The Role of Natural Causes and Human Activities in Climate Change

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Abstract: *Scientific research has revealed a number of changes in the Earth's climate system in the past century. This section addresses changes observed in human and ecological systems that may be associated with, and perhaps caused by, the observed climate changes. Impacts of climate change over the past few decades are visible on human activities and ecosystems. There is a likely bias that favors the reporting of detected changes, rather than the reporting of no changes. Nonetheless, observations confirm that most biological and physical systems studied are responding to warming and other climate changes over the 20th Century in ways scientists would expect, but there have also been some surprises.*

Keywords: *Earth's climate, climate changes, human activities, observations.*

1. Earth's Climate in Changing

Scientists agree that the Earth's climate is changing. The average global surface temperature has increased since the Industrial Revolution, by about 0.6 to 0.8°C from 1880 to today. The global climate of the past few decades is likely approaching, or has already passed, the warmest since the rise of human civilizations around 12,000 years ago [5]. Precipitation in the 20th Century has increased by about 2%, more in the high northern latitudes, while drying has occurred in parts of the tropics, especially in the Sahel and southern Africa. Extreme precipitation events have increased in most of the few locations where data are adequate for analysis.

Global Temperature. The average temperature of the Earth's surface, the *global mean temperature* (GMT), has increased about 0.6 to 0.8°C from 1880 to 2004 (Figure 1) [14]. Warming occurs over lands and sea surfaces [13]. The warming during the 20th century, however, was not smooth. Global warming occurred from around 1910 to 1945, followed by a period of slightly declining or stable temperatures into the 1970s. Since 1979, warming has returned to about twice the rate of the 20th Century average, at about 0.18°C per decade. A panel of the National Academy of Science has reconciled earlier disagreement in confirming that warming has occurred also in the mid-troposphere, though less than at the surface.

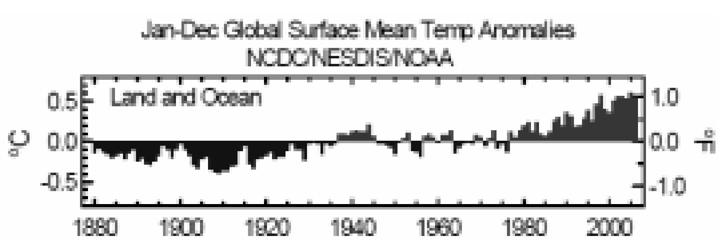

Fig. 1. Global temperature change since the industrial revolution [3].

Globally, 2005 was the warmest in nearly 130 years of direct measurements; 2006 was the sixth warmest year on record. The 10 warmest years on record have occurred since 1994.

Strong evidence of global warming since 1955 comes from measurements of heat content of the world's upper oceans, overall by 0.04°C since 1955 [8]. Because oceans store about 84% of the heat on Earth, this small warming is considered a strong signal of long-term change. Additional evidence of global warming comes from the detection of increasing continental temperatures (measured by boreholes into rock below the surface), by about 0.02°C, during the past five decades [8]. Both ocean and continental warming corroborate the elevated surface air temperatures.

Global Precipitation. Humans and ecosystems are affected by many aspects of climate, including precipitation, which has increased over the past century. This observed increase is consistent with scientific understanding that as warming temperatures increase evaporation, precipitation will increase to maintain balance in the water cycle. Over land, precipitation has increased by about 2% since 1900, but the patterns are highly variable across time and in different locations.

Climate Extremes. Few patterns of change have emerged globally in the frequency or intensity of most types of extreme events, according to NOAA's National Climatic Data Center (NCDC) [12]. No trend in global thunderstorm frequencies has been identified. Though there has been a clear trend toward less frequent extremely cold winter temperatures in some locations, there is no trend in the frequency of extremely high temperatures. Researchers at NOAA's National Center for Atmospheric Research (NCAR) have found that "[w]idespread drying occurred over much of Europe and Asia, Canada, western and southern Africa, and eastern Australia. Rising global temperatures appear to be a major factor" [2]. Drought area increased more than 50%, mostly due to conditions in the Sahel and southern Africa over the past few decades. Researchers have found that great floods worldwide increased significantly during the 20th Century, especially in the latter half of the period. The frequency of floods exceeding the 200-year flood levels also increased significantly, while the frequency of floods having return periods shorter than 100 years did not increase significantly [9]. In most regions, insufficient data remain a challenge for assessing trends in climate variability, because of the infrequency of events (by definition) and their spatial variability.

Contentious debate continues regarding trends in hurricane or cyclone frequency and intensity. For about 85% of the world's oceans, data are inadequate to detect long-term changes. Only in the extra-tropical Atlantic basin has research established a positive relationship between sea surface temperatures and increased number and severity of hurricanes or cyclones. Since the mid-1980s, satellite data reveal a distinct increase in tropical cyclone activity associated with higher eastern Atlantic sea surface temperatures, as well as other factors [3]. Much longer series of high-quality observations and improved understanding of tropical cyclones are needed to provide definitive attribution of changes in hurricane activity to natural variability, greenhouse gas (GHG) forcing, or other processes. A November 2006 meeting of international experts on tropical cyclones, convened by the World Meteorological Organization, concluded that "[d]espite the diversity of research opinions on this issue, it is agreed that if there has been a recent increase in tropical cyclone activity that is largely anthropogenic in origin, then humanity is faced with a substantial and unanticipated threat".

Scientific research has revealed a number of changes in the Earth's climate system in the past century. This section addresses changes observed in human and ecological systems that may be associated with, and perhaps caused by, the observed climate changes.

Impacts of climate change over the past few decades are visible on human activities and ecosystems. There is a likely bias that favors the reporting of detected changes, rather than the reporting of no changes. Nonetheless, observations confirm that most biological and physical systems studied are responding to warming and other climate changes over the 20th Century in ways scientists would expect, but there have also been some surprises.

2. The Causes of Global Climate Change

The evidence is strong that the Earth's climate is changing; the forces thought to be driving observed climate changes are discussed below, including the evidence that human activities, particularly greenhouse gas emissions, have contributed a large influence on top of ongoing natural variability.

The Earth's climate is driven by the energy balance of the Sun's radiation coming into and leaving the Earth's atmosphere. The more active the Sun, the closer the Earth to the Sun, or the greater the ability for the Sun's energy to penetrate the atmosphere and be absorbed by the Earth, the greater will be the warming tendency on Earth. On the other hand, the less active the Sun, the farther the Earth is from the Sun, the more the Earth's atmosphere or surface reflect the radiation back out to space, the greater the cooling tendency. The tilt of the Earth's axis in its orbit around the Sun, making one or the other hemisphere closer to the Sun most of the year, drives the heating and cooling of the seasons outside of the tropics. Scientists understand well the fundamental drivers of the Earth's climate through geologic time; for example, how the pattern of an irregular orbit around the Sun has led to regular climate swings in and out of ice ages, or how massive volcanic eruptions can spew particles into the atmosphere that block incoming radiation and cause temporary cooling.

2.1. Natural Causes that Influence Climate

The Earth's climate is variable, and scientists understand, to varying degrees, the forces that have driven climate changes of the past. Many factors contribute to changes in climate, regionally and globally, and no single factor acts alone. The principal natural factors determining climate through geologic time include the Earth's orbit around the Sun, solar activity, ocean variability, volcanoes, release of methane clathrates from the ocean bed, and chaotic variability.

Earth's Orbit Around the Sun. The shape of the Earth's orbit around the Sun is not perfectly round. The Earth's axis is tilted, and wobbles as it turns. These and other other orbital behaviors are fairly well understood and predictable in the ways they influence the Earth's climate. Generally, when the Earth is closer to the Sun, the Earth receives more incoming radiation and warms.

Solar Activity. Several aspects of solar activity have been suggested as contributors to climate change, although they remain disputed: total solar *irradiance*, the *ultraviolet* component of irradiance, *cosmic rays*, and *earth/solar magnetism*. Although the validity and magnitude of these remain in dispute, cosmic rays and earth/solar magnetism remain particularly complex and poorly understood.

Satellite measurements from 1978 dramatically improved the measurement of solar activity; while there is a clear correlation between solar sunspots and an 11-year radiation cycle, some scientists conclude that variations in solar output have been too small since 1978 to have significantly induced the observed global warming of the past three decades [4].

Ocean Variability. At least one scientist has hypothesized that the natural dynamics of ocean systems may be periodic and have an influence at least on regional or hemispheric climates. Understanding of the oceans may also elucidate factors that can trigger abrupt climate changes. For example, evidence exists that periods of increased freshwater flow to the North Atlantic and Arctic Oceans from the Laurentide ice sheet (over Canada) may be responsible for abrupt and significant climate events in NW Europe that took place in the Late-glacial and early Holocene.

Volcanic Eruptions. The presence of certain *aerosols*, or tiny particles suspended in the atmosphere, can reflect sunlight away from the Earth. Over geologic time, and in certain recent eruptions, the aerosols jetted into the atmosphere have caused significant cooling for one to several years after an eruption. About 71,000 years ago, an eruption of Mt. Toga in present-day Indonesia thrust about 2,800 times as much aerosol dust into the atmosphere as the Mt. St. Helens eruption of 1980, and may have been sufficient to cause a six-year *volcanic winter* and instigate a 1,000-year ice age. More recently, in 1992, the eruption of Mt. Pinatubo was sufficient to lower global average temperatures significantly for a few years [11].

Release of Methane Clathrates from Ocean Beds. Methane is a potent greenhouse gas. Methane clathrates (or methane hydrates) are a form of ice with methane trapped in their crystalline structures that exist at cold temperatures and high pressures on the Earth's ocean floor and in Arctic

continental shelves (the latter of which may be very shallow or even above ground). Some hypothesize that the sudden release of methane clathrates may have been implicated in the Earth's most severe extinction event, which occurred suddenly about 252 million years ago, resulting in a 5°C temperature increase globally, and with an estimated loss of about 96% of marine species and 70% of terrestrial vertebrate species.

Water Vapor. Water vapor exists naturally in the Earth's atmosphere and is the most important greenhouse gas, accounting for around two-thirds of the 33°C of additional warming our planet receives because of the presence of its atmosphere [7]. However, a change in water vapor content of the atmosphere can have warming or cooling effects, depending on where it is in the atmosphere, in latitude and altitude. Warmer temperatures globally will tend to increase the water vapor in the atmosphere, a *positive feedback* that tends to amplify the warming. To the degree that certain clouds increase, especially low clouds, with increased water vapor, a *negative feedback* may result, reducing the warming. Much of the warming predicted by climate models in response to GHG results from amplification by increased water vapor in the atmosphere from the initial increase in GHG-forced temperature. Feedbacks to clouds are among the least understood processes and account for large differences among climate model results. Although significant scientific advances in understanding clouds have been made since the year 2000, it will be at least several years before these are fully incorporated into scientific assessments, and no doubt considerable uncertainty will remain for decades.

Chaotic Variability. Climate scientists say that there is natural or "chaotic" variability in the climate system, meaning that there is a certain amount of random or unexplained behavior of the climate. To some degree, this natural variability reflects what science has not identified, cannot explain, or does not find a regular statistical pattern to describe. The presence of unexplained variability does not mean that scientists cannot make meaningful and useful statements about the past or future; it means that there is an amount of uncertainty, resulting from unidentified or poorly understood factors or randomness, that will remain in forecasts of the future.

2.2. Impacts of Human Activities in Climate Change

Virtually all climate scientists agree that human activities have changed the Earth's climate, particularly since the Industrial Revolution. Consumption of fossil fuels and clearing of land, as well as industrial and agricultural production release socalled greenhouse gases (GHG). Other human-related influences on climate include air pollution, such as tropospheric ozone, aerosols (tiny particles), land use change, paving and urban development, and airplane emissions. These different ways in which humans are affecting climate change are discussed in the following sections.

Greenhouse Gases. Greenhouse gas concentrations in the Earth's atmosphere have increased dramatically since the Industrial Revolution, with carbon dioxide growing from about 280 ppm in 1850 to about 380 ppm today. The presence of greenhouse gases is critical to trapping the Sun's energy and warming the planet to habitable temperatures. Human activities, such as use of fossil fuels, production of crops and livestock, and manufacture of various products, now emit

certain gases in sufficient quantities to have raised concentrations higher than they have been for hundreds of thousands of years; the elevated concentrations are changing the balance of solar radiation in and out of the Earth's atmosphere and, consequently, altering the Earth's climate.

Greenhouse gases (GHG) in the atmosphere allow the Sun's short wavelength radiation to pass through to the Earth's surface, but once the radiation is absorbed by the Earth and re-emitted as longer wave-length radiation, GHG trap the heat in the atmosphere. The best-understood greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and certain fluorinated compounds, including chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFC), perchlorofluorocarbons (PFC), and sulfur hexaflouride (SF_6). These greenhouse gases remain in the atmosphere for decades to thousands of years and are generally *well-mixed* around the globe; hence, their warming effects are largely global. Moreover, the long atmospheric residence time and the cumulative effects of gases have important implications for possible policy responses. Because these GHG affect radiative balance of the Earth in similar ways, they can be compared using measures of *radiative forcing* or *Global Warming Potentials* (GWP), the latter being an easier but imperfect approximation.

The following human-related sources of the principal greenhouse gas emissions have been identified:

- Carbon dioxide (CO_2): combustion of fossil fuels, solid waste, wood, and wood products; cement manufacture. Human activities can also enhance or reduce removals of CO_2 from the atmosphere by vegetation and soils (e.g., via reforestation or deforestation);
- Methane: coal mining, natural gas handling, trash decomposition in landfills, and digestion by livestock. Significant natural sources include wetlands and termite mounds.
- Nitrous oxide (N_2O): nitrogen fertilizers, certain industrial manufacturing, and combustion of solid waste and fossil fuels.

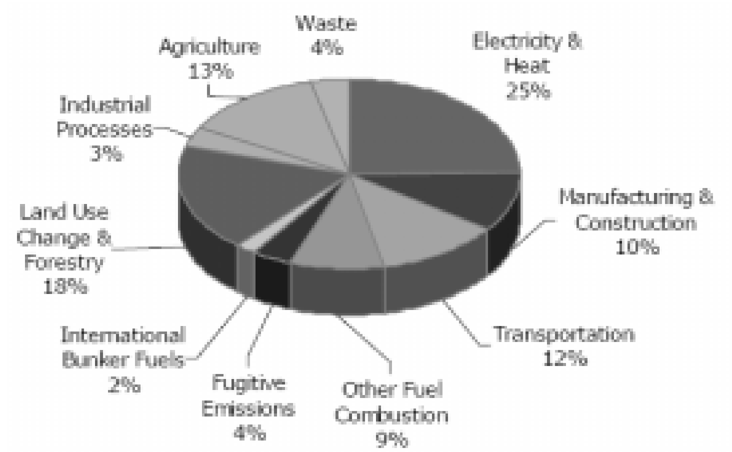

Fig. 2. Sectoral shares of global GHG emissions in 2000

- Chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6): commercial, industrial, and household products.

For the year 2000, CO_2 constitutes approximately 72% of the human contribution to GHG emissions; CH_4 is about 18% and N_2O is about 9%. There is considerable uncertainty regarding some of the historical estimates, especially prior to the 1950s.

Although most of the GHG occur naturally to some degree, the human-driven emissions of GHG are increasing above the rate of their natural removals from the atmosphere. Scientists are certain that GHG emissions from human activities have increased GHG concentrations in the atmosphere to levels unprecedented for hundreds of thousands, possibly even millions, of years. Over the past 150 years, CO_2 concentrations have increased globally by more than one-third, from about 280 ppm to current levels of about 380 ppm (Figure 3). Methane has increased by about 150%, although the rate of increase has declined over the past decades, down to essentially no growth (varying slightly) in recent years. N_2O concentrations have increased by 16% since the Industrial Revolution (for data sourcing, see Figure 3).

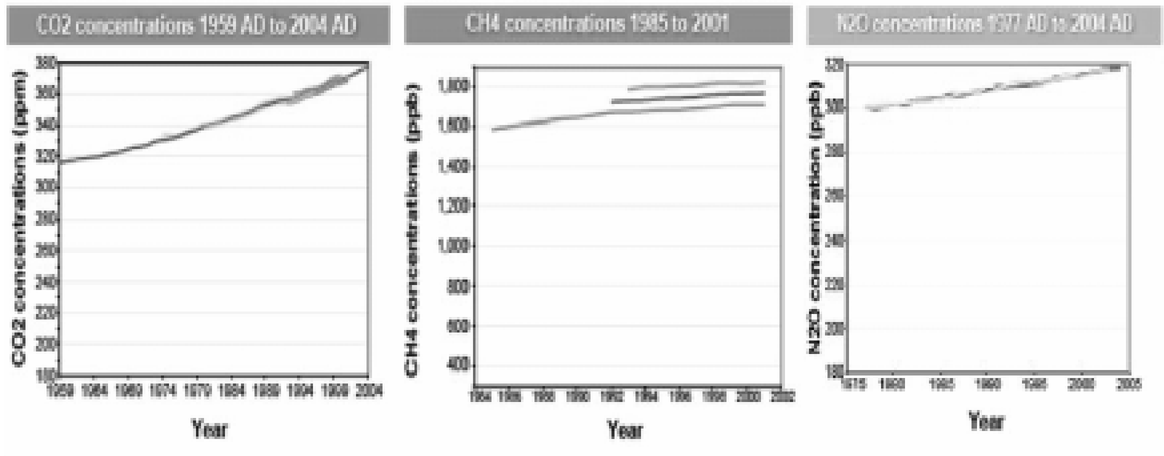

Fig. 3. CO_2, methane and nitrous oxide concentrations [1]

Tropospheric Ozone. Ozone is another greenhouse gas, but it is not emitted directly by humans. Although it occurs naturally, tropospheric ozone is elevated by polluting emissions, such as nitrogen oxides from fuel combustion or volatile organic compound (VOC) emissions from fuel leakage, solvent evaporation, etc. Tropospheric ozone concentrations, both background levels and episodes of high concentrations, have been increased, perhaps 50%, by polluting emissions since the Industrial Revolution [6]. Ozone forms and dissipates quickly, so its concentrations are unevenly distributed in time and space; hence it is difficult to compare the forcing of troposphere ozone with other GHG through *Global Warming Potentials*. Tropospheric ozone pollution drifting into the Arctic region may be responsible for one-third to one-half of the warming observed in its springs and summers.

Sulfur and Carbon Aerosols. Aerosols are tiny particles suspended in the air; some are there from natural sources, such as volcanoes and forest fires, whereas others result from human pollution, such as emissions from powerplants or vehicles. The principal aerosols of concern to climate change are sulfates, black carbon, and organic carbon. Aerosols can scatter or absorb light, with cooling or warming effects, respectively, depending on the size, color, composition, and other

characteristics of aerosols. Black carbon aerosols are thought primarily to warm the atmosphere; organic carbon aerosols (emitted largely by forest fires) are thought to have mostly a cooling effect.

Sulfur aerosols (sulfates) scatter incoming solar radiation and have consequent cooling influence on climate. This has been well known for decades but only included in climate modeling since the early 1990s. Sulfate aerosols are a byproduct of sulfur emissions, largely from the burning of coal and oil, as well as some industrial processes. Sulfur emissions and their aerosols have increased dramatically over the past century.

Aerosol effects on temperature are both regional and short-lived (as particles typically remain suspended in the atmosphere for days to weeks). Aerosol concentrations in the atmosphere fluctuate greatly, are difficult to measure, and consequently are uncertain by a factor of two or more. Aerosols are also understood to affect precipitation patterns downwind of their emissions, although research is just beginning to reveal the processes involved; they may influence monsoon water cycles as well. Aerosols may having amplifying or dampening effects when interacting with such factors as sea surface temperatures and snow cover. The role of aerosols in driving various aspects of climate is one of the major uncertainties being tackled by monitoring and research.

Emissions from Aviation. Emissions from fuel consumption by aircraft and water vapor emissions in their exhaust both contribute to climate change in special ways. First, these GHG are emitted at high altitudes, where few other GHG are present, and therefore do not overlap other gases' absorbing spectra, increasing their relatively small contribution to global surface temperatures. They also affect the vertical distribution of temperatures in the atmosphere. More complex, the emissions of small particles and water vapor form ice crystals in aviation *contrails* that can produce more clouds in the upper troposphere. These clouds can have a cooling or warming effect depending on the characteristics of the ice crystals; most scientists believe that the overall climate effect of contrails is a net warming. These are not globally distributed and therefore have stronger regional than global effects.

Land Surface Changes. Although the Earth's land surface changes naturally, as part of ecosystem processes, humans have had a major impact on land cover and land uses that, in turn, affect the climate system. At least one scientist has provided evidence that human forest clearing and rice production, beginning roughly 8,000 and 5,000 years ago, respectively, may have significantly affected carbon dioxide and methane concentrations, as could the carbon sequestration from forest regrowth following abandonment of farms in Medieval times after the bubonic plague [10].

Land Cover Feedbacks. Land cover change also results from climate change, and therefore can be a *feedback* within the climate system. On the one hand, CO_2 in the atmosphere is effectively a nutrient to plants, and this higher *carbon fertilization* will tend to increase vegetation growth and remove more CO_2 from the atmosphere. Where precipitation increases, and, to a lesser degree, where currently cool locations warm, vegetation is expected to increase, creating a negative feedback to climate warming. To the degree that vines and other weedy plants thrive better in higher CO_2 and warmer temperatures than woody trees, the enhanced carbon uptake may be short-lived. Moreover, warmer temperatures and greater moisture will tend to speed up decomposition, and even potentially cause die-back at high levels, generating a positive feedback to climate warming. In addition, trees and other vegetation transpire water vapor (another GHG) into the atmosphere. Also, land cover can alter the amount of dust raised by wind into the atmosphere.

Albedo. The reflectivity of the Earth's surface is called *albedo*. Where the Earth's surface has low albedo (i.e., is not very reflective), the Sun's radiation is absorbed and warms the surface. Particles deposited on the snow/ice surface (e.g., from pollution) can darken the surface and increase melting. In places covered with snow or ice, the surface has very high albedo; as the extent of snow and ice diminishes with climate warming, the reflectivity decreases and creates a positive feedback to climate, leading to more warming. Land cleared of its vegetation may reflect light more than the dark leaves that previously shaded it, increasing reflection of solar energy, and having a cooling impact. When snow is on the ground, the removal of trees can have a particularly strong albedo cooling effect, but mostly in winter or locations with permanent snow or ice. Land clearing tends to warm temperatures near the equator and cool them at high latitudes.

3. Conclusions

Impacts of climate change over the past few decades are visible on human activities and ecosystems. There is a likely bias that favors the reporting of detected changes, rather than the reporting of no changes. Nonetheless, observations confirm that most biological and physical systems studied are responding to warming and other climate changes over the 20th Century in ways scientists would expect, but there have also been some surprises.

Multiple factors simultaneously influence the Earth's climate, and scientists have developed a variety of methods that help determine which forcings are contributing, and are likely most important, at any period. Several different lines of evidence discovered in the past decade have led a large majority of scientists to conclude that human-related greenhouse gas emissions have contributed substantially to the increase in global mean temperature and other climate changes observed since the 1970s, and probably over the past century. Additional factors also contribute, including solar variability, volcanoes, and natural variability.

In conclusion, a variety of natural and human-related forces have influenced observed climate change throughout the 20th Century, including greenhouse gases accumulating in the atmosphere, other air pollutants, land use change, solar variability, and volcanoes. The relative importance of each of these factors is not well quantified. Nonetheless, relying on a variety of tests, a preponderance of scientists have concluded that the observed climate change over the 20th Century cannot be explained without including the effects of rising concentrations of greenhouse gases.

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