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Ice Sheets and the Anthropocene

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Abstract: Ice could play a role in identifying and defining the Anthropocene. The recurrence of northern hemisphere glaciation and the stability of the Greenland Ice Sheet are both potentially vulnerable to human impact on the environment. However, only a very long hiatus in either would be unusual in the context of the Quaternary Period, requiring the definition of a geological boundary. Human influence can clearly be discerned in several ice-core measurements. These include a sharp boundary in radioactivity due to atmospheric nuclear testing; increases, unprecedented at least in the Holocene, in Greenland concentrations of sulphate, nitrate and metals such as lead; the appearance in ice-core air bubbles of previously undetectable compounds such as SF_6; and the rise, unprecedented in the last 800 ka, in concentrations of carbon dioxide and methane. Some combination of these changes could be used by future generations to clearly identify the onset of a new epoch defined at a particular calendar date. However, it is not yet clear what the character of the fully developed Anthropocene will be, and it might be wise to let future generations decide, with hindsight, when the Anthropocene started, acknowledging only that we are in the transition towards it.

Lifeless planets evolve in response to changing energy levels from their Sun, bombardment by material from space, and internal geological forces. Many aspects of the Earth, however, have long been influenced by the appearance of new forms of life. For example, the emergence of cyanobacteria led to the formation of an oxygen-rich atmosphere over 2 billion years ago, while the emergence of land plants significantly altered the Earth's albedo. Individual species can dominate local habitats, and significantly change their appearance. However, in the recent past, a single species (*Homo sapiens*) has begun to alter major aspects of the Earth system at a global scale. Perhaps the most obvious manifestation of this occurs in the carbon cycle, where increased concentrations of carbon dioxide (CO_2), well beyond the natural range, are due to anthropogenic emissions. These increases are expected to lead to global-scale climate change and acidification of the ocean, with effects lasting for thousands of years.

In this and a number of other aspects of the Earth system, human activity is now a force that is stronger than geological activity, and one that overwhelms the buffering abilities of natural systems. It has therefore been proposed that we are now in a new period of time, coined the 'Anthropocene', in which humans have become a controlling influence of the Earth system (Crutzen 2002; Steffen *et al.* 2011). This is an interesting concept for describing the extent of human influence on the environment, and therefore for emphasizing the extent of human responsibility for managing that environment. However, it has now been taken further, with some authors proposing that the Anthropocene should be formally recognized as a geological epoch (Zalasiewicz *et al.* 2008, 2011), on a level with the Holocene and Pleistocene that precede it.

Such an idea has to be considered from the viewpoint of a geologist viewing sequences thousands or millions of years in the future. Would they be able to recognize that defining characteristics of the preceding epochs had been definitively replaced by new ones in which anthropogenic forces dominated? What would they characterize as the features of the new epoch? What date would they assign as the start of the new epoch, and what feature would they want to use to delineate that start?

One difficulty in answering these questions is that, in contrast to all other geological time periods, we do not yet know what the Anthropocene will look like. CO_2 concentrations have so far risen from about 280 ppmv in pre-industrial times to just under 400 ppmv in 2013. Under current trends, they could easily rise to between 500 and 1000 ppmv. Climate change is under way, and although global mean temperature remains within the bounds already seen during the Holocene (Marcott *et al.* 2013), this is unlikely to be the case later this century. The Greenland and Antarctic Ice Sheets have not yet created large changes in landscape or sea level, but some projections suggest they might in the next few centuries.

Alternatively, political and technological mitigation could kick in quickly, such that the present level of perturbation of the carbon cycle represents the major effect of the Anthropocene. One could argue that only when all these issues play out will scientists see in retrospect what the environment controlled by humans looked like, and be able to make an objective assessment of what the Anthropocene was and when it began.

In this paper I consider the different roles that ice plays in this debate. First, how, if at all, should the existence and evolution of ice sheets play into the definition of the new epoch? Second, what do ice-core records of atmospheric composition tell us about the unusual nature of the current period in comparison to the preceding epochs? Third, are there signals in ice cores that can be used to define the start of the new epoch, in the same way that ice-core signals have been used to define the start of the Holocene epoch (Walker *et al.* 2009)?

Ice sheets

Ice sheets are a major facet of the Earth system. Their existence (or not) on Earth is one of the signs of global climate state that is visible from outer space. Ice sheets, mainly because of their impact on albedo, form a very important climate feedback. They control the landscape in areas that they periodically cover. They also influence the nature of sediments in areas around them, and in the case of ice-rafted debris carried by icebergs, across large areas of the ocean. Finally, because polar ice sheets always consist of water molecules that are depleted in heavy isotopes (i.e. their water has a negative oxygen isotope ratio, $\delta^{18}O$), they form a principal control over the oxygen isotope content of the ocean, which is reflected (but only as one factor) in the $\delta^{18}O$ preserved in shells within marine sediments globally. The appearance or disappearance of different ice sheets is therefore an attribute, widely detectable, that might be used to define large-scale changes sufficient to warrant that a change in epoch had occurred.

Before discussing whether ice sheets can be of any help in defining the existence of the Anthropocene, we need to consider their role in shaping the preceding epochs. The Quaternary Period, consisting so far of the Pleistocene and Holocene epochs, was recently redefined as starting at a Global Stratigraphic Section and Point (GSSP) 2.588 Ma ago (Gibbard *et al.* 2010). This point is formally defined as the base of a layer in a rock succession in Sicily. However, from the discussions that surrounded the adoption of this date, it is clear that one of the concepts behind the new definition of the Quaternary Period (and hence the Pleistocene

Epoch) is that of the onset of major northern hemisphere glaciations. If this is the case, then we might wonder if the end of the sequence of northern glaciations would signal the end of the Quaternary. Would the loss of the Antarctic Ice Sheet, which has apparently been present in some form for at least 35 Ma (Zachos *et al.* 2008), signal another geological boundary?

The role of climate and ice in defining a more limited boundary, the end of the Holocene, should have been clear. This is because, in reality, the natural Holocene (i.e. that which would have occurred without human intervention) would have been just another unremarkable interglacial in a long sequence of events of a broadly similar nature. These other interglacials have regional stage names and marine isotope stage (MIS) numbers, but the Holocene is unique in being an epoch, named only because the first geologists lived during it. It would have been ended conceptually by the next glacial inception, and, by analogy, as with its start (Walker *et al.* 2009), would probably have been defined by an abrupt climate cooling seen in a Greenland ice core. Because we are in a time of low eccentricity, the precessional forcing that controls summer northern hemisphere insolation, and hence the inception of ice sheets, is unusually weak. As a result, some modelling studies suggest that the Holocene would have been an unusually long interglacial, delayed by one or two precessional cycles (Berger & Loutre 2002); that is, for 50 ka.

We can consider three ice-sheet issues that are so significant that they might require some kind of geological boundary to be declared: the occurrence of glacial cycles affecting northern-hemisphere ice sheets; the stability of the Greenland Ice Sheet; and the stability of the Antarctic Ice Sheet.

In relation to the first issue, already discussed above, if the glacial/interglacial cycles that have characterized the Quaternary ceased because the Laurentide and Fennoscandian ice sheets did not return (or alternatively became permanent), this would appear to be a conceptual change that could, according to the reasoning that decided the start of the Quaternary, signal its end. Modelling studies show, as expected, that the insolation reduction required for glacial inception, as well as the ice volume that can be achieved, has a strong dependence on CO_2 concentration (Berger & Loutre 2002; Ganopolski & Calov 2011), although the exact concentration required to deny inception remains uncertain. However, we can observe that, in the last 800 ka, glacial inception (by one definition) has never occurred at a CO_2 concentration above 260 ppmv (Tzedakis *et al.* 2012). One way to describe what happens in 'normal' interglacials is that during and at the end of an interglacial, natural processes bring the CO_2 concentration down from

an interglacial peak to a level at which changes in northern hemisphere insolation can induce inception to occur. It is therefore reasonable to assume that these processes will be insufficient as long as the CO_2 concentration remains more than a few tens of ppmv above normal interglacial levels. In a recent synthesis (Archer *et al.* 2009) of modelling studies in which a pulse of CO_2 was treated with a range of models with an interactive carbon cycle, a pulse took the atmospheric concentration from a baseline of 280 ppmv to around 700 ppmv. It remained between 330 and 400 ppmv after 10 ka in the studies examined, and the silicate weathering feedback, with a lifetime on the order of 100 ka, was needed to remove the remaining CO_2. This discussion suggests that human activity on the scale envisaged in the next century might delay the next glacial inception by as much as 100 ka. However, unless other changes are also induced, then it is likely that glacial cycles would resume after that.

The Greenland Ice Sheet contains enough ice to raise the sea level by *c.* 7 m if it were all to melt. Modelling studies (Gregory *et al.* 2004; Robinson *et al.* 2012) suggest that it would be vulnerable to sustained temperature increases of the order of $1-5°$, a range that is clearly within the realms of possible outcomes for the next few centuries. However, a recent study of a new Greenland ice core (NEEM Community Members 2013) suggested that the altitude-corrected temperature above at least part of Greenland could have been as much as $8°$ higher than the present value during the last interglacial (*c.* 125 ka ago), yet much of the Greenland Ice Sheet clearly survived. The evidence for the very high temperature of this period needs further confirmation before the true significance of this result can be assessed. Very high concentrations of pollen during MIS 11 (*c.* 400 ka ago) in a marine core from just south of Greenland (de Vernal & Hillaire-Marcel 2008) indicate the establishment of forests over southern Greenland at that time, suggesting that a significant portion of the ice sheet was lost in response to temperatures that were probably not much higher than those of today, but sustained through a particularly long interglacial. The loss of a significant part of the Greenland Ice Sheet during MIS11 is consistent with the most recent estimates of the MIS11 sea-level being 6–13 m above present (Raymo & Mitrovica 2012).

The evidence is thus somewhat contradictory in terms of the influence of small changes in temperature on the stability of the Greenland Ice Sheet, but it seems probable, based on the evidence above, that it suffered significant loss in MIS 11. It has been asserted that the initial growth of the Greenland Ice Sheet in the late Pliocene (*c.* 3 Ma ago) was the result of a reduction in atmospheric CO_2 concentration to below 400 ppmv. This, along with the earlier estimates of the lifetime of CO_2 enhancements, suggests that any loss of the ice sheet could be reversed after a few thousand years (once CO_2 returned to below 400 ppmv). This means that it would not be dissimilar to what we believe occurred during MIS11, and could not therefore be considered unusual enough to warrant declaration of a geological boundary.

Finally, the West Antarctic Ice Sheet (containing 4.5 m sea-level equivalent, including the Antarctic Peninsula; Fretwell *et al.* 2013) is considered vulnerable to future climate change, and indeed may have contributed to sea-level rise during both the last interglacial (NEEM Community Members 2013) and MIS11 (Raymo & Mitrovica 2012). However, the threshold for loss of the much larger East Antarctic Ice Sheet (53 m sea-level equivalent; Fretwell *et al.* 2013) is considered much further away. Furthermore, the timescale for dynamic wastage of the ice sheet is very long. Loss of this ice sheet would apparently be unprecedented in 40 Ma, would have widespread implications (easily detected in a range of measures), and would probably warrant the declaration of a geological boundary. However, at present, the most likely warming scenarios are not expected to lead to significant loss of this ice sheet.

In summary, the recurrence time of northern-hemisphere glaciation and the stability of the Greenland Ice Sheet are both potentially vulnerable to anthropogenic climate change. However, neither event appears as if it would be completely irreversible (on timescales of 10–100 ka), and neither is so qualitatively different from previous events in the Pleistocene that they would necessarily warrant the erection of a geological boundary.

Signals of anthropogenic change in ice-core records

Ice cores record signals directly from the atmosphere, and are well suited for recording changes in atmospheric composition. They record atmospheric composition in two ways. First, aerosol material is collected by falling snow and dry deposition at the surface of the ice sheet. Because aerosol has a short lifetime in the atmosphere, this material is often deposited heterogeneously, and may only record local sources. Only if multiple sources lead to pervasive change at a global scale, or if material enters the stratosphere, will signals be recorded in ice cores worldwide. An advantage of the material trapped in the snow is that the time resolution is excellent; at some sites, with tens of centimetres of snowfall each year, it is capable of resolving events shorter than a year, with the age of the

material being the same as the snow, which can often be well dated.

The second recording medium in ice takes the form of air bubbles trapped below the porous firn layer in the ice sheet. These contain a record of the stable gases in the atmosphere (N_2, O_2 and Ar, but also trace gases such as CO_2 and CH_4). Although latitudinal gradients exist for some of these gases, most are rather well mixed, and an ice core at either pole will reflect global-scale temporal variations. The disadvantage of records from air bubbles is that the gas enclosure process imposes a natural smoothing (ranging from a decade to over a millennium, depending on the site), and the gas record has an age offset compared to the climate and other records in the snow phase.

Numerous aerosol chemical species have been affected, directly or indirectly, by human activity. Here I summarize only a few of the more direct ones. One very clear anthropogenic signal that can be detected in ice is radioactive material from the atmospheric nuclear bomb tests that occurred from the 1950s until (formally) 1986, when the last country carrying out atmospheric tests abandoned their use. This shows up in ice-core records worldwide (summarized, for example, in Wolff & Peel 1985) as a huge jump in beta radioactivity in 1954, a further jump in 1964 in response to very large tests in the early 1960s, and then a slow decay towards natural background levels as the material was removed from the atmosphere and its radioactivity decayed (Fig. 1). At their peak in 1966, the levels of beta radioactivity and tritium in snow were almost a factor of 100 above background levels. The signal can also be observed in radioisotopes with longer half-lives; for example, a clear signal in ^{239}Pu has been observed in an Alpine ice core (Gabrieli *et al.* 2011). This can certainly be seen as a signal of one aspect of humanity's potential to overwhelm its environment, in this case through the destructive ability of nuclear weapons and the associated ability to pollute the environment with radioactive material.

Industrial activity has taken over the sulphur cycle in many parts of the world, with the result that ice-core records from ice sheets and glaciers across the northern hemisphere at least show sustained increases that have not been observed before in the Holocene. In Greenland ice, in 1980, sulphate concentration rose to about a factor of four above its pre-industrial peak (Fig. 1), with the main increases in the periods 1900–1920 and 1940–1980 (Fischer *et al.* 1998). The peak concentration remains below the brief excursions in sulphate concentration that occur after the largest volcanic eruptions, and below the elevated concentrations that occurred during the last glacial maximum (Legrand *et al.* 1997). No significant recent increase in sulphate concentration has been observed in Antarctica, which still remains too remote to see the effects of a species with a rather short atmospheric lifetime.

Human activity has similarly taken over the nitrogen cycle in many parts of the world (Wolff 2013). Elevated ammonium concentrations in mid-latitude glaciers are ascribed to agricultural emissions, while increased nitrate concentrations across at least the northern hemisphere are due to NO_x emissions from combustion. Nitrate in Greenland snow and ice rose by a factor of two (Fig. 1) during the twentieth century (Fischer *et al.* 1998), but in this case the main period of increase was 1950–1980, and levels in the 1980s were probably somewhat higher than at any point in the past 100 ka. Again, no significant increased signal is observed in Antarctic ice cores (Wolff 2013).

The cycles of many metals have also been taken over by human activity. A prime example is lead. Smelting and mining activities as long ago as the Greek and Roman periods elevated lead concentrations in Greenland snow above their Holocene background concentration (Hong *et al.* 1994), suggesting that, at least for this metal, anthropogenic control across much of the northern hemisphere was already in place 2000 years ago. However much more significant increases took place in the eighteenth century and later; these were hugely enhanced from the 1950s due to emissions from leaded petrol. At the high point, in the 1960s (Boutron *et al.* 1991), the concentration of lead in Greenland snow was elevated above its Holocene background level by a factor of 200, and just exceeded the maximum concentrations seen in the last glacial maximum, when concentrations of many metals were elevated due to increased dust transport (Hong *et al.* 1996). Removal of lead from petrol has led to a very significant subsequent decrease. The twentieth-century elevation of lead in the atmosphere was global, with an increase by a factor of five over the pre-industrial Holocene level observed in Antarctic snow (Wolff & Suttie 1994).

From atmospheric gases recorded as air bubbles in polar ice sheets, ice cores provide critical records of increasing concentrations of long-lived greenhouse gases in the recent past (Fig. 1). CO_2 (Lüthi *et al.* 2008) and CH_4 (Loulergue *et al.* 2008) (Fig. 2), and also N_2O (Schilt *et al.* 2010), are all now at concentrations higher than observed in any ice cores for the last 800 ka. The ice cores contain no data for earlier periods, but pCO_2 inferred from measurements of the isotope ^{11}B in marine sediments appears to extend this observation to at least 2 Ma (Hönisch *et al.* 2009). The ice-core data (MacFarling Meure *et al.* 2006), supplemented by measurements in the atmosphere over the last
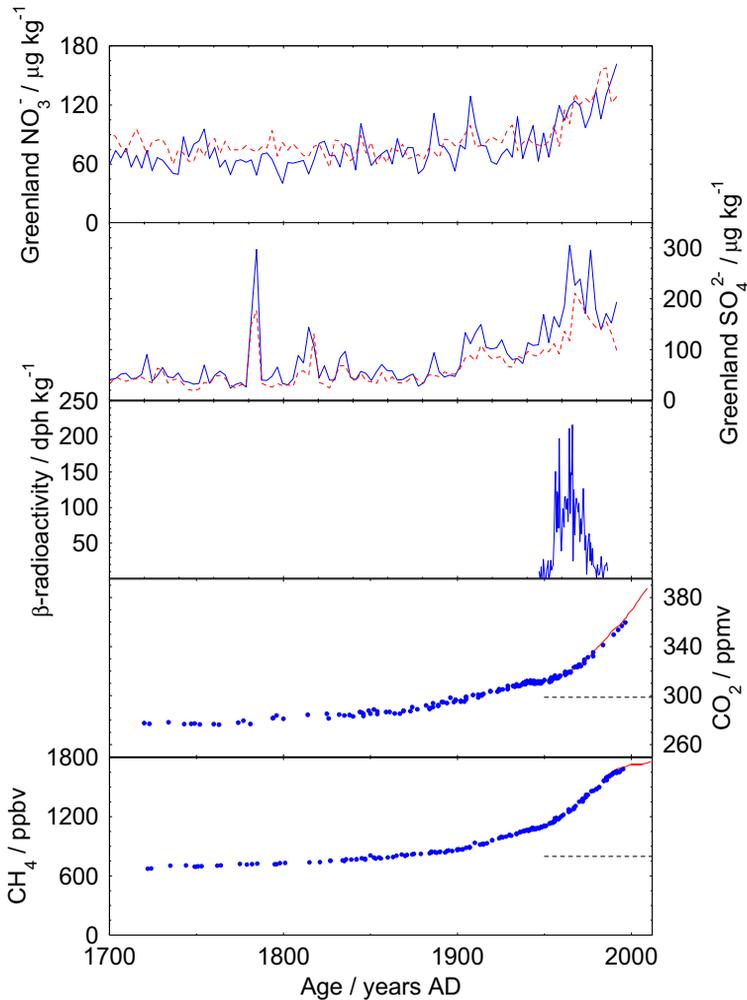
Fig. 1. A range of indicators of human influence since 1700 AD. For CH_4 and CO_2, the blue dots are ice-core data from Law Dome, Antarctica (MacFarling Meure *et al.* 2006), the red lines are recent atmospheric data from Mauna Loa (CO_2, courtesy of NOAA ESRL) and Cape Grim Observatory (CH_4, courtesy of CSIRO Marine and Atmospheric Research and Australian Bureau of Meteorology). The horizontal dashed lines are the highest values observed in ice cores of the last 800 000 years prior to the period shown. Beta radioactivity is shown from a snow pit in Coats Land, Antarctica (Wolff *et al.* 1999): values are assumed to remain low prior to the measurement period. Sulphate and nitrate are shown for two cores from Greenland: B16 (dashed red, 73.94°N, 37.63°W) and B21 (solid blue, 80.00°N, 41.14°W) (Fischer *et al.* 1998). The eighteenth- and nineteenth-century spikes in sulphate are signals of volcanic eruptions.

c. 50 years, show that CO_2 concentrations rose above the previous Holocene range in the early nineteenth century and have risen 40% above any previous Holocene level and 30% above the highest value of the last 800 ka. CH_4 concentrations similarly rose above their Holocene range in the early nineteenth century, and are now double any value observed in the last 800 ka. The isotopic content of CO_2 in the atmosphere today is also highly unusual, with a $\delta^{13}CO_2$ value below $-8‰$ (the

range in the previous 25 ka was always between $-6.3‰$ and $-6.8‰$; Schmitt *et al.* 2012). There is some discussion in the literature as to whether rising levels of CO_2 during the last 8 ka, and of CH_4 during the last 6 ka, could also be the result of human activity (land clearance and the widespread adoption of agriculture; Ruddiman 2003). However, this idea of an early to mid-Holocene start to anthropogenic control of the carbon and methane cycle is controversial (Claussen *et al.*
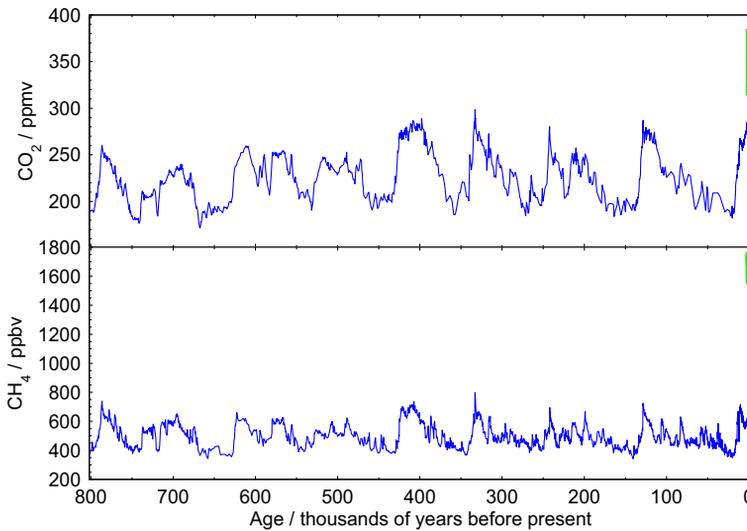
Fig. 2. CO_2 and CH_4 over the last 800 ka from Antarctic ice cores. The blue lines are data from Dome C (CH_4) (Loulergue *et al.* 2008) and from Dome C and Vostok (CO_2) (Lüthi *et al.* 2008). The red lines are high-resolution data from Law Dome (MacFarling Meure *et al.* 2006 and papers therein). The green data are recent atmospheric measurements.

2005; Broecker & Stocker 2006; Singarayer *et al.* 2011). Because the concentration levels, trends and rates of change of CO_2 and CH_4 between 8 ka and 200 years ago are not unique in the 800 ka ice-core record, there is no clear basis for asserting that humans had taken these cycles outside any natural range before the last 200 years.

A final candidate indicating an anthropogenic influence is the range of chemicals with no natural sources that are now detectable in ice cores. This includes persistent organic pollutants found in the snow phase (e.g. Gabrieli *et al.* 2010), but also a group of long-lived gases that have become measurable in firn air, and with large enough samples could be measured in ice cores. Of particular interest are the halogenated gases, such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and SF_6 (Butler *et al.* 1999), many of which are detectable in air dated to the 1960s and later. When viewed from the perspective of the far future, many of these gases will show a rise from undetectable levels, and in the case of those with very long (millennial and beyond) atmospheric lifetimes their continuing presence will be a long-lasting reminder of humanity's abilities to fill the atmosphere with new molecules.

In summary, a wide range of chemicals measured in ice cores have left an imprint in the ice that shows humankind's influence on the atmosphere and on important biogeochemical cycles. Of those I have discussed, only lead can be said to show a clear and unequivocally anthropogenic imprint before

the last 200 years. Even then, the pre-1800 concentrations of lead in Greenland ice do not exceed those found naturally in the last glacial period. Some of the records discussed above are shown in Figure 1. CO_2 profiles in ice cores are those that future generations will most clearly be able to identify as showing anthropogenic control of the Earth system. Concentrations are clearly elevated significantly above any concentration observed in the last 800 ka, and this conclusion can probably be extended to 2 Ma and beyond through marine records. The isotopic change is also highly unusual, indicating that the release of fossil carbon is involved. Concentrations are approaching levels at which significant impacts on the climate and the carbonate chemistry of the ocean are inevitable, and the effective lifetime of CO_2 in the atmosphere (Archer *et al.* 2009) means that the concentration profile will appear as a step increase, followed by a slow rampdown towards typical interglacial levels, which will probably take thousands of years.

Should ice cores be used to define the start of the Anthropocene?

Finally, I will discuss whether it would make sense to use an ice-core signal as a 'golden spike' for the start of the Anthropocene, as has been done for the start of the Holocene (Walker *et al.* 2009). Several of the signals described above give a clear signal

of the dominance of human activity, and any one or combination of them could be used to define the start of a new Anthropocene epoch. However, some have significant drawbacks.

The sharp increase in radioactivity seen in ice cores at 1954 is a very sharp boundary, and has the advantage that it is correlatable across numerous glaciers and ice sheets, is precisely dated, and is also recorded in other media. However, the main measured species (beta radioactivity based mainly on isotopes with half-lives of 30 years and tritium with a half-life of 12.3 years) will decay beyond detection limit within a few half-lives. Although there are longer-lived isotopes in the ice (e.g. ^{36}Cl from bomb tests carried out at oceanic sites; Elmore *et al.* 1982), these have not been extensively characterized and are not yet in a state to be used as a boundary marker.

Twentieth-century increases in nitrate, sulphate or lead all clearly indicate the impact of human activity on important biogeochemical cycles. However, because of the short lifetime of aerosol in the atmosphere, these are all influenced by regional rather than global emissions and will show different patterns (at decadal resolution) in different glaciers. One could therefore only adopt the increase above some threshold in a particular location (probably Greenland). Thinking from the perspective of a geologist many millennia in the future, care must be taken, as the sustained late-twentieth-century concentrations of sulphate and lead, although unique in the context of the Holocene, are not unusual in the context of the late Pleistocene.

The appearance of new chemicals (such as SF_6) in air bubbles in ice cores forms a sharp indicator of industrial activity. Owing to their long lifetime (at least several centuries), their onset would, with analytical improvements, form an easily recognized boundary that could be found in both Greenland and Antarctic ice, offering the potential for secondary correlations with other records in both hemispheres. However, because air bubbles are only closed off below the permeable firn layer (typically 60–100 m depth), the boundary containing a sharp change in gas concentrations is offset from the ice layer containing climatic and other information of the same age. In addition, the boundary is smoothed over decades to centuries depending on the snow accumulation at the ice-core sites.

Finally, the increase in CO_2 above a threshold (say 300 ppmv) offers a unique (within probably the last 2 Ma) marker that is most relevant to the environmental changes that anthropogenic activity may induce. However, it suffers from the same issues that have been described in the previous paragraph, meaning that a sharp and well-dated boundary could be used only in a core with very high snow accumulation rate.

Ice cores present several possible candidates to identify the start of the time at which humans controlled major features of the environment. We can, in principle, choose a date on which we say that the Anthropocene started. A golden spike could then be placed in a Greenland or Antarctic ice core sequence at that date, and we could describe it as having a particular age relationship with any of the sharp changes above (e.g. sharp jump in a long-lived isotope, SF_6 onset, CO_2 exceedance of a threshold), so that the same age can easily be found in other ice cores (using increasingly well-understood relationships between the age of air and the age of ice to remove the gas age–ice age offset). This layer could be correlated to other (non-ice) sequences through a range of measures (e.g. known volcanic eruption spikes in ice cores correlated to their geological manifestation; ^{10}Be patterns in ice cores correlated to ^{14}C patterns in tree rings; Steinhilber *et al.* 2012). It is not clear to me whether such a definition, essentially using a calendar date and a series of identifiers, meets the official criteria for a GSSP (Remane *et al.* 1996), but that definition was not designed for a period where we have observed changes in real time and can place calendar dates on many of our records.

Some philosophical issues

Despite the possibility of using ice cores to help future generations identify a defined-date start of the Anthropocene, there are some philosophical issues to consider. The first concerns the potential impermanence of the ice-sheet record. Ice layers are preserved in monotonous sequences for typically 100 ka in central Greenland and 1 million years in central Antarctica, but then become folded or melted in older ice near the ice-sheet bed. This means that the GSSP can be preserved in the field only for this length of time – not long in geological terms. Clearly, the wastage of the Greenland or Antarctic ice sheets in response to climate change, were it to occur, would be another threat to the sequence in the field. This is not a fatal drawback if the boundary has been transferred to secondary and more permanent sequences.

A second issue concerns what we should consider the Anthropocene to be. All other epochs except the Holocene were defined only after they were complete and their dominant characteristics were clear. We do not yet know if the period of human dominance of the environment will be one in which CO_2 concentrations peak at just above 400 ppmv, or will rise to as much as 1000 ppmv. If the former applies, then we are at the start of a long plateau; if the latter is relevant, we are at the

bottom of a long rise towards a later plateau. For the base of the Holocene, a point has been chosen (Walker *et al.* 2009) that, for most characteristics, is the very end of a several-thousand-year transition. If we choose a time that has already occurred for the start of the Anthropocene, then we are making a very different choice, in which the start of the transition is defined as the base of the new epoch. While acknowledging that humans have taken control of important parts of the Earth system, I wonder if it may be more sensible to describe ourselves as being firmly in the transition into the Anthropocene, but to leave future generations to define, with the benefit of hindsight, when the epoch actually starts or started.

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