Title: The Anthropocene is functionally and stratigraphically distinct from the Holocene


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Abstract:
Human activity is leaving a pervasive and persistent signature on the Earth’s geology. Vigorous debate continues about if and how to define this as a new geological time unit, the Anthropocene. We review anthropogenic markers in the stratigraphic record of functional changes in the Earth system that exceed Holocene Epoch ranges. Manufactured materials in sediments, including aluminum, plastics and concrete, coincide with global spikes in fallout radionuclides and fossil-fuel combustion particulates. Carbon, nitrogen and phosphorus cycles have been significantly modified over the last century. Sea-level rise rates and human perturbation of the climate system exceed Late Holocene values. Biotic changes include species invasions worldwide and accelerating extinctions. The combined signals render the Anthropocene stratigraphically distinct from the Holocene.

Introduction
The term ‘Anthropocene’ is currently used informally to reflect different concepts, including geologic, sociologic and anthropologic. The origins of the concept of the Anthropocene, its terminology and its socio-political implications are widely discussed (1, 2). However, here, as members of the Anthropocene Working Group (AWG), we are concerned solely with the stratigraphic definition of this unit, based on evidence relevant to our parent body, the Subcommission on Quaternary Stratigraphy, and in turn the International Commission on Stratigraphy (ICS), the organization charged with deciding whether or not the Anthropocene should be formalized via a vote of its component subcommissions. This paper represents a synthesis of our analysis into the geological nature of the Anthropocene, to help wider discussion.

When considering the definition of the Anthropocene, there are two basic questions: Have humans changed the Earth System such that geologic deposits forming now and in the recent past include a fingerprint distinct from that of the Holocene Epoch, with high potential to remain in the geological record? If so, when has that change (not necessarily the first detectable anthropogenic change) become recognizable worldwide? This is considered here in the context of how stratigraphic units have been recognized earlier in the Quaternary Period.

Proposals for recognizing the start of the Anthropocene have included: an ‘early Anthropocene’ reflecting the advent of agriculture, animal domestication, extensive deforestation and, arguably, gradual increases in atmospheric carbon dioxide and methane levels thousands of years ago (3, 4); the Columbian Exchange of Old World and New World species following colonization of the Americas (5); the beginning of the Industrial Revolution at ~1800 C.E. (6, 7); and the mid-twentieth century ‘Great Acceleration’ of population growth, industrialization, mineral and energy use (8-10).

Here we review evidence, summarized in Fig. 1, which suggests Anthropocene stratigraphic signatures are distinct from those of the Holocene. Comparison is made with how other Quaternary stratigraphic time units are defined, setting the benchmark for assessing the scale of modern environmental changes. Earlier Quaternary time unit subdivisions are defined using signals in response to climatic change, driven by cyclical forcings such as variance in Earth’s orbit, solar irradiance and irregular events such as volcanic eruptions. Although these forcings continue, the Anthropocene saw the appearance of a further key driver, that of human...
modification of global environments at unprecedented rates. There is a wide range of ensuing anthropogenic stratigraphic signals (Fig. 1), including examples that are variously novel in Earth history, global in extent and offering fine temporal resolution. The signals vary in their development: some already advanced and others at early stages. We describe these signals and suggest how they may be used in stratigraphic characterization and correlation of a potential Anthropocene Epoch.

**How are Quaternary stratigraphic units defined?**

The Quaternary Period, which commenced 2.6 Ma ago, is subdivided into geochronologic time units (epochs and ages) with the recognition of boundaries at least in part linked to climate change events (expressed as Marine Isotope Stages), in association with paleomagnetic reversals (I1). This contrasts with most of the Phanerozoic Eon (the last 542 Ma), for which the first or last appearance of key fossil species is typically used to define time units, but which occurs at rates too slow and time-transgressive for the geologically recent past in which the time units are of comparatively short duration (tens of thousands rather than millions of years). In the material record of sediments and glacial ice, these time intervals are expressed as chronostratigraphic units (series and stages), ideally defined at a single locality as a Global Boundary Stratotype Section and Point (GSSP), typically in marine strata (I2).

The start of the Holocene Epoch (Series) is based upon the transition from the last glacial phase into an interval of warming and ~120 m of sea-level rise, which was neither instantaneous nor globally synchronous. In the Northern Hemisphere, a suitable level was at the abrupt end of the ‘Younger Dryas’ cooling event. The GSSP chosen to define the base of the Holocene was the NGRIP ice core from central Greenland (I3). The core contains a detailed archive of environmental change preserved in the composition of air bubbles trapped in the ice and the chemical and physical characteristics of the ice. A multi-decade warming/moistening trend is inferred from oxygen isotopes showing rising δ18O, and reduced dust content. About midway on this trend, the sharpest change, and the one used to define the base of the Holocene Series in this ice core, is a decrease in excess deuterium, interpreted as representing a reorganization of North Atlantic ocean/atmospheric circulation at 11.7 ka before 2000 C.E. (11.65 ka B.P.) +/- 99 yr at 2 σ (I3).

The Holocene Epoch (Series) is being considered for subdivision into three component Sub-epochs (Sub-series), again using climatic signatures to guide the positioning of their bases. The base of the Lower Holocene, by default, is the base of the Holocene Series, as described above. The base of the Middle Holocene has been proposed to be taken at a short-lived (150 ± 30 years) cooling event at 8.2 ka B.P., reflected in a marked shift to low 18O/16O values in the Greenland Ice Sheet (I3). Additionally, Greenland ice cores show low deuterium/hydrogen (D/H) values, a decline in annual layer thickness, an atmospheric CH₄ minimum and a volcanic marker characterized by a high fluoride content, which has led to the proposal that such core should be used to define the GSSP (I3). Although most strongly evident at localities adjacent to the North Atlantic, it is proposed to be a global signature evident in lakes as changes in pollen assemblages and oxygen isotopes, cave speleothems and marine foraminiferal assemblages and increased aridification in the vicinity of the Mediterranean broadly coinciding with the Mesolithic-Neolithic transition (I3).
Fig. 1. Summary of the magnitude of key markers of anthropogenic change indicative of the Anthropocene. Novel markers, such as concrete, plastics and plutonium fallout and long-ranging signals such as nitrates, radiocarbon, global black carbon, carbon dioxide, methane and global temperatures, which show continuum of change, indicate consistent change during the mid-20th century exceeding Holocene ranges.
The base of the Upper Holocene has been proposed to occur at a mid/low-latitude aridification event at 4.2 ka B.P. (13). This appears to have coincided with cooling of the North Atlantic and tropical Pacific, cooler and wetter conditions in Europe and weakening of the Asian monsoon (13). As this event has limited expression in the polar ice caps the proposed stratotype is in a speleothem record from Mawmluh Cave in north-east India, taken at a mid-point in a two-stage shift of δ¹⁸O values in calcite from initially more positive values and then more negative ones which took ~375 years (I3).

**Human population change as a driver for stratigraphic signatures**

The human driving force responsible for many of the signatures described in this study are a consequence of the two linked force multipliers of improvements in technology and increased consumption of resources, whether that be metals and minerals, fossil-fuels, fertilizers to increase productivity, and the land itself as it is modified from natural biomes to agriculture and wild animals are replaced by domesticated species to meet growing demands for food. The increased consumption is closely linked to the growth of human population. Behaviorally, modern Homo sapiens emerged ~200,000 years ago (14). By 10,000 B.C.E., approximating to the start of the Holocene, humanity had colonized all of the continents, except Antarctica and the South Pacific islands, and the total human population is estimated at 2 million (15, 16). To this point human influence on the Earth System was comparatively minor, other than contributing to the extinction of part of the Pleistocene megafauna (17). The key signals used to recognize the start of the Holocene Epoch (see above) were not directly influenced by human forcing, a key distinction from the proposed Anthropocene Epoch.

Humans have had a growing stratigraphic influence throughout the Holocene Epoch as population gradually increased. It has been argued that ~8,000 years ago, with global population estimated at less than 18 million (15, 16), the initiation of agricultural practices and forest clearances began to gradually increase atmospheric CO₂ levels (3). But it was not until ~1800 C.E. that the global population first reached 1 billion (16). Increased mechanization and the drive to urbanization during the Industrial Revolution, initially in Western Europe and slowly expanding globally (18), facilitated significant population increase. This population growth is commonly considered as increasing exponentially through the 19th and 20th centuries (cf. 8, 9). However, using recent population estimates (15, 16), the growth can be differentiated into two almost linear curves, from 1750–1940 C.E. and 1950–2010 C. E. The inflection point at ~1950 C.E. coincides with the ‘Great Acceleration’ (8, 9), a prominent upturn in economic activity and resource consumption which accounts for the marked mid-20th century upturns in the anthropogenic signals detailed below.

**New anthropogenic materials**

Recent anthropogenic deposits, the product of mining, waste disposal (landfill), construction and urbanization (19), contain the greatest expansion of new minerals since the Great Oxygenation Event some 2400 Ma ago (20), accompanied by new forms of ‘rock’. Over many millennia, humans have manufactured new materials, such as pottery, glass, bricks and copper alloys; still in use today, these have already generated a persistent and widespread geological
signature. But the migration of these technologies across the Earth was markedly time-transgressive (21). By contrast, elemental aluminum, almost unknown in native form before the 19th century, has seen 98% of its cumulative global production of ~500 Tg since 1950 C.E. (22; Fig. 2A). Concrete, invented by the Romans, became a primary building material from World War 2 (1939–1945 C.E.). The last 20 years accounts for more than half the 50,000 Tg of concrete ever produced (22, 23; Fig. 2A), equivalent to ~1kg per m² of the planet surface. Concrete and aluminum are widely disseminated across terrestrial, particularly urban, settings.

Similarly, manufacture of new organic polymers (plastics), initially developed in the early 1900s, sharply climbed from the 1950s to current annual production of about ~300 Tg (24; Fig. 2A), comparable to the present human biomass. Plastics spread rapidly into terrestrial settings (25, Fig. 2A) and are now widespread in both shallow and deep-water marine sediments as macroscopic fragments, and virtually ubiquitous as microplastic particles (microbeads, ‘nurdles’ and fibers; 26), dispersed by both physical and biological processes (25). The decay-resistance of plastics suggests they will leave a significant fossil record.

These and other new materials are commonly shaped into abundant artifacts with the capacity to be preserved in, and help date, future geologic deposits. Analogous to biotic fossil remains, these technofossils of the future (27) provide a decadal to annual stratigraphic resolution (22, 19), far greater than possible through first and last fossil appearances, the commonest means of correlating stratal sections (28).

Fossil fuel combustion disseminates unburnt particles as black carbon (BC), Inorganic Ash Spheres (IAS) and Spherical Carbonaceous Particles (SCPs). BC increases markedly towards the end of the 19th century and especially from ~1970 C.E. and peaks at 6.7 Tg yr⁻¹ in ~1990 C.E. (29; Fig. 2B). IAS, locally detectable in the stratigraphic record from the 16th century, shows increases across Britain, Scandinavia and North America from ~1835 to 1960 C.E. (30). SCPs, first recorded in various sites in the UK from 1830–1860 C.E., show near-synchronous global increase around 1950 C.E., with peak signatures from the 1960s–1990s (31, 32; Fig. 2B). BC, IAS and SCPs, being airborne particulates, leave a permanent marker within both sediments and glacial ice. An ancient analogue, which demonstrates the probable longevity of SCPs, is the carbon spherules disseminated at the Cretaceous–Paleogene boundary following the Chicxulub bolide impact (33).

Modification of sedimentary processes

Anthropogenically modified materials extend across terrestrial settings, most evident in anthropogenic (artificial) deposits described above, though also in soils associated with cultivation. Sedimentary processes, too, can be sufficiently modified to leave clear expressions in river, lake, windblown and glacial deposits (34). This influence is increasingly extending into the oceans, both directly with coastal reclamation works, sediment reworking through trawler fishing and aggregate working, and also indirectly through sedimentary facies response to rising sea levels, eutrophication of coastal environments and coral bleaching events (34). The human modification also increasingly extends into the subsurface, with drilling into the Earth’s crust to extract minerals, store wastes or to host utilities (35). Mineral extraction alone accounts for the displacement of ~57,000 Tg yr⁻¹ of artificial sediments, exceeding the current rate of river-borne sediment transport by almost a factor of 3 (36).
**Fig. 2. The production of selected new anthropogenic materials.** (A) Cumulative growth of manufactured aluminum in the surface environment (adapted from data in 23, assuming a recycling rate of 50%). Cumulative growth of production of concrete, assuming most cement goes into concrete and that ~15% of average concrete mass is cement (from 22, derived from United States Geological Survey global cement production statistics). Annual growth of plastics production (from 24) and synthetic fibers production (Gg yr⁻¹) from 25. (B) Global mid-20th century rise and late-20th century spike in spheroidal carbonaceous particles normalized to the peak value in each lake core (modified from 31) and global black carbon for available annual fossil fuel consumption data of 1875–1999 C.E. (29).

Human impact has also increased sediment fluxes in many fluvial systems, through increased deforestation, livestock grazing and cropland development. Clearing of primary
forests for agriculture, usually by burning, began in early- to mid-Holocene, especially in temperate woodland biomes, shifting diverse primary forest communities towards domesticates and early successional species and leaving widespread, but time-transgressive, geologic traces including profound shifts in plant and animal remains, charcoal, and sediment deposits from soil erosion (37, 38). In recent decades, secondary forests have recovered across much of the temperate zone and forest clearing has shifted towards tropical regions, where forest change dynamics include periods of rapid deforestation in Amazonia, Indonesia, and other regions in Asia and Africa in response to economic and governance dynamics (39).

Extensive sediment retention behind dams constructed across major river systems has formed a more rapid global signal. Most dams were built in the past 60 years, at an average of more than one large dam per day (8, 9) and will last 50 to 200 years, so will continue to influence sediment transport to the oceans. The reduced sediment flux to major deltas, combined with increased extraction of groundwater, hydrocarbons and sediments (for aggregates), has caused many large deltas to subside, beginning in the 1930s (40) at rates faster than modern eustatic sea-level rise (see below).

Widespread changes in sedimentation patterns and resulting stratal geometries have resulted from the transformation of more than 50% of the land surface for human use, in the form of agricultural fields, urban areas and roads (41). Human geomorphic features, such as the construction of mountain roads, are resulting in significant surface erosion and landslides (42). These various signals, abrupt on geological time scales, are however diachronous at a decadal scale.

**Changed geochemical signatures in contemporary sediments and ice**

Anthropogenic materials and the human influence of sedimentary environments have near-global expression, but it is geochemical signatures, and particularly those with airborne transport pathways, that reach all global environments, including the ~12% of the Earth’s surface permanently covered by ice.

Human activities have altered the composition of sediments themselves, introducing many distinct geochemical signatures. These include elevation in polyaromatic hydrocarbons (PAHs) and increased \(^{207/206}\)Pb ratios associated with leaded petrol from the early 20th century, and elevation in polychlorinated biphenyl (PCB) levels and appearance of pesticide residues, both from ~1945–1950 C.E. (43-46). Such temporal variations in geochemical signatures will, however, differ from place to place; in the case of \(^{207/206}\)Pb ratios lead smelting during Roman times provides an extensive marker (46).

Nitrogen (N) and phosphorus (P) in soils have doubled in the past century through increased fertilizer use (8, 9, 47). Mining of P, now ~23.5 Tg yr\(^{-1}\), is double the background weathering rate of P during the Holocene (48). Human processes, notably the use of the Haber process from 1913 C.E., have increased the amount of reactive nitrogen (Nr) in the Earth System by 120% compared to the Holocene baseline (49), with also increased nitrogen oxides (NOx) flux sourced from combustion of fossil fuels (50; Fig. 3).

These changes have stratigraphic consequences; influx of excess Nr and P to lakes and seas has led to seasonal oxygen deficiency, impacting local microbiotic assemblages (51). Northern Hemisphere lakes show increasingly negative \(\delta^{15}\)N values (52, 53), beginning ~1895.
C.E. (Fig. 3) and accelerating over the past 60 years. In Greenland ice, declining $\delta^{15}$N values start ~1850 C.E. (46), whilst the main phase of increase in nitrate levels was 1950–1980 C.E., the latter culminating in values higher than those observed for the previous 100 ka (54). These are markers distinct from the Holocene background.

Industrial metals such as Cd, Cr, Cu, Hg, Ni, Pb, Zn have been widely and rapidly dispersed since the mid-20th century, although many of the metals can show much earlier and markedly diachronous signals associated with mineral extraction and processing (46, 55). A great acceleration in the use of metals and rare earth elements (REEs) began after World War 2, resulting in an increase in their amount, global spread of deposition, and diversity. Metals, or their derivatives, are spread through inadequate processing, a lack of recycling/reuse, or loss during everyday use, for example platinum, rhodium and palladium loss from automobile catalytic converters, which accumulates in soils adjacent to highways (56).

Fig. 3. Perturbations of the nitrogen cycle since the start of the Industrial Revolution. Relative change in sediment $\delta^{15}$N from 25 Northern Hemisphere lakes (inner left ordinate), relative change in $\delta^{15}$N-NO$_3^-$ from the Greenland Summit ice core (outer left ordinate), annual N fertilizer production (52) and NOx emissions from combustion (50); NO$_3^-$ concentrations ($\mu$g Kg$^{-1}$) for two Greenland ice cores (54).

**Radiogenic signatures in contemporary sediments and ice**

Potentially the most widespread and globally synchronous anthropogenic event is the fallout from nuclear weapons testing. The start of the Anthropocene might be defined by a Global Standard Stratigraphic Age (GSSA) coinciding with detonation of the Trinity atomic device at Alamogordo, New Mexico on July 16, 1945 C.E. (10). But, fallout from 1945–1951 C.E. involved fission (“atomic”) devices with only localized deposition of radionuclides. Fallout from thermonuclear weapons tests that began in 1952 C.E. and peaked in 1961−1962 C.E. left a clear global signature that is concentrated in the mid-latitudes of each hemisphere and maximal in the Northern Hemisphere where most testing occurred (46, 57, 58; Fig. 4B). Useful potential markers include excess $^{14}$C, an isotope common in nature, and $^{239}$Pu, a naturally rare isotope. The Holocene segment of the IntCal13 $\Delta^{14}$C curve, corrected for radiogenic decay (R$^{14}$C), shows past natural fluctuations and a linear normalized decrease from 1.2 to approximately 1.0
related to changes in $^{14}$C production rate and global carbon cycling (59; Fig. 4A). An excess in $^{14}$C forms a sharp bomb spike, starting in 1954 C.E. (10) and peaking in 1964 C.E. (5), both suggested as potential markers for the start of the Anthropocene. However, the peak is diachronous between hemispheres (60; Fig. 4B). $^{239}$Pu, with a long half-life (24,110 years), low solubility and high particle reactivity particularly in marine sediments, may be the most suitable radioisotope for marking the start of the Anthropocene (58, 61). The appearance of a $^{239}$Pu fallout signature in 1951 C.E., peaking in 1963–1964 C.E. (Fig. 4B) will be identifiable in sediments and ice for the next 100,000 years (58, 61), decaying to a layer enriched in $^{235}$U and ultimately stable $^{207}$Pb.

![Graph](image)

**Fig. 4. Radiogenic fallout signals as a marker for the Anthropocene.** (A) Age-corrected atmospheric $^{14}$C concentration ($F^{14}$C) based on IntCal13 curve prior to nuclear testing (59); (B) concentration of $^{14}$C ($F^{14}$C) measured in atmosphere (60) and $^{239-240}$Pu (61) radiogenic fallout from nuclear weapons testing plotted against atmospheric weapons test yields (57).

**Carbon cycle evidence from ice core**

Atmospheric CO$_2$, now above 400 ppm, is currently being emitted into the atmosphere ~100 times as fast as the most rapid emission of the past 800 ka (62) and concentrations have exceeded Holocene levels since at least 1850 C.E. (Fig. 5). During the Late Pleistocene–Early Holocene, atmospheric CO$_2$ preserved in air bubbles within glacial ice in Antarctica showed a
stepped 70 ppm rise over 6,000 years (63, 64); an average rise of 1ppm per ~85 years. Subsequent Holocene CO₂ concentrations remained approximately stable, a very slow rise of 260 to 285 ppm from ~7000 B.C.E. (Fig. 5A), being ascribed to early human agriculture (3), albeit controversially (63). CO₂ concentrations show a change from a slightly decreasing trend from ~11–8 ka and slight rising trend commencing about 7,000 ago (Fig. 5A). Thus, putative anthropogenic impact on atmospheric CO₂ at this time was both gradual and much lesser than subsequent changes over the last 200 years. The 8.2 ka and 4.2 ka events proposed to mark the Mid- and Late Holocene Sub-epochs, respectively (13), show no major change in CO₂ concentrations.

The Antarctic ice core record shows steady enrichment in δ¹³C values from Late Pleistocene to Mid Holocene time (63, 64), reflecting carbon uptake by the terrestrial biosphere and carbon release from oceans (63; Fig. 5A), but shows no changes at the proposed Mid- and Late Holocene Sub-epoch boundaries.

Fig. 5. Perturbations of the carbon cycle evidenced for CO₂ and CH₄ concentrations and carbon isotopic ratios. (A) Atmospheric CO₂ from the Antarctic Law Dome and EPICA Dome C ice cores combined with data from observed measurements (sourced from 63 and references therein), and δ¹³C from atmospheric CO₂ (63, 64); (B) CO₂ concentration and δ¹³C from atmospheric CO₂ from the Law Dome ice cores (from 63) showing a 10 ppm dip in CO₂ recognized as the ‘Orbis’ event (3); (C) CO₂ concentration and δ¹³C from atmospheric CO₂ from the Law Dome ice core, firm data and air samples (from 63) showing inflections at ~1965 C.E.; (D) Antarctic (shown as squares) and Greenland (shown as circles) ice core and firm records for CH₄ concentration and δ¹³C for the last two millennia (68-71) and for Greenland ice core throughout the Holocene (67).
The Antarctic ice record shows approximately constant CO₂ and δ¹³C values continuing from 1200–1600 C.E. (57; Fig. 5B). A short-lived dip at ~1610 C.E. of about 10 ppm in the CO₂ curve, and synchronous minor enrichment in δ¹³C, has been proposed as a marker for the start of the Anthropocene (5), though these fluctuations do not exceed natural Holocene variability (58; Fig. 5A).

The striking change in atmospheric CO₂ concentrations is the ~120 ppm increase since ~1850 C.E. (65; Fig. 5B, C) rising at ~2ppm/year over the past 50 years, 120 times faster than that at the start of the Holocene. This coincides with a steep fall of >2 per mil to -8.5 δ¹³C for atmospheric CO₂ (65; Fig. 5C), due to an increase in ¹²C from burning fossil hydrocarbons. Also recorded in archives such as tree-rings, limestones, speleothems and calcareous fossils, it forms a permanent record.

Ice core records show atmospheric methane (CH₄) concentrations range from 590–760 ppb through much of the Holocene (67-71) up to 1700 C.E. Then, there is unprecedented increase to 1700 ppb by 2004 C.E. (68), some 900 ppb higher than recorded in Antarctic ice core at any time in the last 800,000 years (71), rising above Mid- to Late Pleistocene and Holocene maxima by ~1875 C.E. (Fig. 5D). The δ¹³C curve for CH₄ shows a marked decrease of ~1.5 per mil from ~1500–1700 C.E., perhaps a response to reduced biomass burning (68) and subsequent abrupt rise from ~1875 C.E. to present of ~2.5 per mil reflecting increasing pyrogenic emissions.

Climate change and rates of sea level change since the end of the last Ice Age

The proposed subdivision of the Holocene Epoch into sub-epochs (described above) reflects proxy signals for climate change (13). Greenland ice cores show abrupt, brief cooling events, expressed as decreases in δ¹⁸O values, at 11.4 ka, 9.3 ka and 8.2 ka (73; Fig. 6A), the latter proposed to define the start of the Mid-Holocene (13). These events are less apparent in equivalent Antarctic ice cores (74; Fig. 6A). A 4.2 ka climate shift, proposed to mark the start of the Late Holocene (13), is not expressed in these curves. The overall trend during the Mid- to Late Holocene is of gradual cooling (Fig. 6B), which culminated in the Little Ice Age from 1250–1800 C.E. (Fig. 6C). The cooling followed orbitally-related insolation decline, with small fluctuations representing changes in solar intensity, controlled by modulators such as the 208-year Suess cycle (73). Given that the orbital trend is continuing, the Earth should still be cooling.

A slight change to less negative δ¹⁸O in Greenland ice from ~1900 C.E. (Fig. 6A) signals a shift to significant warming (76, 77; Fig. 6C). This is well outside the declining natural envelope of temperature change for the past 2000 years (Fig. 6C), mainly due to greenhouse gases released from burning of fossil fuels and deforestation (75, 77, 78). Average global temperature increase of 0.6–0.9°C between 1906 and 2005 C.E., with a doubling of the rate of rise in the last 50 years (79), is still comparatively small, though beginning to rise above Holocene variation (Figs. 6B, C). The warming evident since 1900 C.E. and its expression in δ¹⁸O is of smaller magnitude than that of the 8.2 ka cooling event marking the base of the Mid-Holocene, but larger than that at the base of the Late Holocene.
Average global sea levels are currently higher than at any point within the last ~115,000 years (80), since the termination of the last interglacial of the Pleistocene Epoch. However, when considering the effects upon displacement of sedimentary facies, it is the rate of change of sea-level compared with rates of sediment accumulation and subsidence due to compaction that is crucial. For example, a rapid sea-level rise can cause delta tops to become flooded and show a sharp transition into overlying relatively deep marine and anoxic muds, marking a flooding surface. By the time of peak sea-level the rate of rise is slower and fluvial systems can resupply sediment to re-establish the delta as a progradational succession building up and out from the coast.

Very high rates of sea-level change (> 40 mm yr\(^{-1}\)) occurred at about 14.6–14.3 ka B.P. during the Bølling warming event, with rapid ice sheet disintegration during the transition between the last glacial phase and the current interglacial phase (81). The magnitude of the rate of rise caused widespread inundation of coastal areas and sedimentary facies backstepped (retrograded landwards).

The last 7,000 years of the Holocene Epoch, when ice volumes stabilized near present-day values, provides the baseline for discussion of anthropogenic contributions. Relative sea-level records indicate that from ~7 to 3 ka, global mean sea level rose ~2 to 3 m to near present-day levels (80). Based on local sea-level records spanning the last 2000 years, there is medium confidence that fluctuations in global mean sea level during this interval have not exceeded ~0.25 m on time scales of a few hundred years. As a consequence, coastlines have been more or less fixed and sediment accumulation within beaches, tidal flats and deltas has been progradational.

The most robust signal captured in salt marsh records from both Northern and Southern Hemispheres supports a transition from relatively low rates of change during the Late Holocene (some tenths of mm per year) to modern rates of 3.2 ± 0.4 mm yr\(^{-1}\) from 1993-2010 C.E. (80). By combining paleo sea-level records with tide gauge records at the same localities, it is clear that sea level began to rise above the Late Holocene background rate between 1905 and 1945 C.E. (82); if continued, this will lead towards a return to dominantly retrogradational shifts in sedimentary facies along coastal zones.

Sea-level reconstructions from the Atlantic coast of USA suggest the rising sea-level rate is not linear (83). A rate of rise of 0.06–0.39 mm per year during the 18\(^{th}\) century shows a change from 1827–1860 C.E. with a subsequent late 19\(^{th}\) century rate of 1.22–1.53 mm per year and a secondary and less pronounced change in 1924–1943 C.E., with resultant rise of 1.9–2.22 mm per year (83). The timing of the inflections in this rising sea-level curve matches, with an approximate decade delay, the stepped changes in CO\(_2\) concentrations (Fig. 4c).

Compared to other stratigraphic changes described above, the climate and sea level signals of the Anthropocene are not yet strongly developed but, responding now to anthropogenic forcing, they seem likely to exceed the envelope of Quaternary, and not just Holocene, conditions (75). Changes in global average surface temperature or rise in sea-level are manifestations of changes in the surface energy balance. Perhaps a more fundamental measure of human perturbation of the climate system is the human-driven change to the planetary energy balance at the Earth’s surface, as measured by change in radiative forcing. Human activities, primarily the burning of fossil hydrocarbons, have increased the radiative forcing by 2.29 (1.13–3.33) W m\(^{-2}\) relative to 1750 C.E., with more rapid increase since 1970.
C.E. than during prior decades. Overwhelming the natural changes in radiative forcing during the Late Holocene (changes in solar irradiance), estimated to be 0.05 (0.00–0.10) W m\(^{-2}\) (78), this human-driven forcing seems set to amplify stratigraphic signals associated with warming and sea-level rise.
Fig. 6. Climate variations during the Holocene indicated by oxygen isotopic ratios and modelled temperature variations. (A) Holocene profiles of $\delta^{18}O$ for the three Greenland ice cores with three short-duration cooling events indicated by shading (73) and comparison with Antarctic EPICA (EDML) ice core (74); (B) Temperature reconstructions for the Holocene and global temperatures for the last 2000 years (77); (C) standardized global mean temperature for the last 2000 years, represented by 30 year means (76, 77), showing natural temperature envelope for the past 2000 years (based on 75), including the LIA- Little Ice Age; and MWP-Medieval Warm Period (Medieval Climatic Anomaly) of the Northern Hemisphere.
**Biotic change as an indicator of the Anthropocene**

Most Phanerozoic time intervals are defined using either first or last appearance of key fossil species (28). Evolution/extinction rates are mostly too slow and diachronous to provide an obvious biological marker for the start of the Anthropocene, but important biotic change is clearly taking place (84). While Earth still retains most of the species that were present at the start of the Holocene, extinction rates, calculated conservatively, are far above background (Fig. 7A) since 1500 C.E., with notable increase in the 19th century (85; Fig. 7B). Current trends of habitat loss and over-exploitation, if maintained, would push the Earth into the sixth mass extinction event (with ~75% of species extinct) in the next few centuries (86), a process likely already underway (85).

Irrespective of the number of extinctions, species assemblages and relative abundances have altered worldwide, especially in recent decades, due to geologically unprecedented transglobal species invasions, and biological assemblage changes associated with agriculture on land, and fishing in the sea (87). The terrestrial biosphere saw a dramatic modification from 1700 C.E., when almost 50% of the global ice-free land area was wild and only ~5% was intensively used by humans, to 2000 C.E. when the respective figures were 25% and 55% (88). The paleontological expression of these assemblages will markedly differ from the typical Holocene fossil record as clearly recognizable, new biostratigraphic zones (89) and has already permanently reconfigured Earth’s biological trajectory. These biotic changes are not synchronous, but accelerated after 1500 C.E. on land and again after 1950 C.E. (90), the latter also affecting near-coastal microfauna/flora (51).

**The case for a new epoch**

The stratigraphic signatures described above (Fig. 1) are either entirely new with respect to those found in the Holocene or pre-existing epochs, or are consistently greater than those evident for Holocene subdivisions. These changes support the formalization of the Anthropocene as a stratigraphic entity equivalent to other formally defined geological epochs, and, we consider, are consistent with potential addition to the geological time scale, with a boundary to be placed following procedures of the International Commission on Stratigraphy.

If such formalization is to be achieved, further work needs to be done. Firstly, it needs to be determined how the Anthropocene is to be defined, whether by GSSA (calendar age) or GSSP (reference point in a stratal section; 10), or combination of both. Whichever is ultimately chosen, location and comparative analysis of candidate stratotype sections is necessary, not least to explore how effectively any chosen levels may be traced and correlated within sedimentary deposits. This is linked to the question of when exactly the Anthropocene may be determined to begin. While the analysis above is most consistent with a mid-20th century beginning, within that interval a number of options have already been suggested, ranging from 1945 to 1964 C.E. (5, 10), and these (and other possibilities) need to be decided between. Then, there is the question of whether it is helpful to formalize the Anthropocene, or better to leave it as an informal, albeit solidly founded geological time term, as are currently the Precambrian and the Tertiary. This is a complex and as yet unresolved question not least because - unlike with other geological time terms - the potential utility of a formal Anthropocene reaches well beyond the geological community.
Fig. 7. Increased rates of vertebrate extinctions. A) The approximate rise in mammal extinction rates when calculated over varying time intervals as extended backwards from the 2010 C.E. The line indicates the amount the extinction rate was/is elevated above the rate of 1.8 E/MSY (see 83; sourced from 22): B) Cumulative vertebrate species extinctions as a percentage of total species with ranges between conservative rates (includes extinctions, extinctions in the wild and possible extinctions) and lower highly conservative rates (verified extinctions only). A background rate of 2E/MSY is shown for comparison (after 84). E/MSY is the empirically derived number of species extinctions per million species per year.
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