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Estimating methane emissions in the Arctic nations using surface observations from 2008 to 2019

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Table S1. *Selected atmospheric observation sites for this study, by decreasing latitudes. "Environmental characteristics" gives a brief description of the surrounding of each station.*

ID	Site, country	Latitude	Longitude	Elevation (masl)/ Intake height (magl)	Time Period	Environmental characteristics
ALT	Alert, CAN	82.5 °N	62.5 °W	185/5	from 1988	snow covered cliffs, sparse polar desert vegetation
ZEP	Zeppelin, NOR	78.9 °N	11.9 °E	474/5	from 1994	mountains and glaciers, small village
SUM	Summit, GRL	72.6 °N	38.4 °E	3210/5	from 1997	year-round dry snow and ice
TIK	Tiksi, RUS	71.9 °N	128.9 °E	19/10	from 2010	Lena river delta
BRW	Barrow, USA	71.3 °N	156.6 °W	11/3	from 1986	thermokarst lakes
CBY	Cambridge Bay, CAN	69.1 °N	105.1 °W	35/12	from 2012	largest port of the Northwest Passage
INK	Inuvik, CAN	68.3 °N	133.5 °W	113/10	from 2012	Arctic Tundra, Mackenzie Delta channel
PAL	Pallas, FIN	68.0 °N	24.1 °E	565/5	from 2004	wetlands, lakes and patches of forest
CRV	CARVE, USA	65.0 °N	147.6 °W	611/32	2015 – 2016	evergreen forest, shrubland and woody wetlands
BLK	Baker Lake, CAN	64.3 °N	96.0 °W	95/10	from 2017	Arctic Tundra, small lakes
NOY	Noyabrsk, RUS	63.4 °N	75.8 °E	100/43	2005 – 2018	taiga forest, wetlands
ICE	Storhovdi Island, ISL	63.4 °N	20.2 °E	118/5	from 1992	grassy slopes and coastal cliffs
IGR	Igrim, RUS	63.2 °N	64.4 °E	25/47	2005 – 2013	10.000 inhabitant town, wetlands
BCK	Behchoko, CAN	62.8 °N	115.9 °W	160/60	from 2010	mixed forests, lakes and ponds
YAK	Yakutsk, RUS	62.1 °N	129.4 °E	130/70	2007 – 2013	taiga
DEM	Demyanskoe, RUS	59.8 °N	70.9 °E	75/63	2007 – 2013	taiga forest surrounded by wetlands
FNE	Fort Nelson, CAN	58.8 °N	122.6 °W	361/15	from 2014	boreal forest, southern fringe of permafrost region
CHU	Churchill, CAN	58.7 °N	93.8 °W	29/60	from 2011	Arctic Tundra, boreal wetlands
KRS	Karasevoe, RUS	58.3 °N	82.4 °E	50/67	2005 – 2018	taiga forest, wetlands
BRZ	Berezorechka, RUS	56.1 °N	112.5 °E	150/80	2008 – 2017	taiga, boreal forest
CBA	Cold Bay, USA	55.2 °N	162.7 ° E	21/4	from 1983	wet tundra
LLB	Lac La Biche, CAN	55.0 °N	112.5 °W	540/50	from 2007	peatlands and forest
AZV	Azovo, RUS	54.7 °N	73.0 °E	100/50	2009 – 2018	steppe, large city
VGN	Vaganovo, RUS	54.5 °N	62.3 °E	200/85	2008 – 2018	steppe, large city
ETL	East Trout Lake, CAN	54.3 °N	105.0 °W	500/105	from 2005	close to the southern edge of boreal forest
MHD	Mace Head, IRL	53.3 °N	9.9 °W	5/5	from 1991	boggy, small hills covered with grasses and sedges
SHM	Shemya Island, USA	52.7 °N	174.1 °W	23/3	from 1985	small remote island in Bering Sea
EST	Esther, CAN	51.7 °N	110.2 °W	707/50	from 2005	open prairie and cattle ranches

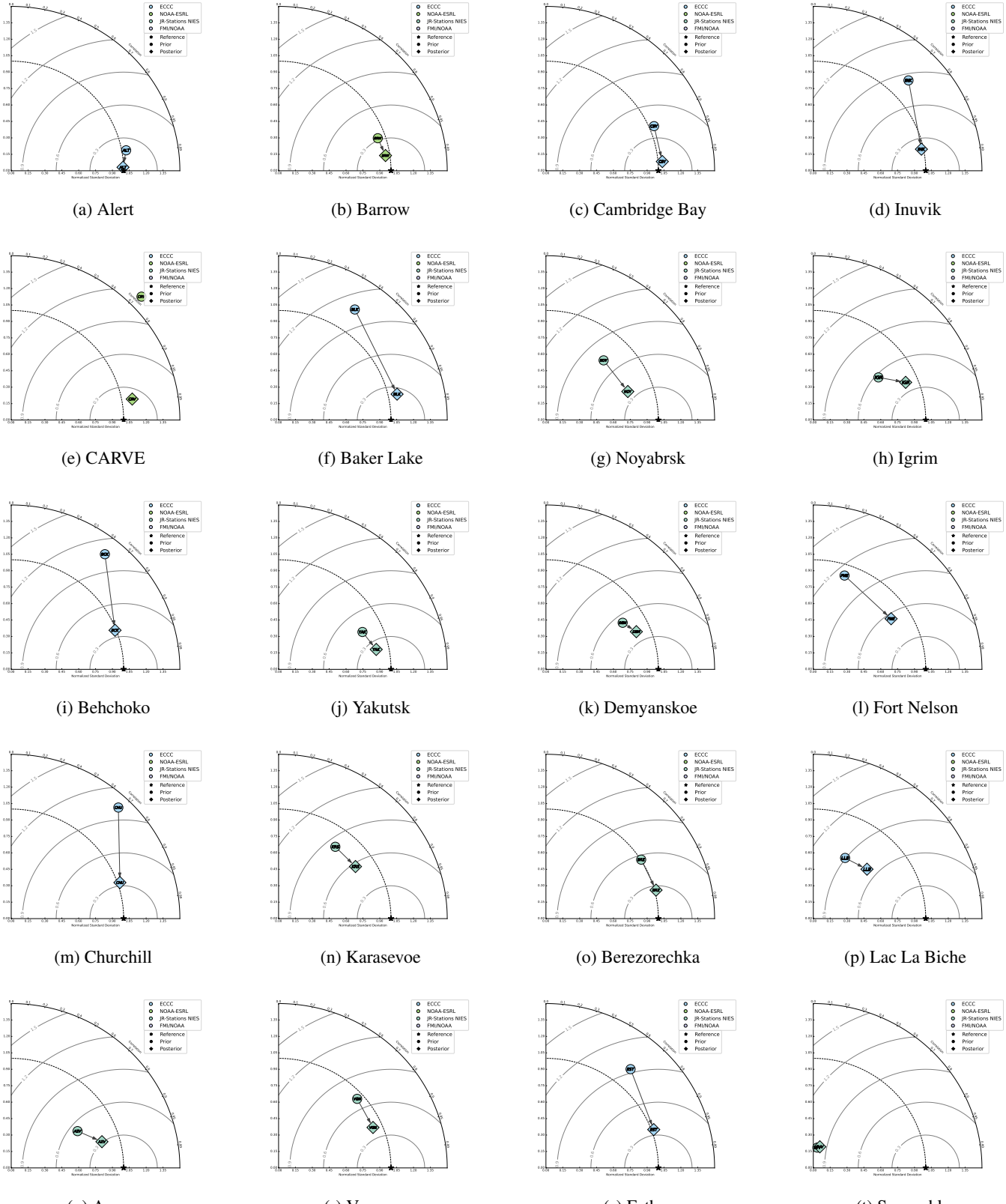
ID	Site, country	Latitude	Longitude	Elevation (masl)/ Sampling height (magl)	Time Period	Environmental characteristics
SVV	Savvushka, RUS	51.3 °N	82.1 °E	400/52	2014	steppe, small village
BRA	Bratt's Lake, CAN	50.2 °N	104.7 °W	595/35	from 2009	prairie, very flat topography
FRD	Fraserdale, CAN	49.9 °N	81.6 °W	210/40	from 1990	boreal forest, extensive wetland coverage
CPS	Chapais, CAN	49.8 °N	75.0 °W	391/40	from 2011	boreal forest, many lakes in surrounding area
CHB	Chibougamau, CAN	49.7 °N	74.3 °W	393/30	2007 – 2011	boreal forest, many lakes in surrounding area
ESP	Estevan Point, CAN	49.4 °N	126.5 °W	7/40	from 2009	surrounded by forests, Pacific Ocean to the west
ABT	Abbotsford, CAN	49.0 °N	122.3 °W	40/33	from 2014	close to Pacific Ocean, proximity to large cities
EGB	Egbert, CAN	44.2 °N	79.8 °W	251/25	from 2005	mixed woodland, small rural village
WSA	Sable Island, CAN	43.9 °N	60.0 °W	5/30	from 2003	remote island, grass and low-growing vegetation
DWN	Downsview, CAN	43.8 °N	79.5 °W	198/20	from 2003	urban site (Toronto)
HNP	Hanlan's Point, CAN	43.6 °N	79.4 °W	87/10	from 2014	urban site (Toronto Island, Lake Ontario)
TKP	Turkey Point, CAN	42.6 °N	80.6 °W	231/35	from 2012	mixed woodlands, close to Lake Erie

Table S2. *Yearly traces of sensitivity and influence matrices.*

Year	$tr(\mathbf{HK})/tr(\mathbf{KH})$	$tr(\mathbf{KH_{emis}})$	$tr(\mathbf{KH_{back}})$	**Number of observations**
2008	154.29	15.31	139.00	217
2009	167.72	17.07	150.65	250
2010	196.27	21.66	174.61	298
2011	210.05	25.78	184.27	318
2012	216.00	27.32	188.68	334
2013	200.35	24.80	175.55	323
2014	212.31	31.33	180.98	362
2015	222.30	32.33	189.97	379
2016	229.98	29.69	200.29	378
2017	227.34	29.05	198.29	367
2018	250.87	28.87	222.00	384
2019	185.69	20.86	164.83	266

Table S3. *Prior and Posterior emissions from different sectors in North America (NA), East Eurasia (EE), West Eurasia (WE) and the Arctic (AR). Note that the posterior results as well as the prior uncertainties only refer to one specific configuration of the ensemble of posterior states ($\mathbf{x}^{\mathbf{a}}_{\mathbf{max}}$).*

Sector	Prior				Posterior			
	NA	EE	WE	AR	NA	EE	WE	AR
Wetlands	30.4±26.1	13.8±11.9	3.3±2.9	13.2±11.4	18.8±13.0	12.2±9.5	3.2±2.7	9.8±7.9
Other natural	5.5±4.1	6.0±4.6	1.1±0.9	6.1±4.7	5.1±3.8	5.7±4.3	1.1±0.9	5.8±4.4
Anthropogenic	6.8±4.6	16.1±10.9	4.6±3.1	3.8±2.5	7.0±4.6	16.1±10.7	4.6±3.1	3.7±2.4
Total	42.6±34.8	35.9±27.3	9.0±6.8	23.1±18.5	30.8±21.4	34.1±24.6	8.9±6.6	19.4±14.8



(a) Alert (b) Barrow (c) Cambridge Bay (d) Inuvik

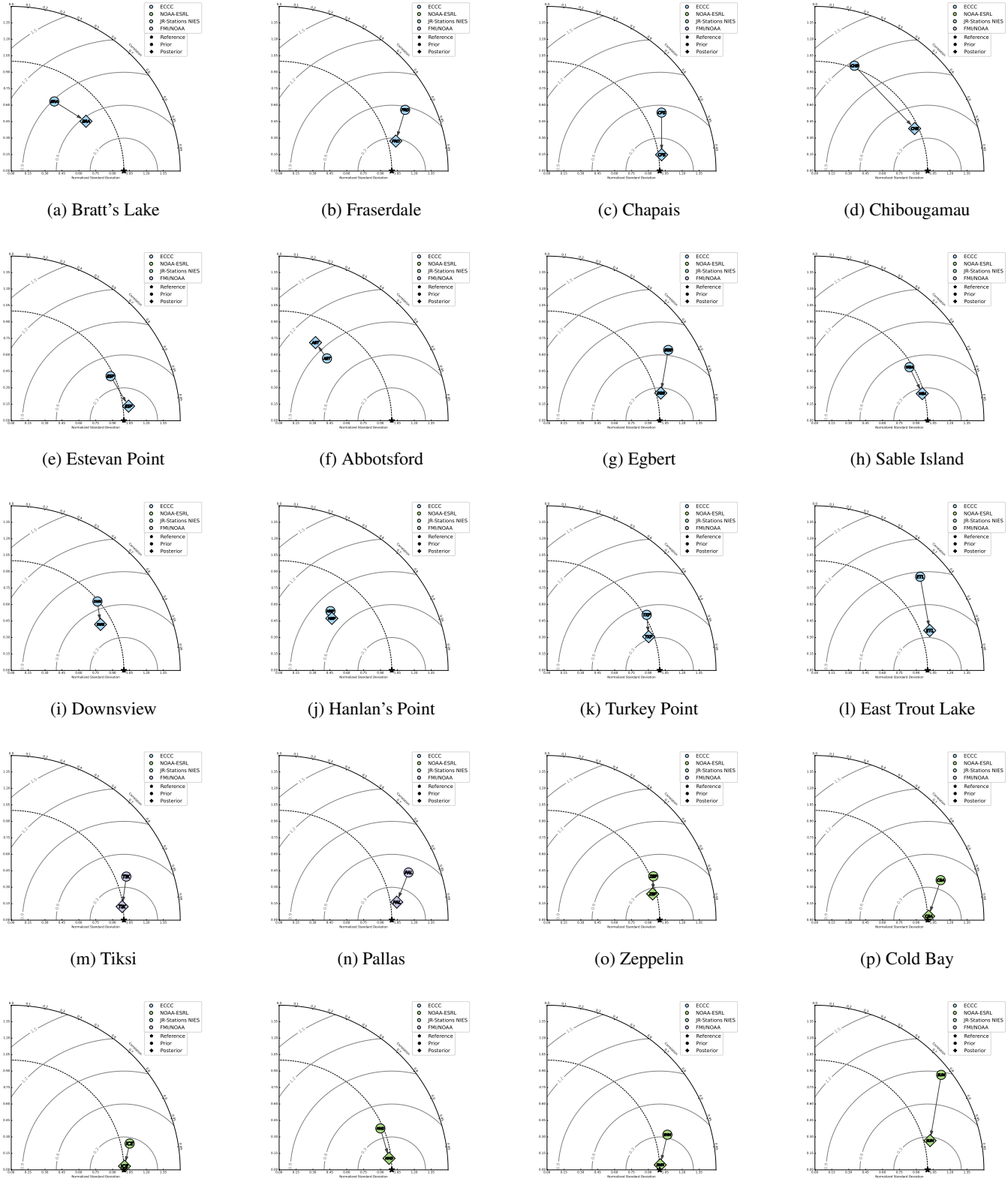
(e) CARVE (f) Baker Lake (g) Noyabrsk (h) Igrim

(i) Behchoko (j) Yakutsk (k) Demyanskoe (l) Fort Nelson

(m) Churchill (n) Karasevoe (o) Berezorechka (p) Lac La Biche

(q) Azovo (r) Vaganovo (s) Esther (t) Savvushka

Figure S1. Exemplary Taylor diagrams of different observation sites.



(a) Bratt's Lake (b) Fraserdale (c) Chapais (d) Chibougamau

(e) Estevan Point (f) Abbotsford (g) Egbert (h) Sable Island

(i) Downsview (j) Hanlan's Point (k) Turkey Point (l) East Trout Lake

(m) Tiksi (n) Pallas (o) Zeppelin (p) Cold Bay

(q) Storhovdi Island (r) Mace Head (s) Shemya Island (t) Summit

Figure S2. Exemplary Taylor diagrams of different observation sites.

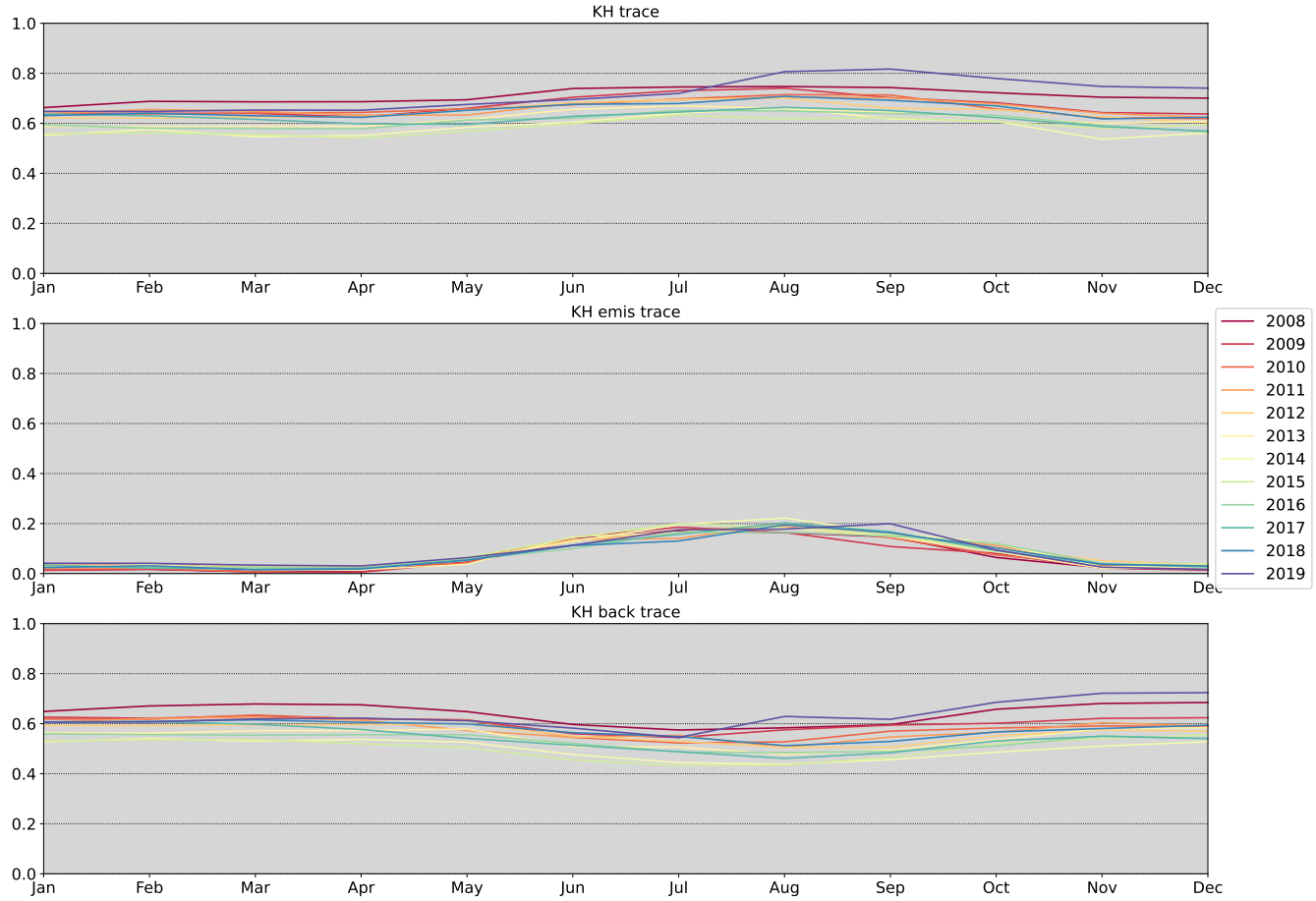
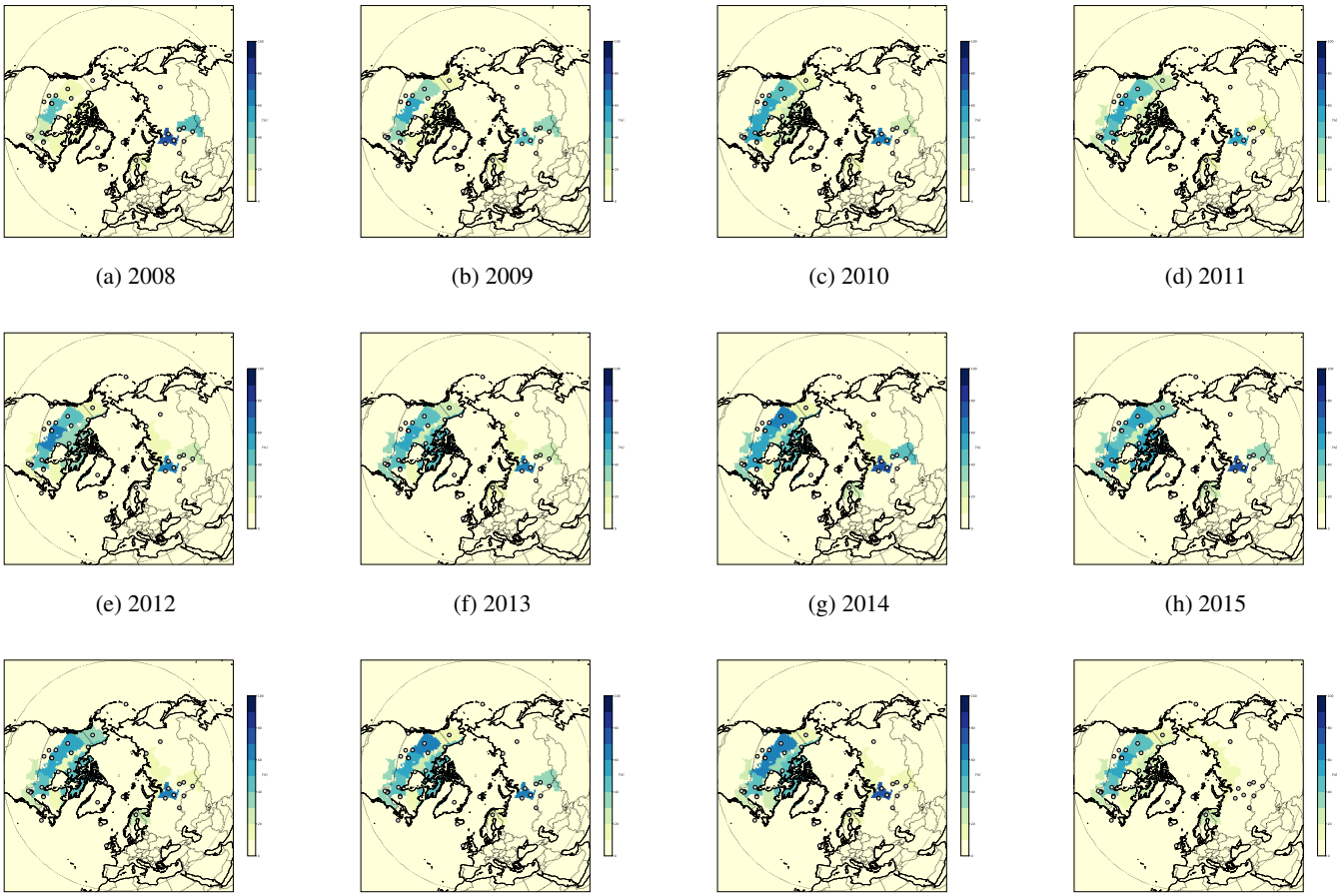


Figure S3. Seasonal variation of $tr(\mathbf{KH})$ for all years from 2008 to 2019. The monthly traces are divided by the number of available observations for the corresponding month.



(a) 2008 (b) 2009 (c) 2010 (d) 2011

(e) 2012 (f) 2013 (g) 2014 (h) 2015

(i) 2016 (j) 2017 (k) 2018 (l) 2019

Figure S4. Regional constraints on wetland emissions as derived from the influence matrix **KH**. Darker areas thereby indicate higher constraints. The percentages of the areas refer to the corresponding summed elements of **KH**. The observation sites are marked as grey circles.

Table S4. *Share of total modelled CH_4 mixing ratios from background and combined methane sources and sink. The values show the average over the whole period of monthly mixing ratios and, respectively, only over the summer and winter months.*

Station ID	Background							Source contribution						
	Total		SD	Summer		Winter		Total		SD	Summer		Winter	
	[ppb]	[%]	[ppb]	[ppb]	[%]	[ppb]	[%]	[ppb]	[%]	[ppb]	[ppb]	[%]	[ppb]	[%]
ALT	1907.1	99.7	16.6	1884.1	99.7	1922.8	99.6	6.0	0.3	2.8	5.1	0.3	8.2	0.4
ZEP	1912.3	99.9	18.9	1886.6	99.9	1931.3	99.8	2.8	0.1	1.3	2.1	0.1	4.1	0.2
SUM	1902.5	99.9	24.2	1880.2	99.9	1918.5	99.9	2.4	0.1	1.1	2.7	0.1	2.1	0.1
TIK	1916.5	98.4	20.7	1890.6	98.0	1938.5	98.6	30.6	1.6	10.4	39.3	2.0	26.9	1.4
BRW	1908.1	99.0	16.7	1885.7	98.8	1923.8	99.1	19.5	1.0	8.6	22.4	1.2	18.2	0.9
CBY	1908.6	99.4	16.0	1887.6	99.2	1924.5	99.5	12.0	0.6	9.4	15.3	0.8	8.9	0.5
INK	1905.6	98.6	14.7	1886.7	97.8	1918.3	99.1	28.1	1.4	20.7	42.0	2.2	17.3	0.9
PAL	1910.8	98.8	18.4	1887.5	98.8	1929.8	98.5	23.8	1.2	10.4	23.8	1.2	29.4	1.5
CRV	1897.5	99.3	16.1	1876.7	98.7	1907.6	99.7	13.2	0.7	10.2	24.6	1.3	6.3	0.3
BLK	1908.4	99.2	14.9	1889.6	98.9	1923.3	99.6	14.6	0.8	13.7	20.2	1.1	7.7	0.4
NOY	1925.3	95.1	26.5	1895.6	93.2	1957.3	95.5	99.4	4.9	39.2	139.3	6.8	93.1	4.5
ICE	1907.3	99.9	15.6	1885.8	99.9	1921.7	99.9	2.7	0.1	1.2	2.5	0.1	2.8	0.1
IGR	1923.7	97.8	26.5	1893.6	97.8	1955.0	97.1	43.4	2.2	17.7	43.4	2.2	58.8	2.9
BCK	1905.2	98.4	15.2	1887.4	97.3	1920.5	99.3	31.6	1.6	29.0	53.2	2.7	13.2	0.7
YAK	1918.1	98.9	22.1	1892.9	98.9	1943.7	98.5	22.2	1.1	8.2	22.0	1.1	29.7	1.5
DEM	1924.8	96.1	25.9	1896.9	94.3	1955.9	96.4	79.3	3.9	31.0	115.4	5.7	73.5	3.6
FNE	1893.2	98.6	16.6	1874.5	98.1	1904.2	98.9	26.3	1.4	15.1	36.5	1.9	20.3	1.1
CHU	1908.1	98.6	13.3	1892.4	97.5	1921.3	99.6	27.1	1.4	28.2	49.4	2.5	7.8	0.4
KRS	1926.3	97.1	25.2	1901.8	96.1	1956.7	96.9	58	2.9	20.3	77.8	3.9	63.1	3.1
BRZ	1925.4	97.4	23.9	1903.7	97.4	1954.1	96.7	50.6	2.6	15.0	50.8	2.6	67.3	3.3
CBA	1903.4	99.9	21.0	1873.2	99.9	1919.7	99.9	1.5	0.1	0.6	1.6	0.1	1.4	0.1
LLB	1894.7	97.8	15.5	1878.2	96.8	1905.5	98.1	43.0	2.2	20.4	62.2	3.2	37.5	1.9
AZV	1925.3	97.8	25.1	1901.1	97.7	1956.9	97.0	43.8	2.2	13.7	43.9	2.3	60.0	3.0
VGN	1920.6	98.1	22.7	1896.1	98.5	1947.5	97.2	37.3	1.9	13.7	29.4	1.5	55.6	2.8
ETL	1901.6	97.8	14.2	1886.3	96.2	1915.1	98.7	43.2	2.2	27.0	74.0	3.8	25.6	1.3
MHD	1904.5	99.9	14.7	1884.5	99.9	1916.7	99.9	2.4	0.1	1.0	2.4	0.1	2.1	0.1
SHM	1906.1	99.9	22.7	1873.2	99.9	1924.2	99.9	1.6	0.1	0.6	1.4	0.1	1.8	0.1
EST	1893.9	99.1	14.9	1875.4	97.9	1907.1	99.8	17.9	0.9	20.2	40.6	2.1	4.5	0.2

Station ID	Background							Source contribution						
	Total		SD	Summer		Winter		Total		SD	Summer		Winter	
	[ppb]	[%]	[ppb]	[ppb]	[%]	[ppb]	[%]	[ppb]	[%]	[ppb]	[ppb]	[%]	[ppb]	[%]
SVV	1918.8	97.6	19.7	1903.0	96.2	1941.4	97.6	48.2	2.4	23.1	74.7	3.8	47.3	2.4
BRA	1897.4	99.1	14.8	1880.2	98.0	1911.5	99.8	17.5	0.9	17.5	37.9	2.0	4.0	0.2
FRD	1901.8	99.4	17.6	1892.4	98.9	1916.4	99.8	11.9	0.6	11.6	21.6	1.1	3.4	0.2
CPS	1908.1	99.3	11.3	1898.8	98.8	1917.9	99.8	12.6	0.7	12.8	22.8	1.2	3.2	0.2
CHB	1907.9	99.3	11.2	1898.7	98.8	1917.6	99.8	12.6	0.7	12.8	23.0	1.2	3.2	0.2
ESP	1887.1	99.4	15.2	1864.7	98.7	1895.9	99.7	11.4	0.6	10.3	25.5	1.3	6.0	0.3
ABT	1884.8	98.8	14.8	1863.0	97.9	1894.5	99.4	22.6	1.2	16.3	40.8	2.1	11.8	0.6
EGB	1906.2	98.6	11.2	1898.3	97.3	1915.5	99.7	26.5	1.4	24.8	53.0	2.7	6.5	0.3
WSA	1901.7	99.0	11.7	1889.3	98.4	1911.0	99.4	18.9	1.0	11.2	30.6	1.6	11.6	0.6
DWN	1905.8	96.9	11.4	1897.4	96.0	1915.3	97.4	60.8	3.1	20.2	79.1	4.0	51.7	2.6
HNP	1905.5	96.9	11.5	1896.9	96.0	1915.1	97.3	61.7	3.1	19.7	79.2	4.0	53.1	2.7
TKP	1904.6	97.4	11.5	1895.5	96.6	1914.5	97.7	51.3	2.6	16.3	66.8	3.4	44.6	2.3

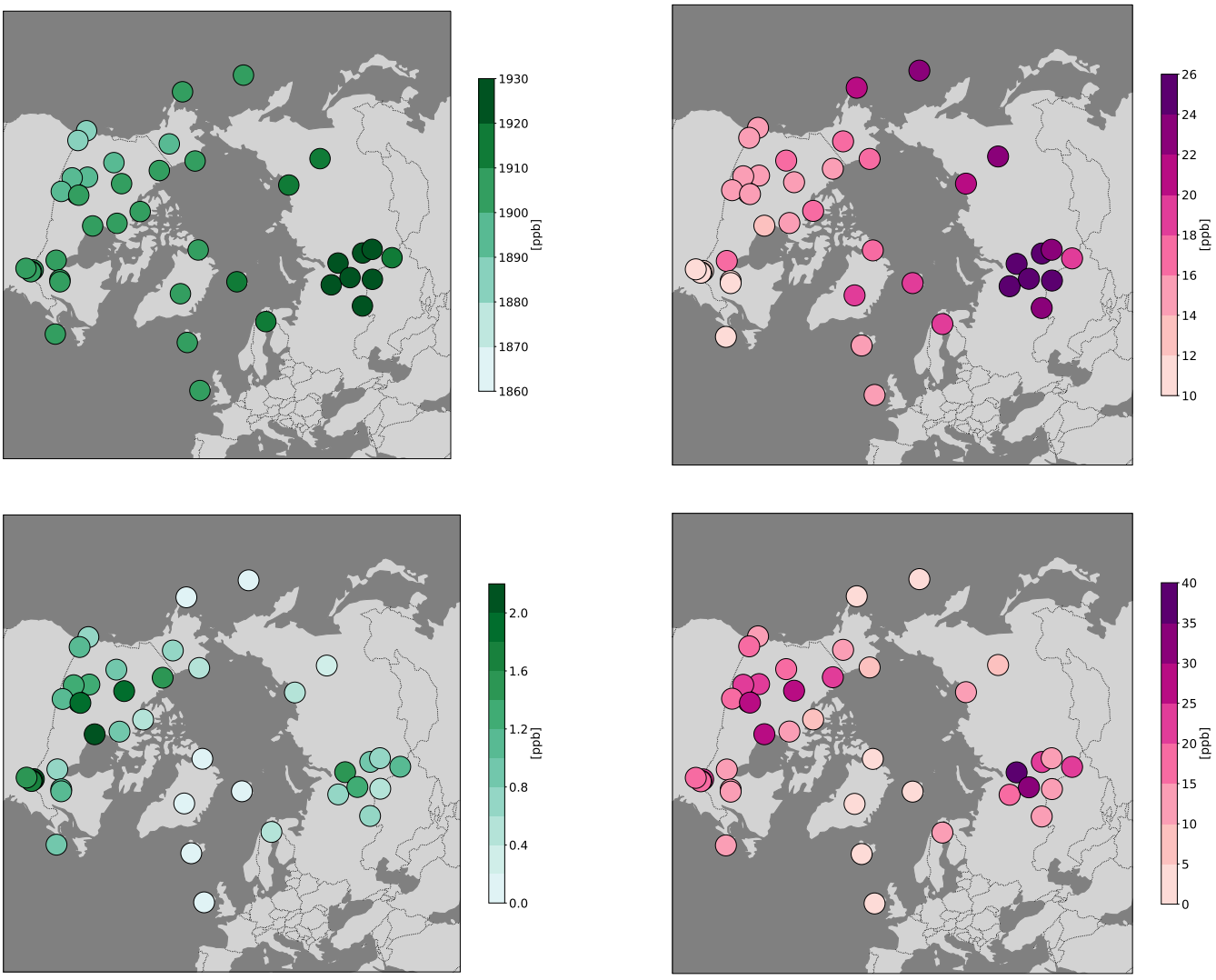


Figure S5. Contributions to the total simulated mixing ratio signals at each observation site. Left panels show average contributions, right panels the standard deviations of the contributions for the background (top) and regional emissions (bottom) respectively.