12 ANTHROPOGENIC GLOBAL WARMING IN THE CONTEXT OF PALEOCLIMATE

Our current understanding is that, during almost all of Earth's history, interactions between Earth's interior, surface processes, and global climate feedbacks regulated atmospheric greenhouse gas concentrations so that temperatures were in the habitable range over most of the planet. Certainly this statement is true for the last 600 Myr, while Earth was inhabited by animals; uncertainty exists for most earlier times because we can't accurately characterize surface temperatures.

Evidence of ice in the tropics suggests that the climate went haywire at about 2.4 Ga (2.4 billion years ago), when atmospheric O_2 levels rose, and again about 710 and 630 Ma during Snowball Earth. Otherwise there is little evidence for great ice ages except for the Late Paleozoic (about 360–270 Ma) and the last half of the Cenozoic (34 Ma to the present). Like so many statements about past climate, some qualification is necessary; there were isolated glacial events earlier in the Paleozoic, and nearshore successions of sediment facies reflecting different water depths suggests that, at times in the Precambrian, sea levels changed as ice sheets waxed and waned.

The Late Paleozoic ice ages were followed by a long, ice-free period culminating in the equable climates of the Cretaceous and early Cenozoic. After a period of maximum warmth at around 50 Ma, the planet progressively cooled. Seminal events in this cooling occurred at 34 Ma (development of large ice sheets around Antarctica), 3 Ma (development of large ice sheets on the Northern Hemisphere continents and the origin of 40 Kyr ice age cycles), around 1 Ma (origin of the 100 Kyr ice age cycles), and 10 Ka (the end of the last glacial termination and the rise of atmospheric CO_2 to "preindustrial" levels).

An interesting feature of the Cenozoic climate is that the amplitude of climate change became larger as the mean climate became cooler. This pattern has two main causes. First, when the climate cooled below a certain threshold, large ice sheets developed that led to additional cooling from the ice albedo. Second, there were positive feedbacks between the physical climate system and the atmospheric CO_2 concentration that enhanced the magnitude of glacial-interglacial cycles; cooling climates led to changes in ocean circulation that caused the CO_2 concentration to fall. One could imagine a world with different continental positions where cooling would cause changes in ocean circulation leading to a higher CO_2 concentration. In this case, CO_2 would provide a negative feedback on glacial-interglacial climate change, and climate would be locked into some (presumably cool) intermediate state. Such locking probably occurred at times in the deep past but this phenomenon would be difficult to recognize in the sedimentary record.

Our ancestors gradually evolved in a world of changing climate. Human ancestors split from chimpanzees, our closest relatives, at around 7 Ma. Over the following millions of years, the bodies and brains of our ancestors became larger, bipedality developed, and they gradually evolved into us. The details are controversial. Many anthropologists would say that Neandertals appeared around 250 Ka, and anatomically modern humans developed sometime after 200 Ka. In deposits dating back to about 30 Ka, beautifully sculpted tools and spectacular carvings and cave paintings indicate that *Homo sapiens* had faculties fully equivalent to our own. By about 25 Ka anatomically modern man had interbred with Neandertals, or replaced them in their last European redoubts.

Climate change had a profound influence on human migrations. For example, around 14 Ka, the region of the Bering Straits became habitable enough that Asians could cross over into North America before sea level rose enough to cover the land bridge. The peopling of the Americas was soon followed by the extinction of most large American mammals. The cause(s) of this megafaunal extinction is contentiously debated. One contingent invokes human hunting to extinction. A second view is that the megafauna died because of disease linked to human habitation. Common to these hypotheses is the view that climate change in some way played a large role in the chain of events leading to the mass extinction, as well as the migration to the Americas.

Humans and human ancestors, like all other animals, evolved physically and culturally in a way that was shaped by climate. Our present physiognomy must reflect the long Cenozoic climate deterioration and the evolutionary pressures of the large glacial-interglacial cycles. There is a considerable literature dealing with human origins and climate, but it is difficult to attribute specific biological characteristics to specific climate phenomena.

Around 10 Ka, our ancestors discovered farming, setting the stage for large communities, division of labor, tyranny, and the development of powerful political entities. There seem to have been two requirements for the development of agriculture. The first was the development of the necessary level of intelligence. It seems reasonable to speculate that, by about 30 Ka, anatomically modern humans had evolved the capabilities for the task. The second was the rise of atmospheric CO_2 to the preindustrial level; this occurred by about 10 Ka. This change may have been essential for agriculture to become sustainable. The growth of plants can be limited by the availability of CO_2 in the atmosphere. The crop yield might have allowed farming to compete with hunting and gathering only when CO_2 had risen to preindustrial levels. Subsequently, advances in agriculture allowed larger and larger political entities to develop, leading to the modern world.

Climate has shaped civilization in many ways. Here is one obvious example: fertile areas of the planet are more heavily populated than deserts and ice-covered regions. However, there are many more subtle examples.

Civilization has developed to the point where humankind is now interacting with climate rather than merely responding. The primary way we are doing this is by adding CO_2, the leading agent for natural climate change over the Phanerozoic and beyond. We can assess the effects of this action using models that predict future climate, and by intelligently judging the implications of the paleoclimate record. Our best understanding is that fossil fuel emissions will lead to global warming, sea level rise, and large regional changes in rainfall during the coming centuries. With a high probability, we are already experiencing these effects in our climate. Already the planet has warmed by nearly 1°C. Sea level is rising at the rate of about 30 cm/century, and this rate is likely to increase as the planet warms.

How should we view the prospect of anthropogenic climate change? From the perspective of paleoclimate, it might not be particularly troubling, or even seem unwelcome. The present world is good enough for human habitation. However, it would improve if Greenland and Antarctica were unglaciated and habitable, and if there was more rainfall in areas that are currently deserts. For humans, in other words, the world might be more habitable if conditions resembled the high CO_2 equable climates of the Cretaceous, Paleocene, and Eocene.

The problem of anthropogenic global change, then, is not necessarily that we are heading for a less habitable planet. The problem is that both natural ecosystems and civilizations are aligned to the historic pattern of climate and water resources. Global warming will destroy this alignment is some regions. The most obvious example is sea level rise, which will render regions uninhabitable that are now occupied by tens or hundreds of millions of people. Shifting temperatures and rainfall belts will open some northern areas to agriculture while making agriculture impossible in some currently farmed regions. The disappearance of mountain glaciers will make water unavailable for agriculture in the seasons it is needed, and will supply water at other times when it may not be used efficiently.

The continued burning of fossil fuels will cause the atmospheric CO_2 concentration to rise. If we burn all readily available fossil fuels in the next few hundred years, we are likely to drive the atmospheric CO_2 concentration up to 1500 ppm or so, over five times the preindustrial level. This estimate takes into account that over hundreds of years, a large fraction of CO_2 is taken up rather quickly by the growth of forests and by dissolution in the oceans.

This high atmospheric CO_2 level would be unsustainable. The warm temperature and high CO_2 burden mean that once fossil fuels were exhausted, weathering would consume CO_2 faster than it is added by natural sources. The excess CO_2 would thus be slowly consumed and dissipated by weathering, exactly as for the Paleocene-Eocene Thermal Maximum. Carbon dioxide concentrations would fall, over a period of about 100,000 years, back toward their natural equilibrium level. With such a long horizon, two other factors would come into play. The first is orbital change and the natural climate cycle, which would push Earth back toward a glacial mode at some point. The second is additional transformations of the environment by humans. These tranformations are likely to be severe but cannot now be predicted. As for the past 4.5 Ga, Earth's climate in the near geologic future will be determined by changes in greenhouse gases, albedo, Milankovitch forcing, and perhaps solar variability. However, we cannot now know the forcings that will dominate climate change hundreds of thousands of years or more in the future, and hence cannot judge how climate will respond. Stay tuned.