

## THE ANTHROPOCENE: THE CURRENT HUMAN-DOMINATED GEOLOGICAL ERA

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Figure 1 shows me more than 70 years ago in the lap of my grandmother. I have changed a lot, but so has much on our planet. Human population has increased threefold during my lifetime, reaching about six thousand million, with the largest rise, 1.8% per year, after the Second World War. As shown in the partial listing of Table 1, many human activities impact on earth's environment, often surpassing nature with ecolog-



Figure 1.

TABLE 1.

<b>Anthropocene</b>
• During the past 3 centuries human population has increased tenfold to 6000 million
• Cattle population increased to 1400 million (one cow/family)
• Urbanisation has increased tenfold in the past century; almost half of the people live in cities and megacities
• Industrial output increased 40 times during the past century; energy use 16 times
• Almost 50 % of the land surface has been transformed by human action
• Water use increased 9 fold during the past century to almost 1000 m <sup>3</sup> per capita; 65 % for irrigation, 25 % industry, ~10 % households
• Fish catch increased 40 times
• The release of SO <sub>2</sub> (160 Tg/year) by coal and oil burning is at least twice the sum of all natural emissions; over land the increase has been 7 fold, causing acid rain, health effects and poor visibility due to aerosols
• More nitrogen is now fixed and used as fertilizers in agricultural than is produced by natural processes on land.
• Releases of NO to the atmosphere from fossil fuel and biomass burning is larger than its natural inputs, causing high ozone levels over extensive regions of the globe
• Several climatically important "greenhouse gases" have substantially increased in the atmosphere, eg. CO <sub>2</sub> by 30%, CH <sub>4</sub> by more than 100%.
• The production of chlorofluorocarbon gases has caused major changes in the chemistry of the stratosphere, leading to ozone loss, which has been particularly large in the spring over the Antarctic continent, the so-called ozone hole.

ical, atmospheric chemical and climatic consequences. Under the pressures of growing human populations, their need for food, water, and improved living conditions, land use changes have been substantial. For instance, during the period 1990-1997 the global annual rate of deforestation has been 0.5%/year with a maximum of 0.9%/year in South-East Asia. Human activities have especially accelerated after the Second World War, several examples of which are shown in Figures 2a and 2b. Starting

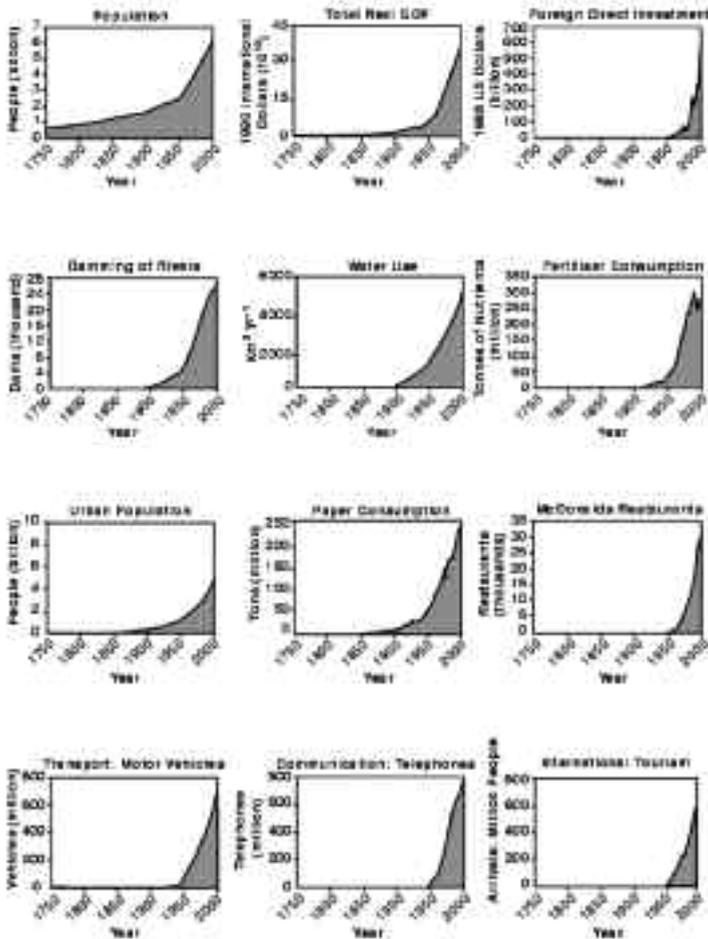


Figure 2a.

especially by the end of the 18th century, the growing disturbance of earth's natural systems by human activities created a new geological era, which I have dubbed the 'Anthropocene'.

In this paper, we will discuss the consequences of human activities on the earth's atmosphere and climate during the 'Anthropocene'. Figure 3 shows the probably most cited diagrams on the consequences of human activities on the atmosphere. The upper curve shows the rise in atmospheric carbon dioxide concentrations since the end of the 1950s, as meas-

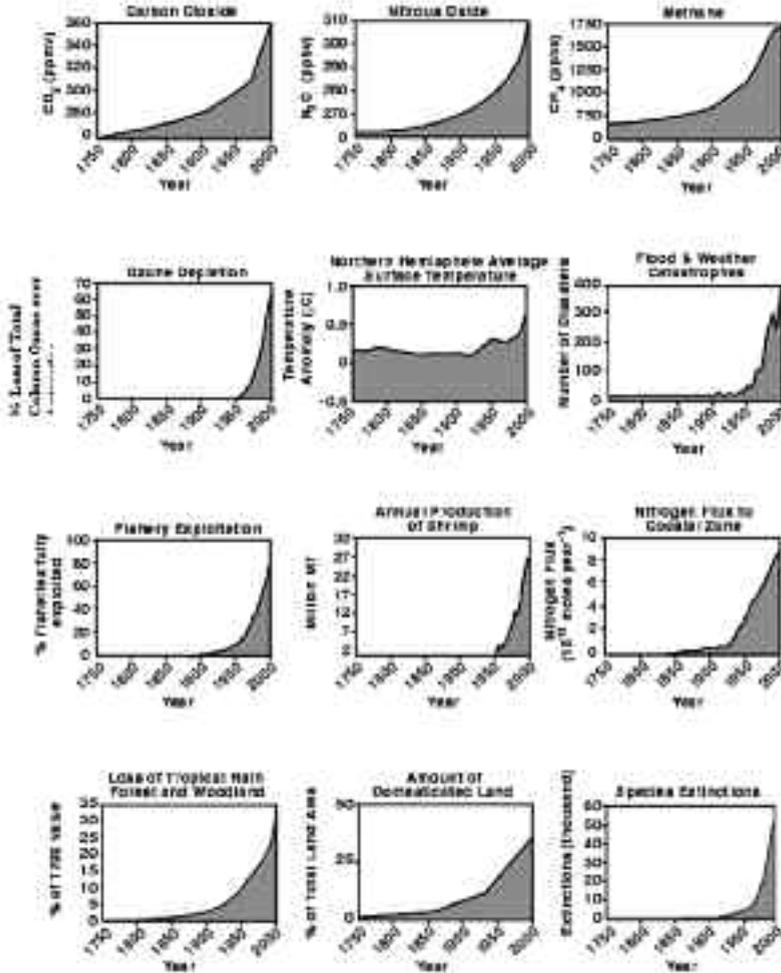


Figure 2b.

ured at the Mauna Loa observatory on the island of Hawaii. Superimposed on a long-term upward trend are seasonal variations with lowest values in the northern hemisphere during spring and summer, reflecting uptake of atmospheric CO<sub>2</sub> by vegetation during the growing season, and highest values in fall and winter due to the release of CO<sub>2</sub> from rotting vegetation. The lower two panels in Figure 3 show the 'ozone hole', the drastic loss of ozone which now regularly occurs in the stratosphere over the Antarctic continent

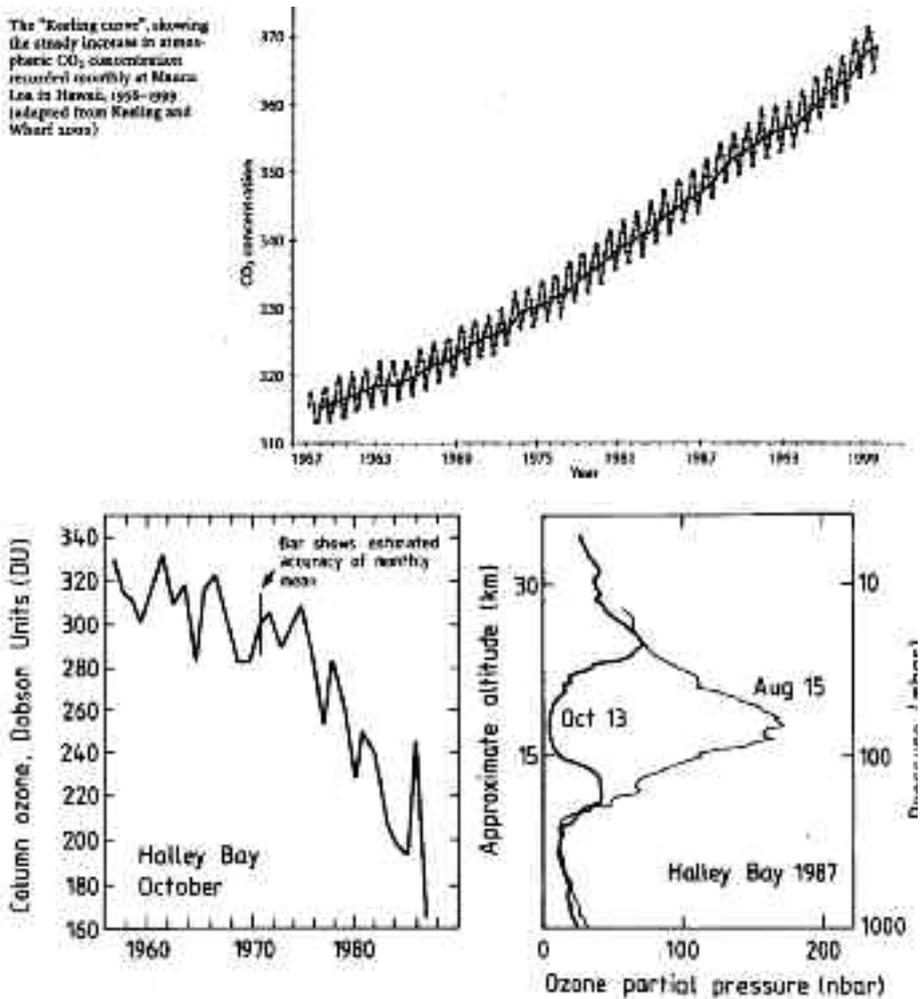


Figure 3.

in springtime. The total ozone column depicted in the lower left, shows a total ozone loss since the 1960-1970s by a factor of two in October. After two months ozone is completely destroyed between about 15 and 22 km altitude, exactly where naturally maximum ozone concentrations are found (right, lower panel). The ozone hole came as a total surprise. It is due to a number of originally unexpected, positive feedbacks, which start with the

development of very cold temperatures, colder than about 195 K, during the south polar winter, causing formation of ice particles and production of very reactive, industrial chlorofluorocarbon-derived, ozone-destroying chlorine atoms and chlorine oxide molecules by catalytic reactions on the particle surfaces in the presence of sunlight during late winter/early spring. Although emissions of chlorofluorocarbon (CFCs) gases no longer take place in the industrial world, because of the longevity of the CFCs, the ozone hole will not heal before near the middle of this century. The ozone hole could only develop by a series of positive (reinforcing) feedbacks, something to remember when we later discuss the human influence on earth's climate system.

In Figure 4 (see page 292) we depict estimated changes in radiative forcings relative to pre-anthropocene, A.D. 1750, conditions. The radiative climate forcing due to the growth in the atmospheric greenhouse gases –  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , the CFCs, and tropospheric ozone – add up to about  $2.7 \text{ W/m}^2$ . This heating term is well-known. Solar variability constitutes a radiative forcing by up to about  $0.3 \text{ W/m}^2$ , about 10% of the anthropogenic greenhouse warming. Land use changes through urbanization and deforestation, and albedo changes by ice sheet and glacier melting, also affect earth's radiation budget by a similar amount, but do not constitute dominating factors. The most important, but also most uncertain, negative radiative forcings are related to the presence of aerosol particles (sulfates and organics) and clouds in the atmosphere. These terms are very uncertain, thus the large error bars. Except for black carbon (soot) containing aerosol, in general particles exert a negative forcing on earth's radiation budget due to their propensity to scatter a fraction of the incoming solar radiation back to space. Another important negative forcing is related to what is called the aerosols' indirect effect, which is caused by the increased reflectivity of sunlight by clouds due to enhanced number concentrations of aerosol, which serve as cloud condensation nuclei (CCN). As a consequence, for the same liquid water content, but with larger CCN number concentrations, the polluted clouds will consist of a greater number of smaller droplets, increasing the surface of cloud droplets, in turn leading to enhanced backscattering of sunlight to space by the clouds. Although it may sound contradictory, dirty clouds are brighter than clean clouds. Furthermore, under such conditions, rain formation, which depends on coalescence of cloud droplets to create bigger precipitating drops, also decreases, thus diminishing cloud precipitation efficiency, producing longer-lived clouds and increasing cloudiness.

A tentative energy budget derived by the author and Prof. V. Ramanathan, also a member of the Pontifical Academy, for present atmospheric conditions compared to pre-anthropocene conditions is shown in Figure 5. As mentioned before, greenhouse radiative forcing is  $2.7 \text{ W/m}^2$ . Uptake of heat by the oceans over the period 1955 to 1998 on average was  $0.3 \text{ W/m}^2$ . Enhanced upward flux of infrared radiation at the ‘top of the atmosphere’ due to the increase by  $0.6 \text{ K}$  in global average surface temperature cools the planet by about  $1 \text{ W/m}^2$ , assuming unaltered relative humidity in the atmosphere, which is a reasonable, but not totally proven, assumption. This implies an energy surplus by  $1.4 \text{ W/m}^2$ , which earth can only have got rid of by increasing its albedo via enhanced backscattering of solar radiation by clouds and anthropogenic aerosols. This is about half of the greenhouse infrared radiative heating, indicating the possibility of a doubling in fully realized greenhouse gas forcing, if the atmosphere would become free from anthropogenic aerosol. Future reductions in air pollution, which by themselves are desirable because of the negative health effects of atmospheric particles, may, therefore, double climate warming by the greenhouse gases, constituting a major policy dilemma.

It is here very informative to compare the infrared greenhouse gas radiative forcing of  $2.7 \text{ W/m}^2$  with the direct heat release by humanity's

$\Delta$	<b>Greenhouse gas forcing (since pre-industrial times)</b>	$\approx 2.7 \text{ W/m}^2$
	<b>Heating of the ocean</b>	$\approx 0.3 \text{ W/m}^2$
	<b>Increased upward IR (from hotter surface of earth)</b>	$\approx 1 \text{ W/m}^2$
$\therefore$	<b>Increased albedo effect</b>	$\approx 1.4 \text{ W/m}^2$ ( $\approx 50\%$ of GHF)
	<b>Heat release to atmosphere from fossil fuel burning (1995)</b>	$0.025 \text{ W/m}^2$

Figure 5.

energy use, which is only  $0.025 \text{ W/m}^2$ . Thus production of the greenhouse gases, and not the direct heating of the atmosphere by energy production, is the problem. A major effort to develop alternative energy sources other than burning of fossil fuels is the only way to prevent excessive climate warming. Carbon dioxide is not the only factor. Together, other greenhouse gases have provided almost as much greenhouse warming as  $\text{CO}_2$ . Reductions in their emissions may be more easily possible, for instance  $\text{CH}_4$  from fossil fuel production, cattle holdings, and rice fields,  $\text{N}_2\text{O}$  from the application of nitrogen fertilizers in agriculture, and  $\text{NO}$  from automobiles, which results in a reduction of tropospheric ozone.

As shown in Figure 6, many complex and uncertain processes, with positive, as well as negative, feedbacks determine earth's climate. In accordance with what is expected from the growth in anthropogenic greenhouse gases, as shown in Figure 7, global mean temperatures on earth have increased since 1860 when direct temperature readings became possible in many parts of the world. The temperature rise since 1970 can currently only be explained by the anthropogenic greenhouse effect. A significant part in the rise in global temperatures over the period 1910 to 1940, however, reflects contributions from factors other than greenhouse gas emissions, such as heat release from the ocean, internal climate variability, or increase in solar

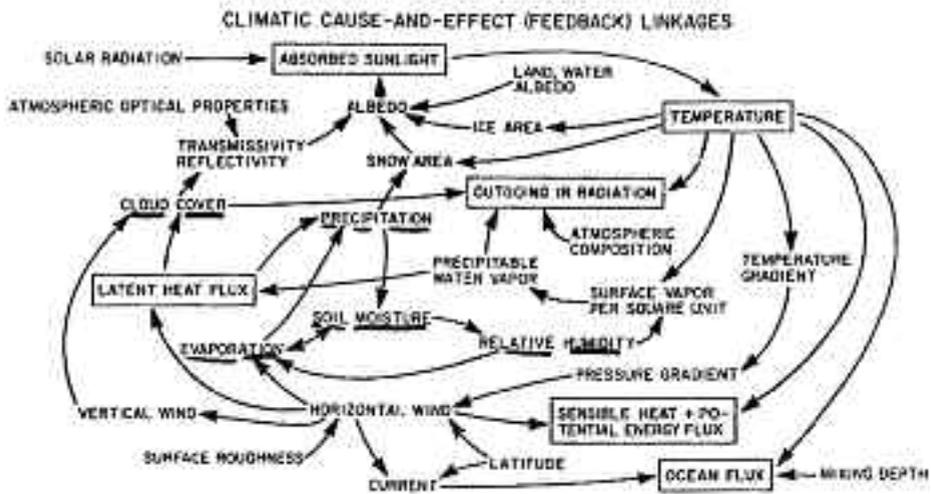


Figure 6.



Figure 7.

irradiation. If the latter were the main factor in climate warming, as some claim, it would imply a very high climate sensitivity  $dT_s/dQ=0.4^{\circ}\text{C}/(0.3\text{ W/m}^2)=1.3^{\circ}\text{C m}^2/\text{W}$ , where  $dT_s$  is the increase in global average surface temperature and  $dQ$  the increase in radiative forcing in Watts per  $\text{m}^2$ . With such a high climate sensitivity, the expected equilibrium surface temperature rise caused by the current greenhouse gas and aerosol forcings, according to the simple budget derived earlier, would be about  $1.3 \times 1.4 = 1.8^{\circ}\text{C}$ , much larger than the observed  $0.6^{\circ}\text{C}$  (see Figure 7).

Earlier, the Intergovernmental Panel on Climate Change (the IPCC) had projected global average surface temperatures increases by 1.4-5.8 K over the current century, the large range being due to uncertainties, in particular in the modelling of the hydrological cycle (clouds, precipitation) and future scenarios of greenhouse gas and particle emissions to the atmosphere. The IPCC report of 2001 stated: 'There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities'. The warming would be accompanied by sea level rises of about 10-90 cm during the present century. Thus, uncer-

tainties are large, not to speak about potential surprises as in the ozone hole case, briefly discussed before.

To prevent major global warming, drastic reductions in greenhouse gas emissions are needed. To stabilize the atmospheric concentrations of global  $\text{CO}_2$  and  $\text{N}_2\text{O}$ , anthropogenic emission reductions by some 60% are called for, a very difficult, if not impossible, task in a world in which the majority of nations are still in a state of underdevelopment, as shown in Figure 8 (see page 292), which depicts the current per capita use of carbon in metric tons per year. Unfortunately, as shown in Figure 9, Nature does

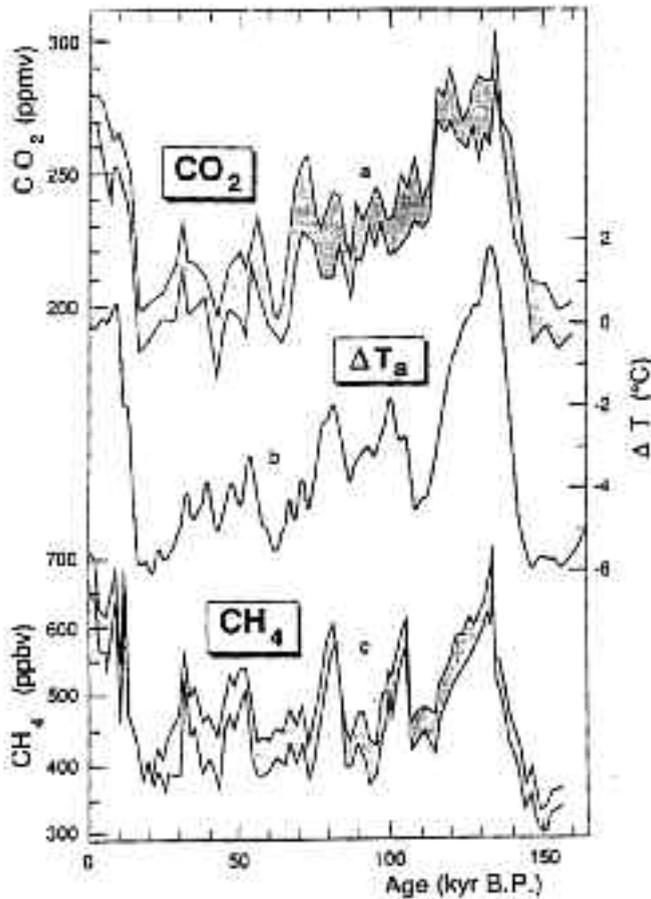


Figure 9.

not come to the rescue. During the past million years (the figure only shows the past 150,000 years) at any time when temperatures, derived from ice core data, were high, also the atmospheric concentrations of CO<sub>2</sub> and CH<sub>4</sub> were highest, thereby actually strengthening climate warming which is initially triggered by the behaviour of earth's orbital parameters. A major uncertainty is the stability of earth's climate system with all its complications. Especially sensitive may be the climates of the polar regions where largest climate warming is observed and also calculated by models. Questions have especially been raised about the stability of the thermohaline ocean circulations and the North Atlantic gulfstream which transports heat from lower latitudes to Europe.

Although earth's climate may be most vulnerable at high latitudes, the greatest future impact of human activities on earth's climate may well be in the tropics, especially in rapidly industrialising Asia. Heavy air pollution now covers large parts of the tropics and subtropics with high loadings of aerosol particles, containing relatively large amounts of black carbon, which produces the so-called Asian Brown Cloud. This is clearly visible from space, showing an extensive haze plume over India and flowing southward over the Indian Ocean, towards the Maldives.

Besides soil dust, the aerosol consists of a mixture of sulfates, organics, ammonia, and black carbon (see Figure 10, page 293), produced by fossil fuel and biomass burning, and by agricultural activities. Especially because of the strong absorption of solar radiation by the black carbon fraction of the aerosol, major disturbances in the radiative budget of the atmosphere over south, southeast and east Asia occur during the dry season. As a result, substantial absorption of solar radiation takes place in the atmosphere which can reach values of some 30 W/m<sup>2</sup> over the Asian continent during the dry season, which lasts from November to May. This is accompanied by a similar decrease of the solar energy absorption at the earth's surface. These numbers are about ten times larger than the global anthropogenic energy disturbance at the 'top of the atmosphere'. As a consequence of the enhanced energy uptake in the atmosphere and decrease at the earth's surface, the atmosphere will warm and the surface will cool, leading to a reduction in water evaporation at the earth's surface, reduced cloudiness and less rainfall, and slow-down of the hydrological cycle, which may also affect regions downwind of the polluted regions. This Atmospheric Brown Cloud (ABC) is most pronounced over the Asian continent, but is also present over Africa, and South America. The formation and persistence of the so-called brown clouds are favoured by the long dry season which hinders

the removal of the aerosol particles by precipitation. Because of the strongly growing economic development of Asia, the ABC phenomenon will become an increasingly major factor in anthropogenic regional climate change and rainfall characteristics, especially over Asia. But there remains the dilemma: combating air pollution by reducing aerosol emissions, may very well lead to a warmer climate.

Finally, to finish where I began, Figure 11 (see page 293) shows me in 1999 together with my then two-year-old grandson Jan Oliver. And I ask myself how the earth will be like during his lifetime which will cover most of the twenty-first century. What is clear is that in order to keep the earth habitable, major restrictions are needed in the use of earth's resources, below ground, at the earth's surface and in the atmosphere. Mankind has a long way to go when it comes to a wise use of natural resources.

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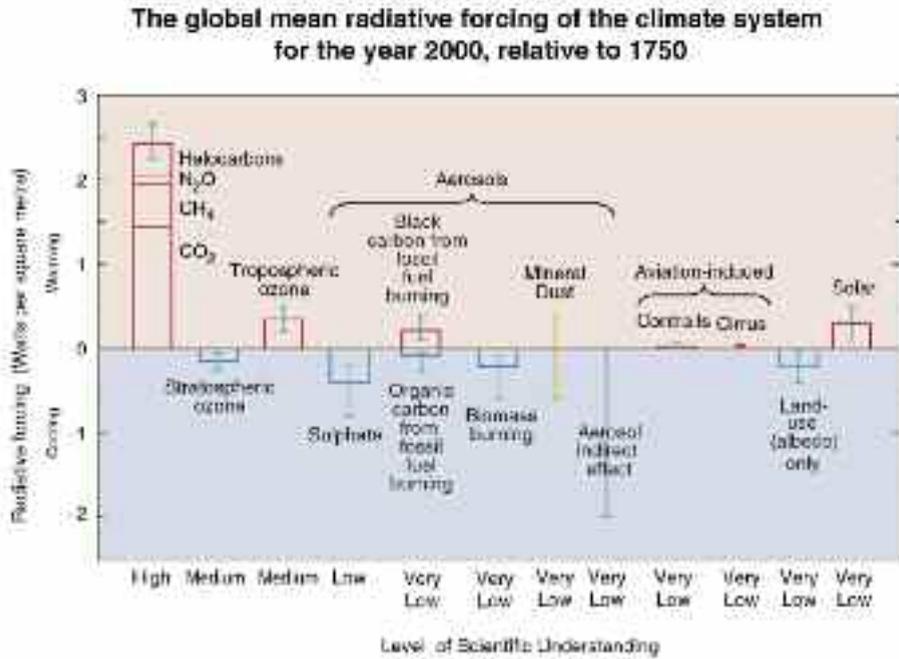


Figure 4.

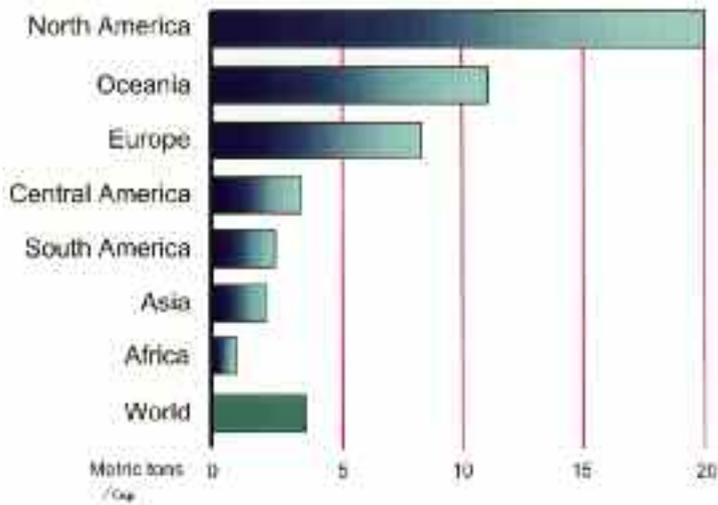


Figure 8.

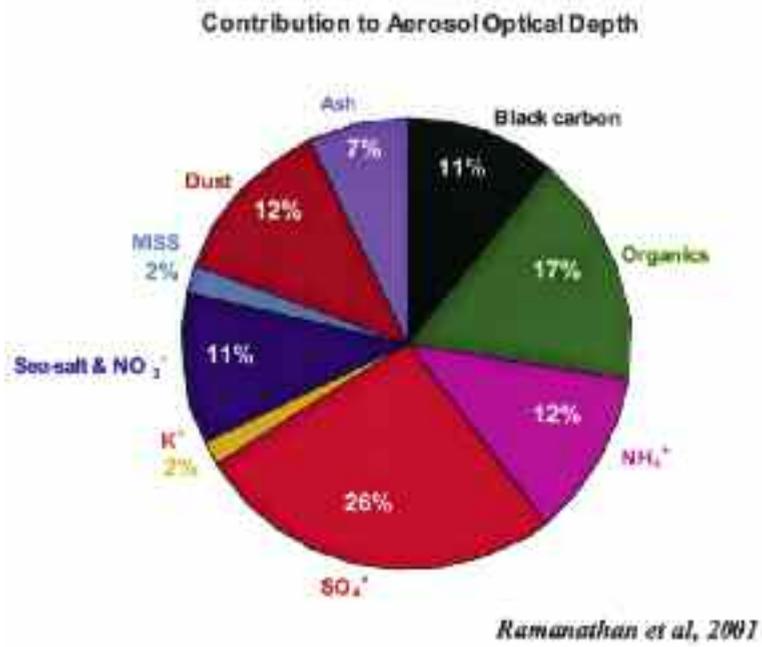


Figure 10.



Figure 11.