environmental sciences proceedings

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Proceeding Paper

Detection of Methane Point Sources with High-Resolution Satellites †

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† Presented at the IV Conference on Geomatics Engineering, Madrid, Spain, 6–7 July 2023.

Abstract: Methane is the second most important anthropogenic greenhouse gas, whose emissions need to be mitigated to curb global warming. There is a large uncertainty about its point source, but thanks to a new generation of high-spatial-resolution satellites, this situation is changing drastically, revealing thousands of emission point sources worldwide. In this paper, several hotspot areas are mapped, looking for methane emission point sources with different types of high-resolution satellites. Our results demonstrate the potential of satellite remote sensing to reveal methane emission point sources in different scenarios.

Keywords: methane emissions; high-resolution remote sensing; point source emissions; anthropogenic emissions

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Citation: Irakulis-Loitxate, I.; Roger, J.; Gorroño, J.; Valverde, A.; Guanter, L. Detection of Methane Point Sources with High-Resolution Satellites. *Environ. Sci. Proc.* **2023**, *28*, 29. https://doi.org/10.3390/environsciproc2023028029

Academic Editors: María Belén Benito Oterino, José Fernández Torres, Rosa María García Blanco, Jorge Miguel Gaspar Escribano, Miguel Ángel Manso Callejo and Antonio Vázquez Hoehne

Published: 26 February 2024

1. Introduction

Due to the current climate emergency [1], the mitigation of anthropogenic greenhouse gas (GHG) emissions has become an important task.

In this context, CO_2 has historically been the most visible GHG and the most widely known one in society. However, little has been said about methane (CH_4). CH_4 is the second most important anthropogenic GHG, whose global warming potential is about 84 times higher than that of CO_2 over 20 years [2,3]; however, it has a relatively short lifetime in the atmosphere (about 12 years). Those characteristics make CH_4 emissions a good target for curbing global warming on the short and medium time scales. CH_4 can be emitted from natural (e.g., wetlands, lakes, rivers, ruminants, or termites) or anthropogenic sources (e.g., agriculture, oil and gas sector, coal mining, wastewater, and sewage).

However, there is still much uncertainty about the source of the emissions and the actual amount emitted by each sector and country [4].

In an effort to solve this problem, satellites have proven to be valuable tools, as they may have the ability to detect CH_4 emissions globally and continuously from space [5]. Until a few years ago, satellites capable of measuring CH_4 had high spectral resolution (<1 nm) at the expense of low spatial resolution (>1 km) to ensure a good signal-to-noise ratio. This provided accurate measurements but made it impossible to attribute emissions to specific facilities or sources. Fortunately, in recent years, significant technological advances have been made, allowing the detection of CH_4 emissions from high-spatial-resolution satellites. In 2016, the GHGSat company launched the first private high-resolution satellite specifically made to detect CH_4. After that, in 2019, the PRISMA hyperspectral satellite (30 m pixel resolution) from the Italian space agency (ASI) was launched, which, due to its characteristics, can detect CH_4 signals [6]. With similar characteristics to PRISMA, in 2022, the EnMAP satellite, from the German space agency, was launched. In addition, recent research has found that some multispectral satellites already in orbit, such as Sentinel-2 and Landsat 4-9, can also detect large CH_4 emissions under favorable conditions [7,8]. All these satellites have the great advantage of being public.

Among the types of CH_4 emissions, we distinguish two groups: diffuse emissions, i.e., CH_4 emitted from many different points over a large area (e.g., landfills, open-pit coal mines, or livestock emissions), and point source emissions, which come from a single relatively small source that emits a high volume of CH_4 (e.g., leaks at an oil or gas facility, or a venting shaft in an underground coal mine). The latter group tends to form emissions with plume-like shapes (see examples in Figure 1) that facilitate their detection by satellites [5].

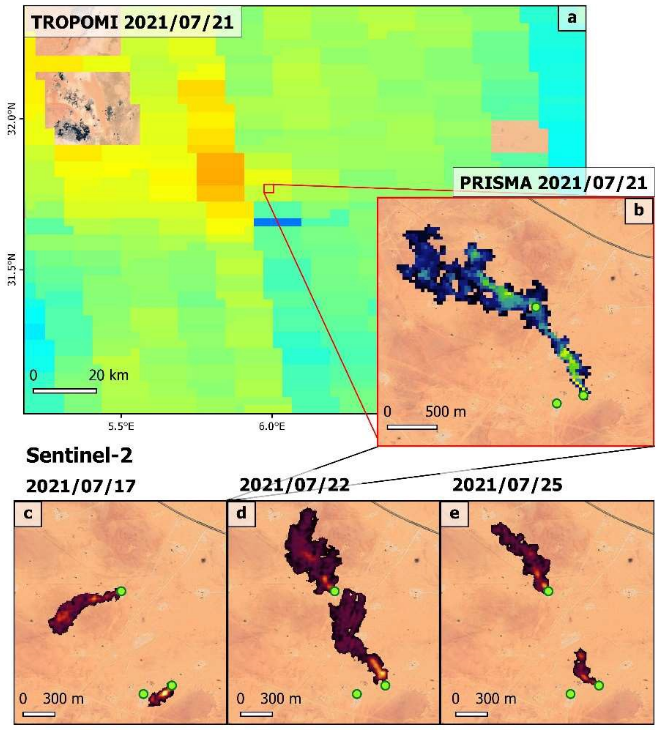

Figure 1. Methane emissions detected from different satellites over the same location in Algeria. In panel (**a**), methane enhancement detected with TROPOMI on 21 July 2022 in the Hassi Messaoud oil and gas field. In (**b**), the plume detected by PRISMA on the same day as a result of mapping the TROPOMI pinpointed area. In (**c**–**e**), the plumes detected by Sentinel-2 in the same location. The green dots indicate the point sources identified throughout the study. Image background from Google Earth.

In this article, we focus on the detection of point source emissions in terrestrial areas. We explain the methodology developed in recent years to detect this type of emission in different geographical areas. The main results so far show that the areas of high emissions observed by low-resolution satellites in different fossil fuel areas are generally the result of several point sources of emissions, i.e., different facilities that emit independently. Moreover, even if they are all fossil fuel-derived emissions, in each country or region, the problem behind the emissions varies. The following section provides a brief description of the data and methods used in this study. Then, in Section 3, our results are described, and conclusions are presented in the last section.

2. Data and Methods

The first step for high-resolution CH_4 emission detection is to identify the area of interest. For this, we use the European Space Agency's TROPOMI low-resolution data, which are daily global data at a 5.5×7 km^2 pixel resolution. Focusing on those areas where

TROPOMI detects high CH_4 concentrations, we can use high-resolution satellites to find the point sources [9,10] (Figure 1).

We distinguish two types of satellite data, hyperspectral (e.g., PRISMA and EnMAP) and multispectral (e.g., Sentinel-2 and Landsat 4-9). Hyperspectral satellites are characterized by having hundreds of very narrow bands that allow characterizing the Earth's surface with high accuracy and provide relatively high sensitivity to CH_4. However, the images are usually obtained on demand, i.e., the satellites are not continuously collecting data. In our work, we use the Matched Filter method [6] to obtain CH_4 maps in hyperspectral images. We mainly use the PRISMA satellite and, to a lesser extent, also the Chinese Gaofen-5 and ZY1 hyperspectral satellites, which are not completely public [11], but their sensitivity to CH_4 is better than that of EnMAP and PRISMA. On the other hand, multispectral satellites are characterized by fewer bands and lower spectral resolutions, making them less sensitive to CH_4. However, in the case of Sentinel-2 and Landsat, they do continuously collect data. This compensates for the lack of continuous hyperspectral data and provides a tool to monitor sources previously identified with hyperspectral satellites (see Figure 1).

To obtain CH_4 retrievals in the multispectral data, we applied the Multi-Band–Multi-Pass method defined by Varon et al. [7], which consists of obtaining the difference between the radiance received in the band located in the strong CH_4 absorption window (B12 in the case of Sentinel-2 and B07 in the case of Landsat 4-9) and the radiance received in the closest band with residual sensitivity to CH_4 (B11 in Sentinel-2, B06 in Landsat 7-9 and B05 in Landsat 4-5) on an emission day, and then obtaining the difference between that result and the one obtained on a nearby day without emission.

In this work, we used Sentinel-2 and Landsat to detect CH_4 emissions, as long as the study area was appropriate for them (see below). The data are public and freely available on the official portals of each mission, i.e., ESA's Copernicus Open Access Hub for Sentinel-2 and USGS's EarthExplorer for Landsat data.

Given the different CH_4 sensitivities of the satellites, different scenarios require different approaches. For instance, in desert and homogeneous land areas, such as Turkmenistan, Algeria, and Iraq, we used both hyperspectral and multispectral satellites, although hyperspectral satellites can provide more information on smaller emissions, while multispectral satellites are limited to larger emissions. On the other side, in vegetated and heterogeneous land areas such as the Permian Basin and the Shanxi region in China, hyperspectral images are required since the surface variability generates false positives when using only multispectral data. Finally, it has recently been demonstrated that high-resolution satellites can also detect emissions over water [12], but we will not delve into this field in this manuscript.

Once the CH_4 plume was detected, we proceeded to overlay the satellite image on a very-high-resolution map, such as Google Maps or Bing Aerial, to visually identify the potential emitting source.

3. Results

Applying the methodology described above, we mapped different world areas where TROPOMI pinpointed high emission concentrations. In this way, we aim to find the point sources and understand the issues behind the emissions, as well as the potential and limitations of each satellite.

3.1. Results in the U.S. Permian Basin

The Permian Basin oil and gas extraction area is between New Mexico and Texas. This is the largest oil and gas basin in the United States and one of the world's largest CH_4 emission hotspots. At the time we mapped this area, EnMAP was not yet operational, but we used data from two Chinese hyperspectral satellites, Gaofen-5 and ZY1. By mapping the area of interest in the basin, we identified a total of 31 CH_4 emissions from different facilities. The analysis of the sources showed that most of the emissions came from compressor stations (50%), gas flaring facilities (21%), storage tanks (24%), and extraction wellheads (6%). In addition, we noted that most of the emitting facilities were relatively new, indicating that much of the problem lay in the too-rapid growth of the basin with little control of the facilities [11].

3.2. Results in Turkmenistan, Algeria, and Iraq

The east coast of Turkmenistan has been a major emission hotspot for decades. The Turkmenistan west coast mapping revealed 29 emission point sources, the vast majority of them (24 out of 29) being excess gas flaring facilities that remained unlit, i.e., they were not flaring the gas but venting large amounts of CH_4 into the atmosphere [9].

After that, we also mapped the Algerian and Iraqi oil and gas fields, where TROPOMI pinpointed four areas and one area of high emissions, respectively. In the case of Algeria, we identified about 80 emission point sources active at least in the years 2020 and 2021, and in the case of Iraq, 25 point sources, all of them in the area pointed out by TROPOMI. In both cases, we found that most emissions come, as in Turkmenistan, from unlit gas flaring facilities, although emissions were also found in gas storage tanks, wellheads, and pipelines. Historical data from the Landsat satellite constellation show that some facilities have been emitting large amounts of CH_4 for many years and that most of them are decades old.

3.3. Results in Chinese and Australian Coal Mines

Moving away from oil and gas emissions, we decided to map other emission hotspots in coal mining areas. The selected areas are in the Shanxi region of China and eastern Australia.

With these mappings, we verified that the emissions from open-pit mines are too diffuse and complicated to be detected correctly. On the other hand, the underground mine mapping provided satisfactory results, showing a large number of plumes emitted from the venting shafts. In addition, we also identified emissions from other mine installations, but with lower emission fluxes and to a lesser extent.

4. Summary and Conclusions

The results of the studies presented in this paper indicate that the areas of high emission concentration identified by low-resolution satellites in the selected regions are the result of several emission point sources. At the same time, it is concluded that, although all these emissions are related to the fossil fuel sector, the reason behind them changes from one country to another.

Identifying the point source of the emission is a significant step forward in reducing GHG emissions since it makes the data actionable. In the case of our studies, the results point, on the one hand, to malfunctioning or leaking oil and gas infrastructure as major sources of CH_4 emissions in the oil and gas regions studied, which are quickly abatable and, in some cases, even cost-effective, as gas leaks are an economic loss for companies. On the other hand, in the case of the mining region of Shanxi, the results point to venting shafts as the mean sources of emissions, which are also fixable through, e.g., carbon capture systems.

Finally, results from the Australian mines showed that, with current technology, many large emissions are still challenging to study with high-resolution satellites. This situation is expected to change in the next few years with the arrival of new, more accurate public satellites [5] that can measure both diffuse and point source emissions at a high enough resolution to attribute the emission's source accurately.

Author Contributions: Conceptualization, I.I.-L.; methodology, all authors; formal analysis, I.I.-L.; investigation, all authors; writing—original draft preparation, I.I.-L.; writing—review and editing, all authors; visualization, I.I.-L.; supervision, L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data related to the Permian Basin study can be found in this Harvard Dataverse repository https://doi.org/10.7910/DVN/K8SN73. The satellite data used in this paper are freely available on the official portals of each mission: TROPOMI and Sentinel-2 on the Copernicus Open Access Hub, PRISMA on the ASI- PRISMA portal, EnMAP on the EnMAP portal, and Landsat on the USGS EarthExplorer.

Acknowledgments: The authors thank the co-authors of the Permian and Turkmenistan studies cited above for their support.

Conflicts of Interest: The authors declare no conflicts of interest.

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