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PERSPECTIVE

Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources

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Climate stabilization remains elusive, with increased greenhouse gas concentrations already increasing global average surface temperatures 1.1 °C above pre-industrial levels (World Meteorological Organization 2019). Carbon dioxide (CO₂) emissions from fossil fuel use, deforestation, and other anthropogenic sources reached ~43 billion metric tonnes in 2019 (Friedlingstein et al 2019, Jackson et al 2019). Storms, floods, and other extreme weather events displaced a record 7 million people in the first half of 2019 (IDMC 2019). When global mean surface temperature four million years ago was 2 °C–3 °C warmer than today (a likely temperature increase before the end of the century), ice sheets in Greenland and West Antarctica melted and parts of East Antarctica’s ice retreated, causing sea levels to rise 10–20 m (World Meteorological Organization 2019).

Methane (CH₄) emissions have contributed almost one quarter of the cumulative radiative forcings for CO₂, CH₄, and N₂O (nitrous oxide) combined since 1750 (Etminan et al 2016). Although methane is far less abundant in the atmosphere than CO₂, it absorbs thermal infrared radiation much more efficiently and, in consequence, has a global warming potential (GWP) ~86 times stronger per unit mass than CO₂ on a 20-year timescale and 28-times more powerful on a 100-year time scale (IPCC 2014).

Global average methane concentrations in the atmosphere reached ~1875 parts per billion (ppb) at the end of 2019, more than two-and-a-half times preindustrial levels (Dlugokencky 2020). The largest methane sources include anthropogenic emissions from agriculture, waste, and the extraction and use of fossil fuels as well as natural emissions from wetlands, freshwater systems, and geological sources (Kirschke et al 2013, Saunois et al 2016a, Ganesan et al 2019). Here, we summarize new estimates of the global methane budget based on the analysis of Saunois et al (2020) for the year 2017, the last year of the new Global Methane Budget and the most recent year data are fully available. We compare these estimates to mean values for the reference ‘stabilization’ period of 2000–2006 when atmospheric CH₄ concentrations were relatively stable. We present data for sources and sinks and provide insights for the geographical regions and economic sectors where emissions have changed the most over recent decades.

1. Methods

We use the same data and approaches to estimate CH₄ emissions as in Saunois et al (2020). One approach we use is a top-down (TD) ensemble of 11 inversions using atmospheric CH₄ concentrations to constrain total possible emissions and partition them to primary sources. The TD inversions were constrained by surface observations for the period 2000–2006, and by surface and/or satellite observations in 2017. Prior fluxes, treatment of observations, and optimization configurations varied somewhat across the 11 inversions as described in the supplementary material of Saunois et al (2020). Most of the inversions considered the same OH field, constant over time, attributing changes in methane atmospheric concentrations to altered emissions rather than to...
atmospheric oxidative capacity. Consequently, the inferred changes in methane emissions would be higher if OH is increasing in the atmosphere, as suggested by chemistry climate models (e.g. Zhao et al 2020) or lower if OH is decreasing in the atmosphere, as suggested by some methyl chloroform-based studies (e.g. Rigby et al 2017). Uncertainties in regional and sectoral partitioning vary across models based on transport errors, prior flux ratios, and inversion baselines. Our TD ensemble derived an estimated uncertainty of ±5% on total global emissions, a range larger than for transport model errors alone of ±2%–3% attributable to different inversion systems (Locatelli et al 2013). We were unable to include uncertainties in TD total emissions attributable to uncertainties in the methane chemical sink; uncertainty on the global burden of OH is about 10%–15% and translates to an uncertainty of approximately ±9% on total global emissions (Zhao et al 2020).

The second approach is a detailed bottom-up (BU) accounting method that uses global inventories and biogeochemical modeling that provides a more detailed attribution to sources but lacks the total atmospheric growth rate constraint that accompanies TD approaches. BU trends in methane emissions are available for anthropogenic emissions using four global inventories (EDGARv4.3.2, CEDS, GAINS and EPA2012), for biomass burning using three fire products (GFEDv4.1s, QFED, and FINN) and for wetlands calculated by 13 biogeochemical models (see Saunois et al 2020). However, estimates for other natural sources such as geological, termites, permafrost, rivers, lakes, and reservoirs available in the literature do not provide any temporal changes in methane emissions and trends cannot be calculated for these sources. Uncertainties in ‘natural emissions’ for wetlands plus all other inland waters arise from factors that include wetland flux density, seasonal to interannual variability in wetland extent, and some double-counting of wetland and small inland waters, contributing to higher BU estimates for natural sources than in the TD inventory. For the 2000–2017 methane budget (Saunois et al 2020), the Wetland Area Dynamics for Methane Modeling dataset (WAD2 M) was developed to avoid some double counting by removing inland waters from surface inundation data to estimate these fluxes separately, combining Landsat-based (Pekel et al 2016) and radar-based observations (Jensen and Mcdonald 2019).

2. Global and latitudinal sources and sinks of methane

Average estimated global methane emissions for 2017 were 596 Tg CH₄ yr⁻¹ (figure 1, table 1) based on 11 top-down atmospheric inversions, with an ensemble max.-min. range of 572–614 Tg CH₄ yr⁻¹. This value is 9% (50 Tg CH₄ yr⁻¹) higher than the average for the period 2000–2006 (546 Tg CH₄ yr⁻¹, range 538–555), with the increase attributable primarily to greater anthropogenic emission sources (table 1). Anthropogenic sources also contributed 61% of total TD global methane emissions in 2017. The estimate from the BU approach yielded an increase of 51 Tg CH₄ yr⁻¹, from 696 (560–834) Tg CH₄ yr⁻¹ in 2000–2006 to 747 (602–896) Tg CH₄ yr⁻¹ in 2017 (table 1). Anthropogenic sources contributed an estimated 51% of total global BU emissions in 2017. The difference of ~150 Tg CH₄ yr⁻¹ in total global emissions between TD and BU methods arises primarily from a divergence in estimates of natural sources, particularly from freshwater and geological ones (table 1) and from the absence of TD atmospheric constraints for BU approaches (see below).

The latitudinal attribution of methane emissions highlights the role of tropical and temperate sources relative to boreal and Arctic systems (figure 2). Based on TD methods in 2017, tropical sources (<30°N) emitted 64% (383 Tg CH₄ yr⁻¹; 351–405) of global methane emissions and northern mid-latitude sources (30°N-60°N) contributed 32% (185 Tg CH₄ yr⁻¹; 171–209). High-latitude (>60°N) systems yielded only 4% of global methane emissions (24 Tg CH₄ yr⁻¹; 21–28).

Increased methane emissions from 2000–2006 to 2017 arose primarily from tropical and temperate latitudes (figure 3). Average methane emissions increased by 29 and 32 Tg CH₄ yr⁻¹ in the tropics (<30°N) for TD and BU approaches, respectively, and by 15 and 23 Tg CH₄ yr⁻¹ in northern mid-latitudes (30°N-60°N) (figure 3). In contrast, we find no evidence to date for increasing methane release from the Arctic. Despite rapidly warming air temperatures (World Meteorological Organization 2019), methane emissions from northern high-latitude systems (>60°N) were virtually unchanged in 2017 relative to the average value for 2000–2006: –0.4 and –1.6 Tg CH₄ yr⁻¹ for TD and BU methods, respectively.

The average global atmospheric and soil methane sink estimated for 2017 increased to 571 (540–585) Tg CH₄ yr⁻¹ from 546 (531–555) Tg CH₄ yr⁻¹ for the 2000–2006 average based on the TD approaches. Partitioning the global methane sink into components in the atmosphere (CH₄ destruction from tropospheric OH and Cl and total stratospheric losses) and soil (microbial consumption) for 2017 yields an average TD atmospheric sink of 531 (502–540) Tg CH₄ yr⁻¹ and an average soil sink of 40 (37–47) Tg CH₄ yr⁻¹ (table 1).

3. Regional attribution and anthropogenic emissions

Specific regions contributed the most to greater methane emissions in 2017 compared with 2000–2006. Three regions (Africa and the Middle East; China; and South Asia and Oceania) each
increased emissions by ~10–15 Tg CH₄ yr⁻¹ assessed using both TD and BU methods (figure 3). The next-largest changes occurred in North America, with growth of 6.7 and 5.0 Tg CH₄ yr⁻¹ for TD and BU approaches, respectively (figure 3), mostly from the United States (5.1 and 4.4 Tg CH₄ yr⁻¹ for TD and BU, respectively). Europe was the only region where CH₄ emissions appear to have decreased in 2017 relative to 2000–2006, with emissions down ~1.6 Tg CH₄ yr⁻¹ for TD methods and ~4.3 Tg CH₄ yr⁻¹ for BU methods.

Anthropogenic sources are estimated to contribute almost all of the additional methane emitted to the atmosphere for 2017 compared to 2000–2006 (table 1). TD estimates of mean anthropogenic emissions in 2017 increased 40 Tg CH₄ yr⁻¹ (12%) to 364 (range 340–381) Tg CH₄ yr⁻¹ (table 1). Agriculture and Waste sources (table 1). Increasing emission estimates from anthropogenic sectors over the past two decades are consistent with previous work from Saunois et al 2017, although the relative contribution of fossil fuel and agriculture and waste sectors differs across studies (e.g. Schwietzke et al 2016) owing to different time periods, modelling systems, and data included.

Mean annual methane emissions rose sharply in some sectors from 2000–2006 to 2017 (figure 4). Increased agricultural emissions predominated in South Asia/Oceania, Africa, and South America, with increases of 9–10 Tg CH₄ yr⁻¹ in South Asia/Oceania and 7–9 Tg CH₄ yr⁻¹ in Africa (figure 4). By comparison, Europe’s agricultural methane emissions decreased ~1.4 to ~2.8 Tg CH₄ yr⁻¹ for TD and BU methods, respectively. Increased emissions from the fossil fuel sector were the largest in China (5.3 and 12.2 Tg CH₄ yr⁻¹ for TD and BU, respectively) and North America, Africa, and South Asia and Oceania (4 to 6 Tg CH₄ yr⁻¹ in all three regions and using both approaches). Fossil fuel-related methane emissions in the United States increased 3.4 to 4.0 Tg CH₄ yr⁻¹ for TD and BU estimates, respectively, approximately

Table 1. Mean global methane emissions by source type in Tg CH₄ yr⁻¹ for the period 2000–2006 (middle column) and 2017 (right column) using bottom-up (BU) and top-down (TD) approaches. Because top-down models cannot fully separate individual processes, only five categories of emissions are provided (see Saunois et al 2020). Uncertainties are reported as [min-max] range of reported studies. Differences of 1 Tg CH₄ yr⁻¹ in the totals can occur due to rounding errors. ‘Total chemical loss’ includes atmospheric loss from tropospheric OH and Cl as well as stratospheric loss.

| Period of time | BU 2000–2006 | TD 2000–2006 | BU 2017 | TD 2017 |
|---------------|--------------|--------------|---------|---------|
| Approaches    |              |              |         |         |
| Natural sources |              |              |         |         |
| Wetlands      | 146 [102–176]| 184 [166–196]| 145 [100–183]| 194 [155–217]|
| Other natural sources | 222 [143–306]| 36 [21–47]| 222 [143–306]| 39 [21–50]|
| Freshwaters   | 159 [117–212]|             | 222 [143–306]| 39 [21–50]|
| Geological    | 45 [18–65]   |              | 222 [143–306]| 39 [21–50]|
| Wild animals  | 2 [1–3]      |              | 222 [143–306]| 39 [21–50]|
| Termites      | 9 [3–15]     |              | 222 [143–306]| 39 [21–50]|
| Permafrost soils (direct) | 1 [0–1] | | 222 [143–306]| 39 [21–50]|
| Biogenic ocean (open and coastal) | 6 [4–10] | | 222 [143–306]| 39 [21–50]|
| Total natural sources | 368 [245–482]| 220 [198–243]| 367 [243–489]| 232 [194–267]|
| Anthropogenic sources |              |              |         |         |
| Agriculture and waste | 189 [176–203]| 203 [194–213]| 213 [198–232]| 227 [205–246]|
| Enteric ferm. and manure | 102 [99–108]| 115 [110–121]| 222 [143–306]| 39 [21–50]|
| Landfills and waste | 59 [54–61]| 68 [64–71]| 222 [143–306]| 39 [21–50]|
| Rice cultivation | 28 [23–34]| 30 [24–40]| 222 [143–306]| 39 [21–50]|
| Fossil fuels   | 106 [90–123]| 135 [121–164]| 108 [91–121]|         |
| Coal mining   | 29 [22–39]  | 44 [31–63]  | 222 [143–306]| 39 [21–50]|
| Oil and gas    | 72 [59–83]  | 84 [72–97]  | 222 [143–306]| 39 [21–50]|
| Industry      | 2 [0–5]     | 3 [0–8]     | 222 [143–306]| 39 [21–50]|
| Transport     | 4 [1–10]    | 4 [1–13]    | 222 [143–306]| 39 [21–50]|
| Biomass and biof. burn. | 33 [26–49]| 30 [27–36]| 29 [24–38]| 28 [25–32]|
| Biomass burning | 20 [15–35]| 16 [11–24]| 222 [143–306]| 39 [21–50]|
| Biofuel burning | 12 [9–14]| 13 [10–14]| 222 [143–306]| 39 [21–50]|
| Total anthropogenic sources | 328 [315–352]| 324 [308–341]| 380 [359–407]| 364 [340–381]|
| Total sources  | 696 [560–834]| 546 [538–555]| 747 [602–896]| 596 [572–614]|
| Sinks         |              |              |         |         |
| Total chemical loss | 510 [501–515]| 531 [502–540]| 28 [25–32]|         |
| Soil uptake   | 30 [11–49]  | 35 [30–41]  | 30 [11–49]| 40 [37–47]|
| Total sinks   | 546 [531–555]| 571 [540–585]|         |         |
80% of the total increase for North America from 2000–2006 to 2017.

4. Natural methane sources

Global methane emissions estimated from natural sources are relatively unchanged from 2000–2006 to 2017, albeit with large uncertainties (table 1). Mean top-down estimates for natural methane sources were 232 (194–267) Tg CH₄ yr⁻¹ in 2017 compared with 220 (198–243) Tg CH₄ yr⁻¹ for 2000–2006 (table 1); mean bottom-up estimates were substantially higher: 367 (243–489) and 368 (245–482) Tg CH₄ yr⁻¹ for the two periods, respectively. Natural sources remain more poorly constrained than anthropogenic ones, with divergent estimates for the bottom-up and top-down emissions. Vegetated wetlands contributed 194 (155–217) Tg CH₄ yr⁻¹ of the total, about 83% of natural sources based on TD methods (table 1). In contrast, BU methods estimate vegetated wetland emissions to be 145 (100–183) Tg CH₄ yr⁻¹ in 2017, a value unchanged from the 2000–2006 average but only three-quarters of the TD estimate (that also includes inland water emissions).

Wetlands and freshwater systems more broadly are the largest source of methane but also the greatest
source of uncertainty to the global methane budget. Their inclusion in BU methodologies leads to a difference of roughly 150 Tg CH$_4$ yr$^{-1}$ when compared to the atmospheric constraint. Wetland definitions and challenges in properly understanding the location of wetlands have led to ‘double counting’ of inland waters and vegetated wetlands in previous studies. Our use of the Wetland Area Dynamics for Methane Modeling (WAD2M) dataset reduced the effect of double counting by ~35 Tg CH$_4$ yr$^{-1}$ compared to the previous budget in Saunois et al (2016), with vegetated wetlands accounting for 101–179 Tg CH$_4$ yr$^{-1}$. However, the inland waters estimate is revised to a range of 117–212 Tg CH$_4$ yr$^{-1}$, higher than in Saunois et al (2016) due to newer studies that measured higher emission factors in freshwater systems.
(Delsontro et al. 2018, Saunois et al. 2020). Reconciling the wetland methane emissions flux requires continued attention and the use of independent lines of data from isotopes, flux towers, and satellite observations (e.g. Knox et al. 2019).

Another source of uncertainty is the amount of methane released from natural geological sources, particularly seeps and mud volcanoes. The new global BU estimate for natural geological sources (terrestrial and marine) of 45 (range of 18–65) Tg CH₄ (Etiope et al. 2019, Saunois et al. 2020) is 7 Tg CH₄ smaller than the value in Saunois et al. (2016a). However, recent studies analyzing radiocarbon methane (¹⁴CCH₄) in ice cores have concluded that pre-industrial emissions of thermogenic (i.e. ancient or ‘fossil’) methane were close to zero (~0–5.4 Tg CH₄; Hmiel et al. 2020)—substantially less even than the 15.4 Tg CH₄ estimated for the abrupt warming event that occurred between the Younger Dryas and Preboreal intervals ~11 600 years ago (Petrenko et al. 2017). Hmiel et al. (2020) also conclude that current estimates of CH₄ emissions from the fossil fuel industry are therefore too low by 30 to 40 Tg CH₄ (Lassey et al. 2007). However, the uncertainties in isotopic budget studies remain substantial due to the uncertainties in the isotopic signature of the sources.

Unlike top-down approaches, bottom-up inventories estimate activity and emissions factors separately. In contrast to the results of Hmiel et al. (2020), a new annual estimate of natural methane emissions from the East Siberian Arctic Shelf alone is 3.0 Tg CH₄, most of it thermogenic methane (Thornton et al. 2020). A number as small as 5 Tg CH₄ per year for all natural geologic emissions (Hmiel et al. 2020) seems difficult to reconcile with the results of Thornton et al. (2020), the work of other researchers more broadly, and with BU approaches generally. Research is needed to constrain geologic sources fully.

Additional focus and monitoring is also needed to track the potential for rapid methane release from the Arctic (e.g. Post et al. 2019, Zhang et al. 2019). Average surface temperatures in the Arctic have risen twice as fast as the global average of 1.1 °C over the past two decades (compared to the period 1850–1900; WMO 2019). As a result of permafrost thaw and other changes in peatland ecosystems, many investigators and models predict a substantial increase in Arctic methane emissions this century. However, our latitudinal estimates from TD methods shows no evidence for the start of such a transition through year 2017 (figure 4; see also Saunois et al. 2020).

5. Conclusions

Methane emissions have continued to rise over the past decade and are tracking concentrations most consistent with the warmest marker scenario of the Intergovernmental Panel on Climate Change (RCP8.5, a representative concentration pathway) that yields an estimated global warming of 4.3 °C by year 2100 (Saunois et al. 2016b, 2020, Nisbet et al. 2019). Current trajectories in socioeconomic development also suggest the world is likely to follow IPCC Shared Socioeconomic pathways (SSP) leading to relatively higher emission trajectories over the next decade (Saunois et al. 2020). Estimates for 2018 and 2019 show increases in atmospheric methane of 8.5 and 10.7 ppb, respectively, two of the four highest annual growth rates since 2000 (Dlugokencky 2020).

Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner et al. 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.

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Data Availability Statement

The data that support the findings of this study are openly available at globalcarbonproject.org.

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https://orcid.org/0000-0001-8846-7147
Kirschke S et al 2013 Three decades of global methane sources and sinks Nat. Clim. Change 6 813–23

Knorr S H et al 2019 FLUXNET-CH4 synthesis activity: objectives, observations, and future directions Bull. Am. Meteorol. Soc. 100 2607–32

Lassey K R, Etheridge D M, Lowe D C, Smith A M and Ferretti D F 2007 Centennial evolution of the atmospheric methane budget: what do the carbon isotopes tell us? Atmos. Chem. Phys. 7 2119–39

Locatelli R et al 2013 Impact of transport model errors on the global and regional methane emissions estimated by inverse modelling Atmos. Chem. Phys. 13 9917–37

Nisbet E G et al 2019 Very strong atmospheric methane growth in the four years 2014–2017: implications for the Paris Agreement Glob. Biogeochem. Cycles 33 318–42

Pekel J-F, Cottam A, Gorelick N and Belward A 2016 High-resolution mapping of global surface water and its long-term changes Nature 540 418–22

Petrdenko V V et al 2017 Minimal geological methane emissions during the Younger Dryas–Preboreal abrupt warming event Nature 548 443–6

Post E et al 2019 The polar regions in a 2°C warmer world Sci. Adv. 5 eaaw9883

Rigby M et al 2017 Role of atmospheric oxidation in recent methane growth Proc. Nat. Acad. Sci. USA 114 5373–7

Saunois M et al 2016a The global methane budget 2000–2012 Earth Syst. Sci. Data 8 697–751

Saunois M et al 2017 Variability and quasi-decadal changes in the methane budget over the period 2000–2012 Atmos. Chem. Phys. 17 11155–11161

Saunois M et al 2020 The global methane budget 2000–2017 Earth Syst. Sci. Data 12 1561–623

Saunois, M, Jackson R B, Bousquet P, Poulter B and Canadell J G 2016b The growing role of methane in anthropogenic climate change Environ. Res. Lett. 11 120207

Schwietzke S et al 2016 Upward revision of global fossil fuel methane emissions based on isotope database Nature 538 88–91

Thornton B F, Prytherch J, Andersson K, Brooks I M, Salisbury D, Tjernström M and Grill P M 2020 Shipborne eddy covariance observations of methane fluxes constrain Arctic sea emissions Sci. Adv. 6 ezaa7934

Turner A J, Frankenberg C and Kort E A 2019 Interpreting contemporary trends in atmospheric methane Proc. Natl. Acad. Sci. USA 116 2805–13

World Meteorological Organization 2019 United in Science (Geneva: WMO)

Zhang Z, Zimmerman N E, Stenke A, Li X, Hodson E L, Zhu G, Huang C and Poulter B 2019 Emerging role of wetland methane emissions in driving 21st century climate change Proc. Nat. Acad. Sci. USA 114 9647–52

Zhao Y et al 2020 Influences of hydroxyl radicals (OH) on top–down estimates of the global and regional methane budgets Atmos. Chem. Phys. Discuss. (submitted) (https://doi.org/10.5194/acp-2019-1208)