

Supplementary Information

The Spatial and Temporal Distribution Patterns of XCH₄ in Iran: New Insights from TROPOMI Observations

5 Ali Rahimi¹, Manuchehr Farajzadeh¹, Yousef Ghavidel¹, and Christoffer Karoff²

¹ Department of Physical Geography, Tarbiat Modares University, Tehran, 14155-4838, Iran

² Department of Geoscience, Aarhus University, Aarhus, 8000 Aarhus C, Denmark

Correspondence to: Christoffer Karoff (email: karoff@geo.au.dk), Manuchehr Farajzadeh (email: farajzam@modares.ac.ir)

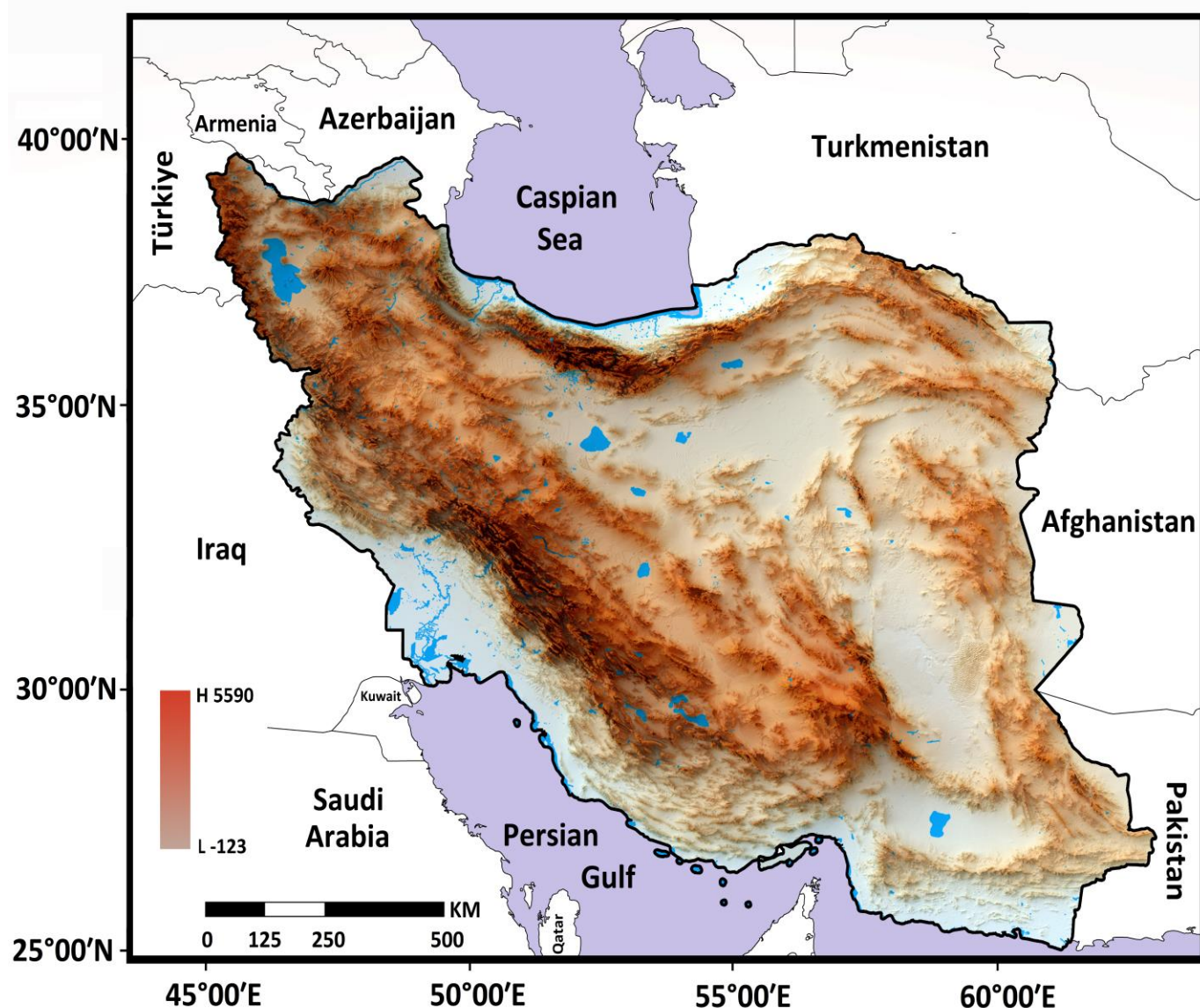


Figure S1: Digital Elevation Model (DEM) of Iran

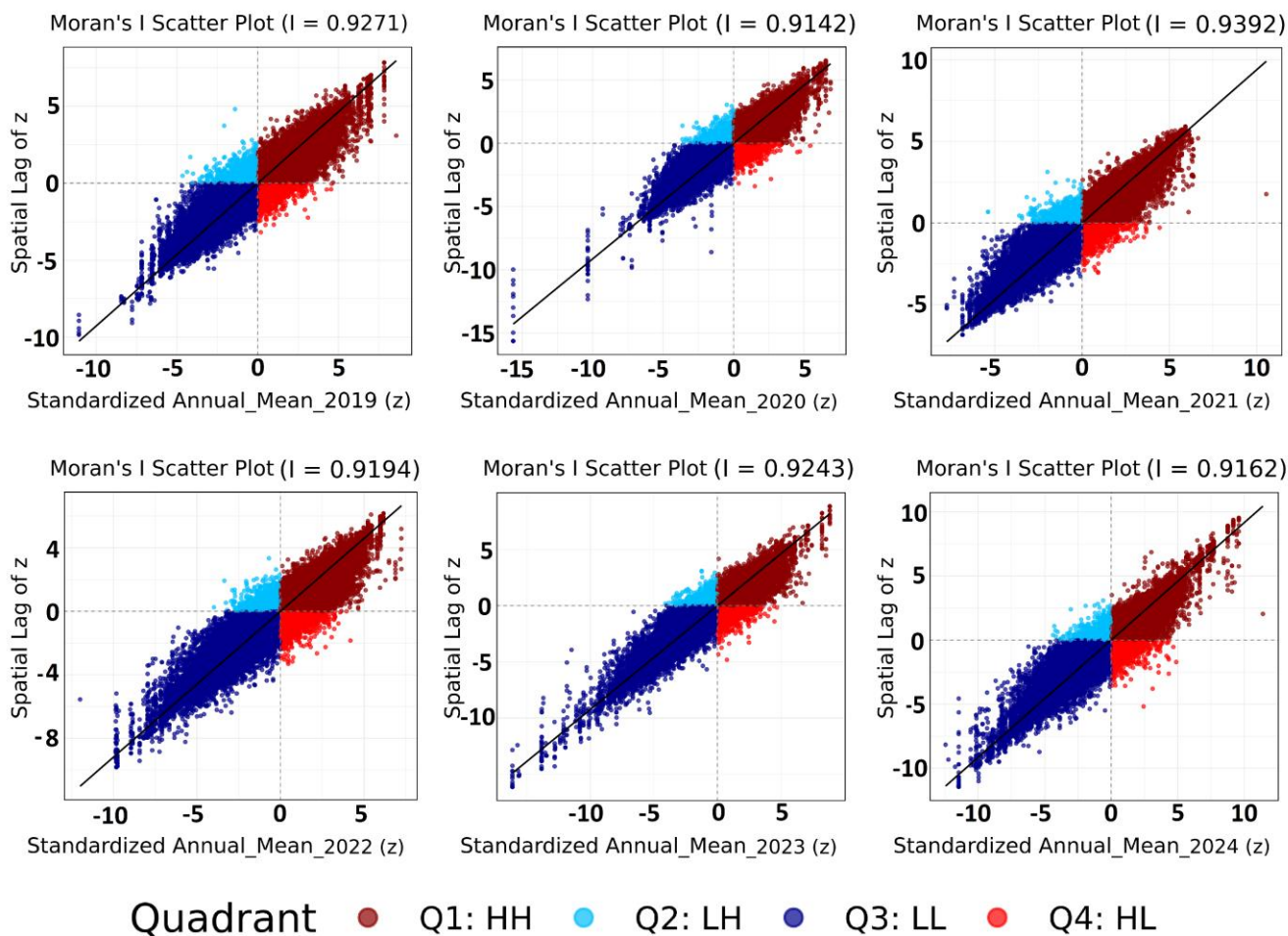


Figure S2: Global Moran's I values for methane (CH_4) concentrations in Iran from 2019 to 2024. Positive and statistically significant values indicate that high (or low) methane concentrations are spatially clustered rather than randomly distributed across the country.

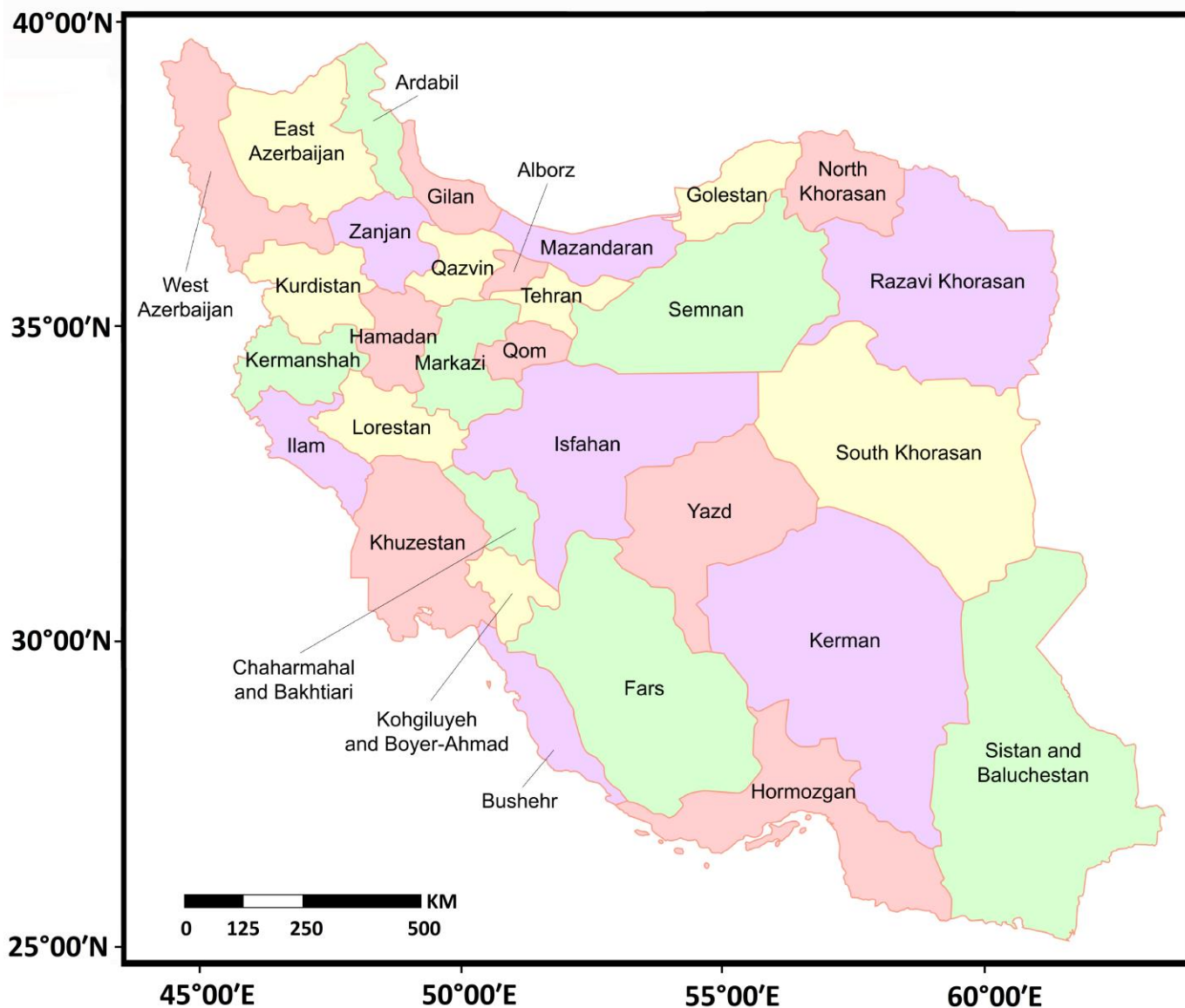


Figure S3: Provincial map of Iran showing the locations of northern (Gilan, Mazandaran, Golestan), southern and southwestern (Khuzestan, Bushehr, Hormozgan), central (Fars, Isfahan, Qom, Markazi), western and northwestern (Kurdistan, Chaharmahal and Bakhtiari, Ardabil, Zanjan), and eastern (South Khorasan, Sistan and Baluchestan, parts of Yazd) provinces referenced in the methane hotspot and cold spot analysis.

Year	CO ₂ Emissions (Mt/yr)	GHG Emissions (Mt CO ₂ eq/yr)	CO ₂ per Capita (t/person/yr)	GHG per Capita (t CO ₂ eq/person/yr)	CO ₂ Intensity (t CO ₂ /kUSD)
1990	205	320	3.6	5.7	0.42
2005	468	666	6.6	9.5	0.56
2018	670	926	8.2	11.3	0.61
2020	690	n/a	8.3	n/a	0.66

Table S1: Trends in CO₂, Greenhouse Gas Emissions, and Related Indicators in Iran (1990–2020) Based on EDGAR Data.

Year	Agriculture (t)	Buildings (t)	Fuel Exploitation (t)	Industrial Combustion (t)	Power Industry (t)	Processes (t)	Transport (t)
2019	20,960,814	586,287	100,968,905	65,079	221,276	421,749	2,299,970
2020	21,531,602	600,345	95,145,236	68,324	244,251	426,360	2,382,323
2021	22,892,702	616,075	107,424,847	70,152	252,982	425,815	2,444,278
2022	22,858,777	634,214	112,227,800	73,073	260,744	413,950	2,548,084
2023	23,388,526	643,066	127,760,160	74,253	266,680	424,172	2,597,164

Table S2: Sectoral Distribution of Methane (CH₄) Emissions in Iran based on EDGAR v8.1.

Class	Province	Area (km²)	n_hotspots	Annual mean XCH ₄ (ppb)	Hotspot density (hotspots/km²)
1. Northern Agro-Hotspots	Golestan	20,205	13,595	1915	0.673
	Mazandaran	23,725	7,044	1880	0.297
	Gilan	14,086	4,055	1885	0.288
2. Central Urban-Dense Hotspots	Tehran-Alborz	24,647	10,491	1900	0.426
	Qom	11,514	5,250	1905	0.456
	Isfahan	106,754	24,920	1910	0.233
	Fars	122,779	12,550	1905	0.102
3. Southern Industrial-Fossil Hotspots	Khuzestan	63,928	19,434	1920	0.304
	Hormozgan	68,809	18,606	1915	0.270
	Bushehr	22,766	10,097	1905	0.444
4.Low-Emission Provinces	Markazi	29,088	1,359	1885	0.047
	Lorestan	28,199	871	1880	0.031
	Semnan	97,193	30,746	1910	0.316
	Qazvin	15,559	1,865	1885	0.120
	North Khorasan	28,341	1,793	1882	0.063
	Kermanshah	24,867	442	1880	0.018
	Kohgiluyeh and Boyer-Ahmad	15,498	905	1880	0.058
	Hamedan	19,329	293	1882	0.015
	Chaharmahal and Bakhtiari	16,305	91	1870	0.006
5. Very-Low-Emission Provinces	Ilam	20,023	250	1870	0.013
	Kurdistan	29,048	510	1875	0.018
	Ardabil	17,902	647	1872	0.036
	Zanjan	21,783	1,118	1875	0.051
	South Khorasan	83,932	4,835	1880	0.058
	Sistan and Baluchestan	178,850	16,878	1910	0.094
	Yazd	128,464	23,015	1895	0.179
	Razavi Khorasan	127,223	24,112	1915	0.189
	East Azerbaijan	45,757	5,144	1885	0.112

Table S3: Provincial classification and descriptive statistics of methane emission hotspots across Iran (2019–2024).

Caption: Provinces are grouped into five categories (Northern Agro-Hotspots, Central Urban-Dense, Southern Industrial-Fossil, Low-Emission, and Very-Low-Emission Provinces) based on hotspot density and dominant methane drivers. Data include provincial area, hotspot counts, annual mean XCH₄ concentrations, and emission sources.

Month	Mean	Median	Mode	SD	Min	Max	Q1	Q3	IQR	CV
January	1893	1894	1892	14.8	1739	2023	1885	1901	15.9	0.0078
February	1883	1884	1853	15.3	1758	2063	1875	1891	15.7	0.0081
March	1883	1884	1884	14	1769	1968	1875	1891	15.6	0.00745
April	1887	1887	1854	12.9	1750	1999	1880	1893	13.4	0.00683
May	1888	1888	1841	12.3	1756	2002	1881	1894	12.5	0.00654
June	1884	1885	1787	14.1	1765	1989	1878	1892	13.7	0.00751
July	1896	1897	1923	14.3	1795	2011	1890	1904	14.1	0.00755
August	1915	1917	1857	13.2	1805	2026	1910	1922	11.6	0.0069
September	1912	1913	1835	12.2	1805	1997	1906	1919	12.4	0.00641
October	1909	1910	1830	12.2	1714	2011	1903	1915	11.4	0.00638
November	1910	1911	1958	13.4	1722	2051	1904	1918	14	0.00699
December	1910	1911	1908	13.5	1699	2141	1903	1917	14.6	0.00704

Table S4: Monthly statistics of column-averaged methane (XCH₄, ppb) over Iran (2019–2024), including mean, median, mode, standard deviation (SD), minimum, maximum, quartiles (Q1, Q3), interquartile range (IQR), and coefficient of variation (CV).

Season	Mean	Median	SD	Min	Max	Q1	Q3	IQR	CV
Winter	1901.85	1906.09	16.02	1645.85	2264.10	1895.85	1929.07	33.22	0.00843
Spring	1888.72	1889.97	11.99	1736.36	2036.62	1884.75	1901.10	16.35	0.00634
Summer	1914.28	1916.53	13.05	1740.58	2052.05	1909.28	1941.00	31.72	0.00682
Autumn	1910.46	1912.75	13.45	1757.21	2160.69	1907.25	1939.07	31.82	0.00704

Table S5: Seasonal descriptive statistics of XCH₄ concentrations (ppb) over Iran for 2019–2024. Data are grouped by climatological seasons: Winter (DJF), Spring (MAM), Summer (JJA), and Autumn (SON).

Year	Mean	Median	SD	Min	Max	Q1	Q3	IQR	CV
2019	1872.551	1873.018	11.92248	1740.582	1974.862	1865.9	1878.742	12.84167	0.006367
2020	1887.882	1888.082	13.75866	1672.696	1982.647	1880.098	1895.621	15.52234	0.007288
2021	1902.831	1902.179	14.03082	1794.162	2050.798	1894.875	1910.98	16.10452	0.007374
2022	1900.781	1901.983	10.97808	1769.12	1980.247	1895.418	1906.898	11.47998	0.005776
2023	1904.713	1906.119	11.80239	1714.279	2009.091	1899.308	1911.417	12.10925	0.006196
2024	1918.606	1919.484	11.2427	1778.747	2046.708	1912.899	1925.061	12.16205	0.00586

Table S6: Annual descriptive statistics of column-averaged methane (XCH₄, ppb) over Iran for 2019–2024, including mean, median, standard deviation (SD), minimum, maximum, first and third quartiles (Q1, Q3), interquartile range (IQR), and coefficient of variation (CV).

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Month	1_Count	1_Percent	2_Count	2_Percent	3_Count	3_Percent	4_Count	4_Percent
Feb	60023	3.1	1396056	72.2	285960	14.79	191544	9.91
Mar	59134	3.06	1390850	71.93	287776	14.88	195821	10.13
Apr	60714	3.14	1395106	72.15	292540	15.13	185193	9.58
May	68285	3.53	1407127	72.77	292040	15.1	166154	8.59
Jun	58220	3.01	1390010	71.89	302087	15.62	183337	9.48
Jul	56372	2.92	1392368	72.01	304041	15.72	180824	9.35
Aug	51075	2.64	1360273	70.35	309187	15.99	213135	11.02
Sep	45955	2.38	1312536	67.87	312595	16.17	262671	13.58
Oct	62223	3.22	1371174	70.91	290335	15.01	209954	10.86
Nov	56516	2.92	1359854	70.32	291641	15.08	225677	11.67
Dec	60997	3.15	1369965	70.84	285856	14.78	216985	11.22
Jan	69414	3.59	1407871	72.81	277419	14.35	178905	9.25

Table S7: Statistical comparison of monthly methane hotspots observed by TROPOMI and modeled by EDGAR v8.1 Grid cells are categorized as follows: 1 – significant in both TROPOMI and EDGAR, 2 – non-significant in both datasets, 3 – significant only in EDGAR, 4 – significant only in TROPOMI.