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The future extent of the Anthropocene epoch: A synthesis

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ABSTRACT

We synthesize research from complementary scientific fields to address the likely future extent and duration of the proposed Anthropocene epoch. Intensification of human-forced climate change began from about 1970 onwards with steepening increases in greenhouse gases, ocean acidification, global temperature and sea level, along with ice loss. The resulting distinction between relatively stable Holocene climatic conditions and those of the proposed Anthropocene epoch is substantial, with many aspects irreversible. The still-rising trajectory of greenhouse gas emissions 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 with carbon emissions lowered to net zero (where anthropogenic CO_2 emissions = anthropogenic 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, with expected levels of warmth by the end of this century not seen since the early Late Pliocene. Interglacial conditions are likely to persist for at least 50,000 years 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, suppressing the pronounced expression of Milankovitch cyclicity typical of the later Pleistocene Epoch. This major perturbation alone is sufficient to justify the Anthropocene as terminating the Holocene Epoch. The wider and mostly irreversible effects of climate change, not least in amplifying reconfiguration of the biosphere, emphasize the scale of this departure from Holocene conditions, justifying the establishment of a new epoch.

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.

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1. Introduction

The proposed establishment of an Anthropocene epoch recognizes that all aspects of the Earth System (atmosphere, hydrosphere, cryosphere, biosphere and lithosphere) are intimately connected and have experienced dramatic change away from the conditions that characterized Holocene time. Paul Crutzen originally aligned its start with the Industrial Revolution commencing in the late 18th century (Crutzen and Stoermer, 2000; Crutzen, 2002), amid research into the magnitude of the growing human impacts on the planet within the International Geosphere-Biosphere Programme (Crutzen and Stoermer, 2000; Steffen et al., 2004, 2007, 2015). Subsequently, the international Anthropocene Working Group (AWG), then of the Subcommission on Quaternary Stratigraphy (SQS), posited that this clear break with the past is best placed at the beginning of a marked increase in human population, energy use, industrial activity, technological innovation and globalization, termed the Great Acceleration, that began in the mid-20th century (Steffen et al., 2004, 2007, 2015; McNeill and Engelke, 2014; Head et al., 2022). Analysis of the geological record (e.g. Waters et al., 2016; Zalasiewicz et al., 2019, 2024a; Syvitski et al., 2020; Turner et al., 2024) led to conceptualization of the Anthropocene 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).

Abundant evidence was assembled to demonstrate that we are effectively living in a new geological epoch (e.g. Zalasiewicz et al., 2017, 2019; Syvitski et al., 2020) reflected in a distinct stratigraphic record (e.g. Williams et al., 2022; Waters et al., 2023), and that post-mid-20th century human impacts have already fundamentally moved the Earth System away from the general stability that characterized the Holocene Epoch. We have shifted into an Anthropocene state that is increasingly physically, chemically and biologically perturbed outside Holocene norms (Steffen et al., 2016; Ripple et al., 2023; Richardson et al., 2023; Rockström et al., 2024).

The formal proposal to inaugurate the Anthropocene as a new epoch of the international Geological Time Scale was submitted in October 2023 (Waters et al., 2024). A contested decision by the International Commission on Stratigraphy in March 2024 rejected the proposal (IUGS, 2024). Despite that, substantial global planetary change caused by human activities continues. Here we synthesize the evidence that allows assessment of how long the perturbed conditions of this proposed new epoch may last. We focus on the climate shift caused by increasing greenhouse gases through burning fossil fuels and expanding animal husbandry and other agricultural practices (Fig. 1), and the effects now reverberating across the atmosphere, hydrosphere, cryosphere,

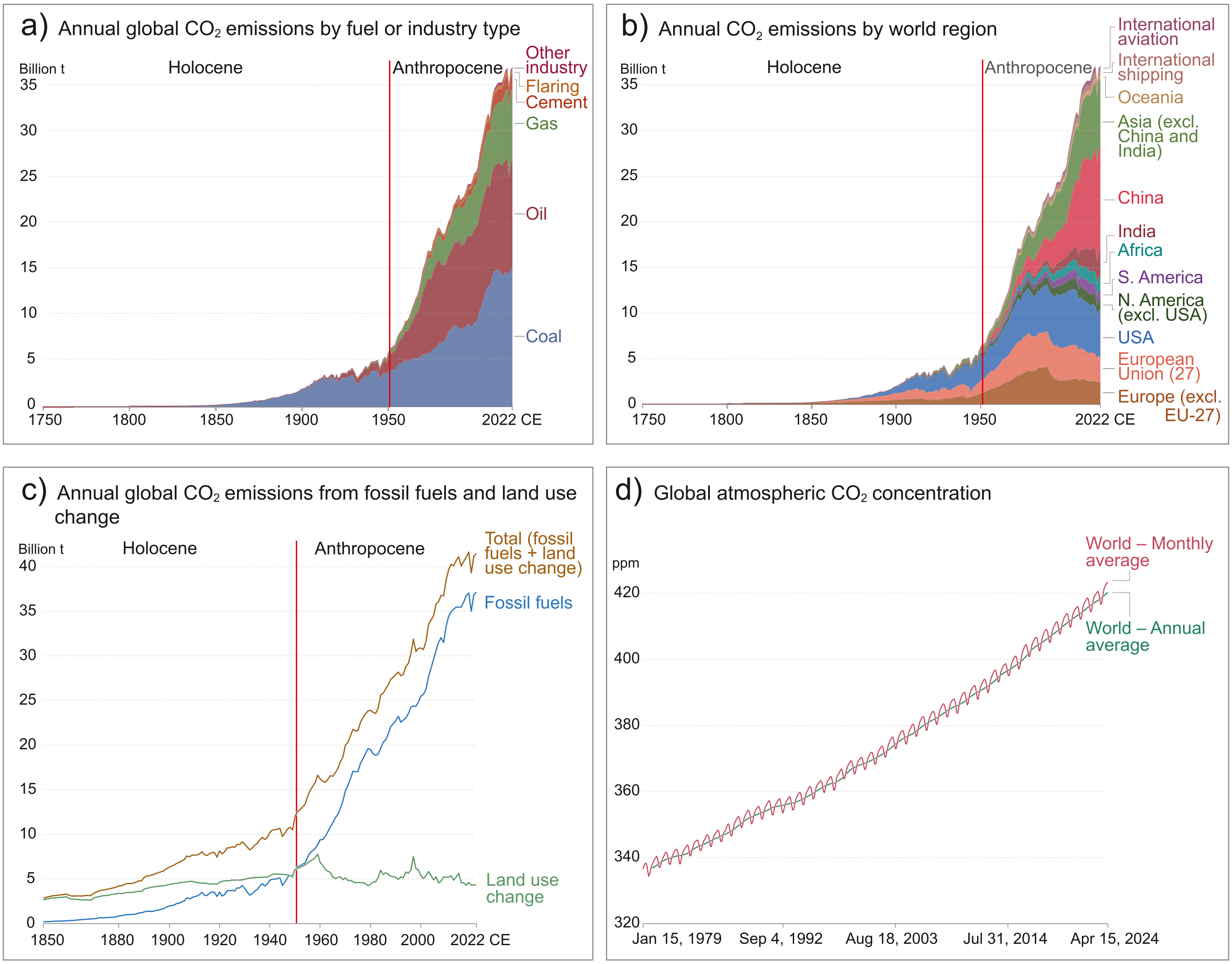

Fig. 1. Global atmospheric CO_2 levels, based on annual anthropogenic emissions (a–c) and total concentrations (d). Graphs (a) and (b) represent fossil fuel and industry emissions, with land-use change not included. Note that while anthropogenic emissions have begun to level off in recent years, total concentrations have continued to rise unabated. 'Net zero' would require CO_2 emissions from fossil fuels (a–c) to drop to zero, not merely level off. From Our World in Data (2024).

lithosphere and biosphere. This article complements analysis by Williams et al. (2024) of future paleontological signatures of the Anthropocene and their distinct character when compared with those of previous epochs. The term Anthropocene continues to be widely used, and is increasingly embedded in academic and public institutions (Zalasiewicz et al., 2024b). A reconstituted Anthropocene Working Group continues its activities independently of the SQS. The Anthropocene persists through the reality of its changed planetary conditions and its importance in both academic and societal discourse, despite it being not yet formally recognized as a geological time unit. This analysis of its future extent underscores the continuing significance of the Anthropocene epoch.

2. 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 (Fig. 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, 2023); ~ 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 (NOAA, 2022), 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 additional potent greenhouse gases, notably nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) (IPCC, 2021, 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).

Ignoring the additional greenhouse gases, today's CO_2 levels alone are similar to those last seen in the early Late Pliocene, around 3 Ma (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 Ma) (Steinthorsdottir et al., 2021; The Cenozoic CO_2 Proxy Integration Project (CenCO_2PIP) Consortium, 2023). Intergovernmental Panel on Climate Change (IPCC) projections based on intermediate emissions scenarios (SSP2–4.5) 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)(IPCC, 2021).

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 W/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 zettajoules/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 various 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, 2021, 2023). The Central England Temperature dataset, which starts in 1659, shows that current UK temperatures have increased since 1900 by just above 1.0 °C, significantly less than the 1.6 °C global 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, this area of the world ocean being the only one that has notably cooled since the 19th century (see Section 7). The average warming in the Arctic, by contrast, is between 3 and 4 times the global average (Rantanen et al., 2022). Coastal seas are also warming; for instance, over the past ~60 years, while the North Atlantic has warmed by ~0.20 °C, the North Sea has warmed by ~0.22 °C/decade, and its marginal seas (e.g. Helgoland Roads) by ~0.33 °C/decade (de Amorim et al., 2023).

If greenhouse gas concentrations 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.

3. Feedbacks and tipping points

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, leading towards tipping points within the climate system (Lenton et al., 2023). Tipping points take the form of positive feedbacks with geologically long-term effects; once crossed, they cannot be easily reversed, and will tend to amplify climate change. Postulated near-future tipping points include the possible disappearance of ice-sheets (e.g. loss of the West Antarctic Ice Sheet; Naughten et al., 2023), 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)), 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).

One such positive feedback system is the increase of water vapor, a potent greenhouse gas not counted as part of the CO_2 equivalent (or CO_2-eq) by the IPCC. Basic physics shows that a rise in average global surface temperature of 1 °C 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. The increase in water vapor is already leading to more extreme rainfall in certain regions, especially over Europe, Australia and eastern North America (Zhang et al., 2024). Global warming is also amplified by decreasing day-time cloud cover (thus reducing its short wavelength albedo effect) and increasing night-time cloud cover (thus increasing its long wavelength greenhouse effect) (Luo et al., 2024). These various effects are set to expand into the Anthropocene as CO_2 and related greenhouse gas emissions increase, exacerbating the direct effect of the gases themselves.

According to NASA, water vapor is responsible for ~50 % of atmospheric global warming, with clouds (not water vapor 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 have previously been under-reported (IEA, 2023).

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), and so increase Earth's temperature. Highly reflective snow and ice in the polar regions and high mountains help to moderate Earth's climate 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). The polar regions tend to remain cold in part because their coldness prevents significant evaporation, which until now has been focused between the north and south polar circles, thus depriving the polar regions of Earth's primary greenhouse gas, water vapor (e.g. Hay, 2021, p. 481, fig. 21.4). This situation is now changing with the progressive loss of sea ice from both hemispheres in summer beginning a significant reduction in Earth's albedo.

Permafrost is gradually thawing beneath both the land surface 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 thaw 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. The provision of either CO_2 or CH_4 from thawing permafrost provides yet another positive feedback to global warming, the extent of which will depend on the depth to which the permafrost eventually thaws and the rate of thawing (e.g. Jones et al., 2023; McGuire et al., 2018). During the last four major interglacials, when peak temperatures approached or 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 thawing may be exaggerated. Recent research shows that permafrost thawing parallels global warming and shows no signs of reaching some hypothetical tipping point (Nitzbon et al., 2024). Permafrost thaw and the release of CO_2 (or CH_4 rapidly oxidised to CO_2) may have increased plant growth that prevented a corresponding atmospheric increase. In passing, we note that the rates of thawing at glacial terminations were much slower than are modern rates. McGuire et al. (2018) concluded that while aggressive climate mitigation pathways could prevent extensive permafrost thaw, maintaining it as a net store of soil carbon, less aggressive options could lead to substantial emissions of soil carbon to the atmosphere after 2100.

Because CH_4 has a very short residence time in the atmosphere and is produced rapidly, its occurrence in ice cores at both poles provides a useful means of time-correlating ice cores from Greenland with those from Antarctica. During prior glacial terminations 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, CH_4 values initially fell along with a decline in high latitude insolation, as they did also in previous interglacial intervals. They then began to rise over the past 3000 years. While Ruddiman et al. (2016, 2020) proposed that this rise was in response to the development of rice farming in eastern Asia, modeling by Singarayer et al. (2011) suggested instead that the rise was caused by enhanced CH_4 emissions in the Southern Hemisphere tropics that were linked to precession-induced modification of seasonal precipitation, a proposition strongly supported by carbon isotopic analyses of methane from ice cores (Beck et al., 2018). The CH_4 signal then stabilized before rising abruptly again along with the modern warming (IPCC, 2021, 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).

4. Effects of global warming to date

Global warming continues, with 2023's summer warming in the Northern Hemisphere being unparalleled over the past 2000 years and exceeding the pre-instrumental mean by 2.2 °C (Esper et al., 2024). Exemplifying this change, the average global temperature in 2023 was 1.48 °C warmer than the 1850–1900 level (Copernicus, 2024). Every day within that single year exceeded the 1850–1900 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). 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 2023 the ocean had warmed to almost 21 °C, 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 in 2023, which experienced its worst fire season in modern history (Germond, 2023), as did Texas in 2024 (Texas A&M Forest Service, 2024).

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, 2021, 2023) (Fig. 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. Oceanic warming is presently working its way slowly into deeper water, and now reaches at least 2000 m below sea level (Abram et al., 2019). As Wong et al. (2024) observed, not only is the global ocean becoming warmer, more acidic, and losing oxygen, but also there is a growing tendency for it to experience extreme events (e.g. ocean heat waves, sudden falls in pH and/or oxygen) that are becoming more intense and lasting longer, with deleterious effects on marine organisms. Such events, which tended to last 10–30 days between 1961 and 2020, occur mainly in the tropics and high latitudes. They occupied up to 20 % of the global ocean volume towards 2020, locally reducing the habitable space for marine organisms by up to 75 %, especially in water 50–300 m deep (Wong et al., 2024). Such events are likely to increase with further global warming. Moreover, recent years have seen a substantial increase in the extent of coral bleaching on the great Barrier Reef, constituting an existential threat to this environment, with negative consequences for biodiversity and ecosystem services (Henley et al., 2024).

While it has been widely recognized that the oceans and the land surface each absorb ~25 % of CO_2 emissions, continued heating appears to be diminishing the amount taken up by land plants. The record global warming of 2023 strongly reduced uptake of CO_2 by terrestrial ecosystems (Ke et al., 2024). As the ocean warms it will not be able to take up as large a fraction of CO_2 emissions as it does now, leaving more in the atmosphere.

Antarctica remains colder than the Arctic for several reasons (Ramanathan et al., 1979): (i) the troposphere is thinner over the South Pole 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 directly proportional to atmospheric pressure, the atmosphere traps less outgoing heat in the south than in the north at comparable latitudes, and so warms less; (ii) Antarctica also has a far larger area of ice than the Arctic in most

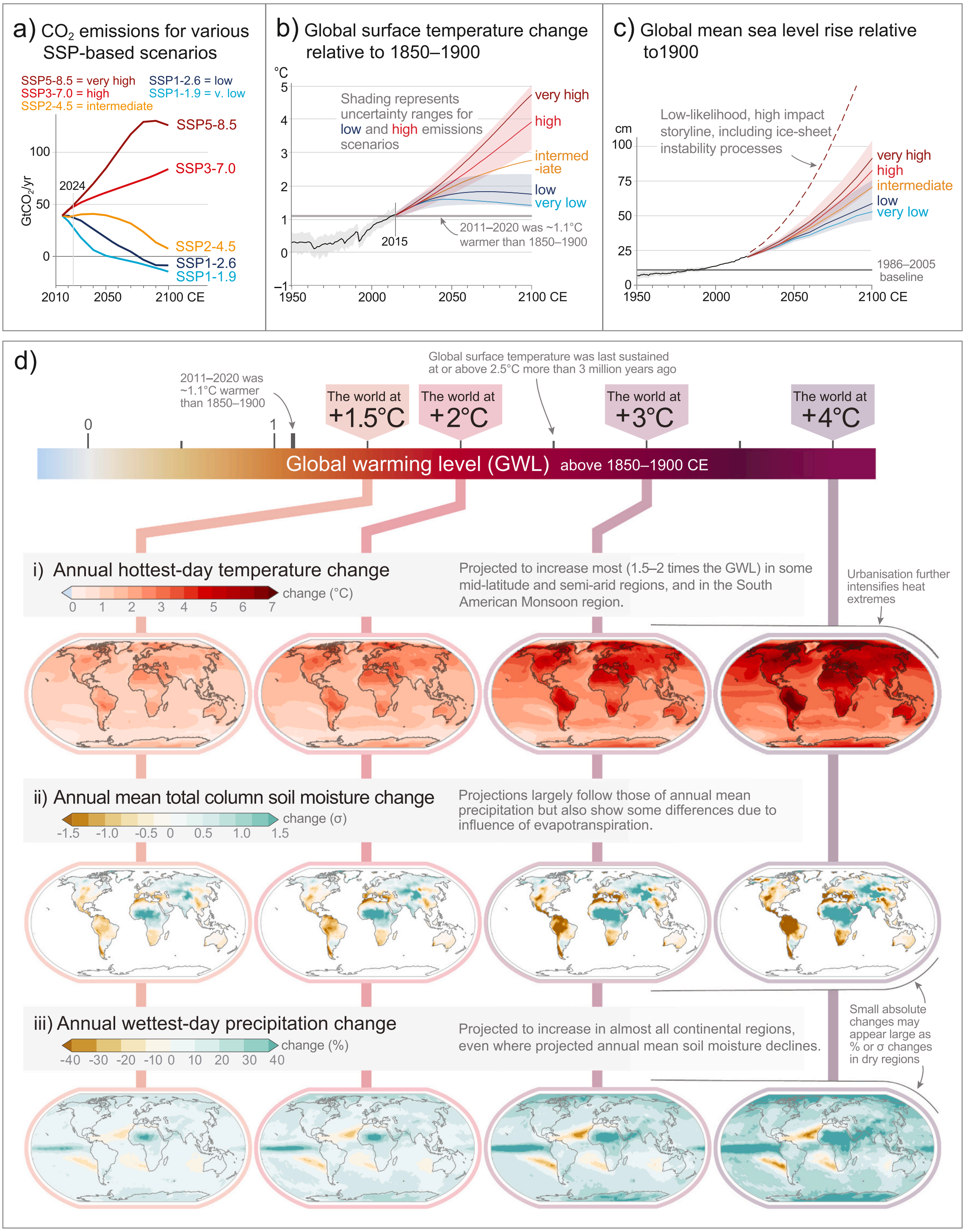

Fig. 2. Projections of Earth's future climate state to the year 2100 for SSP-based (SSP = Shared Socio-economic Pathway) scenarios that use a range of CO_2 emissions trajectories reflecting differing mitigation strategies. a) CO_2 emissions trajectories upon which SSP-based scenarios are based, where 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°C by 2050 assuming an intermediate emissions scenario (b). Based on figures from pages 65 (a), 75 (b, c), and 14 (d) of the IPCC (2023).

seasons, amplifying its albedo, which cools the south more than is the case in the north; (iii) Antarctica is also 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); (iv) 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; (v) Antarctica's cold atmosphere operates as a freeze trap for water vapor, making the ice sheet virtually a desert; (vi) strong westerly circum-Antarctic winds help keep warm surface conditions from the north impinging on the continent, as does the Antarctic Circumpolar Current (ACC) – despite this, surface waters around the Antarctic Peninsula have warmed by about 2.5 °C since 1950, making it among the fastest warming places on Earth (Thomas et al., 2009).

The main greenhouse gas in Antarctica is CO_2. Besides that, the growth of the ozone hole over Antarctica created a connection to the cold lower stratosphere (the troposphere being much thinner here than over the tropics), which will eventually disappear as the ozone hole heals (perhaps by 2080). Even so, the heights of East Antarctica are now showing signs of warming, with temperatures in March 2022 as warm as −10.1 °C at Dome C and −17.7 °C at Vostok Station (Chown et al., 2022). These rises represented the most extreme 'heatwave' ever recorded globally, when surface temperature anomalies of up to 38.5 °C above normal were observed, although the overall temperature remained below zero (Siegert et al., 2023).

Meanwhile, near sea level, Seymour Island on the east coast of the Antarctic Peninsula experienced a summer temperature of 27.5 °C in February 2020 (Halliday, 2023), while a record high temperature of 18.3 °C was recorded on the Antarctic Peninsula at the same time (WMO, 2021) and attributed to global warming (González-Herrero et al., 2023).

Sea ice forms on the ocean around Antarctica in the winter when temperatures fall to −1.8 °C (unlike the Arctic, there are no rivers to supply fresh water for freezing). As the ice forms, salt is expelled, making a brine that increases the density of sub-ice waters, which then sink to form Antarctic Bottom Water. Antarctic sea ice extent has been declining substantially since 2015, reaching a record low in 2023 of 2.5 million km^2 below the winter (July) average for the satellite era (post 1978) (Siegert et al., 2023; Diamond et al., 2024), with a summer low of 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). It will take decades for the sea ice extent to recover (Diamond et al., 2024). This raises the prospects 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. More on this below.

At the Antarctic coast, easterly winds move surface waters west in an Antarctic Coastal Current. Under the influence of the Coriolis Force, the current's surface waters tend to move landwards. However, beneath them is an eastward-directed undercurrent, in which warm Circumpolar Deep Water wells up towards the coast and penetrates the cavities beneath Antarctica's surrounding ice shelves, melting them from below (Herraiz-Borreguero and Naveira Garabato, 2022; Si et al., 2024). The thinned ice shelves move seawards faster, weakening their buttressing effect and thus allowing more ice to slide into the ocean from the hinterland. The outer edges of the ice shelves become unstable, creating icebergs. This process ultimately contributes to sea-level rise as the icebergs melt. The upwelling of warm and relatively dense saline deep water into the under-ice cavities is strengthened in a positive feedback by the upward and oceanward movement of newly created and relatively fresh meltwater beneath the ice shelves (Si et al., 2024). This entire process is expected to accelerate as the Southern Ocean warms, potentially destabilising the West Antarctic Ice Sheet and allowing its meltwater to contribute to sea-level rise (Si et al., 2024). New discoveries from the Thwaites Glacier show that warm-water intrusions driven by tidal processes penetrate for many kilometers beneath its surface, suggesting that glaciers like this one may be more vulnerable than previously supposed to melting from a warming ocean (Rignot et al., 2024). Pine Island, Smith and Thwaites glaciers are losing about 60 % more ice than is replaced by snowfall, bringing closer the eventual disintegration of the West Antarctic Ice Sheet (Hay, 2021, p. 896).

As ice is increasingly lost from the interior, the land very slowly rises through glacial isostatic adjustment, which eventually will regionally mitigate 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 glacial isostatic rebound.

The intrusion of warm saline seawater below the surface also affects the seaward ends of Greenland's tidewater glaciers (those that end in the sea). 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 its base, and so speed ice flow, there (Slater and Straneo, 2022).

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. These developments together constitute one of the most radical environmental changes on the face of the planet.

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 (see earlier), large swings in sea ice area, and a warming of the subsurface waters that impinge on Antarctica's ice shelves (Li et al., 2023; Voosen, 2023a), culminated in recent massive decreases in Antarctic sea ice area. To a large extent these regional patterns are a response to the effect of global warming on the Antarctic Circum-Polar Current (ACC), where winds have increased in strength by 40 % over the past four decades (Lin et al., 2018). Evidence is emerging of associated strengthening of the ACC, and its continuation under further global warming seems likely along with eventual retreat of the West Antarctic Ice Sheet and less absorption of atmospheric CO_2 by the Southern Ocean around Antarctica (Lamy et al., 2024). A decrease in sea ice production will lead to a slowing of the supply of Antarctic Bottom Water, the density of which depends on the supply of brine by the exclusion of salt as sea ice forms.

According to Naughten et al. (2023), the Amundsen Sea is now committed, over the 21st 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 the ocean warming that increasingly threatens the collapse of the West Antarctic Ice Sheet (Naughten et al., 2023). Moreover, warming over Antarctica has led in recent years to a progressive increase in surface melt and the development of slush zones and (as is common on the Greenland Ice Sheet) of meltwater ponds, which (see Section 6) need to be integrated into regional models of Antarctic ice melt (Dell et al., 2024). The presence of slush and meltwater ponds reduces the albedo of ice shelves, and the creation of meltwater ponds facilitates the absorption of more solar energy, which may lead to water penetrating the ice shelf interior, possibly leading to hydrofracturing, as occurred in the destruction of the Larsen B ice shelf in 2002 (e.g. Dell et al., 2024).

5. 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 and 5 ka. 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 Middle to 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. Fischer et al. (2018) observed that the so-called Holocene Thermal Maximum (between ~11 and 5 ka) occurred while ice cover and sea level had not yet reached post-glacial equilibrium, and continental ice sheets in North America and Eurasia were still retreating. At the time, insolation was greatly enhanced in the Northern Hemisphere polar regions (Fig. 3), which makes it likely that its signal was primarily regional and biased towards summer seasonal inputs. For example, the western Arctic away from the Laurentide Ice Sheet warmed, while northeast Canada closer to the ice sheet stayed cool until the ice had melted away by the Middle to Late Holocene (Kaufman et al., 2004). It appears that the so-called 'neoglacial' was primarily a Northern Hemisphere/Arctic trend reflecting the pattern of Northern Hemisphere insolation.

Recognizing that proxy data suggested Holocene global temperature cooling, while models suggested Holocene warming – the so-called 'Holocene temperature conundrum' – Osman et al. (2021) assimilated proxy data into numerical models for a Last Glacial Maximum reanalysis that showed that global mean temperature slightly but steadily warmed (by 0.5 °C) since the Early Holocene. Their analysis confirmed that the rate and magnitude of modern warming are unusual relative to the changes of the past 24,000 years (Osman et al., 2021).

The warming since the Early Holocene paralleled a slight rise of about 20 ppm in CO_2 over the same period, remarked upon by Ruddiman et al. (2016, 2020). The rise in CO_2 may 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. Indeed, 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).

Insolation data provide clues to the drivers of Holocene climate change. Fig. 3 shows that summer insolation was substantial, especially in the north of the Northern Hemisphere at ~9 ka, with its peak shifting to the southern hemisphere by 3 ka. 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 at ~11 ka, and farthest from the Sun today. Similarly, a decrease in obliquity (the tilt in the Earth's axis) from 9 ka 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 (Fig. 4). Early in the Holocene, when summer insolation was high (Fig. 4), incoming solar radiation gradually melted away the remnants of the Northern Hemisphere ice sheets, which, for as long as they persisted, kept the high-latitude Arctic relatively cool. The development of the neoglacial conditions, as defined above, and which we now see as a polar phenomenon in response to changing insolation (Figs. 3 and 4, and Vinther et al., 2009), can be explained by albedo increase as ice cover expanded in polar regions in the Late Holocene in tandem with declining Northern Hemisphere summer insolation (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.

Evidence compiled by Fischer et al. (2018) showed that compared with pre-industrial temperatures the Last Interglacial was probably

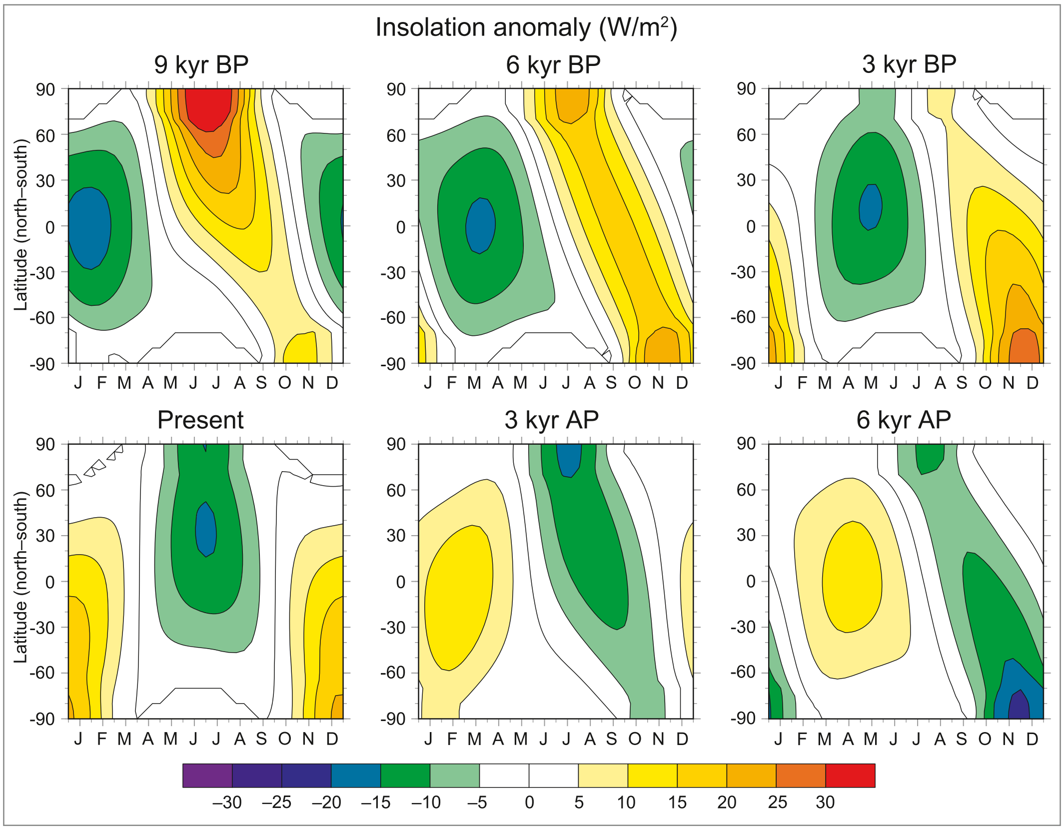

Fig. 3. Distribution of shortwave radiation (insolation) received from the Sun at the top of the atmosphere between 9 kyr ago (BP = before present) and 6 kyr into the future (AP = after present). A mean distribution of insolation assuming no eccentricity and a mean obliquity of 23° 20′ was subtracted 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 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 onwards. From Fig. 4.4 in Crucifix (2009).

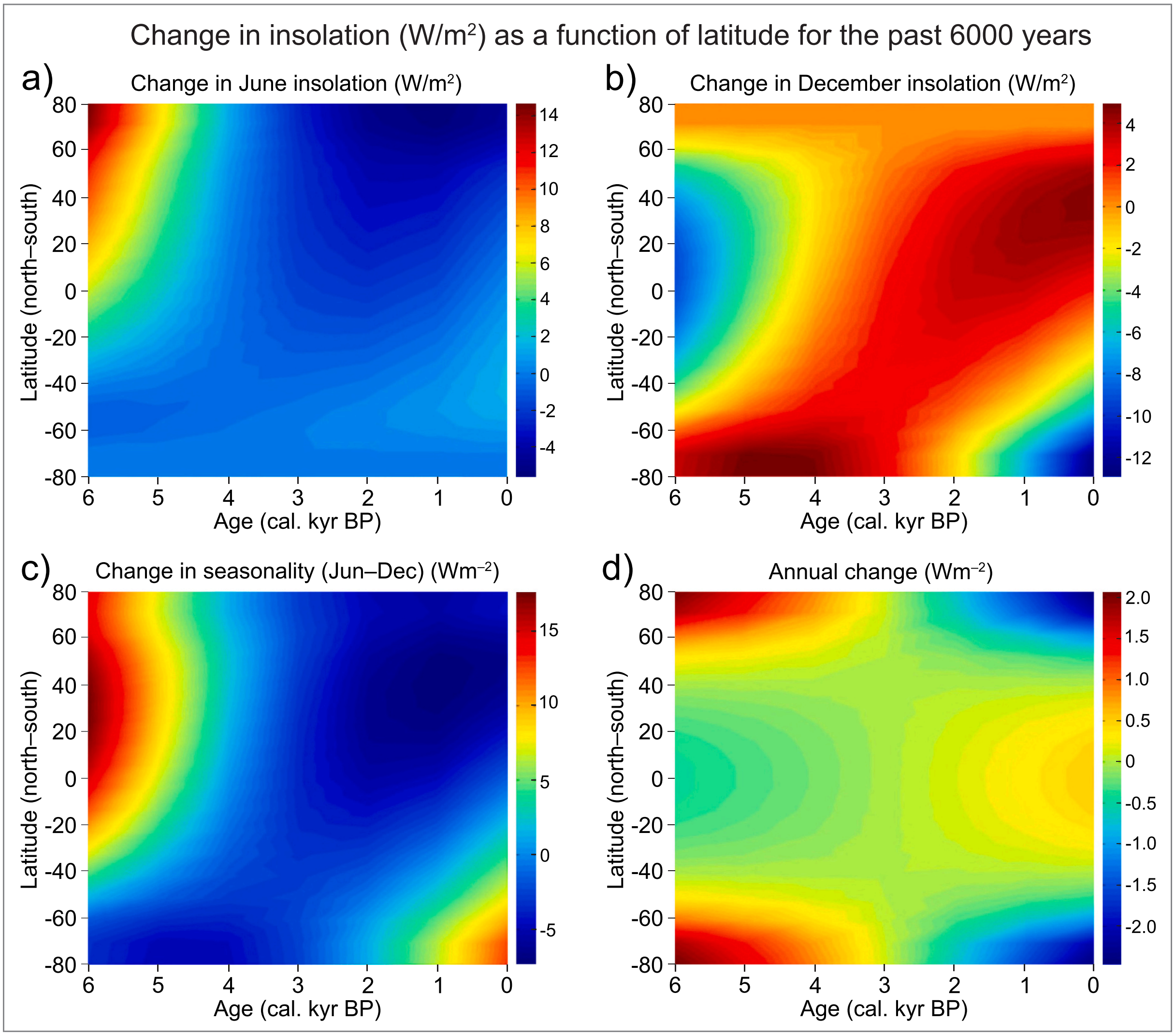

Fig. 4. Calculated deviations of the insolation from the long-term mean values (W/m^2) as a function of latitude for the past 6000 years: (a) June (boreal summer), (b) December (austral summer), (c) seasonality (difference between June and December), (d) annual mean. From fig. 6 in Beer and Wanner (2012).

~0.8 °C (maximum 1.3 °C) warmer than the average for the Holocene, and that the northern high-latitude oceans warmed then by >1–4 °C and surface air temperatures by >3–11 °C. A similarly strong polar amplification was estimated for the North Atlantic and Russian Arctic during the mid-Piacenzian Warm Period centred on ~3 Ma (see Section 9), with a rise in air temperature by some 8 °C, similar to projected warming at 2100 for the IPCC's most extreme warming scenario (IPCC, 2021, 2023). Given that the CO_2 levels of the mid-Piacenzian Warm Period are like those of today (see Section 9), this suggests that current climate models may underestimate the warming response of the polar regions to increased CO_2 abundance, most likely because they lack or oversimplify key processes such as interactive ice sheets, cloud processes and biogeochemical feedbacks that impact long-term Earth System Sensitivity (Fischer et al., 2018).

While there are differences in insolation between the northern and southern polar regions (Fig. 3), the two areas remain intimately connected through the ocean's global thermohaline conveyor, which transfers heat and salt around the world (see Section 7, below) (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, supplies a significant component of North Atlantic Deep Water to the deep Southern Ocean (yet more NADW comes from the circulation of Atlantic Water through the deeps of the Arctic Ocean (see Section 7, below)). 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 NADW as far north as Lisbon, Portugal. The timescale 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 2000 years. Along the routes of these long teleconnections, local and regional climatic variability (e.g. 4–7 yr periodicity for El Niño events and the 20–25 yr periodicity for the 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 ~7 ka (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 ka) and 7 ka as the great Northern Hemisphere ice sheets melted away (Clark 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 (Fig. 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 gone. Only Greenland, Antarctica and mountain icefields 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 ~3–5 m).

Why did sea level not rise along with the slight 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 responded to the regional decreases in insolation there (Figs. 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, recognizable 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 changes in solar output in the Late Holocene 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, during which the River Thames in London froze over in winter. A recent analysis of *Pinus sylvestris* trees in Fenno-Scandinavia has provided high-fidelity proxy measurements of temperature variability during the warm season: these show that the peak summer temperatures of the MWP in northern Europe were substantially cooler than those of the present day, in agreement with models of insolation (Björklund et al., 2023). Evidently, today's climate is warmer than it was during the MWP in the Northern Hemisphere summer (Björklund et al., 2023).

In the IPCC's 2023 Synthesis Report of its 6th Climate Change Assessment, the Summary for Policy Makers indicates global warming to be already 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 (Fig. 2). In high emissions scenarios, CO_2 emissions nearly double by 2100, with warming reaching ~4 °C above pre-industrial levels. In intermediate emissions scenarios, CO_2 emissions remain at about current levels until 2050 and then decline, limiting warming by 2100 to ~2.5–3.0 °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; Fig. 2). It now seems almost inevitable (IEA, 2023) 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 two and four 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 at 34 Ma (Beerling and Royer, 2011; Foster et al., 2017; The Cenozoic CO_2 Proxy Integration Project (The 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 from 1.3 mm/yr (from 1901 to 1971), to 1.9 mm/yr (from 1971 to 2006) and then to 3.7 mm/yr (from 2006 to 2018) (IPCC, 2021, 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 much 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 groundwater) 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).

6. Future warming and greenhouse gas emissions

Future climate evolution will reflect how much of the Earth's fossil fuel reserves and resources (still considerable) are burnt over the coming decades and centuries. For now, 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, 2023), vis-a-vis national intentions as stated emissions targets.

The International Energy Agency's annual World Energy Outlook (e.g. IEA, 2023) indicates that between now and 2050 most energy provision will continue to come from the burning of fossil fuels, the contribution of which is flattening and is likely to peak in the current decade as growth in the renewables sector continues to increase. Energy demand is set to decrease as electrification proceeds, given the improved efficiency of electric over fossil-fuel-powered vehicles and heat pumps over gas boilers, along with strong growth in solar and wind energy. The IEA forecast suggests that the emissions of CO_2, and of fugitive CH_4 from leaky extraction and supply systems will reach a broad peak centred on about 2025 (IEA, 2023). However, if nothing is done to extract new emissions of these gases from the air, they will add to the total greenhouse gas burden, with attendant global warming (IPCC, 2023).

The Intergovernmental Panel on Climate Change (IPCC), co-sponsored by the World Meteorological Organization (WMO) and the UN Environment Programme (UNEP), provides regular assessments by experts on the state of the climate system and the roles of the greenhouse gases in global warming, at intervals of about 5 years. The latest of these dealing with the science base was published in 2021 (IPCC, 2021, with a summary in IPCC, 2023) and was thus based on scientific publications dating up to 2020. But these 5-yearly reports are not the only source of such information. The less well-known Global Climate Observing System (GCOS), also co-sponsored by the WMO and UNEP, along with the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the International Council for Science (ISC), provides annual assessments of these matters. Arguing that the Earth's 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 in 2020 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 W/m^2, so as to bring Earth back towards energy balance (von Schuckmann et al., 2020). 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. The increase in the EEI makes 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 atmospheric greenhouse gas concentrations are maintained. From a comprehensive study 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 × CO_2), a value substantially greater than the ECS of 3 °C adopted by the IPCC in their AR6 report (IPCC, 2021, 2023). Using these new data, 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 discrepancy 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 thawing permafrost. Incorporating the effect of reflective aerosols would reduce the 10 °C to 8 °C (Hansen et al., 2023). This new analysis suggests that more warming is 'in the pipeline' than is indicated by the IPCC's analysis. These findings suggest that we are on route to approaching the levels of warming of the mid-Eocene, which were ~ 11 °C higher than today (Lunt et al., 2021). Given the overturning period for the global ocean, one might expect a rise of this magnitude to be reached sometime in the next 500–1000 years.

Hansen et al. (2023) considered the discrepancy between the EEI approach that he and the GCOS community had taken and the conclusions of the IPCC (2021, 2023) reflected (i) the IPCC's consensus-taking position being somewhat conservative; (ii) the IPCC's focus on the use of Climate General Circulation models (which have their limitations); and (iii) the reliance of Hansen and colleagues on using paleoclimatic data from the Cenozoic (instead of relying on IPCC-type climate models) to see what nature had done in the recent geological past. The discrepancy between the IPCC's and Hansen's forecasts may result from weaknesses in climate modeling of the polar regions, which is known to be less robust than at lower latitudes (e.g. Binschadler et al., 2009). For instance, Casado et al. (2023) noted that failure to consider feedback loops causing polar amplification could lead to an underestimation of the magnitude of anthropogenic warming and its consequences in Antarctica, while Dell et al. (2024) noted that surface melt in Antarctica is unaccounted for in regional models, likely leading to under-estimates in projections of ice sheet melting.

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 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 myr (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, showing that climate sensitivity in the CESM1.2 model increased 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) agreed 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 anticipated 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 (Head et al., 2023; Hansen et al., 2023). More recently, a further reduction in aerosol supply by shipping (forced since 2020 by legislation to burn less sulfur-rich fuels) has been implicated in the marked subsequent warming of surface ocean waters (Voosen, 2023b).

The IPCC (2021) report found medium confidence that, by 2300, an intermediate scenario for emissions would lead to global surface temperatures of 2.3–4.6 °C higher than 1850–1900, similar to the mid-Piacenzian Warm Period (2.5–4.0 °C), about 3.2 Ma, and the high CO_2 emissions scenario would lead to temperatures of 6.6–14.1 °C by 2300, which overlaps with the Early Eocene Climate Optimum (10–18 °C), about 50 Ma (see Section 9). The report noted that many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level. For instance, over the next 2000 yrs, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5 °C, 2 to 6 m if limited to 2 °C and 19 to 22 m with 5 °C of warming, and it will continue to rise over subsequent millennia (IPCC, 2021). These findings are consistent (although with somewhat reduced estimates) with the conclusions of Hansen et al. (2023).

7. Arctic Ocean Circulation and the role of the Atlantic Meridional Overturning Circulation (AMOC)

A full understanding of global climate change requires an appreciation for the role of the Great Ocean Thermohaline Conveyor that connects the global ocean's water masses and slowly transports heat and salt around the world, modifying regional and global climate in the process (Broecker, 2010)(see Section 5). The Atlantic Meridional Overturning Circulation (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 mostly 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 influenced 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 Antarctic Bottom Water. Yet when this sea ice area becomes extensive during all seasons, as during peak glacial times, that Antarctic process too may have been weakened or even switched off (Rahmstorf, 2002). Here we will consider the separate roles of Arctic and Antarctic circulation, and how they may change in future, affecting regional climate change, as global warming progresses.

Much Arctic sea ice derives from the freezing of the freshwater output of Siberian rivers onto the East Siberian continental shelf. Winds and currents move this sea ice south across the North Pole in the Trans-Polar Drift, and ultimately into the Northeast Atlantic via the East Greenland Current. The southward motion of this relatively light surface water with its cargo of ice floes is balanced by the northward flow of warm saline Atlantic Water (AW) along the Norwegian coast. On its path, the AW cools, becomes denser, sinks and circulates as Intermediate Water at depths of 400–1000 m beneath the colder and fresher surface water. The overall circulation has been described as 'estuarine', with freshwater and sea ice floes moving south via the Trans-Polar Drift and saline AW moving north along the Norwegian margin and through the Barents Sea (Timmermans and Marshall, 2020). Since the 1950s, the incoming Atlantic Water has warmed substantially, being reported as exceptionally warm in the 2000s (Polyakov et al., 2012).

The incoming AW increases the northward transport of heat into the Arctic Ocean, thus making a major contribution to the melting of Arctic sea ice (Tsubouchi et al., 2021). As a result of global warming, the rate at which sea ice is supplied to the central Arctic Ocean has lessened in recent decades (Krumpen et al., 2019). The sea ice 'nursery' of the East Siberian, Laptev and Kara seas now supplies much less sea ice than formerly to the Transpolar Drift that takes sea ice south into the Atlantic through the Fram Strait, where the sea ice is also 30 % thinner than it was formerly.

The AW circulates anticlockwise along the Arctic continental margins, exiting the Arctic as a deep-water component of the outflowing East Greenland Current (Wefing et al., 2021). This corroborates the analysis of Mauritzen (1996), who showed AW flowing south across the Greenland-Scotland Ridge at a rate of 6–7 Sv (1 Sverdrup = 1×10^6 m^3/s) to form the principal component of NADW. This rate has remained more or less constant over the past two decades (Tsubouchi et al., 2021).

The increased northern heat transport by the incoming AW contrasts with the slowing of northward heat transport by the AMOC at mid-latitudes, indicating a discontinuity between what the AMOC is doing at those latitudes, and the supply of NADW from the Arctic to the Atlantic (Tsubouchi et al., 2021). Timmermans and Marshall (2020) suggested that the Arctic Ocean's estuarine circulation and AW inflow were likely to be driven in part by the strength of the Iceland Low Pressure Cell in the atmosphere, and thus may persist regardless of the waning strength of the AMOC.

The oceanographic observations of Mauritzen (1996) and Tsubouchi et al. (2021) cast doubt upon the likelihood that the further melting of Arctic sea ice and Greenland ice might lead to a sufficient southward flood of cold fresh surface water to slow the AMOC further and cool both the Arctic atmosphere and nearby northwestern Europe, a bleak prospect outlined among others by Rahmstorf (2024) and Van Westen et al. (2024). 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 south of Greenland. Although 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 beyond the 13 % by which it weakened 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 prognoses of Rahmstorf (2024) and 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. For the somewhat longer term that prognosis seems to be confirmed by Lunt et al. (2024), who used paleoclimate data and the latest CMIP6/PMIP4 model ensemble mean to show that during the mid-Piacenzian Warm Period (see Section 9) the sea surface temperature over the region of the Sub-Polar Gyre and the surrounding Northeast Atlantic was substantially warmer than the rest of the world ocean (where CMIP = Coupled Model Intercomparison Project, and PMIP = Paleoclimate Modeling Intercomparison Project).

Even so, Galaasen et al. (2020) found that NADW production did fluctuate irregularly but substantially during the past three interglacial periods, suggesting that such fluctuations may be an intrinsic feature of centennial-scale variability in warm climate states. The possible collapse of the AMOC has been suggested as one of a number of possible 'tipping points' that may result from continued global warming (Lenton et al., 2023). The closest paleoclimatic analogue for such an event leading to regional cooling might be that of the Younger Dryas event of the Northern Hemisphere (12.9–11.7 ka), which interrupted the end phase of the warming during the transition from the Last Glacial Maximum to the Holocene, cooling Greenland by 4–10 °C, and leading to temporary glacial advances across the Northern Hemisphere. The trigger might have been a set of powerful volcanic eruptions (Abbot et al., 2021), or a meteorite impact (Powell, 2022), setting off a temporary decline in the northward transport of heat by the AMOC. The more likely cause was a change in atmospheric forcing by alterations in the jet stream and sea ice distribution driven by the changing geometries of the Northern Hemisphere ice sheets as they gradually melted away (Abdul et al., 2016).

While the Younger Dryas was primarily a circum-North Atlantic event, it had a global impact through the associated change in global sea level (Abdul et al., 2016). Regardless of its cause, the Younger Dryas Event occurred when there was still a remnant Laurentide Ice Sheet on North America, with the potential to supply ice and meltwater at a rapid rate to the northern North Atlantic. The Younger Dryas of the Northern Hemisphere was accompanied by warming of the Southern Hemisphere and may be the latest example of the operation of the so-called bipolar seesaw, which over the past 640 kyr has been typical of the mid-glacial climate phase between interglacial and glacial maxima (Broecker, 1998; Stocker, 1998; Seidov et al., 2001), and which led to periodic rapid warmings of the Arctic known as Dansgaard-Oeschger Events after their discoverers (see Summerhayes, 2020).

During such mid-glacial cold phases in the North Atlantic, large periodic catastrophic outbreaks of icebergs from the North American and Greenland ice sheets (named Heinrich Events) disrupted the AMOC. Heinrich Events reflect flickering of the climate system during an interval when it was in transition from interglacial to full glacial state (e.g. Jouzel et al., 2013; Summerhayes, 2020) and should not characterize the modern and largely ice-free Arctic climate system or its future. However, analysing the sedimentary record of iceberg debris from the North Atlantic, Zhou and McManus (2024) found that today's discharge of icebergs from Greenland is not much different from that during past Heinrich Events. But, the modern discharge is occurring under warm conditions when the AMOC is relatively strong, not under cold conditions like those of past Heinrich Events, when the AMOC was weak. Also, unlike past Heinrich Event times, there is no accompanying discharge of icebergs from the now vanished Laurentide ice sheet. As the relatively small Greenland ice sheet melts away and retreats from the coast, it will cease to be a source of massive iceberg calving, which will be replaced by meltwater from the Greenland interior, presenting less of a threat to the stability of the modern and relatively strong AMOC (Zhou and McManus, 2024). Hence repeats of the Dansgaard-Oeschger cool periods of mid-glacial times, and associated cessation of the AMOC, seem highly unlikely in the progressively warming world of the Anthropocene, despite the prognosis of Smolders et al. (2024), with its evident uncertainty.

At around 8.2 ka, the breakout of freshwater from large ice-bound lakes in North America (Lake Agassiz and Lake Ojibway) led to a further, though much smaller and shorter, cooling of the Arctic that lasted between 400 and 600 years (Alley et al., 1997; Rohling and Pälike, 2005). This event cooled the region by about 2 °C (Vinther et al., 2009). Such lakes disappeared with the demise of the Laurentide Ice Sheet and no longer form a threat. Nevertheless, similar but very much less extreme events, apparently caused by variations in solar output during the Holocene (Magny, 2004, 2007; Bond et al., 2001), caused

Arctic ice melt events that put a temporary freshwater lid on the northernmost North Atlantic, which was associated with increased ice rafting south of Iceland and rises in European lake levels (Magny, 2004, 2007; Bond et al., 2001). A repeat of the 8.2 ka event is unlikely, given the absence of (sub-)Arctic glacial lakes and dams.

Does what happens to the AMOC help us predict a future pause in global warming such as that which seemed to occur between 2002 and 2011? Although Chen and Tung (2018) considered that fluctuations in the AMOC might have caused such an apparent pause in global warming between 2002 and 2011, 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). *Re*-examination of all available sea surface temperature (SST) data, including the addition of previously missing Arctic data, shows that the global rates of warming of sea surface temperature for 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).

8. What can we expect for a future warmer Arctic Ocean?

Paleoclimatic analyses show that Arctic sea ice has been a feature of the Arctic Ocean since 47 Ma following a decline in atmospheric CO_2 after the Paleocene-Eocene Thermal Maximum. For at least the past 13 or 14 myr it has covered at least some of the Arctic Ocean (Polyak et al., 2010). Hence its loss will represent a major environmental change in Earth's climate system. When the sea ice is gone, the air will take on the temperature of the water (Hay, 2021). Currently, the seawater below the ice is at about −1.5 °C, the air above is about −30 °C in winter and just above 0 °C in summer. Hence, without the sea ice the air is likely to become some 30 °C warmer in winter. This will increase the water vapor content of Arctic air by a factor of about 4 (Hay, 2021, p.875), giving the Arctic a strong water vapor greenhouse effect, which it now lacks (water vapor being concentrated in the air south of the Arctic Circle).

We can also expect some melting of the Greenland Ice Sheet, which has lost ~5000 Gt of ice since 2003 (Otosaka et al., 2023). Ice cores show that warming in the first decade of the 21st century exceeded the range of variability for the past 1000 years and was on average 1.5 ± 0.4 °C warmer than the 20th century, reflecting the operation of a long-term warming trend, which was accompanied by enhanced meltwater runoff (Hörhold et al., 2023).

Based on studies of Arctic sediments dating back to 18 ka, further warming of the Arctic Ocean will destabilize seabed permafrost, releasing methane from decomposing methane clathrates (Altuna et al., 2021). The warming Arctic Ocean will also emit more CO_2 from its surface (Timmermans and Marshall, 2020). Further powerful feedbacks include the exposure of the ocean surface to winds (whose effect is currently depressed by the sea ice surface), which will break up the already thinned sea ice cover. Reducing the sea ice cover will decrease the Arctic's albedo, leading to yet more warming.

The sea ice cover of the Arctic Ocean has created a permanent high-pressure system in the air over the North Pole, which has stabilized the Northern Hemisphere atmospheric circulation for thousands of years. That stabilizer is now diminishing as sea ice shrinks. This caused the development of a polar low-pressure cell over the Arctic Ocean in summer 2012, which pushed the Greenland high pressure system south, contributing to the westward deflection over New York of Hurricane Sandy (Hay, 2021, p. 605). The development of a perpetual summer low pressure system over the pole will further destabilize current atmospheric circulation, interfering with the westerly air stream.

The boundary between high pressure polar air and lower pressure air at mid-latitude creates a strong atmospheric front along which runs the polar jet stream. The stream meanders in Rossby Waves that migrate eastwards. The decreasing thermal gradient between the tropics and the pole caused by global warming has made these meanders larger, taking cold air outbreaks south in winter over eastern North America and northwestern Europe, separated by warm air intrusions over Greenland. At times these waves may become stuck for days to weeks. Further warming of the Arctic is likely to lead to further such meanders and accompanying climatic instability.

Modeling now suggests that the first single occurrence of a fully ice-free Arctic Ocean during September might happen by the 2030s under all emissions trajectories, and is likely by 2050 (Jahn et al., 2024).

9. Evidence from Cenozoic Paleoclimates

By adding anthropogenic carbon emissions to the atmosphere, we have pushed our climate along a trajectory towards levels last seen during previous very warm times in Earth's geological history (e.g. Archer, 2009; 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 Ma); at the Miocene Climatic Optimum (16.9–14.7 Ma); at the Early Eocene Climatic Optimum (53–49 Ma) and at the Paleocene-Eocene Thermal Maximum (55.9–55.7 Ma).

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 data suggest (i) that early Cenozoic 'hothouse' CO_2 concentrations peaked near 1600 ppm at 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 C_4 plants inhabiting grasslands and deserts today that use carbon-concentrating pathways; and (iv) that CO_2 remained low for the rest of the Cenozoic. The last time that CO_2 concentrations were consistently higher than at present was 16 Ma during the Middle Miocene, when sea level may have been some 50 m higher than today.

9.1. 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; Fig. 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 myr 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 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 have exceeded model projections and would be accentuated in the higher latitudes. Burton et al. (2024) combined model outputs and proxy data from a number of oceanic drill sites to investigate climate change within the same mid-Pliocene interglacial time slice (Marine Isotope Stage KM5c) centred on 3.205 (± 0.01) Ma, when orbital forcing was very similar to that of modern times, and CO_2 concentrations were much like modern ones, averaging 371 ppm (range 403–342 ppm). Temperature change was driven primarily by CO_2 forcing, and, based on PlioVAR data, the equilibrium climate sensitivity for doubled CO_2 (ECS) ranged from 3.44

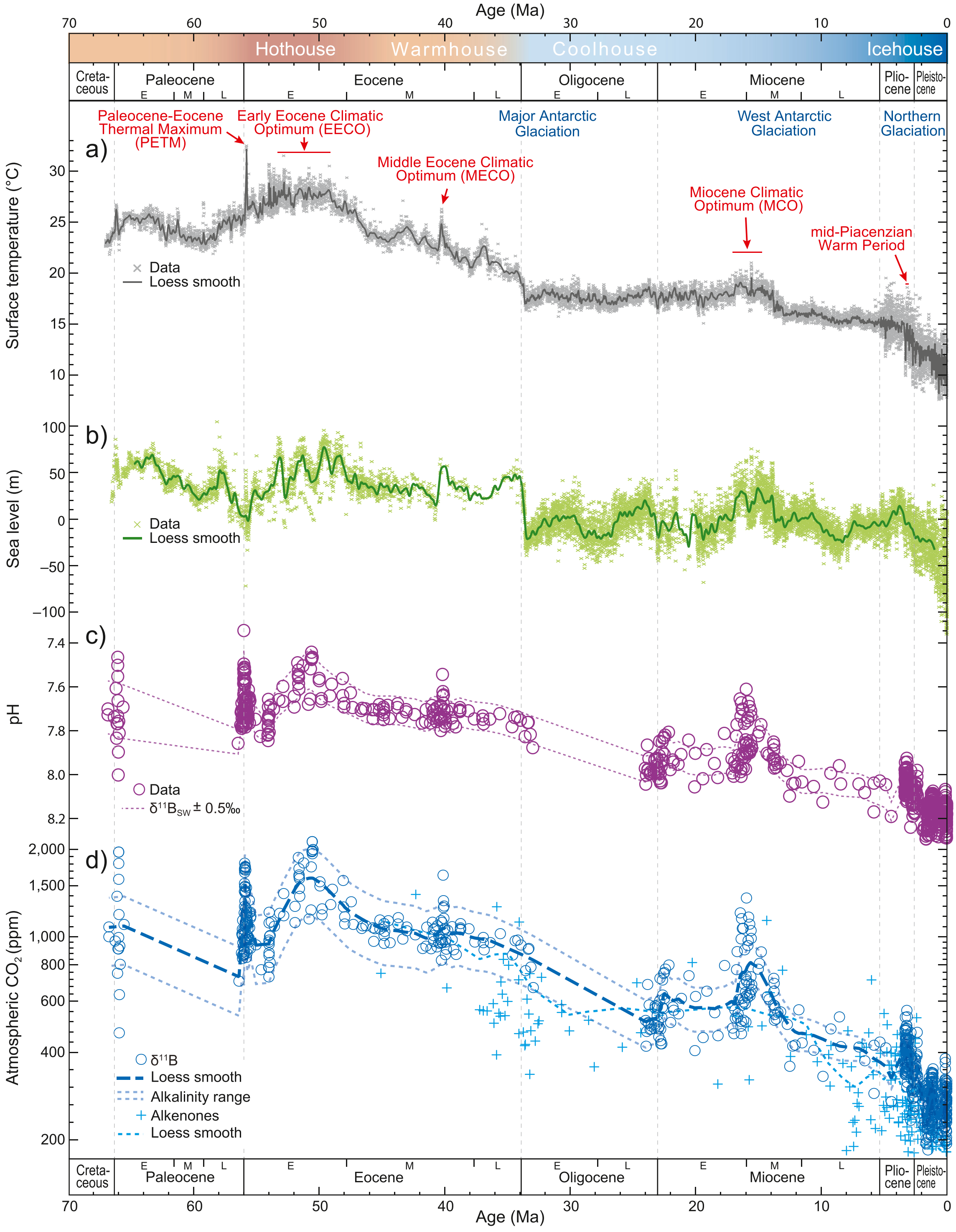

Fig. 5. Overview of Cenozoic CO_2 and global climate. Earth's climate state is moving towards conditions last seen during earlier warm intervals of the geologic past, as shown here. a) Surface temperature estimated from the benthic $\delta^{18}O$ stack of Westerhold et al. (2020); (b) Sea-level estimates 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). Modified from figures 5 and 6 of Rae et al. (2021). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to 4.15 °C. The Earth System Sensitivity (which includes lags induced by changes in ice volume, albedo and sea level) was shown to be 6.5 °C. As mentioned earlier, Lunt et al. (2024) show that sea surface temperatures around Greenland and across the northeast Atlantic were substantially warmer than preindustrial levels (1850–1900).

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 regions (see Zhang et al., 2012).

9.2. Miocene Climatic 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 hence 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 they are today, at ~470–630 ppm (Sosdian et al., 2020), and mean surface temperatures were 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 adds weight to the arguments of Hansen et al. (2023) that climate is more sensitive to CO_2 increases than is generally assumed.

9.3. 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 Ma, when CO_2 concentrations were of the order of 1500 ppm (Rae et al., 2021; Fig. 5). This occurred 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). The latest CMIP6/PIMP4 model ensemble mean confirms both surface air and ocean temperatures were significantly elevated at the time, compared with preindustrial times (Lunt et al., 2024).

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, 2021, 2023). Nevertheless, while the very warm conditions of Eocene times centred on 50 Ma may provide some indication of where current warming may lead, given that its CO_2 levels were some three times preindustrial levels (Lunt et al., 2021), the Eocene is not especially useful as an analogue for the future Anthropocene because its continental configurations differed significantly from those of modern times. Global mean surface warming is calculated as 10.5 °C above preindustrial levels, half due to CO_2 and water vapor increases and feedbacks from clouds, and half due to changes in surface albedo, because of the absence of ice, changes in vegetation and clouds, and the lower altitude of ice-free Antarctica (Lunt et al., 2021). With polar ice absent, the tropical to polar thermal gradient decreased, leading to substantial polar amplification, averaging ~12 °C (Lunt et al., 2021). We can consider this as an extreme outlier, given the very low likelihood of most Antarctic ice disappearing.

A clear illustration of what happens when a pulse of carbon is injected to the atmosphere 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 10-15 m through thermal expansion and ice melt (Fig. 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 led to 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., 2007a). 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 valuable deep-time context to the differences already evident between Holocene and nascent Anthropocene strata, and so it is useful to explore the differences between the two cases.

$\delta^{13}C$ data suggest the release of 2000+ Gigatons (Gt) of ^{12}C-rich carbon, as CH_4 subsequently oxidised to CO_2, in both the ocean and atmosphere (Zachos et al., 2001). Arctic temperatures rose from 17 to 25 °C (Miller et 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 and Overpeck, 2007).

Carbon was added to the Earth System during the PETM at 0.3–1.7 GtC/yr (Cui et al., 2011), far less than the modern rate of carbon emissions of ~10 GtC/yr (Montañez et al., 2011). Turner (2018) used data and models 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 myr, yet only a tenth of modern rates of carbon release, leading Zeebe et al. (2016) to note that we are now in a 'no analogue' state representing 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., 2007b; 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 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 benthic 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 was 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 declined, returning 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 (Williams et al., 2024).

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).

10. 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 multi-millennial-duration climate change. Astronomical forecasts 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 in the development of glacial maxima are attributed to Earth's present low orbital eccentricity, which suppresses the amplitude of precession and thereby causes weak minimum summer insolation and is projected to continue for a considerable time (Talento and Ganopolski, 2021). However, 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 (see Section 9). In Fig. 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 full glacial conditions not attained until ~90 kyr after present (Talento and Ganopolski, 2021).

We can also expect weak 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), which initiated 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 it would likely decline to a level comparable to that of the Dalton Sunspot Minimum (centred on about 1810), followed by a slow increase to ~2400, further enhancing global warming (Steinhilber and Beer, 2013). Given a continued increase in global warming, continuation of the sort of ice rafting events identified for the Holocene by Bond et al. (2001) seems unlikely.

If we cease the emission of CO_2 (the net zero scenario) 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 atmosphere 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 atmospheric lifetime of those CO_2 emissions is thus 30–35 kyr, much longer than commonly appreciated. As long as our CO_2 emissions stay in the air, temperatures will remain 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 timescale 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; Ganopolski et al., 2016) used a climate model to demonstrate that even already achieved cumulative CO_2 anthropogenic emissions (500 GtC) 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 GtC or higher, as is achievable in the next two to three centuries if humans do not curb the usage of fossil fuels, the Northern Hemisphere landmass is likely to be nearly 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. This will prolong present warmth (Archer et al., 2009). Rohling (2021) calculated that this oceanic outgassing of CO_2 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 (DeConto et al., 2021)? We must consider here any hysteresis effects (Abe-Ouchi et al., 2013). With respect to Antarctica, currently observed ice-sheet losses 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, 2021, 2023; Fig. 2c) as an unavoidable consequence of continued deep ocean warming and melting ice sheets. 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, 2021, 2023).

The 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 ka, when sea level may have reached ~14 m above today's level (e.g. Rohling et al., 2019, but see below), or the early Late Pliocene, 3 Ma, when the IPCC recognized that global mean sea level was likely up to 20 m higher than today, at a time when global temperatures averaged 2.5–2.0 °C higher than in 1850–1900 (IPCC, 2021, 2023). The IPCC accepted that due to deep uncertainty in ice sheet processes, it could not rule out the possibility that global mean sea level might approach 2 m by 2100 and in excess of

15 m by 2300 under a very high emissions scenario (IPCC, 2021, 2023). If Greenland and West Antarctica were to melt entirely, sea level would rise by ~12 m (7 m from Greenland and up to 5 m 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 meters above present levels are not unusual in the perspective of Quaternary sea-level history. During the Last Interglacial ~125 ka, 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 +5.7 m (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 sea level would rise by up to 2.7 to 5 m, reaching 5 to 9 m by 2300. 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 consistent with 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 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 (+5–14 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 523 ppm CO_2-eq; NOAA, 2023a). 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 Climatic 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 ~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 sediment starvation resulting from 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, is all 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 (i) direct, e.g. accelerated sea-level rise, larger and more intense tropical cyclones, extreme precipitation events and changes in river discharge, and (ii) indirect through drought, water stress, wildfires, melting polar sea ice and decreased freshwater delivery to coasts (Day et al., 2023). 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 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 and Gulf of Mexico. 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 greater 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 exceeded (Fig. 2b in Head et al., 2023).

11. Implications for net zero and negative emissions strategies

These various observations beg the question, by how much would we need to reduce atmospheric CO_2 to diminish 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 air 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 less 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 its current abundance, governments are being urged to aim for net zero emissions, which means that by 2050 the same amount of greenhouse gas must be removed as is emitted. If accomplished, this will leave in the atmosphere the same high abundance 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).

However, maintaining such a high residual abundance of CO_2 in the atmosphere would be highly likely to sustain the amount of warming already established, thus continuing the warming that is already shrinking the sea ice cover at both poles, melting mountain ice, and threatening the stability of ice sheets. 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 providing critical positive feedback. The resulting persistence of warmth at global average temperatures of between 1.5 or 2.0 °C this century is likely to (i) sustain high levels of evaporation, amplifying global warming through the emission of yet more water vapor (a potent greenhouse gas) from the ocean; (ii) further warm the ocean, causing (a) sea-level rise by thermal expansion, and (b) natural emission of CO_2 from warm surface waters; (iii) exacerbate ice melt, contributing yet more to sea-level increase; and (iv) further decrease albedo through ice and snow loss, allowing yet more warming through increasing absorption of solar energy by the Earth's surface (e.g., Summerhayes, 2024).

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). 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) argued 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, not least because CO_2 emissions involve multiple distributed sources (e.g. vehicle tailpipes, aircraft engines), as do CH_4 emissions (animal farms, manure slurries, well heads, pipelines etc.).

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 299 ppm CO_2 and for the most part was never above 280 ppm (Lüthi et al., 2008; Bereiter et al., 2015), which is generally taken as the abundance prior to the Industrial Revolution (NOAA, 2022; Friedlingstein et al., 2023). 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 0.6–0.7 °C warmer than in 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 the interval from 1850 to 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) (see Section 10).

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).

12. 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 (Barnosky, 2008; Bar-On et al., 2018; 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 (Ellis, and C., Ramankutty, N., 2008). 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 is becoming permanently and conspicuously distinguishable from that of all previous epochs (Williams et al., 2024).

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 (Smale et al., 2019; Wyatt et al., 2023). Current global warming threatens most reefs worldwide, in part due to increased ocean stratification leading to excessive warming of upper ocean water (Goreau and Hayes, 2024). Modern ocean 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). Marine organisms are becoming increasingly subjected to both ocean acidification and declines in oxygen concentration, likely to have deleterious effects on them (e.g. Feely et al., 2018; Pitcher et al., 2021).

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 (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 occur, if loss rates persist, within a few centuries or less (Barnosky et al., 2011; Ceballos et al., 2015, 2020).

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).

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

In this synthesis we have considered not only the current climate record and its likely projection as greenhouse gas emissions increase, but also the relevant components of the paleoclimate record, along with results from a variety of numerical models of likely future change (not just Global Climate Models), as well as the current understanding of the ocean's role in climate change (such as Arctic Ocean circulation and the Atlantic Meridional Overturning Circulation) and how global warming is affecting sea ice, ice sheets, Earth's albedo, the Earth's Energy Imbalance (EEI), sea level, ocean acidification and biodiversity.

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 late 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 426.9 ppm in May 2024 (NOAA, 2024) and still rising. 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 increase since 1975), and of the yet further delayed sea-level rise (~20 cm over the last century, though now increasing to ~4.77 mm/yr) (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) and rising. In effect, Earth is likely 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 those of hyperthermal spikes such as the PETM (see Section 9). 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, thawing permafrost 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 atmospheric abundance of CO_2-eq, following whichever pattern of feedback effects has been triggered. The climate modeling discussed earlier strongly suggests that the climate effects are likely to persist for at least 50 kyr, and probably for as much as 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 underpinned by basic physics, together with evidence from 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, far longer than the Holocene climate state, creating a unique stratigraphic and paleontological signature. Indeed, this record has already begun to accumulate, as demonstrated by Zalasiewicz et al. (2024a) and Williams et al. (2024).

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 500 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 (Steinthorsdottir et al., 2021; Burke et al., 2018), the question of more substantial disruption arises. 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 quasi-Milankovitch orbital 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 the anthropogenically modified ecologies of 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), 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 for equilibrium warming on the 500–2000 year timescale of global ocean circulation assuming the eventual stabilization of atmospheric greenhouse gas abundance, once there is no longer solar shading by anthropogenic aerosols and long-term feedbacks have run their course (e.g. Hansen et al., 2016, 2023). These changes are slightly less than those inferred for maximal emissions in the latest IPCC reports (IPCC, 2021, 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).

The biological fallout of Anthropocene warming and ocean acidification cannot fail to be profound. If emissions continue over this century to approach Eocene levels (Burke et al., 2018), this will have 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 (Williams et al., 2024). A new stratigraphic entity has arrived.

Open research

No new data were used in this study.

Credit authorship contribution statement

C.P. Summerhayes: Writing – original draft, conceptualization. **J. Zalasiewicz:** Writing – original draft. **M.J. Head:** Writing – original draft. **J. Syvitski:** Writing – review & editing. **A.D. Barnosky:** Writing – review & editing. **A. Cearreta:** Writing – review & editing. **B. Fiałkiewicz-Kozieł:** Writing – review & editing. **J. Grinevald:** Writing – review & editing. **R. Leinfelder:** Writing – review & editing. **F.M.G. McCarthy:** Writing – review & editing. **J.R. McNeill:** Writing – review & editing. **Y. Saito:** Writing – review & editing. **M. Wagreich:** Writing – review & editing. **C.N. Waters:** Writing – review & editing. **M. Williams:** Writing – review & editing. **J. Zinke:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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