Cold climate during the closest Stage 11 analog to recent Millennia

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Abstract

The early part of marine isotopic Stage 11 near 400,000 years ago provides the closest analog to Holocene insolation levels of any interglaciation during the era of strong 100,000-year climatic cycles. The CH4 concentration measured in Vostok ice fell to ~450 ppb, and CO2 values to ~250 ppm. These natural decreases contrast with the increases in recent millennia and support the early anthropogenic hypothesis of major gas emissions from late-Holocene farming. During the same interval, δD values fell from typical interglacial to nearly glacial values, indicating a major cooling in Antarctica early in Stage 11. Other evidence suggests that new ice was accumulating during the closest insolation analog to the present day: a major increase in δ18O atm at Vostok, a similar increase in marine δ18O values, and re-initiation of ice rafting in the Nordic Sea. The evidence permits extended (>20,000 year) intervals of Stage 11 interglacial warmth in the Antarctic and North Atlantic, yet it also requires that this warmth ended and a new glacial era began when insolation was most similar to recent millennia. The Holocene CO2 anomaly was produced only in part by direct anthropogenic emissions; over half of the anomaly resulted from the failure of CO2 values to fall as they had during previous interglaciations because of natural responses, including a sea-ice advance in the Antarctic and ice-sheet growth in the northern hemisphere.

1. Introduction

Ruddiman (2003a) proposed that early farming produced enough CO2 and CH4 during the millennia prior to the industrial era to boost gas concentrations in the atmosphere and counter the natural decreases that would otherwise have occurred. Natural CO2 and CH4 trends for the late Holocene were estimated from those in early interglacial marine isotopic Stages 5, 7, and 9, when concentrations in Vostok ice reached late-deglacial maxima and then fell for more than 10,000 years early in each interglaciation (Petit et al., 1999). During the most recent deglaciation, CH4 and CO2 concentrations also reached a late-deglacial peak and began similar decreases, but gas levels then rose rather than falling during recent millennia (Fig. 1). The total gas anomalies reached just before the start of the industrial era—the difference between the observed rises and the predicted drops—were estimated at 40 ppm for CO2 and 250 ppb for methane. The CH4 anomaly was attributed mainly to irrigation for rice, and the CO2 anomaly to clearance of forests.

Another part of the early anthropogenic hypothesis was the inference that these early emissions averted a natural global cooling that would otherwise have initiated a new glacial cycle in the northern hemisphere (Fig. 2). This conclusion was based in part on an energy-balance model study showing that northeast Canada has been close to a state of glacial inception in recent centuries (Williams, 1978) and that a relatively small cooling would be needed to start a new glacial cycle in North America or Eurasia. Additional support came from ice-volume trends simulated by a numerical model that estimated time-dependent δ18O responses to summer insolation changes in the northern hemisphere (Imbrie and Imbrie, 1980).
The choice of the first part of marine isotopic Stages 5, 7, and 9 as analogs to the Holocene can be questioned. Eccentricity modulates precession at the 413,000-year period, and insolation variations during the current interglaciation have been smaller in amplitude than those during the last three interglaciations, although moving in the same direction. As a result, the early anthropogenic hypothesis can be challenged: the reduced amplitude of forcing during the Holocene might have resulted in natural climatic responses smaller than those during the last three interglaciations.

Isotopic Stage 11 is a better analog to the Holocene. Because of comparably low eccentricity at that time, insolation variations were smaller in amplitude and closer to modern values (Fig. 3). The analog is not perfect: the tilt and July precession maxima were out of phase on the Stage 12/11 deglaciation (termination V) but were very nearly in phase on the Stage 2/1 deglaciation, while the subsequent insolation minima at tilt and precession were nearly in phase during Stage 11 but are out of phase now. Still, Stage 11 is the closest available analog to Holocene insolation levels within the interval of dominant 100,000-year climatic cycles.

One method used to compare Stages 1 and 11 is to determine the length of the Stage 11 interglaciation and use it to forecast the duration of the current interglaciation. This approach has led to a widespread view that Stage 11 was an unusually long interglaciation, and that by implication the current interglaciation could last many thousand of years into the future (Burckle, 1993; EPICA Community Members, 2004). Some simulations of ice volume with zonal climatic models even show an ice-free interval lasting for tens of thousands of years (Loutre and Berger, 2000). Although these results seem to refute the overdue-glaciation hypothesis, Sections 2–5 of this paper will show that such a conclusion is unjustified.

The first issue considered here is the response of the climatic system during the part of Stage 11 that provides the closest insolation analog to the recent millennia of...
the Holocene (Berger and Loutre, 2003). During this closest-analog interval, spanning the millennia just prior to 397,000 years ago, July 65°N summer insolation values fell to a minimum very near the present-day level (Fig. 3). Incoming July radiation was ~14 W/m² below the modern level, compared to values 20–35 W/m² lower during the most similar parts of interglacial isotopic Stages 5, 7, and 9.

The behavior of the climate system during this closest-analog portion of Stage 11 provides a stringent test of the early anthropogenic hypothesis. If the trends during this time match those during Stage 1, it will be difficult to argue that the Holocene trends are anomalous compared to the natural behavior of the climate system, and the early anthropogenic hypothesis will be refuted. But if the Stage 11 trends show major reductions in greenhouse gases and a substantial climatic cooling as predicted in Figs. 1 and 2, the hypothesis that the Holocene trends are anthropogenic rather than natural in origin will be supported.

2. Comparison of Stages 11 and 1: Vostok ice

The occurrence of typical full-interglacial values of CH₄, CO₂, δD, and δ¹⁸O atm in the lower tens of meters of Vostok ice indicates that it reaches deep into Stage 11. Petit et al. (1999) pinned the lower portion of their GT4 time scale at Vostok by correlating a feature near 3265 m ice depth to marine isotopic substage 11.24 of Bassinot et al. (1994), who had refined the earlier SPECMAP time scale of Imbrie et al. (1984). This choice linked the first major shift of climatic proxy signals in Vostok ice from full-interglacial (substage 11.3) values to partly glacial (substage 11.24) values with the equivalent transition in marine δ¹⁸O records.

The Petit et al. (1999) choice was later verified by two independent methods. Shackleton (2000) tuned the Vostok δ¹⁸O atm record to northern hemisphere autumn (early September) insolation, and Bender (2002) correlated O²/N² variations in Vostok ice to changes in summer (December 21) insolation at 78°S. These time scales confirmed that the interval of Vostok ice showing the first major shift of proxy signals away from full interglacial values dates from 400,000 to 390,000 years ago, the interval that includes the closest insolation analog to the late Holocene and the near future (Fig. 3).

The time scale used to plot the Vostok records in Fig. 4 uses two minor refinements of these time scales based on separating the proxy climatic signals in Vostok ice into ‘early’ and ‘late’ responders. A key early responder is atmospheric methane, which varies in phase with July insolation at the precession cycle, as shown by the ~10,500-year age of the last CH₄ maximum in annually layered GRIP ice (Blunier et al., 1995). This July phasing was used to tune the CH₄ time scale at Vostok back to 340,000 years ago by Ruddiman and Raymo (2003). Using this same rationale, the prominent early methane minimum during Stage 11 in Vostok ice falls at 397,000 years ago, the age of a significant precession insolation minimum. Other proxies like CO₂ and δD that have long been considered early responders (Lorius et al., 1985; Jouzel et al., 1987; Waelbroeck et al., 1995) also reach minimum values at or near the level of this CH₄ minimum.

The classic ‘late responder’ in the climate system is northern hemisphere ice volume, which lags ~5000 years behind northern hemisphere summer insolation (Milankovitch, 1941; Hays et al., 1976; Imbrie et al., 1984). The proxy in Antarctic ice cores tied most closely to northern hemisphere ice volume is δ¹⁸O atm, which records changes in average seawater δ¹⁸O (a measure of ice volume) and in monsoon-driven biomass (Bender et al., 1994). During climatic transitions, the slow ice-volume component embedded in the δ¹⁸O atm signal should cause it to lag behind the faster-responding parts of the climate system. The transition from the substage 11.3 interglacial peak into substage 11.24 at Vostok (Petit et al., 1999) shows the expected lag: maximum δ¹⁸O atm values are reached a few 1000 years later than minima in CH₄, CO₂ and δD.
Bassinot et al. (1994) dated the substage 11.24 $\delta^{18}$O maximum to 390,000 years ago, consistent with the SPECMAP time scale (Imbrie et al., 1984). Petit et al. (1999) then used this age estimate to anchor the GT4 time scale for Vostok ice. Later studies have suggested that the SPECMAP time scale is too old by an average of 1500–2000 years (Pisias et al., 1990; Shackleton, 2000; Ruddiman and Raymo, 2003). Allowing for this adjustment, the likely age of the substage 11.24 feature is probably nearer 392,000 years.

Based on the above considerations, the time scale used to create Fig. 4 places the Stage 11 CH$_4$ minimum at 397,000 years ago and the $\delta^{18}$O$_{atm}$ maximum at 392,000 years ago. Ages are linearly interpolated between these levels, and ages older than 397,000 years ago are derived by aligning the lowermost region of high CH$_4$ values at Vostok with the precession insolation maximum 408,000 years ago, using the method of Ruddiman and Raymo (2003). For the key interval between 400,000 and 392,000 years ago, these various time scales disagree by no more than a few thousand years.

The greenhouse-gas concentrations at 397,000 years ago, the time of the closest insolation analog to modern levels, confirm the predictions of the early anthropogenic hypothesis from Fig. 1: CH$_4$ values fell to ~445 ppb (Fig. 4a), just below the predicted value of 450 ppb, and CO$_2$ values fell to ~250 ppm (Fig. 4b), just above the predicted range of 240–245 ppm. Compared to the measured concentrations actually reached prior to the industrial era (~282 ppm for CO$_2$ and ~680 ppb for CH$_4$), the Stage 11 values indicate that late-Holocene concentrations were anomalously high by more than 30 ppm for CO$_2$ and ~235 ppb for methane, close to the size of the anomalies predicted by the hypothesis.

Other proxy climatic signals in Vostok ice record major shifts toward glacial conditions at high southern latitudes. The $\delta D$ signal decreased from typically interglacial values to ~75% of full-glacial values, and estimates of Antarctic temperature derived from the $\delta D$ signal dropped to near-glacial levels (Fig. 4c). In addition, the Na$^+$ (sea-salt ion) concentration increased halfway from interglacial to glacial levels (Petit et al., 1999). These observations indicate that shortly after 400,000 years ago the Antarctic region had shifted toward a cold glacial state in an insolation regime similar to that today and at greenhouse-gas levels very close to those that should prevail today in the absence of anthropogenic overprints.

In contrast, the Holocene $\delta D$ (and Na$^+$) signals at Vostok drifted only slightly toward glacial values (Fig. 4c). The failure of these proxies to shift farther toward glacial values during the Holocene suggests that today’s Antarctic climate is anomalously warm compared to the natural trends observed during the most analogous part of Stage 11.

The $\delta^{18}$O trend in air from Vostok ice can be used to test the prediction that a late-Holocene glacial cycle is overdue in the northern hemisphere (Fig. 2). As noted earlier, the $\delta^{18}$O$_{atm}$ signal in ice is controlled both by sea-water $\delta^{18}$O (~ice volume) and biomass changes linked to tropical monsoons (Bender et al., 1994). The average glacial-interglacial amplitude of the $\delta^{18}$O$_{atm}$ signal for the last several climatic cycles at Vostok is ~1.5‰. An estimated 1.05‰ of the 1.5‰ change at the Stage 2/1 deglaciation can be attributed to changes in global ice volume (Duplessy et al., 2002; Schrag et al., 2002), leaving the remaining 0.45‰ as a monsoon-related biomass contribution. Between substages 11.3 and 11.24, $\delta^{18}$O$_{atm}$ values increased by 0.65‰ (Fig. 4d). Subtracting the (estimated maximum) biomass component of 0.45‰ from 0.65‰ leaves a residual $\delta^{18}$O$_{atm}$ increase of 0.2% that can plausibly be attributed to ice growth. This result suggests that new ice was growing in the northern hemisphere during and after the closest Stage 11 analog to the late Holocene. If the Dole effect were assumed to have been at less than maximum strength during the substage 11.3/11.24 transition, a larger ice-volume residual would be required.

3. Comparison of Stages 11 and 1: EDC ice

EPICA Community Members (2004) published preliminary results from the EDC ice core extending back ~740,000 years. The $\delta D$ and dust-concentration analyses span all of Stage 11, while the published CO$_2$ and CH$_4$ analyses cover only the Stage 12/11 transition and the early part of Stage 11. The EPICA group concluded that warmer interglacial temperatures in Antarctica during Stage 11 lasted for 28,000 years. Because only 12,000 years of similar interglacial conditions have elapsed in Stage 1, they concluded that the current interglacial warmth will persist for 16,000 years more, in disagreement with the overdue-glaciation hypothesis.

On the other hand, the major drop in $\delta D$ values in the EDC record that marks the end of this interval of Antarctic warmth began before 400,000 years ago and was nearly complete by 390,000 years ago, a timing that is close to that observed at Vostok (Fig. 4c), given the considerable dating uncertainties at EDC. As a result, the EDC $\delta D$ record supports the evidence in Section 2 that peak interglacial warmth had ended by 397,000 years ago, the time of the closest insolation analog to the present day.

Both of these predictions obviously cannot be correct. Does the current interglaciation still have 16,000 years left to run, or should it have ended during the last few millennia?

The resolution of this dilemma lies in the alignment used by EPICA to compare Stages 11 and 1. Their choice (Fig. 5 of their paper) places the present-day $\delta D$
value opposite the Stage-11 δD value at 409,000 years ago, but that selection results in the alignment of the modern-day 65°N insolation minimum with a Stage 11 insolation maximum 409,000 years ago.

This error on EPICA’s part resulted from their decision to align terminations V and I and to assume that the two interglaciations then developed in complete parallel (Fig. 6, top). This approach carries considerable risk. The timing of terminations is thought to be critically dependent on the close alignment of insolation maxima from both precession (which dominates the 65°N insolation signal) and from obliquity (Imbrie et al., 1992; Raymo, 1997). Termination I, centered at 13,000 years ago, resulted from the nearly coincident insolation maxima for precession (11,000 years ago) and obliquity (10,000 years ago).

In contrast, for the interval near termination V, the insolation maximum from the obliquity signal fell at 418,000 years ago, midway between insolation maxima from the June 21 precession signal at 429,000 and 408,000 years ago. SPECMAP (Imbrie et al., 1984) placed marine δ18O termination V at 415,000 years ago near the obliquity insolation maximum, a choice that still remains uncertain. Because the relative forcing from obliquity and precession were so different on these two terminations, aligning the two interglacial stages at the terminations is risky. EPICA’s attempt to do so produced the implausible misalignment of insolation trends shown in Fig. 5.

The correct alignment of Stage 1 against the latter (rather than the earlier) part of Stage 11 (Fig. 6, bottom) allows for an unusually long (>20,000 year) interval of warmth in Antarctica during Stage 11, but at the same time allows that warmth to come to an end during the time that was the closest insolation analog to the present day. This alignment supports the hypothesis that the Stage 1 peak of interglacial warmth in Antarctica should now be over, with a major cooling well underway. For the rest of this paper, the prominent cooling at the substage 11.3/11.24 transition is used as the boundary between peak-interglacial conditions in ‘early’ Stage 11 and the ‘late’ portion of Stage 11 that lasted until the Stage 11/10 transition near 352,000 years ago (Imbrie et al., 1984).

4. Comparison of Stages 11 and 1: marine sediments

The conclusion from the δ18Oam evidence at Vostok that new ice sheets began growing at the substage 11.3/11.24 transition is at odds with the interpretation that Stage 11 was a uniquely long interglaciation in which no new ice grew in North America and Eurasia (Burckle, 1993). In apparent support of this interpretation, a high-resolution study of Stage 11 in the subpolar North Atlantic showed that the ocean surface remained warm for at least 30,000 years after termination V (McManus et al., 2003). However, closer scrutiny shows that ice was not absent from North America and Eurasia for this entire interval. McManus et al. (2003) actually stated that that the “relatively ice-free portion” of Stage 11 “lasted longer than other peak interglacials”. This careful wording permits a relatively early onset of new ice in Stage 11.

Another problem with the interpretation of a long ice-free interglaciation is that North Atlantic sea-surface temperatures cannot be used as a sensitive indicator of northern hemisphere ice volume. Lagging warmth (and
the absence of ice-rafted debris) often characterized the North Atlantic south of Iceland during intervals when ice sheets were growing on nearby landmasses (Ruddiman and McIntyre, 1979). During isotopic substage 5a, the subpolar North Atlantic was at or close to full-interglacial warmth (Sancetta et al., 1972), even though sea level was 15–20 m below its modern position (Chapell and Shackleton, 1986; Bard et al., 1990). The volume of ice required to drop sea level by 15–20 m was equivalent to the glacial-maximum Scandinavian ice volume of ice required to drop sea level by 15–20 m.

Several marine proxies further support the Vostok δ18Oatm evidence that new ice appeared on land during the substage 11.3/11.24 transition. One line of evidence comes from marine δ18O signals, which record changes in ice volume and variations in local ocean temperature and salinity. The maximum size of the temperature–salinity (T–S) overprint at any location can be estimated from changes that occurred during the most recent deglaciation. As noted earlier, the ice-volume contribution to the δ18O shift across termination I is estimated at 1.05%o (Duplessy et al., 2002; Schrag et al., 2002). Any additional isotopic change on termination I beyond this amount can be attributed to the combined effects of local temperature and salinity, and this ‘excess’ δ18O change on termination I can be used to estimate the maximum T–S overprint present elsewhere in the record, including isotopic Stage 11. The tacit assumption in this method is that the temperature–salinity overprint added to the δ18O signal in Stage 11 is unlikely to have been larger than the amount removed during a full deglacial transition.

Marine cores in the equatorial Atlantic (Tiedemann et al., 1994, Bickert et al., 1997) and tropical Indian Ocean (Bassinot et al., 1994) record δ18O increases as large as 1.0%o during the substage 11.3/11.24 transition. Because δ18O shifts during the last deglaciation in these regions were also very large (~2%o), indicating T–S overprints of about 1%o, it is just barely possible to avoid a requirement for ice growth by invoking the maximum T–S overprint. Observed δ18O changes in the eastern tropical Pacific do, however, require ice growth (Table 1). Benthic foraminiferal δ18O signals from ODP sites 846 and 849 (Mix et al., 1995a, b) register a δ18O change of 1.61% from Stage 2 to Stage 1, implying a maximum T–S overprint of 0.56 ± 0.1%o. During the transition into substage 11.24, δ18O values increased by 0.72–0.74%o. Subtracting the maximum T/S overprint of 0.56%o leaves a residual of 0.16–0.18%o as the estimated ice-volume effect. This independent estimate is close to the 0.2%o ice-volume residual estimated from the δ18Oatm trend at Vostok. If each 0.1%o change in δ18O represents ~11 m of sea-level change, the growth of ice during substage 11.24 would have amounted to ~20 m of sea-level fall.

This amount of ice growth would have accumulated by the substage 11.24 peak at ~392,000 years ago, a time equivalent to roughly 5000 years from now according to the insolation trends in Fig. 3. More pertinent to the early anthropogenic hypothesis is the question of whether or not ice was already growing 397,000 years ago, the time when the insolation configuration was most analogous to the present day. Several lines of evidence indicate that it was.

First, the δ18Oatm trend at Vostok had already increased by more than 0.55%o by the time of the minima in CH4, CO2, and δD ~397,000 years ago (Fig. 4). At least 0.10%o of this δ18Oatm increase (the amount in excess of the assumed 0.45%o biomass overprint) should represent increased ice volume. Second, Bauch et al. (2000) dated the renewal of ice-rafted deposition in Nordic Sea sediments to 398,000 years ago. In order to calve icebergs to the ocean by that time, ice growth must have been underway in the north for several 1000 years. Third, a sensitivity-test experiment with the GENESIS 2 climate model showed that lowering greenhouse-gas concentrations to the levels reached during the Stage 11 insolation analog to the present day resulted in year-round snow cover in parts of Baffin Island, Canada (Ruddiman et al., 2005). Finally, it seems unlikely that 20 m of sea-level-equivalent ice volume could have accumulated by 392,000 years ago without any of the ice having grown by 397,000 years ago.

In summary, marine evidence requires the growth of ice sheets equivalent to ~20 m of sea level drop by

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### Table 1

<table>
<thead>
<tr>
<th>ODP site</th>
<th>Measured δ18O increase</th>
<th>Max. T–S contribution</th>
<th>Measured δ18O increase</th>
<th>Minimum ice contribution</th>
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<td>0.56</td>
<td>0.74</td>
<td>0.18 ± 0.1</td>
</tr>
</tbody>
</table>

aAssumed ice-volume contribution of 1.05%o (Duplessy et al., 2002; Schrag et al., 2002).

bMix et al. (1995a).

cMix et al. (1995b).
substage 11.24 (~392,000 years ago). The evidence further indicates that some of this ice was growing by 397,000 years ago, the closest insolation analog to the present day.

5. Comparison of Stages 11 and 1: ice-volume simulations

During the current July 65°N insolation minimum, solar radiation values lie 2/3 of the way toward the glacial extreme of the orbital range over the last several hundred thousand years, yet no new ice has appeared in response to this forcing. McManus et al. (2003) termed this absence of new ice a ‘skipped beat’ in orbital forcing of ice volume.

This ‘skipped beat’ creates a dilemma for modeling efforts that attempt to simulate ice-sheet growth and decay in response to orbital forcing. The dilemma is that 65°N summer insolation will not fall as low as it is now for the next 55,000 years (Fig. 7a). With no ice today, and with higher summer insolation levels far into the future, there seems to be no reason to expect ice to grow for a very long time. Some simulations with time-dependent ice-sheet models project no ice growth for that entire interval (Loutre and Berger, 2000; Berger and Loutre, 2003). Added to the 6000 years of the Holocene without significant ice on North America and Eurasia, the current interglaciation would then last more than 60,000 years.

But a 60,000-year interglaciation would be without precedent in all 2.75 million years of the northern hemisphere ice age. Even during the smaller ice-volume fluctuations between 2.75 and 0.9 million years ago, ice sheets grew and melted mainly at a 41,000-year cycle, with only about 20,000 years between glaciations. During the 100,000-year cycles of the last 0.9 million years, ice sheets have been present in the northern hemisphere for ~90% of the time, with interglaciations lasting an average of just 10,000 years (Shackleton, 1987). No interglaciation has ever lasted 60,000 years, and no obvious reason exists to think that the natural climate system has just entered such an unprecedented ice-free era.

Stage 11 points the way to an answer to this dilemma. Insolation trends late in Stage 11 were very similar to those during the Holocene and the future (Fig. 7a). Not surprisingly, the same model simulations of Berger and Loutre (2003) that produced no ice growth late in Stage 1 and for 55,000 years into the future also simulated no ice-sheet growth until the Stage 11/10 boundary near 350,000 years ago (Fig. 7b). Yet the evidence from changes in Vostok δ18O atm (Section 2) and in marine δ18O and Nordic Sea ice rafting (Section 4) indicates that new ice was already growing before 392,000 years ago, in disagreement with the simulation shown in Fig. 7b.

On the other hand, ice-volume simulations that include CO2 forcing based on the Vostok ice record have been able to match the evidence for ice growth earlier in Stage 11, thus avoiding an unrealistically long ice-free interval (Berger and Loutre, 2003). These results, combined with evidence in Sections 2 and 4, suggest a solution to the dilemma of the long ice-free Holocene and future. If the large anthropogenic overprints of CO2 and CH4 during the late Holocene were removed, thereby allowing natural gas concentrations to fall to levels like those early in Stage 11, the resulting model simulations should produce results similar to Stage 11, with early growth of ice and no implausibly long ice-free interval.

This nucleus of late-Holocene ice would be important to the progression of the next (current) glacial cycle. Growing ice sheets create positive feedbacks that favor additional glaciation, including albedo-temperature feedback, elevation-temperature feedback, orographic precipitation along south-facing slopes, and slow radial ice flow across unglaciated terrain (Andrews and Mahaffy, 1976). After ice first appeared during the transition into substage 11.24, ice growth appears to
have been nearly continuous for the rest of Stage 11 and all of Stage 10, in part because of ice feedbacks on the climate system. The same process would presumably be underway now if natural forcing had prevailed.

6. Discussion

Comparison of late-Holocene climatic trends with those during the closest Stage 11 insolation analog supports the major predictions of the early anthropogenic hypothesis: CH₄ and CO₂ levels dropped to levels close to those predicted (Fig. 4a and b); the early responding Southern Hemisphere cooled dramatically (Fig. 4c); and ice sheets began to grow in the northern hemisphere (Fig. 4d). In contrast, during the middle and late Holocene, gas concentrations rose, south-polar climate cooled only slightly, and northern ice sheets did not grow.

The cause of these very different Holocene trends is not likely to lie in natural factors. Not only were insolation trends similar during the two intervals (Fig. 3), but key terrestrial boundary conditions early in Stage 11 were nearly identical to those in the Holocene: northern ice sheets had melted, sea level was high, and vegetation had reached a full-interglacial state. Any differences in insolation and in terrestrial boundary conditions seem too small to account for the fundamentally different direction of the Holocene trends. If natural forcing can be ruled out, the anomalous Holocene gas increases have to be anthropogenic in origin.

This conclusion is seemingly at odds with the analysis of Joos et al. (2004), who concluded that direct anthropogenic emissions of CO₂ from forest clearance are insufficient to explain the proposed 40-ppm anthropogenic CO₂ anomaly. They estimated that 550–700 Gt C of direct CO₂ emissions from forest burning would be needed to explain a 40-ppm anomaly, well above the 250–320 GtC calculated by Ruddiman (2003a) based on Indermuhle et al. (1999), and even further above their own estimate of 60–80 Gt C based on DeFries et al. (1999). Joos et al. (2004) also noted that the small amplitude of the negative δ¹³C trend in late-Holocene CO₂ found by Indermühle et al. (1999) appears to limit terrestrial carbon emissions to amounts smaller than those needed to account for a 40-ppm CO₂ anomaly. These estimates of Gt C emissions are all based on carbon-cycle models that include both fast exchanges among surface carbon reservoirs as well as the slow uptake of CO₂ by the deep ocean and subsequent dissolution of seafloor CaCO₃.

These findings seem irreconcilable. How can the Holocene CO₂ anomaly be entirely anthropogenic in origin if direct anthropogenic carbon emissions from humans are too small to account for it? The resolution to this impasse may lie in processes that contribute to the size of the CO₂ anomaly without requiring direct emissions of CO₂.

Ruddiman (2003a) defined the Holocene anthropogenic CO₂ anomaly as the difference between the observed CO₂ rise and the predicted CO₂ fall (Fig. 1b). The predicted drop in CO₂ was based on natural trends measured during the early parts of previous interglaciations, when concentrations fell by 30–50 ppm (Petit et al., 1999). The Stage 11 trend shown in Fig. 4b shows a natural drop from ~282 to ~250 ppm.

Implicit in this definition of the Holocene CO₂ anomaly are two distinct components: (1) direct anthropogenic carbon emissions that caused CO₂ values to rise, and (2) natural factors that prevented CO₂ values from falling as they had in previous interglaciations. The resolution of the impasse noted above could lie in the second group of mechanisms. If the natural processes that drove CO₂ lower during previous interglaciations were overridden during the Holocene, the prevention of a natural drop in CO₂ would have added to the size of the CO₂ anomaly, but would not have required direct emissions of carbon. Such an explanation would be consistent with the claim that the entire CO₂ anomaly is anthropogenic in origin, yet it would not violate the carbon-budget and δ¹³C constraints.

In the concept proposed here (Fig. 8), direct emissions from human activities account for most of the 250-ppb CH₄ anomaly (Ruddiman and Thomson, 2001), although the magnitudes are difficult to quantify. In the case of CO₂, direct emissions only account for a fraction of the estimated anomaly of 32–40 ppm. The part of the Holocene CO₂ anomaly that obviously requires direct anthropogenic emissions is the 14-ppm increase between the natural CO₂ peak of ~268 ppm that occurred 10,500 years ago and the ~282 ppm value reached just before the industrial era (Fig. 1b). For a full anthropogenic anomaly of 32–40 ppm, the 14-ppm increase from direct emissions would then represent 35–45% of the total anomaly.
These direct emissions of CH$_4$ and CO$_2$ would have produced an anomalous (anthropogenic) warming effect that prevented Holocene climate from following the major cooling trend that had occurred during previous interglaciations, including early Stage 11. Suppression of this natural cooling would have stifled the natural internal responses that would have driven CO$_2$ values still lower and added to the size of the anthropogenic CO$_2$ anomaly (Fig. 8).

Two climate-system responses that could have produced a natural CO$_2$ drop are evident in the Vostok trends from early in Stage 11 (Fig. 4). Stephens and Keeling (2000) proposed that advances of Antarctic sea ice are a plausible mechanism for driving down atmospheric CO$_2$ values by reducing carbon exchanges between Southern Ocean surface water and the atmosphere. The deuterium-based temperature trends in the Antarctic show a major cooling to near-glacial levels early in Stage 11, but little cooling during the Holocene (Fig. 4c). A cooling to near-glacial levels during Stage 11 must have caused a major advance of sea ice in the Southern Ocean, but any Holocene advance has been far smaller. If anthropogenic emissions averted most of the natural Holocene sea-ice advance, the natural reduction in atmospheric CO$_2$ from this process must have been largely overridden. This interpretation fits a long history of Southern Ocean studies. The southern hemisphere ocean has been regarded as a locus of early responses to orbital forcing since the work of Hays et al. (1976), as well as later studies (CLIMAP, 1984; Waelbroeck et al., 1995; Brathauer and Abelmann, 1999). Antarctic temperatures reconstructed from deuterium signals are also regarded as a part of this early response (Jouzel et al., 1987; Waelbroeck et al., 1995).

A different mechanism may have been at work in the Northern Hemisphere on the slower time scale of response of northern ice sheets. Imbrie et al. (1992) suggested that one of many ways in which ice sheets enhance their own growth is by reducing the CO$_2$ content of the atmosphere. Ruddiman (2003b) found that the phases of the 41,000-year component of the Vostok CO$_2$ signal and the 41,000-year component of $\delta^{18}$O agree, indicating that the CO$_2$ signal at the obliquity cycle is a fast feedback on ice volume, rather than a driver. Plausible mechanisms by which ice sheets might alter CO$_2$ include: (1) control of North Atlantic Deep Water flow and its ‘fast-alkalinity’ response (Broecker and Peng, 1989); and (2) control of eolian dust fluxes that fertilize planktic algae (Martin, 1990). Because proxies for deep-water circulation (Raymo et al., 1990) and dust fluxes (Clemens and Prell, 1990; Kuila et al., 1990) have phases close to the 41,000-year $\delta^{18}$O (ice-volume) signal, they are potential mechanisms for explaining positive CO$_2$ feedback to ice sheets. If ice grew early in Stage 11, but was prevented from doing so in the Holocene (Fig. 4d), its failure to appear in recent millennia would have eliminated any ice-driven CO$_2$ decrease.

If these two mechanisms prevented Holocene CO$_2$ levels from falling as they did in the analogous part of Stage 11, the result would have been an indirect anthropogenic contribution to the size of the Holocene CO$_2$ anomaly (Fig. 8). Assuming that direct CO$_2$ emissions explain ~14 ppm out of a total anomaly of 32–40 ppm, this indirect contribution would then be 18–26 ppm. Given that CO$_2$ values fell by 30–50 ppm for entirely natural reasons during similar intervals in the four previous interglaciations, an indirect effect of 18–26 ppm seems plausible. Based on model results from Joos et al. (2004), a 14-ppm anomaly would require slightly less than 200 Gt C of direct emissions, a value midway between the estimates of Ruddiman (2003a) and Joos et al. (2004).

In summary, the use of Stage 11 as an analog for the natural behavior of the climate system during the Holocene supports the major predictions of the early anthropogenic hypothesis. During the last several millennia, CO$_2$ and CH$_4$ levels should have fallen, climate should have cooled, and ice sheets should have begun to grow. The failure of these changes to occur is best explained by early anthropogenic intervention in the operation of the global climate system. This intervention included both direct greenhouse-gas emissions from human activities and indirect climate-system feedbacks that resulted from the direct emissions.

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References


Bender, M., Sowers, T., Labeyrie, L., 1994. The Dole effect and its variations during the last 130,000 years as measured in the Vostok ice core. Global Biogeochemical Cycles 8, 363–376.


composition of seawater during the last glacial maximum. Quaternary Science Reviews 21, 331–342.