The duration of the Anthropocene epoch: A synthesis

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Abstract: We synthesize research from complementary scientific fields to address the likely extent and duration of the proposed Anthropocene epoch. Ongoing intensification of human-forced climate change began in the mid-20th century, with steepening increases in greenhouse gases, ocean acidification, global temperature and sea level, along with the restructuring of Earth's biota. The resulting distinction between relatively stable Holocene conditions and those of the proposed Anthropocene epoch is substantial, irreversible, and likely to persist indefinitely. The still-rising trajectory of greenhouse gas emissions from the energy requirements of a growing global population is leading to yet greater and more permanent divergence of the Anthropocene from the Holocene Earth System. We focus here on the effects of the ensuing climate transformation and its impact on the likely duration of this novel state of the Earth System. Given the magnitude and rapid rise of atmospheric carbon dioxide (CO_2), its long lifetime in the atmosphere, and the present disequilibrium in Earth's energy budget (expressed as the Earth's Energy Imbalance, or EEI), both temperatures and sea level must continue to rise – even if carbon emissions were lowered to net zero (where CO_2 emissions = CO_2 removals) – until the energy budget balance is eventually restored. Even if net zero were achieved immediately, elevated global temperatures would persist for at least several tens of millennia. The expected levels of warmth have not been seen since the early Late Pliocene, and interglacial conditions are likely to persist for at least 50,000 years from now under already-accumulated CO_2 emissions and Earth's low eccentricity orbit. Continued increases in greenhouse gas emissions are likely to extend that persistence to around 500,000 years and will likely suppress the pronounced expression of Milankovitch cyclicity typical of the Pleistocene Epoch. This major perturbation alone is sufficient to justify the Anthropocene as an epoch terminating the Holocene Epoch; the wider effects of climate change in driving further, mostly irreversible, restructuring of the biosphere amplifies this distinction.

Introduction

The proposed establishment of an Anthropocene epoch recognizes that all aspects of the Earth System (atmosphere, hydrosphere, cryosphere, biosphere and lithosphere) have experienced dramatic change away from conditions characterising Holocene time. This break with the past began with a marked increase in humanity's energy use, industrial activity, technological innovation and globalization beginning in the mid-20th Century. Due to the growing pressure of human activities, the Earth System has been forced into a new state, warranting a new classification. The magnitude of the growing human impacts on the planet was addressed initially by research conducted within the International Geosphere Biosphere Program (Crutzen and Stoermer, 2000; Steffen et al., 2004, 2007, 2015), and subsequently described in detail by members of the Anthropocene Working Group (e.g. Waters et al., 2016; Zalaziewicz et 2019; Syvitski et al., 2020; Turner et al. 2024; Zalasiewicz et al., 2023 submitted). These various studies explain how the Anthropocene is conceptualized as a chronostratigraphic unit with a proposed start in the mid-20th century (Waters et al. 2016; Zalasiewicz et al. 2015, 2020; Head et al. 2022). Although Crutzen initially thought that the Anthropocene might be considered to date from the latter part of the 18th Century (Crutzen and Stoermer, 2000), he later agreed that it should commence at the start of the major change in the state of the Earth's System in the mid 20th Century (Zalasiewicz et al. 2015). Here we focus on how long this proposed new epoch might last.

The change from Holocene to Anthropocene conditions in part reflects the growth in the human population from 1.6 billion in 1900, to 2.5 billion people in 1950, and to 8.0 billion currently (UNPF 2023). Although human activities had gradually increasing impacts throughout the Holocene as population slowly grew, these were mostly local to regional, in contrast with the situation from about 1950 onwards, during which the human energy footprint sharply increased in response to population growth and became essentially global (e.g. WBGU 2009, 2011). The resulting dramatic increase in energy consumption (Syvitski et al. 2020) and the associated production of goods (Elhacham et al. 2020) has been termed the Great Acceleration (Steffen et al. 2007, 2015; McNeill and Engelke 2014; Head et al. 2022), and has resulted in an array of distinct geological signals in sedimentary environments worldwide (Waters et al. 2023).

Recent projections of 'peak' population (to 10.4 billion; UN 2022), reflect increases in human lifespan, and global birth rates exceeding replacement values. Massive amounts of energy and natural resources will continue to be required to meet growing human needs. Fulfilling those needs will affect the biosphere and other aspects of the Earth System far into the future, even if a technological transformation to renewable and nuclear energies, and to ubiquitous recycling eventually gives rise to a 'circular' economy (e.g. Raworth, 2017).

Post-mid-20th Century human impacts have already fundamentally moved the Earth System away from the general stability that characterized the Holocene Epoch, into an Anthropocene state that is increasingly physically, chemically and biologically perturbed (Steffen et al. 2016; Zalasiewicz et al. 2019; Williams et al. 2022; Ripple et al., 2023). Exemplifying this change, the average global temperature in 2023 was 1.48°C warmer than the 1850–1900 pre-industrial level (Copernicus, 2024). Every day within that single year exceeded the 1850–1900 pre-industrial level by 1°C, ~50% of days were more than 1.5°C warmer, and two days in November 2023 were for the first time >2°C warmer (Copernicus 2024). Antarctic sea ice in 2023 reached just 1.79 million km^2 (NSIDC 2024), some 2.67 million km^2 less than the 1991–2023 average, and its lowest daily extent since the advent of satellite data in 1978 (Ripple et al., 2023). By February 2024 it was at a similarly record low level, 1.99 million km^2 (NSIDC 2024). This raises the prospects, among others, of (i) warm ocean water moving closer to Antarctic ice shelves, speeding their melt and so raising global sea level, and (ii) diminishing Antarctic sea ice cover reducing the production of the Antarctic Bottom Water that aerates the deep ocean floor.

We focus here on the climate shift caused by increasing greenhouse gases through burning fossil fuels and expanding animal husbandry and other agricultural practices (Figure 1), the effects now reverberating across the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. Even if these greenhouse gas emissions were halted today, their effects already in play would last for hundreds of thousands of years because of (1) the long residence time of CO_2 in the atmosphere; (2) the reduced ability of the global ocean to sequester carbon (less CO_2 will dissolve in a warmer ocean); and (3) the release to the atmosphere of CO_2 currently stored in the ocean, to maintain chemical equilibrium between the ocean and atmosphere if and when emissions of CO_2 decline (Archer et al. 2009). This tight relationship between CO_2 concentration and climate is exemplified by atmospheric CO_2 and temperature proxies being closely in step in ice cores covering the past 800,000 years (Bereiter et al. 2015), and through marine records of boron isotopes showing that atmospheric CO_2 concentrations have been closely coupled with climate change for at least the past 66 million years (Rae et al. 2021; see also The CenCO2PIP Consortium, 2023).

Figure 1 here

Global atmospheric CO_2 levels, based on anthropogenic emissions (a–c) and total concentrations (d). Graphs a and b represent fossil fuel and industry emissions, with land-use change not included. Note that while anthropogenic emissions have begun to level off in recent years, total concentrations have continued to rise unabated. From Our World in Data (2023).

Continued fossil fuel usage and resulting carbon emissions will affect global warming into future millennia, given the principles of carbon chemistry and physics combined with constraints on forward projections of climate conditions (Steffen et al. 2018; Benner et al. 2021).

Climate change also exacerbates changes to the biosphere. In recent decades habitat destruction, human-caused extinctions, biotic homogenizations, increasing numbers of domesticated animals and plants, ocean acidification and pollution have already set in place new and irreversible evolutionary and ecological trajectories (Saintilan et al. 2023; Conrad et al. 2024; Williams et al. 2024 submitted). Such changes to the biota are intensifying (IPBES 2019; Duarte et al. 2007; WBGU 2013; Rockström et al. 2023). Global warming is adding to these human pressures, and amplifying this indelible signal in the paleontological record.

Projections of the amounts and effects of global warming beyond 2100 can appear alarming, even as society works to minimize the potential impacts (Ritchie, 2023). Nevertheless, concerns about future global warming and its effects can also drive change, given sufficient political will. However, modern economic theory still typically sees the environment as a valueless externality, an approach that contributes to global climate change and needs radical revision (Carney, 2021; Raworth, 2017). We already possess many of the technologies required to reduce atmospheric greenhouse gas levels (e.g. Gates, 2021; Project Drawdown, 2017). But, even with substantial mitigation measures in place soon, the Anthropocene's duration as regards climate will certainly exceed that of the Holocene.

Here we review the evidence for a long Anthropocene, and briefly consider what might be done to temper its effects on human civilization.

Energy Use and Global Warming in the Anthropocene to Date

The world we inhabit is built and powered by fossil fuels, with more than 90% of all human consumption of coal, oil and gas occurring since 1950 (BP 2022) (Figure 1). This combustion has been by far the largest component in releasing ~2.45 trillion tonnes of CO_2 into the atmosphere since the Industrial Revolution (Friedlingstein et al. 2022); ~ 25% of this anthropogenic CO_2 has been fixed in the biosphere, and ~25% has been dissolved in the oceans. Much of the remaining 50% has accumulated in the atmosphere in the form of the ~140 ppm increase in CO_2 over the pre-industrial baseline of ~280 ppm, which translates into ~1.1 trillion tonnes of injected anthropogenic CO_2. This has been accompanied by a similarly rapid and proportionally larger increase in atmospheric methane (CH_4) of >150% (i.e., pre-industrial baseline of ~800 ppb to current levels of ~1900 ppb; Ritchie et al. 2020; Nisbet et al. 2023), and parallel rises in powerful greenhouse gases such as nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) (IPCC 2023).

Intensification of the greenhouse effect results from the growth in emissions of the CO_2 equivalent (CO_2-eq), calculated as the sum of the effects of CO_2+CH_4+N_2O+CFCs and other trace gases, with their concentrations converted to the equivalent amount of CO_2. According to NOAA (2023a), in spring 2022, when the concentration of CO_2 in the air was 417 ppm, the CO_2-eq had reached 523 ppm. Paleoclimatic analyses show that such a combined increase in atmospheric CO_2 and other greenhouse gases is unprecedented over at least 800,000 years (Lüthi et al. 2008). Today's CO_2 levels are similar to those were last seen in the early Late Pliocene, around 3.5 million years ago (Grant and Naish 2021; Raymo et al. 2011; Rohling et al. 2022; Haywood et al. 2020), and are nearing values typical of the mid-Miocene (16.9–14.7 Myr ago) (Steinthorsdottir et al. 2021; The Cenozoic CO_2 Proxy Integration Project (CenCO_2PIP) Consortium, 2023). IPCC projections based on intermediate emissions scenarios (SSP- 2-4.5) place us on track by 2100 to reach CO_2 concentrations of 600 ppm, with a mean global temperature of ~+2.7°C, certainly higher than for any time during the Quaternary (the past 2.6 myr), and that is based on CO_2 alone.

The Earth's Energy Imbalance (EEI) – the difference between the heat energy retained by the Earth and that radiated into outer space – has been increasing in tandem with atmospheric greenhouse gas rises and now averages 1.36 Watts/m^2 (Hansen et al. 2023), with ~400 zettajoules of energy (mostly as heat) accumulated by the Earth since 1971 (von Schuckmann et al. 2023); by comparison, humanity's direct energy use is ~0.5 zettajoule/year (Forster et al. 2021; von Schuckmann et al. 2023). Most (89%) of this excess energy has been absorbed by the oceans, 6% by the land surface, and 4% by the cryosphere. Just 1% has gone into heating the atmosphere (von Schuckmann et al. 2023). Noting the different heat capacities of these different realms, the globally averaged climate has warmed by almost 1.5°C since 1900 (Copernicus 2024), with a significant land–sea difference: on average, the surface ocean has warmed by about 0.88°C, while the land surface has warmed by about 1.6°C (IPCC 2023). The Central England Temperature database, which dates back to 1659, shows that current UK temperatures have increased since 1900 by just above 1.0°C, significantly less than the 1.6°C land surface average (Met Office 2023); this difference is likely due to the influence on the British Isles of the maritime climate of the Northeast Atlantic and the prevailing westerly winds. The average warming in the Arctic, by contrast, is between 3 and 4 times the global average (Rantanen et al. 2022).

If greenhouse gas levels were steadied with a net zero emissions state, i.e. emissions of CO_2 balanced by subtractions of CO_2 from the atmosphere, the energy balance at the Earth's surface would still be out of equilibrium, with 'locked-in' warming persisting until energy equilibrium between the atmosphere and the ocean, a massive heat source, was restored over many millennia. The course of this inevitable warming will be strongly affected by the interplay of various feedbacks, and will likely take millennia, as explained below.

Feedbacks

The rate of heat capture has increased systematically over the last half-century, as greenhouse gas levels built up, with various feedbacks amplifying the warming. One feedback system is the increase of water vapor, a potent greenhouse gas not counted as part of the CO_2-eq by the IPCC. Basic physics shows that a rise in average global surface temperature of 1ºC will evaporate 7% more water vapor from the ocean (Held and Soden 2006; O'Gorman and Muller 2010), contributing directly to global warming in the mid- to lower troposphere. According to NASA, water vapor is responsible for ~50% of atmospheric global warming, with clouds (not water vapour but aggregates of minute droplets of water and / or ice) responsible for ~25% and CO_2 responsible for ~20% of the effect, the remaining ~5% coming from minor greenhouse gases such as ozone (O_3) and CH_4, and a small amount from aerosols (Schmidt et al. 2010). Water vapor does not reach the stratosphere, the cold temperatures there converting it into ice crystals, and effectively freezing H_2O out of the greenhouse gas equation at such altitudes. However, a more recent evaluation by the International Energy Agency demonstrated that methane may be responsible for as much as 30% of global warming since 1900, 60% of that contribution being anthropogenic; these figures include much data that has previously been under-reported (IEA 2022a).

Global warming also contributes to the melting of ice and snow, exposing dark surfaces on land and oceans that therefore absorb more incoming solar energy (i.e. reducing Earth's albedo), thus increasing Earth's temperature. Highly reflective snow and ice in the polar regions and high mountains help to keep Earth's overall climate relatively cool by reflecting solar energy back into space. In that sense the world's icy regions act as Earth's refrigerator, a feature that we are beginning to lose as ice and snow melt away (Summerhayes 2023).

Permafrost is gradually melting beneath both the land and the drowned seabed of the Arctic continental shelf, facilitating the decomposition of enclosed organic matter, which releases CH_4 if the conditions are reducing, and CO_2 if they are oxidising. During the summers of the relatively cool early 20th century, the permafrost surface would melt to a depth of between 0.3 and 3 m (Hjort et al. 2018), and then refreeze in winter, in an overall stable balance. As the Earth has warmed, summer melting depths have increased, aided by a lengthening of the summer melt period. Will the emissions of CO_2 or CH_4 from thawing permafrost contribute substantially to global warming? That will depend on the depth to which the permafrost eventually melts. During the last four major interglacials, when peak temperatures were higher than they are today, CH_4 values measured in ice cores did not show a major increase, leading Wolff (2011) to suggest that the fear of a 'methane bomb' from permafrost melting may be exaggerated.

CH_4 has at times increased rapidly in the geological past, triggered by rises of insolation as earlier glacial phases gave way to interglacial phases, a feature that makes this gas extremely useful for correlating ice cores from Greenland with those from Antarctica. As with CO_2, methane did not rise beyond a well-documented peak interglacial level (~700 ppb, compared with >1900 ppb now) (Bazin et al. 2013). During the Early Holocene, after an initial rise, CH_4 values initially fell along with a decline in high latitude insolation, as they did also in previous interglacial intervals. Then they began to rise over the past 3000 years, plausibly in response to the development of rice farming in eastern Asia (Ruddiman et al. 2016). The CH_4 signal then stabilized before rising abruptly again along with the modern warming (IPCC 2023). The major source for CH_4 in recent years appears to have been agriculture and land use (Xu et al. 2021), along with feedback from the warming of tropical wetlands (Nisbet et al. 2016, 2023; Huang et al. 2021). Fugitive CH_4 plumes associated with gas production sites (such as hydraulic fracturing, or 'fracking' centers), and/or from poorly maintained gas extraction and storage systems, are also important contributors of CH_4 release to the atmosphere (Albertson et al. 2016; Schneising et al. 2020).

Positive feedbacks with geologically long-term effects include 'tipping points' that, once crossed, cannot be easily reversed, and which would amplify climate change (White et al. 2013). These include the possible disappearance of ice-sheets (e.g. loss of the West Antarctic Ice Sheet; Naughten et al., 2023), possible expansion of tropical ecosystems, changes in oceanic thermohaline circulation patterns (e.g. a reduction in the strength of the Atlantic Meridional Overturning Circulation (AMOC; van Westen et al., 2024) that brings heat to western Europe), and loss or severe reduction of the Amazon rainforest, seagrass, coral reefs, coastal wetlands and other ecosystems which today collectively represent major carbon sinks. The likelihood of such changes is thought to increase as warming progressively exceeds +1.5°C above 1900 levels (McKay et al. 2022), with rising temperatures and sea-levels inevitably leading to the erosion and retreat of low-lying coastlines and reef islands (e.g. Saintilan et al. 2023; Ripple et al. 2023; Li et al. 2024).

Effects of global warming to date

Physical changes to the Earth System have included melting ice and snow, leading to reductions in glacier lengths worldwide (Zemp et al. 2015, 2019; Hugonnet et al. 2021), along with decreasing polar ice sheet masses (Rignot et al. 2019; Mouginot et al. 2019), and a noticeable decline in Northern Hemisphere-scale March snowpack over the 1981–2020 period (Gottlieb and Mankin, 2024). These all contribute directly to the 1901–2018 rise in sea level of 0.20 m (IPCC 2023) (Figure 2), while part (~40%) of that rise is attributable to the warming and expansion of the ocean. Indeed, ~90% of the current global warming is contained within the world's oceans, mostly in the upper 500 m of the water column (Cheng et al. 2023, 2024). This is because the oceans have very high heat capacity; the top 3 m of the ocean carries as much heat as the entire atmosphere. The heat of global warming is presently working its way slowly into deeper water, with warming now reaching at least 2000 m below sea level (Abram et al. 2019). On land, June 2023 was the warmest June on record (NOAA 2023b); July 2023 was the warmest July (Copernicus 2024), with an average temperature 1.54°C above preindustrial levels (Tollefson 2023); and by August 1st the ocean had warmed to almost 21°C, well above the previous August record of ~20.7°C (Rannard et al. 2023). This recent warming, with 2023 forming the warmest year yet (Copernicus (2024), coincided with wildfires in many areas, including Canada 2023, which experienced its worst fire season in modern history (Germond 2023), as did Texas in 2024 (https://fire-information-tfsgis.hub.arcgis.com/pages/historical-fire-statistics).

Figure 2 here

Projections of Earth's future climate state to the year 2100 for SSP-based (SSP = Shared Socio-economic Pathway) scenarios that use a range of CO_2 *emissions trajectories reflecting differing mitigation strategies. a)* CO_2 *emissions trajectories upon which SSP-based scenarios are based, where color coding represents each of the five SSP-based scenarios for very low to very high emissions. b) Global surface temperature change relative to 1850–1900 for the five SSPs shown in (a). c) Global mean sea level rise relative to 1900 for the five SSPs shown in (a). d) Projected changes to the distributions of surface temperature, soil moisture, and precipitation based on a global rises of 1.5°, 2°, 3° and 4°C relative to 1850–1900. Note that global surface temperatures surpass 2° by 2050 assuming an intermediate emissions scenario (b). Based on figs. from pages 65 (a), 75 (b, c), and 14 (d) of the IPCC (2023).*

Antarctica is not warming as fast as the Arctic, except on the Antarctic Peninsula, which projects far to the north of the bulk of the continent, and where a record high temperature of 18.3°C was recorded in February 2020 (WMO 2021) and attributed to global warming (González-Herrero et al. 2023). In March 2022, East Antarctica, the higher and thus colder part of the continent, experienced the most extreme 'heatwave' ever recorded globally, when surface temperature anomalies of up to 38.5°C were observed, although the overall temperature remained below zero (Siegert et al. 2023). In the southern summers of 2023 and 2024 (NSIDC 2024), Antarctica also experienced record losses of sea ice, while the winter extent for 2023 remained at a near-record low (Siegert et al. 2023).

Strong westerly circum-Antarctic winds help keep warm surface conditions from the north impinging on the continent, as does the Antarctic Circumpolar Current (ACC). The westerly winds acting on the Southern Ocean surface cause warm subsurface water to rise towards the surface through marine upwelling. The incursion of these warm subsurface waters beneath thick floating ice shelves (Herraiz-Borreguero and Naveira Garabato 2022) melts them from below, causing the shelves to thin. While this process does not raise sea level directly, it weakens the buttressing effect of ice shelves, allowing yet more inland ice to contribute to sea-level rise. As ice is increasingly lost from the interior, the land very slowly rises through glacial isostatic adjustment, which will regionally mitigate against the effect of sea-level rise. For instance, Hudson Bay in Canada is still rising today even though the Laurentide Ice Sheet of North America, one of whose domes covered the bay area, had melted away by about 7000 years ago (Simon et al. 2016). However, global warming and associated ice melt is now occurring at far greater rates than glacioisostatic rebound.

Much intrusion of warm subsurface seawater also affects the seaward ends of Greenland's tidewater glaciers (those that end in the ocean). However, most of Greenland's loss of ice comes from melting of the surface of the ice sheet, part of which simply runs as meltwater into the sea, while part creates surface ponds whose water melts its way down through the ice sheet via fissures to lubricate, and so speed, ice flow at its base (Slater and Straneo 2022).

Surface ponds rarely develop in Antarctica, which is much colder than Greenland (Ramanathan et al. 1979). The troposphere is thinner in the Southern Hemisphere than it is over the North Pole, which means that surface air pressure is 20% lower at 80°S than at 80°N. As the transparency of the atmosphere to infrared radiation (heat) is proportional to atmospheric pressure, the atmosphere traps less outgoing heat in the south at comparable latitudes, and so warms less than in the north. Secondly, Antarctica also has a far larger area of ice than the Arctic in most seasons, amplifying its albedo, which cools the south yet more. Thirdly, Antarctica is the highest continent in the world when including its ice sheets, with an average height of 3000 m, helping to make it much colder than the Arctic (though not at the Antarctic coast). Finally, Antarctica is also surrounded by the cool Southern Ocean, and is thermally insulated by the Antarctic Circumpolar Current and associated West Wind Drift, while the almost land-locked Arctic Ocean receives heat through the air, and through the North Atlantic (mainly) and the North Pacific oceans.

Global warming has led to a dramatic decline in Arctic sea ice, which now in summer occupies about half of the area it did in 1980 (NSIDC 2023). The remaining sea ice is also much thinner than it was in 1980, when much of it was up to 5 m thick (NSIDC 2023). Most of the remaining sea ice is now only a meter thick, with the thicker ice being restricted to the coasts and channels of the Canadian Arctic Islands. In contrast, because of continental Antarctica's geographical situation and thermal isolation, its sea ice did not, until recently, show any such decline, its average area remaining more or less constant, despite ups and downs, since satellite measurements of ice area began in 1978 (NSIDC 2023). Since 2014, however, large swings in sea ice area, and a warming of the subsurface waters that impinge on the Antarctic ice-sheet (Li et al. 2023; Voosen 2023), culminated in recent massive decreases in Antarctic sea ice area. According to Naughten et al. (2023), the Amundsen Sea is now committed, over the twenty-first century, to warming at triple the historical rate for the Southern Ocean, and thus to widespread increases in ice-shelf melting. Their results suggest that mitigation of greenhouse gases now has limited power to prevent ocean warming that increasingly threaten the collapse of the West Antarctic Ice Sheet (Naughten et al. 2023).

Holocene Climate and the Future to 2100

To understand the origins of present climatic conditions and how they may change in the future, we first examine climate change during the Holocene (the past 11,700 years). Following the Last Glacial Maximum some 20,000 years ago, temperatures rose along with rising incoming solar radiation (insolation), before flattening between 10,000 and 5,000 years ago. Paleoclimate data from tree rings and ocean sediment cores had suggested that global temperatures declined from an initial climatic optimum during the Early and Middle Holocene (Ljungqvist et al. 2012; Marcott et al. 2013). This supposed Late Holocene cooling trend, visible for instance in temperatures from Greenland (Vinther et al. 2009), was thought to be leading Earth's climate into a 'neoglacial' period. However, Liu et al. (2014) and Baker et al. (2017) found that the neoglacial cooling trend opposed a Holocene warming trend simulated by climate models. Subsequent examination of global insolation data by Bova et al. (2021) showed that the *global* insolation average trend for the Holocene was almost flat, with a very slight increase of about 1W/m^2 over the past 7 kyr. This paralleled a slight rise of about 20 ppm in CO_2 over the same period, remarked upon by Ruddiman et al. (2016), leading Bova et al. (2021) to suggest that the Holocene climate should have warmed very slightly over the past 5,000 years or so. The rise in CO_2 could reflect the warming of the ocean caused by the rise in insolation, contrary to Ruddiman's hypothesis that the CO_2 rose due to increasing human activities. Broecker argued that the most likely source for the CO_2 had to be the ocean, which holds by far the largest CO_2 reservoir on the planet (Broecker et al. 1999; Broecker and Stocker 2006). The association of slightly rising CO_2 with the slightly rising mean annual insolation noted by Bova et al. (2021) may vindicate Broecker's notion. Nevertheless, Ruddiman is probably correct in arguing that the slight rise in CH_4 of the past 3 kyr did reflect the rise in rice farming in east Asia (Ruddiman et al. 2016). According to Bova et al. (2021), the post-industrial increase in global mean annual surface temperatures rose from the warmest background state of the Holocene, making current temperatures the warmest observed over the past 12,000 years and probably reaching the warmth of the Last

Interglacial, 125,000 years ago, when Milankovitch insolation was greater than at the beginning of the Holocene owing to higher orbital eccentricity.

Insolation data provide clues to the drivers of Holocene climate change. Figure 3 shows that summer insolation was substantial, especially in the north of the northern hemisphere at ~9 kyr BP, with its peak shifting to the southern hemisphere by 3 kyr BP. This shift was due to the change in the precession of the equinoxes, which led to the northern summer solstice being closest to the Sun ~11 kyr BP, and farthest from the Sun today. Similarly, a decrease in obliquity (the tilt in the Earth's axis) from 9 kyr BP to today reduced overall summer insolation in both hemispheres (Crucifix 2009). Over the past 6 kyr, insolation increased in the tropics and mid-latitudes while decreasing at both poles (Figure 4). Early in the Holocene, when summer insolation was high (Figure 4), incoming solar radiation gradually melted away the remnants of the Northern Hemisphere ice sheets, which, for as long as they persisted, kept high-latitude Arctic relatively cool. The development of the neoglacial conditions, as defined above, and which we now see as polar in response to changing insolation (Figures 3 and 4, and Vinther et al. 2009), can be explained as due to albedo increase as ice cover increased in polar regions in the Late Holocene in tandem with Northern Hemisphere summer insolation decline (e.g. McKay et al. 2018; Crucifix, 2009). Evidently, the 'neoglacial' was a polar and not a global phenomenon, and such variations will continue to influence climate after the end of the present century.

Figure 3 here

Distribution of shortwave radiation (insolation) received from the Sun at the top of the atmosphere between 9 ka ago (Before Present, or BP) and 6 ka into the future (After Present, or AP). A mean distribution of insolation assuming no eccentricity and a mean obliquity of 23º 20' was subtracted from the annual insolation in order to highlight the effects of changes in precession and obliquity. Precession redistributes heat across the seasons (positive anomalies around July 9 ka ago in the north and around January at present in the south). The decrease in obliquity during the Holocene reduces summer insolation in both hemispheres from 9 ka ago onwards. From Figure 4.4 in Crucifix (2009).

Figure 4 here

Calculated deviations of insolation from the long-term mean values (W/m^2) as a function of latitude for the past 6000 years: annual mean. From Figure 6(d) in Beer and Wanner (2012).

While there are differences in insolation between the northern and southern polar regions (Figure 3), the two areas remain intimately connected through the ocean's global thermohaline conveyor, which transfers heat and salt around the world (Broecker, 2010). The sinking of cooled dense salty Gulf Stream surface water in the Norwegian-Greenland Sea and Labrador Sea, transported by the North Atlantic Current, provides North Atlantic Deep Water to the deep Southern Ocean. Under the driving influence of powerful westerly winds, these deep waters well up to the surface around Antarctica, where they provide a source for cold Antarctic Bottom Water that sinks down the Antarctic continental slope and aerates the deep ocean floor of the Atlantic beneath North Atlantic Deep Water as far north as Lisbon, Portugal. The time scale for these exchanges is of the order of ~220 years in one direction, and ~500 years for the round trip (WAIS 2013). The connection between the North Pacific and Greenland through the conveyor takes longer – about 1000 years in each direction, providing complete ocean circulation over a period of about 2,000 years. Along the routes of these long teleconnections, local and regional climatic variability (e.g. 4–7 year-long El Niño events and the 20–25 year-long so-called Pacific Decadal Oscillation) introduce potentially global but relatively small-amplitude climate variability.

There is a substantial lag in the Earth System's response to global warming that needs to be considered when estimating future rates of sea-level rise. For instance, sea level did not reach its Holocene equilibrium level until some 7 kyr BP (Clark et al. 2016), ~5000 years after the Holocene had reached maximum insolation. Sea level rose by 45 m between the peak of post-glacial insolation (~12 kyr BP) and 7 kyr BP as the great Northern Hemisphere ice sheets melted away (Clarke et al. 2016). A similar disequilibrium relationship is to be expected between the modern rapid temperature rise and sea-level rise, with the current rate of sea-level rise appearing misleadingly slow, with much higher rates likely in future until sea level, temperature, and global ice volume equilibrate (Figure 2c). Nevertheless, we would not expect a 45 m sea-level rise in the near future, because the extensive Northern Hemisphere ice sheets have already largely melted away. Only Greenland, Antarctica and mountain ice-fields remain as potential meltwater sources (melting of the Greenland Ice Sheet would raise sea level by 7 m, while melting of the West Antarctic Ice Sheet and parts of the East Antarctic coast would raise sea level by between 3 and 5 m).

Why did sea level not rise along with the rise observed in global average insolation and CO_2 over the past 7 kyr? It seems most likely that the Late Holocene neoglacial increases in ice growth in the polar regions (mentioned earlier) responded to the regional decreases in insolation there (Figures 3 and 4). These operated against the warming that might have been expected from average global insolation to cause ice melt. Evidently, global temperature change and ice melt do not operate on a simple 1:1 basis in response to changes in either insolation or CO_2. It matters where the ice is distributed on the Earth's surface.

Aside from insolation changes driven by the slow cycles of orbital eccentricity (~100 and 400 kyr), axial obliquity (or tilt) (~40 kyr) and precession (~23 kyr) and their harmonics, the Holocene also experienced faster (but much weaker) periodic changes in insolation caused by variations in solar output, such as those identified from ^{14}C data by Stuiver et al. (1998) and from ^{14}C and ^{10}Be data by Steinhilber et al. (2012). These variations caused local climate variability, as recognized for instance from variations in European lake levels (Magny 2004, 2007) and in the patterns of ice-rafted debris in North Atlantic marine sediment cores (Bond et al. 2001). Similar solar variability will continue past the end of the present century, causing minor global fluctuations.

The most recent of the larger changes in solar output were those of the Medieval Warm Period (MWP: solar warming centered on the year 1000 CE), and the so-called Little Ice Age, which occurred during the Maunder Sunspot Minimum centered on ~1650 CE, and which made the River Thames in London freeze over in winter. A recent analysis of *Pinus sylvestris* trees in Fenno-Scandinavia has provided high fidelity proxy measurements of instrumental temperature variability during the warm season: these show that the peak summer temperatures of the MWP were substantially cooler than those of the present period, in agreement with models of insolation (Björklund et al. 2023). Evidently, today's climate is warmer than it was during the MWP.

In the IPCC's Synthesis Report of its 6th climate change assessment, the Summary for Policy Makers indicates global warming to already be affecting Earth's climate state and its weather extremes for every region of the planet. This includes increases in heatwaves, heavy rains, droughts, and the intensity of tropical cyclones (IPCC 2023). To explore how Earth's climate may evolve in the near geological future, the IPCC highlighted five scenarios based on shared socio-economic pathways and their associated atmospheric CO_2 concentrations (Figure 2). In high emissions scenarios, CO_2 emissions nearly double by 2100 CE, with warming reaching ~4°C. In intermediate emissions scenarios, CO_2 emissions remain at about current levels until 2050 and then decline, limiting warming by 2100 to ~2.5–3°C. In low and very low emissions scenarios, CO_2 emissions decline to net zero in 2050–2070, and are followed by net negative CO_2 emissions, limiting warming to 1.5°C (IPCC 2023; Figure 2). It now seems inevitable that global average temperatures will pass 1.5°C between 2030 and 2050, and highly likely that they will exceed 2°C before 2100 (IPCC 2023). Presently, on the basis of current politically-agreed aspirations, via Nationally Determined Contributions, warming is projected to average about 2.7°C by 2100 (Carbon Action Tracker 2022). Arctic temperatures are likely to rise between 2 and 4 times the global average (Rantanen et al. 2022).

The lowest of those projections are conservative. If the rate of CO_2 rise continues at ~2.6 ppm/yr, then over the next 77 years CO_2 concentration would rise by 200 ppm, reaching around 620 ppm by 2100, with CO_2-eq reaching around 700 ppm, a value not seen since Eocene times before the initiation of the Antarctic Ice Sheet 34 million years ago (Beerling and Royer 2011; Foster et al. 2017; The Cenozoic CO_2 Proxy Integration Project (CenCO2PIP) Consortium, 2023), when redwood forests grew in the high Canadian Arctic (Eberle and Greenwood 2012).

For coastal cities and communities, the accelerating rise in global mean sea level represents a key threat from global warming. This rate increased at 1.3 mm/yr (from 1901 to 1971), at 1.9 mm/yr (from 1971 to 2006) and at 3.7 mm/yr (from 2006 to 2018) (IPCC 2023). Between 2014 and 2023 it reached 4.77 mm/yr (WMO 2024). Relative to 1995–2014, the likely global mean sea-level rise under the IPCC's low emissions scenario is 0.15–0.23 m by 2050 and 0.28–0.55 m by 2100; while for the IPCC's high emissions scenario (continuance of present rates of increase) it is 0.20–0.29 m by 2050 and 0.63–1.01 m by 2100 (IPCC 2023). Other projections are less conservative. For instance, Grinsted et al. (2010) suggested a rise of 0.9–1.3 m by 2100, while Rohling et al. (2013) noted, on geological grounds, that by then sea level would likely rise by up to 0.9 to 1.8 m, creating serious problems (such as periodic flooding, and salt-water intrusion into ground water) for the extensive communities and cities of the world's coastal zone (e.g. Ohenhen et al., 2024) and diminishing coastal biodiversity (Saintilan et al. 2023; Lyon et al. 2021).

The trajectory of greenhouse gas release

Future climate evolution will reflect how much of the Earth's fossil fuel reserves and resources (still considerable) are burnt over coming decades and centuries. For the present, the most practical guide to which emissions pathway will emerge is given by the forecasts of industrial bodies, and by published patterns of investment, which, as we write, continue to rise for both renewable and fossil-fuel-based energy (e.g. IEA 2022b), vis-a-vis national intentions as stated emissions targets.

The International Energy Agency's annual World Energy Outlook (e.g. IEA 2022b) indicates that, between now and 2050, most energy provision will continue to come from the burning of fossil fuels. The IEA expects energy from fossil fuel production to rise from ~495 exajoules in 2020 to a broad peak of ~510 exajoules by 2025, falling to 475 exajoules by 2050 (1 exajoule is equivalent to ~0.5 million barrels of oil equivalent – from oil, gas, or coal). Because of a projected rise in renewable energy over this same period, the proportion of fossil fuels in the energy supply mix is forecast to decline from 80% in 2020 to 60% in 2050 (IEA 2022b). The IEA forecast implies in turn a rise in the proportion of renewable energy + nuclear energy, from ~20% of the total energy mix in 2020 to 40% in 2050. This picture is already changing, for example as China ramps up renewable energy sources; fossil fuels now account for less than half of China's total installed power capacity (Yale E360, 2023).

The IEA forecast also suggests that the emissions of CO_2, and of fugitive CH_4 from leaky extraction and supply systems, will also reach a broad peak centred on 2025 (IEA 2022b). However, if nothing is done to extract new (post-2023) emissions of these gases from the air, they will add to the total greenhouse gas burden, with attendant global warming (IPCC 2023).

By How Much Might Climate Warm with Continued Emission of CO_2?

In assessing the potential for further global warming, Hansen et al. (2023) noted that by 2020–2023 the EEI had reached 1.36 W/m^2. Evidently, the Earth's Energy Imbalance is increasing, making yet more difficult the stabilization of climate at or near current values. Hansen et al. (2023) calculated how high future temperatures may reach, simply if present greenhouse gas levels are maintained. From current understanding of global temperature change during Quaternary glacial-to-interglacial transitions and more generally during the Cenozoic (past 66 million years), they suggested that the fast-feedback equilibrium climate sensitivity (ECS) is 1.2 ± 0.3°C per W/m^2 (including the amplifications from disappearing ice sheets and non-CO_2 greenhouse gases). This translates to a 4.8°C ± 1.2°C global temperature rise for doubled CO_2 ($2 \times CO_2$), a value substantially greater than the ECS of 3°C adopted by the IPCC in their AR6 report (IPCC 2023). Using this, Hansen et al. (2023) calculated that equilibrium global warming for today's greenhouse gas levels, and after slow feedbacks operate, is about 10°C, which dwarfs the present global average temperature rise of ~1.5°C. Much of this anticipated large rise in temperature (greater than between glacial-to-interglacial transitions) reflects not merely the effect of greenhouse gases currently in the atmosphere, but also the effect of declining albedo due to long-term ice melt, plus the slow release of accumulated heat and CO_2 from the ocean as it equilibrates with the atmosphere, and the slow release of CH_4 and CO_2 from melting permafrost. Incorporating the effect of reflective aerosols would reduce the 10°C to 8°C (Hansen et al. 2023). Nevertheless, this new analysis means that more warming may be 'in the pipeline' than is widely assumed based on the IPCC's analysis. These findings suggest that we are on route to approaching the levels of warming of the mid-Eocene, some 13°C higher than today. All things being equal, one might expect a rise of this magnitude to be reached after ~2,000 years (the overturning period for the global ocean – see above).

Hansen et al. (2023) considered that the discrepancy between their results and those of the IPCC were a reflection of (a) the IPCC's consensus-taking position being cautious and conservative; (b) the IPCC's focus on the use of Climate General Circulation models (which have their limitations); and (c) Hansen et al. using paleoclimatic data from the Cenozoic (instead of on IPCC-type climate models) to see what nature had done in the recent geological past. In this respect, climate modelling in the polar regions is known to be less robust than at lower latitudes (e.g. Binschadler et al., 2009), while Casado et al. (2023) noted that failure to consider the feedback loops causing polar amplification could lead to an underestimation of the magnitude of anthropogenic warming and its consequences in Antarctica.

A study of the climate of the past 3 myr by Yun et al. (2023), using up-to-date climate models fed with the IPCC's Representative Concentration Pathways (RCPs) of 2.6, 4.5 and 8.5 (based on rises in greenhouse gas concentrations that led to radiative forcing values of 2.6, 4.5 and 8.5 W/m^2), found that the Late Pleistocene glacial/interglacial global average temperature range of 4–6°C was comparable in amplitude to the RCP8.5 greenhouse gas warming projection over the next 7 decades. But, the anthropogenic projections applied to the model produced warming rates that exceeded the natural variability by almost two orders of magnitude (Yun et al. 2023). Such warming rates would be likely to push global ecosystems way outside the range of temperature stress that they experienced naturally within the last 3 million years (Yun et al, 2023), consistent with the findings of Hansen et al. (2023). Similarly, Zhu et al. (2019) used a state-of-the-art Earth System model to simulate the extreme warmth and low meridional temperature gradient of the Eocene and its associated Paleocene–Eocene Thermal Maximum (PETM, see below) with age-appropriate estimates of past CO_2 and without altering the model's physics. Their Eocene simulations matched well with proxy data, reflecting climate sensitivity in the CESM1.2 model increasing substantially with CO_2-induced warming. The cloud feedback processes responsible for the increased climate sensitivity in their Eocene simulations are also active under modern conditions. Their results suggest a higher climate sensitivity in a warmer future than typically estimated by the IPCC (Zhu et al., 2019), in agreement with Hansen et al. (2023) and Yun et al. (2023).

Hansen et al. (2023) observed that substantial emissions of aerosols from dirty industrial processes and the burning of coal in home heating between 1940 and 1970 delayed the warming expected from climbing concentrations of greenhouse gases, thus postponing the rise in temperature by more than two decades after the Great Acceleration that began ~1950. As aerosols decreased and the air became cleaner with the introduction of national Clean Air Acts, the aerosol cooling effect diminished, allowing the effect of cumulative and new greenhouse gas emissions to have a greater effect from 1970 onwards (Hansen et al, 2023). More recently, a further reduction in aerosol supply by shipping (forced since 2020 by legislation to burn less sulphur-rich fuels) has been implicated in the marked subsequent warming of surface ocean waters (Voosen 2023b).

The Role of the Atlantic Meridional Overturning Circulation (AMOC)

The Great Ocean Conveyor connects ocean water masses and slowly transports heat and salt around the world, modifying regional and global climate in the process (Broecker 2010). The AMOC is the Atlantic branch of the conveyor that connects both polar regions. Fluctuations in the AMOC are thought to have exacerbated the fluctuations in climate between glacial and interglacial times, with the AMOC in the 'on' position during warm interglacial periods, and in the 'off' position during glacial periods, in response to Milankovitch cycles in insolation (e.g. Broecker 2010). For instance, the sinking of deep water near both poles is controlled to some extent by sea ice. When sea ice extends south in the North Atlantic, as it did during peak glacial times, the production of North Atlantic Deep Water is switched off (Rahmstorf, 2002). When sea ice forms around Antarctica, the process excretes salt, making cold surface water dense enough to sink, so accentuating the production of Antarctica Bottom Water. Yet when this sea ice area becomes extensive during all seasons, as during peak glacial times, that process too may have been weakened or even switched off (cf. Rahmstorf, 2002).

A continued rise in global warming could have the counterintuitive effect of producing a lid of cold Greenland melt water on the Norwegian-Greenland and Labrador Seas, shutting down the AMOC, thus preventing the Gulf Stream and its northern branch, the North Atlantic Current, from continuing to transport heat towards western Europe, leading to cooling there. A recent modelling experiment by Van Westen et al. (2024) suggested that the AMOC is advancing towards a tipping event that will substantially reduce the northwards transport of heat and salt by the Gulf Stream and associated currents, thus cooling the Northern Hemisphere, while the Southern Hemisphere warms as a consequence (the bipolar seesaw, see below). Weakening of the AMOC has already led to cooling of the north-central North Atlantic between Labrador and the British Isles, where the post-1850 warming of the Northern Hemisphere was not reflected in the sea surface temperatures of the Sub-Polar Gyre (Rahmstorf et al. 2015). The Gyre waters have failed to warm in concert with their Northern Hemisphere surroundings since ~1970, resulting in what has been described as a 'Cold Blob' in the surface waters over a substantial area. Rahmstorf et al. (2015) concluded that the weakness of the AMOC after 1975 was unprecedented in the past millennium, and that further melting of Greenland's ice in coming decades could contribute to further weakening of the AMOC. Nevertheless, although the AMOC did weaken by 13% between 1950 and 2019, this trend is thought to be statistically insignificant at present, due to the large interannual and decadal variability of the Sub-Polar North Atlantic (Chafik et al. 2022). Countering the modelled prognosis of Van Westen et al. (2024), Chen and Tung (2024) found no hard evidence at present for impending collapse of the AMOC. Moreover, new data show that at times when Greenland lost substantial ice over the past 40 years, creating a more extensive fresh water lid on the ocean, European summers got warmer rather than cooler (Oltmanns et al. 2024), suggesting that fears of the AMOC switching off due to Greenland ice melt may prove groundless.

Although Chen and Tung (2018) considered that fluctuations in the AMOC might have caused the apparent pause in global warming between 2002 and 2013, the record of global oceanic heat storage (0–2000 m) shows no substantial temperature pause over that period (Zanna et al. 2019; Cheng et al. 2023, 2024). Indeed, careful re-examination of all available sea surface temperature (SST) data, including the addition of previously missing Arctic data, shows that the rates of warming of SST during that period were underestimated because of the lack of effective use of data from floating buoys, Argo floats and radiometer-based satellite measurements that were developed and deployed during the past two decades (Hausfather et al, 2017). Hence the supposed global warming pause of 2002–2013 seems now to be a reflection of the inefficient use of data rather than a real climatic signal (Hausfather et al, 2017).

A slowdown of the AMOC did take place in the Holocene, with a sudden cooling centred on 8.2 kyr BP and lasting between 400 and 600 years (Alley et al., 1997; Rohling and Pälike, 2005). This event is attributed to the breaching of an ice dam holding back the large glacial Lake Ojibway-Agassiz (a precursor to the modern Great Lakes). The lake water cascaded down the Mackenzie and/or St Lawrence Rivers into the Arctic Ocean, forming a temporary freshwater lid on the northern North Atlantic, preventing the northward extension of the AMOC (via the Gulf Stream and North Atlantic Current) and thus cooling the surrounding landmasses, much as suggested may happen with Greenland melting (see above). This event is thought to have cooled the region by about 2°C (Vinther et al., 2009). Similar but much less extreme events, apparently caused by variations in solar output during the Holocene, caused Arctic ice melt events that put a temporary freshwater lid on the northernmost North Atlantic. This was associated with increased ice rafting south of Iceland and rises in European lake levels (see earlier). A repeat of the 8,200 event is unlikely, given the absence of Arctic glacial lakes and dams.

Similar but more abrupt changes in temperature resulted from fluctuations in the AMOC at intermediate levels of glaciation between ~60 kyr and 30 kyr BP, when Greenland's temperatures increased at times by between 10° and 15°C in as little as 50 years, reverting to 'normal' after a few hundred years. These changes (the Dansgaard-Oeschger events visible in Greenland ice cores) were caused by natural oscillations in the AMOC, as part of what came to be named the bipolar seesaw (Broecker 1998; Stocker 1998; Seidov et al. 2001). The seesaw involves gradual displacements of warm water from the Southern Ocean to the North Atlantic, causing abrupt warming there, alternating with reversions. As mentioned above, while the AMOC brings warm waters north during interglacials, it switches off during glacials, when the northern seas are largely covered by sea ice as far south as a line between Boston and Lisbon. The dramatic oscillations of the mid-glacial period (60–30 kyr ago) reflect flickering of the climate system during an interval when it was in transition from interglacial to full glacial. In these seesaw events, the Southern Hemisphere warmed gradually while Greenland cooled, and cooled gradually while Greenland warmed abruptly. CO_2 was not the driver for these changes, but exacerbated them when the warming Southern Ocean emitted up to 20 ppm CO_2, which was taken up again when the Southern Ocean cooled (Ahn and Brook 2009). Such extreme changes in temperature as those in Greenland seem confined largely to cold glacial intervals when there was still abundant ice to melt during warmings.

Evidence from Cenozoic Paleoclimates

By adding anthropogenic carbon emissions to the air, we have pushed our climate along a trajectory towards levels last seen during previous very warm times in Earth's geological history (e.g. Steffen et al. 2018; Arias et al. 2021). To illustrate the point, we look below at the mid-Piacenzian Warm Period of the early Late Pliocene (~3.26–3.03 million years ago); at the Miocene Climate Optimum (16.9–14.7 million years ago); at the Early Eocene Climatic Optimum (53–49 million years ago) and at the Paleocene-Eocene Thermal Maximum (55.9–55.7 million years ago).

Estimates of changes in CO_2 in relation to temperature for the Cenozoic have been refined by the Cenozoic CO_2 Proxy Integration Project, led by Bärbel Hönisch (The CenCO$_2$PIP Consortium, 2023). The new record suggests (i) that early Cenozoic 'hothouse' CO_2 concentrations peaked near 1600 ppm 51 Ma; (ii) that the continent-wide Antarctic glaciation 34 Ma coincided with an atmospheric CO_2 concentration fall to 720 ppm; (iii) that by 32 Ma atmospheric CO_2 had dropped to 550 ppm, which coincided with the origin and diversification of plants inhabiting grasslands and deserts today that use carbon-concentrating pathways; and (iv) that CO_2 remained low for the remainder of the Cenozoic. The last time that CO_2 concentrations were consistently higher than at present was 16 million years ago during the Middle Miocene, when sea level may have been some 50 m higher than today.

1. Mid-Piacenzian Warm Period (mPWP)

Early Late Pliocene atmospheric CO_2 levels reaching ~430 ppm (de la Vega et al. 2020; Rae et al. 2021; Figure 5) are already close to being exceeded by contemporary levels of 420 ppm and rising, and we appear to be headed for a kind of climate last seen more than 3 million years ago during warm intervals of the Pliocene Epoch (Dowsett et al. 2016; Haywood et al. 2020), when boreal forests grew on land now covered by tundra in Ellesmere Island in the high Canadian Arctic (Salzmann et al. 2011). There, an estimated warm-month mean temperature of 10–15°C would have been typical of boreal forests now growing more than 9° (and in some cases more than 29°) of latitude south of the island (Tindall et al. 2022). The mPWP was the last time in geological history when our planet's climate was substantially warmer for a prolonged period than it is today. Sea levels were then higher than today by somewhere between ~5 and 20 m (Grant and Naish 2021; Raymo et al. 2011; Rohling et al. 2021), and global surface temperature was 2.5°C to 4°C warmer relative to 1850–1900, with those temperatures likely being reached by 2300 CE under moderate CO_2 emissions scenarios (IPCC 2023). Indeed, on the basis of analyses from a single interglacial stage within the mPWP, McClymont et al. (2020, p. 1600) found that even under low-CO_2 emission scenarios, surface ocean warming may exceed model projections and will be accentuated in the higher latitudes. This time interval, then, provides us with a realistic near-future 'best case' climate scenario for the Anthropocene, even if greenhouse gas emissions are reduced immediately and substantially from current levels (Burke et al. 2018). This period has the advantage for modeling in that plate tectonic configurations are largely similar to the present day, with a few exceptions including an open (although shoaling) central American seaway. Closing of the central American seaway in the mid-Pliocene converted the prior westwards warm equatorial Atlantic flow into the Pacific to poleward flow that intensified the AMOC and took heat through the Atlantic into both polar regiosn (cf. Zhang et al. 2012).

Figure 5 here

Overview of Cenozoic CO_2 and global climate modified from figs. 5 and 6 of Rae et al. (2021). Earth's climate state is moving towards conditions last seen during earlier warm intervals of the geologic past, as shown here. a) Surface temperature estimated from the benthic $\delta^{18}O$ stack of Westerhold et al. (2020); (b) Sea level estimates from Miller et al. (2020). (c) Boron isotope-derived estimates of pH; (d) Atmospheric CO_2 reconstructions from boron isotopes (blue dashed lines show influence of alkalinity range and alkenones).

2. Miocene Climate Optimum (MCO)

Earth is likely to exceed Pliocene-like atmospheric CO_2 concentrations within the next decade if CO_2 emissions continue rising (Rae et al. 2021), and the MCO may provide a plausible analogue for Earth's near-future climate (Steinthorsdottir et al. 2021). CO_2 levels were modestly higher then than for today, with evidence suggesting ~470–630 ppm (Sosdian et al. 2020), and mean surface temperatures 7–8°C higher than pre-industrial levels. At that time there were no major Northern Hemisphere ice sheets, and the Antarctic ice sheet is inferred to have been highly dynamic, with a minimum ice volume close to complete Antarctic deglaciation (Steinthorsdottir et al. 2021; Miller et al. 2020). Sea level may have been between 28 and 50 m above today's level (Rohling et al. 2022). Climate modelers have found it difficult to reconcile these indications of considerable global warmth, especially at high latitudes, with the relatively modest atmospheric CO_2 levels inferred (Rae et al. 2021; Steinthorsdottir et al. 2021). This might add weight to the arguments of Hansen et al. (2023) that climate is more sensitive to CO_2 increases than is generally assumed.

3. Early Eocene Climatic Optimum (EECO) and the Paleocene–Eocene Thermal Maximum (PETM)

With even higher greenhouse emissions, climatic conditions would ultimately evolve towards those resembling the EECO 53–49 million years ago, when CO_2 concentrations were of the order of 1500 ppm (Rae et al. 2021; Figure 5), before the glaciation of Antarctica, and when deep-sea bottom water temperatures were ~10°C higher than they are today, lush forests occurred at both poles, and sea levels were ~60–70 m higher than at present (e.g. Foster and Rohling 2013; Burke et al. 2018; Scotese et al. 2021). Plausibly, such conditions might be reached by 2300 CE under the highest CO_2 emission scenarios, where global surface temperature rises of 10–18°C have been suggested (IPCC 2023).

The geological record includes a clear illustration of what happens naturally when a pulse of carbon is injected to the atmosphere. This occurred at the end of the Paleocene Epoch, when, in a brief interval centred on 56 Ma, temperatures increased by about 5–6°C globally and by as much as 8°C at the poles, and sea level rose by as much as 12 m through thermal expansion as there was little land ice to melt (Figure 5). The PETM was superimposed onto the warming of the early Cenozoic and caused one of the largest extinctions of deep-sea benthic organisms in the last 90 million years, acidified the surface ocean as well as the deep ocean (Thomas 2012), and saw significant changes in terrestrial biota, including the first appearance of the ancestors of modern hoofed mammals and rapid reorganization of plant communities in response to climatic and environmental change (Sluijs et al. 2007). The lasting changes in geochemical signatures and permanent changes in biota represented in the fossil record mark the transition between the Paleocene and Eocene epochs. They provide useful deep-time context to the differences already evident between Holocene and nascent Anthropocene strata, and it is useful to explore the differences between the two cases.

$\delta^{13}C$ data suggest the release of 2,000+ Gigatons (Gt) of ^{12}C-rich carbon, as CH_4 subsequently oxidized to CO_2, in both the ocean and atmosphere (Zachos et al., 2001). Arctic temperatures rose from 17°C to 25°C (Miller at al. 2010), with similar rises identified in the Tasman Sea at a paleolatitude of 65°S (Sluijs et al. 2011). Transgressive sedimentary deposits showed that this warming led to a rise in sea level, with thermal expansion of the ocean contributing around 5 m, and the melting of all or part of the relatively small inferred Antarctic mountain ice caps likely contributing >10 m in addition (Jansen et al. 2007) as there was no Antarctic ice sheet.

Carbon was added to the Earth System during the PETM at 0.3–1.7 GtC/yr (Cui et al. 2011), much less than the modern rate of carbon emissions of ~10 GtC/yr (Montañez et al. 2011). Turner (2018) combined data and modelling studies to conclude that the carbon emissions occurred over a few thousand years at a rate ten times slower than present rates (also see Zeebe et al. 2016). This carbon release rate at the PETM was the highest across the past 66 million years, yet only a tenth of modern rates of carbon release. Zeebe et al. (2016) observed that we are now in a 'no analogue' state that 'represents a fundamental challenge in constraining future climate projections'.

Enrichment in ^{12}C of the PETM's carbon suggests a predominately marine source, perhaps destabilization of methane hydrates (clathrates) on continental margins by earthquakes associated with North Atlantic Igneous Province volcanism (Sluijs et al. 2007; Dickens 2011; Frieling et al. 2019; see also Lovell 2010). Volcanic emissions of CO_2 may also have been substantial (Gutjahr et al. 2017). The addition of large volumes of CO_2 acidified the ocean by 0.3 pH units globally (Babila et al. 2018), dissolving deep-sea carbonates and raising the Carbonate Compensation Depth (CCD) from 5 km to 2.5 km in the Atlantic, causing $CaCO_3$-rich sediments to disappear from much of the deep sea floor. Both ocean acidity and warming were likely factors in the demise of benthic deep-sea foraminiferal species (Thomas 2012) and shallow-water coral reefs, with concomitant changes in marine plankton populations

(Kelly et al. 1998; Frieling et al. 2017, 2018). It took 100+ kyr for the CCD to return to its previous level (Zachos et al. 2008).

Lyons et al. (2019) realised that CO_2 inputs continued long after the initial rapid onset, creating the main body of the PETM's carbon isotope excursion. They inferred that much of this extra ^{12}C-rich carbon had been reworked from soils and coastal sediments during a marine transgression, creating an order-of-magnitude increase in the delivery of fossil carbon to the oceans that began 10–20 kyr after the onset of the event. Once warming-driven sea level rise ceased, the addition of ^{12}C-rich organic material would have declined, helping to return conditions to the pre-PETM norm. Oxidation of this remobilised organic material likely released between 10^2 and 10^4 Gt of carbon as CO_2 during the PETM, sustaining the elevated atmospheric CO_2 levels through the carbon isotope excursion across 100 kyr, with full recovery of the climate system across another 100 kyr.

Warming at the PETM accelerated the hydrological cycle, further drying dry regions such as the interior of the American continent, and further wetting humid regions such as northern Iberia (Chen et al. 2018) and East Asia (Kiehl et al. 2018); this has clear implications for the course of Earth's contemporary rise in CO_2. Although the climate, carbon, and sedimentary systems of the PETM largely recovered over 100 kyr, PETM-caused extinctions had permanent consequences, with effects on continental biota still present today. Similarly, the Anthropocene will provide a highly distinctive paleontological signature that will persist until another notable change in the tree of life is wrought in the future (Cowie et al. 2022; Williams et al. 2024 submitted; Conrad et al. 2024)(see below).

Understanding how modern climate will warm further would be helped by effective models of PETM climate. Although the background climate state of the Late Paleocene–Early Eocene was characterized by an extremely low latitudinal temperature gradient, initially making it difficult to model its climate system (Valdes 2011), this problem has been overcome by the recent modeling applied to Eocene times by Zhu et al. (2019).

Possible Future Duration of Warming and High Sea Levels

The natural changes that drove Holocene climate will continue to operate, forced by variations in the Earth's orbit (axial and orbital precession moderated by eccentricity, and the tilt of the Earth's axis), driving millennial-duration climate change. Astronomical forecasts, for instance, suggest that, without global warming, Earth's climate would likely continue at its current 'mid-glacial to weak interglacial' level for some 40 kyr before the next glacial maxima at 55 kyr, 100 kyr and 130 kyr from now, punctuated by warm interglacial periods driven by high insolation 70 kyr and 115 kyr from now (Berger and Loutre 2002). These long delays are attributed to Earth's low orbital eccentricity, which suppresses the amplitude of precession and is projected to continue for a considerable time (Talento and Ganopolski, 2021). With continued emissions of CO_2 and global warming, future glacial intervals would become more like today's interglacial conditions, while the future interglacial intervals would likely be at least as warm as mid-Piacenzian conditions. In Figure 3, Crucifix's projections of changing insolation for 3 kyr and 6 kyr into the future show a slight gradual increase in polar summer cooling with an initial focus on the Arctic at 3 kyr, shifting to the Antarctic by 6 kyr – suggesting continuation of the gradual polar neoglacial trend (Fig. 4), if continued global warming does not overturn the effects of this insolation trend. Even assuming no further anthropogenic CO_2 emissions the inception of glacial conditions is not expected until ~50 kyr after present, with glacial maxima conditions not attained until ~90 kyr after present (Talento and Ganopolski, 2021).

We can also expect less climatic variation on finer time scales induced by continued fluctuations in solar output, like those identified for the Holocene (Stuiver et al. 1998; Steinhilber et al. 2012), initiating modest fluctuations in ice-rafting in the North Atlantic (Bond et al. 2001) and flooding in western Europe (Magny 2007). Steinhilber and Beer (2013) used the spectra of solar activity for the Holocene to project probable solar activity for the next 500 years, finding that by 2100 CE it would likely decline to a level comparable to that of the Dalton Sunspot Minimum (centred on about 1810 CE), followed by a slow increase to ~2400 CE, further enhancing global warming (Steinhilber and Beer 2013).

If we cease the emission of CO_2 and related greenhouse gases, equilibration of the atmosphere with the ocean will eventually absorb into the ocean much of our past emissions of CO_2 (Archer et al. 2009). Once we have stopped emissions of CO_2, 50% of those emissions will still be in the air 300 years from now, decreasing to 17–33% 1000 years from now, to 10–15% 10 kyr from now, and to 7% 100 kyr hence (Archer et al. 2009). The mean lifetime of those CO_2 emissions in the air is thus 30–35 kyr, much longer than commonly appreciated. As long as our CO_2 emissions stay in the air, temperatures will stay warm, melting progressively more ice. On a timescale of 10 kyr, the CO_2 loading of the ocean will lead to the gradual formation of more carbonate sediment acting as a CO_2 sink as the ocean-atmosphere system approaches equilibrium (Archer et al. 2009). Over a time-scale of 400 kyr, continued warmth due to residual amounts of our CO_2 emissions still in the air would enhance the chemical weathering of silicate rocks, to draw down yet more of our fossil fuel CO_2 emissions (Archer et al. 2009).

Talento and Ganopolski (2021; see also Archer and Ganopolski 2005 and Ganopolski et al. 2016) used a climate model to demonstrate that even already achieved cumulative CO_2 anthropogenic emissions (500 Pg C) can influence the climate for up to 500 kyr, and that full glacial conditions are unlikely to occur before 180 kyr from the present, a delay of at least 90 kyr relative to such conditions under natural CO_2 levels. If cumulative anthropogenic CO_2 emissions were to rise to 3000 PgC or higher, as is achievable in the next two to three centuries if humanity does not curb the usage of fossil fuels, the Northern Hemisphere landmass could be ice-free for the next half a million years (Talento and Ganopolski 2021).

Today's ocean has absorbed not only heat, but also 25% of the emitted CO_2, to remain in chemical equilibrium with the atmospheric load of CO_2. Therefore, when we start reducing CO_2 emissions, CO_2 must inevitably be released back into the atmosphere from the CO_2-enriched ocean to maintain the ocean's physicochemical equilibrium with the atmosphere. Thus, the CO_2 content of the atmosphere will not decline as rapidly as emissions do, helping to prolong present warmth (Archer et al. 2009). Recognizing this, Rohling (2021) calculated that oceanic outgassing means that 1.6–1.7 times more CO_2 must be captured from the atmosphere to achieve a particular atmospheric CO_2 concentration target. A 1 ppm CO_2 change in atmospheric concentration alone equates to a mass change of ~2.12 GtC (= 7.81 $GtCO_2$). Ocean outgassing means that reducing the atmospheric CO_2 concentration by 1 ppm will actually require the removal of ~3.5 GtC (=12.9 $GtCO_2$). While easily overlooked, this factor is fundamental when considering how much CO_2 can realistically be removed directly from the atmosphere (Rohling 2021). Furthermore, ~90% of the heat of global warming is trapped in the ocean, and eventually has to go somewhere. As atmospheric CO_2 and associated atmospheric heating decline, some of this oceanic heat will be transferred to the atmosphere to preserve the ocean-atmosphere thermal equilibrium.

Is it indeed inevitable that ice shelves cannot recover in a warm ocean (De Conto et al. 2021)? We must consider here any hysteresis effects (Abe-Ouchi et al. 2013). With respect to Antarctica, currently observed ice-sheet configurations will not be regained in the future, even with a return to preindustrial temperatures. The West Antarctic Ice Sheet is especially vulnerable and, if reduced in area, would not regrow to its original (i.e. early 20th century) geographical extent unless global temperatures fell to least 1°C below pre-industrial levels

The implications for future sea levels are clear. Above the UN's upper guardrail of a global average temperature of 2°C, the West Antarctica Ice Sheet melts and sea level rises by 3–5 m over a few centuries; this excludes what may happen to Greenland or East Antarctica and mountain ice. If the area of the West Antarctic ice sheet shrinks, it will not grow back to its original (i.e. early 20th century) volume until global mean surface temperatures drop to around 3°C below pre-industrial temperatures (Garbe et al. 2020). Under these circumstances, current attempts to slow, stop, and even reverse global warming will not restore Earth's refrigerator in the short to medium term, although they should help to slow the rate at which parts of it disappear, and help to retain the rest. Sea level will keep rising for millennia whatever we do (IPCC 2023; Figure 2c) as an unavoidable consequence of continued deep ocean warming and melting ice sheets. Over the next 2 kyr, sea levels might increase by 2–3 m if warming is limited to 1.5°C, and by 2–6 m if warming is limited to 2°C (IPCC 2023). An increase of between 2°C and 3°C would see several additional meters of sea-level rise as the Greenland and West Antarctic ice sheets melt, effectively irreversibly and almost completely over many millennia (IPCC 2023).

IPCC's projections of multi-millennial global mean sea level rise, however, are lower than the reconstructed sea levels during past warm climate periods, such as the Last Interglacial, 125 kyr BP, when sea level may have reached close to 14 m above today's level (e.g. Rohling et al., 2019), or the early Late Pliocene, 3 Ma, when even the IPCC recognized that global mean sea level was likely up to 25 m higher than today, at a time when global temperatures averaged 2.5–2.0°C higher than in 1850–1900 (IPCC 2023). The IPCC accepted that global mean sea level rise above the range they deemed likely – that is, approaching 2 m by 2100 and in excess of 15 m by 2300 under a very high GHG emissions scenario – could not be ruled out due to deep uncertainty in ice sheet processes (IPCC 2023). If Greenland and West Antarctica were to melt entirely, sea level would rise by ~12m (7m from Greenland and up to 5m from West Antarctica). Beyond that, Hansen et al. (2023) suggested that the associated equilibrium sea level change for a rise in global average temperature of 10°C would be 60 m or more, approaching the sea level of mid-Eocene times.

Rises in sea level of several metres above present levels are not unusual in the perspective of Quaternary sea-level history. During the Last Interglacial ~125 kyr BP, global average temperature is inferred at 1.5°C above the Holocene maximum, reflecting higher insolation than during the Holocene because of greater orbital eccentricity at that time (although its atmospheric CO_2 levels at ~280 ppm did not exceed those of the pre-industrial Holocene). Different estimates of this higher sea level have been suggested: around 6–9 m (Dutton et al. 2015); up to +14 m (Rohling et al. 2019), to +5 m (Dyer et al. 2021), and to +5.7m (Barnett et al. 2023); the reduced levels in the latter studies include the amount of glacial isostatic adjustment due to land rising as the weight of overlying ice is removed. These rises were mostly ascribed to melting of the West Antarctic Ice Sheet along with other parts of

Antarctica, with contributions from the Greenland Ice Sheet. The Rohling et al. (2019) study deduced three episodes of rapid sea-level rise, of respectively 2.8 m, 2.3 m and 0.6 m/century, lending credibility to projections of rapid sea-level rise in the centuries to come.

As regards future sea-level rise, independent analyses tend to agree with the higher end of the range of IPCC forecasts. For example, Rohling et al. (2013) estimated that by 2200 CE sea level would rise by up to 2.7 to 5 m, reaching 5 to 9 m by 2300 CE. Similarly, Miller et al. (2020) observed that both modeling and ancient sea level analogues (reflecting slow feedback mechanisms) suggest that 2°C of warming will lock in ~10 m of global mean sea level rise over coming millennia, when all elements of the climate system reach equilibrium. Miller et al. (2020) noted that emissions to date have committed humanity to a eustatic sea level rise on a scale not seen for 3 myr.

DeConto et al. (2021) calculated that if global warming was limited to 2°C or slightly less, Antarctic ice loss would continue at a pace similar to today's: i.e. if warmth persisted, ice would continue to be lost, with losses in the most recent calculated interval, 2016–2020 CE, averaging 372 Gt/yr (Otosaka et al. 2023). However, if global warming stabilized at an average global rise of 3°C – which is possible given present national commitments – Antarctica's buttressing ice shelves would be lost, and the pace of Antarctic ice loss from the interior would increase after 2060 CE to a level ten times faster than today, with ice-sheet retreat continuing for centuries regardless of CO_2 reduction (DeConto et al. 2021). Ice shelves cannot recover in a warm ocean when pinning points are lost.

Given currently rising CO_2 and temperature trends, will sea levels exceed those for the Last Interglacial (as much as 14 m) if we continue emitting CO_2? Although Foster and Rohling (2013) suggested not, provided that CO_2 stays within the range 400–700 ppm (note that combined greenhouse gases, excluding water vapor, already amount to 500 ppm CO_2-eq). However, geological evidence indicates that the terrestrial Wilkes Subglacial Basin of East Antarctica lost a substantial amount of ice during the Last Interglacial (Lizuka et al. 2023). And, during the Miocene Climate Optimum, when proxy evidence suggests CO_2 levels were only modestly higher than present (see below), there was substantial ice melting in East Antarctica. Hence, with further warming, East Antarctic melting might well begin in earnest.

Even if only Greenland and West Antarctic ice loss is considered, a rise of the order of 10 m in globally-averaged sea level would produce a substantial Anthropocene transgression, with drowning of low-lying coastal plains and deltas worldwide – a process exacerbated by the extraordinary Anthropocene accumulation of dams on most of the world's streams and rivers (Syvitski et al. 2020). The 900,000 km^2 area of global modern deltas, hosting more than 350 million people and infrastructure, all are less than 10 m in elevation (Syvitski et al. 2022).

Most economic activity and populations are now concentrated in coastal areas, and impacts on coastal zones as a consequence of climate change are both (a) direct, e.g. accelerated sea-level rise, larger and more intense tropical cyclones, extreme precipitation events and changes in river discharge, and (b) indirect through drought, water stress, wildfires, melting polar sea ice and decreased freshwater delivery to coasts (Day et al. 2024 in press). Already the relative rise of sea level along the Louisiana coast is 8.1 mm/yr, which is leading to the loss of wetlands, of which between 75 and 90% are likely to be lost by the end of the century in the early stages of the Anthropocene transgression (Li et al. 2024), and much the same is expected on similar subsiding coasts.

Much of the coastal land likely to be flooded is underlain by organic-rich soils and/or coastal marshes replete with organic materials (net global carbon storage in coastal ecosystems is estimated to be 25 Pg (=25 Gt) by Duarte et al. (2013). If these carbon sinks were to be reworked and oxidised during transgression, they would provide a large ancillary source of carbon to amplify the global CO_2 signal, much as suggested by Lyons et al. (2019) for the transgression during the PETM episode (discussed earlier), prolonging the tail of CO_2 emissions with time, and thus the associated thermal effects.

The organic-rich materials supplied to coastal waters by a major Anthropocene transgression would have a similar effect on coastal zones to the current oversupply of nitrate and phosphate fertilizer washed off farm fields by rain, namely the development of coastal oceanic ‘dead zones’ like those of the modern Baltic Sea, Gulf of Mexico and Black Sea. There, deoxygenation occurs as excess nutrients stimulate algal growth, with the decomposing algae stripping oxygen from the water column. More generally, ocean deoxygenation is a further side-effect of global warming, because warming allows less oxygen to remain dissolved in the ocean. Reduced oxygen solubility can explain about 50% of current oxygen loss in the upper 1000 m of the warming ocean. Deoxygenation is also increasing due to increasing oceanic stratification, as global warming heats the upper layers of the ocean, slowing ocean circulation and preventing the vertical mixing that could supply oxygen from both above and below (Breitburg et al. 2018; Limburg et al. 2020).

In summary, once anthropogenic CO_2 emissions into the atmosphere cease, CO_2 decline has a very long tail, which in turn means that so too does the warming, ice melt, and sea-level rise with which it is associated, at least for 100 kyr if we cease CO_2 emissions now. Prolonged emissions made the PETM last for 200 kyr. If CO_2 emissions continue, then warming, ice melt and sea level rise will likely continue for 500+ kyr. A long Anthropocene lies ahead, the more so as the envelope of natural Quaternary variability is progressively more greatly exceeded (fig. 2b in Head et al. 2023).

Climate impact on biota

The Earth’s biosphere has already changed dramatically from its typical Holocene state as a result of human impacts unrelated to climate change. Humans only account for 0.01% of all living carbon biomass on Earth (Bar-On et al. 2018), but they and their domesticated livestock now comprise ~98% of the mammal biomass on land (Bar-On et al. 2018; Smil 2011; Barnosky 2008; Greenspoon et al. 2023); human-made material mass now in use exceeds total (dry) biomass on Earth (Elhacham et al. 2020). In addition, more than 70% of the planet’s landscapes, and thus species compositions, have been modified by humans (UN 2022). The resulting shift in evolutionary and ecological trajectories with respect to typical Holocene conditions is already evident in nascent paleontological records (Williams et al. 2022). The projections of climate change discussed above will exacerbate these biotic changes, in effect acting as a threat multiplier, changing both the distribution and survival of countless species, such that the paleontological record of the Anthropocene will be permanently and conspicuously distinguishable from that of all previous epochs (Williams et al. 2024, submitted).

The current modification of Earth’s climate zones is already inducing numerous biotic changes. The tree line in the Arctic is migrating north. Much of the Northern Hemisphere’s conifer forest has died due to beetle activity (as winter temperatures are no longer cool enough to hold beetle populations in check) and drought. Abnormally long strings of drought years have led to tree mortality and forest turnover through widespread wildfires. In many ecosystems, the vegetation replacing fire-killed trees and shrubs is different from historical growth, as vegetation adjusts to shifting climatic zones and new fire regimes (Kelly et al. 2020). Increasing aridity has contributed to a reduction of rainforests. The geographic ranges of many species are shifting as they attempt to follow moving climate zones: for example, grizzly bears and polar bears, previously with largely allopatric ranges, are now coming into frequent contact and even interbreeding (Popescu 2016). Marine ecosystems across high and low latitudes have been impacted yet more sharply by global warming, given the narrower thermal tolerances of marine organisms compared to terrestrial ones: planktonic and pelagic populations have been recorded as shifting polewards by up to 200 km/decade over the past half-century, an order of magnitude faster than range shifts on land (Edwards 2021). One result is a widespread shift of planktonic foraminiferal assemblages away from their pre-industrial, Holocene, composition (Jonkers et al. 2019). In the tropical oceans, continued warming is bringing increasingly severe 'marine heat waves' (Oliver et al. 2021), which have depleted coral reefs substantially: the 2016 ocean heating event led to severe coral bleaching in >60% of coral reefs worldwide (Hughes et al. 2017, 2018; Smale et al. 2019; Edgar et al. 2023; Wyatt et al. 2023). These heatwaves are driving changes in coral composition towards more stress-tolerant and generalist genera (e.g. Zinke et al. 2018). Coral reefs in their current degraded state will be less able to adjust to future sea-level rise, with repercussions for coastal geomorphology (e.g. Toth et al. 2023; Leinfelder 2019). Indeed, they may already be 'zombie ecosystems' (Bradbury 2012) incapable of surviving the extra warmth that is already in the pipeline. Even if that fate is avoided by immediate, dramatic greenhouse gas emissions reductions, Anthropocene reef habitats will differ in composition and areal distribution from Holocene ones (Leinfelder 2019).

Overlaying such ongoing and projected impacts of climate change on extinction risk indicates, conservatively, that a high percentages of species not now considered vulnerable to extinction will become so by 2100 in response to the climate change trajectory currently underway, including 17–41% of bird species, 11–29% of amphibian species, and 9–22% of coral species (Foden et al. 2013; IUCN 2014; Ricke et al. 2013). Adding this to species that are threatened by non-climatic drivers suggests that by 2100 at least 50% of species could be threatened by extinction (Barnosky 2015). Studies that do not take future climate change into account, but look instead only at the comparison of current extinction rates with background rates, predict that the Sixth Mass Extinction – marked by loss of at least 75% of species commonly preserved as fossils – will be imminent within a few centuries or less (Barnosky et al. 2011; Pimm et al. 1995; Ceballos et al. 2015, 2020; Cowie et al. 2022).

Thus, even best-case scenarios indicate that, as climate change intensifies, its biotic effects will cause the paleontological record of the Anthropocene to become yet more sharply distinct from that of the Holocene (Williams et al. 2024, submitted).

Net Zero and Negative Emissions Strategies

These various observations beg the question, by how much would we need to reduce atmospheric CO_2 to reduce or eliminate Earth's Energy Imbalance. Arguing that the Earth Energy Imbalance (EEI) is the most fundamental metric of how well the world is doing in the task of bringing climate change under control, the GCOS community concluded that "The amount of CO_2 in the atmosphere would need to be reduced from 410 to 353 ppm to increase heat radiation to space by 0.87 Wm^2, so as to bring Earth back towards energy balance (von Schuckmann et al. 2020). Earlier, Jim Hansen, a member of the GCOS drafting group, had noted independently that CO_2, the dominant climate forcing factor must be reduced to no more than 350 ppm to restore planetary energy balance and keep climate near the Holocene level, if other forcings remain unchanged (Hansen et al. 2016). Given Hansen's recent conclusion that the EEI has now increased to 1.36 W/m^2 (Hansen et al. 2023), the challenge is even greater (Summerhayes, 2024).

To address the risks of allowing atmospheric CO_2 to rise much above current levels, governments are being urged to aim for net zero emissions, which means the same amount of greenhouse gas must be removed as is emitted. If accomplished, this will leave in the atmosphere the same amount of CO_2 as exists when net zero is achieved, but only if contributions from natural feedbacks do not increase. The UK government, for example, has signed up to reaching net zero by 2050 (HM Government 2021).

Achieving net zero, even if realized, would be unlikely to keep warming from exceeding the UN's uppermost guardrail of 2°C (Summerhayes, 2024). Substantial amounts of ice are already being lost at an average global temperature approaching 1.5°C (above 1900 levels), with an attendant loss of albedo as a critical positive feedback. The persistence of warmth at global average temperatures of 1.5°C or 2.0°C is likely to (a) sustain high levels of evaporation, amplifying global warming through the emission of yet more water vapor (a greenhouse gas) from the ocean; (b) further warm the ocean, causing (i) sea-level rise by thermal expansion, and (ii) natural emission of CO_2 from warm surface waters; (c) exacerbate ice melt, contributing yet more to sea-level increase; and (d) decrease albedo through ice and snow loss, allowing yet more warming through increasing absorption of solar energy by the Earth's surface.

The IPCC agreed in 2018 that if net zero could be achieved by 2050, we would need further large reductions after that (i.e. negative emissions) to extract progressively more CO_2 from the air, the amounts extracted rising to as much as 20 Gt CO_2/yr by 2100. Depending on the pathway taken, this would remove between 100 and 1000 Gt CO_2 over the course of the 21st century (IPCC 2018). Hansen et al. (2023) suggested that negative emissions be used to reduce atmospheric levels of CO_2 to 350 ppm, as they were in 1988. Carbon extraction and its eventual sequestration has yet to begin on the scale needed to achieve net zero or negative emissions. Frankhauser et al. (2022) agreed that net-zero commitments are not an alternative to urgent and comprehensive emissions cuts. Indeed, achieving net zero demands greater focus on eliminating difficult emissions sources than has so far been the case. While Jenkins et al. (2023) argued that net zero can be achieved through a combination of geological CO_2 storage) and nature-based solutions, the likelihood of rapid action towards carbon capture and storage is questionable.

Is 350 ppm CO_2 an adequate target for Earth's atmosphere? Paleoclimatologists know that for the main interglacial warm phases of the past 800,000 years the atmosphere contained no more than 280 ppm CO_2 (Lüthi et al. 2008). Atmospheric CO_2 was at 350 ppm CO_2 in 1988 when Hansen testified to the US Congress on the potential dangers of further increasing CO_2 emissions. By that time, the climate was already 0.6°C–0.7°C warmer than in the industrial era (1850–1900). For that reason, to stabilize Earth's climate at a level involving minimal risk to human civilization, CO_2 levels would need to be reduced to ~300 ppm, i.e. close to the 280 ppm representing not only the maximum for previous major warm interglacial periods, but also the level typical of the interval from 1850–1900. The last time global CO_2 levels were at 300 ppm was around 1930, when the global average temperature was about 0.1°C above that of 1850–1900. At that sort of global average temperature, some sea ice and mountain ice might start re-growing, moving the Earth's refrigerator back towards its state at the beginning of the 20th century and thus ameliorating climate change and its associated impacts on the biosphere (Summerhayes 2023). However, because of hysteresis, it is likely that even more cooling would be required to stimulate the regrowth of ice (Garbe et al. 2020), as explained below.

There is no possibility of rapidly reversing the global overheating problem. Even if we stop emitting CO_2, the long residence time of our CO_2 emissions (discussed earlier), along with slowly increasing insolation and the effects of inertia on the climate system, mean that the climate would stay warm for very many millennia (Archer 2011).

The duration of climatic perturbation, and of the Anthropocene: a synthesis

The course of global warming is a moving target, as greenhouse gas levels in the atmosphere continue to rise at a rate without known precedent in Earth's history, at least an order of magnitude more rapidly than average rises in CO_2 during the formation of the Siberian Traps at the end of the Permian and the Deccan Traps at the end of the Cretaceous (Jiang et al. 2022). Those emissions stemmed from massive, widespread and long-lived volcanic activity in Large Igneous Provinces, greatly different from the kind of eruptive activity focused on single volcanic centers such as Vesuvius, Etna or Mauna Loa.

CO_2 levels began to exceed the ~280 ppm pre-industrial baseline in the mid-19th century, and had risen to a little over 300 ppm by the mid-20th century. Then the rate of increase in atmospheric concentrations of CO_2 rose sharply to reach ~370 ppm by 2000, with a continued rising rate of increase to reach ~420 ppm (and still rising) today. Atmospheric CH_4 levels have increased yet more steeply over that time, and there have been increases too of other greenhouses gases such as N_2O and CFCs. This rapid evolution of atmospheric chemistry, and of Earth's consequent mean surface temperature rise as it catches up with the planetary heat imbalance (~1.5°C now, with ~1.0°C since 1975), and of the yet further delayed sea level rise (~20 cm over the last century, though now increasing to ~4.77 mm/year) (WMO 2024), has been a constantly shifting background to the analysis of, and policy discussions on, global warming. These various changes are already affecting the sedimentological and hence the stratigraphic record.

Atmospheric CO_2 levels are now outside Quaternary norms, and close to the ~430 ppm estimate for the mid-Piacenzian Warm Period of the Pliocene (de la Vega et al. 2020; Rae et al. 2021). Adding in the effects of more-than-doubled atmospheric CH_4 and other greenhouse gases (for which there are no precise deep-time stratigraphic proxies beyond the range of the ice core record), we are already at a CO_2-eq level of some 523 ppm (NOAA 2023a). In effect, Earth is beyond Pliocene levels of greenhouse gases and nearer to those of the even warmer Miocene Climatic Optimum. Continued emissions over this century could take the climate system into the territory of the Early Eocene climate system, and perhaps to levels comparable with hyperthermal spikes such as the PETM (see above). A review of CO_2 concentrations during the Cenozoic suggests that during this period there were occasional 'jumps' in CO_2 and the climate state (Rae et al. 2021) that might be relevant to our future climate. Studying a high-resolution Antarctic ice-core record of CO_2 across Marine Isotope Stage 11, which is considered a low-obliquity orbital analogue for the Holocene, Nehrbass-Ahles et al. (2020) noted that some CO_2 'jumps' coincided with rapid rises in methane. Jumps like these could be triggered by future tipping points such as changes in ice growth, cloud properties, ocean currents, shifts in the position of the Intertropical Convergence Zone and its effects on methane production from tropical wetlands through associated changes in monsoonal rainfall, and other feedbacks. Notably, the solubility of CO_2 in water decreases with increasing temperature, so continued warming will increase the rate of outgassing of CO_2 from the oceans.

The implication of the high and rising EEI is that the Earth will continue to warm, and sea level will continue to rise, until radiative equilibrium is re-established at some higher than present level of CO_2-eq, following whichever pattern of feedback effects have been triggered. The climate modeling discussed earlier strongly suggests that the climate effects are likely to persist for at least 50 kyr, and likely for 500 kyr, before the excess atmospheric CO_2 is absorbed through the effective but extremely slow feedback of silicate weathering. Given these outcomes, and recognizing that these conditions are above anything experienced in the Holocene as well as being likely to last between five and fifty times as long as the Holocene has done to date, there is clearly adequate reason for the Anthropocene to exist as a geological epoch in its own right, based at least on issues of duration and planetary perturbation. Although the Anthropocene is, so far, of extremely short duration, soundly based climate modeling together with evidence of past climate perturbations indicates that the new Anthropocene Earth System climate state will most likely persist for tens to hundreds of thousands of years into the future, creating a unique stratigraphic and paleontological signature. Indeed, this record has already begun to accumulate, as demonstrated by Zalasiewicz et al. 2023, submitted).

At the largest scale, the duration of the proposed Anthropocene epoch depends on how far the emerging climate perturbation affects Earth's long-term climate pattern, and more specifically how great the disturbance is to the current Quaternary icehouse state, with its major ice-sheets in both northern and southern polar regions. Modest perturbation at this scale is already in train (Talento and Ganopolski 2021), with a multi-millennial disruption of Quaternary glacial-interglacial cycles that are eventually inferred to resume in normal fashion. The climatic disturbance under intermediate CO_2 emissions is likely to delay full glacial conditions for at least 550 kyr into the future (Ganopolski et al. 2016; Talento and Ganopolski, 2021).

If emissions continue to reach levels typical of Middle Miocene and Eocene analogues (Stenthorsdottir et al. 2021; Burke et al. 2018), the question of more substantial disruption appears. The example of the Miocene Climatic Optimum suggests that much of the mass of the Antarctica ice sheet can melt away at atmospheric CO_2 levels only modestly higher (by ~100–200 ppm) than those of today, possibly to be subsequently re-established over timescales of one or two Milankovitch 100 kyr eccentricity cycles (Steinthorsdottir et al. 2021).

Climate change affects far more than surface temperatures, sea level, and resulting geological signals; it is a key driver of change to the biosphere, both through simple temperature effects vis-à-vis individual species' tolerances, and through related effects such as (i) reduction in marine oxygenation levels within a more stratified ocean, a phenomenon that is already beginning (Limburg et al. 2020) and (ii) ocean acidification through dissolution of atmospheric CO_2 in the ocean. So far, the considerable biosphere changes already apparent (e.g. Williams et al. 2022, 2024), some without precedent in Earth history, have been driven largely by human predation, human-driven habitat loss, and species translocations. As climate warms, a wide range of other biosphere effects will be initiated or exacerbated. For instance, the geographical range and length of transmission seasons for many infectious diseases will increase (Caminade et al. 2019). Resultant pathogen invasions will impact anthropogenically modified ecologies, such as agriculture (Lin 2011), and dense human populations (Mora et al. 2022). Species translocations, already widespread (Seebens et al. 2021), will be extended, potentially resetting the structure of many ecologies (Walther et al. 2009; see also Miranda et al. 2019).

With global surface temperatures already exceeding annual records for 2023 (Copernicus 2024), and with another El Niño event approaching, it seems highly likely that global average annual temperatures will soon exceed +1.5°C. Entire ecosystems such as coral reefs, already decimated by burgeoning 'marine heatwaves' (Frölicher et al. 2018; Leggat et al. 2019), will then likely be lost (Dixon et al. 2022). Warming is likely to stress global ecosystems severely (Yun et al. (2023). Such biospheric changes, coincident with, and exacerbated or driven by, climate change will be effectively irreversible and will leave a distinctively transformed fossil record long into the future (Williams et al. 2022, 2024).

Substantial losses of the Greenland and West Antarctic ice sheets also represent essentially irreversible transformations of Earth's climate state on the scale of hundreds of thousands of years, lowering albedo, accelerating sea-level rise, and disrupting the thermohaline circulation of the global ocean through meltwater input.

Given such perspectives, the Anthropocene epoch represents what will become a lasting and substantial change in the Earth System. It is the Holocene Epoch at only 11,700 years duration that will appear as the 'blip' in the Geological Time Scale, a brief interval when complex, settled human societies co-existed with, but did not overwhelm, a stable Earth System. Indeed, human activities prior to the Great Acceleration of the mid 20th century might have contributed to this stability, by very small emissions of greenhouse gases to prevent glacial inception late in the Holocene (Ganopolski et al. 2016).

The kind of temperature difference, 7–8°C, that separates the present world from that of the Miocene Climatic Optimum, is of the same order as that projected from ultimate stabilization at today's greenhouse gas levels, once there is no longer solar shading by anthropogenic aerosols and long-term feedbacks have run their course (e.g. Hansen et al. 2023). This difference is greater than the ~5–6°C temperature rise associated with the PETM, which saw a modest extinction event, though not as large as the >10°C global warming inferred as a major kill factor in the greatest Phanerozoic mass extinction event, at the Permo-Triassic boundary, even though warming at that time interval seems to have been gradual, protracted over some 300,000 years (Gliwa et al. 2022). Nevertheless, the biological fallout of Anthropocene warming and ocean acidification cannot fail to be profound and, if emissions continue over this century, to approach Eocene levels (Burke et al. 2018), thus having catastrophic effects on the fixed installations of human society and on human populations themselves.

The Anthropocene climate system is thus already a major, and growing, element in this proposed new epoch, and, if global warming is unchecked, will become an overwhelmingly dominant driver of the Earth System to come. Geochemical signals and impacts of global warming above Holocene norms will continue to accumulate and be preserved in geological strata for at least hundreds of thousands of years, and the novel climate state will exacerbate biotic change that is permanent, already evident and even now entering the paleontological record. A new stratigraphic entity has arrived.

Open Research

No new data were used in this study

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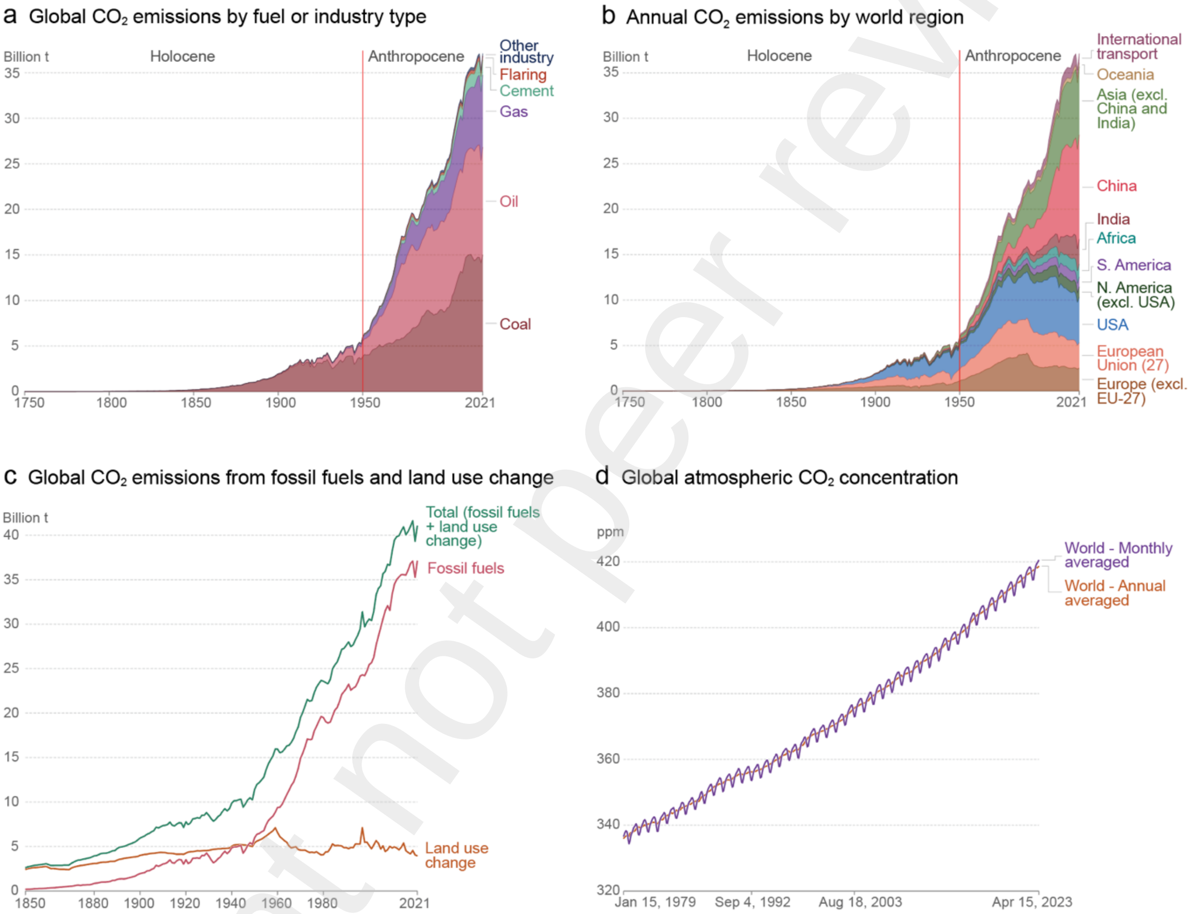

Figure 1. Global atmospheric CO_2 levels, based on anthropogenic emissions (a–c) and total concentrations (d). Graphs a and b represent fossil fuel and industry emissions, with land-use change not included. Note that while anthropogenic emissions have begun to level off in recent years, total concentrations have continued to rise unabated. From Our World in Data (2023).

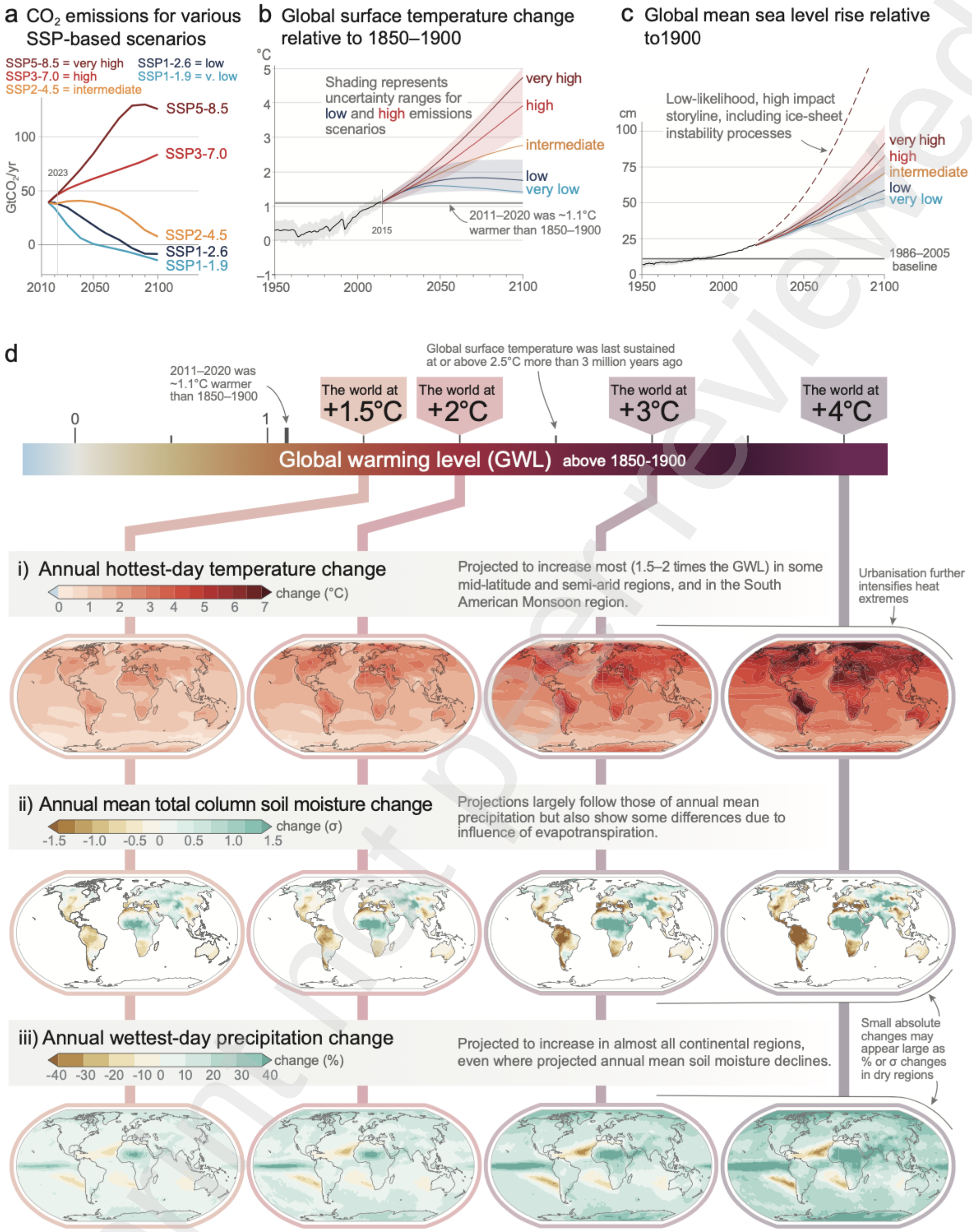

Figure 2. Projections of Earth's future climate state to the year 2100 for SSP-based (SSP = Shared Socio-economic Pathway) scenarios that use a range of CO_2 emissions trajectories reflecting differing mitigation strategies. a) CO_2 emissions trajectories upon which SSP-based scenarios are based, where color coding represents each of the five SSP-based scenarios for very low to very high emissions. b) Global surface temperature change relative to 1850–1900 for the five SSPs shown in (a). c) Global mean sea level rise relative to 1900 for the five SSPs shown in (a). d) Projected changes to the distributions of surface temperature, soil moisture, and precipitation based on a global rises of 1.5°, 2°, 3° and 4°C relative to 1850–1900. Note that global surface temperatures surpass 2° by 2050 assuming an

intermediate emissions scenario (b). Based on figs. from pages 65 (a), 75 (b, c), and 14 (d) of the IPCC (2023).

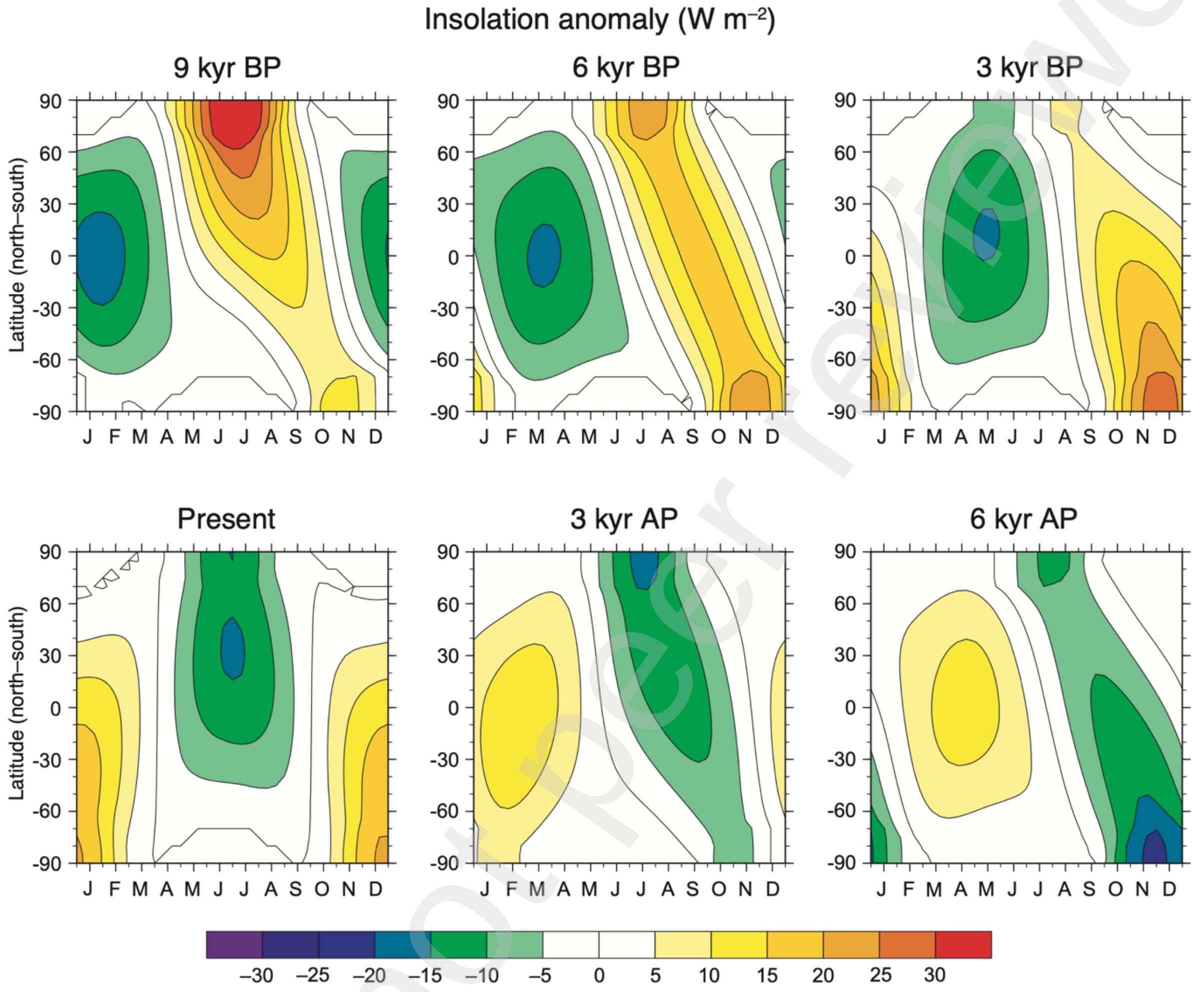

Figure 3. Distribution of shortwave radiation (insolation) received from the Sun at the top of the atmosphere between 9 ka ago (Before Present, or BP) and 6 ka into the future (After Present, or AP). A mean distribution of insolation assuming no eccentricity and a mean obliquity of 23º 20' was subtracted from the annual insolation in order to highlight the effects of changes in precession and obliquity. Precession redistributes heat across the seasons (positive anomalies around July 9 ka ago in the north and around January at present in the south). The decrease in obliquity during the Holocene reduces summer insolation in both hemispheres from 9 ka ago onwards. From figure 4.4 in Crucifix (2009).

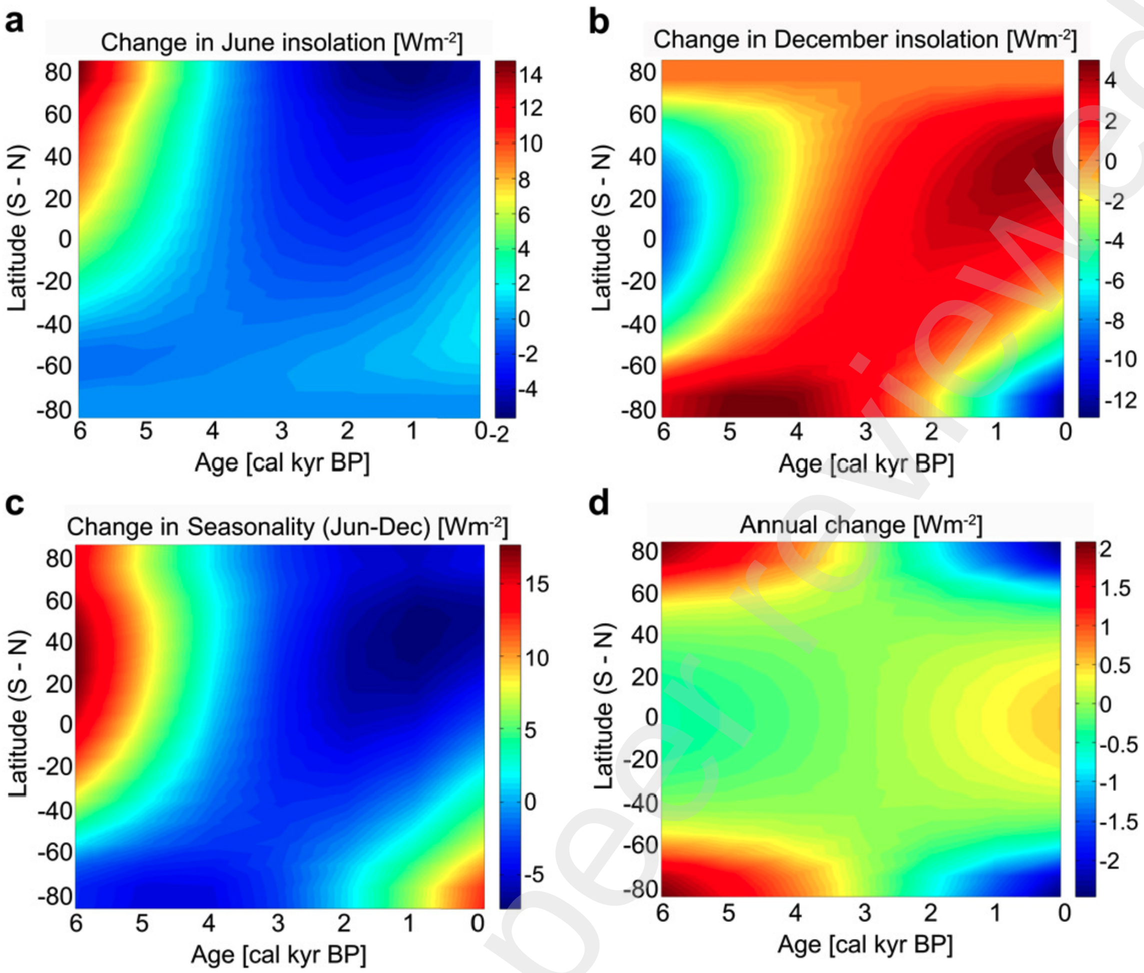

Figure 4. Calculated deviations of the insolation from the long-term mean values (W/m^2) as a function of latitude for the past 6000 years: (d) = annual mean. From figure 6 in Beer and Wanner (2012).

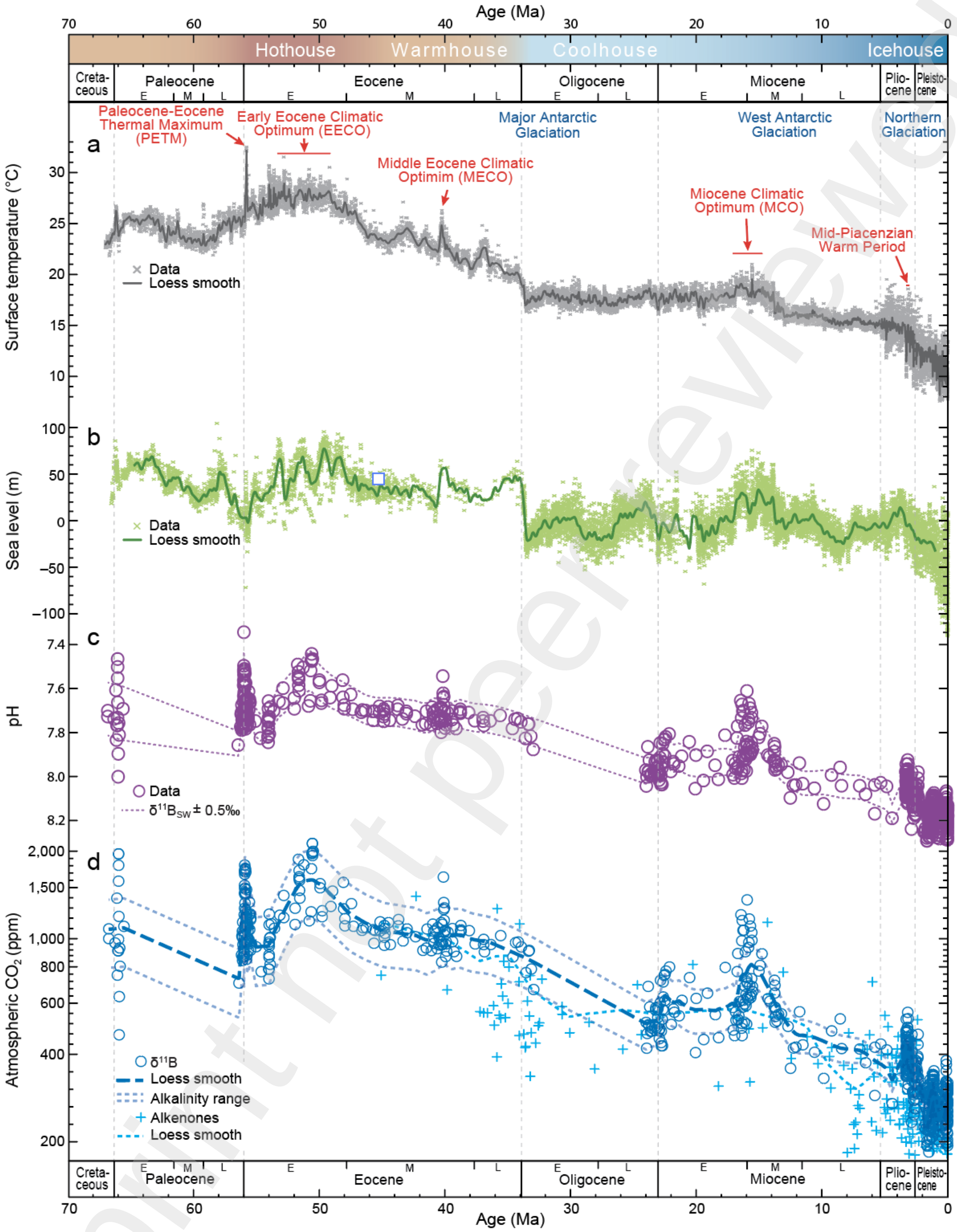

Figure 5. Overview of Cenozoic CO_2 and global climate modified from figs. 5 and 6 of Rae et al. (2021). Earth's climate state is moving towards conditions last seen during earlier warm intervals of the geologic past, as shown here. a) Surface temperature estimated from the benthic $\delta^{18}O$ stack of Westerhold et al. (2020); (b) Sea-level estimates from Miller et al. (2020); (c) Boron isotope-derived estimates of pH; (d) Atmospheric CO_2 reconstructions from boron isotopes (blue dashed lines show influence of alkalinity range and alkenones).