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PERSPECTIVE

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R B Jackson[1], M Saunois[2], P Bousquet[2], J G Canadell[3], B Poulter[4], A R Stavert[5], P Bergamaschi[6], Y Niwa[7,8], A Segers[9] and A Tsuruta[10]

[1] Department of Earth System Science, Woods Institute for the Environment, and Precourt Institute for Energy, , Stanford University, Stanford, CA 94305-2210, United States of America
[2] Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay, 91191 Gif-sur-Yvette, France
[3] Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, ACT 2601, Australia
[4] NASA Goddard Space Flight Center, Biospheric Sciences Laboratory, Greenbelt, MD 20771, United States of America
[5] Global Carbon Project, CSIRO Oceans and Atmosphere, Aspendale, VIC 3195, Australia
[6] European Commission Joint Research Centre, 21027 Ispra (Va), Italy
[7] Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan
[8] Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan
[9] TNO, Dept. of Climate Air & Sustainability, NL-3508-TA Utrecht, The Netherlands
[10] Finnish Meteorological Institute, FI-00101 Helsinki, Finland

E-mail: rob.jackson@stanford.edu

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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 (CO_2) 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 (CH_4) emissions have contributed almost one quarter of the cumulative radiative forcings for CO_2, CH_4, and N_2O (nitrous oxide) combined since 1750 (Etminan *et al* 2016). Although methane is far less abundant in the atmosphere than CO_2, it absorbs thermal infrared radiation much more efficiently and, in consequence, has a global warming potential (GWP) ~86 times stronger per unit mass than CO_2 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 CH_4 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 CH_4 emissions as in Saunois *et al* (2020). One approach we use is a top-down (TD) ensemble of 11 inversions using atmospheric CH_4 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 CH_4 yr^{-1} (figure 1, table 1) based on 11 top-down atmospheric inversions, with an ensemble max.-min. range of 572–614 Tg CH_4 yr^{-1}. This value is 9% (50 Tg CH_4 yr^{-1}) higher than the average for the period 2000–2006 (546 Tg CH_4 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 CH_4 yr^{-1}, from 696 (560–834) Tg CH_4 yr^{-1} in 2000–2006 to 747 (602–896) Tg CH_4 yr^{-1} in 2017 (table 1). Anthropogenic sources contributed an estimated 51% of total global BU emissions in 2017. The difference of ~150 Tg CH_4 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 CH_4 yr^{-1}; 351–405) of global methane emissions and northern mid-latitude sources (30°N-60°N) contributed 32% (185 Tg CH_4 yr^{-1}; 171–209). High-latitude (>60°N) systems yielded only 4% of global methane emissions (24 Tg CH_4 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 CH_4 yr^{-1} in the tropics (<30°N) for TD and BU approaches, respectively, and by 15 and 23 Tg CH_4 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 CH_4 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 CH_4 yr^{-1} from 546 (531–555) Tg CH_4 yr^{-1} for the 2000–2006 average based on the TD approaches. Partitioning the global methane sink into components in the atmosphere (CH_4 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 CH_4 yr^{-1} and an average soil sink of 40 (37–47) Tg CH_4 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

Table 1. Mean global methane emissions by source type in Tg CH_4 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 CH_4 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	2000–2006		2017	
Approaches	BU	TD	BU	TD
		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]			
Geological	45 [18–65]			
Wild animals	2 [1–3]			
Termites	9 [3–15]			
Permafrost soils (direct)	1 [0–1]			
Biogenic ocean (open and coastal)	6 [4–10]			
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]	
Landfills and waste	59 [54–61]		68 [64–71]	
Rice cultivation	28 [23–34]		30 [24–40]	
Fossil fuels	106 [90–123]	92 [70–113]	135 [121–164]	108 [91–121]
Coal mining	29 [22–39]		44 [31–63]	
Oil and gas	72 [59–83]		84 [72–97]	
Industry	2 [0–5]		3 [0–8]	
Transport	4 [1–10]		4 [1–13]	
Biomass and biof. burn.	33[26–49]	30 [27–36]	29 [24–38]	28 [25–32]
Biomass burning	20 [15–35]		16 [11–24]	
Biofuel burning	12 [9–14]		13 [10–14]	
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]
Soil uptake	30 [11–49]	35 [30–41]	30 [11–49]	40 [37–47]
Total sinks		546 [531–555]		571 [540–585]

increased emissions by ~10–15 Tg CH_4 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 CH_4 yr^{-1} for TD and BU approaches, respectively (figure 3), mostly from the United States (5.1 and 4.4 Tg CH_4 yr^{-1} for TD and BU, respectively). Europe was the only region where CH_4 emissions appear to have decreased in 2017 relative to 2000–2006, with emissions down −1.6 Tg CH_4 yr^{-1} for TD methods and −4.3 Tg CH_4 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 CH_4 yr^{-1} (12%) to 364 (range 340–381) Tg CH_4 yr^{-1} (table 1). Agriculture and Waste contributed 60% of this increase and Fossil Fuels the remaining 40%, with a slight decrease estimated for Biomass and Biofuel Burning. Based on BU methods, anthropogenic emissions in 2017 rose 52 Tg CH_4 yr^{-1} (16%) to 380 (range 359–407) Tg CH_4 yr^{-1} (table 1), with 56% of the increase coming from Fossil Fuels and 44% from 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 CH_4 yr^{-1} in South Asia/Oceania and 7–9 Tg CH_4 yr^{-1} in Africa (figure 4). By comparison, Europe's agricultural methane emissions decreased −1.4 to −2.8 Tg CH_4 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 CH_4 yr^{-1} for TD and BU, respectively) and North America, Africa, and South Asia and Oceania (4 to 6 Tg CH_4 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 CH_4 yr^{-1} for TD and BU estimates, respectively, approximately

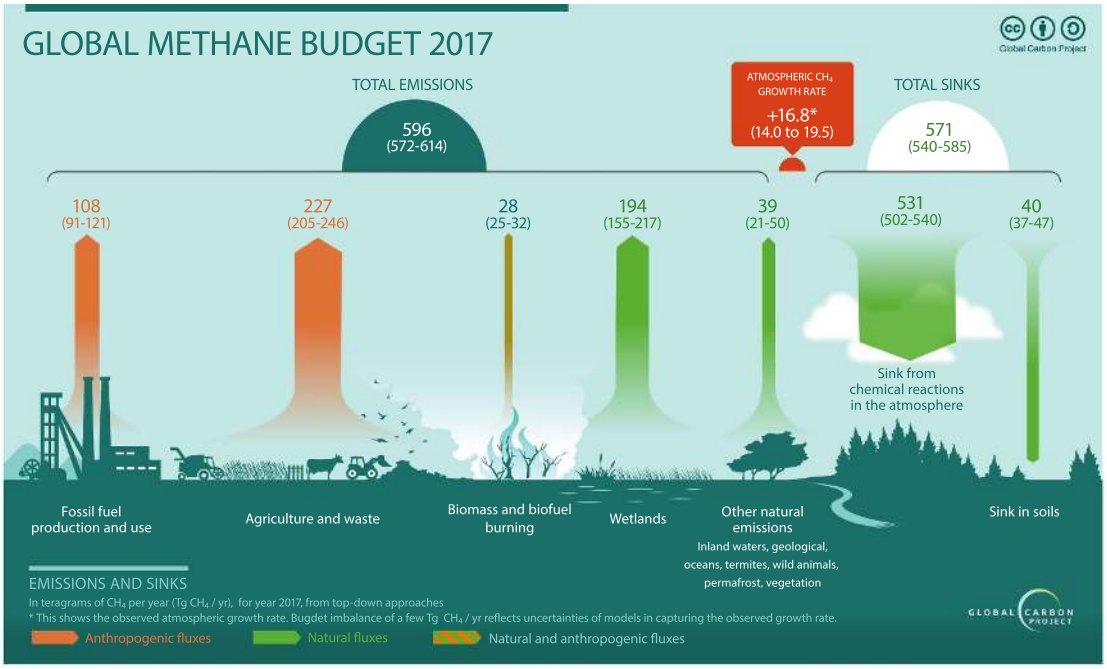

Figure 1. The global methane budget for year 2017 based on top-down methods for natural sources and sinks (green), anthropogenic sources (orange), and mixed natural and anthropogenic sources (hatched orange-green for 'biomass and biofuel burning').

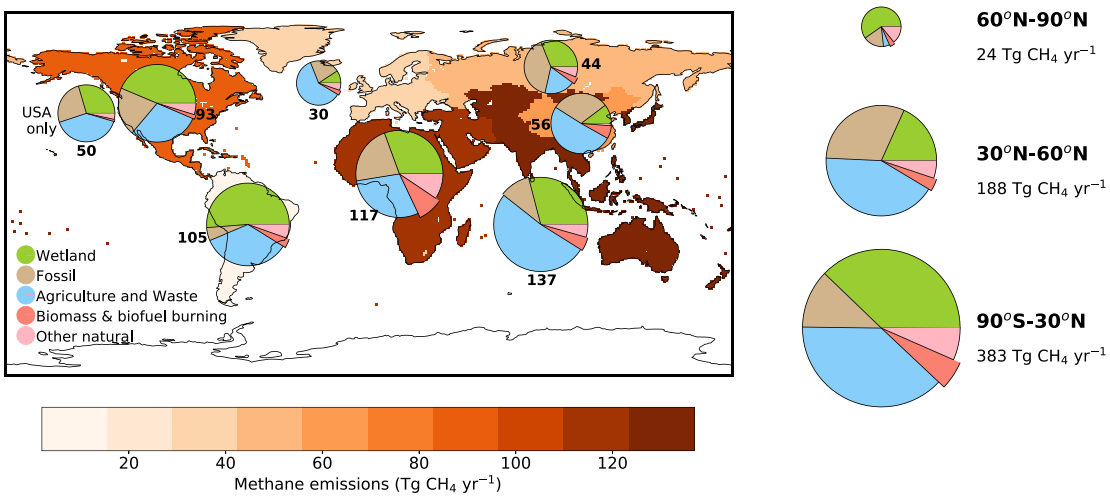

Figure 2. Methane emissions (Tg CH_4 yr^{-1}) for 2017 by region, source category, and latitude. The mean estimates shown arise from the ensemble of top-down inversion models described in Saunois *et al* (2020).

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 CH_4 yr^{-1} in 2017 compared with 220 (198–243) Tg CH_4 yr^{-1} for 2000–2006 (table 1); mean bottom-up estimates were substantially higher: 367 (243–489) and 368 (245–482) Tg CH_4 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 CH_4 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 CH_4 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

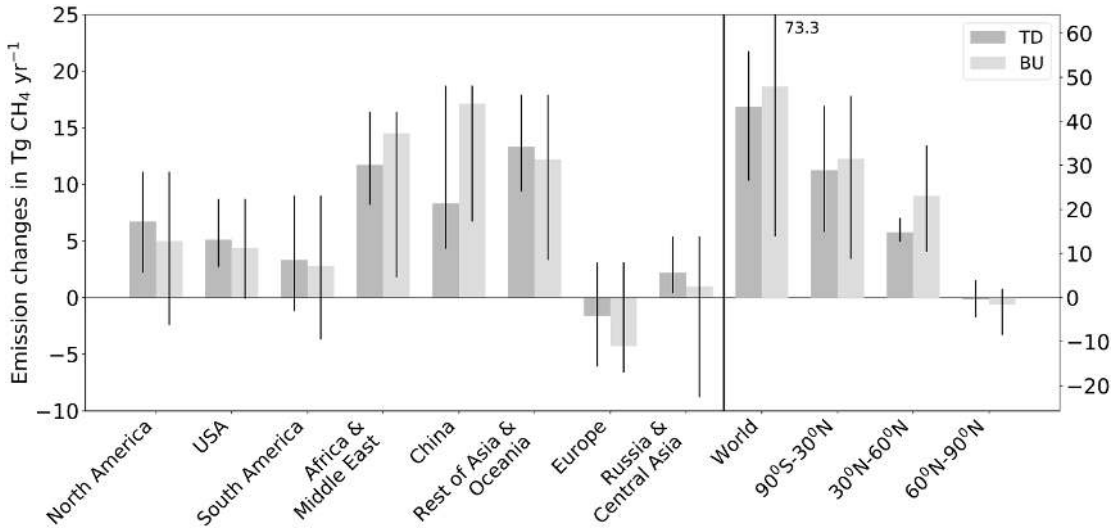

Figure 3. Changes in total methane emissions (mean and min-max range in Tg CH_4 yr^{-1}) in 2017 compared with mean values for 2000–2006 by region (left panel) and latitude (right panel; note different *y*-axis scales). Each pair of bars presents top-down (dark gray) and bottom-up (light gray) emissions estimates. See the figure 2 legend for a map of the regions. Positive values reflect emissions that were larger in 2017 than in the period 2000–2006. For top-down (TD) estimates, the mean, minimum and maximum values correspond to values across the ensemble of 11 model inversions. For bottom-up (BU) estimates, they are the mean, min and max values of the total emissions ensemble obtained by combining 4 anthropogenic inventories with 3 fire products and 13 wetland emissions model results.

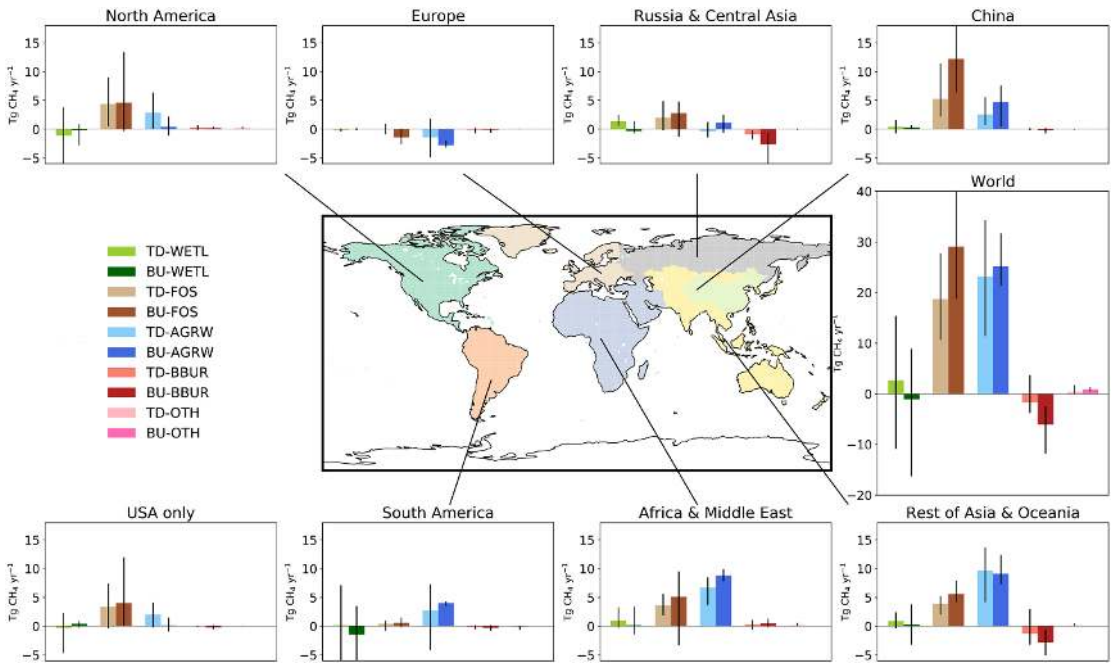

Figure 4. Changes in methane emissions (Tg CH_4 yr^{-1}; min-max range) by region and source for year 2017 compared with the mean annual value for the period 2000–2006. Positive values represent annual emissions that were larger in 2017. Abbreviations in the color legend refer to top-down (TD) and bottom-up (BU) methods and to 'wetland,' 'fossil,' 'agriculture and waste,' 'biomass burning,' and 'other' sources. See section 1 and the figure 3 legend for descriptions of max-min ranges across inventories, models, and products.

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 CH_4 (Etiope *et al* 2019, Saunois *et al* 2020) is 7 Tg CH_4 smaller than the value in Saunois *et al* (2016a). However, recent studies analyzing radiocarbon methane ($^{14}CH_4$) 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 CH_4; Hmiel *et al* 2020)—substantially less even than the 15.4 Tg CH_4 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 CH_4 emissions from the fossil fuel industry are therefore too low by 30 to 40 Tg CH_4 (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 CH_4, most of it thermogenic methane (Thornton *et al* 2020). A number as small as 5 Tg CH_4 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.

ORCID iDs

R B Jackson
https://orcid.org/0000-0001-8846-7147

M Saunois
https://orcid.org/0000-0003-3983-2931
J G Canadell
https://orcid.org/0000-0002-8788-3218
B Poulter
https://orcid.org/0000-0002-9493-8600
P Bergamaschi
https://orcid.org/0000-0003-4555-1829
A Tsuruta
https://orcid.org/0000-0002-9197-3005

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