A note on the relationship between ice core methane concentrations and insolation

Gavin A. Schmidt and Drew T. Shindell

NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, New York, New York, USA

Susan Harder

Environmental Science Program, Washington State University, Vancouver, Washington, USA

Received 22 July 2004; revised 27 October 2004; accepted 10 November 2004; published 10 December 2004.

[1] We re-examine the link between July 30°N insolation and methane in the Vostok ice core. Based on this link, *Ruddiman* [2003] suggested that an anthropogenic source of methane must have been present after 5 kyr BP in order to prevent concentrations from declining as insolation decreased through the Holocene. We conclude however, that since precessional forcing does not explain the large glacial-interglacial excursions, the component of methane variability associated with precession is significantly smaller than assumed by *Ruddiman* [2003]. The implied decrease from 10 kyr BP to the present associated with precession alone is 60 ppbv or less. We argue that increased emissions controlled by northern wetlands and river delta development likely contributed to the observed increase, consistent with similar stable CH_4 levels at MIS 11 in the Vostok and Dome C records. Therefore a significant anthropogenic input is not obviously required to explain the late Holocene record. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology. **Citation:** Schmidt, G. A., D. T. Shindell, and S. Harder (2004), A note on the relationship between ice core methane concentrations and insolation, *Geophys. Res. Lett.*, *31*, L23206, doi:10.1029/2004GL021083.

1. Introduction

[2] Methane (CH_4) both affects climate (through it's role as a greenhouse gas [*Wang et al.*, 1976]) and is affected by climate (for instance, through temperature and precipitation influence on natural wetland emissions [*Walter et al.*, 2001]). These links are most clearly demonstrated in the co-varying CH_4 amounts and temperature proxies seen in ice cores [*Petit et al.*, 1999; *Blunier et al.*, 1998; *Severinghaus and Brook*, 1999]. The natural methane cycle is therefore key to judging the degree to which anthropogenic modifications to CH_4 levels have occurred and possibly understanding the glacial-interglacial changes in the Earth system.

[3] Global atmospheric methane levels have more than doubled from the pre-industrial level of around 700 ppbv to around 1750 ppbv. This is mainly due to increased emissions from rice paddies, mining, coal and natural gas usage, domesticated animals, biomass burning and landfills [*Prather et al.*, 2001]. Methane levels seen in ice cores are slightly different from the global mean (lower in Vostok, higher in Greenland) due to the slight north-south gradient [*Chappellaz et al.*, 1997]. The minimum level of CH_4 (≈600 ppbv) in the Holocene (seen in a Greenland ice core) occurred around 5 kyr BP, after the peak (≈700 ppbv) at around 10 kyr BP coincident with the maximum in northern hemisphere insolation [*Berger*, 1978; *Blunier et al.*, 1995], and contemporaneous with the drying seen at the end of the African Humid period (≈5.5 kyr BP) [*deMenocal et al.*, 2000]. The question naturally arises as to what controlled the subsequent increase of around 100 ppbv prior to the start of the industrial period (ca. 1850). Assuming present day rates of atmospheric oxidation (and therefore atmospheric residence time), this implies that sustained increased emissions of around 30–40 Tg/yr would have been necessary. Given the uncertainties in natural emissions and their variability at the present, changes in the tropical hydrological cycle and the further development of boreal wetlands could account for this increase along with a small potential for anthropogenic inputs [*Chappellaz et al.*, 1997].

[4] However, a recent paper by *Ruddiman* [2003] (hereinafter referred to as R03) has significantly recast the problem. *Ruddiman and Raymo* [2003] (hereinafter referred to as RR03) noted the relationship of Vostok methane to July 30°N insolation and used this to form the basis for a new timescale for the gas age in the ice core. This timescale is a little different from the standard GT4 chronology [*Petit et al.*, 1999] but similar to that developed by *Shackleton* [2000]. For the sake of this article, we will use the RR03 timescale for CH_4 since that will clearly show the best relationship with insolation. There is a danger of circularity here, and so the results should be seen as demonstrating the maximum possible correlation. In R03, this relationship was assumed to control the long term variations in CH_4, and in particular the magnitude of the transition from the Last Glacial Maximum to the early Holocene (see Figure 1 in R03). Using that relationship the decrease of CH_4 that would have been expected from the early Holocene peak to the start of the industrial period would be around 250 ppbv, i.e., a further decline on the order of 150 ppbv from the 5 kyr BP minimum. Since CH_4 actually rose by 100 ppbv, that would have implied an extremely significant additional (anthropogenic) input of methane ≈90 Tg/year. Whether this extrapolation is justified is the principle subject of this note.

2. Regression of Vostok CH_4 and Insolation

[5] The insolation time series was calculated in 100 year time slices from 400 kyr BP to the present for each calendar

Copyright 2004 by the American Geophysical Union.
0094-8276/04/2004GL021083$05.00

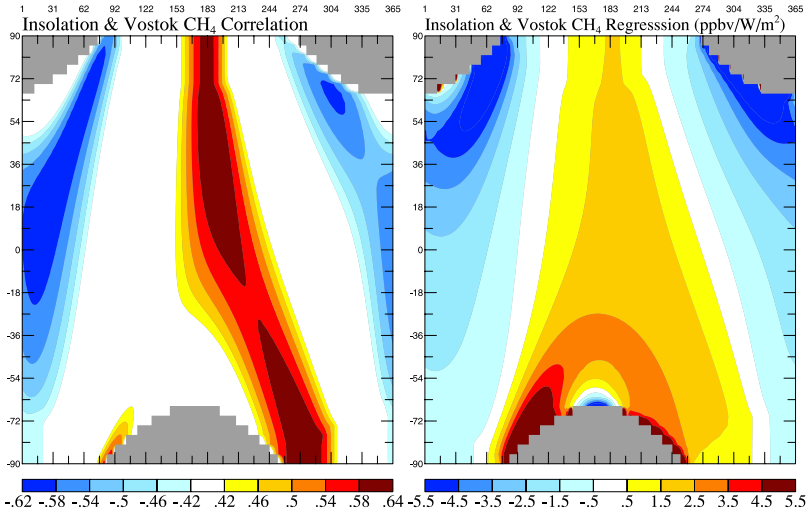

Figure 1. Correlation coefficients and linear regression of Vostok CH_4 and insolation as a function of Julian day and latitude. From the degree of lagged auto-correlation in the CH_4 time series, the number of degrees of freedom is around 30 to 40. However, in correlating to the insolation to which the series has been tuned, there is a significant loss of degrees of freedom due to the 32 tie points used in RR03. If we conservatively assume a residual 10 degrees of freedom, correlations of magnitude above 0.58 are significant at the 95% level based on Student's t-test.

day and for each 4° latitude band [*Berger*, 1978]. The Vostok methane record [*Petit et al.*, 1999] was interpolated to these times (with 100 year resolution) and correlated to the insolation for each Julian day and latitude (Figure 1). The correlation only used values back to 350 kyr BP to avoid going back too far beyond the last tie point (344 kyr BP) in the RR03 time scale. Correlations are smaller using the Shackleton time scale (and smaller still for GT4) [*Shackleton*, 2000; *Petit et al.*, 1999] since these were not tuned specifically to the CH_4 record, but the pattern is similar.

[6] It is clear from Figure 1 that northern mid-latitude summer time insolation correlates most strongly with the Vostok methane. While R03 and RR03 suggest July 30°N (r = 0.62) as the most suitable predictor, the maximum correlation is slightly earlier in the year and further north. The maximum correlation on the Shackleton (r = 0.43) and GT4 (r = 0.18) timescales are for July 70°N and July 54°N respectively, but the practical differences from July 30°N are small. The key result is given by the linear regression coefficient - the change of methane concentration as a function of the change in insolation. For the northern summer insolation time series that have the highest correlation, the regression is around 2 ppbv per W/m^2. This is significantly smaller than used by R03 (6 to 11 ppbv per W/m^2 depending on the figure). The regression is smaller (≈1 ppbv per W/m^2) using the other age models, and so this calculation can be thought of as the maximum likely regression assuming that the RR03 timescale is correct. Note that the higher magnitude regression coefficients in the northern and southern high latitude winters are due to the small changes in insolation at those latitudes and seasons, and do not lead to larger predicted excursions in CH_4. For the decline of July 30°N insolation since the early Holocene, (≈30 W/m^2) the linear regression would imply a decrease of around 60 ppbv, compared to 250 ppbv or more postulated by R03.

[7] If the time series of insolation and methane are plotted together using the regression coefficients as the scaling and offset so that the means over the record are the same, it is easy to see why the difference with R03 arises (Figure 2). In essence, the linear regression ensures that the predominantly precessional changes in methane that occur throughout the record are correctly matched in amplitude. However, the larger excursions seen at peak glacial and interglacial times are not. By contrast, the R03 scaling matches these glacial-interglacial changes but significantly over-predicts the precessional component. Thus it is implicit in the R03 analysis that it is the glacial-interglacial changes in methane that are directly controlled by insolation.

[8] In performing a linear regression, we attempt to demonstrate the limits of linear extrapolation for the climate/methane relationship. Perhaps surprisingly, the linear hypothesis works well for the precessional forcing in between the large glacial-interglacial transitions, however

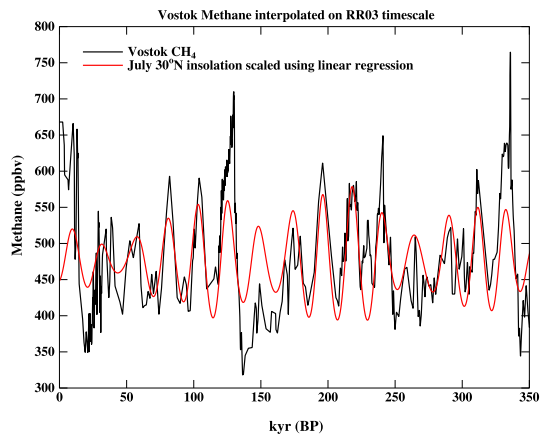

Figure 2. Time series of Vostok CH_4 (on the RR03 timescale) compared to the time series of July 30°N scaled according to the linear regression (2 ppbv per W/m^2) shown in Figure 1.

the magnitude of this relationship is much less than postulated in R03.

3. Discussion

[9] Natural methane emissions (and concentrations) clearly respond to climate, however they do not respond directly to insolation variations. Process model studies of wetlands show that temperature changes (that alter the rate of anaerobic decomposition and net primary productivity) and water table variations (which alter the amount of available oxygen in the substrate and control the degree of out-gassing) are the dominant controls [e.g., *Walter et al.*, 2001; *Kaplan*, 2002]. Precessional forcing is clearly implicated in the changes to the tropical hydrological cycle, and thus to tropical methane emissions. However, temperature and precipitation changes related to the presence of large northern hemisphere ice sheets will also play a role. Since the ice sheets have followed a predominantly 100 kyr cycle over the last 800 kyr, there is a significant 100 kyr periodicity in the methane cycle itself. Since methane can be considered in equilibrium with its sources and sinks over periods longer than a few hundred years, this periodicity is tied purely to the ice sheets. The disappearance of the Laurentide and Fenno-Scandinavian ice sheets from 20 kyr to 10 kyr BP would therefore be expected to have a large impact on methane levels. Additionally, recent higher resolution analyses of the Vostok methane record [*Delmotte et al.*, 2004] show that millennial variability is ubiquitous during glacial periods, again showing clearly that factors other than precessional forcing are important.

[10] There are a number of elements in the methane cycle that would predominantly respond to the ice sheets and boreal climate rather than tropical insolation (see *Kennett et al.* [2003, and references therein] for a summary). Specifically, emissions from boreal wetlands are likely to be severely curtailed at peak glacial times [*Chappellaz et al.*, 1997] and during interglacials will have grown as a function of peat deposits (e.g., as seen in the West Siberian Lowland up to the present day [*Smith et al.*, 2004]). Thawing and freezing of permafrost can also have large impacts on emissions [*Christensen et al.*, 2004]. Finally, the variations in ice sheets are associated with significant sea level changes. Large river delta systems (Nile, Amazon, Niger etc.) rely on a relatively stable sea level to develop (otherwise they are either drowned or drained). Most extant deltas have therefore only developed since the mid-Holocene [*Stanley and Warne*, 1994]. Emissions from deltas are significant and, as long as sea level is stable, would be expected to rise as they develop. They would not therefore be significantly affected by precessional forcing which, inter alia, might lead to changes in nearby lake levels. These three elements thus provide plausible reasons to expect the interglacial variations in methane to be decoupled from precession, suggesting that the appropriate scaling is close to that seen in Figure 2.

[11] Support for a northern methane source driving changes in methane concentration for some periods during the last glacial cycle is found in the variability of the inter-polar methane gradient obtained from polar ice core records. For example, the warm Bölling-Alleröd and Preboreal periods (both following major cold events with low methane concentrations, the last glacial maximum and the Younger Dryas, respectively) are characterized by sustained high atmospheric methane concentrations. However, differing inter-polar gradients for the two periods point to different methane source regions. While a tropical increase is indicated during the Bölling-Alleröd, the larger Preboreal gradient requires a significant increase in northern emissions during that time. This growth of northern sources has been attributed to warming and the retreat of the North American and Fennoscandian ice sheets resulting in expansion of northern boreal wetlands [*Brook et al.*, 2000]. Similar analysis of the inter-polar gradient further suggests that changes in methane concentration associated with interstadial events of the last glacial period also resulted from changes in northern sources [*Dällenbach et al.*, 2000].

[12] This argues against a solely precessional forcing that would favor tropical and subtropical sources. Looking specifically at the recent Holocene, the inter-polar methane gradient was greater during the 2500 years immediately following the 5 kyr B.P. concentration minimum than for the previous 2000 years [*Chappellaz et al.*, 1997]. This suggests that northern sources were responsible for the initial recovery and box model studies of the inter-polar gradient suggest a concomitant decrease of the tropical source and an increase of the boreal source at this time. Tropical sources may have begun to increase after 2.5 kyr B.P., though no gradient is calculated for this period, and are indicated more recently for the period 0.25 to 1 kyr B.P. [*Chappellaz et al.*, 1997]. This change in source region is difficult to reconcile with a primarily anthropogenic basis for the concentration increase over the entire period from 5 kyr to the present.

[13] What then of the other interglacial periods which appear to have a different pattern from that of the current Holocene period? The previous three interglacials were of relatively short duration ($\approx$10 kyr) associated with the large values of eccentricity at these times [*Loutre and Berger*, 2000] and are thus not necessarily good analogues for methane behaviour in the Holocene. Estimates for the duration of Marine Isotope Stage 11 (MIS 11, ca. 400 kyr BP) from the recent EPICA Dome C results [*EPICA Community Members*, 2004] and marine sediments [*McManus et al.*, 2003] indicate a much longer interglacial ($\approx$30 kyr) at a time when orbital forcing (low eccentricity) was most similar to today. However, given estimated age errors at 400 kyr BP of around ±15 kyr [*Petit et al.*, 1999], there is a wide latitude in directly aligning the Holocene record with that from MIS 11 [*EPICA Community Members*, 2004, Figure 5]. The preliminary gas concentration analyses from the Dome C record, while not yet complete, indicate that methane levels were stable during MIS 11 at around 650 ppbv, extremely similar to pre-industrial values seen in Vostok 640–665 ppbv [*EPICA Community Members*, 2004]. Additionally, the duration of the MIS 11 is clearly longer than one precessional cycle, demonstrating that, during periods of low eccentricity, not all precessional minima lead to significant methane decreases [*Loutre and Berger*, 2000].

[14] In conclusion, while the precessional influence on methane, presumably due to tropical hydrological changes, is important, it is not dominant on the glacial-interglacial scale. Even assuming that the RR03 timescale is 'best', we

have demonstrated that the most likely impact of the change in precession over the Holocene would have lead to only a minor decrease in concentrations (<60 ppbv) over the last 10,000 years. In addition, there are good reasons to expect emissions from boreal wetlands and river deltas to have increased over this period. Previous conclusions regarding anthropogenic inputs prior to the industrial era cannot therefore be regarded as definitive until improved process models and carbon inventories can definitely rule out such natural effects.

[15] **Acknowledgments.** We would like to thank Georg Hoffmann and Jean Jouzel for useful discussions regarding methane and ice cores. We would also like to thank Maureen Raymo for providing the Vostok methane record on the RR03 timescale.

References

Berger, A. (1978), Long-term variations of daily insolation and Quaternary climatic changes, *J. Atmos. Sci.*, *35*, 2362–2367.

Blunier, T., J. Chappellaz, J. Schwander, B. Stauffer, and D. Raynaud (1995), Variations in atmospheric methane concentration during the Holocene epoch, *Nature*, *374*, 46–49.

Blunier, T., et al. (1998), Asynchrony of Antarctica and Greenland climate during the last glacial, *Nature*, *394*, 739–743.

Brook, E. J., S. Harder, J. P. Severinghaus, E. J. Steig, and C. M. Sucher (2000), On the origin and timing of rapid changes in atmospheric methane during the last glacial period, *Global Biogeochem. Cycles*, *14*, 559–572.

Chappellaz, J., T. Blunier, S. Kints, A. Dällenbach, J.-M. Barnola, J. Schwander, D. Raynaud, and B. Stauffer (1997), Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the Holocene, *J. Geophys. Res.*, *102*, 15,987–15,999.

Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson (2004), Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, *Geophys. Res. Lett.*, *31*, L04501, doi:10.1029/2003GL018680.

Dällenbach, A., T. Blunier, J. Flückiger, B. Stauffer, J. Chappellaz, and D. Raynaud (2000), Changes in the atmospheric CH_4 gradient between Greenland and Antarctica during the last glacial and the transition to the Holocene, *Geophys. Res. Lett.*, *27*, 1005–1008.

Delmotte, M., J. Chappellaz, E. Brook, P. Yiou, J. M. Barnola, C. Goujon, D. Raynaud, and V. I. Lipenkov (2004), Atmospheric methane during the last four glacial-interglacial cycles: Rapid changes and their link with Antarctic temperature, *J. Geopyhs. Res.*, *109*, D12104, doi:10.1029/2003JD004417.

deMenocal, P., J. Ortiz, T. Guilderson, and M. Sarnthein (2000), Coherent high and low-latitude climate variability during the Holocene warm period, *Science*, *288*, 2198–2202.

EPICA Community Members (2004), Eight glacial cycles from an Antarctic ice core, *Nature*, *429*, 623–628.

Kaplan, J. O. (2002), Wetlands at the Last Glacial Maximum: Distribution and methane emissions, *Geophys. Res. Lett.*, *29*(6), 1079, doi:10.1029/2001GL013366.

Kennett, J. P., K. G. Cannariato, I. L. Hendy, and R. J. Behl (2003), *Methane Hydrates in Quaternary Climate Change: The Clathrate Gun Hypothesis*, AGU, Washington, D. C.

Loutre, M. F., and A. Berger (2000), Future climatic changes: Are we entering an exceptionally long interglacial?, *Clim. Change*, *46*, 61–90.

McManus, J., D. Oppo, J. Cullen, and S. Healey (2003), Marine isotope stage 11 (MIS 11): An analog for Holocene and future climate?, in *Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question*, *Geophys. Monogr. Ser.*, vol. 137, pp. 69–85, AGU, Washington, D. C.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, *Nature*, *399*, 429–436.

Prather, M., et al. (2001), Atmospheric chemistry and greenhouse gases, in *Climate Change 2001: The Scientific Basis*, edited by J. T. Houghton et al., p. 881, Cambridge Univ. Press, New York.

Ruddiman, W. F. (2003), The anthropogenic greenhouse era began thousands of years ago, *Clim. Change*, *61*, 261–293.

Ruddiman, W. F., and M. E. Raymo (2003), A methane-based time scale for Vostok ice, *Quat. Sci. Rev.*, *22*, 141–155.

Severinghaus, J. P., and E. J. Brook (1999), Abrupt climate change at the end of the last glacial period inferred from trapped air in polar ice, *Science*, *286*, 930–934.

Shackleton, N. J. (2000), The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity, *Science*, *289*, 1897–1902.

Smith, L. C., G. M. MacDonald, A. A. Velichko, D. W. Beilman, O. K. Borisova, K. E. Frey, K. V. Kremenetski, and Y. Sheng (2004), Siberian peatlands: A net carbon sink and global methane source since the early Holocene, *Science*, *303*, 353–356.

Stanley, D. J., and A. G. Warne (1994), Worldwide initiation of Holocene marine deltas by the decelaration of sea-level rise, *Science*, *265*, 228–231.

Walter, B. P., M. Heimann, and E. Matthews (2001), Modeling modern methane emissions from natural wetlands: 2. Interannual variations, *J. Geophys. Res.*, *106*, 34,207–34,219.

Wang, W.-C., Y. L. Yung, A. A. Lacis, T. Mo, and J. E. Hansen (1976), Greenhouse effects due to man-made perturbation of trace gases, *Science*, *194*, 685–690.

S. Harder, Environmental Science Program, Washington State University, 14204 NE Salmon Creek Avenue, Vancouver, WA 98686, USA. (harders@vancouver.wsu.edu)

G. A. Schmidt and D. T. Shindell, NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University, 2880 Broadway, New York, NY 10025, USA. (gschmidt@giss.nasa.gov)