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Minimum detection limits of the TROPOMI satellite sensor across North America and their implications for measuring oil and gas methane emissions

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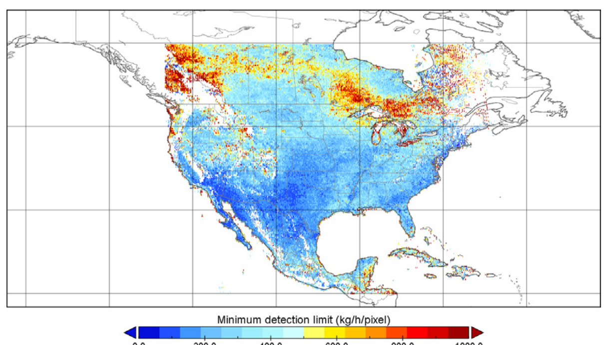
HIGHLIGHTS

- Minimum detection limits vary from 500 to 8800 kg/h/pixel for a single overpass.
- These decrease to 50–1200 kg/h/pixel for a yearlong campaign.
- 14.4 % of total yearly methane emissions can be detected in a yearlong campaign.
- Assuming gas sites contain super-emitters this rises to 35.6 % - 41.1 % of emissions.
- For a single measurement this is lower at 0.04 % or 4.5 % - 10.1 % with super-emitters.

GRAPHICAL ABSTRACT



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ABSTRACT

Methane emissions from natural gas are of ever-increasing importance as we struggle to reach Paris climate targets. Locating and measuring emissions from natural gas can be particularly difficult as they are often widely distributed across supply chains. Satellites are increasingly used to measure these emissions, with some such as TROPOMI giving daily coverage worldwide, making locating and quantifying these emissions easier. However, there is little understanding of the real-world detection limits of TROPOMI, which can cause emissions to go undetected or be misattributed. This paper uses TROPOMI and meteorological data to calculate, and create a map of, the minimum detection limits of the TROPOMI satellite sensor across North America for different campaign lengths. We then compared these to emission inventories to determine the quantity of emissions that can be captured by TROPOMI. We find that minimum detection limits vary from 500–8800 kg/h/pixel in a single overpass to 50–1200 kg/h/pixel for a yearlong campaign. This leads to 0.04 % of a year's emissions being captured in a single (day) measurement to 14.4 % in a 1-year measurement campaign. Assuming gas sites contain super-emitters, emissions of between 4.5 % - 10.1 % from a single measurement and 35.6 % - 41.1 % for a yearlong campaign are captured.

1. Introduction

Methane is a potent greenhouse gas (GHG) that has a warming potential far higher than carbon dioxide (Balcombe et al., 2018b), meaning small increases in its concentration in the atmosphere have huge effects. Natural gas supply chains are responsible for over 12 % of anthropogenic methane emissions, with a similar percentage coming from oil (IEA, 2020). Natural gas use has grown over the last decade in its role as a transition fuel, used to displaced coal (Wilson and Staffell, 2018), as well as flexible support for intermittent renewables (Aguilera and Aguilera, 2020). However,

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methane is emitted across the supply chain, via venting, incomplete combustion and fugitive emissions (Balcombe et al., 2018a). These emissions could make natural gas too carbon intensive to be used in an energy system striving for net-zero emissions.

Technologies to measure and quantify methane in the oil and gas sector fall into two categories; bottom-up which takes measurements of specific point-sources at a selection of facilities and then extrapolates to a larger population (Balcombe et al., 2017); top-down, which measures atmospheric methane and then disaggregate this to point sources (Murakami et al., 2013). Each technology has its flaws and advantages, such as bottom-up taking a long time and not being able to reach all sources and top-down having large uncertainty bounds and not being able to correctly allocate emissions. As technology advances, measurement tools are improving. However, there are disagreements between technologies and results often differ (Vaughn et al., 2018). This is problematic, especially as methane emissions reporting is increasingly being required by governments (EU, 2020; UNFCCC, 2014). Should each technology give a different result, or inaccurate measurements are reported, it could jeopardise carbon budgets. From this debate, satellites have emerged as a new technology that could measure inaccessible facilities, verify reporting, as well as aid in the compilation of inventories via daily monitoring.

Satellites work by taking a snapshot of the methane concentration in the atmosphere at a certain point in time which can then be converted into an emission rate (Jacob et al., 2016). A snapshot is taken using backscattered sunlight and a spectrometer to measure the quantity of methane in a column going through the earth's atmosphere (Hasekamp et al., 2019). Satellites differ in return times to retake this image and have different pixel sizes (resolution). These characteristics are important for quantifying emissions, leading to some satellites being far more suitable for oil and gas emissions than others.

There are many studies which have used satellites to measure methane emissions (Bergamaschi et al., 2007, Wecht et al., 2014, Turner et al., 2015, Turner et al., 2016, Pandey et al., 2019, Schneising et al., 2020, Zhang et al., 2020, Irakulis-Loitxate et al., 2021, Shen et al., 2022). These studies demonstrate the effectiveness of satellites in measuring methane emissions, particularly from oil and gas infrastructure. However, while these give estimates for total methane emissions in an area, they often fail to mention the restrictions and capabilities of the satellite used. This results in large uncertainties in the results, which can skew how accurate the results are believed to be. Studies such as Varon et al. (2019) use very high resolution satellites (GHGSat) these have very different roles to play than TROPOMI. These satellites are not open-source but are well suited for quantifying emissions from individual facilities (Cooper et al., 2022), and have more well defined minimum detection limits than TROPOMI, which makes using the satellite correctly easier. Furthering understanding of the limitations of large scale, open-source satellites such as TROPOMI will aid policy makers in developing regulations and understanding where TROPOMI can be used.

Jacob et al. (2016) discusses the minimum detection limits (MDLs) of satellites, including TROPOMI and how these can be affected. However, they did not use real data and did not consider how MDLs change over time and space. This is important as having one widely quoted MDL for all regions and conditions is misleading and can result in incorrect assumptions on the capabilities of TROPOMI. This could lead to emissions being misattributed or not detected. More recently (Jacob et al., 2022) again reviewed satellites and minimum detection limits, however, this was for favourable winds, and a single figure was given for each satellite.

With new focus on methane emissions, since the global methane pledge was announced at COP26 (EU, 2021), a real world understanding of TROPOMI is vital. As far as the authors are aware, no other paper has looked in this level of detail at the MDL of TROPOMI, nor combined this varying MDL with inventories to ascertain the capabilities of TROPOMI for oil and gas sector methane emissions across North America. This paper will combine TROPOMI data for 2019 in North America with North American reanalysis meteorological (NOAA) and cloud fraction data to calculate real world detection limits across the year. These will be compared to emissions inventories to determine the quantity of emissions that could be captured by TROPOMI over varying campaign lengths. The effect this could have on the use of satellites in the oil and gas sector, alongside policy implications will also be evaluated.

The aims of this paper are to:

- Create a map of the MDLs for the TROPOMI satellite across North America
- Compare this to current inventories to determine the quantity of emissions that could be detected over different campaign lengths
- Examine how super-emitters within the inventories could affect the total quantity of emissions measured
- Determine the effect MDLs could have on inventory corroboration

2. Methodology

2.1. What is a Minimum Detection Limit (MDL)?

An MDL is the smallest emission/enhancement that can be reliably detected above the background variation in methane. This is a commonly used term in analytical chemistry (Succop et al., 2004; Rousseau, 2001). In this work we use the commonly used criteria that the MDL must be 3.3 σ over the value of the blank (Armbruster and Pry, 2008) (where blank refers to no methane detected, which in our case is the background level of methane), where σ is the precision of the satellite.

Uncertainty within a satellite measurement is comprised of two elements, the accuracy and the precision of the instrument. The accuracy refers to the systematic error, which is the error that repeats over every measurement. This often occurs due to a bias in the measurement, and for this reason bias correction factors can be implemented after the satellite has collected data. This way it is reducible. The precision is a quantification of the random errors associated with a measurement. These are not possible to reduce through correction factors. However, it is established that repeat measurements should reduce the effect of random errors via the central limit theorem (Kulawik et al., 2016). This paper is concerned with the precision of the satellite.

2.2. How is MDL calculated

To understand how the MDL of a satellite can change under certain conditions let us consider a single pixel with a constant emitting source, e and no wind. If a satellite were to measure the methane in this pixel every 24 h, over time the methane emitted from e will accumulate until eventually it will be above the satellite's MDL i.e. $et > MDL$. Where et is the mass of the methane in the pixel.

If we add a constant wind speed, after a certain length of time some of this methane will no longer be in the pixel, and it will reach a steady state. This means the methane in the pixel will be equal to $et - methane\ leaving\ pixel$. This methane leaving will be proportional to the wind speed, u, and the size of the pixel, r, such that methane leaving the pixel is $\propto \frac{u}{r}$.

However, the size of a pixel is proportional to the mass of methane it contains. Therefore, each increase in σ will correspond to a larger quantity of methane. The MDL is, by definition, proportional to σ which is proportional to r^2. Combing these gives us the relationship that the MDL of a pixel is proportional to ru.

2.3. Vertical wind speed

The vertical wind speed, or the vertical rise of the plume will also have an effect. However, this effect will be limited in the change it causes in the horizontal wind speed. As the methane rises, it will be acted on by a different horizontal velocity until it leaves the pixel.

2.4. Equation for MDL

To work out how the MDL is calculated we can use the relationships from Sections 2.2–2.3. The time for the methane to leave the pixel t_{tlp}, will be equal to:

$$t_{tlp} = \frac{r}{\sqrt{u(x,y,z,t)^2 + v(x,y,z,t)^2}} \tag{1}$$

Where $u(x,y,z,t)$ and $v(x,y,z,t)$ are the wind speeds that change with location and time and r is the size of the pixel. Therefore, the vertical wind speed can be viewed as a change in the horizontal wind speeds rather than a separate factor. In this way it has no direct correlation to the MDL.

The mass of methane in a pixel will be equal to:

$$M = V * concentration \tag{2}$$

Where V is the volume of the pixel. This value can be calculated using ideal gas laws. Combining these, the equation for MDL is:

$$MDL = \frac{q\sigma M}{t_{tlp}} \tag{3}$$

Where q is 3.3 and σ is the precision of the satellite. However, we must also consider that pixels are not isolated, and instead when methane leaves a pixel it enters another. In this way the MDL would decrease, as methane moves between pixels. This value would depend completely on the environment and emission characteristics. In this way the MDL we have calculated is actually the maximum MDL. We could therefore write it as:

$$MDL = \frac{q\sigma M}{t_{tlp}} - E_b \tag{4}$$

Where E_b is the methane blowing into the pixel. However, it is common practice to calculate the background level of methane such that E_b is accounted for. This is either done using on site measurements (Atherton et al., 2017), or using satellite data itself (Schneising et al., 2020).

2.5. Time of overpass/case of an intermittent source

The time of the overpass is of paramount importance. This is as the wind speed preceding the overpass can have significant bearing upon the measurement. To illustrate this let us consider an emitting source that emits all of its methane in the moments just after an overpass. If the wind speed is high enough that the methane has been blown out of the pixel by the time of the next overpass, no detection will be seen, and thus this will be considered a non-emitting source. However, if instead this source emits all of its methane in the moments just before an overpass it will be seen as emitting this amount as the average over the time between overpasses. Thus, it has a greatly increased estimate in emission rate. As the wind speed increases this effect becomes greater as with higher winds speeds less time is required for methane within a pixel to leave, meaning overpasses would need to be more frequent to accurately measure the emission rate.

2.6. Data input

Jacob et al. (2016) used a similar method to calculate the MDLs of several satellites under constant conditions. However, wind speeds vary greatly over the year and over different locations. Moreover, the precision of satellites also varies depending on the location. To garner more understanding of MDLs, we used TROPOMI data, which provides the precision of the column for every measured location. This was achieved by collecting a minimum of 15 days of data for each month in the year 2019. The data gives the column-averaged mixing ratio in ppb of methane for each 7 × 7 km pixel. However, since late 2019 the resolution was upgraded to 5.5 × 7 km when TROPOMI is at nadir. This analysis uses the 7 × 7 km resolution as it is the guaranteed resolution. Therefore, the MDLs calculated may decrease slightly when in more optimal conditions.

This was combined with NOAA reanalysis meteorological data for North America (NOAA, 2021). The NOAA data gives the wind speeds at different pressure intervals over 3-hour time periods for 32 km^2 areas across North America. Using equation Eq. (4) the precision of TROPOMI could be combined with these wind speeds to calculate the MDLs for every measured pixel across North America, assuming a constant 1 m/s vertical speed. The analysis was carried out in MATLAB.

2.7. Comparing to inventory

Once the MDLs across North America were calculated, we used the global inventory of fuel exploitation reported to the UNFCCC (Scarpelli et al., 2020) to compare methane emissions from oil and natural gas. This combined several inventories to create a 0.1-degree by 0.1-degree grid of methane emissions. We also added background methane sources from the EDGAR inventory (EDGAR, 2021) to include non-natural gas sources, which would have an effect on which pixels could be detected. We compared these inventories to the MDL of TROPOMI to examine where satellites are best suited, what percentage of emitting sites are detectable and the effect this would have on total emission estimates.

The inventory gives emissions for 2016, whereas the data we examined is for 2019. Our analysis is not an attempt to quantify emissions, rather it is a hypothetical analysis of what could have been detected if 2016 emissions were present in 2019 when the satellite data was available. Thus the times of the data not overlapping can be assumed to not be an issue. However, updating this work with new inventory data it would be useful in the future.

2.8. Repeated measurements

MDLs can be reduced over repeated measurements. This is as the MDL follows the central limit theory, meaning uncertainty decreases when the measurement is repeated. The central limit theorem states that uncertainty will decrease with the square of measurements theorem (Kulawik et al., 2016). We used this to calculate the possible MDLs over different scenarios to realise the potential of satellites to detect smaller emissions.

We combined the single pass detection limits with cloud data from the Cloud, Albedo and Surface Radiation (CM SAF CLARA-A2) dataset from Advanced Very High Resolution Radiometer (AVHRR) (Karlsson et al., 2017) assuming that at 8 % cloud fraction no readings could be taken, to see how often each pixel would be detected across the year in the same way as in Cooper et al. (2022). This allowed us to calculate the MDL for year-round coverage and compared it to the inventory. Eq. (5) shows the relationship between the number of measurements, $N_o$and the MDL over many overpasses compared to a single overpass MDL_{so}.

$$MDL = \sqrt{N_o} MDL_{so} \tag{5}$$

2.9. Changes in detection limits over months

We examined the changes in the MDL across the year by comparing the same points over each month. This accounted for the fact that some months would have detected points undetected in other months due to cloud coverage etc. This allowed us to examine how the MDLs would change over each month and how this could inform campaign durations.

2.10. Super-emitters

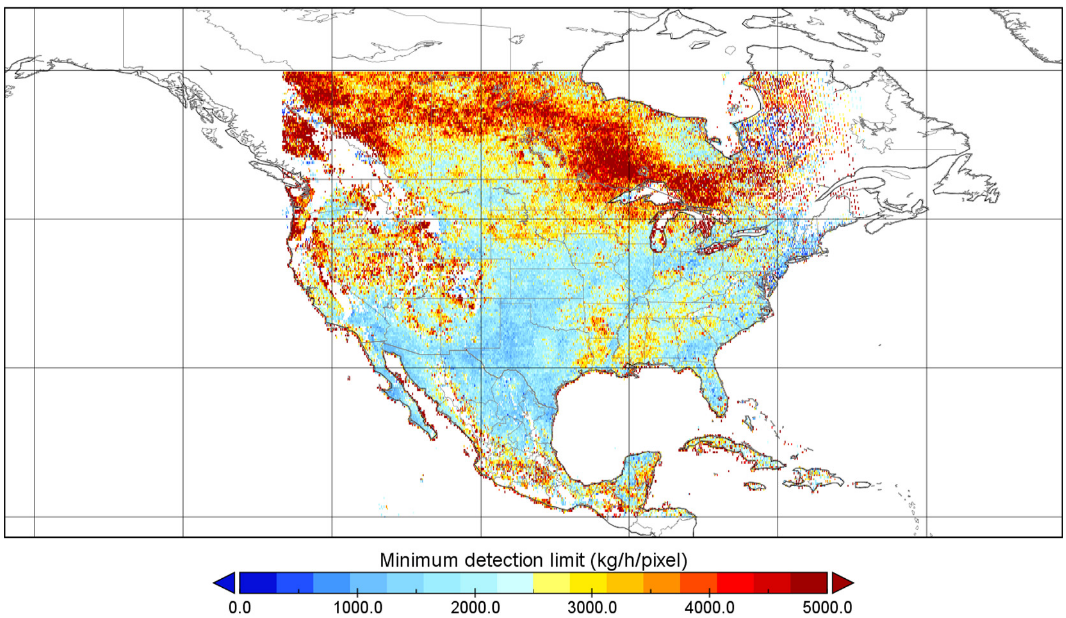
We examine the effect super-emitting sites could have on the total emissions detected by TROPOMI. Super-emitters are a known phenomenon in oil and gas sites and are when a select few pieces of equipment or whole facilities disproportionately contribute to the total emissions. There is debate surrounding the exact definition of a super-emitter and their contribution varies across regions. In this paper, we use the Brandt et al. (2016) definition and define them as the top 5 % of emitters which contribute 50 % of total emissions.

3. Results

Firstly, we present the MDLs of TROPOMI across North America for a single overpass (Fig. 1a) and a yearlong campaign (Fig. 1b). A single overpass is shown here as the average MDL of each day measured and does not refer to any particular day. These show the importance of both location and quantity of measurements in lowering the MDL. Fig. 2 shows a histogram giving the spread of MDLs from Fig. 1a and b.

These show that the MDLs range from 500–8800 kg/h/pixel for a single overpass to 50–1200 kg/h/pixel for a yearlong campaign. By combing with

a)



b)

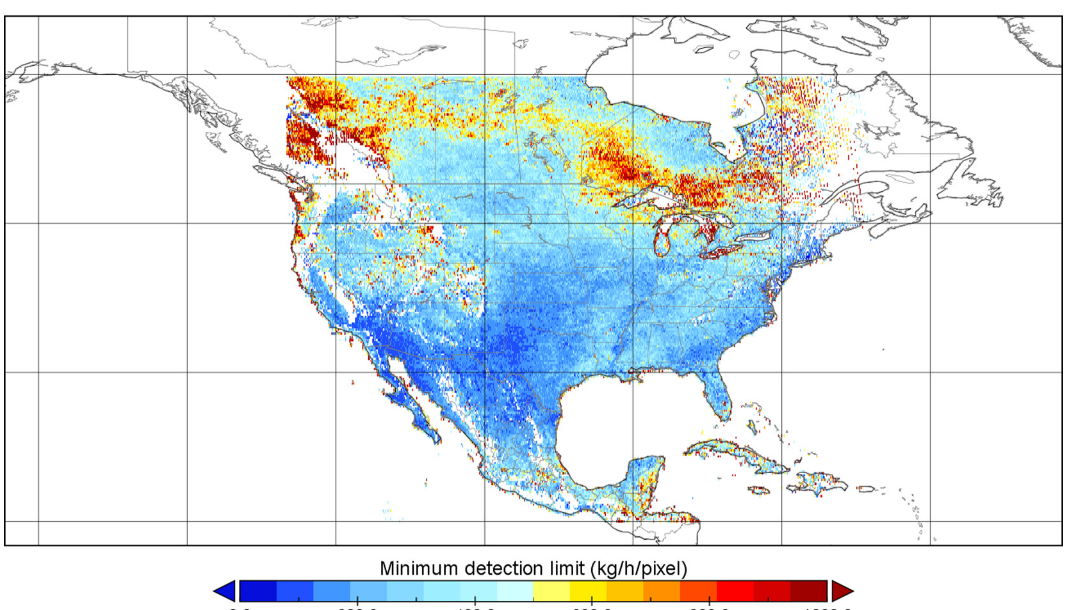


Fig. 1. Minimum detection limits across North America for a) a single overpass. b) a yearlong campaign. White indicates no data.

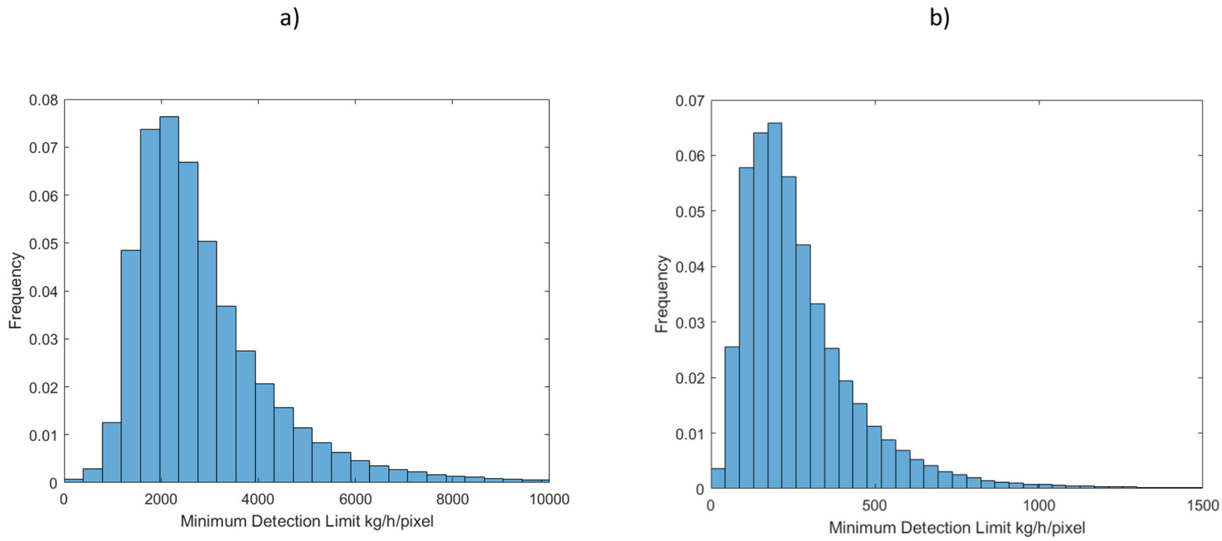


Fig. 2. Histogram of range of MDLs across North America from Fig. 1a and b. a) single overpass. b) yearlong campaign.

the inventories, we can now examine which pixels contain sites that would be captured by the satellite in a single overpass and in a yearlong campaign (Fig. 3) - pixels enlarged for visibility.

Next, from the calculated MDLs we can examine the level of total emissions that can be captured over different durations of successful measurements (Fig. 4). We can see that increasing the campaign length is of paramount importance. However, there is still a large chunk of emissions that cannot be captured, even if every pixel was measured each day of the year (which is not possible). This means for a single overpass 0.04 % of total emissions can be detected rising, to 14.4 % for one-year worth of measurements (due to not all days being measurable due to cloud cover).

We also note that many studies have shown natural gas sites and components to exhibit super-emitting characteristics (Brandt et al., 2016; Zavala-Araiza et al., 2015; Caulton et al., 2019). To account for this, we assumed 5 % of sites were responsible for 50 % of emissions by randomly sampling the sites and artificially increasing 5 % of site emissions 10-fold. This was repeated 10,000 times and the histograms shown in Fig. 5 displays the results for both a single overpass, and a yearlong campaign. Therefore, taking

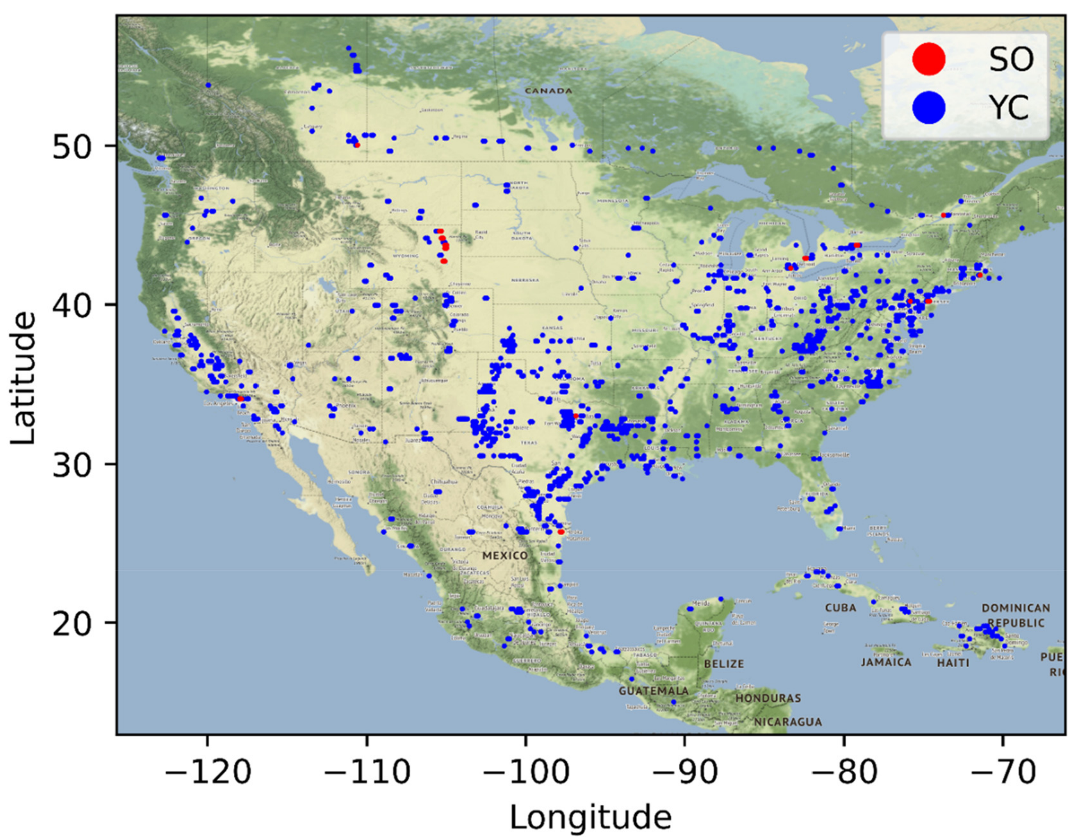


Fig. 3. Pixels detectable over a single overpass (SO) and yearlong campaign (YC). Each dot represents a facility in an inventory, the red dots represent the sources that could be detected over a single successful measurement, and the blue dots represent the sources that could be detected over a yearlong campaign. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

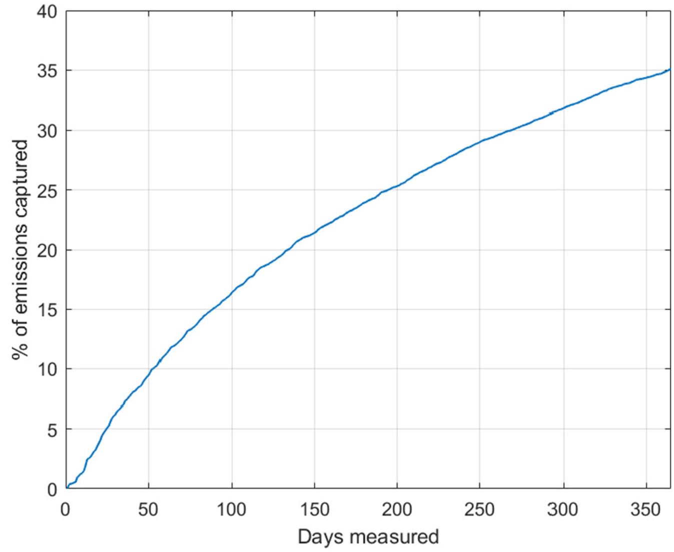


Fig. 4. Percentage of total emissions captured vs days of successful measurement.

the 2 standard deviation range, emissions of between 4.5 % - 10.1 % for a one-day measurement and 35.6 % - 41.1 % for a yearlong campaign can be captured.

Should a campaign not be able to be run for a whole year, the month that is chosen has a significant impact on the emissions that can be detected (Fig. 6). These differences are primarily due to the changes in wind speeds across the different months, with winter having faster winds which move methane in and out of pixels more rapidly. Combined with the summer months having more clear days where measurements can be taken due to lower cloud coverage.

4. Discussion

4.1. Comparison to literature

Jacob et al. (2016) calculated the MDL for TROPOMI over a single overpass and yearlong campaign. They estimated that for a single overpass the dection limit would be 4200 kg/h/pixel, which is comparable to our estimate of 500–8800 kg/h/pixel. For a yearlong campaign they estimated an MDL of 500 kg/h/pixel, which again is comparable to our estimate of 50–1200 kg/h/pixel. The ranges seen in the estimates here reflect the differences in wind speeds and cloud coverage across North America.

4.2. Spatial differences in MDL

Firstly, the area in which a measurement campaign occurs is very important when quantifying emissions from oil and gas activities. Across North America the MDL varies significantly, meaning certain areas are far more suitable for measurement by satellite. Should measurement campaigns be carried out in areas that are less suitable, then either significant quantities of emissions will not be captured, or emissions may be incorrectly attributed. The most suitable areas are in the south and southeastern United States. This is where several major basins such as the Permian, Eagle Ford, Haynesville and Anadarko are located. Thus, these basins are potential research locations for satellite studies, and some have already been studied (Zhang et al., 2020; Schneising et al., 2020).

4.3. Temporal differences in MDL

We can also see that the time of year measured matters. This is due to 2 main reasons. Firstly, the wind speed changes throughout year. Secondly, certain months have lower levels of cloud coverage. These result in the MDL differing by up to 75 % when a month-long campaign is considered, or by 87 % when a single measurement is considered. These are considerable changes which must be considered when deciding the timing and duration of a campaign.

In general, longer, on the scale of months to years, campaigns are preferable as these lower the MDL and ensure changes in emissions throughout the year are captured. However, if this is not possible for some reason, the summer months are the optimal months for carrying out campaigns.

4.4. Quantity of measurements

As was stated in Section 2.8, the number of times you measure an area will change the MDL. We have shown the effect this can have is significant and greatly increases the quantity of emissions that can be captured (Fig. 4). Should there also be a super-emitting distribution among the gas sites, then the quantity of emissions that can be captured will be even larger, greatly improving the use of satellites. It is therefore vital that longer campaigns are planned for a more comprehensive overview of emissions.

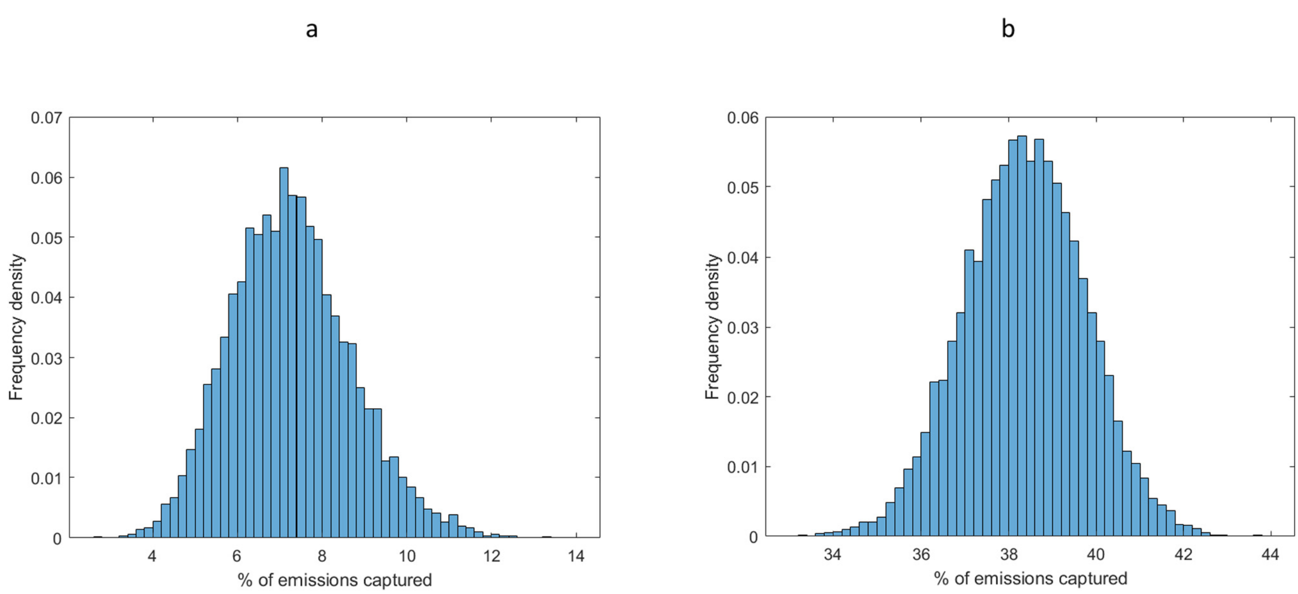


Fig. 5. Histograms of percentage of total emissions captured when super-emitter hypothesis is included for a) single overpass and b) yearlong campaign.

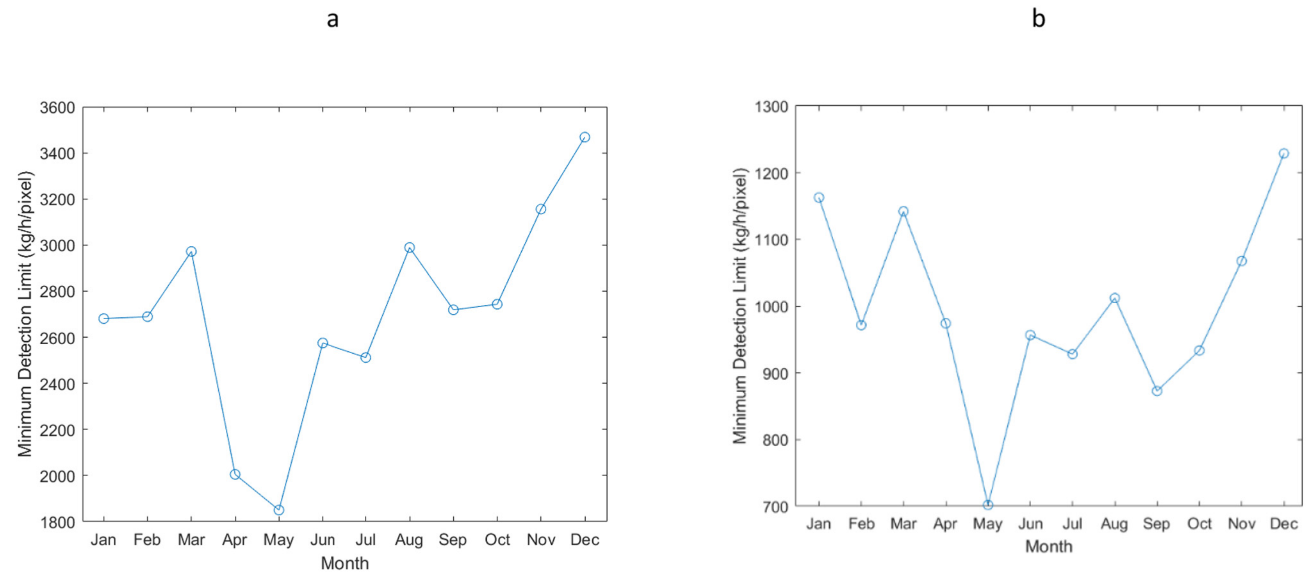


Fig. 6. Change in average MDL over the year a) single overpass. b) 30 days of the month*.
*February was artificially given 30 days.

4.5. The effect of MDL in comparison to satellite studies

Many satellite studies have found emissions to be higher than what is reported in inventories (Schneising et al., 2020; Zhang et al., 2020). However, this appears to be in direct contradiction of the MDLs not being able to fully capture emissions. It should be noted that often satellite studies have large uncertainty ranges, which are essentially a manifestation of the MDL of the satellite. Therefore, it could be the case that the high emissions captured are due to the satellites measuring below the theoretical MDL. Equally, the satellites may also be measuring emissions that were not captured by the inventories and must be included in future compilation. However, there are also many other limiting factors in satellite measurements and quantifications that have not been discussed here, such as pixel resolution and bias to albedo and topography, that will also affect the results and uncertainties.

Another possibility is that the emission profiles gas facilities exhibit are particularly well suited to satellite studies. Emission profiles such as super-emitters or ultra-emitters are well documented in the oil and gas industry and are likely occurrences (Brandt et al., 2016; IEF Methane initiative, 2021). We have shown that should facilities, not just individual components, follow such a distribution then the quantity of emissions detectable is far greater. Super-emitting profiles could result in inventories underestimating total emissions, or that on certain days when satellites measure, they may overestimate emissions (by measuring on an unusually high emitting day). Moreover, other measurement technologies are not as suitable to detecting high emissions as they tend to have MDLs which are far lower than satellites.

As satellite technology improves the quantity of emissions that can be detected will increase, which will make them even more useful. Potentially, satellites could become the major technology used to check emission estimates and total country wide emissions.

4.6. The role of TROPOMI in policy, and how the MDL could affect this

Satellites, and TROPOMI specifically, are beginning to be considered in policy creation as a technology to quantify and limit methane emissions. However, whether policy matches the realistic role satellites could play is vital. In 2020 the EU revealed its methane strategy (EU, 2020), which is a wide ranging piece of policy designed to transform the way methane emissions in the EU and worldwide are viewed. Within this strategy TROPOMI was a cornerstone. This role the strategy foresaw was one of detecting super-emitters and worldwide monitoring for inventory creation. The first role of super-emitter detection is ideally suited, and we have shown to be the best way to use TROPOMI. The second role of inventory creation is more problematic. This is as the majority of emissions, should there be no super-emitter distribution, would be missed. Thus, TROPOMI could only play an assisting role in the creation of inventories. Should newer satellites have lower MDLs, then this role could be possible but the strategy does not yet possess this technology option.

The US Methane Emissions Reduction Action Plan released in 2021 (White House Office of Domestic Climate Policy, 2021) aims to meet the goals of the global methane pledge; 30 % reduction in methane levels relative to 2020 by 2030. The plan mentions the role of satellites in identifying super-emitters via the Carbon Mapper and NASA's Jet Propulsion Laboratory. The role this would play appears more in identifying specific leaks, rather than quantifying. However, as the US adopts its new methane strategy, this paper could provide evidence of the limitation of TROPOMI across the country which may prove useful in determining whether the reductions in methane have been met.

Canada implemented new methane regulations in 2018 where a bottom-up approach was used to create inventories (Canada Ministry of Justice, 2018). This implemented a systematic measurement campaign of individual components in facilities to build up and emission profile. TROPOMI, and satellites more generally, could play a key role in corroborating these measurements which may, without satellites, underestimate total emissions by missing components that are be hard to measure. Using satellites over a yearlong campaign could aid in developing uncertainty bounds for total facility emissions in larger emitting sites.

Similarly, the Mexican methane strategy relies on bottom-up measurements which are collected and categorised by the emitting facility and reported to the government (Olczak and Piebalgs, 2019). Satellites could also be useful here to check emission estimates from the top emitting facilities. However, the majority of emissions within Mexico would not be suitable for quantification using TROPOMI.

The Oil and Gas Methane Partnership (OGMP) 2.0 framework details how companies should measure and address methane emissions in the oil and gas sector (OGMP, 2020). Within this framework both on site measurement and top-down measurements are mentioned. The role satellites could play is explicitly stated as site level measurement, where resolution is sufficient, alongside the use of the international methane emissions observatory for verification. However, the MDLs of satellites are not mentioned. In areas with diverse emission sources, TROPOMI would not be particularly suitable. However, should the only credible source of methane within and area be an emitting facility, it is not a stretch to allocate emissions from that area to said facility and satellites such as TROPOMI could play a key role. Thus, using the MDL work from this paper the TROPOMI instrument could be used over long campaigns at specific facilities and should be acceptable in reporting emissions within the OGMP 2.0 framework.

Due to the quantity of emissions that can be captured in a single overpass, TROPOMI, and satellites in general, should be used with caution. There is little use in using TROPOMI for a single measurement, but sustained measurements over a long period of time have great benefit. This optimal use of TROPOMI should be reflected in the policies that are developed moving forward.

4.7. Limitations and recommended future work

Many assumptions were required in this paper due to data limitations. Detailed gridded inventories were only available for the year 2016, meaning the emissions represented are out of date and could lead to inaccuracies in the total emissions captured by the satellite. The wind speeds were gathered from NOAA reanalysis meteorological data, which gives a 32 km^2 resolution. This will lead to inaccuracies in the local wind speeds which would vary within this grid. The effect of turbulence was also not known, this could have large effects on a local level, varying the wind speed and direction. There are also different methods for utilising satellite data, many of which use a priori data. The use of these rely heavily on the weighting given to the a priori assumptions. This may affect the final MDL as the additional uncertainty in the weighting and calculations thereafter could increases the overall uncertainty and with it the MDL. Moreover, the effect on the MDL would be even greater if little was known about the source or if the terrain is complex as this adds another element of uncertainty to the calculation. Thus, more work into how the MDL changes with different methods to estimate methane from would be greatly beneficial.

Several pieces of work are recommended for future studies which would enable greater use of TROPOMI and satellites in general:

- An expansion of this work to worldwide coverage
- Measurements and modelling of the vertical speed of methane under different conditions
- Detailed policy proposals on how satellites can be used for verification and reporting by individual companies and governments
- Continually updated and improved data sets for meteorological data and inventories of emissions
- A continuation of this work to cover any new satellites launched e.g. MethaneSAT

5. Conclusions

This paper has examined the MDLs of TROPOMI across North America. It has compared these to inventory estimates of methane emissions from oil and gas facilities to determine the quantity of emissions that are detectable over different campaign durations. We find that the MDLs of TROPOMI vary significantly, from between 500–8800 kg/h/pixel in a single overpass to 50–1200 kg/h/pixel for a yearlong campaign. This means any campaign locations must be carefully considered prior to measurement to ensure emissions will be detectable. Moreover, the time of year also influences the MDLs. Thus, should a campaign be truncated into select months, the summer months offer far lower MDLs than in winter.

Increasing the length of the measurement campaign greatly increases the quantity of emissions that can be detected from 0.04 % for one-day to 14.4 % for one-year, when a constant emission rate is assumed. Assuming gas sites display a super-emitting profile, between 4.5 % - 10.1 % of total emissions can be captured in a one-day measurement and 35.6 % - 41.1 % in a yearlong campaign. This means longer campaigns should be carried out to ensure the maximum quantity of emissions are captured.

When combining satellites with policy we can see there is still a gap in what the ability of satellites is, and the policy surrounding them. Across North America satellite specific methane policy is weak. Updating this would give guidance to operators who may be unsure of how satellites could be used to verify and improve reporting. Crucial to this guidance will be understanding the MDLs of any satellite used.

CRediT authorship contribution statement

Luke Dubey: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Jasmin Cooper:** Supervision, Visualization, Writing – review & editing. **Adam Hawkes:** Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aguilera, R.F., Aguilera, R., 2020. Revisiting the role of natural gas as a transition fuel. Miner. Econ. 33, 73–80.

Armbruster, D.A., Pry, T., 2008. Limit of blank, limit of detection and limit of quantitation. Clin. Biochem. Rev. 29 (Suppl. 1), S49–S52.

Atherton, E., Risk, D., Fougere, C., Lavoie, M., Marshall, A., Werring, J., Williams, J.P., Minions, C., 2017. Mobile measurement of methane emissions from natural gas developments in northeastern British Columbia, Canada. Atmos. Chem. Phys. 17, 12405–12420.

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., Hawkes, A., 2017. The natural gas supply chain: the importance of methane and carbon dioxide emissions. ACS Sustain. Chem. Eng. 5, 3–20.

Balcombe, P., Brandon, N.P., Hawkes, A.D., 2018a. Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. J. Clean. Prod. 172, 2019–2032.

Balcombe, P., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2018b. Methane emissions: choosing the right climate metric and time horizon. Environ Sci Process Impacts 20, 1323–1339.

Bergamaschi, P., Frankenberg, C., Meirink, J.F., Krol, M.C., Dentener, F.J., Wagner, T., Platt, U., Kaplan, J.O., Körner, S., Heimann, M., Dlugokencky, E.J., Goede, A., 2007. Satellite chartography of atmospheric methane from SCIAMACHY on board ENVISAT: 2. Evaluation based on inverse model simulations. J. Geophys. Res. 112, D02304. https://doi.org/10.1029/2006JD007268.

Brandt, A.R., Heath, G.A., Cooley, D., 2016. Methane leaks from natural gas systems follow extreme distributions. Environ. Sci. Technol. 50, 12512–12520.

Canada Ministry of Justice, 2018. Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector).

Caulton, D.R., Lu, J.M., Lane, H.M., Buchholz, B., Fitts, J.P., Golston, L.M., Guo, X., Li, Q., McSpiritt, J., Pan, D., Wendt, L., Bou-Zeid, E., Zondlo, M.A., 2019. Importance of superemitter natural gas well pads in the Marcellus shale. Environ. Sci. Technol. 53, 4747–4754.

Cooper, J., Dubey, L., Hawkes, A., 2022. Methane detection and quantification in the upstream oil and gas sector: the role of satellites in emissions detection, reconciling and reporting. Environ. Sci. Atmos. 2, 9–23.

EDGAR, 2021. . Available: https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG. (Accessed 13 January 2021).

EU, 2020. RE: EU Strategy to Reduce Methane Emissions.

EU, 2021. Launch by United States, the European Union, and Partners of the Global Methane Pledge to Keep 1.5C Within Reach.

Hasekamp, O., Lorente, Alba, Hu, Haili, Butz, Andre, Brugh, Joost Aan De, Landgraf, J., 2019. Algorithm Theoretical Baseline Document for Sentinel-5 Precursor Methane Retrieval.

IEA, 2020. Methane Tracker 2020.

IEF Methane Initiative, 2021. Methane Mitigation in the Energy Sector.

Irakulis-Loitxate, I., Guanter, L., Liu, Y.-N., Varon, D.J., Maasakkers, J.D., Zhang, Y., Chulakadabba, A., Wofsy, S.C., Thorpe, A.K., Duren, R.M., Frankenberg, C., Lyon, D.R., Hmiel, B., Cusworth, D.H., Zhang, Y., Segl, K., Gorroño, J., Sánchez-García, E., Sulprizio, M.P., Cao, K., Zhu, H., Liang, J., Li, X., Aben, I., Jacob, D.J., 2021. Satellite-based survey of extreme methane emissions in the Permian basin. Sci. Adv. 7, eabf4507.

Jacob, D.J., Turner, A.J., Maasakkers, J.D., Sheng, J., Sun, K., Liu, X., Chance, K., Aben, I., McKeever, J., Frankenberg, C., 2016. Satellite observations of atmospheric methane and their value for quantifying methane emissions. Atmos. Chem. Phys. 16, 14371–14396.

Jacob, D.J., Varon, D.J., Cusworth, D.H., Dennison, P.E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L.E., Poulter, B., Qu, Z., Thorpe, A.K., Worden, J.R., Duren, R.M., 2022. Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane. Atmos. Chem. Phys. 22, 9617–9646.

Karlsson, K.G., Anttila, K., Trentmann, J., Stengel, M., Fokke Meirink, J., Devasthale, A., Hanschmann, T., Kothe, S., Jääskeläinen, E., Sedlar, J., Benas, N., Van Zadelhoff, G.J., Schlundt, C., Stein, D., Finkensieper, S., Håkansson, N., Hollmann, R., 2017. CLARA-A2: the second edition of the CM SAF cloud and radiation data record from 34 years of global AVHRR data. Atmos. Chem. Phys. 17, 5809–5828.

Kulawik, S., Wunch, D., O'Dell, C., Frankenberg, C., Reuter, M., Oda, T., Chevallier, F., Sherlock, V., Buchwitz, M., Osterman, G., Miller, C.E., Wennberg, P.O., Griffith, D., Morino, I., Dubey, M.K., Deutscher, N.M., Notholt, J., Hase, F., Warneke, T., Sussmann, R., Robinson, J., Strong, K., Schneider, M., de Mazière, M., Shiomi, K., Feist, D.G., Iraci, L.T., Wolf, J., 2016. Consistent evaluation of ACOS-GOSAT, BESD-SCIAMACHY, CarbonTracker, and MACC through comparisons to TCCON. Atmos. Meas. Tech. 9, 683–709.

Murakami, K., Sasai, T., Kato, S., Hiraki, K., Maksyutov, S.S., Yokota, T., Nasahara, K., Matsunaga, T., 2013. Evaluations of carbon fluxes estimated by top-down and bottom-up approaches. AGU Fall Meet. Abstr. 21, A21G–A0145G.

NOAA, 2021. NCEP North American regional reanalysis.Available:NARR [Online] [Accessed] https://psl.noaa.gov/data/gridded/data.narr.html.

OGMP, 2020. Mineral Methane Initiative OGMP2.0 Framework.

Olczak, M., Piebalgs, A., 2019. Regulatory Framework to Mitigate Methane Emissions in North America: The Lessons Learned for Europe.

Pandey, S., Gautam, R., Houweling, S., van der Gon, H.D., Sadavarte, P., Borsdorff, T., Hasekamp, O., Landgraf, J., Tol, P., van Kempen, T., Hoogeveen, R., van Hees, R., Hamburg, S.P., Maasakkers, J.D., Aben, I., 2019. Satellite observations reveal extreme methane leakage from a natural gas well blowout. Proc. Natl. Acad. Sci. 116, 26376–26381.

Rousseau, R.M., 2001. Detection limit and estimate of uncertainty of analytical XRF results. Rigaku J. 18, 33–47.

Scarpelli, T.R., Jacob, D.J., Maasakkers, J.D., Sulprizio, M.P., Sheng, J.X., Rose, K., Romeo, L., Worden, J.R., Janssens-Maenhout, G., 2020. A global gridded (0.1° × 0.1°) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations framework convention on climate change. Earth Syst. Sci. Data 12, 563–575.

Schneising, O., Buchwitz, M., Reuter, M., Vanselow, S., Bovensmann, H., Burrows, J.P., 2020. Remote sensing of methane leakage from natural gas and petroleum systems revisited. Atmos. Chem. Phys. 20, 9169–9182.

Shen, L., Gautam, R., Omara, M., Zavala-Araiza, D., Maasakkers, J., Scarpelli, T., Lorente, A., Lyon, D., Sheng, J., Varon, D., Nesser, H., Qu, Z., Lu, X., Sulprizio, M., Hamburg, S., Jacob, D., 2022. Satellite quantification of oil and natural gas methane emissions in the US and Canada including contributions from individual basins. Atmos. Chem. Phys. Discuss. 2022, 1–22.

Succop, P.A., Clark, S., Chen, M., Galke, W., 2004. Imputation of data values that are less than a detection limit. J. Occup. Environ. Hyg. 1, 436–441.

Turner, A.J., Jacob, D.J., Benmergui, J., Wofsy, S.C., Maasakkers, J.D., Butz, A., Hasekamp, O., Biraud, S.C., 2016. A large increase in U.S. Methane emissions over the past decade inferred from satellite data and surface observations. Geophys. Res. Lett. 43, 2218–2224.

Turner, A.J., Jacob, D.J., Wecht, K.J., Maasakkers, J.D., Lundgren, E., Andrews, A.E., Biraud, S.C., Boesch, H., Bowman, K.W., Deutscher, N.M., Dubey, M.K., Griffith, D.W.T., Hase, F., Kuze, A., Notholt, J., Ohyama, H., Parker, R., Payne, V.H., Sussmann, R., Sweeney, C., Velazco, V.A., Warneke, T., Wennberg, P.O., Wunch, D., 2015. Estimating global and north american methane emissions with high spatial resolution using GOSAT satellite data. Atmos. Chem. Phys. 15, 7049–7069.

UNFCCC, 2014. UNFCCC Reporting Guidelines on Annual Inventories for Parties Included in Annex I to the Convention.

Varon, D.J., McKeever, J., Jervis, D., Maasakkers, J.D., Pandey, S., Houweling, S., Aben, I., Scarpelli, T., Jacob, D.J., 2019. Satellite discovery of anomalously large methane point sources from Oil/Gas production. Geophys. Res. Lett. 46, 13507–13516.

Vaughn, T.L., Bell, C.S., Pickering, C.K., Schwietzke, S., Heath, G.A., Pétron, G., Zimmerle, D.J., Schnell, R.C., Nummedal, D., 2018. Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region. Proc. Natl. Acad. Sci. 115, 11712.

Wecht, K.J., Jacob, D.J., Frankenberg, C., Jiang, Z., Blake, D.R., 2014. Mapping of north American methane emissions with high spatial resolution by inversion of SCIAMACHY satellite data. J. Geophys. Res. Atmos. 119, 7741–7756.

White House Office of Domestic Climate Policy, 2021. US Methane Emissions Reduction Action Plan.

Wilson, I.A.G., Staffell, I., 2018. Rapid fuel switching from coal to natural gas through effective carbon pricing. Nat. Energy 3, 365–372.

Zavala-Araiza, D., Lyon, D., Alvarez, R.A., Palacios, V., Harriss, R., Lan, X., Talbot, R., Hamburg, S.P., 2015. Toward a functional definition of methane super-emitters: application to natural gas production sites. Environ. Sci. Technol. 49, 8167–8174.

Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J.D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M.P., Varon, D.J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R.A., Lorente, A., Hamburg, S.P., Aben, I., Jacob, D.J., 2020. Quantifying methane emissions from the largest oil-producing basin in the United States from space. Sci. Adv. 6, eaaz5120.