

# Are we now living in the Anthropocene?

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## ABSTRACT

The term *Anthropocene*, proposed and increasingly employed to denote the current interval of anthropogenic global environmental change, may be discussed on stratigraphic grounds. A case can be made for its consideration as a formal epoch in that, since the start of the Industrial Revolution, Earth has endured changes sufficient to leave a global stratigraphic signature distinct from that of the Holocene or of previous Pleistocene interglacial phases, encompassing novel biotic, sedimentary, and geochemical change. These changes, although likely only in their initial phases, are sufficiently distinct and robustly established for suggestions of a Holocene–Anthropocene boundary in the recent historical past to be geologically reasonable. The boundary may be defined either via Global Stratigraphic Section and Point (“golden spike”) locations or by adopting a

numerical date. Formal adoption of this term in the near future will largely depend on its utility, particularly to earth scientists working on late Holocene successions. This datum, from the perspective of the far future, will most probably approximate a distinctive stratigraphic boundary.

## INTRODUCTION

In 2002, Paul Crutzen, the Nobel Prize–winning chemist, suggested that we had left the Holocene and had entered a new Epoch—the Anthropocene—because of the global environmental effects of increased human population and economic development. The term has entered the geological literature informally (e.g., Steffen et al., 2004; Syvitski et al., 2005; Crossland, 2005; Andersson et al., 2005) to denote the contemporary global environment dominated by human activity. Here, members of the Stratigraphy Commission of the Geological Society of London amplify and extend the discussion of the effects referred to by Crutzen and then apply the same criteria used to set up new epochs to ask whether there really is justification or need for a new term, and if so, where and how its boundary might be placed.

## THE HOLOCENE

The Holocene is the latest of many Quaternary interglacial phases and the only one to be accorded the status of an epoch; it is also the only unit in the whole of the Phanerozoic—the past 542 m.y.—whose base is defined in terms of numbers of years from the present, taken as 10,000 radiocarbon years before 1950. The bases of all other periods, epochs, and ages from the Cambrian onward are defined by—or shortly will be defined by—“golden spikes” (Gradstein et al., 2004), in which a suitable section is chosen as a Global Stratotype Section, the “golden spike” being placed at an agreed point within it, giving rise to a Global Stratigraphic Section and Point, or GSSP.

To bring the definition of the base of the Holocene into line with all other Phanerozoic boundaries, there are intentions to create a GSSP for the base of the Holocene in an ice core, specifically in the North Greenland Ice Core Project (NGRIP) ice core, at the beginning of an interval at which deuterium values (a proxy for local air temperature) rise, an event rapidly followed by a marked decrease in dust levels and an increase in ice layer thickness (ICS, 2006). This level lies very near the beginning of the changes that ushered in interglacial conditions, but is some 1700 yr older than the current definition for the base of the Holocene. One might question whether ice is a suitably permanent material, but in this instance it is important that the GSSP is a tangible horizon within a stratigraphic sequence, a “time plane” marking an elapsed, distinctive, and correlatable geological event rather than an arbitrary or “abstract” numerical age. We note here, though (and discuss further below), that this logic need not *necessarily* be followed in any putative definition of the beginning of the Anthropocene.

The early Holocene was a time of pronounced rises in global temperature, stabilizing at ca. 11,000 cal. yr B.P., and sea level, stabilizing at ca. 8000 cal. yr B.P. (Fig. 1). Temperatures and sea

level then reached a marked plateau where they have, until very recently, remained. This climate plateau, though modulated by millennial-scale global temperature oscillations of  $\sim 1$  °C amplitude, represents the longest interval of stability of climate and sea level in at least the past 400,000 yr. This stability has been a significant factor in the development of human civilization.

## HUMAN INFLUENCE ON HOLOCENE CLIMATE AND ENVIRONMENT

Prior to the Industrial Revolution, the global human population was some 300 million at A.D. 1000, 500 million at A.D. 1500, and 790 million by A.D. 1750 (United Nations, 1999), and exploitation of energy was limited mostly to firewood and muscle power. Evidence recorded in Holocene strata indicates increasing levels of human influence, though human remains and artifacts are mostly rare. Stratigraphic signals from the mid-part of the epoch in areas settled by humans are predominantly biotic (pollen of weeds and cultivars following land clearance for agriculture) with more ambiguous sedimentary signals (such as sediment pulses from deforested regions). Atmospheric lead pollution is registered in polar ice caps and peat bog deposits from Greco-Roman times onward (Dunlap et al., 1999; Paula and Gerald, 2003), and it has been argued that the early to mid-Holocene increase in atmospheric carbon dioxide from  $\sim 260$ – $280$  ppm, a factor in the climatic warmth of this interval, resulted from forest clearance by humans (Ruddiman, 2003). Human activity then may help characterize Holocene strata, but it did not create new, global environmental conditions that could translate into a fundamentally different stratigraphic signal.

From the beginning of the Industrial Revolution to the present day, global human population has climbed rapidly from under a billion to its current 6.5 billion (Fig. 1), and it continues to rise. The exploitation of coal, oil, and gas in particular has enabled planet-wide industrialization, construction, and mass transport, the ensuing changes encompassing a wide variety of phenomena, summarized as follows.

### Changes to Physical Sedimentation

Humans have caused a dramatic increase in erosion and the denudation of the continents, both directly, through agriculture and construction, and indirectly, by damming most major rivers, that now exceeds natural sediment production by an order of magnitude (Hooke, 2000; Wilkinson, 2005; Syvitski et al., 2005; see Fig. 1). This equates to a distinct lithostratigraphic signal, particularly when considered alongside the preservable human artifacts (e.g., the “Made Ground” of British Geological Survey maps) associated with accelerated industrialization.

### Carbon Cycle Perturbation and Temperature

Carbon dioxide levels (379 ppm in 2005) are over a third higher than in pre-industrial times and at any time in the past 0.9 m.y. (IPCC, 2007; EPICA community members, 2004). Conservatively, these levels are predicted to double by the end of the twenty-first century (IPCC, 2007). Methane concentrations in the atmosphere have already roughly doubled. These changes have been considerably more rapid than those associated with glacial-interglacial transitions (Fig. 1; cf. Monnin et al., 2001).

Global temperature has lagged behind this increase in greenhouse gas levels, perhaps as a result of industrially derived sulfate aerosols (the “global dimming” effect; Coakley, 2005).

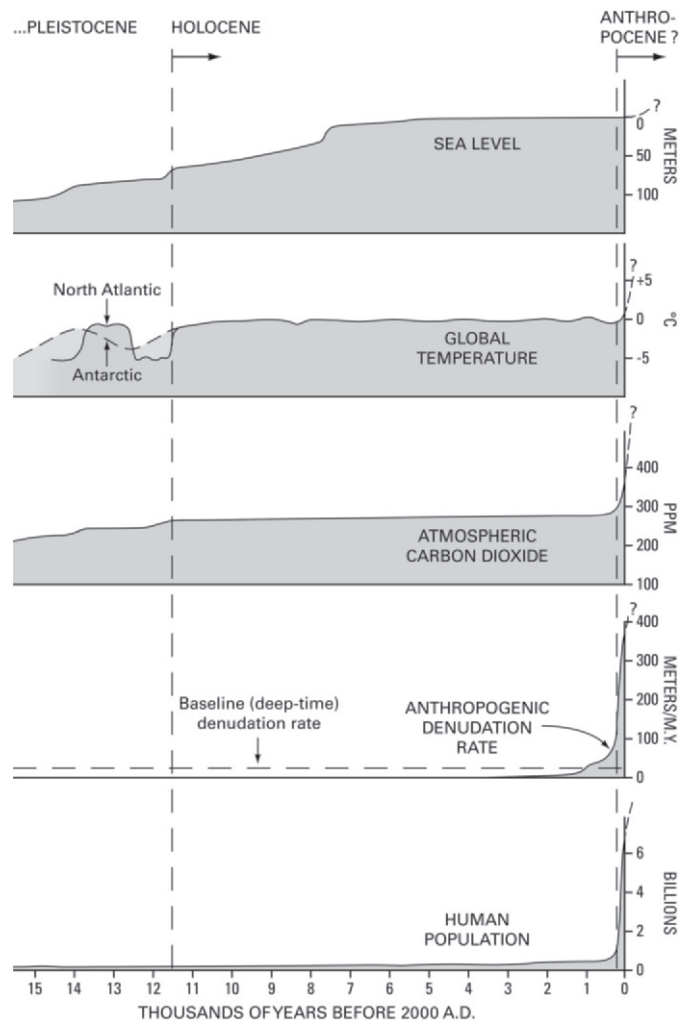


Figure 1. Comparison of some major stratigraphically significant trends over the past 15,000 yr. Trends typical of the bulk of immediately pre-Holocene and Holocene time are compared with those of the past two centuries. Data compiled from sources including Hooke (1994), Monnin et al. (2001), Wilkinson (2005), and Behre (2007).

Nevertheless, temperatures in the past century rose overall, the rate of increase accelerating in the past two decades (Fig. 1). There is now scientific consensus that anthropogenic carbon emissions are the cause (King, 2004; IPCC, 2007). Temperature is predicted to rise by 1.1 °C to 6.4 °C by the end of this century (IPCC, 2007), leading to global temperatures not encountered since the Tertiary. The predicted temperatures are similar to the estimated 5 °C average global temperature rises in the Toarcian (ca. 180 Ma) and at the Paleocene-Eocene thermal maximum (PETM, ca. 56 Ma), which were most probably linked to natural carbon releases into the atmosphere (Thomas et al., 2002; Kemp et al., 2005). While the likely societal effects are clear, in our present analysis we focus on the stratigraphic consequences of increased temperature.

### Biotic Change

Humans have caused extinctions of animal and plant species, possibly as early as the late Pleistocene, with the disappearance of a large proportion of the terrestrial megafauna

(Barnosky et al., 2004). Accelerated extinctions and biotic population declines on land have spread into the shallow seas, notably on coral reefs (Bellwood et al., 2004) and the oceans (Baum et al., 2003; Myers and Worm, 2003). The rate of biotic change may produce a major extinction event (Wilson, 2002) analogous to those that took place at the K-T boundary and elsewhere in the stratigraphic column.

The projected temperature rise will certainly cause changes in habitat beyond environmental tolerance for many taxa (Thomas et al., 2004). The effects will be more severe than in past glacial-interglacial transitions because, with the anthropogenic fragmentation of natural ecosystems, “escape” routes are fewer.

The combination of extinctions, global species migrations (Cox, 2004), and the widespread replacement of natural vegetation with agricultural monocultures is producing a distinctive contemporary biostratigraphic signal. These effects are permanent, as future evolution will take place from surviving (and frequently anthropogenically relocated) stocks.

### **Ocean Changes**

Pre-industrial mid- to late Holocene sea-level stability has followed an ~120 m rise from the late Pleistocene level (Fig. 1). Slight rises in sea level have been noted over the past century, ascribed to a combination of ice melt and thermal expansion of the oceans (IPCC, 2007). The rate and extent of near-future sea-level rise depends on a range of factors that affect snow production and ice melt; the IPCC (2007) predicted a 0.19–0.58 m rise by 2100. This prediction does not factor in recent evidence of dynamic ice-sheet behavior and accelerating ice loss (Rignot and Thomas, 2002; Overpeck et al., 2006; Hansen et al., 2007) possibly analogous to those preceding “Heinrich events” of the late Pleistocene and early Holocene, when repeated episodes of ice-sheet collapse (Bond et al., 1992) caused concomitant rapid sea-level rise (Blanchon and Shaw, 1995). Current predictions are short-term, while changes to the final equilibrium state may be as large as a 10–30 m sea-level rise per 1 °C temperature rise (Rahmstorf, 2007).

Relative to pre-Industrial Revolution oceans, surface ocean waters are now 0.1 pH units more acidic due to anthropogenic carbon release (Caldeira and Wickett, 2003), a change echoed in the stable carbon isotope composition of contemporary foraminiferal tests (Al-Rousan et al., 2004). The future amount of this acidification, scaled to projected future carbon emissions, its spread through the ocean water column, and its eventual neutralization (over many millennia) has been modeled (Barker et al., 2003). Projected effects will be physical (neutralization of the excess acid by dissolution of ocean-floor carbonate sediment, hence creating a widespread nonsequence) and biological (hindering carbonate-secreting organisms in building their skeletons), with potentially severe effects in both benthic (especially coral reef) and planktonic settings (Riebesell et al., 2000; Orr et al., 2005). A similar acidification event accompanied the PETM at ca. 56 Ma, and, indeed, its effect in dissolving strata has hindered the precise deciphering of that event (Zachos et al., 2005).

### **COMPARISON WITH PREVIOUS INTERGLACIALS**

The sensitivity of climate to greenhouse gases, and the scale of (historically) modern biotic change, makes it likely that we have entered a stratigraphic interval without close parallel in

any previous Quaternary interglacial. The nearest parallels seem to be earlier episodes of high atmospheric  $p\text{CO}_2$  and global warming (e.g., Toarcian; the PETM), but the ice volumes then were small, and melting caused only modest sea-level rises (~20 m at the PETM, partly through thermal expansion; Speijer and Marsi, 2002; Speijer and Wagner, 2002). The mid-Pliocene, at 3 Ma, may be a closer analogue: atmospheric  $p\text{CO}_2$  levels may have reached 380 ppm, and the polar ice caps were somewhat smaller than present, with global sea level higher by 10–20 m (Dowsett et al., 1999; Dowsett, 2007).

The present interval might evolve into the “super-interglacial” envisaged by Broecker (1987), with Earth reverting to climates and sea levels last seen in warmer phases of the Miocene or Pliocene (Haywood et al., 2005), most likely achieved via a geologically abrupt rearrangement of the ocean-atmosphere system (Broecker, 1997; Schneider, 2004). Such a warm phase will likely last considerably longer than normal Quaternary interglacials. It is not clear that an equilibrium comparable to that of pre-industrial Quaternary time will eventually resume.

### **STRATIGRAPHIC CRITERIA**

Formal subdivision of the Phanerozoic timescale is not simply a numerical exercise of parceling up time into units of equal length akin to the centuries and millennia of recent history. Rather, the geological timescale is based upon recognizing distinctive events within strata. Time may be divided into specific, recognizable phases in Earth’s environmental history (in particular as regards biota, climate, and sea level), akin to the use of royal dynasties to denote periods of human history (e.g., the Victorian period of the nineteenth and earliest twentieth centuries). Such concepts of the “naturalness” of boundaries underlie, for example, the current debates on the positioning of the boundary of the Quaternary period (Gibbard et al., 2005) and on subdivision of the Precambrian (Bleeker, 2004).

Geologically, units of equivalent rank do not necessarily have to be of equivalent time span, particularly as the present is approached. Thus, the Quaternary, whether its beginning is placed at 1.8 Ma or 2.6 Ma, is by an order of magnitude the shortest period, while the Holocene, at a little under 12,000 calendar years (ICS, 2006) is, by at least two orders of magnitude, the shortest epoch. This inequality has not been seriously disputed, partly because of its practical usefulness. The preceding discussion makes clear that we have entered a distinctive phase of Earth’s evolution that satisfies geologists’ criteria for its recognition as a distinctive stratigraphic unit, to which the name Anthropocene has already been informally given.

We consider it most reasonable for this new unit to be considered at epoch level. It is true that the long-term consequences of anthropogenic change *might* be of sufficient magnitude to precipitate the return of “Tertiary” levels of ice volume, sea level, and global temperature that may then persist over several eccentricity (100 k.y.) cycles (e.g., Tyrrell et al., 2007). This, especially in combination with a major extinction event, would effectively bring the Quaternary period to an end. However, given the large uncertainties in the future trajectory of climate and biodiversity, and the large and currently unpredictable action of feedbacks in the earth system, we prefer to remain conservative. Thus, while there is strong evidence to suggest that we are no longer living in the Holocene (as regards the

processes affecting the production and character of contemporary strata), it is too early to state whether or not the Quaternary has come to an end.

### GOLDEN SPIKE OR YEARS?

For a new epoch to be formally established, either a GSSP needs to be selected or a date for its inception needs to be accepted, which is then ratified by the International Commission on Stratigraphy (ICS). Because it should be possible to select a stratigraphic unit whose age is known in years, the Anthropocene can be defined simultaneously by both criteria, without the uncertainty that bedevils attempts to date older GSSPs. In theory, a point in a section, or a date, that coincides with the end of the pre-industrial Holocene could be selected. However, given that India and China are currently undergoing their own industrial revolution, the selection of a horizon marking the end of pre-industrial (western) history may be inappropriate. Potential GSSPs and ages should allow stratigraphic resolution to annual level, and may be best located in ice cores or stagnant-lake basin cores.

One may consider using the rise of CO<sub>2</sub> levels above background levels as a marker, roughly at the beginning of the Industrial Revolution in the West (following Crutzen, 2002), or the stable carbon isotope changes reflecting the influx of anthropogenic carbon (Al-Rousan et al., 2004). However, although abrupt on centennial-millennial timescales, these changes are too gradual to provide useful markers at an annual or decadal level (while the CO<sub>2</sub> record in ice cores, also, is offset from that of the enclosing ice layers by the time taken to isolate the air bubbles from the atmosphere during compaction of the snow).

From a practical viewpoint, a globally identifiable level is provided by the global spread of radioactive isotopes created by the atomic bomb tests of the 1960s; however, this post-dates the major inflection in global human activity. Perhaps the best stratigraphic marker near the beginning of the nineteenth century has a natural cause: the eruption of Mount Tambora in April 1815, which produced the “year without a summer” in the Northern Hemisphere and left a marked aerosol sulfate “spike” in ice layers in both Greenland and Antarctica and a distinct signal in the dendrochronological record (Oppenheimer, 2003).

In the case of the Anthropocene, however, it is not clear that—for current practical purposes—a GSSP is immediately necessary. At the level of resolution sought, and at this temporal distance, it may be that simply selecting a numerical age (say the beginning of 1800) may be an equally effective practical measure. This would allow (for the present and near future) simple and unambiguous correlation of the stratigraphical and historical records and give consistent utility and meaning to this as yet informal (but increasingly used) term.

### CONCLUSIONS

Sufficient evidence has emerged of stratigraphically significant change (both elapsed and imminent) for recognition of the Anthropocene—currently a vivid yet informal metaphor of global environmental change—as a new geological epoch to be considered for formalization by international discussion. The base of the Anthropocene may be defined by a GSSP in sediments or ice cores or simply by a numerical date.

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### REFERENCES CITED

- Al-Rousan, S., Pätzold, J., Al-Moghrabi, S., and Wefer, G., 2004, Invasion of anthropogenic CO<sub>2</sub> recorded in planktonic foraminifera from the northern Gulf of Aquaba: *International Journal of Earth Sciences*, v. 93, p. 1066–1076, doi: 10.1007/s00531-004-0433-4.
- Andersson, A.J., Mackenzie, F.T., and Lerman, A., 2005, Coastal ocean and carbonate systems in the high CO<sub>2</sub> world of the Anthropocene: *American Journal of Science*, v. 305, p. 875–918, doi: 10.2475/ajs.305.9.875.
- Barker, S., Higgins, J.A., and Elderfield, H., 2003, The future of the carbon cycle: review, calcification response, ballast and feedback on atmospheric CO<sub>2</sub>: *Philosophical Transactions of the Royal Society of London—A*, v. A361, p. 1977–1999.
- Barnosky, A.D., Koch, P.L., Feranec, R.S., Wing, S.L., and Shabel, A.B., 2004, Assessing the causes of Late Pleistocene extinctions on the continents: *Science*, v. 306, p. 70–75, doi: 10.1126/science.1101476.
- Baum, J.K., Myers, R.A., Kehler, D.K., Worm, B., Harley, S.H., and Doherty, P.A., 2003, Collapse and conservation of shark populations in the northwest Atlantic: *Science*, v. 299, p. 389–392, doi: 10.1126/science.1079777.
- Behre, K.-E., 2007, A new Holocene sea-level curve for the southern North Sea: *Boreas*, v. 36, p. 82–102.
- Bellwood, D.R., Hughes, T.P., and Nystrom, N., 2004, Confronting the coral reef crisis: *Nature*, v. 429, p. 827–833, doi: 10.1038/nature02691.
- Blanchon, P., and Shaw, J., 1995, Reef drowning during the last glaciation: Evidence for catastrophic sea-level rise and ice-sheet collapse: *Geology*, v. 23, p. 4–8, doi: 10.1130/0091-7613(1995)023<0004:RDDTLD>2.3.CO;2.
- Bleeker, W., 2004, Towards a ‘natural’ time scale for the Precambrian—A proposal: *Lethaia*, v. 37, p. 219–222, doi: 10.1080/00241160410006456.
- Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S., 1992, Evidence of massive discharge of icebergs into the North Atlantic Ocean during the last glacial period: *Nature*, v. 360, p. 245–249, doi: 10.1038/360245a0.
- Broecker, W.S., 1987, How to build a habitable planet: New York, Eldigio Press, 291 p.
- Broecker, W.S., 1997, Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO<sub>2</sub> upset the current balance?: *Science*, v. 278, p. 1582–1588, doi: 10.1126/science.278.5343.1582.
- Caldeira, K., and Wickett, M.E., 2003, Anthropogenic carbon and ocean pH: *Nature*, v. 425, p. 365, doi: 10.1038/425365a.
- Coakley, J., 2005, Reflections on aerosol cooling: *Nature*, v. 438, p. 1091–1092, doi: 10.1038/4381091a.
- Cox, G.W., 2004, Alien species and evolution: The evolutionary ecology of exotic plants, animals, microbes and interacting native species: Washington, D.C., Island Press, 377 p.
- Crossland, C.J., ed., 2005, Coastal fluxes in the Anthropocene: Berlin, Springer, 231 p.
- Crutzen, P.J., 2002, Geology of mankind: *Nature*, v. 415, p. 23, doi: 10.1038/415023a.
- Dowsett, H.J., 2007, The PRISM paleoclimate reconstruction and Pliocene sea-surface temperature, in Williams, M., Haywood, A.M., Gregory, F.J., and Schmidt, D.N., Deep-time perspectives on climate change: Marrying the signal from computer models and biological proxies: London, The Geological Society, Micropaleontological Society Special Publications, p. 459–480.
- Dowsett, H.J., Barron, J.A., Poore, R.Z., Thompson, R.S., Cronin, T.M., Ishman, S.E., and Willard, D.A., 1999, Middle Pliocene paleoenvironmental reconstruction: PRISM2: U.S. Geological Survey Open-File Report 99-535, 19 p.
- Dunlap, C.E., Steinnes, E., and Flegal, A.R., 1999, A synthesis of lead isotopes in two millennia of European air: *Earth and Planetary Science Letters*, v. 167, p. 81–88, doi: 10.1016/S0012-821X(99)00020-5.
- EPICA (European Project for Ice Coring in Antarctica) community members, 2004, Eight glacial cycles from an Antarctic ice core: *Nature*, v. 429, p. 623–628.
- Gibbard, P.L., Smith, A.G., Zalasiewicz, J.A., Barry, T.L., Cantrill, D., Coe, A.L., Cope, J.C.W., Gale, A.S., Gregory, F.J., Powell, J.H., Rawson, P.R., Stone, P., and Waters, C.W., 2005, What status for the Quaternary?: *Boreas*, v. 34, p. 1–6, doi: 10.1080/03009480510012854.
- Gradstein, F.M., Ogg, J.G., and Smith, A.G., eds., 2004, A Geological Time Scale 2004: Cambridge, UK, Cambridge University Press, 589 p.
- Hansen, J., Sato, M., Kharecha, P., Russell, G., Lea, D.A., and Siddall, M., 2007, Climate change and trace gases: *Philosophical Transactions of the Royal Society*, v. A365, p. 1925–1954.
- Haywood, A.M., Dekens, P., Ravelo, A.C., and Williams, M., 2005, Warmer tropics during the mid-Pliocene? Evidence from alkenone paleothermometry and a fully coupled ocean-atmosphere GCM: *Geochemistry Geophysics Geosystems*, v. 6, doi: 10.1029/2004GC000799.
- Hooke, R.LeB., 2000, On the history of humans as geomorphic agents: *Geology*, v. 28, p. 843–846, doi: 10.1130/0091-7613(2000)28<843:OTHOHA>2.0.CO;2.
- ICS (International Commission on Stratigraphy), 2006, Subcommittee on Quaternary

- Stratigraphy, Annual Report 2006: <http://www.quaternary.stratigraphy.org.uk/about/annualreports/annrepindex.html> (last accessed 28 Apr. 2007).
- IPCC (Intergovernmental Panel on Climate Change), 2007, Climate change 2007: Synthesis report. Summary for policy makers: [http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4\\_syr\\_spm.pdf](http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf) (last accessed 3 Dec. 2007).
- Kemp, D.B., Coe, A.L., Cohen, A.S., and Schwark, L., 2005, Astronomical pacing of methane release in the Early Jurassic Period: *Nature*, v. 437, p. 396–399, doi: 10.1038/nature04037.
- King, D.A., 2004, Climate change science: *Science*, v. 303, p. 176–177, doi: 10.1126/science.1094329.
- Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.S., Reynaud, D., and Barnola, J.-M., 2001, Atmospheric CO<sub>2</sub> concentrations over the Last Glacial Termination: *Science*, v. 291, p. 112–114, doi: 10.1126/science.291.5501.112.
- Myers, R.A., and Worm, B., 2003, Rapid worldwide depletion of predatory fish communities: *Nature*, v. 423, p. 280–283, doi: 10.1038/nature01610.
- Oppenheimer, C., 2003, Climatic, environmental and human consequences of the largest known historical eruption: Tambora volcano (Indonesia) 1815: Progress in Physical Geography, v. 27, p. 230–259, doi: 10.1191/0309133303pp379ra.
- Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y., and Yool, A., 2005, Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms: *Nature*, v. 437, p. 681–686, doi: 10.1038/nature04095.
- Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Kiehl, J.T., 2006, Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise: *Science*, v. 311, p. 1747–1750, doi: 10.1126/science.1115159.
- Paula, A.H., and Gerald, M.C., 2003, Holocene Pb isotope chronological standard curve: A review of the record of the anthropogenic activity in the last 6,000 years: Short Papers—IV South American Symposium on Isotope Geology, p. 465–468.
- Rahmstorf, S., 2007, A semi-empirical approach to projecting future sea-level rise: *Science*, v. 315, p. 368–370, doi: 10.1126/science.1135456.
- Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E., and Morel, M.M., 2000, Reduced calcification of marine plankton in response to increased atmospheric CO<sub>2</sub>: *Nature*, v. 407, p. 364–366, doi: 10.1038/35030078.
- Rignot, E., and Thomas, R.H., 2002, Mass balance of polar ice sheets: *Science*, v. 297, p. 1502–1506, doi: 10.1126/science.1073888.
- Ruddiman, W.F., 2003, The anthropogenic Greenhouse Era began thousands of years ago: *Climatic Change*, v. 61, p. 261–293, doi: 10.1023/B:CLIM.0000004577.17928.f8.
- Schneider, S.H., 2004, Abrupt non-linear climate change, irreversibility and surprise: *Global Environmental Change*, v. 14, p. 245–258, doi: 10.1016/j.gloenvcha.2004.04.008.
- Speijer, R.P., and Marsi, A.-M.M., 2002, Ostracode turnover and sea-level changes associated with the Paleocene-Eocene thermal maximum: *Geology*, v. 30, p. 23–26, doi: 10.1130/0091-7613(2002)030<0023:OTASLC>2.0.CO;2.
- Speijer, R.P., and Wagner, T., 2002, Sea-level changes and black shales associated with the late Paleocene thermal maximum: Organic-geochemical and micropaleontologic evidence from the southern Tethyan margin (Egypt-Israel), in Koerber, C., and MacLeod, K.G., eds., *Catastrophic Events and Mass Extinctions: Impacts and Beyond*: Geological Society of America Special Paper 356, p. 533–549.
- Steffen, W., Sanderson, A., Tyson, P.D., Jaeger, J., Matson, P.A., Moore, B., III, Oldfield, F., Richardson, K., Schnellhuber, H.J., Turner, B.L., and Wasson, R.J., 2004, *Global Change and the Earth System: A Planet under Pressure*: Berlin, Springer-Verlag, 336 p. (See also the executive summary at [http://www.igbp.kva.se/documents/IGBP\\_ExecSummary.pdf](http://www.igbp.kva.se/documents/IGBP_ExecSummary.pdf) [4.23 MB]).
- Svitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., and Green, P., 2005, Impact of humans on the flux of terrestrial sediment to the global coastal ocean: *Science*, v. 308, p. 376–380, doi: 10.1126/science.1109454.
- Thomas, C.D., et al., 2004, Extinction risk from climate change: *Nature*, v. 427, p. 145–148, doi: 10.1038/nature02121.
- Thomas, D.J., Zachos, J.C., Bralower, T.J., Thomas, E., and Bohaty, S., 2002, Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum: *Geology*, v. 30, p. 1067–1070, doi: 10.1130/0091-7613(2002)030<1067:WTFFTF>2.0.CO;2.
- Tyrrell, T., Shepherd, J.G., and Castle, S., 2007, The long-term legacy of fossil fuels: *Tellus B*, v. 59, p. 664–672.
- United Nations, 1999, *The world at six billion*: <http://www.un.org/esa/population/publications/sixbillion/sixbillion.htm> (last accessed 30 Nov. 2007).
- Wilkinson, B.H., 2005, Humans as geologic agents: A deep-time perspective: *Geology*, v. 33, p. 161–164, doi: 10.1130/G21108.1.
- Wilson, E.O., 2002, *The future of life*: New York, Alfred A. Knopf, Random House, 256 p.
- Zachos, J.C., Röhl, U., Schellenberg, S.A., Sluijs, A., Hodell, D.A., Kelly, D.C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L.J., McCarren, H., and Kroon, D., 2005, Rapid acidification of the ocean during the Paleocene-Eocene thermal maximum: *Science*, v. 308, p. 1611–1615, doi: 10.1126/science.1109004.

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