HISTORY, STATUS AND PREDICTION OF GLOBAL CLIMATE CHANGE

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Summary

Tremendous improvements have been made since the last decades of the twentieth century in our understanding and prediction of global climate change. While anticipation of some aspects of climate change may help us to prepare for its impacts, mitigating many of the major environmental changes that an altering climate will impose is unlikely to be simple. In addition to the direct effects of climate change on our health, economy, and vulnerability to extreme events, global climate change is likely to affect the availability of clean, fresh water resources, and cause sea levels to rise, endangering many coastal communities. Crops may fail and insurance premiums will rise, pests could increase their range, and native species of plants and animals may not be able to migrate fast enough to cope with a change in the climate, ultimately leading to their extinction.

Since our predictive capabilities, though continuously improving, are still unsatisfactory in many respects, it might be prudent for us to slow down the rate at which we are probably forcing the climate to change. Legislation against the continued rise of carbon dioxide is potentially costly, yet the question of whether it is more costly to allow the climate to continue to change is still unresolved. Is it wise to continue the global experiment without an answer to this question?

1. Introduction

Climate changes, with or without human influence, at every different timescale and over many orders of magnitude. The climate system sometimes appears overwhelmingly complex, with many possible interacting causes of change, thousands of feedbacks, and a maddeningly short instrumental record. How can we even hope to understand the system, let alone use that understanding to predict the future climate? And yet, we have, since the late 1960s, been able relatively successfully to simulate the climate in computer-based mathematical models and reconstruct the climate going back centuries, millennia, and even millions of years by using a wealth of proxy data. We have been able to identify both the necessary natural role and the potentially disastrous anthropogenic emissions of greenhouse gases, we have for the first time been able to predict and monitor an entire El Niño, and we can now glean annually from ice cores resolved information on the climate from the last ~110 000 years. All of these achievements were unimagined in the mid twentieth century and we become ever more aware that knowledge of the climate system is necessary for understanding our vulnerability and opportunities in the future. We only have to look at human history to be conscious of the important role that climate has played in our development and economy from exploration of the globe to the onset of agrarianism to the tourism boom. Now we are faced with the daunting prospect of unwittingly embarking on a dangerous experiment with the climate. There are no historical analogues for the rate at which we are transferring carbon from its terrestrial reservoir to the atmosphere. It is going to need all our knowledge gained to this point and a great deal more to comprehend fully the role we are playing in altering the climate system. While we, in our heated, air-conditioned homes and offices, feel untouchable by a change in the climate, the reality is that nearly all of our day-to-day existence depends on its relative stability. The harvesting of our food, our health, the availability of water, mobility, and subtler aspects of our economy, such as tourism, urban design, and insurance all depend on weather and climate. It is therefore imperative that we build on our achievements thus far in a continued effort to gain deeper insight into the complex atmosphere and its behavior in the future.

2. History of Global Climate Change Science

A direct human influence on the environment is not new. Clear cutting for agriculture, and changes in faunal composition due to hunting and domestication of animals are known to have occurred thousands of years ago. However, until recently, our influence on the environment has been relatively localized. With the industrial revolution and population increase, many environmental issues have become more widespread in nature with recent and future climate change, or global warming, being an example of a truly global effect of human activity. Only in the second half of the twentieth century did the potential human impact on the climate system emerge, and the possible dimensions of the problem were not fully appreciated until the 1970s. Significant advances in the understanding of the different components of the complex climate system (the atmosphere, hydrosphere, biosphere, cryosphere, and to a certain degree the lithosphere) have been made since then. These give us the tools, not only to investigate processes within subsystems and their complex interactions, but also to realize that their relative roles in changing the climate vary. Once the rapid increase of greenhouse gases was recognized, and data of atmospheric composition of previous centuries and millennia (including the ice ages) became available from ice cores, long known calculations of effects of increasing greenhouse gases were rediscovered. The “large-scale geophysical experiment” was now recognized as potentially dangerous. Today, it is clear that the changes in atmospheric composition are human made. But to what degree have these changes already influenced the climate, and what will their effect be in the future? The challenge is to separate the natural variability from the human-induced changes within the complex climate system. If the predictions are right, this problem become easier to resolve as time moves on. But can we afford to wait?

In the following section, a selection of major advances in our understanding of the climate system is highlighted. It is important to realize that it is only since the middle of the nineteenth century with improved communication technology that a sufficiently large-scale observation network became available. Finally, it was the development of computers that made possible a major advance in our understanding of the complex interactions between components of the climate. More detailed overviews can be found in H.H. Frisinger’s 1977 book *The History of Meteorology to 1800*, H.G. Körber’s 1987 work *Vom Wetteraberglauben zur Wetterforschung*, and J.R. Fleming’s 1996 *Historical*

Essays on Meteorology 1919–1995. A more specific overview of the greenhouse debate is given in G.E. Christianson's 1999 *Greenhouse. The 200-Year Story of Global Warming*.

2.1. The Early Times

The earliest interest in "climate" was of a rather pragmatic nature. The change of the seasons and with it changes in the food supply required adaptations of early hunters and gatherers, even more so after the agricultural revolution, when it became critical to farmers to know when to plant and when to harvest. Therefore, knowledge about the seasons and the annual cycle were and still are crucial in all of the cultural centers, from tribes to large civilizations. It is perhaps not surprising that very precise calendars were compiled in most of the early cultures. Hammurabi (reigned ~1792–1750 BCE) unified the different calendars of Babylon, the Romans improved the calendar to the Julian calendar, and the Maya reached the astonishingly precise determination of the year-length with 365.242 days (currently we use 365.2422).

The foundation of our Western understanding of the climate came from the Greek culture. The source of the word "climate" is the Greek *klinein*, which means "to incline, at an angle." Parmenides (~515–450 BCE) developed the idea of the so-called "solar climate," dividing the earth into five zones with different inclination categories, guiding life on earth. Eratosthenes (276–195 BCE) used the difference of the solar angle at different locations to calculate the circumference of the earth, and Aristotle (384–322 BCE) wrote the four-volume treaty *Meteorologica*, a standard for roughly 2000 years. Much of this knowledge was forgotten until the Enlightenment.

2.2. From the Middle Ages to the Twentieth Century

Only after the development of instruments to measure meteorological parameters did the Aristotelian view of the atmosphere slowly disappear. After receiving information of a first "thermoskop" built in the Netherlands (probably based on old descriptions of Philon of Byzantine (250 BCE)), Galileo Galilei (1564–1642) quickly built his own (*Nineteenth-century reproduction of the "Thermoscope"*). This was around 1640, when the Florentine Academia del Cimento established the first network of stations through Tuscany, using the same type of thermometers at each location. The design of the first thermometers suffered from changes in air pressure, which led to the development of barometers by Berti (1600–1643) and Torricelli (1608–1647). The famous experiment initiated by Pascal and performed by Perrier on September 19, 1648, in which a barometer was carried onto Puy de Dôme and back down, finally confirmed the hypothesis that the air consists of a compressible gas with a measurable weight, began a new view of the atmosphere. Since the beginning of the balloon flight era in 1783, vertical cross sections of atmospheric properties without influence of the surface have been able to be measured. One of the most famous ascents took place in 1862, when Glaisher and Coxwell reached a record altitude of 8839 m (*Balloon ascent of September 5, 1862 by J. Glaisher and H. Coxwell After Coswell (1887)*). Starting in the late 1920s radiosonde measurements replaced direct measurements by humans, and today a large network of automated radiosondes (instruments carried aloft by balloons) report their profiles on a regular basis.

The explorations in the sixteenth and seventeenth centuries brought an increasingly global perspective of climate (e.g. Varrenius' *Geographica Generalis* in 1650), especially with the travel reports of Alexander von Humboldt (1799–1804). Among many other contributions, von Humboldt made use of a network of 58 climate stations to realize that the "solar climate" needed some adjustments (*First map with isotherms of Alexander von Humboldt (1817) based on 58 stations over the Northern Hemisphere.).* At the same latitude, stations on the east side of the Atlantic Ocean were significantly warmer than stations on the western side, pointing to a significant contribution of ocean currents to the global temperature distribution. For the first time in meteorology or climatology, he used isolines (isotherms, i.e. lines connecting points having the same mean temperature) to show the spatial distribution of this property. By including topography and later vegetation, Koeppen published a classification of climatic zones over the globe (*Map of climate zones by Koeppen (1900) including information on global vegetation distribution.)*, the basis of which is still used today.

In the mid nineteenth century, the use of the telegraph to transmit observations of climate and weather parameters rapidly showed the potential of weather forecasting. This led to the foundation of national weather services, and in 1873 to the formation of the International Meteorological Organization. Today, this organization, a part of the United Nations, is called the World Meteorological Organization (WMO) and is located in Geneva, Switzerland. Among many other efforts, the WMO is responsible for World Weather Watch, a program to monitor and analyze climate on a global basis.

2.3. Atmospheric Composition and the Greenhouse Effect

Within about a century of the Puy de Dôme experiment and the conclusions by Descartes that the atmosphere was not uniform but compressible, the basic composition of the atmosphere was established. In 1657, Boyle and Hook found the "life substance," later called oxygen by Lavoisier. Black discovered carbon dioxide (CO_2) (a gas that killed animals but let plants grow) in 1753, and Rutherford found what was later called nitrogen in 1770. It was not until 1894 that Rayleigh and Ramsey found argon by using the technique of spectroscopy. This technique was based on Herschels detection around 1800 that light is a source of energy that is not restricted to the visible range, but also extends through the red spectrum into the infra-red. Maxwell then found that this energy is transmitted by electromagnetic waves, and that the "visible" is only a very small portion of the full spectrum including ultra-violet.

With this background, Fourrier (1768–1830) published a fundamental work about the temperature of the globe in 1824. He linked the temperature of the atmosphere to the atmospheric gases and their conservation of radiation, suggesting that the system acted like a large bell jar. After geologists, led by Agassiz, encountered evidence of ice ages in the geologic past, Tyndall postulated in 1861 that a reduction in CO_2 could lead to a new ice age. This was picked up by Arrhenius in 1896, when he computed the dependence of temperature on atmospheric composition in terms of CO_2 (*Arrhenius' table of varying atmospheric CO2 concentration and the corresponding surface temperature changes for latitudes 70N to 60S (Arrhenius, 1896*)). Although he was strongly underestimating the time period needed for humans to increase atmospheric

CO_2 (he thought it would take about 3000 years to reach a doubling or tripling), his calculations of the temperature response are very similar to estimates of temperature response in present calculations. He referred to the climate for these high CO_2 concentrations as “hothouse” conditions, which Trewartha later (in 1937) termed the “greenhouse effect.” While Arrhenius expected the increased temperatures during these hothouse conditions to be benevolent for humanity, Revelle and Suess realized that the changes were much more rapid and that observing responses to the changing atmospheric composition could offer insight into how the weather and climate works, in this way approximating a big “geophysical experiment.” Callander and then especially the precise CO_2 measurements of Keeling in 1960 showed the rapid increase of CO_2 over the twentieth century (United States, Office of Science and Technology Policy, 1997), a time series recently expanded in much detail by ice cores (Indermuehle et al. 1999). Today we also include methane, nitrous oxide, chlorofluorocarbons (CFCs), and ozone (tropospheric) as additional greenhouse gases.

3. Status of Global Climate Change

Any anthropogenic effects on future climate will be superimposed on a natural variability that may serve to mitigate or amplify these effects. The only method of assessing the role of natural versus anthropogenic forcing is through an understanding of past climate variations. To achieve this, annual or preferably seasonal information needs to be gained for as wide a geographic area as possible. However, instrumental records of weather and climate exist only for the last 100–150 years and prior to this it is necessary to rely on “proxy” information of climate. Great improvements have been made in recent decades to assemble a wealth of annually and seasonally resolved proxy climate data for the last 1000–2000 years and beyond so that we can address our understanding of climate processes with this perspective.

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Biographical Sketches

Caspar Ammann, a paleoclimatologist in ESSL’s Climate and Global Dynamics Division, and specializes in Climate System Models (CCSM3) to study recent climate variability and potential future changes.

Dr.Caspar Ammann's research centers around the high-resolution climate of past centuries and millennia and how this information can help to understand what elements of future climate might be predictable as well as what potential environmental and ecological impacts are to be anticipated given various story lines of climate change scenarios

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