Supplement of

A high-resolution satellite-based map of global methane emissions reveals missing wetland, fossil fuel and monsoon sources

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Text S1. TCCON

Analyses here used all available TCCON data across global sites for 01/2018–02/2020. For site information see the following references: (Blumenstock et al., 2017; De Maziere et al., 2017; Deutscher et al., 2017; Dubey et al., 2017a; Dubey et al., 2017b; Feist et al., 2017; Griffith et al., 2017a; Griffith et al., 2017b; Goo et al., 2017; Hase et al., 2017; Iraci et al., 2017a; Iraci et al., 2017b; Kivi, et al., 2017; Morino et al., 2017a; Morino et al., 2017b; Notholt et al., 2017; Sherlock et al., 2017a; Sherlock et al., 2017b; Shiomi et al., 2017; Strong et al., 2017; Sussmann et al., 2017; Te et al., 2017; Warneke et al., 2017; Wennberg et al., 2017a; Wennberg et al., 2017b; Wennberg et al., 2017c; Wennberg et al., 2017d; Wennberg et al., 2017e; Wunch et al., 2017).

Text S2. WetCHARTs model

We evaluate the drivers of wetland emission variability using the process-based WetCHARTs model ensemble (Bloom et al., 2017). WetCHARTs includes 18 estimates of wetland emissions F at location d and time t:

$$F(t,d) = sA(t,d)R(t,d)q_{10}^{\frac{T(t,d)}{10}} \tag{S1}$$

Here, s is a global scale factor to obtain global emissions of 124.5, 166, or 207.5 Tg CH_4/y; A is wetland extent (m^2 wetland area/m^2 surface area) from GLOBCOVER (Bontemps et al., 2011) or the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004) combined with monthly satellite-based surface water or reanalyzed precipitation datasets (Bloom et al., 2017); R is the heterotrophic respiration rate (mgC/day per m^2 of wetland area) derived from the Carbon Data Model Framework (CARDAMOM) (Bloom et al., 2016); and q_{10} (equal to 1, 2, or 3) is the CH_4:C temperature dependence on temperature T.

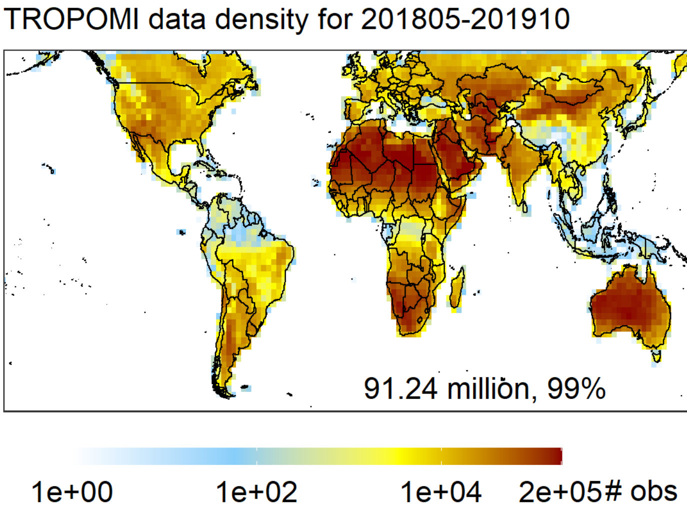

Figure S1. TROPOMI XCH_4 observation density for 05/2018–10/2019. Numbers inset indicate the total number of observations and percent overland coverage.

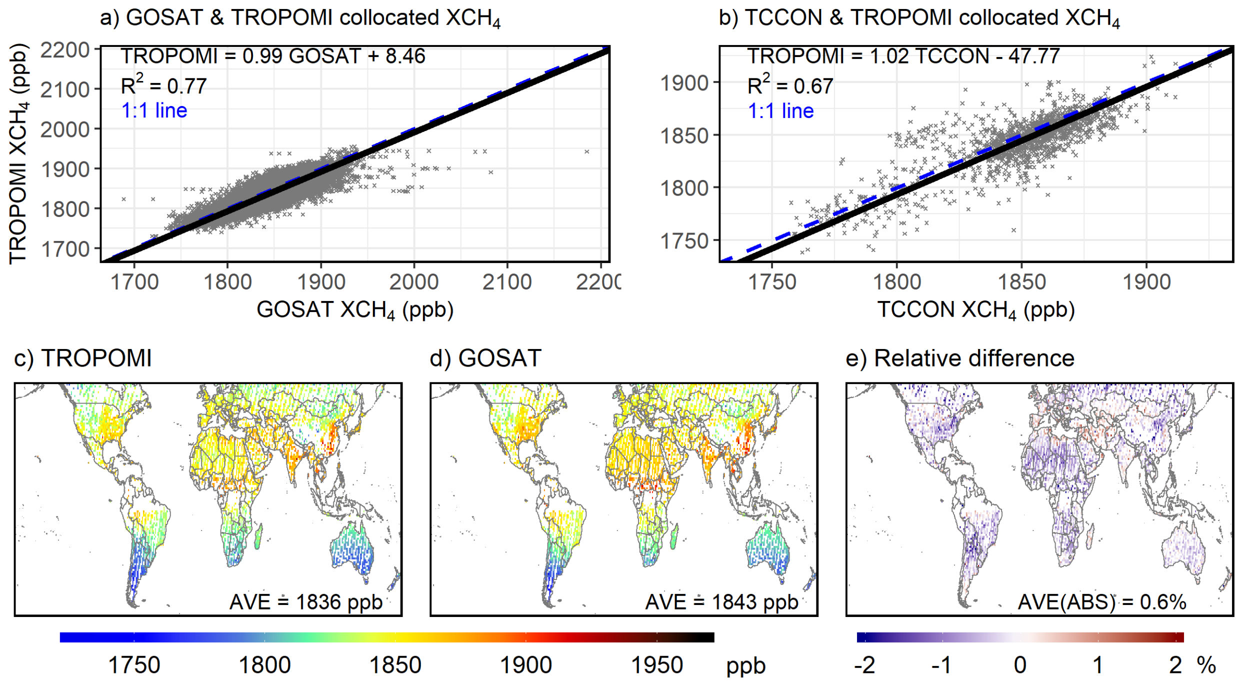

Figure S2. Comparison of TROPOMI XCH_4 measurements against collocated methane column observations from (a) GOSAT and (b) TCCON during 11/2017–02/2020. Bottom panels map the mean column distributions for the same period from c) TROPOMI and d) GOSAT at 1°×1°, along with e) their relative difference (TROPOMI-GOSAT)/0.5(TROPOMI+GOSAT).

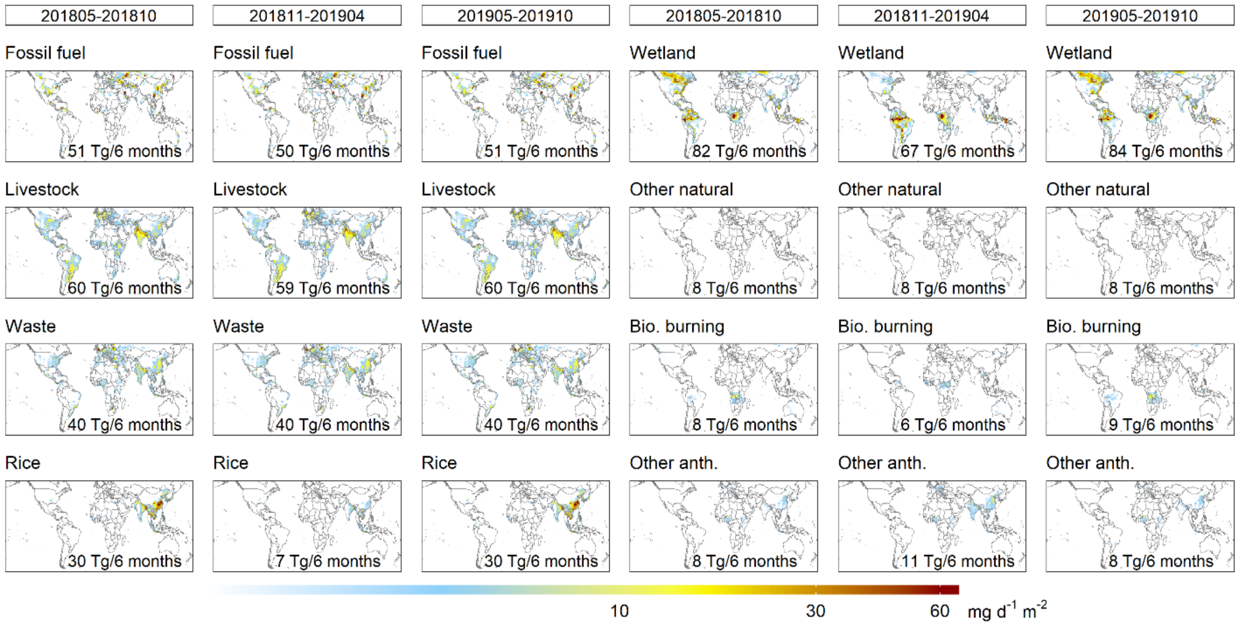

Figure S3. Prior methane emissions by season and sector.

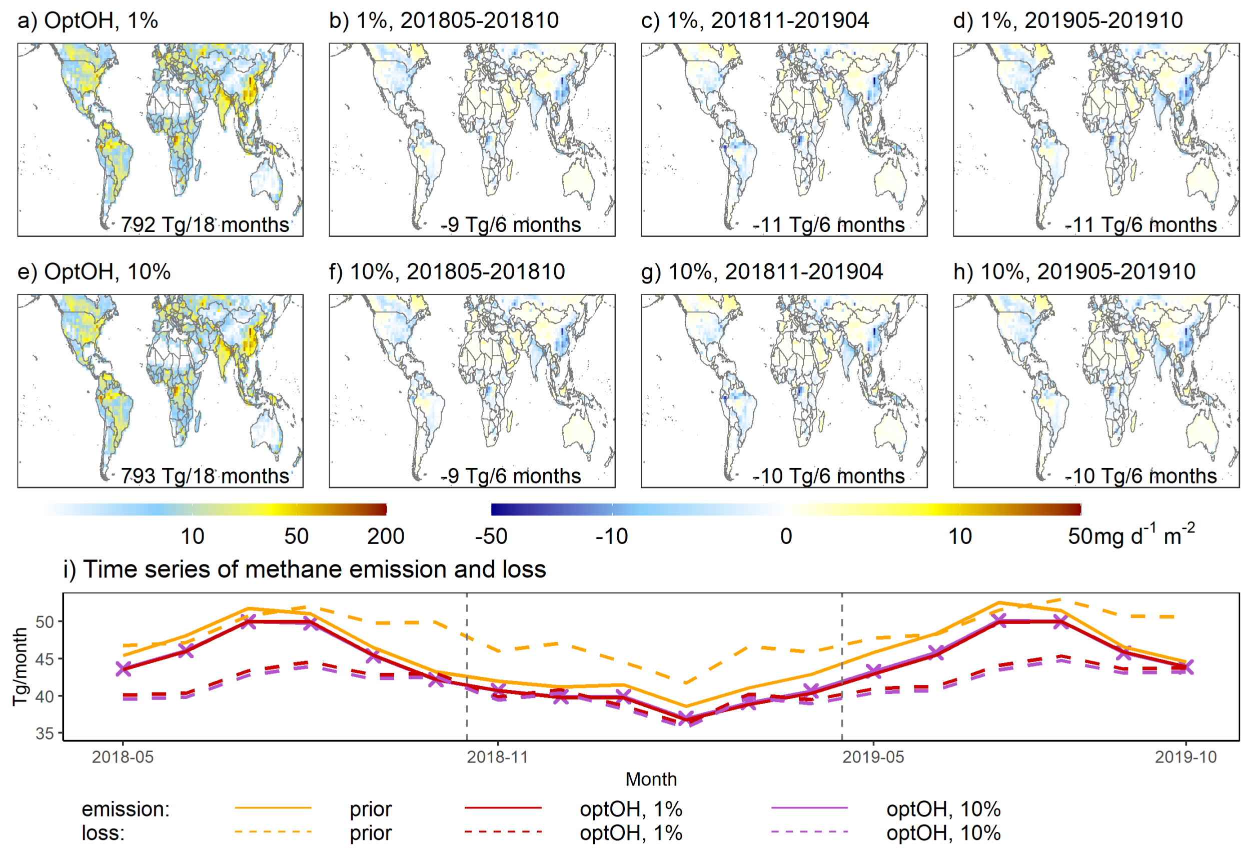

Figure S4. Same as Figure 4, but for the optOH cases with differing prior error estimates for OH.

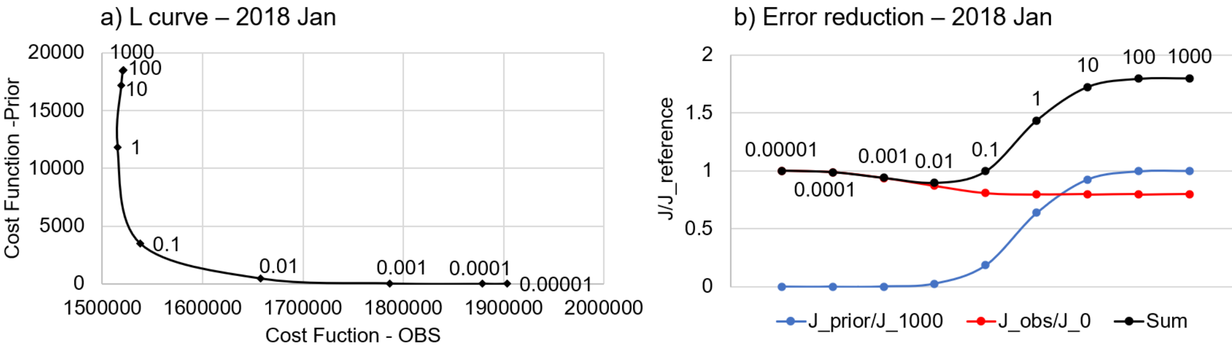

Figure S5. L curve and error reduction curve based on sensitivity inversions for 01/2018. The L curve displays the partitioning of the cost function to its constituent observational and penalty terms. The error reduction plot shows the prior error reduction relative to the solution with regulation parameter $\gamma = 1000$, the observational error reduction relative to the solution with $\gamma = 0.00001$, and their sum. Labels in both plots indicate the corresponding values of γ.

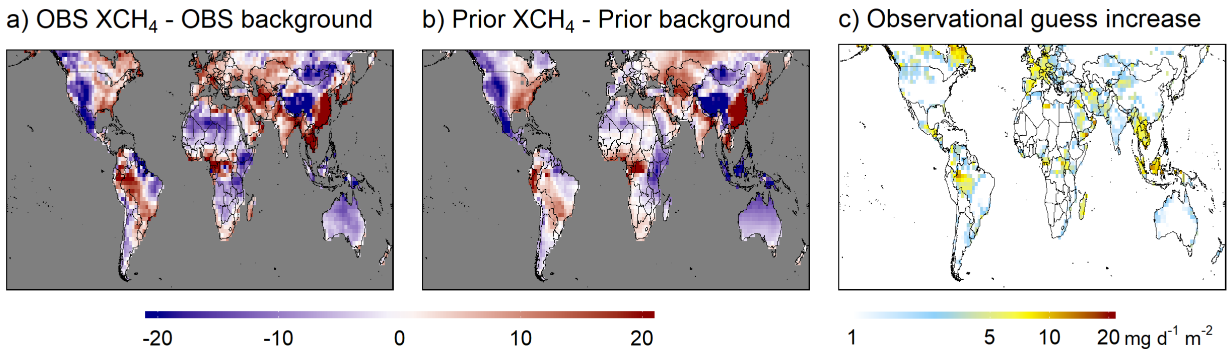

Figure S6. (a) TROPOMI XCH_4 observations for 03/2018–02/2020 gridded to 0.1°×0.1° with the 2°-latitudinal mean subtracted. (b) Same as (a) but for the prior GEOS-Chem simulation. (c) Derived observational guesses used as input for the OG inversions.

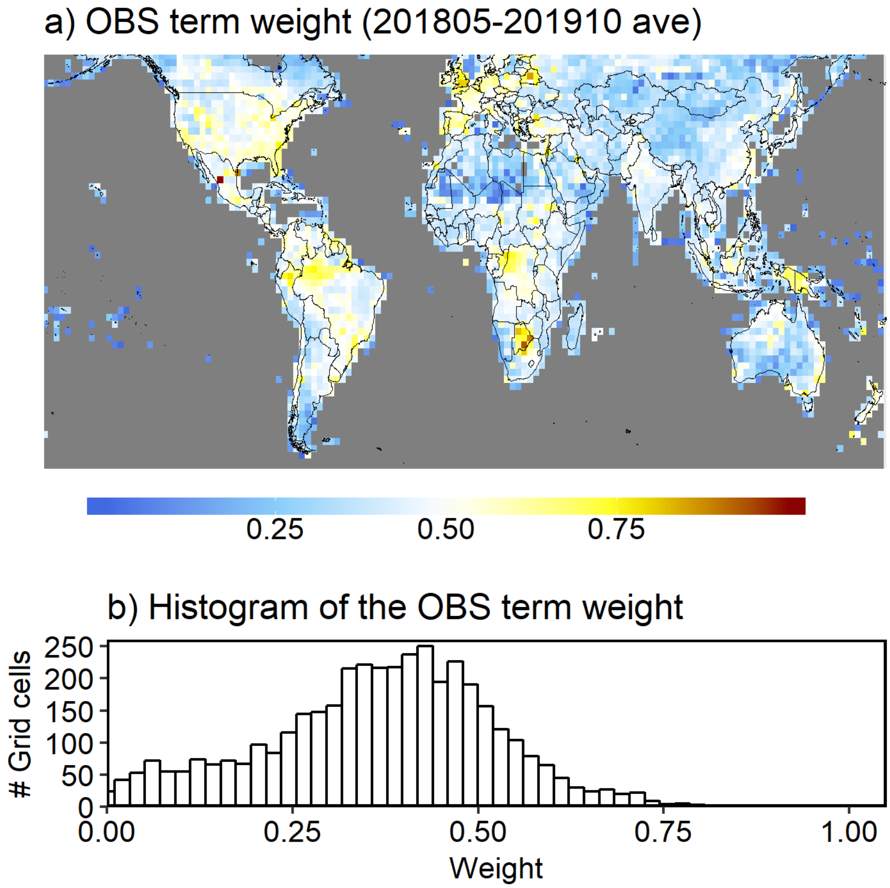

Figure S7. (a) Spatial distributions and (b) histogram of the observational weighting used for spatial downscaling (see Section 2.6 of the main text).

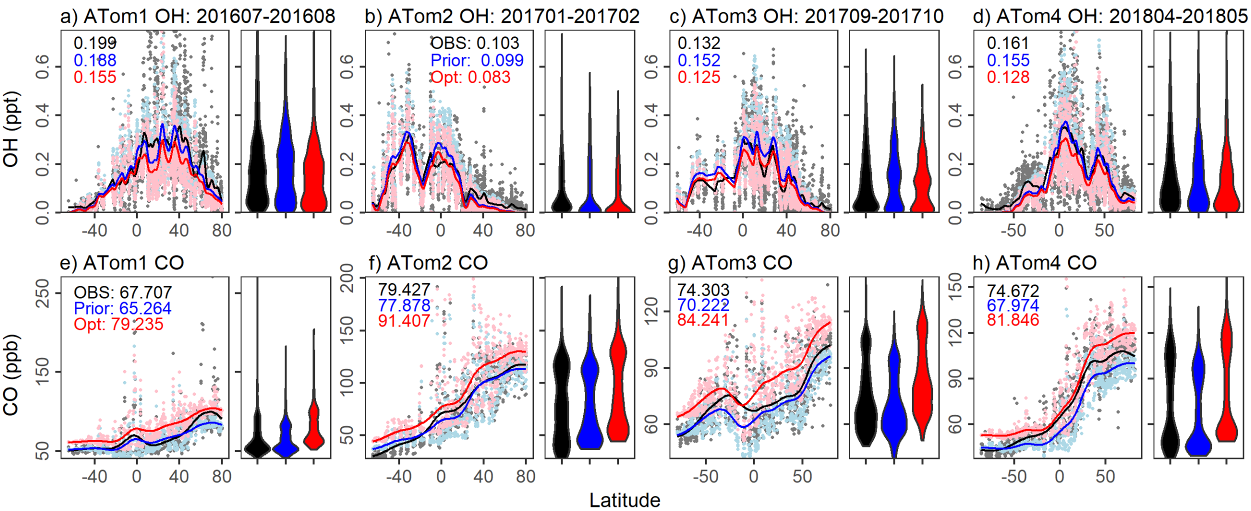

Figure S8. Model-aircraft comparisons for OH and CO as a function of latitude. (a-d) OH measurements from the ATom airborne campaigns compared to GEOS-Chem model predictions. Black: observations, blue: prior OH fields, red: optimized OH fields. Mean values are listed inset with data densities plotted to the right. The full-chemistry GEOS-Chem model is used here as a transfer standard to scale the monthly mean OH fields used in the inversion to the specific location and time of each ATom measurement. (e-h) Same as panels a-d but comparing measured background CO levels (0.1 quantile for each 1° latitude × 1 km altitude bin) against model predictions generated with the above OH fields and the offline CO simulation described by Gonzalez et al. (2021).

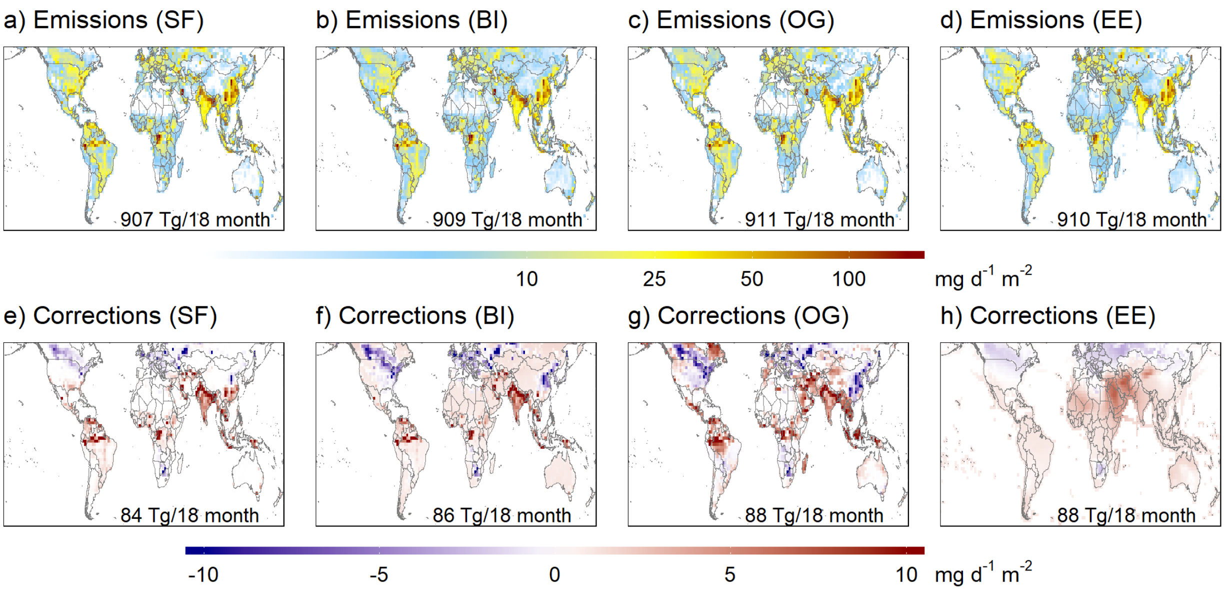

Figure S9. Optimized emissions and emission corrections for the fixOH inversions.

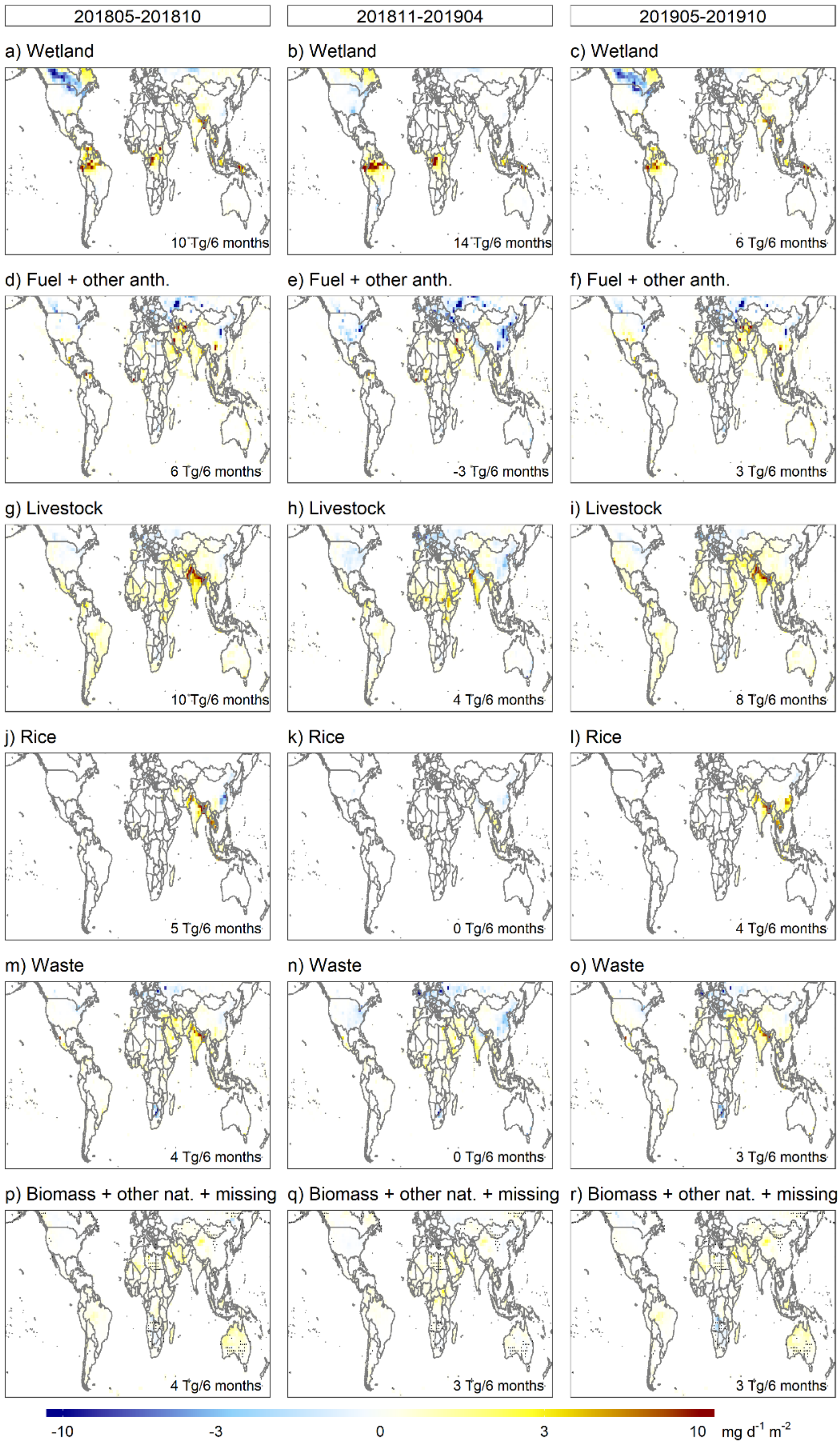

Figure S10. Seasonal emission corrections by sector for the fixOH multi-model mean. Dots in panel p–r show locations with missing sources that are detected by the BI and EE inversions but not by the SF inversion.

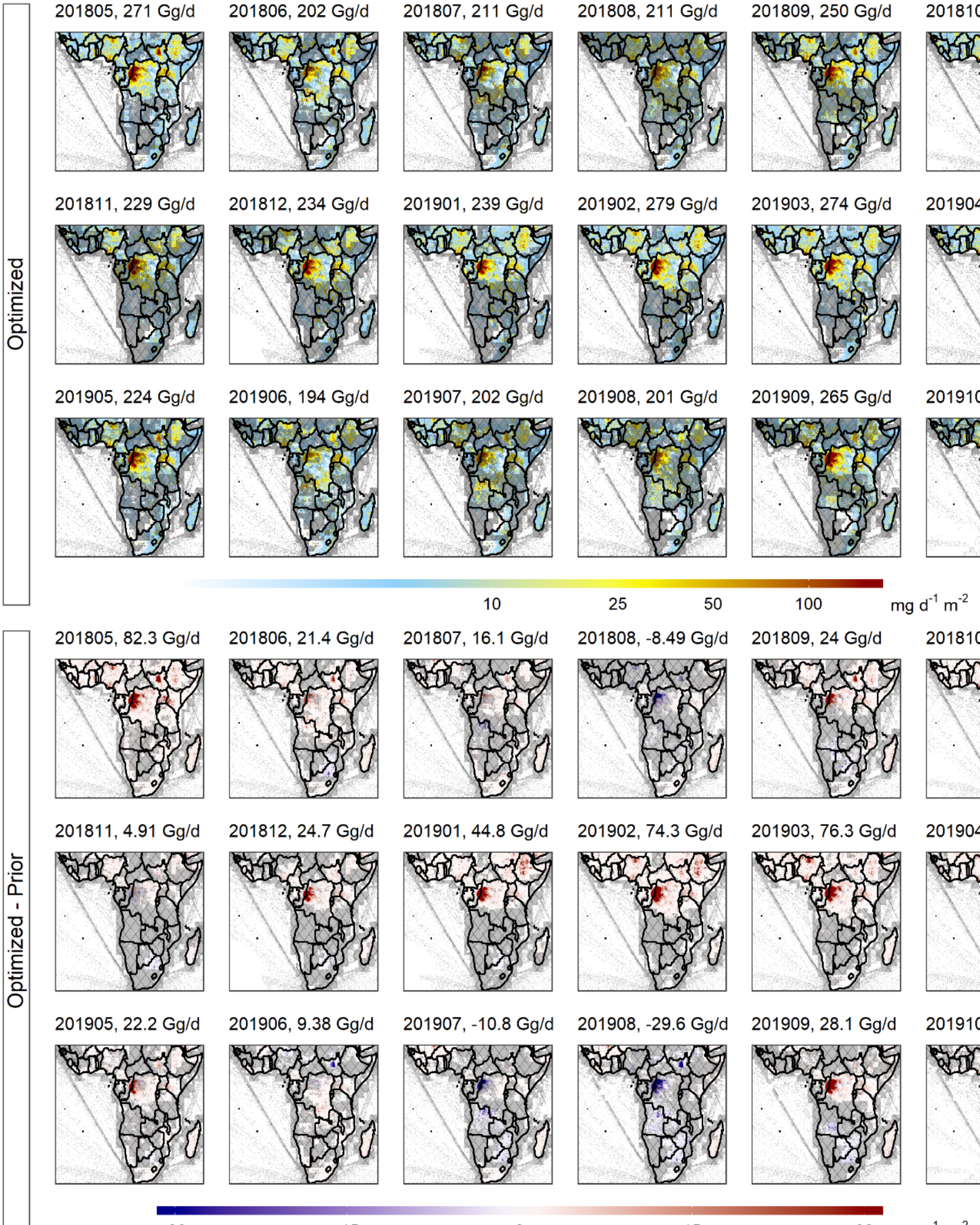

Figure S11. Optimized emissions and emission corrections over central and southern Africa. Hatching shows areas where corrections are not distinguishable from zero (suite of inversions includes both positive and negative adjustments).

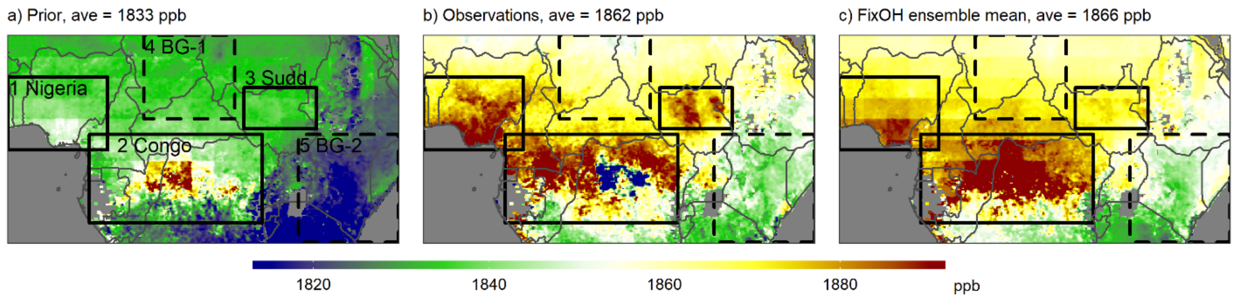

Figure S12. Observed and simulated methane columns over central Africa for 03/2018–02/2020 downscaled to 0.1°×0.1°. a) Prior model predictions. b) TROPOMI XCH_4 observations. c) fixOH multi-model mean optimized simulation. Solid squares indicate source regions discussed in-text: 1) Nigeria, 2) Democratic Republic of the Congo, and 3) the Sudd. Dashed squares show selected background regions, where the mean of the two is used for characterizing source-region enhancements.

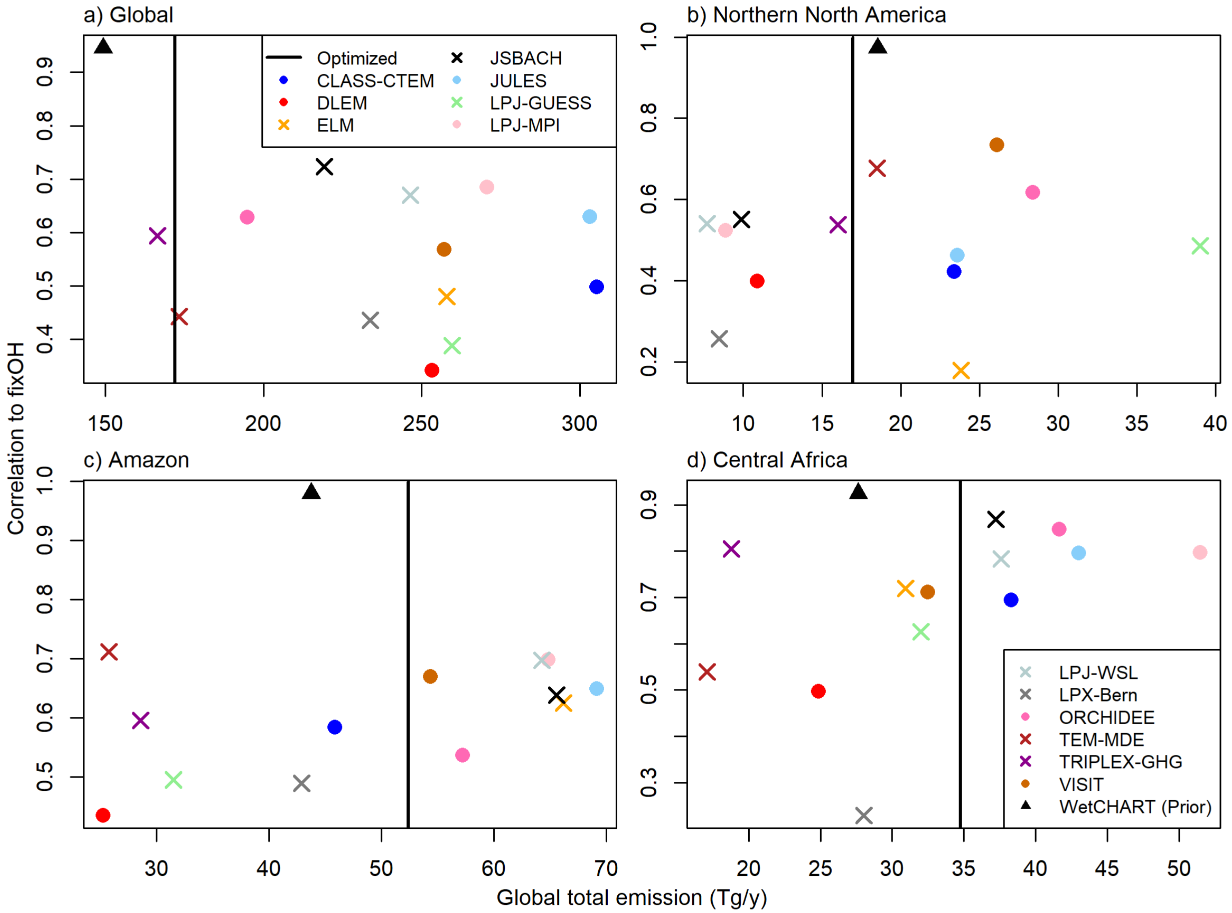

Figure S13. Evaluation of land surface models against the fixOH multi-model mean optimized wetland emissions. Vertical lines indicate the TROPOMI-derived flux for each region.

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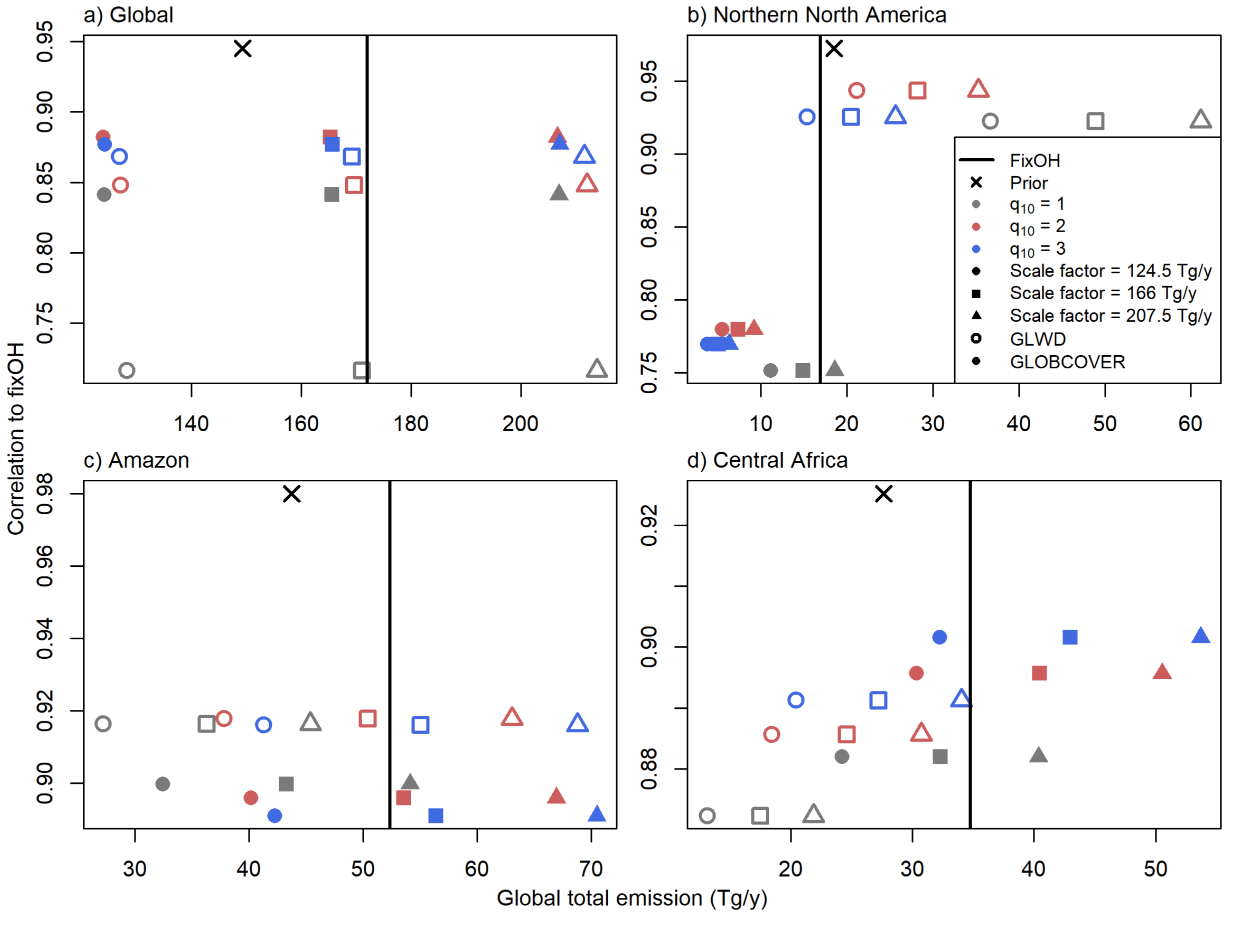

Figure S14. Same as Figure S13 but for the WetCHARTs wetlands model ensemble (Text S2).

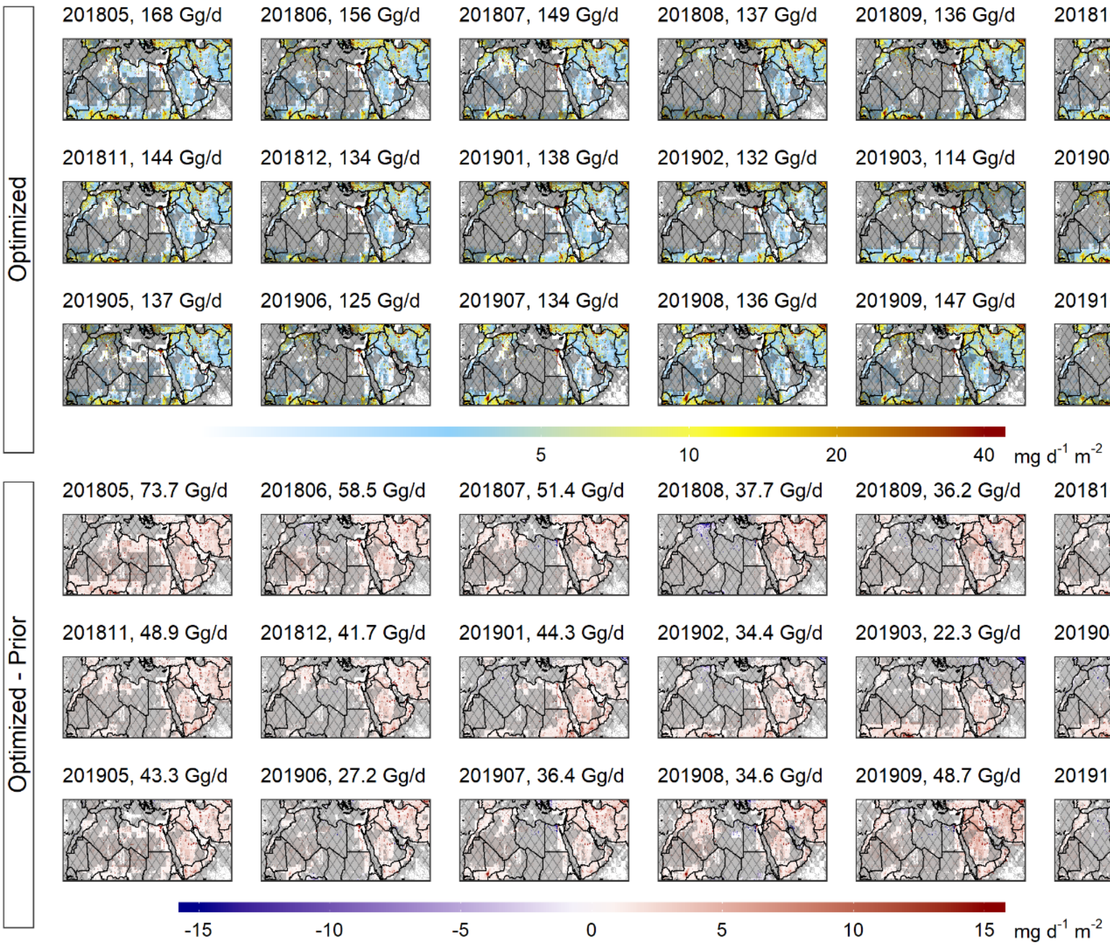

Figure S15. Same as Figure S11, but for the Middle East and northern Africa.

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Table S1. Inversion performance versus TROPOMI, TCCON and ObsPack observations[1]

Dataset	Inversions		Mean bias[2] (ppb)	RMSE (ppb)	R	Slope[3]
TROPOMI (201805–201910)	Prior		-22.65	29.66	0.77	0.83
	FixOH	SF	-2.38	15.87	0.85	0.91
		Background Inc.	-1.44	15.68	0.85	0.91
		Obs. Guess	-1.87	15.54	0.86	0.91
		Enhancement	-1.93	15.42	0.86	0.90
		Multi-model Mean	-0.30	15.08	0.86	0.91
	OptOH	SF	-2.17	16.50	0.83	0.84
		Background Inc.	-3.11	17.18	0.82	0.83
		Obs. Guess	-1.92	16.93	0.82	0.83
		Enhancement	-1.83	17.13	0.82	0.86
		Multi-model Mean	-0.58	16.38	0.83	0.84
TCCON (201805–201910)	Prior		-12.92	22.53	0.81	1.00
	FixOH	SF	3.77	15.31	0.88	0.99
		Background Inc.	4.19	15.45	0.88	0.99
		Obs. Guess	3.69	15.38	0.88	1.00
		Enhancement	3.46	15.27	0.88	0.98
		Multi-model Mean	3.77	15.32	0.88	0.99
	OptOH	SF	4.52	16.03	0.88	0.98
		Background Inc.	3.55	16.03	0.86	0.99
		Obs. Guess	4.53	16.40	0.86	0.99
		Enhancement	4.79	16.42	0.86	1.00
		Multi-model Mean	4.35	16.19	0.86	0.99
ObsPack (201805–201910)[4]	Prior		-13.80	52.51	0.57	0.83
	FixOH	SF	-0.69	49.50	0.60	0.90
		Background Inc.	2.89	49.94	0.58	0.84
		Obs. Guess	3.60	50.79	0.58	0.90
		Enhancement	1.32	49.28	0.60	0.86
		Multi-model Mean	-0.94	48.95	0.60	0.84
	OptOH	SF	6.72	49.20	0.60	0.80
		Background Inc.	10.62	50.77	0.58	0.78
		Obs. Guess	12.28	51.53	0.58	0.83
		Enhancement	7.70	50.19	0.59	0.83
		Multi-model Mean	8.37	49.76	0.59	0.79

[1]Green shading indicates improvement, yellow indicates degradation
[2]Simulated-observed XCH_4
[3]Slope reflects a major axis fit
[4]Excluding outliers (<1600 ppb or >2400 ppb)

Table S2. Top 20 contributors to global methane emissions[1]

	Total emissions (Tg/y)	Change from prior (%)	Sector emissions (Tg/y)			
			Wetland	Agriculture & waste	Fossil fuel	Other
China	61 (56–65)	-3	2 (2–2)	34 (32–36)	18 (16–21)	6 (6–6)
Brazil	59 (55–61)	14	35 (31–37)	20 (19–20)	<0.2	4 (4–4)
US	43 (42–44)	-4	15 (14–15)	16 (15–17)	11 (10–11)	2 (1–2)
India	39 (37–41)	16	2 (2–3)	32 (30–33)	2 (2–2)	3 (3–3)
Russian	38 (35–41)	-13	10 (8–12)	5 (5–6)	21 (17–24)	2 (2–4)
Democratic Republic of the Congo	23 (20–25)	21	20 (17–21)	1 (1–1)	<0.1	2 (2–2)
Indonesia	19 (18–22)	18	9 (8–10)	8 (8–8)	1 (1–1)	2 (2–2)
Canada	19 (17–24)	3	14 (12–18)	2 (2–2)	2 (2–2)	1 (1–1)
Europe Union	19 (17–21)	-8	2 (1–2)	14 (12–14)	2 (2–2)	2 (2–2)
Peru	12 (10–13)	23	10 (9–11)	1 (1–1)	<0.1	0 (0–1)
Pakistan	10 (9–11)	28	<0.1	9 (8–9)	1 (1–1)	1 (1–1)
Iran	9 (8–10)	71	<0.2	2 (2–3)	6 (4–7)	1 (0–1)
Australia	9 (8–10)	16	1 (1–1)	4 (4–4)	1 (1–1)	3 (2–4)
Congo	9 (6–10)	45	8 (6–10)	<0.1	<0.1	<0.2
Venezuela	8 (8–9)	17	3 (3–4)	2 (2–2)	3 (2–3)	1 (1–1)
Bangladesh	8 (5–9)	59	1 (1–1)	7 (4–8)	<0.1	<0.4
Mexico	8 (8–8)	13	1 (0–1)	6 (6–6)	1 (1–1)	1 (1–1)
Colombia	7 (7–8)	14	3 (3–4)	2 (2–3)	1 (1–1)	0 (0–1)
Argentina	7 (7–7)	7	2 (1–2)	4 (4–4)	<0.4	1 (1–1)
Nigeria	6 (6–7)	15	1 (1–1)	3 (3–3)	1 (1–1)	2 (2–2)
Others	173 (152–204)	16	33 (33–35)	85 (81–95)	28 (27–28)	26 (20–34)

[1]Based on the fixOH inversion multi-model mean and range.

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