THE EARLY ANTHROPOGENIC HYPOTHESIS A YEAR LATER

An Editorial Reply

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1. Introduction

Ruddiman (2003) introduced a three-part hypothesis on early anthropogenic influences on late Holocene climate. He proposed that humans reversed a natural decrease in atmospheric CO_2 values 8000 years ago by starting to clear forests for farms, that they reversed a natural methane decrease after 5000 years ago mainly by beginning to irrigate rice, and that they caused an anthropogenic warming sufficient to counter most of a natural cooling and avoided the onset of a new glaciation within the last several thousand years. This hypothesis has attracted considerable attention and some criticism (Joos et al., 2004; EPICA Community members, 2004). In this note, I comment on the current status of the hypothesis in the context of the issues raised by the two accompanying papers (Claussen et al., this volume; Crucufix et al., this volume). I conclude that the critics have not refuted the central argument of the hypothesis.

2. The Stage 11 Analog

One criticism has targeted my use of isotopic stages 5, 7, and 9 as analogs to the Holocene. Changes in the eccentricity of Earth's orbit were larger during the three previous interglaciations than during the Holocene, and changes in solar radiation were more extreme, although moving in the same direction. Critics have correctly noted that stage 11 is a better insolation analog for the Holocene because of its comparably low eccentricity values. Both Crucufix et al. (this volume) and Claussen et al. (this volume) comment on this point.

I recently examined (Ruddiman, in press) the part of stage 11 regarded as the closest insolation analog to the last several millennia of the Holocene and the next few millennia (Berger and Loutre, 2003). This interval occurred in the millennia between 400,000 years ago and ∼390,000 years ago. Three independently derived time scales – those of Petit et al. (1999), Shackleton (2000), and Bender (2002) – all converge on the same age for this key interval deep in the Vostok ice.

During this analog to modern conditions, atmospheric methane concentrations fell to just under 450 ppm and CO_2 values to 250 ppm (Figure 1a and b). In both

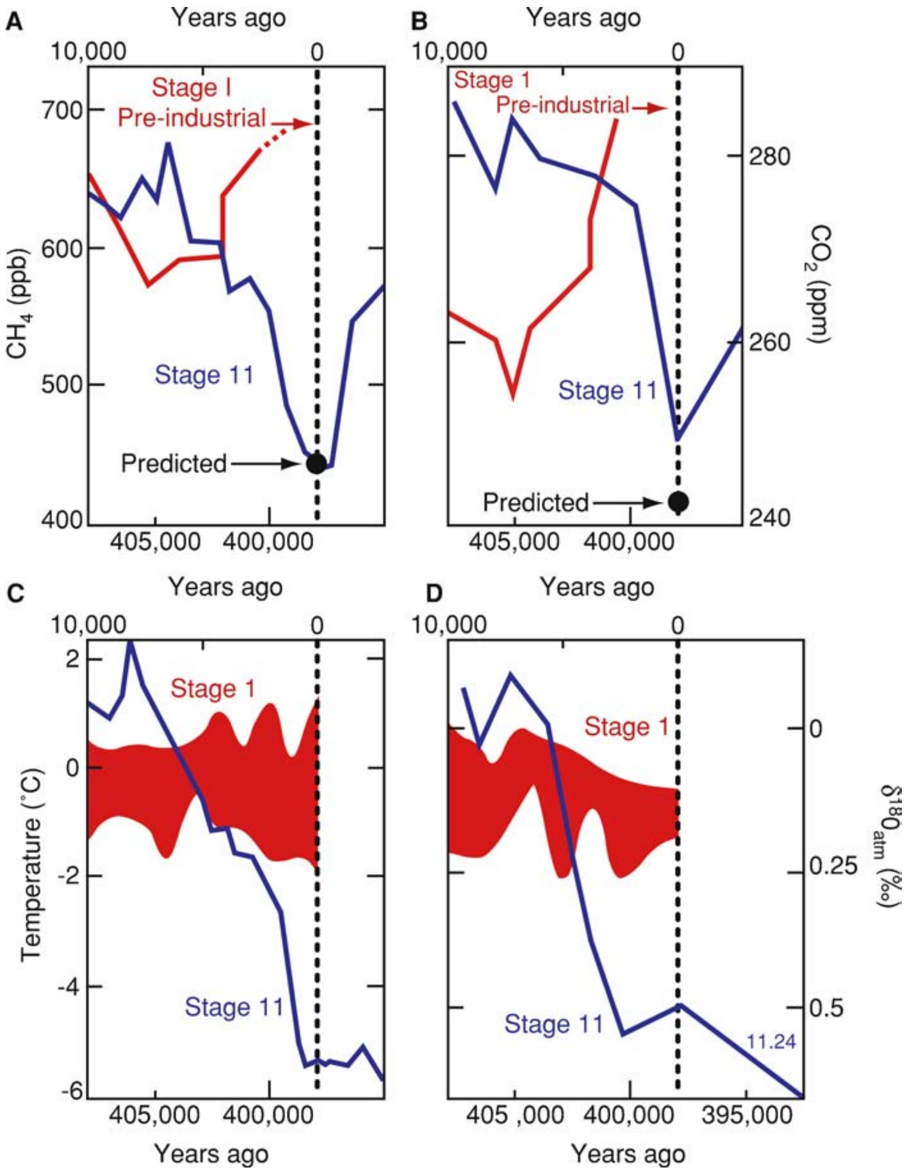

Figure 1. Climate-system responses recorded in Vostok ice for the last 10,000 years (stage 1; in red) compared to changes during the closest insolation analog from interglacial isotopic stage 11 (in blue): (a) CH_4; (b) CO_2; (c) deuterium-based Antarctic temperature; and (d) $\delta^{18}O_{atm}$. Because the stage 11 trends are natural in origin, the different stage 1 trends suggest anthropogenic interference.

cases, the levels reached were very near to the natural Holocene levels predicted in the early anthropogenic hypothesis. As stage 11 was an entirely natural (non-anthropogenic) world in which the insolation forcing was similar to the Holocene, these observations provide strong support for the hypothesis.

The two accompanying papers mainly focus on the third prediction – that a glaciation should have started several thousand years ago but is now "overdue" because of human intervention. Using ice-sheet models of differing complexity, both Claussen et al. and Crucufix et al. find that a very small late-Holocene glaciation would be permitted (but not assured) if atmospheric CO_2 concentrations were lowered to the levels suggested by the hypothesis. These simulations agree with an A-GCM experiment in which greenhouse-gas concentrations were dropped to the predicted levels (Ruddiman et al., 2005). In that simulation, the occurrence of year-round snow cover in several grid boxes on Baffin Island indicated incipient glaciation, and an increase in the duration of snow cover over a broad plateau in central Labrador to 11 months per year brought that region close to a state of glaciation.

These models all fall short of giving a definitive answer to the overdue-glaciation claim. Claussen et al. note that the CLIMBER model is a simplified representation of a very complex climate system, and Crucufix et al. note the uncertainties implicit in modeling ice volume. The possible size of such a glaciation is also poorly constrained. Vettoretti and Peltier (2003) found that large-scale glacial inception should occur for CO_2 values below 260 ppm, well above the level predicted by the hypothesis. It also is not clear that either the Claussen et al. or Crucufix et al. models included the forcing available from the $\sim$250-ppb drop in methane predicted by the hypothesis and supported by the trends in stage 11 (Figure 1a). Including the CH_4 decrease should enhance the radiative forcing from the CO_2 drop by 50% or more.

GENESIS 2, the A-GCM model used by Ruddiman et al. (2005), has similar limitations, including the lack of interactive vegetation and a dynamic ocean. Inclusion of these important feedback processes in the model would likely alter the initial results. In short, neither time-dependent ice models nor GCMs can at this point confirm or deny the 'overdue ice' hypothesis. I agree with the conclusion of Crucufix et al. that "Holocene glacial inception is plausible but not certain, depending on the exact time evolution of the atmospheric CO_2 concentration during this period" (and of the CH_4 concentrations as well).

Several lines of evidence indicate that a glaciation was underway during the part of stage 11 when insolation values were most analogous to the present. Icebergs began carrying abundant debris to Nordic Sea sediments just after 400,000 years ago, following a long interval with negligible deposition (Bauch et al., 2000). For ice rafting to have occurred in that region, new ice must have begun growing either in Scandinavia, the Barents Sea, or along the coasts of Greenland.

Marine and ice-core $\delta^{18}O$ trends also suggest new ice growth. In sediment cores from the Pacific Ocean, benthic $\delta^{18}O$ values increased by 0.72–0.74% by the time of isotopic substage 11.24 early in stage 11 (Mix et al., 1995a,b). If 0.56% of this change is attributed to a temperature-salinity overprint (the size of the overprint on the stage 2/1 deglaciation assuming a 1.05% ice-volume effect), the remaining 0.16–0.18% of the $\delta^{18}O$ increase would represent ice volume. Similarly, values of $\delta^{18}O_{atm}$

in the gas phase of Vostok ice fell by 0.6–0.7% early in stage 11 (Figure 1d). If 0.45% of this change is attributed to a "Dole effect" biomass overprint (Bender et al., 1994), again assuming the same overprint as that on the stage 2/1 deglaciation, based on a 1.05% ice-volume effect, the remaining 0.15–0.25% would represent increased ice volume. These two estimates agree on a possible ice-volume contribution of ~0.20%, equivalent to ~20 meters of sea-level lowering, by isotopic substage 11.24 at ~392,000 years ago (Figure 1d). The portion of this $\delta^{18}O$ increase that would have occurred by the time precisely equivalent to present-day conditions (397,000 years ago) depends critically on the accuracy of the time scale for this part of the Vostok record and therefore remains uncertain, but some accumulation by that time is likely.

Claussen et al. err in saying that I predicted a "large-scale" late-Holocene glaciation. Instead, I simply said, "a glaciation is now overdue" (Ruddiman, 2003), most likely in northeast Canada, but I made no estimate of its magnitude. It stands to reason that large ice sheets would not have accumulated in just a few millennia, especially given the modest levels of insolation forcing, although the stage 11 analog appears to permit a non-trivial volume of ice. This part of my hypothesis remains plausible but unproven and obviously requires further investigation.

A related issue is the unusually long interval of interglacial warmth during stage 11. Subpolar North Atlantic sediments and Antarctic ice both indicate an interval of warmth lasting at least 20,000 years (McManus et al., 2003; EPICA Community Members, 2004). Claussen et al. cite the EPICA interpretation that the current interglaciation must still have many millennia left to run if it is to persist as long as the one in stage 11. But the EPICA interpretation contains what I regard as a fatal flaw. EPICA aligns the beginning of the two interglaciations and compares their subsequent duration (Figure 2A), but this choice results in a total misalignment of the 65°N summer insolation trends in the two interglaciations (Figure 2b). The correct alignment of the insolation trends (used by Berger and Loutre, 2003) matches the modern-day insolation minimum with a similar minimum 397,000 years ago (Figure 2D). This alignment of stage 1 with the end (rather than the beginning) of stage 11 leads to the conclusion that the Holocene interglacial warmth should have already ended (Figure 2C).

3. The Carbon Budget Issue

The second major criticism of the early anthropogenic hypothesis has been that humans could not have burned enough forest biomass to meet a new estimate requiring 550–700 billion tons of carbon to generate an inferred early anthropogenic CO_2 anomaly of 40 ppm (Joos et al., 2004). This model-based estimate is considerably larger than an earlier value based on carbon modeling (Indermuhle et al., 1999). If the new estimate is valid, humans cannot possibly have supplied enough carbon

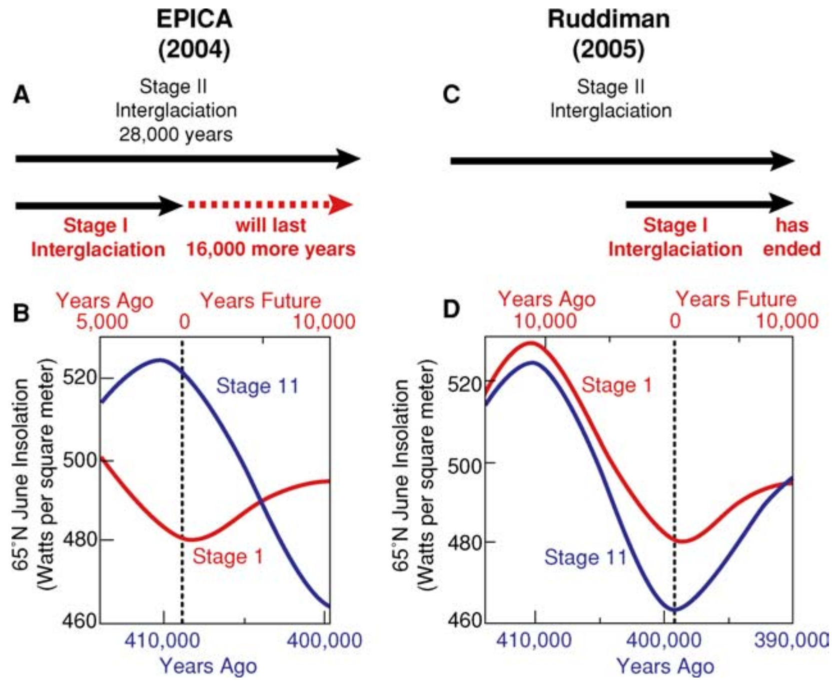

Figure 2. EPICA (2004) aligned stage 1 with the early part of stage 11 (A), but this choice produces an implausible misalignment of 65°N insolation trends (B). The correct alignment of the insolation trends (D), which matches stage 1 with the latter part of stage 11 (C), indicates that the current interglaciation should have ended by now.

to the atmosphere by burning forests to account for the full anomaly. As noted by Joos et al. (2004), this conclusion is further supported by the relatively small shift in $\delta^{13}C$ of CO_2 during the late Holocene.

On the other hand, the stage 11 comparison has provided convincing confirmation that the late-Holocene CO_2 anomaly is at least 30–35 parts per million (Figure 1b), nearly as large as the 40-ppm predicted by the early anthropogenic hypothesis. Both conclusions – a large CO_2 anomaly of anthropogenic rather than natural origin, and the insufficiency of forest burning as a direct explanation of much of the anomaly – seem solid. Can these opposing findings be reconciled?

One plausible solution is that most of the late-Holocene CO_2 anomaly resulted from processes triggered by humans and therefore anthropogenic in origin, but not requiring direct carbon emissions from biomass burning (Ruddiman, 2005). This explanation turns out to have been implicit in my original definition of the Holocene CO_2 anomaly. I calculated the anomaly as the difference between the CO_2 value reached just before the industrial era (280–285 ppm), and the value to which I predicted it should have fallen had natural processes prevailed (240–245 ppm). That anomaly can be separated into two distinct parts: (1) the CO_2 *rise* that occurred in stage 1 but not during previous interglaciations; and (2) the CO_2 *fall* that occurred during previous interglaciations but not during stage 1. Until now, my attention (and that of my critics) has focused on the amount of the CO_2 rise that might be explained by biomass burning and other early anthropogenic sources, but the role of the natural drops in CO_2 has been ignored.

For the four interglaciations prior to the Holocene, CO_2 values fell by 30–45 ppm in the millennia following the late-deglacial/early-interglacial maxima. No such drop occurred in the Holocene, except for the 7-ppm decrease prior to the anomalous reversal in trend 8000 years ago. The obvious implication is that whatever processes caused these natural CO_2 drops in previous interglaciations but prevented them during the Holocene made a major contribution to the size of the Holocene CO_2 'anomaly'.

Two processes are likely candidates (Ruddiman, 2005). Imbrie et al. (1992) proposed that ice sheets create their own positive feedback through several processes, one of which is their impact on CO_2. The failure of ice sheets to appear in the northern hemisphere during the Holocene would have negated a natural CO_2 drop that would have resulted from the effects of growing ice sheets on the fast-alkalinity response of the deep ocean and on dust-flux fertilization of surface-ocean algae.

A second, and probably more important, factor was the suppression of a major late-Holocene cooling in the Antarctic region. Stephens and Keeling (2000) proposed that advances of Antarctic sea ice reduce atmospheric CO_2 by cutting off carbon exchanges between the surface ocean and the atmosphere. Evidence from stage 11 based on deuterium isotopes (δD) shows that air temperatures over Antarctic ice dropped 75% of the way toward full-glacial values during the closest stage 11 analog to late-Holocene conditions (Figure 1c). This large a cooling must have been accompanied by a major sea-ice advance in the nearby ocean. During the Holocene, δD values reveal a much smaller drop in the temperature over Antarctica (Figure 1c). As a result, the Holocene advance in sea ice and the decrease in atmospheric CO_2 would have been much smaller. In support of this interpretation, the A-GCM experiment with modern insolation levels but reduced greenhouse-gas concentrations simulated a cooling of 3–4 °C in the Southern Ocean and a major advance of sea ice (Ruddiman et al., 2005).

The proposed sequence during the Holocene is as follows. Direct carbon emissions from anthropogenic (mostly agricultural) sources accounted for most of the Holocene methane anomaly and a smaller fraction (perhaps a third) of the CO_2 anomaly. These direct emissions caused a climatic warming sufficient in size to cancel the appearance of small northern hemisphere ice sheets and to suppress the size of major advances of southern hemisphere sea-ice. The failure of these natural changes to develop then contributed to the remaining (and larger) part of the CO_2 anomaly as a form of positive feedback to the initial 'direct' anthropogenic impacts.

4. Critiquing the Critics

Most critics of my hypothesis have neglected to respond to the single most powerful argument in its favor. In a notable exception, Crucufix et al. termed this the "sledgehammer argument". During previous interglaciations (stages 5, 7, 9, and now also 11), when nature was in full control of climate, and when insolation trends were headed in the same direction as they are now, concentrations of CO_2 and CH_4 fell in every instance. Alone among the last five interglaciations, stage 1 shows a substantial greenhouse-gas rise. My challenge to the critics is this: Why did CO_2 and CH_4 concentrations rise in the middle and late Holocene, when they had previously always fallen? The seemingly unavoidable implication is that something about stage 1 is different—not "natural". The most plausible answer is the onset of agriculture.

The same argument works in the converse sense: any argument devised to explain the stage 1 greenhouse-gas increase as "natural" in origin has already dug itself a very deep hole. For example, Joos et al. (2004) call on terrestrial vegetation, ocean carbonate, and coral reefs as natural sources of carbon to explain the Holocene CO_2 rise. Given our still-uncertain knowledge of carbon dynamics (Crucufix et al.), these alternative explanations for the late-Holocene CO_2 rise can be proposed, and model simulations can be run that match a portion of the carbon-budget demands. But how will these explanations fare when tested in the past?

Tested against the reality of the last four interglaciations, any such explanation must fail. All of the major climatic boundary conditions during the previous interglaciations were similar to those found today: the major ice sheets had melted, sea level was high, boreal vegetation was in an interglacial state, tropical monsoon vegetation was in retreat, and insolation trends were similar (especially during stage 11). Given this pervasive similarity in the major sources of forcing, the explanations must predict (and the models must presumably simulate) similar rises in CO_2 during the earlier interglaciations. In fact, for those interglaciations with stronger insolation forcing than the Holocene, the predicted CO_2 increases would probably be even larger than the Holocene rise.

But the CO_2 and CH_4 concentrations did not rise during the intervals most similar to today; they fell. It seems inevitable that these naturally based explanations must fail the test on all four previous interglaciations. Indeed, the large increases in gas concentrations these explanations should predict will make it all the more difficult to explain the large decreases actually observed.

A year later, the [slightly altered] "early anthropogenic hypothesis" is alive and well.

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