerosol, *J. Clim.*, **10**: 1562–1577, 1997.

Haywood, J.M. and Ramaswamy, V. Global activity studies of the direct forcing due to anthropogenic sulfate and black carbon aerosols, *J. Geophys. Res.*, **103**: 6043– 6058, 1998.

IPCC (Intergovernmental Panel on Climate Change), 2001. *Climate Change 2001: The Scientific Basis*. Working Group I of the IPCC, World Meteorological Organization-U.N. Environment Program, Geneva, Switzerland. Available at: www.ipcc.ch.

Jacobson, M.Z., A physically-based treatment of elemental carbon optics: Implication for global direct forcing of aerosols, *Geophys. Res. Lett.*, **27**: 217–220, 2000.

Jacobson, M.Z. Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols. *J. Geophys. Res.*, **106**: 1551-1568, 2001.

Koch, D., The transport and direct radiative forcing of carbonaceous and sulfate aerosols in the GISS GCM, *J. Geophys. Res.*, **106**: 20,311– 20,332, 2001.

Kirchstetter, T., Harley, R. Impact of Reformulated Fuels on Particle and Gas Phase Emissions from Motor Vehicles, ARB contract 95-330, March, 1999

Lindberg, J.D., Douglass, R.E. and Garvey, D.M. Atmospheric particulate absorption and black carbon measurement, *Appl. Opt.*, **38**: 2369– 2376, 1999.

Miller, R. and Tegen, I. Climate response to soil dust aerosols. *J. Clim.*, **11**: 3247-3267, 1998.

Mishchenko, M.I., Travis, L.D. Kahn, R.A., and West, R.A. Modeling phase functions for dustlike tropospheric aerosols using a shape mixture of randomly orientated polydisperse spheroids. *J. Geophys. Res.*, **102**: 16831-16847, 1997.

Myhre, G., Stordal, F., Restad, K., and I. Isaksen, S.A. Estimation of the direct radiative forcing due to sulfate and soot aerosols, *Tellus*, **50B**: 463–477, 1998.

Norbeck, et al, "Characterization of Particulate Emissions from Gasoline-Fueled Vehicles", ARB contract 94-319, September 1998.

Technical Support Document
Climate Change Overview

Rampino, M.R., and Self, S. Historic eruptions in Tambora (1815), Krakatau (1883), and Agung (1963), their stratospheric aerosols, and climatic impact: *Quaternary Research*, v. 18, p. 127-143, 1982.

Tegen, I., and Fung, I. Contribution to the atmospheric mineral aerosol load from land surface modification. *J. Geophys. Res.*, **100**: 18707-18726, 1995.

Tegen, I., and Lacis, A. Modelling of particle size distribution and its influence on the radiative properties of mineral dust aerosol. *J. Geophys. Res.* **101**:19237-10244, 1996.

Tegen, I, Lacis, A., and Fung, I. The influence on climate forcing of mineral aerosols from disturbed soils. *Nature* **380**: 419-422, 1996.

Turpin, B.J., Saxena, P., and Andrews, E. Measuring and simulating particulate organics in the atmosphere: Problems and prospects, *Atmos. Environ.*, **34**: 2983– 3031, 2000.

Zielinska, B.; McDonald, J.; Hayes, T.; Chow, J.C.; Fujita, E.M.; and Watson, J.G. Northern Front Range Air Quality Study. Volume B : Source measurements. Prepared for Colorado State University, Cooperative Institute for Research in the Atmosphere, Fort Collins, CO, by Desert Research Institute, Reno, NV., 1998