

Colonization of the Americas, Little Ice Age climate, and bomb-produced carbon: their role in defining the Anthropocene

Members of the Anthropocene Working Group:

Jan Zalasiewicz¹, Colin N Waters², Anthony D Barnosky³, Alejandro Cearreta⁴, Matt Edgeworth⁵, Erle C Ellis⁶, Agnieszka Gałuszka⁷, Philip L Gibbard⁸, Jacques Grinevald⁹, Irka Hajdas¹⁰, Juliana Ivar do Sul¹¹, Catherine Jeandel¹², Reinhold Leinfelder¹³, JR McNeill¹⁴, Clément Poirier¹⁵, Andrew Revkin¹⁶, Daniel deB Richter¹⁷, Will Steffen¹⁸, Colin Summerhayes¹⁹, James PM Syvitski²⁰, Davor Vidas²¹, Michael Wagemann²², Mark Williams¹ and Alexander P Wolfe²³

Addresses:

¹ Department of Geology, University of Leicester, UK

² British Geological Survey, UK

³ Dept. of Integrative Biology, Museum of Paleontology, Museum of Vertebrate Zoology, University of California, USA

⁴ Departamento de Estratigrafía y Paleontología, Facultad de Ciencia y Tecnología, Universidad del País Vasco UPV/EHU, Spain

⁵ School of Archaeology and Ancient History, University of Leicester, UK

⁶ Department of Geography and Environmental Systems, University of Maryland, USA

⁷ Geochemistry and the Environment Division, Institute of Chemistry, Jan Kochanowski University, Poland

⁸ Department of Geography, University of Cambridge, UK

⁹ IHEID, Switzerland

¹⁰ ETH Zurich, Laboratory of Ion Beam Physics, Switzerland

¹¹ APECS-Brazil, Brazil

¹² LEGOS (Université Paul Sabatier, CNRS/CNES/IRD), France

¹³ Institute of Geological Sciences, Freie Universität Berlin, Germany

¹⁴ Georgetown University, USA

¹⁵ Morphodynamique Continentale et Côtière, Université de Caen Basse Normandie, France

¹⁶ Pace Academy for Advanced Environmental Studies, USA

¹⁷ Nicholas School of the Environment, Duke University, USA

¹⁸ The Australian National University, Australia

¹⁹ Scott Polar Research Institute, Cambridge University, UK

²⁰ University of Colorado-Boulder Campus, USA

²¹ Marine Affairs and Law of the Sea Programme, The Fridtjof Nansen Institute, Norway

²² Department of Geodynamics and Sedimentology, University of Vienna, Austria

²³ Department of Biological Sciences, University of Alberta, Canada

Corresponding author: Colin N. Waters, British Geological Survey, Keyworth, Nottingham NG12 5GG, UK.

Email: cnw@bgs.ac.uk

Abstract: A recently published analysis by Lewis and Maslin (2015) has identified two new potential horizons for the Holocene–Anthropocene boundary: 1610 (associated with European colonization of the Americas), or 1964 (the peak of the excess radiocarbon signal arising from atom bomb tests). We discuss both of these novel suggestions, and consider that there is insufficient stratigraphic basis for the former, whereas placing the latter at the peak of the signal rather than at its inception does not follow normal stratigraphical practice. Wherever the boundary is eventually placed, it should be optimized to reflect stratigraphical evidence with the least possible ambiguity.

Keywords

Anthropocene, stratigraphy, Little Ice Age, radiocarbon fallout

Introduction

Since the initial proposal of the Anthropocene as a new interval of geological time (Crutzen and Stoermer, 2000; Crutzen, 2002), the term has become widely used, both within the natural sciences (e.g. Williams et al., 2011 and Waters et al., 2014, and references therein) and those of the social sciences, humanities and arts (e.g. Vidas, 2010, 2011, 2014; Latour, 2015; Chakrabarty, 2015). It is also currently under analysis as a potential formal addition to the Geological Time Scale. A key question – one that needs to be established whether the Anthropocene is to be formalized or not – is when it may be said to have begun. If it is to be regarded as a geological (chronostratigraphic) time unit, it needs to have a defined beginning, be synchronous around the world, and be effectively traceable in geological strata using a range of evidence (fossil, chemical, physical) that expresses changes as clearly as other major boundaries in the stratigraphic record. Other possibilities exist, for instance Edgeworth et al. (2015) suggested an alternative interpretation of the Anthropocene as an archaeology-based time unit with a diachronous lower boundary.

The Anthropocene was initially suggested by Crutzen (2002) as beginning with the Industrial Revolution in the late eighteenth century, along with the initial rise of atmospheric CO₂ and CH₄ concentrations above the Holocene baseline, and James Watt's

the steam engine, patented in 1776. At this time, the global human population surpassed one billion (it is now over seven billion). The first stratigraphic analysis associated with the term proposed a numerical age of 1800 or associated with the 1815 eruption of Mount Tambora (Zalasiewicz et al., 2008).

There have been a wide range of suggested 'Anthropocene' beginning dates, ranging from ideas of an 'early Anthropocene' linked to early human impacts on the globe, associated with hunting and, particularly, the changes to landscape and, arguably, to CO₂ levels associated with the origin and spread of farming (e.g. Ruddiman, 2003, 2013; Smith & Zeder, 2013; Ruddiman et al., 2015), to a number of suggestions based on the large changes to the Earth system in the mid-20th century 'Great Acceleration' (Syvitski et al., 2005; Syvitski and Kettner, 2011; Steffen et al., 2007, 2015) and associated stratigraphic signals (Wolfe et al., 2013; Waters et al., 2014 and references therein, 2015; Zalasiewicz et al., 2015; Corlett, 2015; Rose, 2015).

A recently published Perspective in *Nature* (Lewis and Maslin, 2015) advanced two other dates, 1610 and 1964, to potentially begin the Anthropocene, with the first of these being favoured. Lewis and Maslin's second, 1964, proposal is chronologically close to but conceptually distinct from other mid-20th century proposals. Their wide-ranging study brings valuable insights to the issues involved with selecting an Anthropocene boundary, focuses attention on key historical intervals in Earth history, and brings new logic and ideas to the process of boundary selection. Here we consider the new boundary suggestions of Lewis and Maslin critically, in order to examine whether they show promise to effectively define the Anthropocene.

Events of the sixteenth and seventeenth centuries, and the 'Orbis' hypothesis

The 1610 'Orbis' date, the preferred option of Lewis and Maslin, reflects a short-lived decline in atmospheric CO₂ of ~10 ppm identified in two Antarctic ice cores and "the most prominent feature, in terms of both rate of change and magnitude, in pre-industrial atmospheric CO₂ records over the past 2,000 years" (MacFarling Meure et al., 2015). Like other postulates (Faust et al., 2006), they associated this CO₂ dip with

depopulation in the Americas following European colonization: thus, Lewis and Maslin regard it as an anthropogenic marker of “transoceanic movement of species [that] is a clear and permanent geological change to the Earth system.” However, the magnitude of the CO₂ fluctuation cited by Lewis and Maslin (2015) is not outside the range of natural Holocene variability (Figure 1). Furthermore, the anthropogenic origin of the brief CO₂ transient is not conclusively established, making the 1610 date problematic for marking an epoch’s beginning. The salient points are:

- *The ‘1610 CO₂ downturn’ is not an ideal stratigraphic marker.* The CO₂ concentration curve in the NGRIP ice-core (Monnin et al., 2001) reveals many “sharp and brief dips” in CO₂ of comparable amplitude before 1610. Thus, the 1610 dip seems not a large enough anomaly to stand out as an epoch marker, particularly when compared to post-industrial changes in atmospheric CO₂, not least because the signal is only detectable in select ice core localities. Even then, its precise timing is uncertain because of the lag between snow deposition and closure of air bubbles in ice, which can be allowed for, but not quantified precisely: any ‘golden spike’ is different for air and the surrounding ice by decades to centuries (Ahn et al., 2012). The chosen 1610 date hence combines aspects of a Global Boundary Stratotype Section and Point (GSSP or golden spike) and Global Standard Stratigraphic Age (GSSA), without fully satisfying either one.
- *The 1610 event is not significant with respect to the entire Holocene record.* Atmospheric CO₂ concentrations vary naturally during interglacial periods by about 20–25 ppm. During the pre-industrial Holocene, it varied between 260 and 285 ppm and during the previous interglacials it has varied between 262 and 287 ppm (Barnola et al., 1987; Etheridge et al., 1996; Etheridge et al., 1998; Indermühle et al., 1999; Barnola et al., 2003). Much of this variation may reflect fluctuations in ocean circulation (e.g. IPCC, 2013, Chapter 3 (Observations: Ocean) and Chapter 5 (Information from Paleoclimate Archives)). The carbon stored in the ocean exceeds that stored in land systems by a factor of 20. Therefore, small changes in the marine storage of carbon can significantly change atmospheric CO₂ levels. Hence, the dip of about 10 ppm in the CO₂ curve

at ~1610 (enhanced by the scale chosen for Lewis and, Maslin 2015, Fig. 2c) may well fall within natural variation.

- *The 1610 dip does not match the suggested regional anthropogenic trigger.* The loss of population in the Americas (in aggregate terms) continued until about 1650 (Cook, 1998). If the proposed model is correct, this depopulation should have resulted in forest regrowth and attendant CO₂ uptake until the mid-17th century at least, especially as trees stock carbon fastest at maturity, not as saplings. If depopulation in the Americas drove the downturn in atmospheric CO₂, concentrations should have kept declining until 1650–1680, which is not seen in the ice-core data. The link between depopulation and greenhouse gas declines is further complicated by other factors. With Amerindian depopulation, farmed and burned-over land did not necessarily revert to forest ecosystems, as large herbivores locally underwent population explosions, affecting vegetation dynamics. Furthermore, reduced soil respiration may have resulted from the low temperatures of the Little Ice Age, adding an additional complicating factor (Rubino et al., 2015). The peak cold of the Little Ice Age occurred after the CO₂ event, during the sunspot Maunder Minimum between 1645-1715 (Eddy, 1976).
- *The 1610 dip does not match global trends.* Conceptually, the 1610 date is underpinned by linking the minor downturn of CO₂ with the loss of ~50 million people in the Americas (1492–1650) (Cook, 1998). That link may be questioned, as noted above, and in any case the resulting land-cover changes need be interpreted in a global context. While both regional and global population figures are inexact, outside of the Americas, population was probably rising for most of the 1500s until 1600 or 1620, with consequent deforestation potentially muting the American trend towards forest regrowth and CO₂ uptake. Various large-scale events, including wars, famines, and epidemics probably reduced global population ~1600–1660 (Parker, 2013). Loss of population in north China and Germany (two hard-hit places ~1620–1670) may not have the same implications for forest regrowth and atmospheric CO₂. But, as a first approximation, considering population and forest cover as key CO₂ drivers, and taking an integrative global perspective, one would predict the CO₂ nadir to occur later than 1610. The correlation between native human depopulation in

the Americas and the CO₂ dip of 1610 therefore lacks an unambiguous causal link.

- *The associated global temperature change does not form a distinct stratigraphic marker.* Lewis and Maslin cite the analysis by Neukom et al. (2014) of climate in the last millennium in indicating, within the Little Ice Age, ‘a relatively synchronous cold event noted in geologic deposits worldwide’. It is not clear, though, that an obvious stratigraphic event marker exists here. Neukom et al. (2014) do recognize within the Little Ice Age an interval of a little under a century (1594–1677) as a cold period affecting both hemispheres. However, their reconstruction (Figure 1b) shows an indistinct interval around the late sixteenth and early seventeenth centuries where, although both hemispheres show, unusually for the Little Ice Age, a similar temperature trend, there seems little otherwise to distinguish this from other earlier and later minor climate oscillations. The Little Ice Age overall (~1300–1870) shows considerable geographic variations in climate history (Mann et al., 2008; IPCC, 2013).

Figure 1

- *The global biostratigraphic signal from colonizing the Americas remains incompletely documented.* The two-way spread of invasive/transported species from and to the Americas has considerable biostratigraphic potential, but needs further study to show just how closely these particular signals approximate to globally detectable time planes, and how they compare with the plethora of other invasive-related signals, both earlier and later. Maize, the example quoted by Lewis and Maslin (2015), did become a major crop plant worldwide. However, the spread took place over a few centuries (Figure 2), making the resulting biostratigraphic signal diachronous at the time scale relevant to defining the Anthropocene.

Figure 2

1964 and peak excess radiocarbon

The alternative 1964 date suggested by Lewis and Maslin (2015) is, in contrast to the *dip* (in atmospheric CO₂ in 1610), based rather upon a *peak* in atmospheric radiocarbon recorded in annual tree-rings from pines in the park by Niepołomice Castle, Poland (Rakowski et al., 2013). Such a reference point would be precise - a desirable feature of setting epoch boundaries - and accessible. However, a living tree may not be universally accepted to be 'geological stratigraphical material such as rock, glacier ice or marine sediments', as Lewis and Maslin (2015) note. Other difficulties with this suggestion include:

- *The boundary is not ideally placed relative to the signal.* It is more conventional, and usually more practical in terms of worldwide correlation, to place a boundary based on chemical or isotopic excursion at the beginning, rather than at the peak, of such a major geochemical change in strata. That is the case with the iridium spike at the Cretaceous-Palaeogene boundary (Molina et al., 2006) and the negative $\delta^{13}\text{C}$ excursion for the Paleocene-Eocene boundary (Aubry et al., 2007), for instance. In this way one captures the whole signal and not just part of it, making the interval being defined more easily recognizable, especially in geological situations where the record is incomplete. For the Anthropocene, for instance, another potential boundary-defining isotope curve is the $^{13}\text{C}/^{12}\text{C}$ anomaly produced by the burning of fossil fuels (Dean et al., 2014), which has a clear inception, but which has not yet reached its peak. The onset of the globally significant fallout signature occurred in 1952 (Waters et al., 2015), which brings this GSSP suggestion closer in line to recent suggestions of a boundary associated with the mid-20th century 'Great Acceleration' (Zalasiewicz et al., 2015). In the Niepołomice pine, $\Delta^{14}\text{C}$ measurements were only conducted to 1960 (Rakowski et al., 2013), and so a more extended record is needed to capture the beginning of the signal. There is a conceptual issue concerning use of radioisotopes as a marker for the base of the Anthropocene. As the radioisotopes decay the first inception of a signal will, with time, fall below resolvable detection limits and ultimately (50 000 years for ^{14}C) only the peak signal will be recognizable.

Therefore, a peak signal would be better recognized when nearly decayed, but for immediate use the inception is clearly preferable.

- *The excess radiocarbon signal is diachronous and inconsistent.* The 1964 ^{14}C bomb spike is recorded from atmospheric measurements, and tree rings will suitably record that peak in an annual growth ring for that year. However, the tree-ring radiocarbon curve (Rakowski et al., 2013) is representative of the Northern Hemisphere only, rather than capturing a global signal, with the equivalent but lower bomb-peak evident in the Southern Hemisphere ~1–2 years later (see Fig. 2 of Zalasiewicz et al., 2015 and references therein). Also, there will be a mixed inventory of the ocean's native carbon inventory and the bomb peak, so that the excess radiocarbon signal is likely to be suppressed in marine sedimentary deposits, the typical setting within which most, though not all, GSSPs are defined.
- *Other components of the 'bomb spike' are likely to give a clearer signal than ^{14}C .* Plutonium ($^{239,240}\text{Pu}$) is likely to sorb better to clays and organic compounds within marine sediments and moreover has the advantage of being a mostly artificial radionuclide suite with a longer half-life (24,110 years as opposed 5,730 years for ^{14}C) that will be detectable in sedimentary deposits for some 100,000 years (Waters et al., 2015).

Should choice of human narrative influence boundary selection?

A key factor that lies behind the proposal of Lewis and Maslin (2015) for 1964 as a suggested Anthropocene boundary relates to arguments regarding nuclear weapons, their testing, and the related international treaties. They note that this proposed 'boundary' was when atmospheric nuclear tests – upon reaching their peak in 1963 – began to fall, citing the *reason* behind "rapid decline in atmospheric testing" as the 1963 Partial Test Ban Treaty. They present this to "highlight the ability of people to collectively successfully manage a major global threat to humans and the environment" (Lewis and Maslin, 2015, p.178). In other words, the onset of the Anthropocene according to Lewis and Maslin (2015) is not when nuclear powers started to detonate

nuclear weaponry, but rather when humanity demonstrated collectively the ability to manage this through means of international law.

However, neither is the collective will of people shown in a stratigraphic marker nor was the decrease of atmospheric nuclear tests the result of the 1963 Partial Test Ban Treaty. On the contrary, different interpretations suggest that the Treaty itself resulted from the fact that the three nuclear powers of the time – USA, USSR and UK – by then had reached the technological level allowing them to reduce atmospheric nuclear tests, and to agree on an international treaty hampering other states from developing nuclear weapons to reach the same level (Andrassy, 1978; Mastny, 2008).

By a fluke of timing, the publication of the Lewis & Maslin paper in Nature on 12 March 2015 almost exactly coincided with a milestone in a recent legal case at the International Court of Justice (ICJ): the submission of the Memorandum by Marshall Islands against the UK, scheduled for 16 March 2015 (ICJ, 2014a and ICJ, 2014b). The case relates to accusation of all nuclear states for not fulfilling their obligations with respect to the cessation of the nuclear arms race and to nuclear disarmament (and the unique position of the UK as respondent is related to jurisdictional reasons under international law). Overall, however, this case is also a reminder that the prevention of future stratigraphic ‘bomb peaks’ is still aspiration, and not yet reality.

Lewis and Maslin (2015) observe that the date chosen to begin the Anthropocene will affect perceptions of the narrative of humans on, and affecting, the Earth. There is certainly some truth in this. Hence 1610 may be said to reflect colonialism and indeed genocide (<http://avidly.lareviewofbooks.org/2015/03/22/the-inhuman-anthropocene/>) and global trade expansion, while the use of their second choice, the atmospheric bomb spike of 1964 may symbolize control of great technological power and destructive potential.

We are aware of the narratives that may be built around the Anthropocene, and how these may be influenced by boundary choice. However, we suggest that the positioning of a stratigraphic boundary should simply be pragmatically and dispassionately chosen, by the same manner in which all earlier stratigraphic boundaries were chosen, to allow

the most effective practical division between what would then become (by definition) Anthropocene and pre-Anthropocene strata and history. Such a choice would, we consider, be the best guarantee that wider discussion is solidly founded on the best factual basis available.

Discussion

The study of Lewis and Maslin (2015) is important in stimulating debate on a significant transition in Earth history, which has brought what is now being termed the Anthropocene world into being. However, the stratigraphic evidence for a “1610 Orbis event” as an epoch-scale boundary is not compelling in our view. It is clear that interchange between the Americas and the rest of the world was an event of historic significance with global consequences. It is clear also that, around this time, the world was beginning its trajectory towards its modern, largely fossil fuel-powered, state of operation (Fischer-Kowalski et al., 2014). However, the historic significance is in itself insufficient to allow stratigraphic subdivision as effectively as may be done in the mid-20th century, where the energy use and impact are far greater (Figure 3) and their impacts unquestionably global.

Figure 3

With respect to 1964, the ‘Great Acceleration’ was already well under way, the beginnings of which, a little over a decade earlier, exhibit greater synchrony in the upward inflections of many physical and socio-economic trends and their respective stratigraphic signals, than at the proposed 1610 date (Steffen et al., 2007, 2015). Considerations of the symbolism of the Partial Test Ban Treaty, related to this peak, are understandable, but emphasis should be placed on the actual stratigraphic evidence in making the boundary selection process as pragmatic as possible. Hence, the beginning of the upsurge in bomb-produced radiocarbon recorded in such tree-rings might form a plausible candidate GSSP to be compared with other potential GSSPs around this level.

The discussions of the Anthropocene Working Group are currently working towards defining the Anthropocene. The paper by Lewis and Maslin adds new perspectives and

ideas to the debate, which will stimulate inquiry into the nature of Earth system change that saw the world change from its Holocene to its Anthropocene state, but we consider that their specific suggestions are not as stratigraphically effective as others that have been proposed. A suggestion to downgrade the Holocene from epoch to stage, shown in Option 2 of Lewis and Maslin's Figure 1, is not tenable, given that the term is fully ratified.

Figures

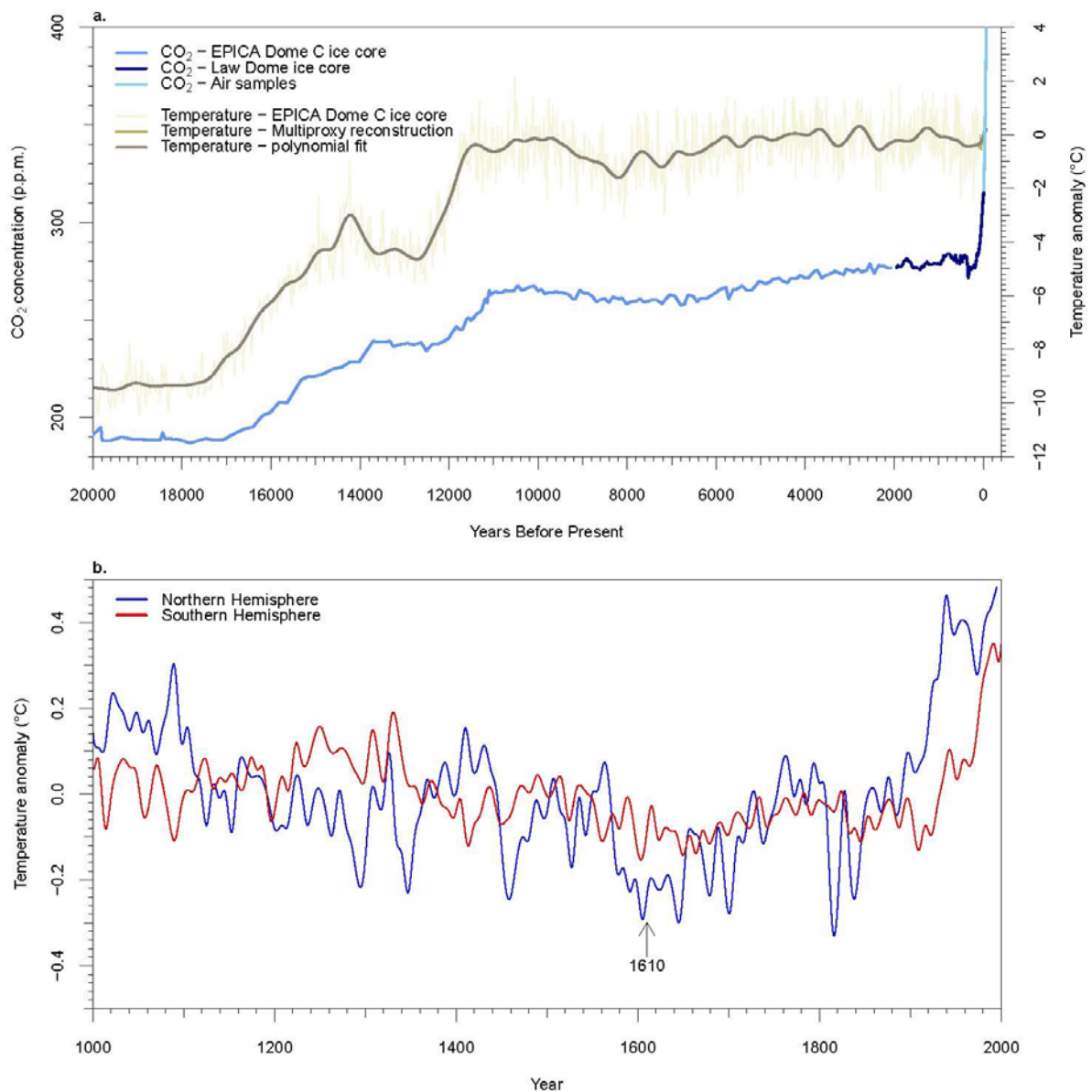


Figure 1. a) atmospheric CO₂ and temperature based upon proxy information from the Law Dome and EPICA Dome C ice cores (MacFarling Meure et al., 2006; Monnin et al., 2001; Jouzel et al., 2007) combined with data from observed measurements (Keeling et al., 2005; Jones et al., 2013); b) Southern (red) and northern (blue) hemisphere temperature anomaly reconstructions from Neukom et al. (2014) showing the temporal and geographical complexity of climate history through the last millennium.

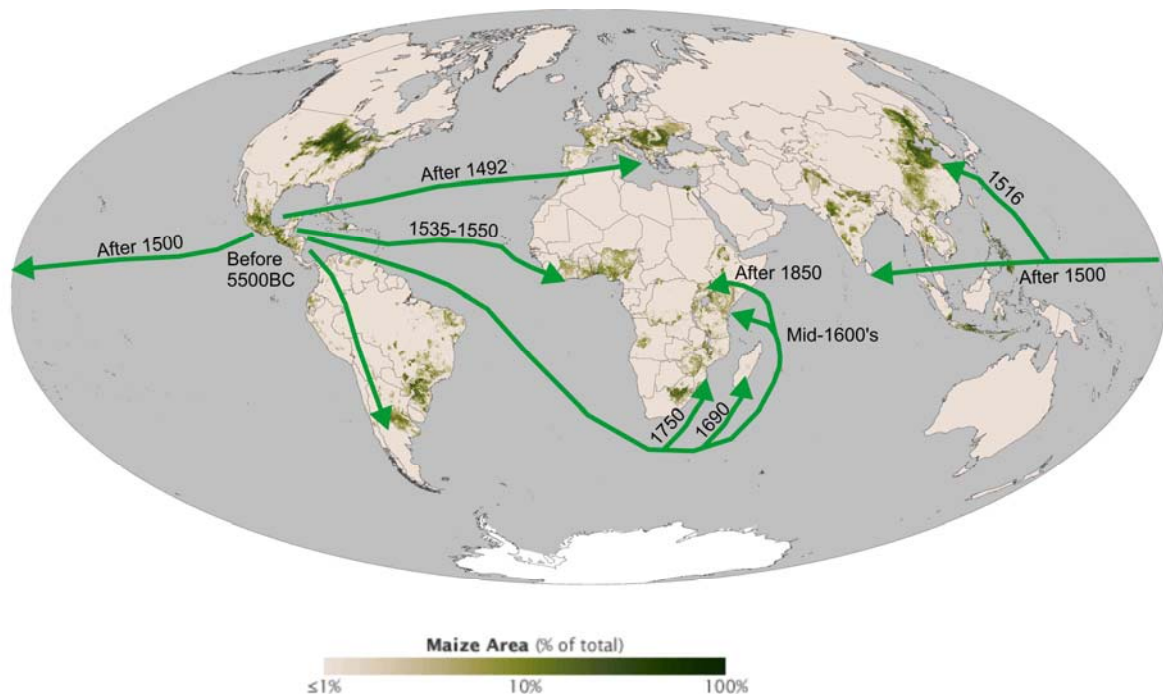


Figure 2. Maize distribution map sourced from NASA: Visible Earth <http://visibleearth.nasa.gov/view.php?id=47250>; The timing of maize transfer and spread sourced from Natural History Museum <http://www.nhm.ac.uk/nature-online/life/plants-fungi/seeds-of-trade/page.dsml?section=crops&page=spread&ref=maize>

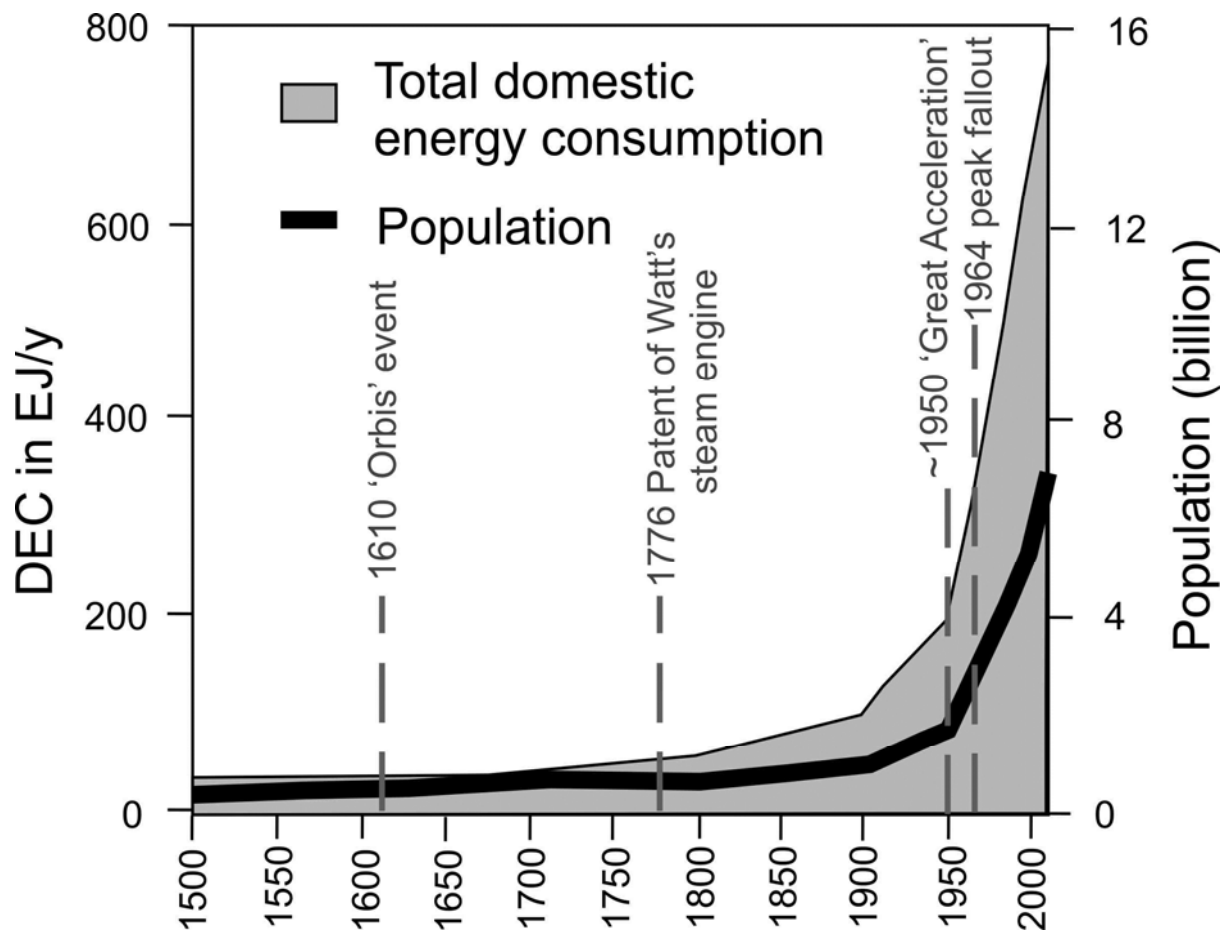


Figure 3. Population and energy use over the last two millennia, modified from Fischer-Kowalski et al. (2014); showing the steep climb in energy use of the mid-20th century 'Great Acceleration'. DEC- Domestic Energy Consumption.

Acknowledgements Colin Waters publishes with the permission of the Executive Director, British Geological Survey (BGS), Natural Environment Research Council, funded with the support of the BGS's Engineering Geology science programme. This research received no other specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contributions The authors are members of the Anthropocene Working Group (AWG) of the Subcommittee on Quaternary Stratigraphy, in turn a component body of the International Commission on Stratigraphy.

Author Information Correspondence should be addressed to CNW, Secretary of the AWG (cnw@bgs.ac.uk).

References

Ahn J, Brook EJ, Mitchell L et al. (2012) Atmospheric CO₂ over the last 1000 years: A high-resolution record from the West Antarctic Ice Sheet (WAIS) Divide ice core. *Global Biogeochemical Cycles* 26: GB2027.

Andrassy, J. (1978). On the Judgment of the International Court of Justice on Nuclear Tests. *Rad* 375, Yugoslav Academy of Sciences and Arts, Zagreb (in Croatian): 5-105.

Aubry M-P, Ouda K, Depuis C et al. (2007) The Global Standard Stratotype-section and Point (GSSP) for the base of the Eocene Series in the Dababiya section (Egypt). *Episodes* 30: 271-286.

Barnola J-M, Raynaud D, Korotkevich YS and Lorius C (1987) Vostok ice core provides 160,000-year record of atmospheric CO₂. *Nature* 329: 408-14.

Barnola J-M, Raynaud D, Lorius C, Barkov NI (2003) Historical CO₂ record from the Vostok ice core. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Chakrabarty D (2015, in press). The Anthropocene and the Convergence of Histories. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a new epoch*. Abingdon: Routledge, 46-56.

Cook ND (1998) *Born To Die: Disease and New World Conquest, 1492-1650*. New York: Cambridge University Press.

Corlett RT (2015) The Anthropocene concept in ecology and conservation. *Trends in Ecology and Evolution* 30: 36-41.

Crutzen PJ (2002) Geology of Mankind. *Nature* 415: 23.

Crutzen PJ and Stoermer EF (2000) The "Anthropocene". *Global Change Newsletter* 41: 17-18.

Dean JR, Leng MJ and Mackay AW (2014) Is there an isotopic signature of the Anthropocene? *The Anthropocene Review* 1(3): 276-287. DOI: 10.1177/2053019614541631.

Eddy J (1976) The Maunder Minimum. *Science* 192 (4245): 1189-1202.

Edgeworth M, Richter DDeB, Waters CN et al. (2015) Diachronous beginnings of the Anthropocene: The lower bounding surface of anthropogenic deposits. *Anthropocene Review* 2(1): 1-26 DOI: 10.1177/2053019614565394.

Etheridge DM, Steele LP, Langenfelds RL et al. (1996) Natural and anthropogenic changes in atmospheric CO₂ over the last 1000 years from air in Antarctic ice and firn.

Journal of Geophysical Research 101: 4115–4128.

Etheridge DM, Steele LP, Langenfelds RL et al. (1998) Historical CO₂ records from the Law Dome DE08, DE08-2, and DSS ice cores. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.

Faust FX, Gnecco C, Mannstein H and Stamm J (2006) Evidence for the Postconquest Demographic Collapse of the Americas in Historical CO₂ Levels. *Earth Interactions* 10: 1-14.

Fischer-Kowalski M, Krausmann F and Pallua I (2014) A sociometabolic reading of the Anthropocene: Modes of subsistence, population size and human impact on Earth. *The Anthropocene Review* 1(1): 8-33.

Indermühle A, Stocker TF, Fischer H et al. (1999) High-resolution Holocene CO₂-record from the Taylor Dome ice core (Antarctica). *Nature* 398: 121–126.

International Court of Justice ICJ (2014a) *Application Instituting Procedures against the United Kingdom*, submitted 24 April 2014. <http://www.icj-cij.org/docket/files/160/18296.pdf>

International Court of Justice ICJ (2014b). Obligations concerning negotiations relating to cessation of the nuclear arms race and to nuclear disarmament (Marshall Islands v. United Kingdom), *Order: Fixing of time limits*, 16 June 2014. <http://www.icj-cij.org/docket/files/160/18342.pdf>

Intergovernmental Panel on Climate Change IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Working Group I contribution to the IPCC Fifth Assessment Report. <http://www.ipcc.ch/report/ar5/wg1/>

Jones PD, Parker DE, Osborn TJ and Briffa KR (2013) Global and hemispheric temperature anomalies—land and marine instrumental records. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. DOI: 10.3334/CDIAC/cli.002.

Jouzel J, Masson-Delmotte V, Cattani O et al. (2007) Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. *Science* 317: 793-797.

Keeling CD, Piper SC, Bacastow RB et al. (2005) Atmospheric CO₂ and ¹³CO₂ exchange with the terrestrial biosphere and oceans from 1978 to 2000: observations and carbon cycle implications. In: Ehleringer JR, Cerling TE and Dearing MD (eds) *A History of Atmospheric CO₂ and its effects on Plants, Animals, and Ecosystems*. New York: Springer Verlag, 83-113.

Latour B (2015, in press) Telling friends from foes in the time of the Anthropocene. In: Hamilton C, Bonneuil C and Gemenne F (eds) *The Anthropocene and the Global*

Environmental Crisis: Rethinking Modernity in a new epoch. Abingdon: Routledge, 145-155.

Lewis SL and Maslin MA (2015) Defining the Anthropocene. *Nature* 519 171–180.

MacFarling Meure C, Etheridge D, Trudinger C et al. (2006) Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33: L14810.

Mann ME, Zhang Z, Hughes MK et al. (2008) Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America* 105: 13252–13257.

Mastny V (2008) The 1963 Nuclear Test Ban Treaty: A Missed Opportunity for Détente? *Journal of Cold War Studies* 10(1): 3–25.

Molina E, Alegret L, Arenillas I et al. (2006) The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, “Tertiary”, Cenozoic) at El Kef, Tunisia - Original definition and revision. *Episodes* 29: 263-273.

Monnin E, Indermühle A, Dällenbach A et al. (2001) Atmospheric CO₂ concentrations over the last glacial termination. *Science* 291: 112–114.

Neukom R, Gergis J, Karoly DJ et al. (2014) Inter-hemispheric temperature variability over the past millennium. *Nature Climate Change* 4: 362–367.

Parker G (2013) *Global Crisis: War, Climate Change, and Catastrophe in the Seventeenth Century*. New Haven: Yale University Press.

Partial Test Ban Treaty (1963). *Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water*. Signed on 5 August 1963 by the Original Parties: the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow, entered into force 10 October 1963. *United Nations Treaty Series*, vol. 480.

Rakowski AZ, Nadeau M-K, Nakamura T et al. (2013) Radiocarbon method in environmental monitoring of CO₂ emission. *Nuclear Instruments and Methods in Physics Research B* 294: 503–507.

Rose, NL (2015) Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene. *Environmental Science and Technology* 49(7): 4155–4162 DOI: 10.1021/acs.est.5b00543.

Rubino M, Etheridge D, Trudinger C et al. (2015) Atmospheric CO₂ and δ¹³C-CO₂ reconstruction of the Little Ice Age from Antarctic ice cores. *Geophysical Research Abstracts* 17: EGU2015-9747-2.

- Ruddiman WF (2003) The Anthropogenic Greenhouse Era began thousands of Years Ago. *Climatic Change* 61: 261-293.
- Ruddiman WF (2013) Anthropocene. *Annual Review of Earth and Planetary Sciences* 41: 45-68. DOI: 10.1146/annurev-earth-050212-123944.
- Ruddiman WF, Ellis EC, Kaplan JO and Fuller, DQ (2015) Defining the epoch we live in. *Science* 348: 38-39.
- Smith BD and Zeder MA (2013) The Onset of the Anthropocene. *Anthropocene* 4: 8-13.
- Steffen W, Crutzen PJ and McNeill JR (2007) The Anthropocene: are humans now overwhelming the great forces of Nature? *Ambio* 36: 614-621.
- Steffen W, Broadgate W, Deutsch L et al. (2015) The trajectory of the Anthropocene: the Great Acceleration. *The Anthropocene Review* 2(1): 81-98.
- Syvitski JPM, Harvey N, Wollanski E et al. (2005) Dynamics of the Coastal Zone. In: Crossland CJ, Kremer HH, Lindeboom HJ et al. (eds) *Coastal Fluxes in the Anthropocene*. Berlin: Springer, pp. 39-94.
- Syvitski JPM and Kettner AJ (2011) Sediment flux and the Anthropocene. *Philosophical Transactions of the Royal Society A* 369: 957-975.
- Vidas D (2010) Responsibility for the seas. In: Vidas D (ed.) *Law, technology and science for oceans in globalisation*, pp. 3-40. Boston, MA: Martinus Nijhoff Publishers/Brill. (doi:10.1163/ej.9789004180406.i-610.9).
- Vidas D (2011) The Anthropocene and the international law of the sea. *Philosophical Transactions of the Royal Society A* 369: 909-925.
- Vidas D (2014) Sea-Level Rise and International Law: At the Convergence of Two Epochs. *Climate Law* 4: 70-84.
- Waters CN, Zalasiewicz J, Williams M et al. (eds) *A Stratigraphical Basis for the Anthropocene*. Geological Society, London, Special Publications, 395: pp.321.
- Waters CN, Syvitski JPM, Gałuszka A et al. (2015) Can nuclear weapons fallout mark the beginning of the Anthropocene Epoch? *Bulletin of the Atomic Scientists* 71(3): 46-57.
- Williams M, Zalasiewicz J, Haywood A et al. (2011) The Anthropocene: a new epoch of geological time? *Philosophical Transactions of the Royal Society* 369A (1938): 833-1112.
- Wolfe AP, Hobbs WO, Birks HH et al. (2013) Stratigraphic expressions of the Holocene–Anthropocene transition revealed in sediments from remote lakes. *Earth-Science Reviews* 116: 17-34.

Zalasiewicz J, Williams M, Smith A et al. (2008) Are we now living in the Anthropocene? *GSA Today* 18 (2): 4-8.

Zalasiewicz J, Waters CN, Williams M et al. (2015) When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quaternary International*.