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Methane Emissions from Large Dams as Renewable Energy Resources: A Developing Nation Perspective

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Abstract By means of a theoretical model, bootstrap resampling and data provided by the International Commission On Large Dams (ICOLD (2003) World register of dams. http://www.icold-cigb.org) we found that global large dams might annually release about 104 ± 7.2 Tg CH_4 to the atmosphere through reservoir surfaces, turbines and spillways. Engineering technologies can be implemented to avoid these emissions, and to recover the non-emitted CH_4 for power generation. The immediate benefit of recovering non-emitted CH_4 from large dams for renewable energy production is the mitigation of anthropogenic impacts like the construction of new large dams, the actual CH_4 emissions from large dams, and the use of unsustainable fossil fuels and natural gas reserves. Under the Clean Development Mechanism of the Kyoto Protocol, such technologies can be recognized as promising alternatives for human adaptations to climate change concerning sustainable power generation, particularly in developing nations owning a considerable number of large dams. In view of novel technologies to extract CH_4 from large dams, we estimate that roughly 23 ± 2.6, 2.6 ± 0.2 and 32 ± 5.1 Tg CH_4 could be used as an environmentally sound option for power generation in Brazil, China and India, respectively. For the whole world this number may increase to around 100 ± 6.9 Tg CH_4.

Keywords Emission mitigation · MDL · Methane recovery · Renewable energy · Reservoir · Spillway · Turbine

1 Introduction

Large dams (LD) present a central role in the civilization development. In several nations, they are responsible for drinking water supply, river flood/drought control, irrigation for food production, and, more recently, for hydroelectric power generation. Although LD have been essential for the well-being of mankind, there are a

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number of environmental shortcomings emerging from damming and flooding pristine river basins. The well-known worldwide impacts of LD are local people displacement (Bartolome et al. 2000), fish community alteration and vanish of commercial fishery practices, lost of biodiversity, lost of natural and agricultural terrestrial ecosystems (Berkamp et al. 2000), and the emission of greenhouse gases to the atmosphere (Rosa and Santos 2000), especially methane (CH_4). In fact, the practice of flooding terrestrial ecosystems might be altering atmospheric CH_4 since the past five thousand years (Ruddiman 2003; Ruddiman et al. 2005).

After carbon dioxide, CH_4 is the most important greenhouse gas. It is responsible for more than 20% of change in the radiative forcing due to anthropogenic greenhouse gas emissions to the atmosphere (Shindell et al. 2005). The anthropogenic increase of the CH_4 mixing ratio in the atmosphere after the XVIII century has been attributed to coal, natural gas, forest clearing/burning, landfill, domestic ruminants and rice cultivation (Wuebbles and Hayhoe 2002). Several authors have shown that LD may also represent a fraction of the anthropogenic CH_4 (Saint Louis et al. 2000; Abril et al. 2005; Soumis et al. 2005; Duchemin et al. 2006). A first estimate indicated that for a global LD area of 1.5×10^6 km^2 about 69.3 Tg CH_4 (1 Tg = 10^{12} g) can be annually released by bubbling and diffusive processes (Saint Louis et al. 2000). Despite the uncertainties on LD upstream (reservoir surface) emissions, a forming consensus is that LD downstream (turbines and spillways) emissions might be responsible for a substantial release of CH_4 to the atmosphere (Fearnside 2002; Abril et al. 2005; Guérin et al. 2006; Kemenes et al. 2006). A ''degas drop-pressure effect'' arises when CH_4-saturated water passes through turbines and spillways (Fearnside 2002; 2004; 2005a, b). In conjunction with turbulence, this effect may lead to cavitation phenomena, creating suitable conditions for bubble (short-term) CH_4 releases immediately downstream to LD. In addition, enriched-CH_4 waters may steadily (long-term) release CH_4 to the atmosphere on the course of several kilometers downstream to LD (Guérin et al. 2006; Kemenes et al. 2006).

Following this rational, Bambace et al. (2007) have proposed a series of engineering solutions to mitigate upstream and downstream CH_4 emissions. These technologies, associated to efficient CH_4 degassing and storage systems, can promote the recover of the non-emitted CH_4 for power generation. In brief, turbine and spillway emissions should be controlled by gate-buoys, allowing only CH_4-depleted surface waters being turbined or spilled downstream. The non-emitted CH_4 can therefore be extracted upstream at the hypolimnion via CH_4 degassing/storage systems (Bambace et al. 2007), before the occurrence of either surface atmospheric emission or oxidation by methanotrophic bacteria in the water column (Guérin and Abril 2004; Lima 2005). For Amazon LD, a first assessment indicates that power generation from biogenic CH_4 is technically and economically viable (Ramos et al. 2007).

In the present paper, we show updated calculations for global LD CH_4 emissions. By means of a theoretical model, bootstrap resampling and data provided by the International Commission On Large Dams (ICOLD 2003) we compute approximations of upstream and downstream LD CH_4 emissions. We further estimate the potential power generation from LD CH_4 recovery in the world, and in three important developing nations owning a considerable number of LD, namely Brazil, China and India.

2 Data sources, model premises and parameterization

Although most premises in the present model are based on published information, chosen parameters can be very specific, and a case-by-case model would be rather impracticable for 31,148 LD available in ICOLD (2003) between 1880 and 2005. The model is then an *a priori* assessment, and an effort to extend the global empirical information is necessary to better define model parameters and to improve the results herein obtained.

2.1 Annual upstream CH_4 emission model

Annual upstream CH_4 emission estimations (f_{up}) were made by using empirical equations determined for temperate lakes by Bastviken et al. (2004, Table 2, p. 6), relating lake surface area to diffusive, bubble and storage (overturn) CH_4 emissions. There are in total 33,071 registered LD in ICOLD (2003). From 1880 to 2005 there are 31,148 registered LD in the world, of which 73% present surface area information (ICOLD 2003).

Uncertainties in the upstream CH_4 emission model are in part associated to log-log regression equations given in Bastviken et al. (2004). Log–log regression indeterminacies are approximately 22, 14 and 59% for bubble, diffusive and overturn emissions (Bastviken et al. 2004). Besides, the equations are given solely for lakes in the temperate region. After several years of impoundment, a *steady state* reservoir tends to present similar bacterial abundance and biomass of surrounding natural lakes (Soumis et al. 2005). It was then assumed that both temperate reservoirs and lakes might exhibit comparable steady state annual upstream CH_4 emissions. We do not consider transient large emission after LD reservoir filling because the time spam to reach steady state of about 10 years is small (Abril et al. 2005; Soumis et al. 2005) in relation to the 125-year period of analysis. Furthermore, CH_4 lifetime in the atmosphere was around 6.2 and 8.4 years between 1880 and 2005 (Lelieveld et al. 1998).

Upstream CH_4 emissions of tropical LD should be 5- to 15-fold superior to upstream CH_4 emissions of temperate LD (Saint Louis et al. 2000; Soumis et al. 2005). For this reason, it was assumed that CH_4 upstream emissions in tropical LD can be roughly 10-fold superior to those in temperate LD. Another simplification and source of uncertainty in the upstream CH_4 emission model is that tropical (temperate) LD were considered those that at lest 50% of the LD nation area is within (outside) the equatorial region between 20° N and 20° S. The same was done for the downstream CH_4 emission calculations.

For consistency assessment in the upstream emission model, we calculated local mean (±1 standard deviation, SD) and median CH_4 emission factors for temperate and tropical LD, and compared them to empirical values of a recent compilation (Table 1). Such compilation however does not include overturn emissions (Soumis et al. 2005). Although all uncertainties cannot be fully assessed for model optimization, the output of the upstream CH_4 emission model is reasonably consistent to empirical data. The model and empirical means were of similar magnitude in both temperate and tropical cases (Table 1). For the tropical case, the model median is about 2.3 above the empirical median, while the separation between model and empirical means is quite narrow. In general, empirical means are 4.8 and 1.2 greater than model means. Coefficients of variation are between 38 and 43% in model and

Table 1 Local upstream mean (±SD) and median CH_4 emission factors for large dams in the world by 2005

	Local mean ± SD, mg CH_4 m^{-2} d^{-1}	Local median, mg CH_4 m^{-2} d^{-1}	*n*	Ref.
Temperate	11.5 ± 4.40	10.8	17315	This study[a]
	55.1 ± 84.7	9.30	26	Soumis et al. (2005)[b,c]
Tropical	109 ± 46.7	103	5536	This study[a]
	136 ± 245	44.6	43	Soumis et al. (2005)[b]

Estimated local CH_4 emission factors in this study are contrasted to a recent compilation of empirical values obtained by Soumis et al. (2005)

[a] Model emission factors that considers diffusive, bubble and storage emissions using equations given in Bastviken et al. (2004). Tropical emissions are assumed to be 10-fold superior to temperate emissions (Saint Louis et al. 2000; Soumis et al. 2005)

[b] Empiric emission factors that considers only diffusive and bubble emissions in Soumis et al. (2005, Table 1, p 204)

[c] Temperate and boreal values in Soumis et al. (2005, Table 1, p 204)

between 154 and 180% in empirical statistics. Differently from the empirical case, means and medians are very close in the model statistics (Table 1). Statistical differences between model and empirical data can result from distinct sample size. On the other hand, it is likely that the upstream CH_4 emission model lacks low frequency extreme events, a source of uncertainties that can underestimate model results. This can emerge from the log-log data smooth resulted from Bastviken et al. (2004) equations. In contrast, it is occasionally advisable to use median instead of mean factors (Soumis et al. 2005), then model might be able to constrain distortions introduced by extreme events, especially in bubble CH_4 emissions (Ramos et al. 2006).

2.2 Annual downstream CH_4 emission model

Downstream CH_4 emissions are here indicated as the total emission taking place downstream to LD, comprising short-term (instantaneous) CH_4 degassing just after the spillways and turbines, and the long-term CH_4 degassing while rivers are flowing several kilometers downstream. For convenience, we assumed that 80% CH_4 is fully degassed downstream. For Amazon LD, this value is consistent to the CH_4 fraction that might be short-term degassed (~60%) after the dam, added to the long-term degassing (~20%) while river is flowing downstream (Abril et al. 2005; Guérin et al. 2006). The lack of data in other regions of the world does not allow evaluating uncertainties associated to downstream degassing. Note, however, that it might be reasonably usual to find series (cascade) of LD in large river basins. For those cases, long-term degassing could be higher than 20%, making our premise likely conservative but still meaningful.

2.3 Estimation of the annual downstream CH_4 emissions

Annual spillway or turbine CH_4 emission (in Tg CH_4 y^{-1}) for a specific large dam was calculated by $f_i = dq_i c_i t_i$, where i denotes spillway (sp) or turbine (tb), d the degassing factor, assumed as 80%, q_i the water outflow (in m^3 day^{-1}), c_i the mean annual CH_4 concentration at the water inlet (in Tg CH_4 m^{-3}), and t_i the annual time

of operation (in days). Annual downstream CH_4 emission for a specific large dam is thus $f_{ds} = f_{sp} + f_{tb}$. Spillway outflow data are available for 18,105 cases or 58% of LD registered between 1880 and 2005 in ICOLD (2003). Turbine outflow (q_{tb}, in $m^3\ s^{-1}$) was calculated by combining dam height (h, in meters) and power generation (p, in MW) in ICOLD (2003) as $q_{tb} = 100p/0.95\ h$. Turbine outflow data are available for 3674 cases or 46% of hydroelectric LD registered between 1880 and 2005 in ICOLD (2003).

From Table 1 and Fig. 3C shown in Abril et al. (2005, p. 4 and 6), a 10-year steady state tropical reservoir may present an annual mean CH_4 water column profile of about 250 μM (4.0 g $CH_4\ m^{-3}$) with values ranging from 0.1 to 1300 μM (0.002–20.8 g $CH_4.m^{-3}$) at the epilimnion and hypolimnion, respectively. The decrease in CH_4 concentrations towards the surface is a result of methanotrophic activities (Guérin and Abril 2004; Abril et al. 2005; Lima 2005). These values can be highly variable among LD and the lack of field data cannot allow us to assert precise values for temperate and tropical regions. Thus we assumed that turbine intakes at tropical reservoir in steady state would present a mean methane concentration around 4.0 g $CH_4.m^{-3}$ (Abril et al. 2005), while for a temperate LD this value would be 10-fold lower, as upstream emission factors are presumed an order of magnitude inferior for temperate LD (Table 1).

Spillways might be usually active in 1/4 of the year to cope with the rainy/defrost season (depending upon latitude and altitude). The rest of time spillways are possibly blocked to keep water stored upstream the dam in the dry/snow season. In contrast, turbines might be active 3/4 of the year, the rest of time kept inactive for maintenance practices, power generation and water level control, fish rescue, etc. The time of operation of both spillway and turbine can be very specific for each LD, and such simplification in the present model imply in additional unquantifiable uncertainties.

2.4 Bootstrap resampling and uncertainty analysis

Upstream and downstream models together $f_{\text{total}} = \sum_{1}^{n} (f_{\text{up}} + f_{\text{ds}})$ provide an approximation of the total CH_4 emissions from LD registered in the ICOLD (2003) database in any specific year or nation within 1880–2005. Well-known uncertainties earlier discussed are hardly quantifiable, however uncertainty analysis mostly associated to the ICOLD (2003) database can be implemented through the computation of pseudo-random samples (iterations) by bootstrap procedures. In specific, the fast and consistent Mersenne-Twister pseudo-random number generator (Matsumoto and Nishimura 1998) is very useful to generate samples with replacement that have similar statistics of the original population. We used the Mersenne-Twister bootstrap procedure to estimate the mean and the standard deviation of global LD CH_4 emissions evolving in time, from 1880 to 2005, and to estimate the mean and the standard deviation of CH_4 emissions and potential CH_4 recovery by 2005 for the world, Brazil, China, India.

The time-evolving analysis was made by annually computing 1000 bootstrap iterations of f_{up}, f_{sp} and f_{tb} (for n LD integrated for each year). It was afterward computed the bootstrap mean (±1 SD) for each year in the 1880–2005 period. The time-evolving CH_4 emission curves were obtained by yearly integrating bootstrap means (±1 SD). On the other hand, the bootstrap mean (±1 SD) CH_4 emissions by

2005 were calculated by computing 1000 iterations of f_{up}, f_{sp} and f_{tb} for the world, Brazil, China and India in the whole 1880–2005 period. For both time-evolving and 2005 calculations, the bootstrap resampling included the (n-N) missing values, thus raising the bootstrap sample size to the total number of LD between 1880 and 2005 in ICOLD (2003).

Besides to the quantification of LD CH_4 emissions and recovery, the bootstrap upstream/downstream model also allowed contrasting historical CH_4 emissions from LD to the observed increase in the atmospheric CH_4 mixing ratio (Etheridge et al. 2002, Dlugokencky et al. 2006), and to well-known anthropogenic CH_4 sources (Stern and Kaufmann 1996; Houghton and Hackler 2002).

3 Results and discussions

3.1 Global CH_4 budget and upstream/downstream CH_4 sources

Atmospheric CH_4 burden is globally modulated by natural and anthropogenic sources. Natural sources as wetlands, termites, oceans, marine sediments, geological sources and wild fires may annually release 145 to 200 Tg CH_4 (Lelieveld et al. 1998; Wuebbles and Hayhoe 2002). Anthropogenic emissions, comprising coal mining and combustion, oil and gas related emissions, biomass burning, domestic ruminants, waste disposal and rice paddies are expected to range in between 340 and 350 Tg CH_4 (Lelieveld et al. 1998; Wuebbles and Hayhoe 2002). The total annual sources can therefore be estimated in between 485 and 550 Tg CH_4. There are uncertainties concerning these values, as it assumes constancy in atmospheric CH_4 removal by sinks, while the strength of natural and anthropogenic CH_4 sources are very variable in space and time (Bousquet et al. 2006). That makes possible the addition of previously unconsidered CH_4 sources, such as geologic (Etiope 2004) and tropical forest emissions (Keppler et al. 2006). Here we provide convincingly evidences to add LD CH_4 sources in the global atmospheric CH_4 budget.

3.1.1 Upstream CH_4 emissions

Figure 1 illustrates time-evolving upstream CH_4 emissions from 1880 to 2005. The circles denote the time-evolving upstream emissions for the original data in ICOLD (2003). The black curve and the shade area correspond respectively to the bootstrap mean and ±1 SD. The bootstrap model departs from the original model by 1950. Between 1950 and 2005 more than 8000 LD were created in the world, however these LD lack area information in ICOLD (2003). Thus time-evolving bootstrap resampling permitted verifying that actual upstream CH_4 emissions from global LD are most likely between 1.7 and 4.1 Tg CH_4. Table 2 shows global 2005 upstream CH_4 emissions estimated from the original ICOLD (2003) and from the bootstrap analysis for the whole resampled ICOLD (2003) database. The bootstrap analysis for the whole database including missing values suggests that global upstream CH_4 emissions are about 3.486 ± 0.230 Tg CH_4 or 37% above the original upstream emission model. This difference results from the inclusion of missing values in the bootstrap resampling procedure.

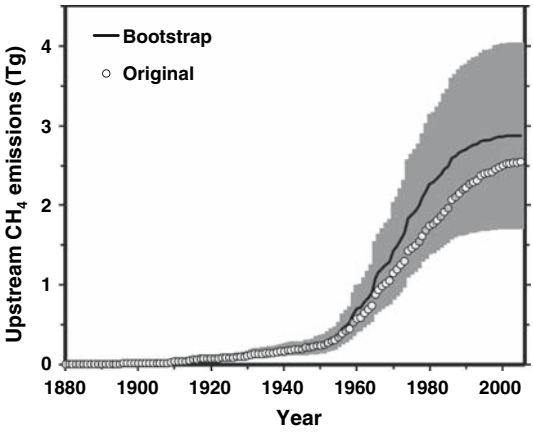

Fig. 1 Model results for the history (1880–2005) of upstream LD CH_4 emissions. Circles denote original mean values, while the dark line and the shaded area correspond respectively to the bootstrap mean and standard deviation

Saint Louis et al. (2000) found that around 69.3 Tg CH_4 would be annually released upstream LD assuming an area of 1.5×10^6 km^2. We computed in ICOLD (2003) an area of 0.436×10^6 km^2 for 22,851 LD in 1880–2005. From 100 to 1879 there are registered 446 LD that covers about 8085 km^2. A bootstrap extrapolation for the 31,148 LD in the 1880–2005 period would extend LD cover area to $0.567 \pm 0.048 \times 10^6$ km^2. The difference between Saint Louis et al. (2000) and our upstream model is twofold. Firstly, they reported a tropical mean emission factor of 300 mg CH_4 m^{-2} d^{-1} (Saint Louis et al. 2000, Table 3, p. 771), approximately three times superior to mean emission factors calculated in this work (Table 1) and in Soumis et al. (2005). Secondly, they use simple linear extrapolations. Assuming model mean factors in Table 1 and linear extrapolation as proposed by Saint Louis et al. (2000), upstream LD emissions are calculated as 25.9 Tg CH_4 for the theoretical 1.5×10^6 km^2 LD area (40% tropical). Indeed, due to non-normal statistical distributions, we may encounter problem when attempting simple extrapolations by purely combining CH_4 emission factors and wide LD areas. The use of Bastviken et al. (2004) equations allows assigning distinct upstream LD emissions, hence preserving log-normal statistic distribution of LD areas (Kolmogorov–Smirnov test statistic = 0.026, $p = 0.0000001$) in LD CH_4 emissions. For example, the linear extrapolation for the 0.436×10^6 km^2 (33% tropical, as we have found) provides about 6.43 Tg CH_4 when using model mean factors given in Table 1. By applying Bastviken et al. (2004) equations, this number falls to 2.54 Tg CH_4 (Table 2). As a result, the theoretical 1.5×10^6 km^2 LD area might annually emit around 10.2 Tg CH_4, which is in the midrange of global natural lake emissions, disregarding plant-mediated flux component (Bastviken et al. 2004, Table 3, p. 10).

3.1.2 Downstream CH_4 emissions

Here we report the first estimation of global downstream LD CH_4 emissions. Figure 2 illustrates time-evolving downstream CH_4 emissions from 1880 to 2005. The time-evolving bootstrap resampling permitted verifying that downstream LD CH_4 emissions from global LD can lie between 35 and 76 Tg CH_4. However, the bootstrap analysis for the entire database suggests that downstream LD CH_4 emissions are 100.8 ± 6.984 Tg CH_4 or 90% above the original downstream emission model (Table 2). The difference between time-evolving bootstrap (Fig. 2) and 2005

Table 2 Annual upstream and downstream CH_4 emissions from large dams with information on year of operation start (ICOLD 2003) in the world, Brazil, China and India

		Brazil	China	India	World
ICOLD (2003) Original	Upstream emissions in Tg CH_4	0.450 (n = 169)	0.043 (n = 2194)	0.501 (n = 2538)	2.542[a] (n = 22,851)
	Downstream emissions in Tg CH_4	12.65 (n = 555; n = 124)	1.822 (n = 4069; n = 965)	12.47[b] (n = 3713)	53.03 (n = 18,105; n = 3674)
	Downstream emissions (%)	97	98	96	95
ICOLD (2003) Bootstrap	Upstream emissions in Tg CH_4	1.657 ± 0.145 (N = 624)	0.091 ± 0.013 (N = 4652)	1.066 ± 0.382 (N = 4005)	3.486 ± 0.230[a] (N = 31,148)
	Downstream emissions in Tg CH_4	20.10 ± 2.421 (N = 624; N = 222)	2.598 ± 0.188 (N = 4652; N = 1875)	13.17 ± 1.757[b] (N = 4005)	100.8 ± 6.984 (N = 31,148; N = 7940)
	Downstream emissions (%)	92	97	93	97

Results were obtained by modeling the original and bootstrap (resampling with 1000 iterations) ICOLD (2003) dataset. Estimated CH4 emissions are integrated for the 1880–2005 period. In parenthesis is provided the number of LD. The number of LD for downstream emissions is for "spillway; turbine"

[a] These numbers might increase to around 10.2 Tg CH_4 if a theoretical 1.5×10^6 km^2 LD area is used (see text for further details)

[b] Only spillway emissions. Turbine emissions (N = 152) from Indian hydroelectric LD could not be modeled due to the lack of turbine outflow data in ICOLD (2003)

Table 3 Estimation of CH_4 production (emission + oxidation) and potential recovery from large dams in the world, Brazil, China and India

	Upstream $TgCH_4$	Downstream $TgCH_4$	Total production $TgCH_4$	Potential recovery $TgCH_4$
Brazil	8.285 ± 0.725	25.12 ± 3.027	33.41 ± 3.752	23.38 ± 2.626
China	0.455 ± 0.065	3.248 ± 0.235	3.703 ± 0.300	2.592 ± 0.210
India	5.330 ± 1.910	40.49 ± 5.402[a]	45.82 ± 7.312	32.07 ± 5.118
World	17.43 ± 1.150	125.9 ± 8.730	143.4 ± 9.880	100.4 ± 6.916

[a] Downstream emissions from Indian LD were calculated by adding spillway emissions in Table 2 to turbine emissions calculated by assuming the proportion between turbine emissions and the number of hydroelectric LD in Brazil and in India (Table 2)

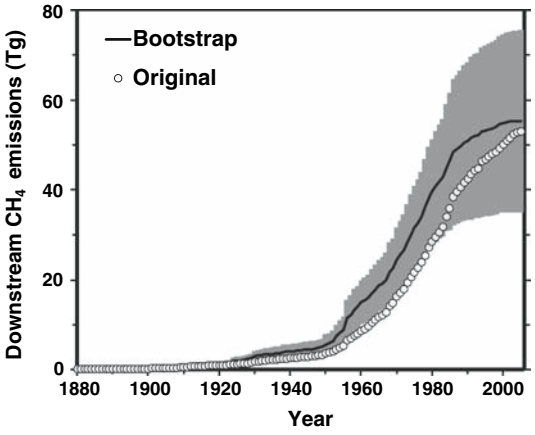

Fig. 2 Model results for the history (1880–2005) of downstream LD CH_4 emissions. Circles denote original mean values, while the dark line and the shaded area correspond respectively to the bootstrap mean and standard deviation

bootstrap calculations (Table 2) is due to the greater $(n\text{-}N)/N$ ratio in time-evolving procedure, i.e., the inclusion of a greater number of missing values when bootstrap is yearly computed. On the other hand, the difference between original and bootstrap models results from the inclusion of missing values in the bootstrap resampling procedure.

3.1.3 Large dams altering atmospheric CH_4 burden

Data from 1880 to 1994 of well-known anthropogenic CH_4 sources as landfill, rice paddies, livestock, coal mining, gas flaring, gas supply and biomass burning were obtained in Stern and Kaufmann (1996). Recalculations of annual biomass burning were made with recent data provided in (Houghton and Hackler 2002), thus improving anthropogenic (SKH) CH_4 sources. In Fig. 3 is shown a plot contrasting atmospheric CH_4 mixing ratio (Etheridge et al. 2002; Dlugokencky et al. 2006) to SKH sources alone and to SKH + LD. Compared to SKH sources alone, LD contribution turn out significant in the middle of the XX century. By summing up bootstrap upstream and downstream emissions we achieve global LD CH_4 emissions of 104.3 ± 7.214 Tg CH_4, which represent about 30 to 31% of the actual anthropogenic CH_4 sources (Lelieveld et al. 1998; Wuebbles and Hayhoe 2002). Consequently, anthropogenic CH_4 sources should lie in roughly 450 Tg CH_4 when LD CH_4 sources are included (Fig. 3).

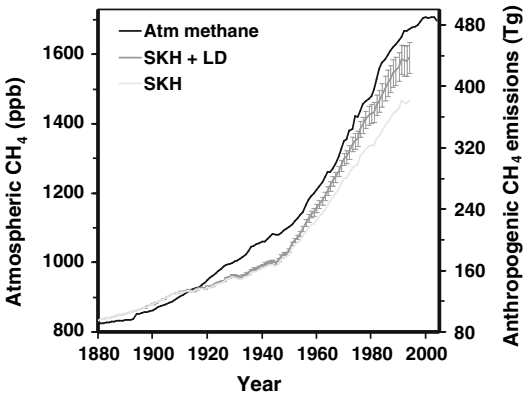

Fig. 3 History (1880–2005) of the atmospheric CH_4 mixing ratio contrasted to well-known anthropogenic CH_4 sources (SKH) and to SKH plus bootstrap (mean ± SD) LD CH_4 emissions (SKH + LD)

Also note in Fig. 3 that atmospheric CH_4 mixing ratio seems to stabilize at 1700 ppb by 1990. Dlugokencky et al. (1998, 2003) attributed this decline of the annual atmospheric CH_4 increments to a decrease in production/consumption of natural gas, oil and coal in northern latitudes. Latest findings, however, suggest that anthropogenic CH_4 sources in northern hemisphere have indeed augmented and the actual decline in the atmospheric CH_4 growth rate is most likely due to a decrease in natural wetland CH_4 emissions (Bousquet et al. 2006). Note however that Figs. 1 and 2 also indicate a stabilization of LD CH_4 emissions by the 1990s, which, in turn, might also partially explain the recent stabilization observed in the atmospheric CH_4 burden.

3.2 CH_4 emissions from large dams in Brazil, China and India

Upstream and downstream CH_4 emissions from three developing nations are presented in Table 2. From the bootstrap analysis around 21.8, 2.69 and 14.2 Tg CH_4 are emitted to the atmosphere from LD in Brazil, China and India. Note that LD CH_4 emissions in India are underestimated due to the lack of turbine flow information in ICOLD (2003). By assuming a proportion between spillway/turbine emissions and the number of hydroelectric LD in Brazil, we roughly estimate that 19.2 Tg CH_4 could be released by Indian LD turbines, thus increasing downstream LD emissions from India to 32.4 Tg CH_4. In contrast, the exceptionally low CH_4 emissions for LD in China resulted from the model ''temperate/tropical'' simplification. China and global LD CH_4 emissions could be underestimated by roughly 16 Tg CH_4, if considering tropical instead of temperate factors in the bootstrap model. In any case, and accordingly to model premises, most of CH_4 emissions took place downstream LD; between 92 and 98% of the total CH_4 emissions in the three developing countries and in the world occurred downstream LD (Table 2).

3.3 Potential recovery of non-emitted CH_4 from large dams

It is possible that atmospheric CH_4 mixing ratio continues to rise in this century due to an increase of anthropogenic emissions (Bousquet et al. 2006; Lelieveld et al. 2006). Very recently, several nations have been promoting a substantial effort to replace fossil fuels by renewable energy resources with the aim of reducing

greenhouse gas emissions and global warming. Hansen and Sato (2004) suggest that the permitted level of continuing CO_2 emissions depends significantly on reducing the magnitude of non-CO_2 climate forcings, particularly CH_4. Eliminating anthropogenic CH_4 emissions would have the largest effect, about 54% of the forcing from CO_2 (Shindell et al. 2005). Mitigating CH_4 emissions tends to increase atmospheric OH and to reduce both tropospheric ozone and stratospheric water vapor, thus indirectly dipping the climate forcing of other greenhouse gases in the atmosphere (Hansen and Sato 2004; Shindell et al. 2005). From this perspective, and assuming consistency in the ICOLD (2003) database and in the present model, much of the greenhouse gas emission mitigation effort can be directed to LD emissions. Essentially, there are direct and indirect mitigations, as long as emissions are converted into renewable power generation, preventing the use of fossil fuel energy.

In order to evaluate the potential amount of CH_4 recoverable from LD, we show in Table 2 estimates of upstream and downstream CH_4 emissions from LD taking place in the world, Brazil, China and India by 2005. For the Indian case, we assume that downstream emissions are possibly around 32.4 Tg CH_4, by including the previous ''Brazilian-derived'' Indian turbine emissions. If we consider that upstream emissions may represent about 20% of the total methanogenesis taking place in the reservoir sediments, and that 20% of the CH_4 is oxidized in the long-term downstream, we are able to calculate the potential CH_4 produced within LD. The obtained values are shown in Table 3. Between 75% and 88% of the produced CH_4 is potentially recovered from downstream emissions.

Assuming the use of a gate-buoy system to minimize downstream emissions, and a degassing system to recover CH_4 upstream in deep waters of the reservoirs, with a recovery efficiency of about 70 % (Bambace et al. 2007), it might be possible to annually recover approximately 58 Tg CH_4 in Brazil, China and India. This amount is about twice the annual CH_4 emission estimated for the Amazon floodplain (Melack et al. 2004) and corresponds to an annual power generation of about 24.7 GW, according to efficiencies described in Bambace et al. (2007). The global warming potential of CH_4 is 23 when compared to CO_2 (Ramaswamy et al. 2001). Hence the recovery of LD CH_4 would avoid about 1267 Tg CO_2-equivalent solely by CH_4 emission mitigation procedures. The replacement of energy supply from natural dry gas (15.3 metric tons $CO_2.TJ^{-1}$ (IPCC 1997)) to biogenic LD CH_4 in Brazil, China and India would raise avoided annual emissions to around 1300 Tg CO_2-equivalent. Specifically to Brazil, the inclusion of CH_4 emissions from LD in the national inventory would increase annual emissions to 4.5 metric tons CO_2 per capita. In contrast, the accomplishment of both mitigation and recovery procedures may drop this value to 1.9, still below the global average of 3.9 metric tons CO_2 per capita. The potential power generation from the recovery of non-emitted LD CH_4 in Brazil likely represents about half of the total natural gas use in social, economic and government sectors (EPE 2006).

For the global LD case, about 42.7 GW is potentially produced from the recover of about 100 Tg CH_4. Therefore, more than half of the global LD CH_4 production is potentially recoverable from the three developing nations here evaluated. The mitigation of the globally produced CH_4 within LD might prevent an emission of about 2317 Tg CO_2-equivalent, while employing such amount for energy purposes would increase global avoided emissions to around 2374 Tg CO_2-equivalent.

4 Concluding remarks

In spite of its simplicity, the a priori model allowed us to estimate LD CH_4 emissions and the corresponding potential CH_4 recover for power production. We also verified that the history of worldwide LD CH_4 emissions follows the increase of well-known CH_4 sources and the atmospheric CH_4 mixing ratio from 1880 to 2005. Further efforts are urged to better characterize emissions and the potential power production from non-emitted LD CH_4. We might be careful with the results herein shown not only due to model uncertainties, but especially because the distribution of LD emissions are log-normal. Accordingly, the effort to recover non-emitted CH_4 should be addressed to more representatives LD in the world, as about 47% of total CH_4 emissions occur for approximately 25% of global LD.

If ICOLD (2003) database and model premises are all suitably consistent, non-emitted CH_4 from LD might represent a promising alternative source of power. The purification of the recovered LD biogas might be a matter of concern because there are large amounts of CO_2 accompanying CH_4 gas. CO_2 may determine the burning efficiency of the gas mixture, but if adequately removed, it can be directly released to the atmosphere because it originates from biogenic (not fossil) activities.

Mitigation of climate change would primarily require the replacement of non-renewable energy resources. Although biomass, wind and solar power have gained notice in the last years, we provide evidences of a neglected clean power source. The CH_4 emission mitigation and the recovery of CH_4 from LD might be very useful, as the recovered biogas can be used in thermopower facilities, industrial sites, villages, or even purified for public vehicle transportation. All this can be implemented under the Kyoto Protocol for the creation of novel Clean Developing Mechanism (and also Joint Implementation) projects.

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