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Future climate change

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Abstract

The climatic effects of rising CO_2 levels will become increasingly significantin the future. Consumption of estimated reserves of fossil fuels in the next two or three centuries will add far more CO_2 to the atmosphere than has been emitted to date unless ambitious conservation efforts or technological innovations reduce the influx. Atmospheric CO_2 concentrations will increase to levels at least twice and possibly four times the highest amounts measured in the last 800,000 years spanned by ice-core records. This warming will overwhelm natural variations in climate and cause climatic and environmental changes unprecedented in human experience. Atmospheric CO_2 levels will eventually decrease as the ocean slowly absorbs much of the excess carbon, but this process will acidify the oceans. After the main pulse of fossil-fuel emissions has passed, atmosphericCO_2 values will decrease back toward preindustrial levels, but enough CO_2 willremain in the atmosphere to prevent future glaciations for tens of thousands of years.

Keywords: Atmosphere; Climate; CO_2; Ocean

1. Introduction

Over the next few centuries, natural factors will continue to affect climate change, but their impacts will remain small (as they have been during recent millennia). The largest driver of future climate will be emissions of greenhouse gases and aerosols from human activities.

1.1. Factors affecting Future Carbon Emission

In recent decades, atmospheric CO_2 concentrations have been rising at rates of, 2 ppm/year, mainly because of burning of fossil fuels, and to a lesser extent because of deforestation in some tropical regions. This rise will continue in the future, but the rates are difficult to predict. The uncertainties in this prediction center mainly on the amount of carbon we will emit but also on the way the climate system will distribute the added CO_2 among its carbon reservoirs. For as long as fossil fuels remain reasonably abundant, future carbon emissions can be approximated by multiplying three factors:

1.2. Increase in carbon emissions = increase in population × change in emissions per person × changes inefficiency of carbon use

This equation could also be expressed as: population growth × economic growth × technology. The number of humans is critical to these projections for obvious reasons: expanding numbers of humans require more fossil fuel for industry, transportation and home heating, and in some regions increasing populations will cut more forest to clear land for farming and urban/suburban growth. As medical advances have extended life expectancy, the number of humans has increased from 1.5 billion in 1990 to over 7 billion today.

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Attempts to project future population increases are complicated by the tendency of birth rates to fall as per capita income rises and by centralized efforts to slow population growth in China. Global population is projected to rise rapidly from 7 billion in the year 2010to 9 or 10 billion by 2050, but with a leveling off of the trend after mid-century. The explosive growth that has occurred between 1900 and 2010 will slow as developing countries reach higher levels of wealth and parents in those countries choose to have fewer children. This trend has already been under way for decades in fully industrialized countries. The change in carbon emissions per person is primarily linked to the average standard of living. Historical examples show that demand for more carbon-based fuel for industrialization, transportation, and home heating and cooling has increased as standards of living have risen. In the near future, the largest changes of this kind will occur in the many countries that shift from semi-industrialized to industrialized status.

The third term in the equation the average efficiency of carbon use is far the most difficult to constrain because of uncertainties about several factors, including the mix of carbon-based fuels. The next few decades will see peaks in annual production of oil followed by a decline in annual production. Natural gas will follow a similar path, but decades later because more gas will become accessible to new recovery techniques.

Compared to coal, oil and gas are relatively "clean" fuels that emit smaller amounts of CO_2 perunit of energy produced. Most high-grade anthracite coal was burned in the early years of industrialization, leaving mostly lower-grade bituminous coal in the ground. Because bituminous coal produces far more CO_2 per unit of usable energy, burning coal will increase global carbon emissions long into the future.

Oil sands found in vast deposits under the western Canadian prairies are another potentially enormous contributor of carbon emissions. If the bulk of the carbon stored in tar sands becomes commercially worth exploiting, CO_2 emissions will rise even higher.

The best hope for reducing (or limiting increases in) future carbon emissions lies in technology, a part of the "efficiency" term in the equation. Humans are a uniquely innovative species, and our ingenuity will inevitably make future breakthroughs in improving the efficiency with which we use fossil carbon sources. Signs of this kind of innovation have begun to appear during the early 2000s as conventional fossils fuels have become more expensive. Promising areas include: solar and wind energy, biofuels (organically based fuels derived from agriculture), hydrogen powered vehicles, and nuclear power plants that do not produce CO_2 or other greenhouse gases. Future increases in the cost of fossil fuels will help to accelerate the technology-based search for alternative energy.

1.3. Projected Carbon Emission and CO_2 concentration

The Intergovernmental Panel on Climate Change (IPCC) has predicted a wide range of possible carbon emission trends for the rest of this century. These projections are based on tons of carbon emitted expressed as tons of CO_2 emitted, the values would be 3.66 times as large. The two projections encompass the range of the IPCC estimates. Because of the huge inherent uncertainties in the distant future, projections beyond the year 2100would be nothing more than guesses. The higher projection is based on the pessimistic assumption that efforts to curb emissions will have little or no effect, because assessments of economic benefits will guide national and individual decisions about energy use.

The lower projection assumes that individuals, civic groups, cities, and nations will take strong action to curb carbon emissions and that advances in technology aid this effort. As a result, carbon emissions build up more slowly, reach smaller peak, and are spread out over a much longer interval. Based on these optimistic assumptions, the lower curve shows worldwide carbon emissions peaking at, 9 billion tons per year near 2050, only about20% above the modern rate, and then falling below the current rate late in this century.

1.4. Effect of Future CO_2 increase on Climate and on the Environment

As atmospheric CO_2 levels rise in the future, Earth's climate will continue the warming already underway. Attempts to estimate the amount of future warming are limited mainly by uncertainties in three factors: the amount of CO_2 emitted by humans, the levels of atmospheric CO_2 reached as the excess carbon is redistributed among various carbon reservoirs, and Earth's sensitivity to higher CO_2 concentrations. Emissions of other greenhouse gases are also a source of uncertainty.

The two projections shown in span the likely range of increased CO_2 concentrations during the next few centuries. Here, we assume that the actual path will fall midway between the "optimistic" ($2\times CO_2$) and "pessimistic" ($4\times CO_2$) projections, reaching a $3\times CO_2$ peak of 800–900 ppm, or three times the 280-ppm preindustrial level. The best current estimate of Earth's sensitivity to a doubling of CO_2 is 3°C . For a peak of $3\times CO_2$, the global average temperature increase should be 4.5°C to 5 °C of which less than a degree of that total has been registered since 1850 and roughly another 4°C is yet to come. Temperature increases at polar and near-polar latitudes will be twice that large.

The high-CO_2 world of the future will be a place of major climatic disequilibrium because the high-CO_2 pulse will arrive too quickly for all parts of the climate system to come into full temperature equilibrium.Our future world will be characterized by a strange mix of faster-responding parts of the climate system like the atmosphere, land surfaces, vegetation, and Upper Ocean, and slower-responding components like the deep ocean and ice sheets. The faster responding parts will register the CO_2 -driven warming within just a few decades, the slower-responding deep ocean will react much more slowly, and the ice sheets on Greenland and Antarctica will not have fully reacted to the high-CO_2 levels even by the time the pulse begins to decline. Near the slow-responding ice sheets, which strongly influence regional climates by their high albedo and their effect on atmospheric winds, the lingering cold caused by the ice will suppress part of the fast response of the atmosphere and the nearby surface ocean to the higher CO_2 levels. Farther from the ice, the faster-responding parts across most of the climate system will react strongly to the new warmth. Because this kind of disequilibrium has not occurred in Earth's past, there are no perfect analogs for future climate.

In a 3 × CO_2 world, north Polar Regions will warm enough to eliminate shallow permafrost, tundra, all summer sea ice and probably most winter sea ice. The Arctic Ocean will be completely ice-free in summer within a few decades, long before the peak 3×CO_2 concentration is reached. In the Antarctic, where most sea ice disappears during modern summers except in a narrow strip along the coast of the continent, the Southern Ocean will likely become entirely ice-free in summer. As a consequence of warmer Arctic winters and the absence or near-absence of winter sea ice, the north polar continents will be transformed by forests moving northward into areas that are now tundra. Tundra will likely disappear in a3 ×CO_2 world, replaced by evergreen forests extending to the Arctic coast.

Fauna and flora on mountainsides will also be affected by future warming. In order to remain in an optimal temperature regime, both will have to shift to higher elevations, and the transition will be easier for relatively mobile life-forms than less mobile ones. In some cases, the warming may push the preferred environment "off the top" of the mountains and cause species extinctions.

The warming during the next two or three centuries will also alter regional patterns of precipitation and evaporation in significant ways. Evaporation will increase worldwide because warmer temperatures will permit air to hold more water vapor. With more water vapor in the atmosphere, global average precipitation will also increase, but in patterns that will vary from region to region. With evaporation increasing, those areas that fail to receive more precipitation will become drier, while those that do receive more precipitation could become wetter.

The deep ocean is one of the slower-responding parts of the climate system, in part because of the 1,000 years or so it takes for an average molecule of water to circulate through the world ocean. Changes in the pattern and rate of this circulation in future centuries and millennia are difficult to predict, but in any case, the ocean will definitely be affected by ocean acidification. The ocean has an"alkaline" (non-acidic) pH that ranges today between 7.8 and 8.5 regionally, well above the 7.0 pH boundary that separates acidic and alkaline conditions. Because the pH scale is logarithmic, a shift from 8.0 to 7.0 in pH units represents a tenfold increase in relative acidity (or decrease in alkalinity) During the 150 years of the industrial era, burning of fossil fuels and forests has added roughly 300 billion tons of carbon to the ocean, pushing the average pH of the ocean, 0.1 unit lower (toward more acidic values), equivalent to an alkalinity decrease of, 30%. Over the previous several thousand years, gradual deforestation by farmers had already added even more carbon to the ocean.

As a result, some coral species will have trouble forming their reef structures, which are made of aragonite, a form of $CaCO_3$. This will add to the problem already faced by many coral reefs: vulnerability to dying during years of unusual warmth caused by large El Ni nos. Other ocean organisms that will also have trouble making $CaCO_3$ shells include several kinds of shellfish and tiny snaillike organisms called pteropods that are one part of the plankton floating in the ocean.

Acidification of the oceans will proceed as long as we keep burning carbon, and it will occur whether we burn it slowly (using conservation measures) or quickly (ignoring the environmental consequences).The only way to reduce acidification is to leave more fossil-fuel carbon in the ground. Other threats to the ocean have only recently been identified. The amount of oxygen in the world ocean has decreased in recent years, partly because warm water holds less oxygen in solution, and partly because warming of surface waters results in lower densities and less sinking of oxygen-rich water to great depths. This general ocean-wide loss of oxygen adds to a problem now underway in many coastal regions where excess runoff of chemical fertilizers from agriculture produces algal "blooms" that strip all of the oxygen out of the near-surface layers and leave seasonal "dead zones.

Methane exists as a gas in the atmosphere, but in Earth's colder regions it also occurs in a frozen form known as methane clathrate, a mixture of methane and slushy ice. Clathrates occur in deep-ocean sediments along continental margins, where the pressure produced by overlying water and sediments makes CH_4 stable at temperatures well above freezing (5C or more). Clathrates also occur in the Arctic, both in shallow ocean sediments and in permafrost layers on land. The volume of CH_4 stored in these reservoirs is enormous, far exceeding all carbon reservoirs in wetlands and livestock combined.

One frequently mentioned possibility is that faster melting of Greenland ice could send enough freshwater to the North Atlantic Ocean to lower its salinity and slow or stop formation of deep water. A relatively small drop in salinity in the Labrador Sea beginning in the 1970s lowered the density of the surface waters enough to prevent them from sinking during winters over the next two decades. Large-scale melting of the Greenland ice sheet or increased precipitation over the North Atlantic caused by greenhouse warming could conceivably add enough low-salinity water to slow formation of deep water.

A likely consequence of such a circulation change would be colder temperatures in northern Europe. Today, the heat extracted from North Atlantic surface waters during formation of deep water is carried eastward into Europe and helps to keep its climate warmer in winter than Canada or Siberia at the same latitude. Without this ocean heat, Europe would become colder than it is now. Recent reassessments suggest, however, that a major cutoff of deep-water formation in the Atlantic is unlikely. The planetary wind system will continue to drive relatively warm and salty surface water northward from the tropical Atlantic Ocean, where relatively cold winter air masses will continue to extract heat. Partial reductions of deep-water formation could occur with minor lowering of salinity, but any cooling effect on Europe is now considered unlikely to offset more than a fraction of the larger greenhouse-gas warming in a 3 $\times$ CO_2 world.

Estimated future changes in climate will likely reach a size comparable to the largest natural changes of the past. The projected 5 °C average global warming in a 3× CO_2 world would match the 5 °C cooling at the most recent glacial maximum 20,000 years ago. We are now, ~0.8°C (~16%)of the way toward that ~5°C warmer future. Unless technology or extreme conservation efforts intervene, we are likely to reach that much warmer future at rates that are unprecedented in Earth's 4.5 billion year climatic history.

In the distant future, most of the pulse of excess CO_2 will disappear into the ocean, and climate will cool back toward its preindustrial level, but not all the way back. The rate of decline will depend mostly on how much of the carbon reservoir buried in the ground we extract between now and then. Part of the excess CO_2 pulse (about 15%) will linger in the atmosphere for tens of thousands of years and keep climate too warm for new ice sheets to accumulate on North America or Eurasia. From the perspective of Earth's past climatic history, it is astounding to realize that we have now put an end to northern hemisphere glacial cycles that had been underway for almost 3 million years.

2. Conclusion

On a philosophical level, if we (meaning humanity) can manipulate climate, and if we choose to do so, what climate will we pick? Our first instinct may be that the safest path will return Earth to a "natural" climate, but what is "natural"? This is not a simple question.

We are not likely to go back to the pre-agricultural natural world that existed 10,000 years ago. The massive clearance of forests and plowing of prairies during the last century and a half will not be reversed because humanity needs the cropland and pastureland to grow enough food for the current global population, not to mention the 10 billion people expected by the middle of this century.

Perhaps a consensus may emerge that the optimal "natural" world was the not-too-warm, not-too-cold climate just prior to the industrial era, even though Earth's surface had already been massively transformed by that time. Or perhaps humanity will be unable to agree on a desirable future climate. In any case, humankind in the near future will likely be weighing the merits of whether to engineer a different climate, and if so which one. Earth's climatic future is now in our hands. What other major transformations will we cause in the future?

Compliance with ethical standards

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