THE MITIGATION OF METHANE EMISSIONS FROM INDUSTRIALIZED COUNTRIES CAN EXPLAIN THE ATMOSPHERIC CONCENTRATION LEVEL-OFF

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Methane (CH4) is the second-most important anthropogenic greenhouse gas after carbon dioxide. Recently, CH4 concentration increase in the atmosphere has been observed to level-off. We analyze the emission trends based on statistics from the United Nations Framework Convention on Climate Change (UNFCCC) and show, using a single box model, that the decrease in the reported emissions from industrialized countries contribute to the reduced increase in CH4 concentration. The total reduction in CH4 emissions from industrial countries was 25 Tg yr−1 between 1990 and 2003. The reductions consisted of landfill gas recovery and other waste management policies, CH4 collection in coal mines, the repairing of gas networks, and structural changes in economy. Our study implies that the reduction of CH4 emissions can effectively mitigate climate change on a short time scale, and that the first results of mitigation measures are already observable in the atmosphere. However, there is an evident risk that the methane concentration will start to rise again due to increasing emissions from developing countries.

KEY WORDS: methane, climate change, emissions reduction, industrial countries

1. INTRODUCTION

Increased methane (CH4) concentration in the atmosphere contributes greatly to the anthropogenic perturbation of the radiative balance of the Earth and to climate change. CH4 is emitted by anthropogenic and annually varying natural sources. CH4 concentration has more than doubled since preindustrial times from around 700 ppb to over 1700 ppb. Its direct contribution to the radiative forcing is about one-third that of carbon dioxide (NOAA, 2005). The growth rate of CH4 concen-
tration in the atmosphere has decreased particularly since 1992 (NOAA, 2005; Dlugokencky et al., 1998, 2003; Hansen and Sato, 2001). Emissions reduction measures in industrialized countries have not been suggested as a reason for the reduced concentration growth rate (Dlugokencky et al., 1998, 2003; Simpson et al., 2002) and halting of the concentration increase. Only the impact of the collapse of the former Soviet Union (FSU) on methane emissions has been recognized (Dlugokencky et al., 1998, 2003; Wang et al., 2004). Recently, deforestation in tropical areas has been suggested as one possible contributor (Keppler et al., 2006). However, the annual emissions reported from industrial countries (Annex I Parties of the UNFCCC) have also decreased from 1990 to 1995 by 13 Tg yr\(^{-1}\) and to 2000 by 25 Tg yr\(^{-1}\) (UNFCCC, 2005).

The objective of this paper is to show, using a single box atmospheric concentration model, that the significant emissions reduction measures in Annex I countries, together with structural changes leading to emissions reduction, could be important contributors in the observed slowdown and level-off of methane concentration increase in the atmosphere.

2. EMISSIONS ESTIMATES AND ASSOCIATED UNCERTAINTY

Current estimates of anthropogenic methane sources emphasize the role of agriculture (43%), energy (35%), and waste (18%) sectors in total emissions (IEA, 2005). The enteric fermentation of ruminants and rice cultivation are the prominent agricultural sources, which are important particularly in developing countries. The mitigation of these emissions is difficult due to increasing human population and the nature of the processes.

In the energy sector, the most important emission sources are coal and gas production, transmission, and distribution. Natural gas consists mainly of CH\(_4\), and leakages from transmission and distribution networks are important sources of CH\(_4\). Biomass burning is also considered to be a significant source of CH\(_4\) emissions globally (Wuebbles and Hayhoe, 2002; Mikaloff Fletcher et al., 2004a; IPCC, 2001); however, there are large uncertainties in the estimates. In the waste sector, the main contributor is the anaerobic degradation of waste in landfills. These emissions can be mitigated by, e.g., the recovery and combustion of methane.

Estimates of global methane emissions vary notably and contain significant uncertainties (Wang et al., 2004; Wuebbles and Hayhoe, 2002; Mikaloff Fletcher et al., 2004a;b; IPCC, 2001). The current best estimates of total global emissions vary from 500 Tg yr\(^{-1}\) up to more than 600 Tg yr\(^{-1}\). It is estimated that around 30–40% of global emissions come from natural sources, of which wetlands and termites are the most important. Keppler et al. (2006) suggest that living plants may contribute as much as 62–236 Tg yr\(^{-1}\) to the global methane budget. Uncertainties in the estimates of natural emissions are even larger than those of anthropogenic emissions due to the spatial variability of emissions and the complex
emission generating phenomena. In addition, year-to-year variation causes uncertainty in the estimates of emissions for an individual year.

The total atmospheric burden of methane can be measured rather accurately, but there are large uncertainties in the estimates of emissions from different source categories (IPCC, 2001). Uncertainties in inventories of anthropogenic methane sources in industrial countries are estimated to vary between 20 and 50% (Rypdal and Winiwarter, 2001; Monni et al., 2004; Monni et al., 2006). These uncertainties are mainly due to the nature of CH\textsubscript{4} sources, which makes an accurate estimation of emissions difficult. Methane formation, e.g., in the digestion systems of ruminants or in anaerobic degradation in landfills, is a complex phenomenon, and the estimation of emissions by calculation models contains uncertainties. Additional uncertainty is associated with activity data and calculation parameters. However, the estimates of changes in emissions are less uncertain in the case of CH\textsubscript{4} recovery in landfills and coal mining; even though the absolute amount of methane from these sources remains unknown, emissions reduction can be estimated at an accuracy of a few per cent when the methane is collected and, e.g., combusted (Rypdal and Winiwarter, 2001).

The total reduction in CH\textsubscript{4} emissions from Annex I parties of the Kyoto Protocol was 25 Tg yr\textsuperscript{-1} between 1990 and 2003 (Table 1) (UNFCCC, 2005). In industrial countries, 60–70% of the emission reductions can be considered to have occurred due to structural change (UNFCCC, 2005; EEA, 2005). About half of emissions reduction from industrial countries is due to the collapse of the FSU and the resulting decrease in economic activity, leading to reduced energy consumption and fugitive emissions from fossil fuel production, transmission, and distribution. In addition, the number of cattle in the Russian Federation has more than halved from 1990 to 2000, leading to a corresponding decline in methane emissions from enteric fermentation (UNFCCC, 2004). Coal mining has decreased in many parts of

\textbf{TABLE 1:} Total annual CH\textsubscript{4} emissions from Annex I parties and the main contributors to the emission decreases between 1990 and 2003 (UNFCCC, 2005). Gap filling has been performed for some parties due to a lack of a complete time series

<table>
<thead>
<tr>
<th>Annex I party</th>
<th>Emissions (Tg CH\textsubscript{4} yr\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>26</td>
</tr>
<tr>
<td>US</td>
<td>29</td>
</tr>
<tr>
<td>Germany</td>
<td>6.3</td>
</tr>
<tr>
<td>UK</td>
<td>3.7</td>
</tr>
<tr>
<td>All Annex I parties</td>
<td>107</td>
</tr>
</tbody>
</table>
the world, particularly in Germany, the UK, and the FSU. In addition, there is a
trend toward more surface mines than underground mines, which also reduces
methane emissions (IEA, 2005).

In many Annex I countries of the Kyoto Protocol, important mitigation measures
of methane emissions have been committed in the 1990s and the 2000s. These in-
clude landfill gas recovery, CH\textsubscript{4} collection in coal mines, repairing of natural gas
networks, and policy measures to reduce the amount of waste landfilled. About
30\% of CH\textsubscript{4} emissions reduction from industrial countries can be explained by re-
ductions in Germany, the US, and the UK. In the US, landfills are the largest an-
thropogenic source of methane. Even though the amount of municipal solid waste
landfilled has increased, emissions have decreased by 24\% (2.0 Tg yr\textsuperscript{-1}) from 1990
to 2003 due to increased landfill gas collection and combustion by landfill opera-
tors. In the US, coal mining is another significant source of methane, where emis-
sions have decreased notably due to mitigation measures. CH\textsubscript{4} emissions decreased
by 34\% (1.3 Tg yr\textsuperscript{-1}) since 1990 due to the mining of less-gassy coal from under-
ground mines and the increased use of methane collected from degasification sys-
tems (EPA, 2005).

In Germany, CH\textsubscript{4} emissions have decreased by 43\% (2.7 Tg yr\textsuperscript{-1}) since 1990.
About 1.0 Tg yr\textsuperscript{-1} of this decrease is due to a reduced amount of waste landfilled,
as policy measures have led to increased recycling and energy recovery from
waste. Fugitive CH\textsubscript{4} emissions from fossil fuels have decreased by 0.9 Tg yr\textsuperscript{-1}
since 1990 due to decreased coal mining activity and to the repair and modern-
ization of gas distribution networks (Umweltbundesamt, 2005).

In the UK, the largest reduction in CH\textsubscript{4} emissions (0.9 Tg yr\textsuperscript{-1} since 1990) has
occurred in fugitive emissions from fuels. The largest contributor is coal mining,
where coal production has decreased to one-third. Since 1990, CH\textsubscript{4} emissions from
landfills have decreased by nearly 70\% (0.7 Tg yr\textsuperscript{-1}) as methane recovery systems
at landfills have been implemented (Baggott et al., 2005). Table 1 summarizes the
main observed changes in methane emissions from Annex I countries.

The anthropogenic methane emissions from the Annex I parties reported to the
United Nations Framework Convention on Climate Change (UNFCCC) can be
compared with the emissions recently published by the International Energy
Agency (IEA) (2005). The latter emissions estimates are based on the Emission
Database for Global Atmospheric Research (EDGAR) database developed by TNO
(the Netherlands Organization for Applied Scientific Research) and MNP (the
Netherlands Environmental Assessment Agency) (Olivier et al., 1999; 2005). The
EDGAR system provides estimates of global anthropogenic emissions of green-
house gases and other air pollutants on a 1 × 1 degree grid. EDGAR applies bot-
tom-up methodology in emissions estimates, with activity data and emission factors
mostly from international publications.

The emissions decrease in industrialized countries between the year 1990 and
2000 is 25 Tg yr\textsuperscript{-1} according to UNFCCC and 16 Tg yr\textsuperscript{-1} according to EDGAR.
The difference may be an indication of the uncertainty of the emissions reductions.
Estimates of CH₄ emissions from developing countries are very uncertain, and most developing countries have reported emissions for only one or two years (typically 1990 or 1994) to the UNFCCC. It is generally assumed that emissions from developing countries are increasing along with the population and activity increase (IEA, 2005). The IEA estimates that total global anthropogenic CH₄ emissions have increased by 3% from 1990 to 2000, indicating that the emissions increase from developing countries would be slightly more than the decrease of emissions from industrial countries. The majority of CH₄ emissions from developing countries stems from agriculture, where the main contributors are enteric fermentation and rice cultivation.

In developing countries, the number of cattle has increased by around 15% from 1990 to 2003 (FAOSTAT, 2005). If we use the Intergovernmental Panel on Climate Change (IPCC) Tier 1 method to calculate the emissions (IPCC, 1997), this means an emission increase of 4–7 Tg CH₄ yr⁻¹. The rice production area has not increased notably (only 2%) from 1990 to 2003 according to statistics from the Food and Agriculture Organization (FAO), and therefore it does not have a major effect on CH₄ emission trends, even though differences between different cultivation methods cause uncertainty in this conclusion. The share of the energy sector in CH₄ emissions from developing countries is around 25%, but its share of emissions increase is larger. CH₄ emissions from the energy sector in developing countries have been estimated to have increased by 12 Tg yr⁻¹ from 1990 to 2000 (IEA, 2005). The emissions derive mainly from coal mining and biomass combustion.

3. DEVELOPMENT OF ATMOSPHERIC CONCENTRATION

The atmospheric CH₄ burden increased between 1984 and 1991 by about 11 ppb yr⁻¹ on average (about 30 Tg yr⁻¹) and between 1992 and 1998 by about 6 ppb yr⁻¹ (16 Tg yr⁻¹) (Dlugokencky et al., 2003). Between 1999 and 2004, the increase of the CH₄ burden was close to zero (NOAA, 2005). The time behavior of the globally averaged concentration of CH₄ is often described with a single box model (Dlugokencky et al., 2003; IPCC, 2001):

\[
dC(t)/dt = -C(t)/\tau + S(t) ,
\]

where \( C \) is the atmospheric CH₄ concentration, \( \tau \) is the lifetime of CH₄ in the atmosphere, and \( S \) is the CH₄ source. The concentration can be assessed on the basis of measurements with quite good accuracy; however, the source and lifetime bear greater uncertainty and variation. Using the single box model with a constant lifetime of 8.9 years, global CH₄ emissions have been estimated to be practically constant from 1984 to 2002 (Dlugokencky et al., 2003).

Because Eq. (1) is linear, any source and its contribution to the total concentration can be considered separately. We estimated the impact of the emissions reductions in industrial countries since 1990 on the concentration using the single box
model [Eq. (1)] with the lifetime of 8.9 years. The source term $S$ in this calculation was the emission reductions described in Table 1. The impact of the emissions reduction on the concentration is about 50 ppb by 2003 (Fig. 1); hence, without the emissions reductions in the Annex 1 countries, the atmospheric concentration of methane would be 50 ppb higher.

This result is sensitive to the strength of the emission reduction. If the emission reductions calculated from the IEA (2005) report are used as $S$, the impact on the concentration is about a third smaller. However, this result is not sensitive to the assumption of the lifetime $\tau$. A change of 0.5 years in the lifetime caused only a 2% change in the reduced concentration in 2003. Close to the equilibrium concentration, the overall concentration is sensitive to the lifetime $\tau$, but when we consider a growing (but negative) concentration component alone, the term $S$ of Eq. (1) is greater than the term $-C(t)/\tau$, and the impact of the variation of $\tau$ is small.

If the impact of the methane emissions reductions on the atmospheric methane concentration (Fig. 1) is added to the measured methane concentration, the total hypothetical concentration seems to increase almost with the same rate as before the year 1990 (Fig. 2).

Thus the decreasing emissions from the Annex 1 countries lead to a decreasing concentration component. At the same time, natural emissions and emissions from non-Annex I countries cause other concentration components. The overall methane concentration in the atmosphere, the sum of all concentration components, is roughly constant after about the year 2000, but it will start to increase if the emissions from developing countries increase.
4. DISCUSSION AND CONCLUSIONS

We demonstrated that significant emissions reduction measures, together with structural changes leading to methane emissions reduction of up to about 25 Tg CH$_4$ yr$^{-1}$ in the industrialized countries, can be important contributors to the observed decrease and level-off of methane concentration increase in the atmosphere. Our conclusion is in agreement with that of Wang et al. (2004), who estimated CH$_4$ emissions based on geographic and seasonal distribution of CH$_4$ sources between 1988 and 1997 and pointed out the emissions decline in the FSU as a probable cause. However, we showed that the concentration increase would not have levelled-off without intentional and unintentional emission reductions from industrial countries, unless we assume that the effective lifetime of methane has changed.

The lifetime of CH$_4$ in the atmosphere is relatively short and, therefore, atmospheric CH$_4$ concentration responds quite rapidly to changes in the emissions if compared, e.g., to carbon dioxide, the effective lifetime of which is in the order of a hundred years (IPCC, 2001). The effects of mitigation measures of some other well-mixed gases have already been observed by atmospheric measurements. For example, the atmospheric concentrations of CFC-11 and CFC-113 have declined in recent years due to emission reductions under the Montreal Protocol signed at the end of the 1980s (Blake, 2005).
Hansen et al. (2000) have proposed that the control of CH\textsubscript{4} emissions is a rapid way to limit the rate of climate change. Our study suggests, on the basis of emissions statistics and model calculations, that the reduction of methane emissions can effectively mitigate climate change on a short time scale, and that the first results of mitigation measures in industrialized countries may already be observable in the atmosphere. This implies that further methane mitigation measures, e.g., in coal mines, gas fields, biomass burning, and waste management could provide efficient potential for the further limitation of atmospheric methane concentrations. Unless this is done, there is an evident risk that methane concentrations will start to rise again.

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