Atmospheric methane levels off: Temporary pause or a new steady-state?

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[1] The globally-averaged atmospheric methane abundance determined from an extensive network of surface air sampling sites was constant at ~1751 ppb from 1999 through 2002. Assuming that the methane lifetime has been constant, this implies that during this 4-year period the global methane budget has been at steady state. We also observed a significant decrease in the difference between northern and southern polar zonal annual averages of CH_4 from 1991 to 1992. Using a 3-D transport model, we show that this change is consistent with a decrease in CH_4 emissions of ~10 Tg CH_4 from north of 50°N in the early-1990s. This decrease in emissions may have accelerated the global methane budget towards steady state. Based on current knowledge of the global methane budget and how it has changed with time, it is not possible to tell if the atmospheric methane burden has peaked, or if we are only observing a persistent, but temporary pause in its increase. *INDEX TERMS:* 0330 Atmospheric Composition and Structure: Geochemical cycles; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Dlugokencky, E. J., S. Houweling, L. Bruhwiler, K. A. Masarie, P. M. Lang, J. B. Miller, and P. P. Tans, Atmospheric methane levels off: Temporary pause or a new steady-state?, *Geophys. Res. Lett.*, *30*(19), 1992, doi:10.1029/2003GL018126, 2003.

1. Introduction

[2] Atmospheric methane's contribution to anthropogenic climate forcing is about half that from CO_2 when direct and indirect components to its forcing are summed [*Hansen and Sato*, 2001], and the increase in its atmospheric burden since 1800 has led to approximately half the estimated increase in global tropospheric ozone during this time [*Prather et al.*, 2001]. All CH_4 emission scenarios considered by the IPCC Special Report on Emission Scenarios [*Nakicenovic et al.*, 2000] resulted in increasing atmospheric CH_4 for at least the next 3 decades, and many of the scenarios projected large increases through the 21st century [*Prather et al.*, 2001]. To mitigate future environmental impacts, methane has been targeted for emissions reductions by the Kyoto Protocol. Before specific sources can be targeted for reduced emissions, we need a better understanding of the CH_4 budget, and how it is changing with time. Here we use CH_4 measurements from a globally distributed network of surface air sampling sites to show that the global annually averaged atmospheric CH_4 abundance was constant from 1999–2002. Further, we use an observed change in the latitudinal distribution of atmospheric CH_4 in combination with a 3-D transport model to show that CH_4 emissions from polar northern latitudes decreased by ~10 Tg yr^{-1} during the early 1990s, in agreement with the Emissions Database for Global Atmospheric Research, version 3 (EDGAR3) [*Olivier and Berdowski*, 2001; *Olivier*, 2002].

2. Experimental Methods

[3] Details of our sampling and measurement methods have been described elsewhere [*Dlugokencky et al.*, 1994]. For this study, measurements from 43 globally-distributed remote boundary layer sampling sites (for data, go to: ftp://ftp.cmdl.noaa.gov/ccg/ch4/flask/) were smoothed [*Dlugokencky et al.*, 1994] to define an evenly spaced matrix of surface CH_4 mole fractions as a function of time and latitude. This matrix is then used to define global and zonal CH_4 averages.

3. Results and Discussion

3.1. CH_4 Observations

[4] Globally averaged surface CH_4 mole fractions (nmol mol^{-1}, abbreviated ppb) are plotted in Figure 1a. Annually-averaged CH_4 (circles) increased from 1625 ppb during 1984 to 1751 ppb during 1999; CH_4 has since remained essentially constant through 2002. The solid line in Figure 1a is the deseasonalized trend determined from a fit to the global averages at ~weekly resolution; its derivative with respect to time represents the instantaneous growth rate of methane, which is plotted in Figure 1b. Also plotted in Figure 1b are annual increases (circles with error bars) determined directly from the trend curve. Though atmospheric CH_4 has increased during most of our measurement record, its growth rate decreased [*Steele et al.*, 1992; *Dlugokencky et al.*, 1998] from ~14 ppb yr^{-1} (corresponding to an imbalance between emissions and losses of 40 Tg yr^{-1}) in 1984, to near zero

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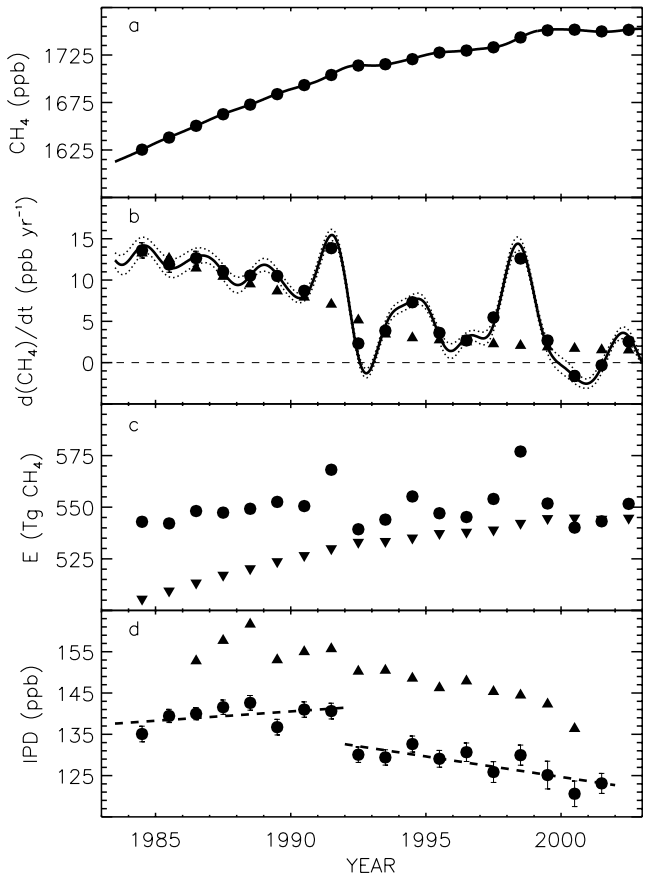

Figure 1. (a). Circles are global, annually averaged CH_4 dry-air mole fractions. Solid line is a deseasonalized trend curve fitted to the global averages. (Note that our CH_4 standard scale yields CH_4 values that are about 1% lower than laboratories using gravimetrically prepared standards [see e.g., *Cunnold et al.*, 2002].) (b). Instantaneous growth rate for globally averaged atmospheric CH_4 (solid line; dashed lines are $\pm 1\sigma$ [*Steele et al.*, 1992]). The growth rate is the time-derivative of the solid line in a. Circles are annual increases, calculated from the trend line in Figure 1a as the increase from January 1 in one year to January 1 in the next. Triangles are annual increase calculated with a 2-box model (i.e., mass balance by hemisphere) using constant CH_4 lifetime and emissions, except for decreased emissions of 5 Tg CH_4 yr^{-1} during 1992 and 1993. (c). Global CH_4 emissions (circles) and losses (triangles) calculated with a 1-box mass balance using observed CH_4 global-annual averages and annual increase, and a constant CH_4 lifetime of 8.9 years (see text). (d). Differences between northern (53°–90°N) and southern (53°–90°S) annual mean CH_4 mole fractions as a function of time (circles), referred to as IPD (interpolar difference) in text. Dashed lines are linear least squares fits to the time periods 1984–1991 and 1992–2001. Triangles are differences calculated from the results of a 3-D transport model.

recently. During 2000 and 2001, global CH_4 decreased, in agreement with *Simpson et al.* [2002]; these decreases were compensated by a small increase in 2002 to maintain constant global annual mean CH_4 from 1999–2002. It is too soon to tell if the small increase in 2002 indicates a return to the small growth rates, ~2 to 7 ppb yr^{-1}, observed in the mid-1990s, or if atmospheric CH_4 is at steady state. Abrupt changes in the CH_4 growth rate during 1991, 1992, and 1998 in Figure 1b have been used to test our understanding of the chemical sink [*Dlugokencky et al.*, 1996], wetland emission rates [*Walter et al.*, 2001; *Dlugokencky et al.*, 2001], and emissions from biomass burning [*Langenfelds et al.*, 2002].

[5] We previously showed that if the atmospheric lifetime of CH_4 were constant, the decreasing CH_4 growth rate could be explained as a system approaching steady state, with constant annual emissions [*Dlugokencky et al.*, 1998]. If this scenario were true, CH_4 would have reached steady state in the mid- to late-2010s at ~1780 ppb. An important assumption in this analysis was that the global [OH] had been approximately constant [*Prinn et al.*, 1995]. Recent measurements of methyl chloroform (MC) in the free troposphere and boundary layer over central Europe [*Krol et al.*, 2003] suggest that previous reports of trends in [OH] [*Prinn et al.*, 2001; *Krol et al.*, 1998] are in doubt, and that our earlier assumption of constant CH_4 lifetime was reasonable. Figure 1c (circles) shows total global CH_4 emissions calculated from $E = d[CH_4]/dt + [CH_4]/\tau$ [*Dlugokencky et al.*, 1998], where E is emissions in Tg CH_4, $[CH_4]$ is the global CH_4 burden determined from the observations, and τ is the CH_4 lifetime (assumed constant at 8.9 yr). Figure 1c suggests that there is no significant trend in emissions during the past 2 decades, but there is significant interannual variability in emission rate (or [OH], which is assumed constant in our analysis).

[6] We next explore changes in the CH_4 latitudinal distribution. Differences in annual mean CH_4 mole fractions between polar northern (PNH = 53° to 90°N) and southern (PSH = 53° to 90°S) latitudes (IPD = interpolar difference) are plotted in Figure 1d as circles (uncertainties are $\pm 1\sigma$). From 1984 to 1991, the difference increased at an average rate of (0.5 ± 0.4) ppb yr^{-1}, but after a decrease of ~10 ppb between 1991 and 1992, the difference has continued to decrease (-1.0 ± 0.3 ppb yr^{-1}), not recovering to pre-1992 levels.

[7] The same temporal pattern as described above for the IPD is seen when individual high northern latitude sites are compared with South Pole. For example, during 1984–1991, the difference between annually averaged CH_4 mole fractions at Barrow, Alaska and South Pole was 151 ± 4 ppb (1σ); during 1992–2001, the difference between these sites decreased to 140 ± 6 ppb. To improve our understanding of where CH_4 sources and sinks were changing to produce the observed change in IPD, we averaged differences in annual mean CH_4 mole fractions between each surface site and South Pole for 1997, 1999, and 2000 (1998 was excluded because there were large anomalous emissions from northern wetlands in that year [*Dlugokencky et al.*, 2001]) and subtracted the average differences calculated for 1984, 1985, and 1986. These differences represent the observed change in CH_4 latitude distribution from the mid-1980s to the late-1990s, and they are plotted as circles in Figure 2. The decrease in gradient is largest at very-high northern latitudes, decreasing towards mid- and tropical-latitudes; this indicates that the change in source/sink imbalance that caused the change in gradient (and IPD) occurred in high northern latitudes. Since little CH_4 is destroyed in polar latitudes, the change in IPD must be

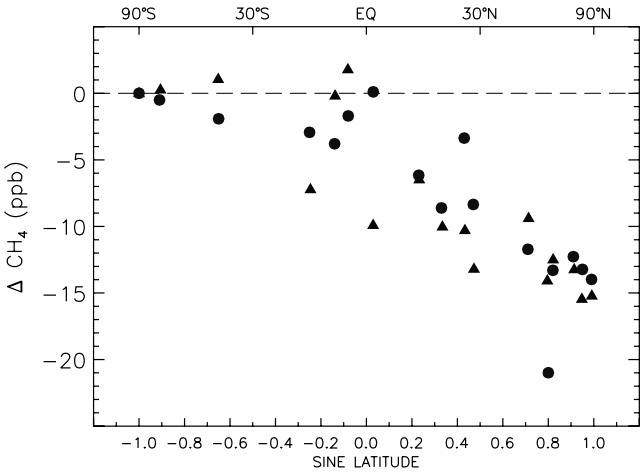

Figure 2. Change in atmospheric CH_4 latitude gradient between mid-1980s and late-1990s. ΔCH_4 is calculated by first determining the difference in annual mean CH_4 mole fraction between each sampling site and South Pole. These differences are then averaged for each site over two time periods: 1984–1986 (to represent the mid-1980s) and for 1997, 1999, and 2000 (to represent the late-1990s). Finally, each plotted symbol is the difference of the late-1990s average minus the mid-1980s average. Circles are based on the CMDL CH_4 data. Sites were included only if they contain at least one full year of measurements in each 3-year averaging period. The site at $\Delta CH_4 = -20$ ppb is Shemya; its difference with South Pole decreased by ~10 ppb from 1991 to 1992, then decreased by another 10 ppb after 1996 (except in 1998). The reasons for the second decrease are unknown. Triangles are ΔCH_4 calculated from the 3-D model results.

caused by a change in emissions, or by a change in atmospheric transport.

3.2. Evidence for Permanent Changes in CH_4 Emissions

[8] The change in IPD provides observational evidence that CH_4 emission rates from polar northern latitudes decreased in the early-1990s. Further observational evidence for this change comes from *in situ* quasi-continuous measurements of CH_4 and CO_2 at Alert, Canada [*Poß et al.*, 2003]. During winter, when there is often strong flow from Eurasia to Alert, CH_4 and CO_2 are highly correlated in well-defined pollution events. The ratio of CH_4/CO_2 during these events decreased, while anthropogenic CO_2 emissions in the former Soviet Union (fSU) decreased by 30% [*Olivier and Berdowski*, 2001; *Olivier*, 2002]. *Poß et al.* [2003] combine these observed ratios with CO_2 emission estimates and a trajectory model and calculate that CH_4 emissions decreased from high northern latitudes by 30 Tg from 1988 to 1999.

[9] Estimates of anthropogenic methane emissions in EDGAR3 [*Olivier and Berdowski*, 2001; *Olivier*, 2002], tabulated for 1980–1995 on 5-year intervals, also support decreased emissions. EDGAR3 emissions from the fSU decreased by 10.6 Tg CH_4 between 1990 and 1995. Major contributors to this decrease come from the fossil fuel sector (gas, coal, and oil) and animal emissions (enteric fermentation in ruminants and waste management). About 8 Tg of the decreased CH_4 emissions from the fSU in EDGAR3 resulted from decreased fossil fuel production: extraction of oil and coal peaked in the late-1980s, dropping to less than 2/3rds of their peak values by the mid- to late-1990s [*B.P. Statistical Review of World Energy*, 2002]. Also, natural gas extraction peaked in 1990, and then fell by 17% between 1991 and 1997. Economic incentives existed for decreased emissions from the natural gas sector after the Soviet economy collapsed in 1992. A comparison of the emission estimates from the natural gas industry in the fSU by *Reshetnikov et al.* [2000] and *Dedikov et al.* [1999] suggests that emissions decreased by more than 20 Tg CH_4 yr^{-1} (worth ~$4 billion) from 1991 to 1997. But, we note that there is no evidence in Gazprom (Russia's partly state-owned gas company) data to indicate that such large decreases in emissions occurred during the early-1990s (*A.I. Reshetnikov*, private communication).

3.3. Model Results

[10] We used a 3-D transport model (Tracer Model, Version 3: TM3 [*Houweling et al.*, 2000]) to see if the changes in emissions as reported in EDGAR3 are consistent with the observed decrease in IPD. A simulation was run at 4° latitude × 5° longitude resolution using assimilated, reanalyzed meteorological fields from the National Centers for Environmental Prediction for 1983–2000. Anthropogenic emission rates were from EDGAR3. Emissions distributions by source sector are available at 5-year intervals for 1980–1995. For other years in our simulation, global totals for lumped sectors were scaled linearly to prescribe emissions for each sector. Emission rates from natural sources and CH_4 sinks, both constant throughout the simulation, were as in *Houweling et al.* [2000], except that the ratio of emissions for bogs/swamps was as in *Bergamaschi et al.* [2001].

[11] Triangles in Figure 1d are model-simulated IPD for 1986–2000 calculated using only those model grid boxes that contain CMDL air sampling sites (the first 3 years of the model run were excluded to remove the influence of the initial conditions). Our simulation overestimates and lacks the abrupt decrease in observed IPD, but the change in IPD from the late-1980s to the late-1990s is of similar magnitude (~15 ppb) to the observed change. A test simulation (not shown) was run with emissions held at 1983 values, but meteorology was allowed to vary. This resulted in interannually varying, but approximately constant IPD, indicating that changes in simulated IPD were due to changes in EDGAR3 emissions, and were not due to changes in transport. Model results (triangles) are also plotted in Figure 2; the general pattern in ΔCH_4 is similar, but agreement in the tropics is poor.

[12] Natural variability in CH_4 emissions and sinks have cumulative effects on the CH_4 burden. In Figure 1b, triangles are CH_4 annual increases calculated by mass balance with constant CH_4 lifetime and emissions, except for a decrease in emissions of 5 Tg CH_4 yr^{-1} during 1992 and 1993 (total decrease of 10 Tg CH_4). The simulated annual increase is consistent with the observations, but interannual variability in observed CH_4 growth rate, particularly since 1990, makes it impossible to confirm that a decrease in emissions of 10 Tg CH_4 yr^{-1} from high northern latitudes during the early-1990s had an impact on observed global CH_4 growth rate. The IPD is not

sensitive to changing emission rates in mid-latitudes and the tropics. In EDGAR3, decreased emissions from the fSU are compensated by increases in emissions at mid- and tropical-latitudes, so global anthropogenic emissions in the inventory were the same for 1990 and 1995 (consistent with Figure 1c). Assuming all other emission and sink rates remained constant, a decrease of 10 Tg CH_4 yr^{-1} would lower the steady-state globally averaged CH_4 mole fraction by ~30 ppb.

4. Summary and Conclusions

[13] Our observations of a decrease in atmospheric CH_4 IPD are consistent with the ~10 Tg CH_4 decrease in emissions from the fSU from 1990 to 1995 reported in EDGAR3; decreased fossil fuel production and economic incentives suggest that the reductions were in the fossil fuel sector. It is unlikely that emissions from any other high northern latitude source decreased so abruptly and permanently. Our observation of constant global average CH_4 during 1999–2002 may in part result from these decreased emissions, but the annual rate of increase in CH_4 is too variable to say so with certainty. The consistency of our observations with the EDGAR3 emissions inventory gives hope that we are gaining a better understanding of past changes in the global CH_4 budget, but our understanding is still not sufficient to tell if the prolonged pause in CH_4 increase is temporary or permanent.

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