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Satellite measurements of carbon monoxide as a tool for air quality assessment

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Abstract: Carbon monoxide (CO) in high concentrations can have severe health effects. For this reason, there are regulations for monitoring it, along with several other gases and particles with negative health effects. However, as the anthropogenic emissions of carbon monoxide have declined, the need for monitoring has diminished and no monitoring station in Finland measures it anymore.

In this work we have used carbon monoxide measurements from TROPOMI instrument onboard Sentinel-5P. We have used the data to support air quality assessment in two different ways. First, we calculated a long-term average over Finland to find the average CO distribution and to recognize areas with possible larger sources. For these areas we could assess the need for continuous monitoring. The long-term average maps were also compared to emission database data.

The other way we utilized satellite observations was to estimate ground level CO concentrations. We used the ground level data from scientific monitoring stations in Helsinki, Sodankylä and Pallas to calculate a simple linear relation between ground level concentrations and the total column concentrations provided by satellite measurements. Using this relation, we evaluated yearly average and maximum ground level concentrations for specific monitoring regions. The average concentrations were lower for the northern Finland with lower population density and less traffic. However, the maximum concentrations can be related to long range transport from for example an intense wildfire region and thus do not follow any clear pattern.

Carbon monoxide concentration guidelines

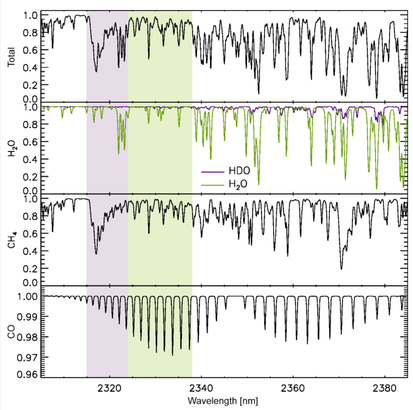
Carbon monoxide is a colorless, odorless and tasteless gas. While 45% of ambient CO is produced naturally by oxidation of methane and other organic volatile compounds the concentration is highest near high traffic and industrial areas. There CO is produced in incomplete fossil fuel burning. When inhaled CO molecules can attach to red blood cells diminishing the oxygen carrying capacity of the blood stream. World Health Organization has set guidelines for ambient CO concentration that could cause negative health effects in different time scales. The guideline values are:

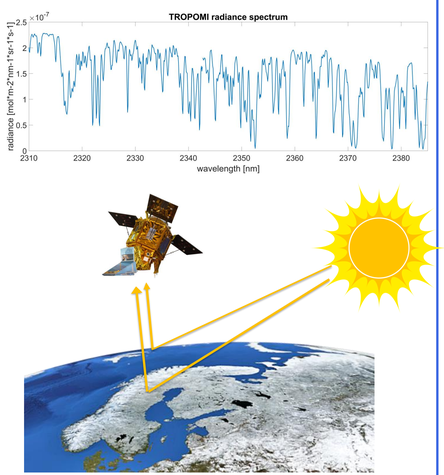
100 mg/m^3 (87 ppm) for 15 min
60 mg/m^3 (52 ppm) for 30 min
30 mg/m^3 (26 ppm) for 1 h
10 mg/m^3 (9 ppm) for 8 h

Recently the concentrations at the air quality monitoring sites have stayed well below the guideline values and thus there is no obligation for continuous monitoring. While the satellite can only measure momentary concentrations, ground-level estimates from satellite measurements exceeding the guideline value for 8-hour average level would give a reason to restart monitoring at those locations.

TROPOMI total column measurements

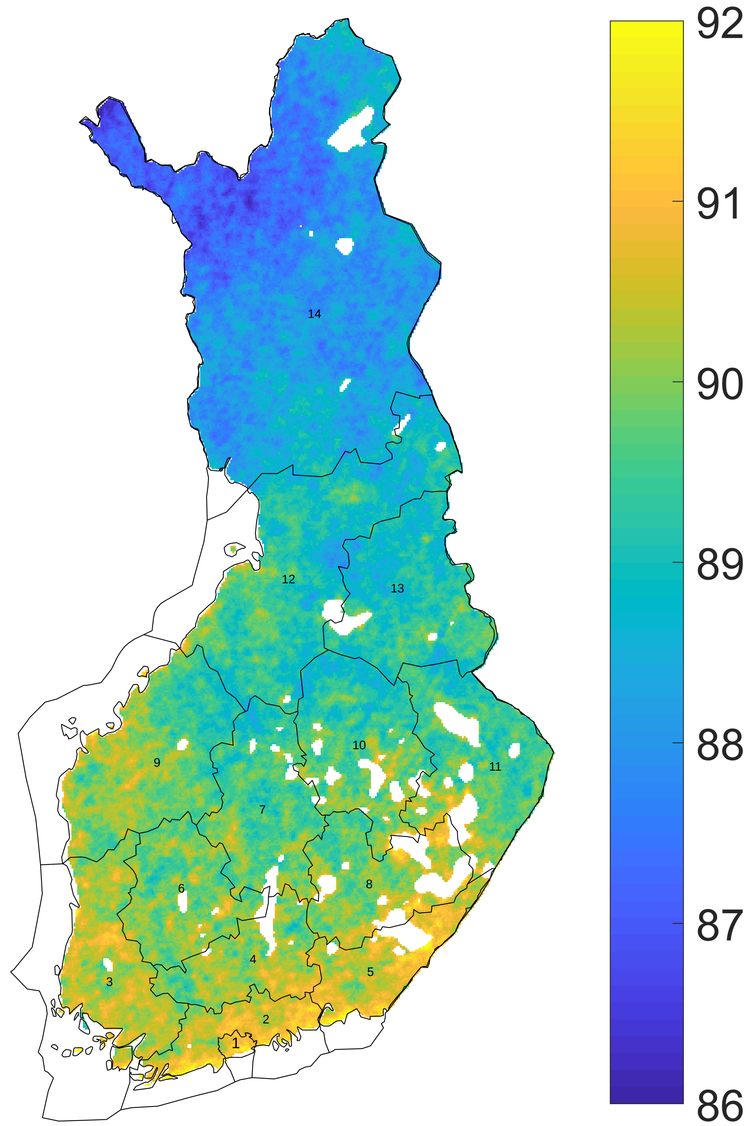
Spectral transmittance of relevant atmospheric species (Landgraf et al. 2016)





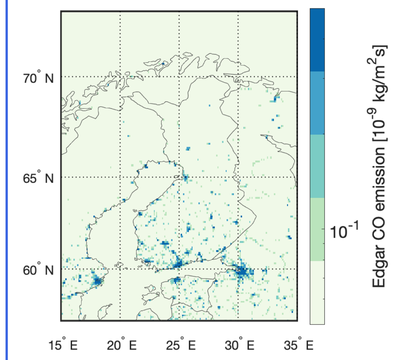
TROPOMI measures the radiance of solar light scattered by the earth surface and by the atmosphere. Each molecule species leaves its own fingerprint to the spectrum. Using the information of the known absorption features the total concentration can be retrieved. Wavelength range 2324–2338 nm is used for CO retrieval. The retrieved value corresponds to the amount of CO in the whole altitude range between ground and the satellite. In cloud covered scenes the instrument can only sense the atmosphere between the cloud top and the satellite, and the total column is estimated using prior estimate of the CO concentration altitude profile. For the analysis we have used quality flag value of 0.7 or higher which allows only low clouds or optically thin clouds. The spatial resolution of the measurement is 7x7 km in nadir and the swath is 2600 km wide enabling daily global coverage.

Average XCO, 2018 - 2020



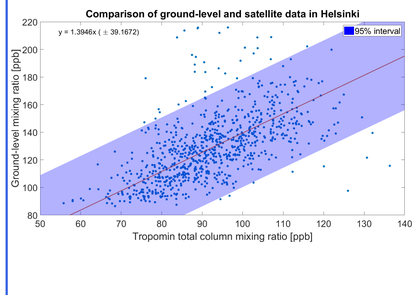
Average total column mixing ratio of carbon monoxide determined using TROPOMI satellite data averaged to 2x2 km grid.

Long term average in supersampled grid and comparison to emission database



To study possible high concentration areas, we sampled the TROPOMI CO retrievals to 2x2 km grid over Finland. For each overpass, every grid point having the center coordinate inside a TROPOMI pixel was assigned the value from that TROPOMI measurement. Large center figure shows the three-year average in the 2x2 km grid. The map shows a clear gradient from north to south as southern Finland has more traffic and industry. However, the differences are small and the yearly average ranges from 86 to 92 ppb.
Because of the small differences and the fact that CO has a moderate lifetime of 1-3 months, it is hard to distinguish clear hotspots. The long-term average map still has many of the features that are seen in the CO emission map from Edgar emission database (left).
Water has really low reflectance in SWIR wavelengths. Thus, the signal measured over lakes and seas is also low. Therefore, the pixels that cover water bodies are without data. Heterogenous illumination of the instrument can also create biases up to ±2%. This can result in small false high concentration areas especially in the eastern part of Finland where there are numerous small lakes.

Ground-level estimation based on satellite measurements



Region		TROPOMI column avg (ppb)	TROPOMI column max (ppb)	ground-level estimate avg (µg/m3)	ground-level estimate max (µg/m3)
Capital area	1	94.15	133.03	164	281
Uusimaa without capital	2	93.91	136.08	164	286
Varsinais-Suomi ja Satakunta	3	93.24	173.63	162	351
Häme	4	93.28	138.45	163	290
Kaakkois-Suomi	5	93.91	145.03	164	301
Pirkanmaa	6	93.11	140.91	162	294
Keski-Suomi	7	92.89	147.35	162	306
Etelä-Savo	8	93.64	154.57	163	318
Etelä-Pohjanmaa ja Pohjanmaa	9	93.04	150.18	162	310
Pohjois-Savo	10	92.71	147.59	162	306
Pohjois-Karjala	11	92.86	144.00	162	300
Pohjois-Pohjanmaa	12	92.04	159.47	160	327
Kainuu	13	92.18	176.01	161	355
Lappi	14	91.23	168.84	159	343

The above left figure shows the correspondence between the TROPOMI total column mixing ratio and the ground-level gas analyzer mixing ratio in Kumpula, Helsinki. A linear relation was used as the basis for ground-level estimates from TROPOMI retrievals. We did similar analysis for scientific background station in Sodankylä and the slope of the linear fit was smaller. In Helsinki, the emissions from traffic and industry are larger and closer, which explains more bottom-heavy atmospheric profile of CO.
On the right are the average and maximum TROPOMI total column mixing ratios during 2019 separated to 14 regions. The table also presents the corresponding estimates for the ground-level concentrations. The average levels follow the long-term average pattern, but the maximums are rather random because many of the occurrences of high CO levels are due to long distance transport. There is also a possibility that the transported air with high CO concentrations resides at higher altitudes and don't affect the air quality on ground.

Summary

- Carbon monoxide concentration needs to be monitored because of negative health effects
- The CO levels have diminished even in high traffic areas because of improvements in motor technologies
  - This has led to closing of monitoring sites
- We have used TROPOMI satellite data to evaluate average and maximum concentrations of CO to confirm that the air quality standards are not exceeded
  - The maximum concentrations may be distributed completely different than averages as the maximums are often caused by transported carbon monoxide from for example wildfires.
  - The average concentration helps to identify areas of more frequent high values and thus to identify areas that might need continuous ground-level monitoring
- CO concentrations in Finland are low
  - Long term average concentrations produce similar spatial pattern as the emission database estimates
- Biases around low-reflecting water bodies and the long lifetime of CO complicate the interpretation of long-term average patterns