IMPLICATIONS OF THE SECONDARY ROLE OF CARBON DIOXIDE AND METHANE FORCING IN CLIMATE CHANGE: PAST, PRESENT, AND FUTURE

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Abstract: A review of the recent refereed literature fails to confirm quantitatively that carbon dioxide (CO_2) radiative forcing was the prime mover in the changes in temperature, ice-sheet volume, and related climatic variables in the glacial and interglacial episodes of the past 650,000 years, even under the "fast-response" framework where the convenient if artificial distinction between forcing and feedback is assumed. Atmospheric CO_2 variations generally follow changes in temperature and other climatic variables rather than preceding them. Likewise, there is no confirmation of the often-posited significant supporting role of methane (CH_4) forcing, which—despite its faster atmospheric response time—is simply too small, amounting to less than 0.2 W/m^2 from a change of 400 ppb. We cannot quantitatively validate the numerous qualitative suggestions that the CO_2 and CH_4 forcings that occurred in response to Milankovic orbital cycles accounted for more than half of the amplitude of the changes in the glacial/interglacial cycles of global temperature, sea level, and ice volume. Consequently, we infer that natural climatic variability—notably the persistence of insolation forcing at key seasons and geographical locations, taken with closely related thermal, hydrological, and cryospheric changes (such as the water vapor, cloud, and ice albedo feedbacks)— suffices *in se* to explain the proxy-derived, global and regional climatic and environmental phase-transitions in the paleoclimate. If so, it may be appropriate to place anthropogenic greenhouse gas emissions in context by separating their medium-term climatic impacts from those of a host of natural forcings and feedbacks that may, as in paleoclimatological times, prove equally significant. [Key words: glacial–interglacial cycles; water vapor, cloud-and-ice insulator, and albedo feedback; Milankovic orbital insulation forcing; atmospheric CO_2 and CH_4 forcing.]

INTRODUCTION

This paper addresses four issues that are fundamental to the debate concerning the role of CO_2 and CH_4 greenhouse gases in the forcing of past glacial–interglacial cycles and the role of such forcing for present and future considerations of climate change. These issues are addressed under four headings: (1) the relationship between atmospheric CO_2 and CH_4 concentrations, temperature, and ice-sheet volume; (2) atmospheric CO_2 radiative forcing as an amplifier of glacial–interglacial climate change; (3) glacial–interglacial climate change, involving a comparison of the role of orbitally moderated insolation forcing at local and regional scales with the effects of global radiative forcing from changing CO_2 concentrations; and (4) problems with CO_2 amplification of global mean temperature, especially the paucity of support provided by computer simulations and several general circulation models. These issues are addressed with reference to a wide range of recent and ongoing

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research, both for and against the primary role of greenhouse gases in climate change scenarios. In conclusion, the paper stresses that changes in insolation in climatically sensitive zones exceed several-fold the global radiative forcing of climate change by CO_2 and CH_4, and that local and regional responses to insolation forcing decide the primary climatic feedbacks and changes observed from past glacial–interglacial cycles, and likely to be observed in the future.

RELATIONSHIPS BETWEEN ATMOSPHERIC CO_2 AND CH_4 CONCENTRATIONS, TEMPERATURE, AND ICE-SHEET VOLUME

One of the most notable, but somewhat surprising, consensus conclusions from ice-core drilling projects and research in Arctic and Antarctic regions (e.g., Fischer et al., 2006; Masson-Delmotte et al., 2006) is the fact that the deduced isotopic temperatures lead other climatic responses, including especially the atmospheric levels of minor greenhouse gases like CO_2 and CH_4. Fischer et al. (1999) first reported that atmospheric CO_2 concentrations increased by 80 to 100 ppm some 600± 400 years *after* the warming of the last three deglaciations (or glacial terminations) in Antarctica and that relatively high CO_2 levels were sustained for thousand of years during glacial inception scenarios when Antarctic temperature had dropped significantly. Later, Monnin et al. (2001) and Caillon et al. (2003) offered clear evidence that temperature change drove atmospheric CO_2 responses during more accurately dated periods near glacial terminations I (at about 18 kyr before present, BP) and III (at about 240 kyr BP), respectively.

Stenni et al. (2001) presented evidence that the rising tendency of atmospheric CO_2 can be interrupted by abrupt events like the Antarctic Cold Reversal and related Oceanic Cold Reversal starting around 14 kyr BP, so that factors like the changes in the southern ocean, high-latitude atmospheric circulation, and dust transport can quickly trigger responses in global carbon cycling. Figure 1 offers a graphic summary of the apparent consensus on atmospheric CO_2 content being driven by change in temperature using the Vostok data first published by Petit et al. (1999). The latest 650 kyr-long record from the EPICA Dome Concordia effort, reported by Siegenthaler et al. (2005), remarkably confirmed the CO_2-temperature lag relation over terminations V, VI, and VII, covering the period from 400 to 650 kyr BP. The analyses by Delmotte et al. (2004) also confirmed that atmospheric CH_4 systematically lags the proxy for Antarctic temperatures by 1100±200 years, adopting the long time scale windows of 50 to 400 kyr for the lead-lag analyses.

Additionally, there are new and innovative analyses of both high-resolution ice and gas data from Antarctica and Greenland (Ahn and Brook, 2007; Loulergue et al., 2007; Kobashi et al., 2007) that are able to better time the complicated relation of atmospheric CO_2 and CH_4 with local and regional temperatures at both locations for specific abrupt warming and cooling events like the Dansgaard-Oeschger warming, Heinrich iceberg rafting, or even the 8.2 kyr cooling events in Greenland. Ultimately, certain local and regional climatic variations and changes must be responsible for driving the responses of the global carbon budget cycles—otherwise, some extra-terrestrial factors and/or extraordinary scenarios would need to be invoked to explain the trigger and maintainence of the atmospheric CO_2 and

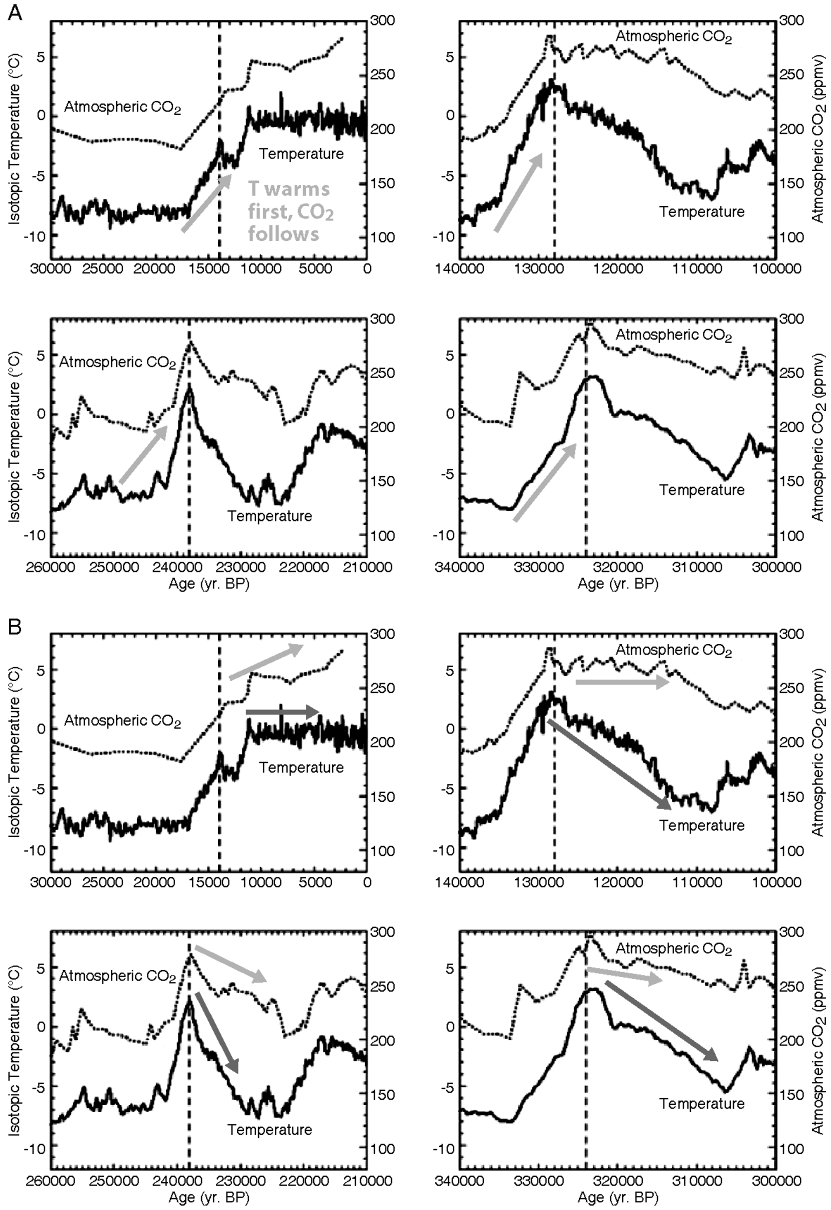

Fig. 1. Vostok temperature and atmospheric CO_2 history for the past 420 kyr, from Petit et al. (1999), showing that Antarctic warming tends to lead the rise in CO_2 concentrations by several hundred years during the last four deglaciations (upper panel), and that relatively high CO_2 levels can be sustained for thousands of years during glacial inception scenarios when the temperature has dropped significantly (lower panel; see also Fischer et al., 1999). Cuffey and Vimeux (2001) and Vimeux et al. (2002) showed that the co-variation of the Vostok atmospheric CO_2 and isotopic temperature, once corrected for effects from changes in moisture source for the temperature, came to much closer timing agreement for the last 150 kyr BP, but as discussed under heading (1), the atmospheric CO_2 content must still somehow be controlled by other local and regional climatic variables.

CH_4 variations every 100 kyr or so for the past 650 kyr. Such a picture is not inconsistent with the recent comprehensive review by Peacock et al. (2006) that manages to specify a combination of distinct climatic, oceanic, and biochemical processes that could explain the co-variation of atmospheric CO_2 during a 100 kyr glacial–interglacial transition.

Synthesis studies by Shackleton (2000), Mudelsee (2001), Pepin et al. (2001), and Ruddiman and Raymo (2003) pointed out that both Antarctic temperatures and atmospheric CO_2 concentrations significantly lead the changes in the large ice sheets of the Northern Hemisphere by at least a few thousand years to as long as 14 kyr over the full 420 kyr of the Vostok record. The scenario that seems most reasonable is that external orbital insolation forcing triggered the fast and large changes in the air temperature in the Antarctic/Southern Hemisphere which, in turn, caused responses in deep-ocean properties (including changes in both the temperature and the volume of southern-sourced deep-water filling the ocean basins; Skinner, 2006) and in the global carbon cycle leading to the changing levels of atmospheric CO_2, which ultimately acted as an amplifier for glacial–interglacial ice-volume variability. Several recent pollen, glacial, and reflectance (i.e., natural gamma rays) records from the mid-latitude Southern Hemisphere clearly support such a scenario, with insolation changes in the Southern Hemisphere occurring first and then followed by related thermal, chemical, hydrologic, and cryospheric responses (Carter and Gammon, 2004; Suggate and Almond, 2005; Vandergoes et al., 2005; Sutherland et al., 2007).

Alley et al. (2002) and Johnston and Alley (2006) offered a different scenario by emphasizing a Northern Hemisphere thermal lead or trigger (see also the new evidence and discussion for the past 360 kyr in Kawamura et al., 2007), instead of a southern-lead scenario, for the consequential chains of variations in solar insolation, air and sea temperatures, CO_2, and global ice volume (mainly of the bulk continental ice sheet in the Northern Hemisphere), but this alternate picture clearly also proposes atmospheric CO_2 as the essential amplifier of the warming and cooling and hence the waxing and waning of global ice volume.

ATMOSPHERIC CO_2 RADIATIVE FORCING AS AN AMPLIFIER OF GLACIAL–INTERGLACIAL CLIMATE CHANGE

It is still unclear as to whether such a plausible CO_2-amplification scenario can be quantitatively confirmed with evidence available to date. The very long lead time by the radiative forcing of atmospheric CO_2 requires better clarification through physical modeling to account for the full dynamics of: (1) the great continental ice sheets—that is, those that can be sustained for 10 kyr in the phase of maximum ice extent, as deduced for the Laurentide Ice Sheet during the Last Glacial Maximum (LGM; Dyke et al., 2002), or for the extension of the ice sheet over the Barents and Kara Seas into the Eurasian continent (Svendsen et al., 1999); and (2) the ice conditions around the Arctic Ocean (Norgaard-Pedersen et al., 2003; Martinson and Pitmann, 2007) and their interactions with the coupled dynamics of the ocean and atmosphere, especially in the tropics (e.g., Ashkenazy and Tziperman, 2006; Roe, 2006).

It is also difficult to presume any significant amplifying role by atmospheric CO_2 for the extremely large winter cooling of 28ºC over the Greenland–Arctic–North Atlantic area during the Younger Dryas event recently hypothesized by Broecker (2006). Similarly Barrows et al. (2007) noted several periods of rapid SST changes in their southern mid-latitude records around 58–38 kyr BP (i.e., Oxygen Isotope Chronozone or Marine Isotope Stage, MIS, 3) and 19.5–18.5 kyr BP (i.e., where a rapid warming of 5ºC in 130 years was recorded at 19.4 kyr BP and a similarly large and rapid cooling starting around 19.2 kyr BP) that are simply difficult to explain by atmospheric CO_2 forcing.

More importantly, Roe (2006) showed that, if one adopts the rate of change of global ice volume rather than the absolute ice volume as a physically more direct measure of ice-sheet dynamics and its thermal connections to summertime temperature and local summertime insolation radiation, the sketched scenario of changing CO_2 leading the change in the global ice volume or ice sheet may not be correct. Instead, careful analyses by Roe found that atmospheric CO_2 actually lags the rate of global ice-volume change by a few thousand years, or CO_2 is at most synchronous with the rate of change in global ice volume. Roe concluded that ". . . variations in melting precede variations in CO_2. . . . This implies only a secondary role for CO_2 . . . variations [which] produce a weaker radiative forcing than the orbitally-induced changes in summertime insolation—in driving changes in global ice volume" (pp. 1 and 4). These issues will be discussed further in the following sections.

Another important empirical consensus that has recently emerged is the fact that older estimates of no more than 1–2ºC changes in the tropical sea surface temperatures (SST) during the Last Glacial Maximum (LGM) around 21 kyr BP, or during other glacial–interglacial transition periods, may have been largely underestimated (e.g., Schrag et al., 1996; Peltier and Solheim, 2004). Lea et al. (2000) showed that the equatorial SSTs in the core area of the western Pacific warm pool, a region that could be a sensitive indicator of global carbon cycling, were 2.8º ± 0.7ºC colder at the LGM than at present. Visser et al. (2003) recently suggested that SST around the Indo-Pacific warm pool area by the Makasar Strait varied by about 3.5–4ºC during the last two glacial–interglacial transitions. Barrows and Juggins (2005) synthesized the proxy SST records from about 165 cores for oceans around Australia, including the Indian Ocean, and their compilations showed a cooling of up to 4ºC in the tropical eastern Indian Ocean and up to 7º to 9ºC in higher latitude regions of the southwest Pacific Ocean during the LGM. Three new alkenone-derived SST records from the midlatitude Southern Hemisphere, presented by Pahnke and Sachs (2006), essentially confirmed the large amplitude change in SST between glacial and interglacial transitions. The consequence of these large-amplitude SST changes in the tropics and higher latitudes has led Visser et al. (2003) to suggest that a substantial portion of the 80 ppm change in atmospheric CO_2 during a glacial–interglacial transition can be simply explained by a direct change in CO_2 solubility in sea water as a function of SST change (see Peacock et al., 2006, for additional processes involving changes in sea level, oceanic circulation, and related chemical and biological responses). Peltier and Solheim (2004) offer a quantitative estimate by explaining "more than 60%" of the observed changes in glacial–interglacial CO_2 contents from air bubbles trapped in ice cores.

There are two additional roles often assigned to CO_2 radiative forcing that highlight the remarkable sensitivity of climate-system behavior and evolution to atmospheric CO_2 (e.g., Saltzman et al., 1993). We will only summarize these briefly here.

First, there are theoretical speculations, on even longer geologic timescales, about the formation of large icesheets in both hemispheres since about 2.7 million years BP (or late Pliocene transition; e.g., overviews in Droxler and Farrell, 2000; Crowley and Berner, 2001; Lisiecki and Raymo, 2007), and about the transition from the "41 kyr world" to the "100 kyr world" (i.e., actually more like ice age cycles every 80 kyr to 120 kyr or so; Liu and Herbert, 2004; Huybers and Wunsch, 2005) starting around 780 kyr ago or in the mid-Pleistocene transition, or MPT (Berger et al., 1999; Clark et al., 2006, described the MPT as a broader transitional variability zone from 1250 kyr to 700 kyr BP). It was suggested that the two phenomena/events happened because the Earth's climate system had been undergoing gradual global cooling from a systematic decrease in atmospheric CO_2 until a dynamical air–sea–ice sheet interaction threshold was crossed. However, the evidence for an overall cooling since 780 kyr BP is not that strong, and the idea has been recently challenged by de Garidel-Thoron et al. (2005). Furthermore, non–CO_2-related explanations involving changes in basal conditions under ice sheets (Clark et al., 1999) may be significant. In addition, the MPT may simply be a dynamic system response to the continuous obliquity pacing as shown and discussed by Liu and Herbert (2004), Huybers and Wunsch (2005), and Huybers (2007). As for the explanation of the late Pliocene cooling, Ravelo et al. (2004) argued that the transition from warm early to middle Pliocene conditions to increasing glaciation in the Northern Hemisphere during the late Pliocene is linked more to nonlinear coupled dynamics of ocean and atmosphere that altered meridional heat and moisture transfers than to any persistent cooling or threshold-crossing tendency due to a decrease in atmospheric CO_2 over the past 3 million years. In two related modeling studies, Barreiro et al. (2006) and Fedorov et al. (2006) found that the physical explanation for great warmth during the early to mid-Pliocene from 5 to 3 million years BP may be connected to the reality of a permanent, rather than intermittent, El Niño condition (see, however, the challenge by Haywood et al., 2007). Such a condition would plausibly involve the collapse of trade winds along the equator, with an attendant large decrease in low-level stratus clouds, a large increase in incoming solar radiation, and an increase in atmospheric water-vapor feedback in heating up the tropical atmosphere and ocean. Huybers and Molnar (2007) recently concluded that a long-term cooling trend in the eastern tropical Pacific alone (which they clearly distinguished from explanations specifying high CO_2 in the early-to-mid-Pliocene), rather than a permanent El Nino scenario, may be sufficient for explaining increased glaciation since 3 million years BP.

The second prominent effect by CO_2 radiative forcing has been framed as follows. Two new studies have suggested that the observed variation of about 30 ppm in CO_2 concentrations during interglacial periods may have contributed significantly to the thermal and moisture instabilities that eventually drove glacial advances (Vettoretti and Peltier, 2004; Kubatzki et al., 2006). But the empirical basis for such a strong nonlinear effect of CO_2 forcing on the climate-system evolution and change is not strong considering the small amplitude of CO_2 radiative forcing (see also comments on p. 275 in Khodri et al., 2003), the CO_2-temperature lagged-response relation, and even the actual simulated results (i.e., rather small relative differences in the near-surface global temperature of no more than 0.5°C and inland ice sheet area of no more than 0.5 million km^2 over North America shown in Fig. 9 of Kubatzki et al., 2006, for two different CO_2 radiative forcing scenarios). In contrast, Bauch and Kandiano (2007) point to significant differences in surface ocean conditions during the last interglacial (~130 kyr BP) and the Holocene, while invoking significant variabilities on centennial and millennial time scales during interglacials in response to intrinsic variations in solar irradiance outputs and subsequent amplification through mechanisms like solar effects on the distribution and transport of Arctic sea ice and changes in the meridional overturning circulation of the North Atlantic, as proposed earlier by Bond et al. (2001) for the Holocene.

GLACIAL–INTERGLACIAL CLIMATE CHANGE: THE ROLE OF ORBITALLY MODERATED INSOLATION FORCING AT LOCAL AND REGIONAL SCALES COMPARED WITH THE EFFECTS OF GLOBAL RADIATIVE FORCING FROM CHANGING CO_2 CONCENTRATION

This section and the one that follows focus more narrowly on the inability to find quantitative support for the putative role of CO_2 radiative forcing in the observed glacial–interglacial cycles of global ice volume and temperatures over the past 650 kyr as dictated by the latest EPICA Dome Concordia's records of climatic variability and trace-gases history (EPICA community members, 2004; Siegenthaler et al., 2005; Spahni et al., 2005).

Soon et al. (2001, p. 261) earlier cautioned against the premature rejection of the role of changes in solar radiation (i.e., from both orbital motion–induced and intrinsic solar magnetism–caused variability) in favor of the rather simplistic, and very possibly incorrect, picture of the domination of the climate system by changes in global radiative forcing related to the man-made emission of atmospheric greenhouse gases like CO_2 and CH_4. The caution was partly related to the illustrative and yet successful modeling experiments by Posmentier (1994) that showed the nonlinear dynamical responses of ice sheets to the lone modulation in seasonality induced by solar insolation.

Figure 2 shows the sharp contrast in the amplitude of variability between global annual-mean insolation and daily summer insolation at 65°N (Laskar et al., 1993). It shows the remarkably small changes of no larger than 0.6 W/m^2 in the net global solar radiation induced by the orbital evolution of the Earth around the Sun over the past 1 million years. This estimate, however, does not account for intrinsic changes to the Sun's irradiance as modulated by solar magnetic activity; an amplitude change of a few W/m^2 over a million years cannot be ruled out. But Figure 2 confirms that large changes in summer solar insolation at a key ice-nucleation location like 65°N (Roe, 2006) are clearly much larger than the relatively small global radiative forcing by changes of CO_2 for the glacial–interglacial transitions of the past 650 kyr, estimated to be 2–3 W/m^2. From the perspective of the climatic system, local summer insolation, as long as the persistency is guaranteed by locked-in

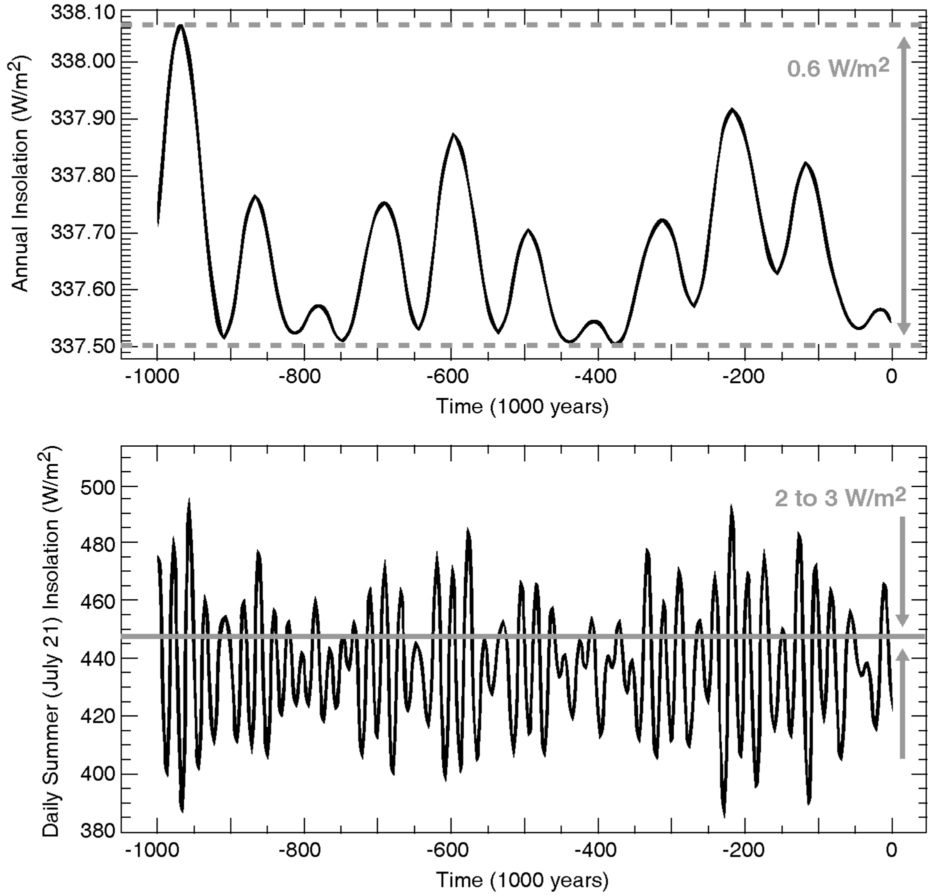

Fig. 2. Sensitivity of the Earth's climate to incoming radiation from the Sun over the past million years, based on calculations by Laskar et al. (1993), accounting (only) for geometric changes in the Sun–Earth orbit. First, the climate receives and reacts to local midsummer insolation (here taken at July 21 at 65°N: lower panel). The influence of persistent, daily, localized insolation at midsummer values is demonstrably of very much greater climatic effect, and hence more relevant in assessing the contribution of insolation to the paleoclimate, than the global annual mean insolation (upper panel) or the paleoclimatological forcing from CO_2 (of about 2 to 3 W/m^2; Joos, 2005). (For a more direct comparison of solar insolation quantity presented here to, say, the radiative forcing from atmospheric CO_2, one needs to weigh in the additional effect of reflection of sunlight by the Earth system.)

orbital motion, is a highly relevant physical quantity for studying and quantifying the local and regional responses of the thermal and hydrologic variables, and may ultimately explain the apparent global statistics of regional weather and climate. Vandergoes et al. (2005) and Sutherland et al. (2007) have emphasized the important role of local summer solar insolation forcing rather than any global annual mean measure, within the context of Southern Hemisphere–lead scenario discussed earlier. Lorenz et al. (2006) supported the key role of local and regional insolation changes and emphasized the nonlinear changes in the entire seasonal cycle of insolation for the spatial heterogeneity of Holocene climate trends. Empirical support for this view comes from the apparent dominance of the global radiative forcing of 2 W/m^2 (e.g., Joos, 2005) estimated from the 80 ppm change in atmospheric CO_2 over the glacial–interglacial cycles of the past 650 kyr, and yet no clear climatic response can be confidently or completely linked to CO_2 as discussed here and in the following section.

A diametrically opposite conclusion has been reached by Archer and Ganopolski (2005), arguing for the great receptivity of the climate system to global radiative forcing by CO_2 when contrasted with the orbital insolation forcing. Their appeal to CO_2 forcing modulation of the threshold of ice age cycles is not dissimilar to some of the dramatic, but qualitative, ideas reviewed earlier. This major disagreement should motivate further serious scientific inquiry. In the present brief paper concerning the quantitative role of CO_2 in glacial–interglacial changes, it is necessary to postpone a more complete synthesis of the external solar and interstellar forcing in accounting for: (1) intrinsic variability of the Sun from its thermo-nuclear and magnetic history (Gough, 1990, 2002; Turck-Chieze et al., 2005; with important insights from geological archives, e.g., Sharma, 2002; Lal et al., 2005; Bard and Frank, 2006); (2) both the long-term (Berger, 1978; Laskar et al., 2004) and shorter term (i.e., from multi-years to decades to centuries; Loutre et al., 1992) perturbations of the Earth's orbital geometry with respect to the Sun; and (3) even for any intrinsic variability related to the local interstellar (Frisch and Slavin, 2006; Muller et al., 2006; Scherer et al., 2006) and galactic (Cox and Loeb, 2007) environments.

However, most constructions of physical theory and modeling of glacial and interglacial changes (Kukla and Gavin, 2005; Roe, 2006; Tziperman et al., 2006; Huybers, 2007; Martinson and Pitman, 2007) do not require CO_2 to be a predominant forcing agent but, instead, strongly hint at both the necessary and sufficient conditions of orbital insolation forcing, its persistency, and its pacing role through nonlinear phase locking. A direct comparison of the 80 ppm change in atmospheric CO_2 for a radiative forcing of about 2 W/m^2 (e.g., Joos, 2005), with 10 W/m^2 summertime shortwave forcing, after properly folding in the albedo of melting ice and summer half-year insolation variation (Roe, 2006), provide us with a clear hint about the secondary role of CO_2 in setting the trend in climate change and other related responses during the glacial–interglacial transitions of the past 650 kyr. Neither does the estimate for radiative forcing of 0.2 W/m^2 (e.g., Joos, 2005) by atmospheric CH_4 change of about 400 ppb over the 100 kyr glacial–interglacial cycle suggest a very prominent role by CH_4, either in isolation or in combination with CO_2.

At this stage, it is relevant to emphasize that the popular scenario for potential episodic releases of methane hydrates, to act as a strong positive feedback commonly tied to seed atmospheric warming by CO_2, may not be so straightforward. First, Milkov (2004) has cautiously lowered the previously accepted high estimate of global hydrate-bound gas from 21×10^{15} m^3 of methane (or about 10,000 Gt of methane carbon) to a much lower range between 1 to 5×10^{15} m^3 of methane (or about 500–2500 Gt of methane carbon). Next, Cannariato and Stott (2005) have recently challenged the possibly incorrect interpretation of the large $\delta^{13}C$

excursions in records of planktonic and benthic foraminifera as clathrate-derived methane release. Nor could a careful examination of the atmospheric methane carbon isotope ratio ($\delta^{13}CH_4$) from the western Greenland ice margin spanning the Younger Dryas–Preboreal transition find support for either catastrophic or gradual marine clathrate emissions (Schaefer et al., 2006). Finally, Bhaumik and Gupta (2007) have recently identified five major episodes of methane release since 3.6 million years BP in the ODP 997A site located on the crest of the Blake Outer Ridge (about 200 km off Georgia and South Carolina, USA). These they link to reduced hydrostatic pressure connected to lowered sea levels and intense glacial events, roughly coinciding with increased glaciation in the Northern Hemisphere.

Thus, many numerical attempts (shown below) to quantify the impacts from variations in two minor greenhouse gases, CO_2 and CH_4, simply do not confirm their predominant roles in explaining the large amplitude changes in thermal, hydrologic, and cryospheric history during glacial–interglacial transitions. This failure to link quantitatively the seed CO_2-induced thermal perturbations to large hydrologic and cryospheric responses is the necessary reason for questioning the CO_2-amplifier idea. Persistent solar insolation forcing at key seasons and geographical locations, and closely related thermal, hydrological, and cryospheric changes (including the water-vapor, cloud, and ice–albedo feedbacks), may be sufficient to explain regional and global climatic changes during glacial–interglacial transitions.

PROBLEMS WITH CO_2 AMPLIFICATION OF GLOBAL MEAN TEMPERATURE: COMPUTER SIMULATIONS AND QUANTITATIVE DATA

Why is the climatic role of CO_2 radiative forcing deemed so hard to confirm? Figure 3 may help explain the inherent difficulty in confirming any radiative impact from added CO_2 forcing using the deduced global net longwave (LW) fluxes available from the International Satellite Cloud Climatology Project (ISCCP) over the 18-year span from July 1983 through June 2001, despite some known data limitations for ISCCP (e.g., Kato et al., 2006; Evan et al., 2007). Over that period, the CO_2 increase is estimated to produce an equivalent global LW forcing of only about 0.3 W/m^2 and this amount is practically not discernible from the large interannual variability of LW fluxes at either the surface, the atmospheric air column, or even the top of the atmosphere. It is understood in scientific discussions, but popularly least appreciated, that the argument for a significant role from added radiative forcing by anthropogenic emissions of CO_2 rests on the assumption that over a sufficiently long interval, say over several decades to a century, the Earth's climate system will be in some form of "equilibrium" state where all the intrinsic LW flux fluctuations shown in Figure 3 will cancel almost exactly to zero. The cancellation would in turn allow the detection and hence all related climatic manifestations of, for example, a systematic increase of about 4 W/m^2 of net radiative LW forcing (3.5 to 4.2 W/m^2 in the CO_2 forcing parameterization of 20 GCMs examined by Forster and Taylor, 2006) from the doubling of CO_2 content roughly over 70 years' time (i.e., a compounded rate of CO_2 increase at 1% per year).

It is thus widely accepted that, although atmospheric CO_2 and CH_4 contents during the glacial–interglacial cycle are a response to climate-induced perturbations to

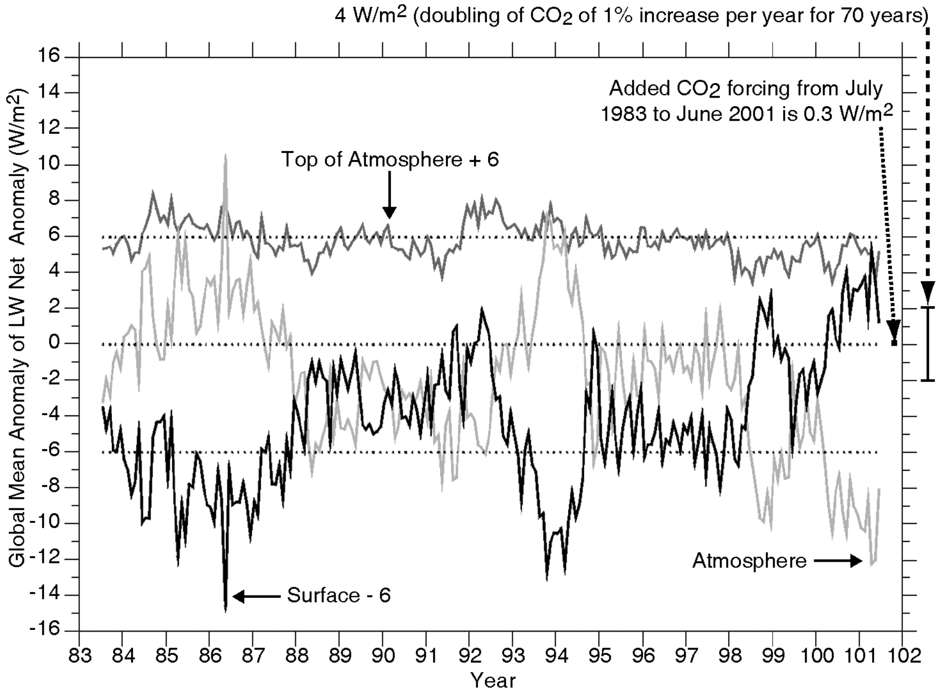

Fig. 3. Global net longwave (LW) fluxes deduced for the surface, atmospheric column, and the top of the atmosphere from July 1983 through June 2001 in comparison to the estimated radiative forcing of 0.3 W/m^2 from increased anthropogenic CO_2 over the same 18-year time span, as well as the 4 W/m^2 estimate for a doubling of atmospheric CO_2, which roughly extends over a 70-year period if one compounded the CO_2 concentration increase at a rate of 1% per year (adapted from the original figure shown in International Satellite Cloud Climatology Project, ISCCP, web page http://isccp.giss.nasa.gov/projects/flux.html, with technical discussion in Zhang et al., 2004). Recent and projected CO_2 forcing are likely to be confused by the LW variations produced by internal variability and solar radiation–induced forcing and feedback through water vapor and cloud variations.

the global carbon and methane reservoirs, both on land and in the surface ocean, continental margin, and deep sea, the CO_2 and CH_4 radiative forcing can in turn act to strongly amplifly and synchronize climatic changes across all weather regimes and climatic zones from south to north poles, ultimately producing a global warming or cooling. However, a closer look reveals that most of the claims, even in many scientific publications (i.e., from Genthon et al., 1987; Lorius et al., 1990; through Hansen et al., 2007), have not offered reliable quantitative support for the claim. The necessity of *a priori* forward calculations for the difficult task of quantifying the climatic role of CO_2 radiative forcing must be contrasted with multivariable regression analyses as performed in those cited studies, adopting rather selective variables that can easily be confused by the concepts of forcing and feedback (see below). This may be the reason for the early caution issued by Genthon et al. (1987, p. 415) that "CO_2 changes might just be a consequence of climatic change without much effect on climatic change itself."

Furthermore, there are clearly too many adjustable values in the estimates of radiative forcing by various other factors. For example, aerosol-dust forcing during the LGM was estimated to be –1.0± 0.5 W/m^2 by Hansen et al. (1993) and then later modified to –0.5 ± 1.0 W/m^2 in Hansen et al. (1997; based on the modeling study of Overpeck et al., 1996, that has since been questioned by Claquin et al., 2003). A significantly larger estimate by Claquin et al. (2003) gave a global dust-forcing value during LGM that ranges from –1.0 to –3.2 W/m^2, with forcing at higher latitudes (poleward of 45º) from –0.9 to +0.2 W/m^2 and 15ºN–15ºS tropical forcing ranging from –2.2 to –3.2 W/m.

It is puzzling that well-accepted roles of atmospheric water vapor and cloud feedbacks (despite the fact that both variations in the isotopic proxies δD_{ice} and $\delta^{18}O_{ice}$ from ice cores are essentially markers of large hydrologic changes) are not often factored in or discussed more seriously when CO_2 as the amplifier of glacial–interglacial warming or cooling is being considered. This is especially so because varying levels of atmospheric CO_2 largely seem to be a climatic feedback response, rather than any external forcing as envisioned in the scenario of anthropogenic emissions of CO_2.[1] Other potentially powerful hydrologic feedbacks, like the LGM hydrologic cycle weakened by a significant lowering of the mean residence time of water vapor from excessive dust loading in the atmosphere proposed by Yung et al. (1996), also have not gained much attention compared to those from added radiative forcing by CO_2. Paleoclimatic studies discussing the modulation of greenhouse effects by water vapor and cloud formation, e.g., over warm ocean areas and follow-up effects by orbital forcing (e.g., Gupta et al., 1996) should be a priority. Priem (1997) even went as far as to suggest that, in an early Earth comprising mainly oceans, the powerful greenhouse effects of water vapor, rather than CO_2, could come a long way toward resolving the "faint young Sun paradox."

Another example of potentially important feedback concerns how the seasonal cycle of surface-penetrating solar radiation is coupled to oceanic biota and the related biogeochemical emissions and atmospheric responses, especially through the production of marine biogenic dimethlysulfide (e.g., Shell et al., 2003; Vallina and Simo, 2007). Finally, beneficial insights may also be gained from studying how orbital forcing affects evolution of water and CO_2 cycles and climate on Mars (e.g., Richardson and Mischna, 2005).

The immediate question then is whether one can find a clear and dominant climatic impact signal by CO_2 radiative forcing in the glacial–interglacial transition from the current state-of-the-art modeling results from various General Circulation Models (GCMs). Let us start by imposing a CO_2 radiative forcing estimate of about 2.5 W/m^2 from the 80 ppm change, which will trigger a warming of 2–3ºC (taking a high value of climate sensitivity of 1ºC per 1 W/m^2), and that falls far short of the calibrated 10–12ºC in Antarctic temperature change. One should note that the climate sensitivity value adopted for this simple estimate has been generous, considering the "black-body" or "nofeedback" sensitivity value of 0.3ºC per W/m^2 or the

[1]Even in this scenario of CO_2 emissions from using fossil fuels, the actual amount of CO_2 ultimately retained in the atmosphere is still limited by climatic, chemical, and biological factors of the global carbon cycle.

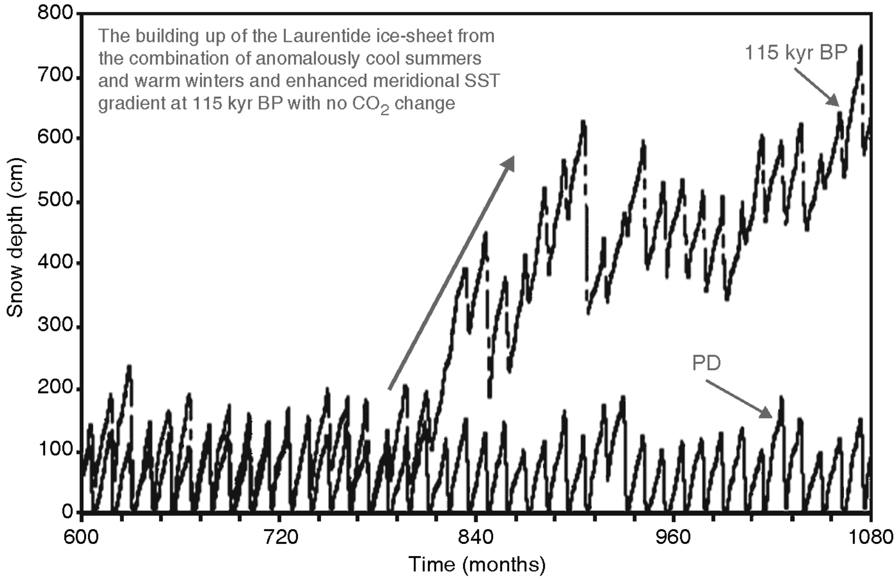

Fig. 4. The successful simulations of a significant snow accumulation in the glacially sensitive location (70°N, 80°W) around the Laurentide ice sheet area for the glacial inception scenario, with orbital forcing conditions around 115 kyr BP (compared to the present day orbital forcing case, PD) and taking into account the coupled ocean-atmosphere feedbacks, but with no change in CO_2 forcing (set at about 270 ppm) between 115 kyr BP and PD (adapted from Khodri et al., 2001). The Laurentide ice sheet was probably formed without much help from CO_2 forcing.

accepted range of values from 0.4 to 1.2°C per W/m^2 after accounting for net gain from all the positive and negative feedback processes (Joshi et al., 2003; Forster and Taylor, 2006). A more concrete estimate comes from recent simulations of LGM by Schneider von Deimling et al. (2006a), where the CO_2 forcing contributes about 1.8°C (or about 31%) of the total 5.7°C cooling over the globe (see also Fig. 4B in Schneider von Deimling et al., 2006b). The amount is impressive but not predominantly large. Also it is clear from the spatial pattern of change that the effects from the ice-sheet forcing (represented as an albedo effect) are clearly more extensive and variable than effects from changes in CO_2 forcing.

More importantly, the notion of what is forcing and what is feedback is sufficiently confused here and has led Hansen et al. (2007) to ponder that:

> [c]limate sensitivity when surface properties are free to change . . . reveals Antarctic temperature increase of 3°C per W/m^2. Global temperature change is about half that in Antarctica, so this equilibrium global climate sensitivity is 1.5°C per W/m^2, double the fast-feedback (Charney) sensitivity. Is this 1.5°C per W/m^2 sensitivity, rather than 0.75°C per W/m^2, relevant to human-made forcings? (pp. 1944 and 1946)

The issue may not be fully resolvable for now, but it is clear that this potential double counting of radiative "forcing" effects by CO_2 would, in Hansen et al.'s

(2007) view, stand as authoritative if no contest or discussion to this problematic proposal is forthcoming. In any case, if the impacts by CO_2 radiative forcing were to be real for large glacial–interglacial transitions, one should be able to verify the large stratospheric warming by up to 7°C at 60 km predicted during the LGM by, for example, Crutzen and Bruhl (1993). It would be also important to see if the CO_2 forcing theory can explain the regional warming around the Seas of Japan and Okhotsk during the LGM (Ishiwatari et al., 2001; Seki et al., 2004) where it was suspected that the anomalously warm sea surface temperature may represent the local equilibrium of thermal energy from trapped solar radiation in shallow water under the highly stratified upper ocean condition of the LGM when the Japan and Okhotsk seas were rather isolated from the open ocean as a result of the lowered sea level. Similarly, a correct CO_2 global radiative forcing theory should also be able to account for the ice-free conditions during the LGM for the coastal oasis regions of the Bunger Hills (Gore et al., 2001) and Larsemann Hills (Hodgson et al., 2006) around East Antarctica.

Another way to assess the role of CO_2 forcing in glacial–interglacial climate change would be to study the quantitative results from variations induced by orbital forcing alone in order to find out if there is any need to invoke CO_2 as a forcing input. Figure 4 shows the successful simulation of a significant snow accumulation in a glacially sensitive location (70°N, 80°W) around the Laurentide ice sheet area for the glacial inception scenario at orbital forcing condition around 115 kyr BP (compared to the present-day orbital forcing case, PD) taking into account the coupled ocean–atmosphere feedbacks but with no change in radiative forcing by CO_2 (set at about 270 ppm) between 115 kyr BP and PD by Khodri et al. (2001). In other words, the Khodri et al. (2001) study confirms the important role of seasonality and the correct accounting of complex feedback mechanisms, involving atmospheric winds, ocean dynamics, and hydrologic cycles with little hint for the need of CO_2 forcing. These results are consistent with modeling experiments of Vettoretti and Peltier (2004). Recent glacial inception modeling experiments by Risebrobakken et al. (2007) have also essentially supported the scenario by Khodri et al. (2001), while stressing dynamics from an enhanced, rather than weakened, Atlantic meridional overturning circulation in creating a strong land–sea thermal gradient together with a strong wintertime latitudinal insolation gradient to promote increased storminess and moisture transport that feeds into the formation of the Northern European ice sheet.

Loutre and Berger (2000) further emphasized the key role of orbital solar radiation forcing in generating the glacial–interglacial cycles of ice-volume changes. The authors showed that, if time-varying CO_2 forcing is prescribed alone, their model is able to generate glacial–interglacial temperature changes, but unable to simulate the simultaneously varying ice-volume cycles of the ice ages and interglacial warm stages. In contrast, the glacial–interglacial ice-volume cycles can be generated by accounting for the orbital forcing alone with a constant level of atmospheric CO_2 lower than 220 ppm. As noted earlier, such a great sensitivity of large continental ice sheet formation to the threshold crossing at a particular low CO_2 level requires more in-depth scientific research, but one can offer a counter-example from other existing CO_2-climate modeling experiments.

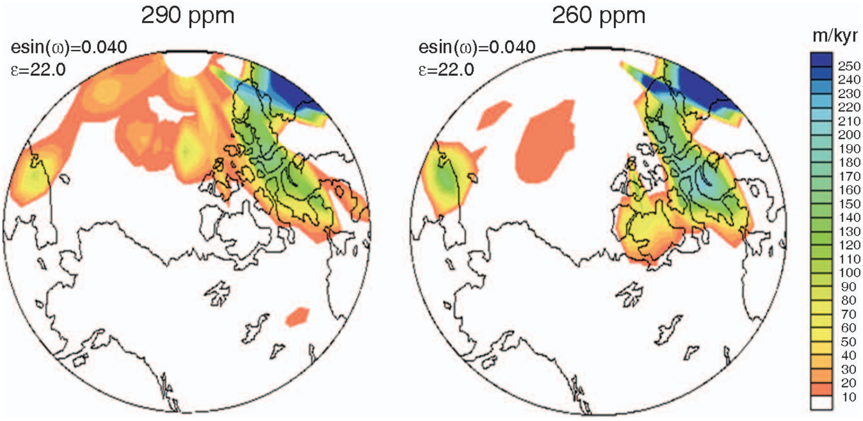

Fig. 5. Perennial snow accumulation rate (in m/kyr) for low tilt angle (ε = 22.0°) and highly eccentric (e sin[ω] = 0.04 with precession parameter ω = 90°) orbital (i.e., near the glacial inception phase) scenarios for CO_2 levels set at 290 ppm (left panel; roughly corresponds to the termination of marine isotope stage 5; 115 kyr BP) and 260 ppm (right panel; roughly corresponds to the termination of marine isotope stage 7; 220 kyr BP; adapted from Vettoretti and Peltier, 2004). Greater CO_2 forcing yields larger snow accumulation over the Arctic Ocean (see discussion in the text).

Figure 5 shows the curious example of a more extensive snow accumulation over the Arctic sea area for a case of high CO_2 level of 290 ppm in contrast to the lower CO_2 level case of 260 ppm shown in Vettoretti and Peltier (2004). Both simulations were set with exactly the same orbital configuration of low tilt angle and high eccentricity (to emulate glacial inceptions near the terminations of MIS stages 5 and 7, respectively), so the results strictly represent the consequences of having differing levels of CO_2 radiative forcing. The results show more extensive snow accumulation, rather than less, with higher CO_2 forcing, although the rates of snow accumulation in the Canadian Arctic and coastal eastern Siberia are higher for the low CO_2 case of 260 ppm. The examination of the simulated land surface temperatures and precipitation-minus-evaporation (P-E) anomalies in the polar region shows that, although polar surface land temperatures may be warmer with less extensive cool-summer areas (i.e., latitudes with temperatures from –4 to –12°C; see Figs. 8f and 8g in Vettoretti and Peltier, 2004) in the 290 ppm case, the positive P-E regions were slightly larger and enhanced in higher polar latitudes for the experiment with 290 ppm of CO_2 (see Figs. 9f and 9g in Vettoretti and Peltier, 2004). The results in Figure 5 may be consistent with the cyrospheric moisture pump scenario for glacial inceptions being more effective at a higher CO_2 scenario, studied earlier by the same authors (Vettoretti and Peltier, 2003), in which an initial cooling at high latitudes by orbital insolation forcing caused evaporation to drop locally more quickly than precipitation, which then created a condition favoring more moisture transport into polar regions via increased baroclinic activity at mid- to high latitudes in the Northern Hemisphere summer season. The results of Vettoretti and Peltier (2004) are consistent with those of Khodri et al. (2001).

What about evidence for a greater role of CO_2 radiative forcing during deglaciation scenarios? The recent hypothesis of Martinson and Pitman (2007) does not

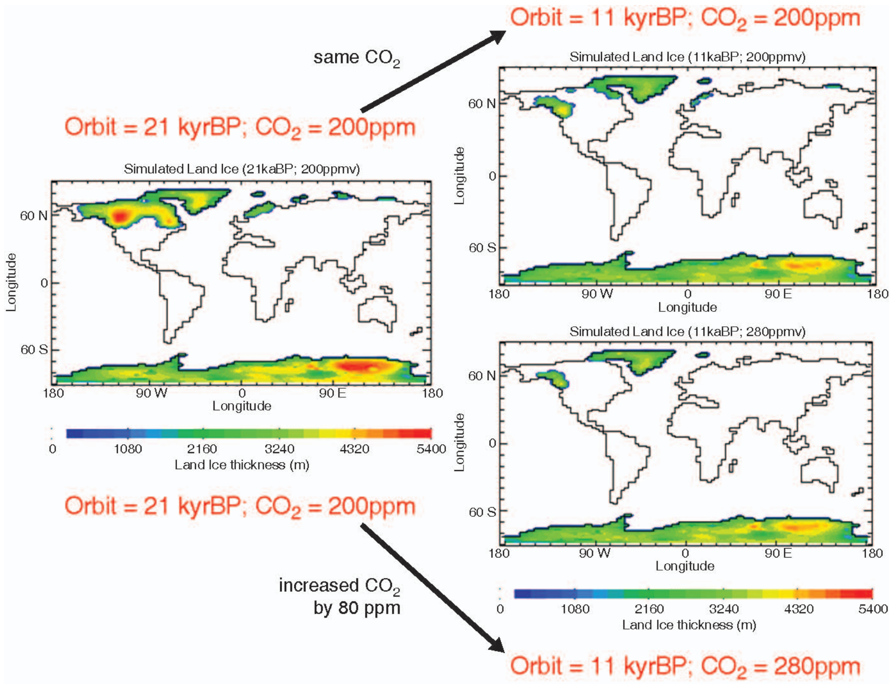

Fig. 6. Simulations of land-ice thickness (in m) for orbital deglaciation scenarios between LGM (21 kyr BP) and the early Holocene (11 kyr BP) with the same CO_2 level at 200 ppm (left panel → top right panel) and with the CO_2 level increased from 200 ppm at LGM to 280 ppm in the early Holocene (left panel → bottom right panel; adapted from Yoshimori et al., 2001). Orbitally induced solar forcing causes greater land-ice response than even a significant increase in atmospheric CO_2 concentration by 80 ppm.

specifiy any prominent role for atmospheric CO_2 but instead details the sufficiency of a sequence of events during the last glacial termination involving the crucial role of the southward expansion of the North American and Eurasian ice sheets, sea ice cover in the North Pacific and North Atlantic, and balancing acts among Arctic freshwater budgets, salinity-driven formation of polynyas (i.e., ice-free areas), and deepwater formation in the Arctic Ocean and its subsequent overflow into the North Atlantic, as well as the incursion of warm surface water from the North Atlantic to the Arctic Ocean. This hypothesis is consistent with the dynamic changes of land and sea ice contributions to the sedimentary record from the central Arctic Ocean (Spielhagen et al., 1997) that did not invoke any contribution from CO_2 radiative forcing.

Figure 6 shows the land ice thickness simulations of the deglaciation scenario from Yoshimori et al. (2001) for orbital conditions from 21 kyr (LGM) to 11 kyr BP (early Holocene), first with a constant CO_2 at 200 ppm, and then with the level of CO_2 changed by 80 ppm for the early Holocene in order to be consistent with ice-core air bubble results. The results clearly suggest a minimal impact of added radiative forcing of CO_2 on the thickness of ice sheets on land. Yoshimori et al. did argue for a "powerful" feedback role by CO_2 forcing in explaining glacial termination, but the authors pointed out that the effect of increasing atmospheric CO_2 from 200 to 280 ppm in their simulation leads to a nominal impact on winter air temperatures over continents adjacent to the North Atlantic. That CO_2 impact in turn contributes to ice-sheet nourishment through slightly enhanced winter precipitation, so that CO_2 acts as negative, rather than positive, feedback for ice-sheet retreat during deglaciation.

The examples in Figures 4, 5, and 6 serve only as the sufficient but not necessary condition of orbital insolation forcing in accounting almost fully for conditions and changes during the glacial–interglacial transition, without the need to invoke the argument for CO_2 as the predominant amplifier of those changes.

One cannot totally discount other contemporary studies (Weaver et al., 1998; Pepin et al., 2001; Lea, 2004) that suggested a "dominant" contribution by CO_2 radiative forcing to the observed glacial–interglacial temperature change while perhaps ignoring the large changes in global ice volume and its effects. Lea (2004; citing Hewitt and Mitchell, 1997; Weaver et al., 1998; and others) claimed that "modeling results for the glacial oceans support the hypothesis that CO_2 variations are the dominant source of radiative forcing in the tropical ocean regions" (p. 2170). However, simulation results from Hewitt and Mitchell (1997) estimated the lowering of CO_2 at 21 kyr BP at the LGM to be a cooling of 1.4ºC or about one-third of the total simulated cooling. Weaver et al. (1998) suggested that "the most important [more so than ice-sheet albedo feedbacks] of these forcings in our model is the change in atmospheric CO_2" but concurrently admitted to underestimating the "ice albedo" effects. More importantly, the model of Weaver et al. suggests that temperatures in the tropics were 2.2ºC less than today and their results show apparent insensitivity to changes in oceanic circulation. These results are not consistent with larger amplitude change in tropical SST of 3.5º–4ºC during the last two glacial–interglacial transitions, as deduced by Visser et al. (2003), and with the importance of oceanic feedbacks for glacial inception scenarios identified with the coupled ocean-atmosphere GCM as discussed by Khodri et al. (2001) and found in climate sensitivity experiments conducted by Vettoretti and Peltier (2004).

CONCLUSIONS

There is no quantitative evidence that varying levels of minor greenhouse gases like CO_2 and CH_4 have accounted for even as much as half of the reconstructed glacial–interglacial temperature changes or, more importantly, for the large variations in global ice volume on both land and sea over the past 650 kyr. This paper shows that changes in solar insolation at climatically sensitive latitudes and zones exceed the global radiative forcings of CO_2 and CH_4 by severalfold, and that regional responses to solar insolation forcing will decide the primary climatic feedbacks and changes (see also independent research and conclusions by Kukla and Gavin, 2005; Lorenz et al., 2006; Roe, 2006).

Persistent orbitally moderated insolation forcing is, therefore, likely to be the principal driver of water-vapor cycling, and the cloud-and-ice insulator and albedo feedbacks. Such a forcing-response scenario has not received enough attention in current research (but with notable exceptions, e.g., Dong and Valdes, 1995; Gupta et al., 1996; Broecker, 1997; Greene et al., 2002; Leduc et al., 2007). A host of other forcings and feedbacks, including dust-and-aerosol forcings, oceanic circulation, and vegetation-cover feedbacks, have not been soundly quantified. The forcing from intrinsic variation of solar radiation and magnetic activity has also been almost entirely ignored in this paper, but several recent studies are beginning to document and formulate testable climatic responses on multidecadal to centennial to millennial timescales resulting from this particularly complex expression of solar change (e.g., Bond et al., 2001; Holzkamper et al., 2004; Mayewski et al., 2004; Holzhauser et al., 2005; Maasch et al., 2005; Soon, 2005; Scherer et al., 2006). There are still questions about how orbital forcings explain glaciation and deglaciation over the past few million years (Roe, 2006; Tziperman et al., 2006; Huybers, 2007; Lisiecki and Raymo, 2007), with the 100-kyr glacial–interglacial cycles not fully explained (but most likely, nonlinearly related to obliquity forcing, thereby emphasizing the key role of the insolation gradient as the driver for climatic processes and feedbacks, as discussed by Raymo and Nisancioglu, 2003; Liu and Herbert, 2004; Loutre et al., 2004; Huybers and Wunsch, 2005; Huybers, 2007).

However, the popular notion of CO_2 and CH_4 radiative forcing as the predominant amplifier of glacial–interglacial phase transitions cannot be confirmed. In this context, the graph of "radiative perturbation" during the last glacial maximum, shown as the top left panel of Figure 6.5 on p. 451 of the IPCC (2007) Working Group I report, may be gravely misleading. It suggests that *global annual mean radiative influences* by orbitally moderated insolation forcing are negligible when compared to *radiative influences* of CO_2, CH_4 + N_2O, mineral dust, continental ice and sea level, and vegetation. In our opinion, the listed influences are very likely to be the responses from the initial orbital insolation forcing and its persistent effects. Provided that the deduced amplitude of 80 ppm and 400 ppb for CO_2 and CH_4 from air-bubble records is not severely underestimated, enhanced greenhouse effects from these two minor greenhouse gases cannot explain the greater part of the large climatic swings and substantial hydrologic and cryospheric changes reconstructed for the glacial–interglacial transitions over the last 650 kyr.

Our basic hypothesis is that long-term climate change is driven by insolation changes, from both orbital variations and intrinsic solar magnetic and luminosity variations. This implies natural warming and cooling variations on decades through millennia (e.g., Bond et al., 2001; Holzkamper et al., 2004; Holzhauser et al., 2005; Maasch et al., 2005; Soon, 2005), together with an eventual cooling of the Earth and an increase in ice-mass accumulation within the past and future horizons of the Holocene and the next few thousand years or so (see Kukla and Gavin, 2005, and Bauch and Kandiano, 2007, for the pioneering research and more in-depth discussion). Such a retrodiction appears consistent with proxy evidence indicating both systematic and significant cooling trends during the Holocene[2] in Greenland

[2]Our brief discussion on the Holocene changes is not intended to be complete; see additional discussion in Mayewski et al. (2004) and Lorenz et al. (2006), as well as the Holocene SST database offered by GHOST (Global Holocene Spatial and Temporal Climate Variability) at http://www.pangaea.de/Projects/GHOST.

(Johnsen et al., 2001), western Arctic (Kaufman et al., 2004), Nordic Seas (Andersen et al., 2004), other regions around the northeast Atlantic and Mediterranean (Marchal et al., 2002; Kim et al., 2007; Magny et al., 2007), northwest Atlantic (Sachs, 2007), northwest Africa and Gulf of Guinea (Kim et al., 2007; Weldeab et al., 2007), western tropical Pacific ocean (Stott et al., 2004), southern mid-latitude seas south of the Indian Ocean and around the Australian–New Zealand region (Ikehara et al., 1997; Pahnke and Sachs, 2006; Barrows et al., 2007), and even the Antarctic Peninsula and both coastal and inland regions of East Antarctica (Masson et al., 2000; Masson-Delmotte et al., 2004; Hodgson et al., 2006; Smith et al., 2007). This predictable tendency and currently observed reality led Sachs (2007) to the conclusion, with which we agree, that the Holocene, often considered a time of climate stability, has been characterized by large secular changes throughout the climate system. Again, following Sachs, perhaps the cooling of northwest Atlantic slope waters during the Holocene is a harbinger of climate deterioration preceding the next glaciation.

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