Three decades of global methane sources and sinks

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Methane is an important greenhouse gas, responsible for about 20% of the warming induced by long-lived greenhouse gases since pre-industrial times. By reacting with hydroxyl radicals, methane reduces the oxidizing capacity of the atmosphere and generates ozone in the troposphere. Although most sources and sinks of methane have been identified, their relative contributions to atmospheric methane levels are highly uncertain. As such, the factors responsible for the observed stabilization of atmospheric methane levels in the early 2000s, and the renewed rise after 2006, remain unclear. Here, we construct decadal budgets for methane sources and sinks between 1980 and 2010, using a combination of atmospheric measurements and results from chemical transport models, ecosystem models, climate chemistry models and inventories of anthropogenic emissions. The resultant budgets suggest that data-driven approaches and ecosystem models overestimate total natural emissions. We build three contrasting emission scenarios — which differ in fossil fuel and microbial emissions — to explain the decadal variability in atmospheric methane levels detected, here and in previous studies, since 1985. Although uncertainties in emission trends do not allow definitive conclusions to be drawn, we show that the observed stabilization of methane levels between 1999 and 2006 can potentially be explained by decreasing-to-stable fossil fuel emissions, combined with stable-to-increasing microbial emissions. We show that a rise in natural wetland emissions and fossil fuel emissions probably accounts for the renewed increase in global methane levels after 2006, although the relative contribution of these two sources remains uncertain.

Reconstructions of atmospheric methane (CH₄) concentrations between 1850 and the 1970s have been made using air trapped in polar ice cores and compacted snow. The data reveal an exponential increase in CH₄ levels in the atmosphere from 830 ppb to 1500 ppb in the late 1970s. Direct measurements of CH₄ in the atmosphere began in 1980, and reached global coverage after 1983. Today, CH₄ concentrations can be assessed using discrete air samples collected regularly at the surface, continuous measurements made at the surface or from space⁴–⁶ (see Supplementary Section ST1). Surface-based observations from four networks (National Oceanic and Atmospheric Administration, NOAA⁴; Advanced Global Atmospheric Gases Experiment, AGAGE¹⁴; Commonwealth Scientific and Industrial Research Organization, CSIRO⁶; and University of California Irvine, UCI¹¹) show consistent changes in the global growth rate of annual CH₄ concentrations since 1980 (Fig. 1 and Supplementary Section ST1). The agreement between these networks has improved with increasing coverage. The standard deviation for the global annual growth rate decreased from ±3.3 ppb yr⁻¹ in the 1980s to ±1.3 ppb yr⁻¹ in the 2000s. These data reveal a sustained increase in atmospheric CH₄ levels in the 1980s (by an average of 12 ± 6 ppb yr⁻¹), a slowdown in growth in the 1990s (6 ± 8 ppb yr⁻¹), and a general stabilisation from 1999 to 2006 to 1773 ± 3 ppb. Since 2007, CH₄ levels have been rising again¹⁴, and reached 1799 ± 2 ppb in 2010. This increase reflects a recent imbalance between CH₄ sources and sinks that is not yet fully understood¹⁵.

Previous reviews of the global CH₄ budget have focused on results from a few studies only¹³,¹⁶–¹⁹. These studies covered different time windows and employed different assumptions, making it difficult to interpret the decadal changes presented. Only very few studies addressed multi-decadal changes in CH₄ levels²⁰,²¹. Here we construct a global CH₄ budget for the past three decades by combining bottom-up and top-down estimates of CH₄ sources and the chemical CH₄ sink (Box 1). We use chemical transport models — constrained by atmospheric CH₄ measurements — to estimate CH₄ fluxes using top-down atmospheric inversions. We compare these fluxes with those simulated by ecosystem models of wetland and biomass burning emissions and by data-driven approaches for other natural sources (Methods and Supplementary Section II). We also gather recent data from fossil fuel CH₄ emission inventories based on energy use statistics, and from agricultural and waste inventories based on livestock and rice paddy statistical data.

Sources and sinks
The global atmospheric CH₄ budget is determined by many terrestrial and aquatic surface sources, balanced primarily by one sink in the atmosphere. CH₄ emissions can be broadly grouped into three categories: biogenic, thermogenic and pyrogenic. Biogenic sources contain CH₄-generating microbes (methanogens)¹⁷, and comprise anaerobic environments such as natural wetlands and rice paddies, oxygen-poor freshwater reservoirs (such as dams), digestive systems of ruminants and termites, and organic waste deposits (such as manure, sewage and landfills). Thermogenic CH₄, formed over millions of years through geological processes, is a fossil fuel. It is vented from the subsurface into the atmosphere through natural features (such as terrestrial seeps, marine seeps and mud volcanoes), and through the exploitation of fossil fuels, that is, through the exploitation of coal, oil and natural gas. Pyrogenic CH₄ is produced by the incomplete combustion of biomass and soil carbon during wildfires, and of biofuels and fossil fuels. These three types of emissions have different isotopic δ¹³C signatures (δ¹³C = [¹³C/¹²C]sample/[¹³C/¹²C]standard – 1) × 1000): −55 to −70‰ for biogenic emissions, −25 to −55‰ for thermogenic emissions, and −13 to −25‰ for pyrogenic emissions²⁰,²²,²³. The isotopic composition of atmospheric CH₄ — measured at a subset of surface stations — has therefore been used to constrain its source²⁰–²⁴. CH₄ emissions by living plants under aerobic conditions do not seem to play a significant role in the global CH₄ budget (Supplementary Section ST8); some very large²⁵ estimates of this source published in 2006 have not been confirmed²⁶.

The primary sink for atmospheric CH₄ is oxidation by hydroxyl radicals (OH), mostly in the troposphere, which accounts for around 90% of the global CH₄ sink. Additional oxidation sinks include methanotrophic bacteria in aerated soils²⁷,²⁸ (~4%), reactions with...
chlorine radicals and atomic oxygen radicals in the stratosphere\(^\text{17}\) (~3\%), and reactions with chlorine radicals from sea salt in the marine boundary layer\(^\text{29}\) (~3\%).

**Global decadal budget**

We combine state-of-the-art top-down and bottom-up approaches (Box 1) using a consistent methodology (see Methods) to assess global CH\(_4\) sources and sinks over the past three decades. At the global scale for the 2000s, top-down inversions yield total global emissions of 548 Tg of CH\(_4\) per year with a minimum–maximum range of 526–569 (six models in Table 1) and a global sink of 540 [514–560] Tg CH\(_4\) yr\(^{-1}\). The source–sink mismatch reflects the observed average imbalance of 6 Tg CH\(_4\) yr\(^{-1}\) of the CH\(_4\) growth rate in the 2000s, which is smaller than that of the 1980s and 1990s (34 Tg CH\(_4\) yr\(^{-1}\) and 17 Tg CH\(_4\) yr\(^{-1}\), respectively; Fig. 1). In fact, stabilization of atmospheric CH\(_4\) prevailed in the early 2000s, and the atmospheric increase resumed after 2006.

Summing up all bottom-up emission estimates, a different picture emerges for the global source for the 2000s. We obtain a value of 678 Tg CH\(_4\) yr\(^{-1}\), which is 20% larger than the inversion-based estimate (\(P<0.01\); Table 1). The higher global source in bottom-up estimates is explained by a larger sum of natural emissions (from wetlands, freshwater, and geological sources) than in the inversions (Table 1). For the 2000s, the bottom-up estimate of the total sink is 632 Tg CH\(_4\) yr\(^{-1}\), with a large range (592–785). Most of this sink — 604 Tg CH\(_4\) yr\(^{-1}\) — is due to the hydroxyl radical CH\(_4\) sink, as estimated by the nine bottom-up chemistry climate models (CCMs)\(^\text{30}\). The OH sink simulated by the seven models that run time slices from the 1980s to the 2000s is found to increase with time, which contrasts with the stability of the OH sink inferred from top-down inversions for the 1990s and the 2000s (Table 1). The positive trend in the OH sink in the CCMs can be explained by the fact that the chemical consumption of OH, for instance through reactions with CH\(_3\) and carbon monoxide, is offset by the production of OH through photolysis reactions, involving water vapour, nitrogen oxides and stratospheric ozone. The stable OH sink inferred from top-down inversions relates to the observed atmospheric record of methyl chloroform, which is used to infer OH changes on decadal scales\(^\text{30}\).

We group decadal estimates of emissions (top-down and bottom-up) into five categories: natural wetlands; other natural emissions (termites, geological, fresh water systems, permafrost and hydrates); agriculture and waste; fossil fuels; and biomass and biofuel burning (Table 1). Freshwater systems include lakes, reservoirs, streams and rivers. In the 2000s, natural wetland emissions (top-down, 142–298 Tg CH\(_4\) yr\(^{-1}\); and bottom-up, 177–284 Tg CH\(_4\) yr\(^{-1}\)) and agriculture and waste emissions (top-down, 180–241 Tg CH\(_4\) yr\(^{-1}\); and bottom-up, 187–224 Tg CH\(_4\) yr\(^{-1}\)) dominate CH\(_4\) emissions, followed by anthropogenic fossil fuel emissions, other natural emissions and emissions from biomass and biofuel burning (Table 1). Together with natural CH\(_4\) emissions from lake and freshwater sources\(^\text{11,2}\), we find an imbalance of almost 50 Tg CH\(_4\) yr\(^{-1}\) (in the 2000s) between the mean global emission and the mean global sink in the
bottom-up approach, which is larger than the observed growth rate of around 6 Tg CH₄ yr⁻¹.

This discrepancy, combined with the fact that the global mean emission is 130 Tg CH₄ yr⁻¹ greater in the bottom-up approach than in the top-down approach (Table 1), suggests that CH₄ emissions are overestimated in the bottom-up approach. Indeed, the bottom-up global emission estimate is obtained by adding up independently estimated flux components, and thus lacks a constraint on its global magnitude. In contrast, the global CH₄ emission derived from the top-down approach is constrained at the global scale by the atmospheric CH₄ growth rate, using atmospheric CH₄ measurements, and by the magnitude of the chemical sink, using proxy atmospheric observations, such as the concentration of methyl chloroform, to estimate OH concentrations. Such proxy methods have proven to be reliable indicators of mean OH levels in the troposphere, although their ability to capture OH changes has been widely discussed. These proxy methods suggest that the mean global chemical sink for CH₄ derived from bottom-up estimates may also be overestimated, especially in the 2000s (Table 1).

When summing up anthropogenic fossil emissions, natural fossil CH₄ from onshore and offshore seeps (part of geological emissions in Table 1) and hydrates, bottom-up total fossil emissions account for 28% (~156 Tg CH₄ yr⁻¹) of the global CH₄ source between 1985 and 2000. This is consistent with an analysis of total CH₄ atmospheric measurements in both hemispheres inferring a 30 ± 2% fossil fraction in the global CH₄ source. However, fossil emissions of this magnitude are not confirmed by a recent analysis of the global atmospheric record of ethane, which is co-emitted with geological CH₄. Top-down inversions cannot provide useful information to settle this debate, as they generally do not separate this source from other natural emissions (Table 1). Consideration of the natural fossil CH₄ source, neglected in previous Intergovernmental Panel on Climate Change (IPCC) assessments, thus represents a significant update to the global CH₄ budget, although it is still debated.

Global budget uncertainty

Uncertainties associated with decadal CH₄ budgets are expressed by the minimum–maximum range between different decadal estimates, due to the small number of studies available for calculating reliable standard deviations (Table 1). For the 2000s, the uncertainty range for bottom-up estimates — defined as (max–min)/mean — is 50% for natural wetlands and typically 100% for other natural sources, though the other individual natural sources have smaller fluxes than wetlands. Anthropogenic sources seem to be known more precisely, with an uncertainty range of 30% for agriculture/waste- and fossil-fuel-related emissions, and 20% for biomass burning. The uncertainty range of the global sink is 40%, but drops to 20% when removing one outlier with very high total OH loss in a recent comparison of climate chemistry models. Note that the uncertainties reported in Table 1 are correlated to some extent. Because of more recent and robust estimates for each decade, each term in the budget has a smaller error range than in the IPCC AR4 report: 50% smaller for wetlands, 60% smaller for biomass burning, and 40% smaller for agriculture and waste emissions (Table 1).

Natural wetlands have the largest absolute uncertainty of any of the emission categories, with a min–max range of 107 Tg CH₄ yr⁻¹ in the bottom-up approach (177–284 Tg CH₄ yr⁻¹). This large range is confirmed by a recent multi-model analysis showing a ±40% range of wetland emissions around an average of 190 Tg CH₄ yr⁻¹. In the three wetland emission models used here, emissions were calculated for each grid point as the product of a flux rate and a wetland area, both having uncertainties. Uncertainties in wetland extent seem to be the dominant source of discrepancy in modelled CH₄ emissions.

The OH sink seems to have a smaller error range using proxy methods in the top-down approach (max–min range of 30 Tg CH₄) than in bottom-up CCMs (max–min range of 250 Tg CH₄ dropping to 110 Tg CH₄ when removing one outlier model from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACMIP)) in which different humidity and temperature fields cause a large spread of the OH sink.

Following IPCC AR5 guidelines for the treatment of uncertainties, we defined a level of confidence for both top-down estimates and bottom-up estimates, based on robustness (number of published studies) and agreement (difference between maximum and minimum estimates, relative to the mean). Many studies have focused on constraining the CH₄ budget during the 1990s and 2000s, but fewer estimates are available for the 1980s. As a result,

Box 1 | New data to assess the CH₄ budget

The top-down approach is based on atmospheric inversion models, which determine ‘optimal’ surface fluxes that best fit atmospheric CH₄ observations given an atmospheric transport model including chemistry, prior estimates of fluxes, and their uncertainties. Global atmospheric inversions provide a time-varying distribution of CH₄ fluxes, albeit with limited insight into the underlying processes when different sources overlap in the same region. This is, for example, often the case for agricultural, waste and fossil emissions in densely populated areas of east Asia, Europe and North America. We collected results from nine inversion systems (Supplementary Table S1).

The bottom-up approach includes process-based models estimating CH₄ emissions, and CCMs estimating the OH sink. Eight bottom-up models for wetland and fire CH₄ emissions are parameterized with empirical knowledge of local processes and driven by global data sets of climate, or satellite-observed burned area, to simulate CH₄ fluxes on spatial and temporal scales relevant for regional and global budgets (Supplementary Section II). Bottom-up emission inventories based on energy use, agricultural activity, and emission factors from different sectors provide yearly or decadal mean estimates of anthropogenic waste-related, rice, livestock, biofuel, and fossil fuel emissions, usually at national scales. Three inventories for anthropogenic emissions are updated, updated to 2008 (Supplementary Information).

The photochemical sink of CH₄ is large and difficult to quantify, given the very short lifetime of OH (~1 sec) and its control by a myriad of precursor species. Direct measurements of atmospheric OH radicals do not have the required accuracy and coverage to derive global OH concentrations and consequently the magnitude of the CH₄ sink. We estimated CH₄ loss due to OH from the output of nine numerical CCMs, which are categorized here as an atmospheric bottom-up approach. The OH concentration as calculated by CCMs can be further adjusted, at a large scale, by inversions based on measurements of tracers with known emissions and whose dominant sink is oxidation by OH, such as methyl chloroform or chloromethanes.

Combining top-down and bottom-up approaches allows us to investigate the consistency of each term of the CH₄ budget. In this comparison, it should be noted that bottom-up models and inventories are not independent from inversions, because they are usually used in inversions to prescribe a prior spatial, and sometimes temporal, distribution of the emissions and sinks. However, inversions use independent atmospheric observations to partially correct the prior values.
estimates for all source categories during the 2000s are more robust, especially for inversions (Fig. 2). Agreement among studies is high (difference is less than 33%) for agriculture and waste (top-down and bottom-up), biomass burning and fossil fuels (bottom-up) and OH loss (top-down), whereas agreement is only medium (33–66%) for natural wetlands (top-down and bottom-up), biomass burning and fossil fuels (bottom-up) and agriculture and waste (top-down) than for fossil fuels, the OH sink, natural wetlands and other natural sources. Overall, higher confidence in global emissions is found for inversions (highest agreement and highest robustness), emphasizing the large uncertainties that remain in our understanding of CH₄ emissions. This can be seen for the fossil fuel and other sources categories, partly because of poorly constrained models, and partly because the results from a single new study can produce a large increase in the spread of emission estimates when very few studies are available.

No source or sink category reaches the highest level of confidence (highest agreement and highest robustness), emphasizing the large uncertainties that remain in our understanding of CH₄ emissions. Overall, higher confidence in global emissions is found for agriculture and waste (top-down) than for fossil fuels, the OH sink, natural wetlands and other natural sources.

Table 1 | CH₄ budget for the past three decades.

| 1980–1989 | 1990–1999 | 2000–2009 |
|-----------|-----------|-----------|
| **Tg CH₄ yr⁻¹** | **Tg CH₄ yr⁻¹** | **Tg CH₄ yr⁻¹** |
| **Natural sources** | **Natural sources** | **Natural sources** |
| **Top-down** | **Bottom-up** | **Top-down** | **Bottom-up** | **Top-down** | **Bottom-up** |
| 203 [150–267] | 355 [244–466] | 182 [167–197] | 336 [230–465] | 218 [179–273] | 347 [238–484] |
| **Natural wetlands** | **Natural wetlands** | **Natural wetlands** | **Natural wetlands** | **Natural wetlands** | **Natural wetlands** |
| 167 [115–231] | 225 [183–266] | 150 [144–160] | 206 [169–265] | 175 [142–208] | 217 [177–284] |
| **Other sources** | **Other sources** | **Other sources** | **Other sources** | **Other sources** | **Other sources** |
| **Fresh water (lakes and rivers)** | **Fresh water (lakes and rivers)** | **Fresh water (lakes and rivers)** | **Fresh water (lakes and rivers)** | **Fresh water (lakes and rivers)** | **Fresh water (lakes and rivers)** |
| 36 [35–36] | 130 [61–200] | 32 [23–37] | 130 [61–200] | 43 [37–65] | 130 [61–200] |
| **Wild animals** | **Wild animals** | **Wild animals** | **Wild animals** | **Wild animals** | **Wild animals** |
| 15 [15–15] | 3 [1–3] | 15 [15–15] | 3 [1–5] | 15 [15–15] | 3 [1–5] |
| **Wildfires** | **Wildfires** | **Wildfires** | **Wildfires** | **Wildfires** | **Wildfires** |
| 11 [2–11] | 46 [16–67] | 11 [2–22] | 46 [16–67] | 11 [2–22] | 46 [16–67] |
| **Termites** | **Termites** | **Termites** | **Termites** | **Termites** | **Termites** |
| 54 [33–75] | 54 [33–75] | 54 [33–75] | 54 [33–75] | 54 [33–75] | 54 [33–75] |
| **Geological (incl. oceans)** | **Geological (incl. oceans)** | **Geological (incl. oceans)** | **Geological (incl. oceans)** | **Geological (incl. oceans)** | **Geological (incl. oceans)** |
| 6 [2–9] | 6 [2–9] | 6 [2–9] | 6 [2–9] | 6 [2–9] | 6 [2–9] |
| **Hydrates** | **Hydrates** | **Hydrates** | **Hydrates** | **Hydrates** | **Hydrates** |
| 10 [0–1] | 10 [0–1] | 10 [0–1] | 10 [0–1] | 10 [0–1] | 10 [0–1] |
| **Anthropogenic sources** | **Anthropogenic sources** | **Anthropogenic sources** | **Anthropogenic sources** | **Anthropogenic sources** | **Anthropogenic sources** |
| **Agriculture and waste** | **Agriculture and waste** | **Agriculture and waste** | **Agriculture and waste** | **Agriculture and waste** | **Agriculture and waste** |
| 208 [187–220] | 239 [180–301] | 239 [180–301] | 209 [180–241] | 209 [180–241] | 200 [187–224] |
| **Biomass burning (incl. biofuels)** | **Biomass burning (incl. biofuels)** | **Biomass burning (incl. biofuels)** | **Biomass burning (incl. biofuels)** | **Biomass burning (incl. biofuels)** | **Biomass burning (incl. biofuels)** |
| 46 [43–55] | 38 [26–45] | 42 [38–45] | 30 [24–45] | 35 [32–39] | 35 [32–39] |
| **Fossil fuels** | **Fossil fuels** | **Fossil fuels** | **Fossil fuels** | **Fossil fuels** | **Fossil fuels** |
| 94 [75–108] | 95 [84–107] | 84 [66–96] | 96 [77–123] | 96 [85–105] | 96 [85–105] |
| **Soils** | **Soils** | **Soils** | **Soils** | **Soils** | **Soils** |
| 21 [10–27] | 28 [9–47] | 27 [27–27] | 28 [9–47] | 28 [9–47] | 28 [9–47] |
| **Total chemical loss** | **Total chemical loss** | **Total chemical loss** | **Total chemical loss** | **Total chemical loss** | **Total chemical loss** |
| 490 [450–533] | 539 [411–671] | 525 [491–554] | 571 [521–621] | 518 [510–538] | 604 [483–738] |
| **Tropospheric OH** | **Tropospheric OH** | **Tropospheric OH** | **Tropospheric OH** | **Tropospheric OH** | **Tropospheric OH** |
| 468 [382–567] | 479 [457–501] | 479 [457–501] | 479 [457–501] | 479 [457–501] | 479 [457–501] |
| **Stratospheric loss** | **Stratospheric loss** | **Stratospheric loss** | **Stratospheric loss** | **Stratospheric loss** | **Stratospheric loss** |
| 46 [16–67] | 67 [51–83] | 67 [51–83] | 67 [51–83] | 67 [51–83] | 67 [51–83] |
| **Tropospheric Cl** | **Tropospheric Cl** | **Tropospheric Cl** | **Tropospheric Cl** | **Tropospheric Cl** | **Tropospheric Cl** |
| 25 [13–37] | 25 [13–37] | 25 [13–37] | 25 [13–37] | 25 [13–37] | 25 [13–37] |
| **TOTALS** | **TOTALS** | **TOTALS** | **TOTALS** | **TOTALS** | **TOTALS** |
| **Sum of sources** | **Sum of sources** | **Sum of sources** | **Sum of sources** | **Sum of sources** | **Sum of sources** |
| 551 [500–592] | 663 [536–789] | 554 [529–596] | 649 [511–812] | 548 [526–569] | 678 [542–852] |
| **Sum of sinks** | **Sum of sinks** | **Sum of sinks** | **Sum of sinks** | **Sum of sinks** | **Sum of sinks** |
| 511 [460–559] | 539 [420–718] | 542 [518–579] | 596 [530–668] | 540 [514–560] | 632 [592–785] |
| **Imbalance (sources–sinks)** | **Imbalance (sources–sinks)** | **Imbalance (sources–sinks)** | **Imbalance (sources–sinks)** | **Imbalance (sources–sinks)** | **Imbalance (sources–sinks)** |
| 30 [16–40] | 12 [7–17] | 12 [7–17] | 12 [7–17] | 12 [7–17] | 12 [7–17] |
| **Atmospheric growth rate** | **Atmospheric growth rate** | **Atmospheric growth rate** | **Atmospheric growth rate** | **Atmospheric growth rate** | **Atmospheric growth rate** |
| 34 | 17 | 6 | 6 | 6 | 6 |

Top-down and bottom-up estimates are listed separately for the different categories in Fig. 1. For top-down inversions, the 1980s decade starts in 1984. Numbers in square brackets represent minimum and maximum values. A balance with the atmospheric annual increase and the sum of the sources has been assumed for inversions not reporting their global sink. Stratospheric loss for bottom-up is the sum of the loss by radicals, a 10 Tg yr⁻¹ loss due to O(1D) radicals and a 20–35% contribution due to Cl radicals. Ranges of total chemical loss are about half the reported ranges (for example, [509–619] for the 2000s) when removing one outlier.
**Regional decadal budget**

The geographical breakdown of emissions per category and per region reveals major CH$_4$ emission zones worldwide and the level of consistency between top-down and bottom-up approaches (Fig. 3 and Supplementary Section ST2 and Tables S2 and S3). Anthropogenic emissions dominate in Europe, North America, China, and the fossil-fuel-producing countries of eastern Europe and central Asia, with good agreement between top-down and bottom-up approaches (Fig. 3). Emission ranges are given in Table S2. Densely populated regions usually emit fossil, agricultural and waste CH$_4$, making these sources difficult to separate in top-down inversions. Noteworthy is the large range of estimates for anthropogenic fossil CH$_4$ emissions from China in the top-down approach, possibly due to the low density of atmospheric CH$_4$ measurements in this region, and to biases in inventories\(^{46}\). The large range of anthropogenic CH$_4$ emission estimates in Europe and North America possibly reflects uncertainties in emission factors, and in the partition between waste and fossil CH$_4$ sources. In emerging economies, agriculture and waste emissions are highest in China (top-down, 29 Tg CH$_4$ yr$^{-1}$; bottom-up, 28 Tg CH$_4$ yr$^{-1}$) and India (top-down, 27 Tg CH$_4$ yr$^{-1}$; bottom-up, 22 Tg CH$_4$ yr$^{-1}$), but are also important in southeast Asia and temperate South America due to extensive rice agriculture and livestock industries (Supplementary Table S2). In India and China, agriculture and waste constitutes the single largest regional source of CH$_4$. However, per capita CH$_4$ emissions in India and China are still 35% and 85%, respectively, of the mean for OECD countries.

When aggregated over large regions, wetlands dominate emissions in tropical South America (top-down, 28 Tg CH$_4$ yr$^{-1}$; bottom-up, 58 Tg CH$_4$ yr$^{-1}$) and Africa (top-down, 36 Tg CH$_4$ yr$^{-1}$; bottom-up, 24 Tg CH$_4$ yr$^{-1}$), with significant emissions in southeast Asia, temperate South America, boreal North America and boreal Eurasia (Supplementary Table S2). Tropical South America shows the largest regional discrepancy between top-down (17–48 Tg CH$_4$ yr$^{-1}$) and bottom-up (39–92 Tg CH$_4$ yr$^{-1}$) wetland emissions (Supplementary Tables S2 and S3). The seven inversions using only surface measurements give the lowest estimates for the 2000s decadal mean wetland emission (17–30 Tg CH$_4$ yr$^{-1}$), and the two inversions using SCIAMACHY column satellite data combined with surface measurements\(^{46}\) (27 and 48 Tg CH$_4$ yr$^{-1}$) agree better with bottom-up estimates (39–92 Tg CH$_4$ yr$^{-1}$). Only short time series of CH$_4$ in situ measurements are available for inland South America, which makes it one of the least constrained regions for inversions using surface measurements. The wetland models used in this study simulate large emissions in the Amazon region, equatorial tropical Africa, tropical Asia (for example, Bangladesh, India, China and Indonesia), Canada and boreal Eurasia. Simulated emission areas are consistent between models for 66 ± 9% of global wetland emissions over the period 1990–2006 (Supplementary Fig. S0).

When aggregated over large regions, emissions from biomass burning are the largest in Africa (top-down, 9 Tg CH$_4$ yr$^{-1}$; bottom-up, 8 Tg CH$_4$ yr$^{-1}$) and in tropical South America (top-down, 5 Tg CH$_4$ yr$^{-1}$; bottom-up, 4 Tg CH$_4$ yr$^{-1}$), but play only a minor role in temperate and boreal regional budgets. The bottom-up estimates are likely to be conservative compared to top-down estimates, as small fires are often undetected by satellite retrieval algorithms\(^{47}\). For biomass burning, simulated emission areas are consistent between models for 38 ± 9% of global emissions over the period 1997–2000, revealing robust large emission zones around the thermal equator in Africa (for example, Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Angola, Zambia and Cameroon), central South America (Brazil and Bolivia), Indonesia, and to a lesser extent in eastern Russia, Laos, and Mexico (Supplementary Fig. S0). Emission zones in northern Australia and in boreal regions (Canada and Siberia) can also be clearly identified.

Other natural sources, including termites, lakes and other fresh waters, and onshore geological emissions show maximum values in Africa and tropical South America, due to the relatively strong contribution of emissions by termites\(^{48}\). A new empirical model of termite CH$_4$ emissions developed in this study indicates that Africa and tropical South America are major contributors to the global
termite source, contributing 30% and 36%, respectively, of the total (Supplementary Section ST7). Finally, CH₄ loss due to OH radicals is largest in the tropical atmosphere, both over land and oceans, as the tropics are the major region of OH production.

**Attribution of temporal changes**

Year-to-year variations of CH₄ fluxes have been intensively studied. The present study confirms the findings from previous ones showing that, over the last three decades, variations in wetland emissions have dominated the year-to-year variability in surface emissions (Supplementary Fig. S5). Interannual variability in wetland emissions surpasses that of biomass burning emissions, except during intense fire periods. Analyses of anomalies in CH₄ fluxes following the Mount Pinatubo eruption in 1991 and the record-high El Niño event in 1997–1998 are summarized in Supplementary Sections ST4 and ST5. Both models and observations compiled in the present study consistently describe small interannual variability in the OH sink in the 2000s compared with the previous two decades (<3%, 1σ of annual means; Supplementary Section ST6), in line with previously reported estimates (<5%).

The observed decadal changes remain much more enigmatic than yearly anomalies (Supplementary Fig. S5). We use a scenario approach, built from our synthesis and from recent publications, to investigate these changes, and the contribution of the different CH₄ sources to them (see Methods). We assume that decadal changes in global mean CH₄ emissions since 1985 are well represented by the mean of those five atmospheric inversions covering the past three decades, averaged on a five-year basis (Fig. 4 and Methods). A global mass balance model based on the atmospheric observations of the four surface networks and on possible changes in CH₄ lifetime is used to provide uncertainties on the mean inversion (blue shaded area at the top of Fig. 4). These observation-driven global CH₄ emissions show three distinct regimes: an increase before 1990, an oscillation around a constant mean value during 1990–2005, and an increase after 2006. A storyline (S₅) is constructed by adding wetland emissions from top-down inversions (average of five inversions) to other estimates (EPA (ref. 55) and EDGARv4.2 (ref. 56) inventories).

**1985–2005.** The S₅ storyline clearly overestimates global emissions after 1990, which calls for corrections to the magnitude of one or several sources in the S₅ scenario (Fig. 4). Using ethane firn air and atmospheric measurements, two recent studies indicated that CH₄ emissions from the fossil fuel sector decreased between 1985 and 2000 at a rate of −0.4 to −0.8 Tg CH₄ yr⁻¹, and attributed such a decline to decreasing fugitive emissions (leaks during extraction, treatment and use of fossil fuels) from oil and gas industries. One of these studies further extended the ethane record up to 2010, with either a slower decline or a stabilization of fossil fuel emissions.
after 2000 (see Fig. 4 of ref. 15 and Methods). Indeed, an intensified coal exploitation after 2000 may have offset a decline in fugitive emissions. In parallel, rice paddy emissions have decreased (−0.4 to −0.8 Tg CH₄ yr⁻¹) according to the EDGAR4.2 inventory during the 1980–2000 period, and remained stable between 2000 and 2005. Assuming that CH₄ fossil fuel fugitive emissions decreased between 1985 and 2000 and were stable from 2000 to 2005, and keeping the other sources as in S₀, leads to a first plausible scenario that is consistent with the observation-driven global emissions (S₁ in Fig. 4). An alternative scenario (S’₁), using bottom-up ecosystem model results for wetland emissions as a storyline instead of top-down inversions, is also consistent with the observation-driven global emissions.

Two different analyses of δ¹³C-CH₄ isotopic composition trends for 1990–2005 reached contradictory conclusions. In one, constant fossil fuel emissions but decreasing microbial emissions in the Northern Hemisphere were inferred, the latter mainly attributed to decreasing rice emissions. In the other, fossil fuel and microbial emissions remained constant. Assuming constant fossil fuel emissions during 1985–2005 and decreasing microbial emissions produces a second scenario that is mostly consistent with observation-driven global emissions when using wetland fluxes from top-down inversions (S₁ in Fig. 4), but not when using wetland fluxes from bottom-up ecosystem models (S’₁). Assuming decreasing fossil fuel emissions before 1990 (as in S₀), but constant fossil fuel and microbial emissions between 1990 and 2005, produces a third scenario that is consistent with observation-driven global emissions, with either top-down or bottom-up wetland emission estimates (S₀ and S’₁ in Fig. 4).

Overall, the three plausible scenarios, among many other possible source compositions matching global decadal changes, suggest that a decrease in fossil fuel CH₄ emissions is a more likely explanation for the stability of global CH₄ emissions between 1980 and 2005 than a reduction in microbial CH₄ emissions. An actual decrease in rice paddy emissions may have been surpassed by an increase in other microbial emissions (natural wetlands, animals, landfills and waste) as found by ecosystem models combined with the EDGAR4.2 inventory. Considering the significant uncertainties reported in a recent isotope study for the 1990–2005 period, decreasing-to-stable fossil fuel emissions, combined with stable-to-increasing total microbial emissions, would reconcile the atmospheric ethane trends with the δ¹³C-CH₄ trends, at least for one δ¹³C-CH₄ data set. Finally, trends in the magnitude of the OH CH₄ sink, which remain uncertain over decadal timescales, can still modulate these incomplete conclusions.

The increase resumes from 2006 onwards. Atmospheric CH₄ levels resumed growth after 2006, with inferred global emissions being 17–22 Tg CH₄ yr⁻¹ greater around 2010 than around 2005 (five-year basis averages; top of Fig. 4). Several studies concluded that a recent surge in natural wetland emissions is one main cause of increasing CH₄ levels, in response to abnormally high temperatures in northern high latitudes in 2007, and increased rainfall over tropical wetlands during 2008–2009 and 2010–2011, two La Niña periods. Furthermore, fossil fuel CH₄ emissions probably increased again after 2005, mostly due to the intensification of shale gas and oil extraction in the United States and coal exploitation by the Chinese and Indian economies.

After 2005, the three scenarios use fossil fuel emission changes from the EPA inventory, and the average of EPA and EDGAR4.2 inventories for all other sources barring natural wetlands. Microbial and fossil fuel sources for all scenarios show positive trends after 2005, resulting in an increase of global emissions of 23–33 Tg CH₄ yr⁻¹ around 2010 as compared to around 2005 (five-year basis averages). This is a 30% overestimation compared with the mean increase derived from the observations (17–22 Tg CH₄ yr⁻¹, see above). Thus, either the increase in fossil fuel emissions is overestimated by inventories, or the sensitivity of wetland emissions to precipitation and temperature is too large in some wetland emission models. The contribution of microbial versus fossil emissions to this increase remains largely uncertain; respective contributions vary from 20 to 80%, if accounting for all additional top-down inversions available for the 2000s (Supplementary Fig. S5 and Table 1).

Shortcomings and uncertainty reductions

Our analyses suggest four main shortcomings in the assessment of regional to global CH₄ budgets. First, decadal means and interannual changes in CH₄ emissions from natural wetlands and freshwater systems are too uncertain. It is critically important to improve wetland mapping, both by refining land surface models (for example, through improving estimates of tropical flood plains in hydrological models, specific model developments for peatlands, and the integration of freshwater systems) and by further developing remotely sensed inundation data sets (for instance for dense tropical forests). The scarcity of wetland CH₄ flux measurements and data sets limits the ability to validate large-scale modelled CH₄ emissions for natural wetlands and fresh waters. The extension of the CO₂ FLUXNET measurements and database to CH₄ fluxes is probably achievable at a reasonable cost, and would provide useful constraints for land surface models. For interannual variations in wetland emissions, the sensitivity of emission rates to warming at
high northern latitudes and to rainfall changes in the tropics needs to be more consistently quantified in wetland models. The Amazon drought in 2010\textsuperscript{39} should have resulted in a drop in wetland CH\textsubscript{4} emissions, and ongoing analyses may allow researchers to test the hypothesis that tropical wetland CH\textsubscript{4} emissions respond strongly to rainfall anomalies and trends.

Second, the partitioning of CH\textsubscript{4} emissions by region and process is not sufficiently constrained by atmospheric observations in top-down models. Regional partitioning of total emissions would benefit from denser and more evenly distributed CH\textsubscript{4} concentration data. This can be achieved by further developing synergies between high precision monitoring of the surface and the lower atmosphere, including poorly sampled key areas such as the Amazon Basin, Siberia and tropical Africa on one hand, and retrievals of global-scale CH\textsubscript{4} columns by satellites and by high precision remote sensing from the ground on the other. Including continuous measurements of the δ\textsubscript{13}C stable isotope (\textsuperscript{13}CH\textsubscript{4}) at surface stations would help separate biogenic emissions from other sources. Measurements of the δD stable isotope (CH\textsubscript{4}-D) at surface stations and the δD stable isotope (CH\textsubscript{4}-D) at surface stations would help constrain the uncertain OH CH\textsubscript{4} sink, which can also be constrained by new proxy tracers\textsuperscript{37,38}. Radiocarbon CH\textsubscript{4} data (\textsuperscript{14}CH\textsubscript{4}) would help constrain the uncertain fossil part of CH\textsubscript{4} emissions, if CH\textsubscript{4} emissions from nuclear installations can be accurately estimated\textsuperscript{39}. Estimating long-term trends of fluxes and concentrations requires equally long-term observations, which in turn require stable and coordinated networks\textsuperscript{40}.

Third, decadal trends in natural and anthropogenic emissions are still very uncertain and limit our ability to definitively attribute changes in emissions from specific sources to observed atmospheric changes since the 1990s. In addition to the (already noted) improvements in land surface models required, inventories for anthropogenic emissions should systematically include an uncertainty assessment, and should improve their representation of emission trends (for instance by more frequently updating the time-dependent factors used in their calculations).

Fourth, uncertainties in the modelling of atmospheric transport and chemistry limit the optimal assimilation of atmospheric observations by increasing uncertainties in top-down inversions. Such uncertainties are also only partly estimated in current inversions. We therefore recommend the continuation of ongoing international model inter-comparisons, which can provide a quantification of transport and chemistry errors to be included in top-down inversions\textsuperscript{41,42}.

From challenge to opportunity

Our decadal CH\textsubscript{4} budgets reveal that bottom-up models may overestimate total natural CH\textsubscript{4} emissions. The various emission scenarios tested — designed to explain the temporal changes in atmospheric CH\textsubscript{4} levels observed in this and previous studies — suggest that the stabilization of atmospheric CH\textsubscript{4} in the early 2000s is likely to be due to a reduction in or stabilization of fossil fuel emissions, combined with a stabilization of or increase in microbial emissions. After 2006, the renewed global increase in atmospheric CH\textsubscript{4} is consistent with higher emissions from wetlands and fossil fuel burning, but the relative contributions remain uncertain.

In the context of climate change mitigation, atmospheric CH\textsubscript{4} poses both an opportunity and a challenge. The challenge lies in more accurately quantifying the CH\textsubscript{4} budget and its variations. Our synthesis suggests that improvements in models of natural wetland and freshwater emissions, the integration of surface networks monitoring CH\textsubscript{4} concentrations and fluxes (including isotopic composition) and new satellite missions (including active space-borne observations\textsuperscript{43}), improvements in anthropogenic emission trends in inventories, and uncertainty reductions in models of atmospheric transport and chemistry, could all help. The opportunity lies in the possibility of developing short-term climate change mitigation policies that take advantage of the relatively short atmospheric lifetime of CH\textsubscript{4} of about 10 years, and the known technological and agronomical options available for reducing emissions\textsuperscript{44}.

The potential intensive exploitation of natural gas from shale formations around the world may lead to significant additional CH\textsubscript{4} release into the atmosphere\textsuperscript{45}, although the potential magnitude of these emissions is still debated\textsuperscript{46}. Such additional emissions, and combustion of this ‘new’ fossil fuel source, may offset mitigation efforts and accelerate climate change. In the longer term, the thawing of permafrost or hydrates could increase CH\textsubscript{4} emissions significantly, and introduce large positive feedbacks to long-term climate change\textsuperscript{47}. A better quantification of the global CH\textsubscript{4} budget, with regular updates as done for carbon dioxide\textsuperscript{48}, will be key to both embracing the opportunities and meeting the challenge.

Methods

Data analysis. Top-down and bottom-up studies addressing the evolution of the CH\textsubscript{4} cycle after 1980 and covering at least five years of a decade were gathered. Therefore, the number and the nature of studies used in this work vary from one decade to another. Top-down inversions include atmospheric chemistry transport models and assimilation systems\textsuperscript{49,50,53,77–79}. Bottom-up approaches comprise modelling studies for wetland\textsuperscript{42–44} and biomass-burning emissions\textsuperscript{55,56,81}, emission inventories for anthropogenic\textsuperscript{51,52,54,55} and natural sources\textsuperscript{44}, and a suite of atmospheric chemistry models within the ACCMIP intercomparison project providing CH\textsubscript{4} chemical loss\textsuperscript{53,82}.

The monthly fluxes (emissions and sinks) provided by the different groups were post-processed similarly: They were re-gridded on a common grid (1°×1°) and converted into the same units (Tg CH\textsubscript{4} per grid cell); then monthly, annual and decadal means were computed for 12 regions based on the TransCom\textsuperscript{44} inter-comparison map, with subdivisions in high-emissions regions. Regional and global means were used to construct Figs 1 and 2, and Supplementary Figs S2 and S3, Table 1 and Supplementary Tables S2 and S3.

The reported ranges and error bars represent the minimum and maximum values obtained among the different studies (Figs 1, 3 and 4 and Table 1). The small number of studies for some categories makes it difficult to properly apply a standard deviation.

Interannual variability (IAV) was computed as the difference between the 12-month running mean and the long-term mean. However a consistent period for estimating the long-term mean was not compatible with all data sources (Supplementary Fig. S5).

Observation-driven global CH\textsubscript{4} emissions. For ‘attribution of temporal changes’, we used the only top-down study that estimates CH\textsubscript{4} emissions over the past 30 years\textsuperscript{57} with five different set-ups. The mean of these five inversions was assumed to represent average global emissions. However these five inversions only partially represented the full range of global CH\textsubscript{4} emissions, due to differences in prior emission scenarios and errors, observations and their errors, OH fields and atmospheric transport representation. To estimate the full range of global CH\textsubscript{4} emissions we complemented the mean inversion with a sensitivity analysis based on a one-box model for the whole atmosphere\textsuperscript{44}. The change in the global burden of CH\textsubscript{4}, is given by:

\[
\frac{d[CH_4]}{dt} = \frac{E}{\tau} - \frac{[CH_4]}{\tau}
\]

where [CH\textsubscript{4}] is the global CH\textsubscript{4} burden, E is the sum of all emissions, and τ is the total atmospheric CH\textsubscript{4} lifetime. Equation (1) can be rearranged to calculate the annual CH\textsubscript{4} source strength E as follows:

\[
E = \frac{d[CH_4]}{dt} + \frac{[CH_4]}{\tau}
\]

In this equation, the annual increase d[CH\textsubscript{4}]/dt and the burden [CH\textsubscript{4}] were given by the yearly—averaged growth rates and mole fractions of Fig. 1. Global CH\textsubscript{4} emissions were generated by computing emissions with equation (2) for each of the four networks and for a lifetime τ varying from 8 to 10 years to include uncertainties in OH changes\textsuperscript{56,57}. Minimum and maximum values of E were extracted for five-year periods to produce the range of emissions plotted around the mean of atmospheric inversions (blue shaded area in Fig. 4, top panel).

Emission scenarios. The emission scenarios are based on five-year average CH\textsubscript{4} fluxes around the years 1985, 1990, 1995, 2000, and 2005. For 2010 we used available years between 2008 and 2012, mainly before 2010. Flux changes from 2005 to 2010 might be slightly biased by missing years after 2010. For example, fossil and microbial emissions both increase between 2005 and 2009; if after 2010 these emissions were further increasing (or decreasing), then the 2005–2010 changes will be underestimated (or overestimated). We assume that such a potential bias does not modify the (mostly) qualitative message of our scenario analysis. The five-year
changes from biomass burning remain small (<2 Tg CH₄ per five-year period) and were not considered here.

The scenarios presented in Fig. 4 use either natural wetland emissions from top-down inversions (Sₜ) or bottom-up models (Sₜ'). Other data are taken from recent publications and EDGAR4.2 and EPA inventories. Sₜ and Sₜ' are built by summing the mean wetland emissions from inversions and the mean of EPA (ref. 55) and EDGAR4.2 (ref. 56) 'other' emissions. Scenarios Sₜ and Sₜ' sum the mean wetland emissions with decreasing (1985–2000), constant (2000–2005), and increasing (2005–2010) fossil fuel emissions to be compatible with a recent analysis. Scenarios Sₜ and Sₜ' sum the mean wetland emissions with constant (1985–2005) and increasing (2005–2010) fossil fuel emissions. Other microbial emissions (mean of EPA and EDGAR) are scaled to a recent study. Scenarios Sₜ and Sₜ' sum the mean wetland emissions with decreasing (1985–1990), constant (1990–2005), and increasing (2005–2010) fossil fuel emissions. Other microbial emissions (mean of EPA and EDGAR) are scaled to remain constant during 1990–2005 according to a recent report. After 2005, all scenarios include fossil fuel emissions from the EPA inventory, wetland emission changes from inversions or bottom-up studies and other emission changes from the mean of EPA and EDGAR4.2.

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