ANTHROPOGENIC CAUSES OF GLOBAL ENVIRONMENTAL CHANGE

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Summary

Since the Industrial Revolution, significant progress in economic development and technological achievement has been made to advance the welfare of humankind. A major downside of the economic development, in addition to the rapid depletion and sometime wasteful use of the limited resources, is the degradation of environment and changes in climate.

The impact of human activity on the atmosphere is now widely recognized: the observed increases of greenhouse gas concentrations (notably carbon dioxide) and ozone depletion as well as the increased particle loading are the outstanding features. These compositional changes in the atmosphere will most likely lead to changes in the environment and climate on a global scale. This theme provides a focused presentation of the core issues concerning the global environmental change and the current approach to these issues. Specifically, the presentation focuses on the history of changes in atmospheric trace constituents (the greenhouse gases and aerosols), and on the modeling studies of the associated climate changes.

1. Introduction

With the advent of industrialization in the late eighteenth century, we have been drastically changing the environment around us. One major by-product of this new lifestyle has been the introduction of various trace constituents (gases and particles) into the atmosphere. Some of these gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were naturally present in the atmosphere, although in small concentrations (parts per million by volume (ppmv) in mixing ratio); other gases, such as chloroflurocarbons (CFCs) with even smaller concentrations of parts per billion by volume (ppbv), are new. Increasingthe concentrations of these gases is enhancing the "greenhouse effect," yielding a warming of the earth's climate referred to as global warming. Increases of tropospheric aerosols (microscopic airborne particles or droplets) affect visibility and modulate clouds. In addition, increasing CFCs, and the emissions of oxides of nitrogen (NO_x) and carbon monoxide (CO) from aviation and biomass burning can also change atmospheric O_3, a greenhouse gas that absorbs most of the harmful ultraviolet radiation; for example, the observed "stratospheric O_3 depletion" can be attributed to the use of CFCs.

The main difference between 1750 and today is the degree of industrialization. It is therefore quite clear that human activities are responsible for the changes in the concentration of these constituents in the global environment. The environment is not static, and will respond to changes that are made to it. There have been large, concerted efforts to develop general circulation models (GCMs) of the earth's climate system to examine the climate responses to the observed changes in concentrations of greenhouse gases, O_3, and aerosols. Though attribution can never be certain, the GCM simulations of climate changes for the past century are not inconsistent with the observed climate changes. These GCMs are also used to assess future climate changes for the next century, based on the projected changes of the atmospheric constituents. The simulations show large regional climate changes. Global warming, stratospheric O_3 depletion, and tropospheric aerosols are, therefore, recognized as potentially destructive influences on the global environment. It is likely that these global environmental changes will be detrimental to human society.

This theme describes the changes in composition of the atmosphere in this century, in particular the greenhouse gases, O_3, and sulfate aerosols, concentrating on aspects of global-scale change that have clearly been brought about by human activities. Two aspects need to be addressed: those concerned with natural systems and those concerned with social systems. These two aspects clearly interact in many ways, but in general,

understanding of the former is best derived through the physical and natural sciences. However, analysis of global change in social systems involves using the methods of sociology, psychology, economics, and political science, which will not be addressed here. Extensive documentation of the study of human-induced climatic and environmental changes can be found in IPCC (2001) and WMO (1999).

2. Atmospheric Constituents and Global Environment

The sun provides the earth's only external source of heat, solar radiation being in the visible and near-infrared spectra, while most of the harmful ultraviolet radiation is absorbed by O_3 in the stratosphere. The earth also radiates energy back into space and, because of a much colder temperature than the Sun, the energy is in the form of infrared radiation. A balance between solar radiation and infrared radiation yields the present-day mean temperature, about –18°C, of the earth atmosphere–surface climate system.

The thermal structure of the atmosphere is influenced by the presence of trace gases and clouds (including aerosols), both of which modulate solar radiation and thermal emission. The principal gaseous absorbers of solar radiation are water vapor (H_2O) in the troposphere and O_3 in the stratosphere. H_2O absorbs primarily in the near-infrared spectral region, while O_3 is of major importance in maintaining the thermal structure in the stratosphere through its absorption of solar radiation in the ultraviolet and visible regions. It is believed that stratospheric O_3 is largely responsible for the existence of the tropopause, a nearly isothermal region separating the radiative equilibrated stratosphere from the more dynamically controlled troposphere. On a global and annual mean basis, about 100 Watts per square meter (Wm^{-2}) of the 340 Wm^{-2} incident solar radiation at the top of the atmosphere are reflected back to space mainly by clouds and surface while about 70 Wm^{-2} are absorbed by the atmosphere and the rest absorbed by the surface.

In the infrared, H_2O effectively blocks thermal emission from the surface except for the "window" region between 7 and 12 micrometers (μm) where CO_2, O_3, CH_4, CFCs, and N_2O with strong absorption bands contribute additional atmospheric opacity. Absorption of the outgoing thermal radiation in the atmosphere, followed by re-radiation at local temperature can lead to an increase of the surface temperature, the so-called "greenhouse effect." Satellite measurements indicate that the atmospheric gases can trap up to 100–200 Wm^{-2} of longwave radiation depending on the regions and seasons, thus keeping the global mean surface air temperature at a habitable 15°C (versus a mean temperature of –18°C). The presence of clouds will further increase the magnitude of the trapping of longwave radiation, about 30 Wm^{-2} on the global mean basis. Note, however, that, in contrast to the greenhouse gases that warm the climate, clouds also reflect large amounts of solar radiation, about 48 Wm^{-2}, and thus cause a net cooling of the climate system.

A perturbation to the energy available to the climate system, defined as "radiative forcing," due to changes in these atmospheric constituents will lead to climate changes with positive forcing for warming (e.g. the enhanced greenhouse effect) and negative forcing for cooling (e.g. stratospheric O_3 depletion and the tropospheric aerosols). As

the atmosphere interacts with the other parts (such as the oceans) of the climatic system, changes in the atmosphere inevitably affect the global environment.

Global warming associated with the enhanced greenhouse effect is presently considered to pose the greatest threat to the earth's climate. The current concern over global warming is related to two observations, first, that the greenhouse gases CO_2, CH_4, CFCs, and N_2O have been increasing over the past few decades (for CO_2 since industrialization) and this trend is expected to continue, and second that the global mean surface air temperature has increased by 0.3°C to 0.6 °C over the past hundred years. In addition, the pattern of observed surface warming is broadly consistent with global climate model simulations. For example, Crowley (2000), who studied the northern hemisphere temperatures and climate forcing over the last 2,000 years, concluded that the large late twentieth century warming is in close agreement with the climate responses simulated from greenhouse gas forcing. In addition, the simulated temporal and spatial patterns are better correlated when other causes, such as volcanic and anthropogenic aerosols, are included.

The link between the long-term build-up of chlorine and the decline of O_3 in the upper stratosphere is firmly established. Most of the mid-latitude column O_3 decreases during the last two decades arose because of depletion in the lower stratosphere, which is also related to the increase in O_3-depleting compounds. It is well established that the chemistry of chlorine and bromine originally from anthropogenic activity contribute to the observed large O_3 losses in the southern hemisphere polar region during spring. Continued increases in anthropogenic emissions of O_3 precursor gases (CO, NO_x and volatile organic compounds) can potentially increase tropospheric O_3.

Decreases in stratospheric O_3 may cool the stratospheric temperature, a characteristic consistent with observations. Radiosonde and satellite measurements indicate that during the period 1979–94, the global, annual-mean stratospheric temperature averaged over 16–21 km had a cooling trend of about 0.6°C/decade, with a larger trend of 0.75°C/decade at mid-latitudes. The cooling trend is substantially larger, about 3°C/decade, in the polar lower stratosphere during late winter/spring in both hemispheres. For a moderate change in atmospheric O_3 amount, the changes in UV flux at the surface are confined to the spectral region around 300–340 nm. A few ground-based spectroradiometers at mid-latitudes have detected an increase in UV-B radiance during the period 1989–97 with values of 1.5 percent/year at 300 nm and 0.8 percent/year at 305 nm, which are consistent with observed O_3 changes. Perhaps more importantly, there are strong regional features in radiative forcing from O_3 changes. Change in radiative forcing due to O_3 changes from pre-industrial times is largest at the northern middle latitudes where the impact on O_3 from emission of pollutants is largest. There are large latitudinal gradients in the calculated change in radiative forcing due to reduced O_3 loss in the lower stratosphere during the last two decades with large reductions at high latitudes. Regional O_3 changes in areas where there has been a strong increase in the emissions of pollutants over the last couple of decades (e.g. South-east Asia) is calculated to have caused a substantial increase in radiative forcing.

Unlike the greenhouse gases, which are evenly distributed, anthropogenic aerosols are not spread evenly across the globe. The release of sulfur dioxide (SO_2) is the main

anthropogenic source of sulfate aerosols. Due to their short lifetimes, which average days to weeks compared to the decades to centuries of greenhouse gases, sulfate aerosols are concentrated locally from where they are emitted. Thus, the increases in their concentrations are not worldwide, and are located around the centers of their production, mainly resulting from the burning of fossil fuels and to a lesser extent from biomass burning. Tropospheric aerosols can absorb and reflect solar radiation and in most cases, they tend to decrease radiative forcing and thus lead to a colder climate. In addition, aerosols serve as cloud condensation nuclei (CCN), which are involved in the complicated processes of cloud droplet formation and precipitation removal processes, an aspect of inadequate understanding at the present stage.

It is important to recognize that climate variations can occur, in the absence of changes in radiative forcing associated with anthropogenic emissions. This happens as a result of interactions on different time and spatial scales among the components of the climate system; for example, the El Niño-Southern Oscillation (ENSO) is a natural phenomenon on the interannual timescale resulting from the couplings between the atmosphere and oceans.

3. Changes in Atmospheric Composition

The composition of the atmosphere has changed since pre-industrial times, around 1750, mainly as a result of human activity. A large part of this change can be seen in the concentrations of greenhouse gases, O_3, and aerosols. For some of these changes, anthropogenic emissions create small but climatologically significant perturbations superimposed on the large natural cycles of the gases; for others, anthropogenic emissions dominate. All of these changes can impact the global environment.

3.1. Trace Gases

The annual mean concentrations of major greenhouse gases at pre-industrial times (1750) and 1998–9 are shown in Table 1. The sources and sinks of these gases are briefly summarized here while detailed information can be found in WMO (1999) and IPCC (2001). It should be pointed out here that, because of the different absorption characteristics, different gases absorb and trap infrared radiation from the surface at different levels of efficiency; for example, on a per molecule basis, CFC-12 has the same effect as about 25,000 CO_2 molecules. Consequently, despite the small concentration of CFC-12 in the atmosphere, its effect on infrared radiation is quite substantial.

	Time period		
Greenhouse gas	**1998–9**	**1750**	**Trends (pptv/year; 1990s)**
CO_2 (ppmv)*	367	280 ± 10	2.9 PgC/year 1990–7
CH_4 (ppbv)*	1 745	700	8.4
N_2O (ppbv)*	314	270	0.8
CFC-11 (ppbv)*	268	0	–1.4
CFC-12 (ppbv)*	533	0	–4.4

Tropospheric O_3 (DU)†	34	25	?
Stratospheric H_2O (ppmv)*	3-6	3–5	?

Notes: *ppmv/ppbv are mixing ratios with unit in parts per million/billion by volume.
†Total column amount using Dobson Unit = 10^{-3} cm.

Table 1. Concentration of greenhouse gases and their recent trends

3.1.1. Carbon Dioxide

For much of the nineteenth century, CO_2 concentration was 280 ± 10 ppmv until the increase in the twentieth century reaching 367 ppmv in 1998–9. The present level is the highest during the past 420,000 years and the sustained rate of increase is the largest during the past 20,000 years.

Naturally, plant and soil respiration releases CO_2, balancing the amount taken in by plants through photosynthesis. Carbon is also taken up by phytoplankton in oceans during production and released during the re-mineralization of organic matter. The anthropogenic sources for CO_2-increases in the atmosphere come from fossil fuel burning and to a lesser extent cement manufacture. Deforestation also contributes by removing plants that could remove CO_2 from the atmosphere. Agricultural land occupies one-fifth of the terrestrial surface, most of which was originally forested. The conversion of this land released carbon into the atmosphere. Table 2 shows the global CO_2 budget. Fossil fuel burning accounted for emissions of 5.5 ± 0.3 (peta (10^{15}) grams of carbon) PgC/year during 1980–9, and 6.3 ± 0.4 PgC/year during 1990–7. However, due to uptakes by oceans and terrestrial ecosystems, the rate of increase in atmospheric CO_2 concentration was smaller than the emissions with values of 3.3 ± 0.1 PgC/year during 1980–9 and 2.9 ± 0.1 PgC/year during 1990–7. Considering the major factors of continued economic development and population increase, it is expected that the CO_2 emissions from fossil fuel burning are certain to dominate the atmospheric CO_2 concentration during the twenty-first century.

Source/sink	**1980–9**	**1990–7**
Atmospheric increase	3.3 ± 0.1	2.9 ± 0.1
Emissions (fossil fuel, cement)	5.5 ± 0.3	6.3 ± 0.4
Ocean–atmosphere flux	–2.0 ± 0.6	–2.4 ± 0.5
Land–atmosphere flux	–0.2 ± 0.7	–1.0 ± 0.6

Note: *PgC/year = 10^{15} gram of carbon/year.
Source: after IPCC (2001).

Table 2. Global CO_2 budgets (PgC/year)*

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Bibliography

Crowley, T. J. 2000. Causes of Climate Change over the Past 1000 Years. *Science*, No. 289, pp. 270–7. [Climatic changes during the last 1,000 years and the relevant causes for such changes are discussed.]

Easterling, D. R.; Meehl, G. A.; Parmesan, C.; Changnon, S. A.; Karl, T.; Mearns, L. O. 2000. Climate Extremes: Observations, Modeling, and Impacts. *Science*, No. 289, pp. 2068–74. [Observed climatic extremes using measurements are discussed and their spatial characteristics are used to check their consistency with climate model simulations.]

Epstein, P. R. 2000. Is Global Warming Harmful to Health? *Scientific American*, No. 283, pp. 50–7. [The implications of climate warming and its effect on health is discussed.]

Grassl, H. 2000. Status and Improvements of Coupled General Circulation Models. *Science*, No. 288, pp. 1991–7. [Progress of climate models is documented and areas for further improvement are indicated.]

Hall, A.; Manabe, S. 2000. Effect of Water Vapor Feedback on Internal and Anthropogenic Variations of the Global Hydrologic Cycle. *Journal of Geophysical Research*, No. 105, pp. 6935–44. [Water vapor is an important greenhouse gas and this paper presents its variability within the hydrologic cycle and its potential feedback during anthropogenic activity.]

IPCC. 1995. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*. J. T. Houghton; L. G. Meira Filho; J. Bruce; H. Lee; B. A. Callander; E. Haites; N. Harris; K. Maskell (eds.). Cambridge, Cambridge University Press. 339pp, [Radiative forcing due to various changes of atmospheric constituents is a good indicator for comparing the subsequent global climate change. The study examines the magnitudes of these radiative forcings and the potential future changes using IPCC scenarios.]

IPCC. 1996. *Climate Change 1995: The Science of Climate Change.* J. T. Houghton; L. G. Meira Filho; B. A. Callander; N. Harris; A. Kattenberg; K. Maskell (eds.). Cambridge, Cambridge University Press. 572pp, [The scientific basis for the climatic changes, in particular global warming, is summarized and potential future changes of climate due to scenarios are suggested.]

IPCC. 2001. *Climate Change 2001: The Scientific Basis*. J. T. Houghton; Y. Ding; D. J. Griggs; M. Moguer; P. J. Van Der Linden; L. Dai; K. Maskell; C. A. Johnson (eds.), 881pp, *Cambridge, Cambridge University Press.* [An update of the IPCC, 1996.]

Karl, T. R.; Knight, R. W.; Baker, B. 2000. The Record Breaking Global Temperatures of 1997 and 1998: Evidence for an Increase in the Rate of Global Warming? *Geophysical Research. Letter*, No. 27, pp. 719–22. [The measurements suggest an accelerated rate of temperatures during 1997 and 1998.]

Rosenfeld, D. 2000. Suppression of Rain and Snow by Urban and Industrial Air Pollution. *Science*, No. 287, pp. 1793–6. [The connection between air pollution and small-scale meteorology is discussed with the potential of decreasing rain and snow amounts.]

Santer, B. D.; Wigley, T. M. L.; Gaffen, D. J.; Bengtsson, L.; Doutriaux, C.; Boyle, J. S.;. Esch, M.; Hnilo, J. J.; Jones, P. D.; Meehl, G. A.; Roeckner, E.; Taylor, K. E.; Wehner, M. F. 2000. Interpreting Differential Temperature Trends at the Surface and in the Lower Troposphere. *Science*, No. 287, pp. 1227–32. [The differences in the surface temperature (from ground measurements) and tropospheric mean temperature (from satellite measurements) are discussed and trends reconciled.]

Solomon, S. 1999. Stratospheric Ozone Depletion: A Review of Concepts and History. *Review of Geophysics*, No. 37, pp. 275–316. [Evolution of the findings concerning stratospheric ozone depletion is presented.]

Stott, P. A.; Tett, S. F. B.; Jones, G. S.; Allen, M. R.; Mitchell, J. F. B.; Jenkins, G. J. 2000. External Control of 20th-Century Temperature by Natural and Anthropogenic Forcings. *Science*, No. 290, pp.

2133 – 7. [The attributes of twentieth-century temperature changes are discussed in the context of natural causes and human induced activity.]

WMO. 1999. Albritton, D. L.; Aucamp, P. J.; Megie, G.; Watson, R. T. (eds.). *Scientific Assessment of Ozone Depletion: 1998*. Global Ozone Research and Monitoring Project, Report No. 44, Geneva, World Meteorological Organization. [The scientific basis of atmospheric ozone changes is summarized.]

Biographical Sketch

Dr Wei-Chyung Wang is a Professor of Applied Sciences at the State University of New York at Albany (SUNYA), USA. Since September 1989, he has been the Head of the Climate System Sciences Section of the Atmospheric Sciences Research Center at SUNYA. Prior to that time he was Vice President for Research at Atmospheric and Environmental Research, Inc. in Cambridge, Mass. Prof. Wang received his B.Sc. from National Cheng Kung University in Tainan, Taiwan in 1965; his M.Sc. from the State University of New York at Buffalo in 1970; and his D.Eng.Sci. from Columbia University in New York in 1973. All three degrees were in mechanical engineering.

Professor Wang has a broad background in atmospheric radiative transfer, climate modeling, and climate data analysis. His research focuses on global and regional climate change due to increases of the atmospheric constituents of greenhouse gases, CO_2, O_3, CH_4, N_2O, and CFCs and aerosols associated with human activities. Professor Wang was the first to publish, in a 1976 issue of *Science*, an article identifying CH_4 and N_2O as important greenhouse gases and in 1980, in *Nature* and *Journal of the Atmospheric Sciences*, articles indicating the important climatic effect of ozone changes in the upper troposphere and lower stratosphere. Professor Wang has been developing global and regional climate models for understanding the physical and chemical processes concerning the greenhouse effect and stratospheric ozone depletion and for assessing future regional climate changes. He is also engaged in research evaluating the effect and impact of climatic changes on social and economic activities, and their policy implications. He has over 100 publications in more than twenty refereed journals, including *Science* and *Nature*. In addition to conducting climate research, Professor Wang teaches graduate courses and is active in graduate education related to global change. He has been a mentor of graduate students in four SUNYA academic departments, the Atmospheric Sciences, Biology, Physics, and Political Science.