The geography factor: How environmental conditions shape methane monitoring from space

Satellites are transforming global methane monitoring, offering unprecedented insights and actionable data to support mitigation efforts. With a growing number of methane-sensing instruments in orbit, a diverse community—including NGOs, governments, and other sectors—are increasingly eager to integrate satellite data into their work. This report serves as a resource for new users, helping them effectively utilise satellite data by identifying regions where environmental conditions may affect data coverage.

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About

This report is intended to help governments, civil society groups, and industry improve their understanding of spaceborne methane observations —a vital step in combating climate change.

A growing number of methane sensors are orbiting the earth, providing unprecedented insight on global emissions. These sensors range from those that measure methane at kilometer-level resolutions to those that monitor emissions at the facility level. Their data is enabling a wide range of applications, from effectively monitoring country-level emissions, to enabling rapid responses to super-emitter events.

However, local environmental conditions might affect the availability of satellite data in some locations and/or times of the year. New satellite users should be aware of these effects and take them into account when considering how to utilize satellite data in their mitigation efforts.

In this report, we explore how environmental conditions — such as cloud cover and terrain roughness — can impact the availability of satellite data in different regions around the world over the course of the year.

By providing these insights, we aim to help new users understand how environmental factors might affect data coverage, highlighting factors they should consider when choosing the most appropriate observation strategy for their needs.

Specifically, we map the regions where methane monitoring by satellite might be challenging due to five factors: cloudiness, terrain roughness (i.e. mountainous regions), surface brightness, windiness, and the availability of sunlight. We focus on locations with oil, gas, and coal extraction sites to explore how environmental factors might influence methane monitoring at these specific points of interest.

Environmental drivers and their impact on satellite methane observations

Methane observations from space are transforming emissions mitigation efforts. An expanding array of satellite sensors now provides data tailored to a wide range of user needs. For instance, flux mappers measure methane over large areas, aiding in the improvement of methane inventories, while point-source imagers deliver high-resolution facility-level data, supporting rapid mitigation actions. Alongside the growing number of sensors, significant efforts have been made to enhance data accessibility. These efforts are proving successful, with an increasing number of potential users—including governments, NGOs, and journalists—exploring ways to integrate satellite methane data into their work. However, to use this data effectively, new users must first navigate the challenge of understanding each data product's characteristics and determining its suitability for their specific tasks.

Integrating spaceborne methane observations into emission mitigation efforts is a crucial task. To reduce methane emissions, 159 countries have signed the Global Methane Pledge, a voluntary commitment to reduce global methane emissions by at least 30% by 2030 compared to 2020 levels. Spaceborne methane instruments are critical for achieving this global target, as they provide new understanding of global methane emissions, bring transparency and accountability to the process and, often, provide the opportunity for rapid repair of large unintentional methane emissions. However, despite their great value and unique vantage point, satellite efficacy will be limited in certain regions by environmental factors like cloud cover, low light conditions during winter, and terrain properties.

This report maps the regional variations of environmental conditions that can make satellites less effective for monitoring methane emissions. It highlights that, for example, many regions in the tropics are affected by persistent cloud cover, while regions in high latitudes receive low levels of light for several months, hindering methane observations from some sensors due to insufficient signal levels. The combined effect of these environmental factors is that in certain regions, some satellites will either be unable to observe methane emissions or will have much reduced efficacy, compared to regions with more favourable conditions, featured in many proof-of-concept studies. This reduced efficacy, might make specific products unfit for specific uses.

The report also estimates that 30% of upstream coal and oil and gas infrastructure lies in regions that might be challenging to observe with spaceborne instruments due to cloud cover, low light conditions, dark surfaces and mountainous terrain.

"Satellites are revolutionising the way we monitor methane from space. With more open satellite data available, there is an ever-growing interest from users to understand how to use these measurements effectively. This report examines how environmental conditions can impact methane detection by satellite, at times limiting data coverage in certain regions. By explaining these constraints, we aim to help users select the most effective satellite data for their use case. Expanding the community of satellite data users creates more opportunities to reduce methane emissions— an essential step toward curbing climate change."

Sarah Shannon
Satellite Data Analyst, Ember

Key takeaways

01 Environmental conditions can limit the ability of satellites to monitor emissions

Environmental conditions such as cloud cover, wind speed, surface brightness, mountainous terrain, and seasonal variations in sunlight availability can all influence satellite-based methane detection. These impacts differ based on the sensor, location, and the time of the year.

For instance, in high-latitude regions, low sun angles during winter reduce available light for satellite sensors, while dark forested or snow-covered surfaces reflect less of the infrared light satellites use to detect methane, making monitoring more difficult. High winds can disperse methane plumes, and mountainous terrain may create local shading, limiting the light needed for detection. In tropical areas, persistent cloud cover can obstruct satellite monitoring of methane.

The extent to which these effects impact satellite-based methane detection depends on the sensor and intended use of the data. For example, area flux mappers, which measure methane over larger, kilometer-scale regions, could be constrained by persistent cloud cover, potentially hindering country-level flux monitoring. In contrast, high-resolution point-source satellite sensors, designed to detect methane from individual facilities, may still identify plumes between broken clouds.

02 30% of global coal is produced in challenging-to-monitor regions

Our analysis of global coal production estimates that a third of operations are situated in regions where satellite methane detection is hindered by environmental factors. For example, Indonesia, a major coal producer, is a particularly challenging area for methane monitoring due to persistent cloud cover and rugged terrain, which may impede the use of some satellite products for areas producing 84% of the nation's coal production.

03 29% of global on-shore oil and gas is produced in challenging-to-monitor regions

Estimates indicate that about a third of global onshore oil and gas production occurs in regions with challenging observation conditions for satellites. In these areas, which include parts of the United States, and Canada, observing systems should be carefully designed to take these limitations into account and possibly rely more heavily on alternative measurements to provide a more complete picture of emissions.

1. Monitoring methane emissions

Satellites will enable effective global methane monitoring

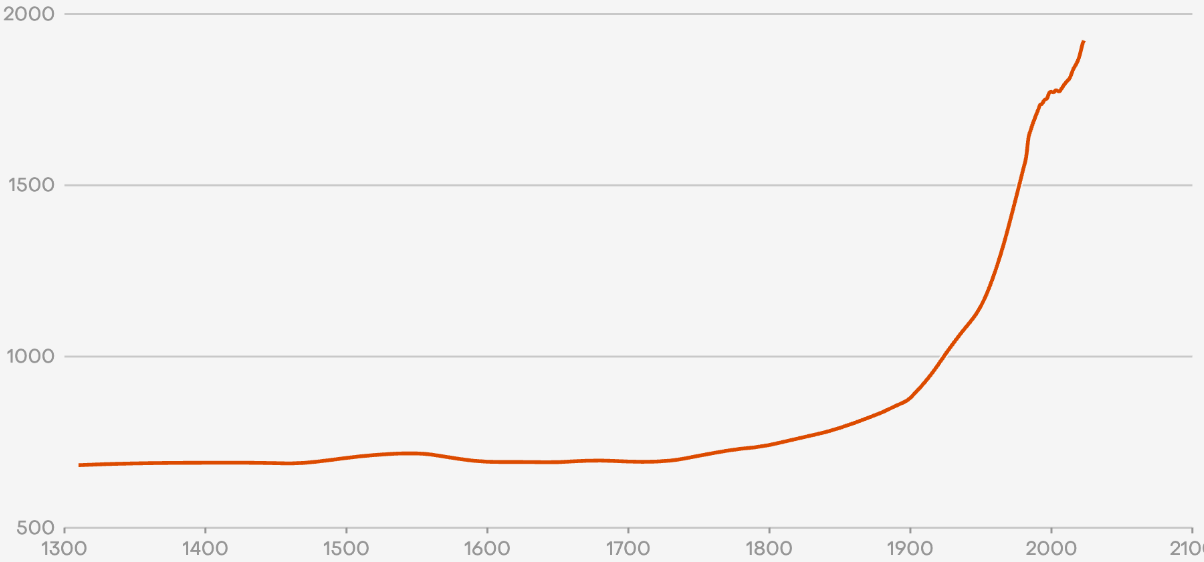
Spaceborne methane measurements are revolutionising global understanding of methane emissions and will form the backbone of an emerging global methane observing system.

Why measure methane?

Methane is a powerful greenhouse gas with a far greater global warming potential than carbon dioxide, being over 80 times more potent per tonne over 20 years and around 30 times more potent over 100 years. Methane concentrations have increased rapidly since preindustrial times and are responsible for causing half a degree (0.5°C) of present-day global warming (1.1°C). A large part of this increase is driven by emissions from a few economic sectors, namely fossil fuels (35%), waste (20%), and agriculture (40%).

Atmospheric methane concentrations have risen dramatically since the turn of the 20th century due to anthropogenic activities

Methane concentrations in parts per billion



Source: Data for 1984-2023 – NOAA GML Trends in Atmospheric CH4 , Data for 1300-1982 – Etheridge et al (1998)

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To keep the Earth's temperature below the 1.5°C aspiration of the Paris Agreement, rapid reductions in methane are urgently needed from all the above-mentioned sectors. For this reason 159 countries have signed the Global Methane Pledge, a voluntary commitment to reduce global methane emissions by at least 30% by 2030 compared to 2020 levels. Reliably monitoring methane emissions worldwide is critical to help guide mitigation efforts, establish transparency and accountability, and monitor progress towards the stated goals.

Until recently, most of our understanding of global emissions came from either scientific studies carried out in a limited geographic area or bottom-up inventories, i.e. accounting of methane emitting activities and generic emission factors. While immensely useful, these cannot account for the variability of methane emissions and the diversity of methane-emitting infrastructures in different parts of the world, limiting mitigation efforts.

The role of satellites in a global observing system

An increasing number of methane-sensing instruments are orbiting the earth, bringing a broader, more global view of methane emissions and providing the fine spatial and temporal coverage missing from our understanding. For example, observations from TROPOMI, a methane-sensing instrument onboard EU's Sentinel-5P satellite, have allowed detailed studies of regional emissions around the world, from continent to city scale. Point source imagers, including GHGSat, EMIT, Sentinel-2, PRISMA, EnMAP, and Gaofen 5 have changed our understanding of methane emissions, showing the prevalence of large emissions from "abnormal" operation conditions in oil and gas operations and the persistence of such emissions from other sectors, including coal and waste. These instruments are increasingly spotting sites with persistent large emissions that can be cost-effective targets for mitigation. Impressively, such observations have even been used to drive rapid-mitigation of substantial previously-undetected but easy-to-fix emissions from the oil and gas industry.

By combining their strengths, these satellites are improving our ability to tackle methane emissions. Satellite observations of large area emission fluxes are highlighting deficiencies and knowledge gaps in existing emission inventories and are guiding efforts to improve our understanding of specific high-emission areas. By comparing regional emissions, these observations are also helping measure the impact of different fossil fuel production practices and regulations on methane emissions and can underpin regulation development and trade agreements. Satellite observations at facility scale can help spot large emission events and drive quick mitigation. They can also attribute emissions to different operators and thus highlight how different operating practices can affect emissions. If enough observations are available, such facility-level observations can be used to check the validity of reported facility emissions, increasing transparency and helping enforce compliance to regulations.

Designing an effective methane observation strategy
No single technology can capture all methane emissions effectively. The choice of technology depends on the specific context. Often, a multi-tiered observing system—a combination of different measurement methods—is required to gain a comprehensive understanding of emissions and to drive effective action. Satellites, with their global reach and relative cost-effectiveness, are well suited to serve as the backbone of this type of observing system.

Here are a few aspects that should be considered when designing such a system.

Purpose of methane monitoring: No observing system can capture all aspects of methane emissions, so designers should aim to collect data fit for their intended application. If the goal is to provide independent, top-down observations to validate and refine reported emissions, frequent satellite coverage over large regions is needed. For detecting large abnormal emissions from a few sites to support methane accounting, facility-scale satellite monitoring may be sufficient. However, if the aim is to support emission mitigation, satellite observations must be complemented by local monitoring tools capable of pinpointing the exact source of emissions within a facility.

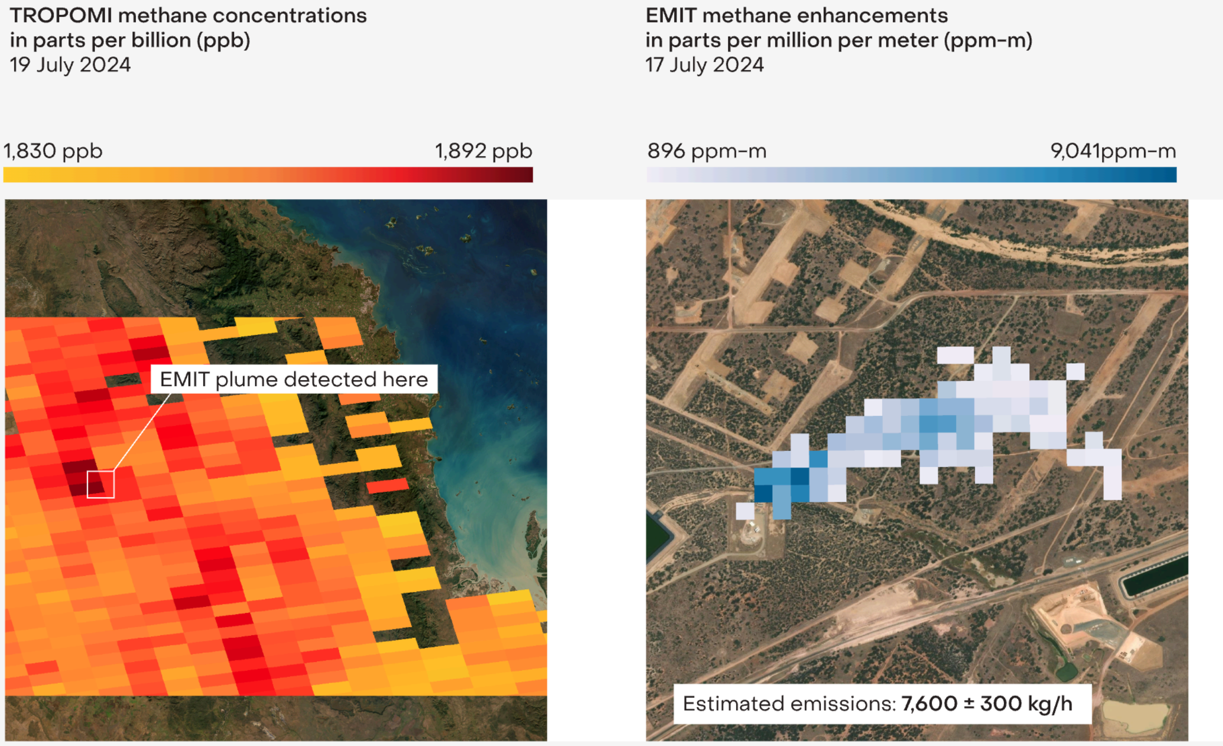
Methane source characteristics: An observing system needs to be adapted to the sources it aims to monitor. For example, if emissions are expected to be intermittent, the system should foresee regular observations to capture rare events. On the contrary, if relatively constant emissions are expected, less frequent observations might be enough.

Environmental conditions: As this report demonstrates, environmental factors, including cloud cover and strong winds, affect the efficacy of methane detection by satellite. The extent of these impacts varies by location and time of the year. All measurement techniques will be affected (in different ways) by environmental conditions, so the observing system should be adapted to such local constraints.

Availability and cost of measurement techniques: Every observing system should be optimised to give the maximum possible benefit given the constraint of the available resources. The availability and cost of various observation technologies varies greatly between regions; moreover, the financial resources and capacity of stakeholders will vary greatly around the world. The design of each observing system should take this into account.

Different satellite sensors can be used in combination to pin-point and quantify emissions

Methane observations from TROPOMI and EMIT instruments, over a coal mining region of New South Wales, Australia



Source: TROPOMI data is from the Sentinel-5p, EMIT methane concentrations and point source emission estimate is from Carbon Mapper

Environmental constraints on satellite methane monitoring

This report aims to show that, despite the huge value they offer, satellites will be less effective in monitoring methane in some locations, as environmental conditions will not allow them to reach every part of the world with the consistency and frequency needed to fully inform global mitigation efforts. For example:

- persistent cloud cover will reduce satellite data coverage in tropical regions;
- during winter months, with the sun remaining low above the horizon, high latitudes will remain relatively dimly lit, depriving sensors of the light needed to effectively observe methane, increasing their already large detection threshold;
- high winds and dark surfaces, like forests, can make even large emission events hard to observe;
- rough terrain in mountain regions will make the interpretation of some satellite measurements harder or impossible, creating a year-round obstacle for reliable methane observations in these areas.

Of course, the diversity of space-borne instruments means that these factors will affect their capabilities differently, and, to some degree, an observing system combining several spaceborne sensors will increase the observability of methane emissions in many parts of the world. Still, the combined environmental challenges may result in areas with reduced data coverage in certain regions.

In this report we map the regional effects of the various environmental parameters that impact methane sensing from space. To do that, we examine the combined effect of five parameters: cloud cover, sun elevation, ground reflectivity, uneven terrain, and wind speed. This report shows where one or more of these parameters should be expected to hinder some satellite observations during significant portions of the year. In many cases, these locations can be observed, but data in those locations will be less available - it will only be available from a subset of methane-observing satellites, and/or only available on an infrequent basis. By mapping these effects, we aim to help governments, academia, and other stakeholders build realistic expectations of satellite data availability in their region and ultimately plan for integrated methane observing systems.

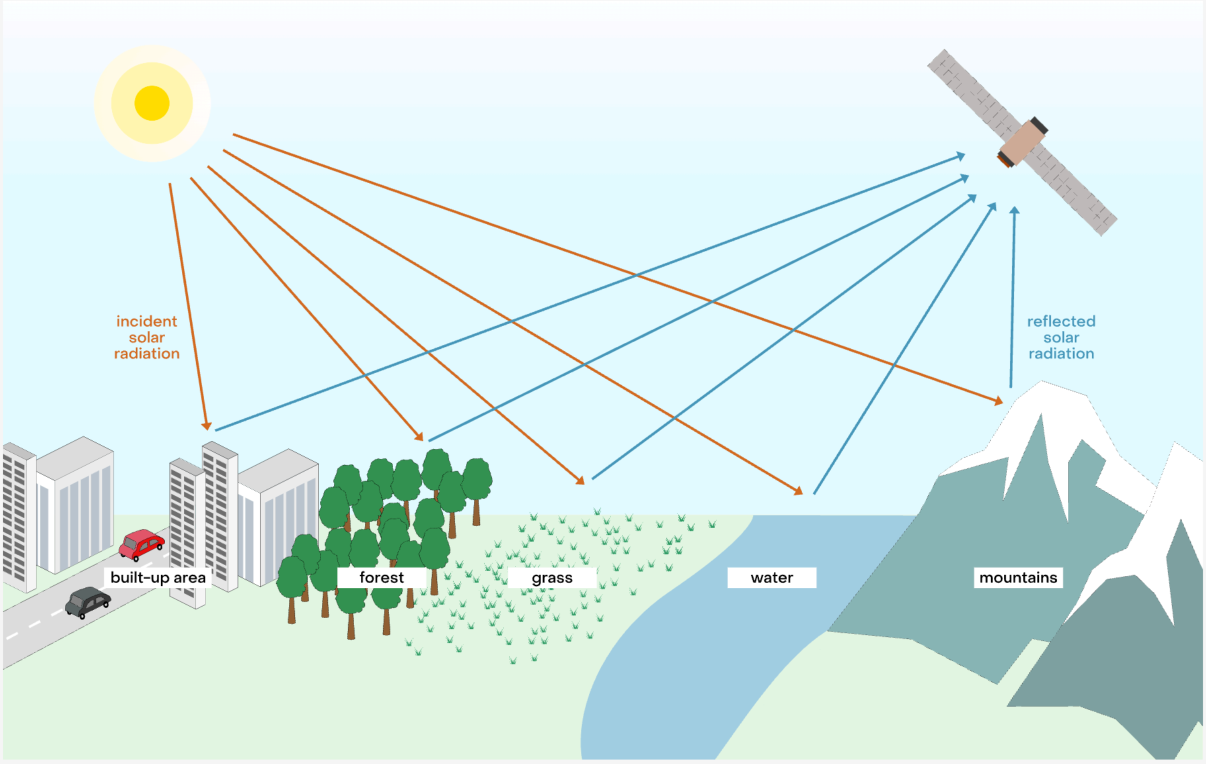
2. Challenging environmental conditions

Environmental conditions can interfere with satellite methane measurements

Local environmental factors, from cloud-cover to rough terrain, can limit satellites' ability to detect methane, underscoring the need for alternative measurements in certain areas.

While methane is invisible to the human eye, it absorbs infrared radiation and can be observed with specialised cameras. Such instruments are now mounted on satellites where they observe the sunlight that passes through the atmosphere, reflects off the earth's surface, and travels again towards space, as illustrated in the following figure. They are tuned to search this light for specific absorption patterns that serve as a fingerprint of methane in the atmosphere. Specialised algorithms are then used to consider many other factors that could influence the amount of radiation that reaches the satellite and infer the amount of methane that was present in the light's path.

Satellite instruments observe the sunlight reflected from the surface of the earth and search for the fingerprint of methane absorption



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Several environmental factors can stop sunlight from reaching the satellite sensor and these may make methane detection more challenging or impossible at times; other factors, like strong winds, can disperse and dilute methane in the atmosphere, hindering methane detection - for example, leading to higher detection limits.

The impacts of environmental conditions are satellite-specific

Satellites are not all equally affected by diverse environmental conditions. The exact way that these conditions will affect satellites' ability to measure and quantify methane emissions will vary depending on each instrument's specific characteristics. For example, instruments built to detect changes in methane concentrations over large areas will be greatly affected even by a few clouds in the area they are studying; at the same time, a high-resolution satellite, trying to detect emissions from a facility in the same area, might be able to see between broken clouds and observe the facility.

Researchers have been long studying the ways that observation conditions will affect different methane-sensing satellite instruments. For example, recent research has highlighted the dramatic impact that a sensor's pixel size will have on its ability to observe methane in the tropics. Other researchers have studied in detail the factors that limit the ability of a specific instrument (TROPOMI) to observe methane around the world.

This report summarises such studies and highlights the broader patterns that affect methane satellite observations in one way or the other by mapping the regions where satellites are most and least affected by these environmental issues, without focusing on the characteristics of specific instruments.

Consequently, we label observation conditions using the generic categories of "favourable", "moderate" and "difficult.". In "favourable" conditions — cloud-free skies and relatively flat bright surfaces — satellites are expected to perform their best. When areas are marked as having "moderate" conditions, methane sources might be frequently covered by clouds and the complex terrain might stop satellites detecting some plumes they would otherwise easily spot. In "difficult" conditions, detecting methane might be impossible for some sensors or happen less frequently and/or for very large plumes.

The exact impact of these environmental conditions on specific satellites should be studied separately for each use case and location.

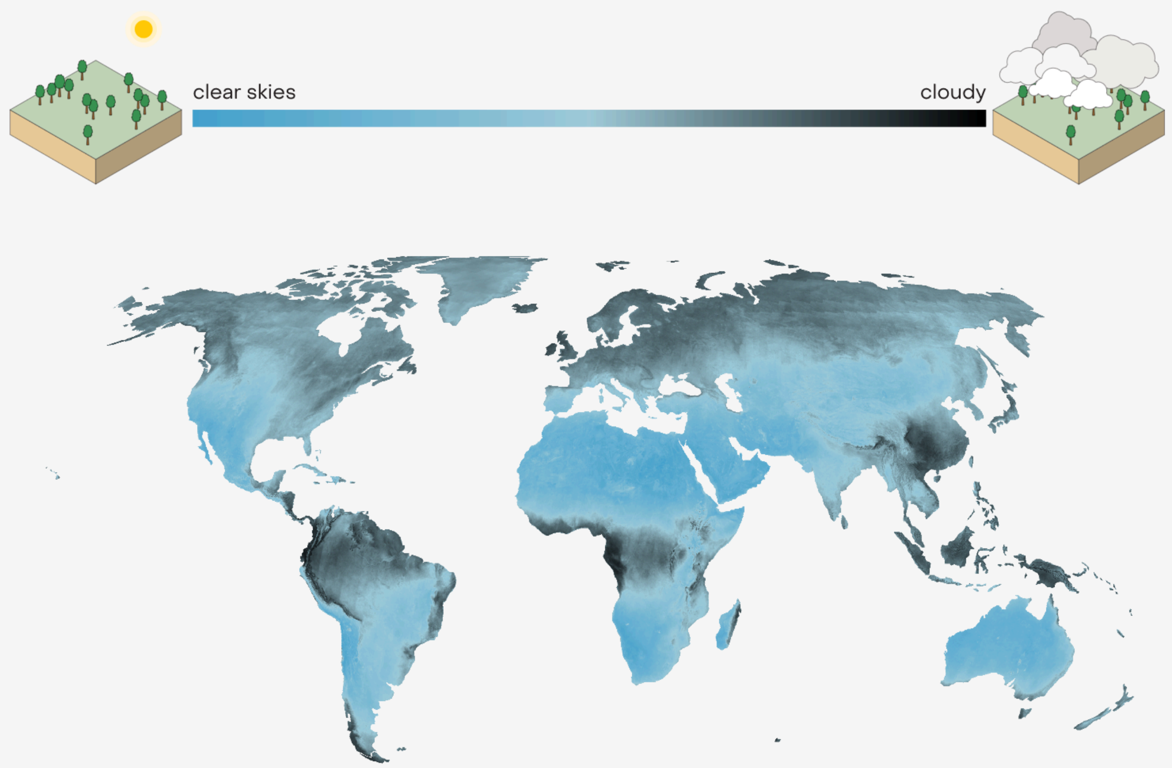
Environmental conditions and their impact

This report considers the following environmental factors and their impact on the ability of satellites to effectively detect methane.

Cloud cover

Clouds hide methane from satellite's view

Methane-sensing satellites cannot see through clouds. In tropical regions, which have persistent cloud cover, this makes methane retrievals difficult all year round



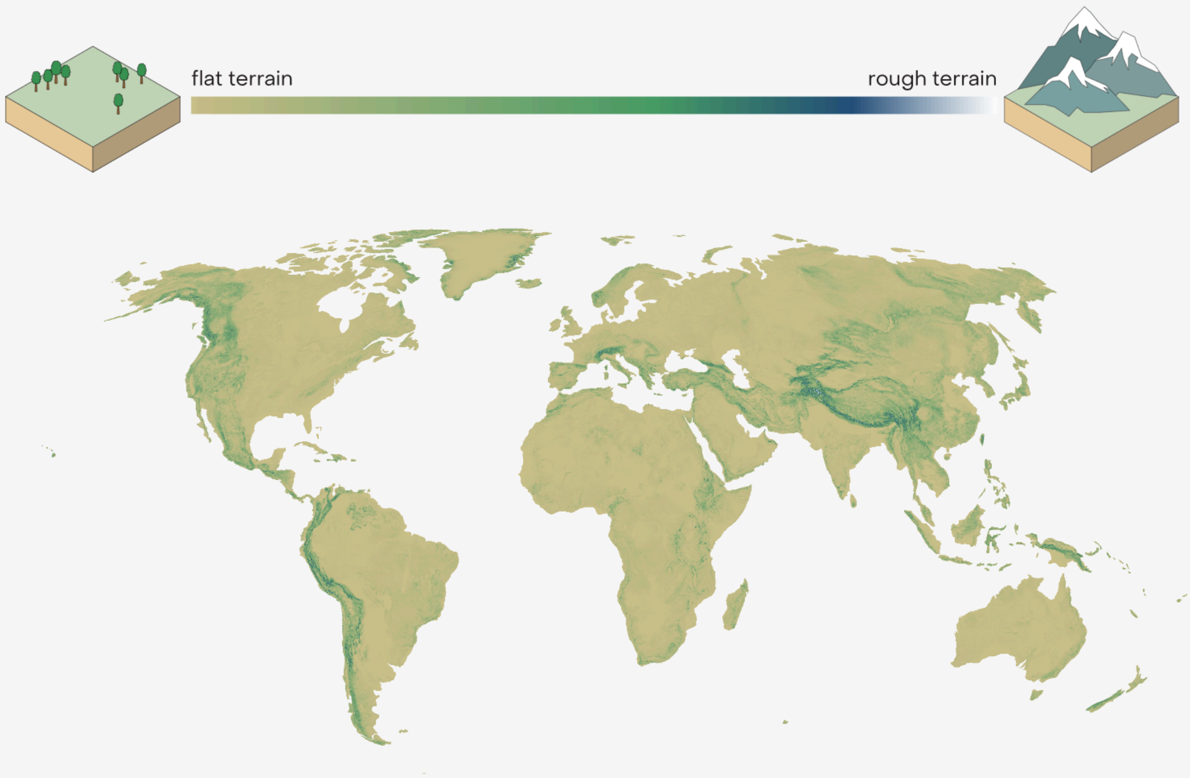
Methane satellites cannot see through clouds and this makes cloud cover the most important obstacle for detecting methane from space. Since they are much brighter than the earth's surface, even a small cloud partly covering the satellite pixel will interfere with the measurements and stop the satellite from detecting methane. In some regions with persistent cloud cover, like the tropics, this can hinder satellite methane observations year round.

Satellite characteristics, like their spatial resolution, will greatly influence how clouds impact their ability to monitor methane. For example, a high-resolution satellite, built to monitor methane from individual facilities, might be able to detect methane between broken clouds, although challenges remain with these observations. In contrast, a satellite built to quantify methane in wider regions, if faced with the same cloud cover, might never find a completely cloud-free view that is needed for its measurements.

Terrain roughness

Mountains make the interpretation of satellite observations harder

Rugged terrain makes the interpretation of the signal received by satellites more complicated.



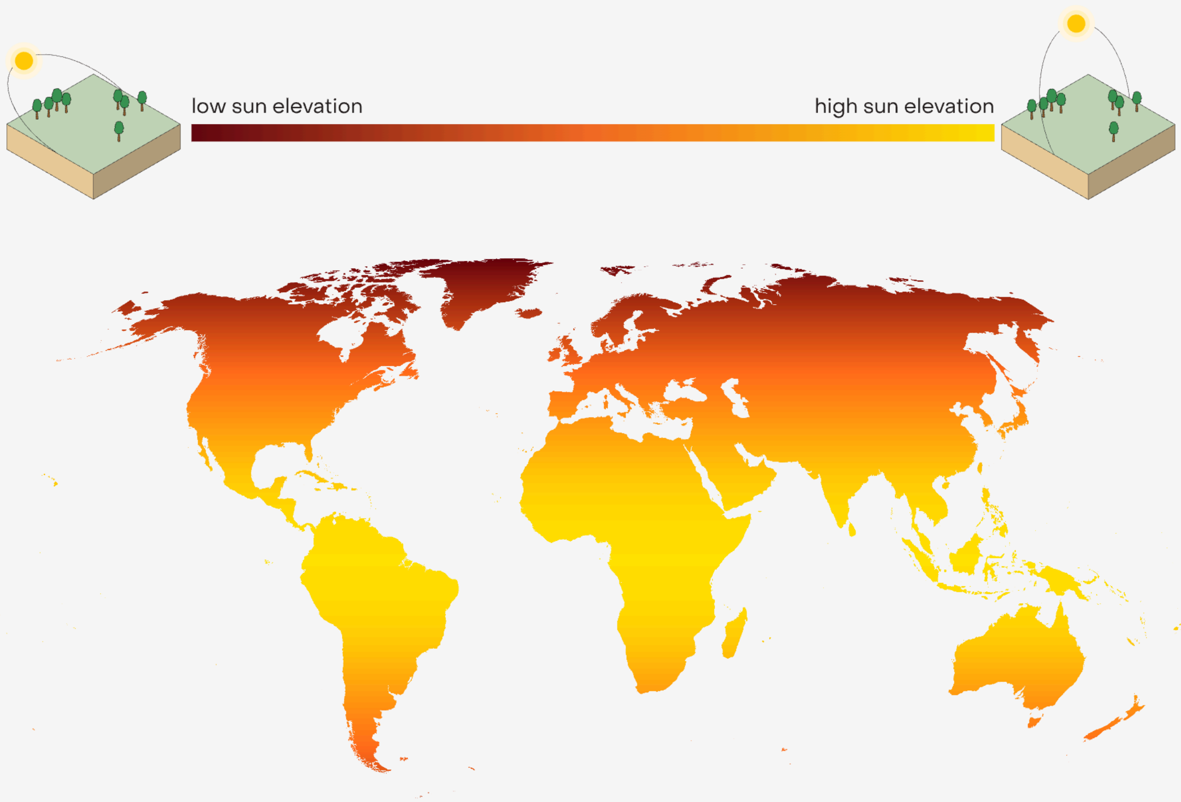
Some satellites find it challenging to estimate methane in regions with mountainous terrain. The uneven ground in such regions will create shadows in part of the observed scene, making it hard to interpret the amount of light that reaches the satellite. As light reflects off different parts of the uneven terrain, it will reach the satellite having passed through different parts of the atmosphere, further complicating the interpretation of satellite signals. In combination, these factors make rough terrain a year-round obstacle for methane sensing. As the map shows, this can affect large parts of the world, including central Asia, western South America, mid-Western North America and the western Balkans.

As with clouds, the way this parameter affects different satellite sensors will greatly depend on its sensor characteristics. A high-resolution sensor might be able to quantify methane over a small flat area around a facility of interest while, in contrast, an area-monitoring satellite might find it impossible to estimate methane emissions over the wider mountainous region.

Sun elevation

Low sun elevation hinders methane retrieval at high latitudes

In northern latitude, the sun will not rise high above the horizon for several months. During these months the ground surface will be dimly lit, compared with the summer months when the sun is higher in the sky. When less light hits the surface, less light is reflected back to the sensor.



Source: Annual average sun elevation.

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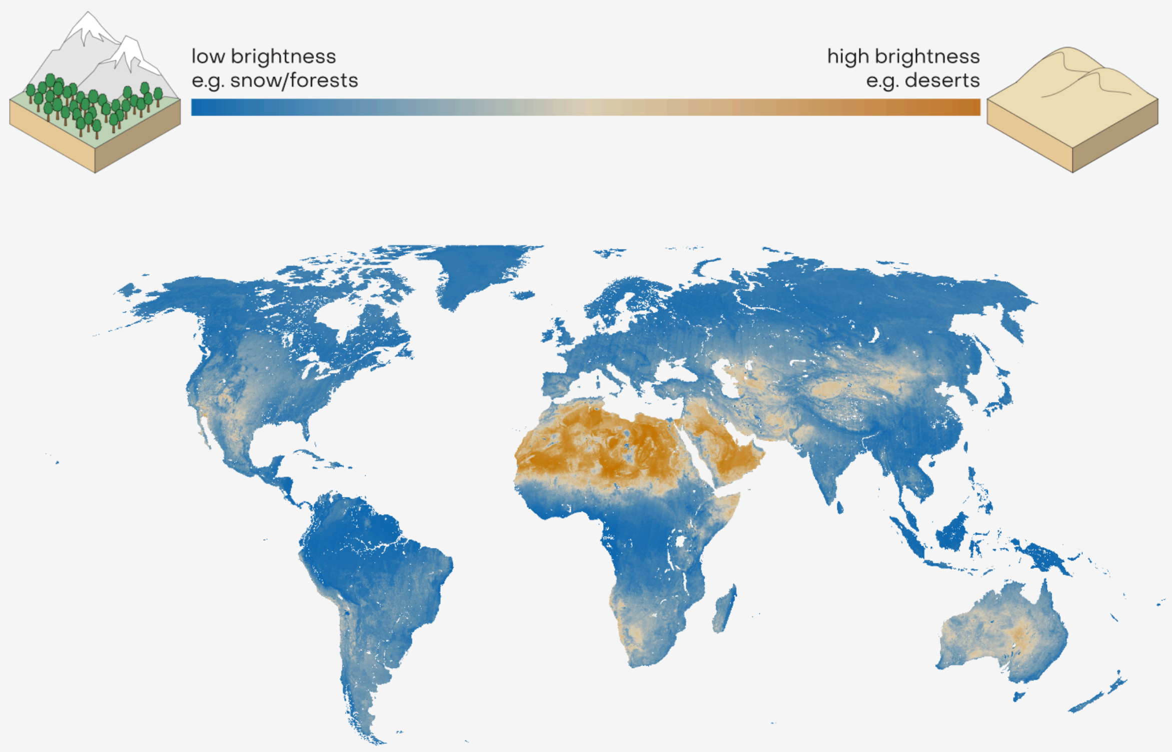
Most methane-detecting satellites that are used to study near-surface methane concentrations require bright sunlight to operate effectively, however, sufficient light is not always available. During winter at high latitude, for example, the sun does not rise high above the horizon, leaving large parts of the earth poorly lit for several months at that time. As a result, data coverage can be significantly reduced during winter for some sensors. Parts of Russia, Canada, and Argentina are strongly affected by this parameter.

The exact impact of low light conditions on each methane-sensing instrument will depend on its design. Instruments that are optimised to operate in low-light conditions might be less affected, but will be negatively impacted in any case. The satellite orbit, which defines the local time that the satellite will orbit over a location, will also affect the impact of this parameter on the specific instrument.

Surface brightness

Dark surfaces make methane harder to spot

Detecting methane is challenging over dark surfaces like forests, bare wet soil, and water, as they don't reflect enough sunlight back to the satellite. Snow also appears dark in the shortwave infrared wavelengths typically used to detect methane.



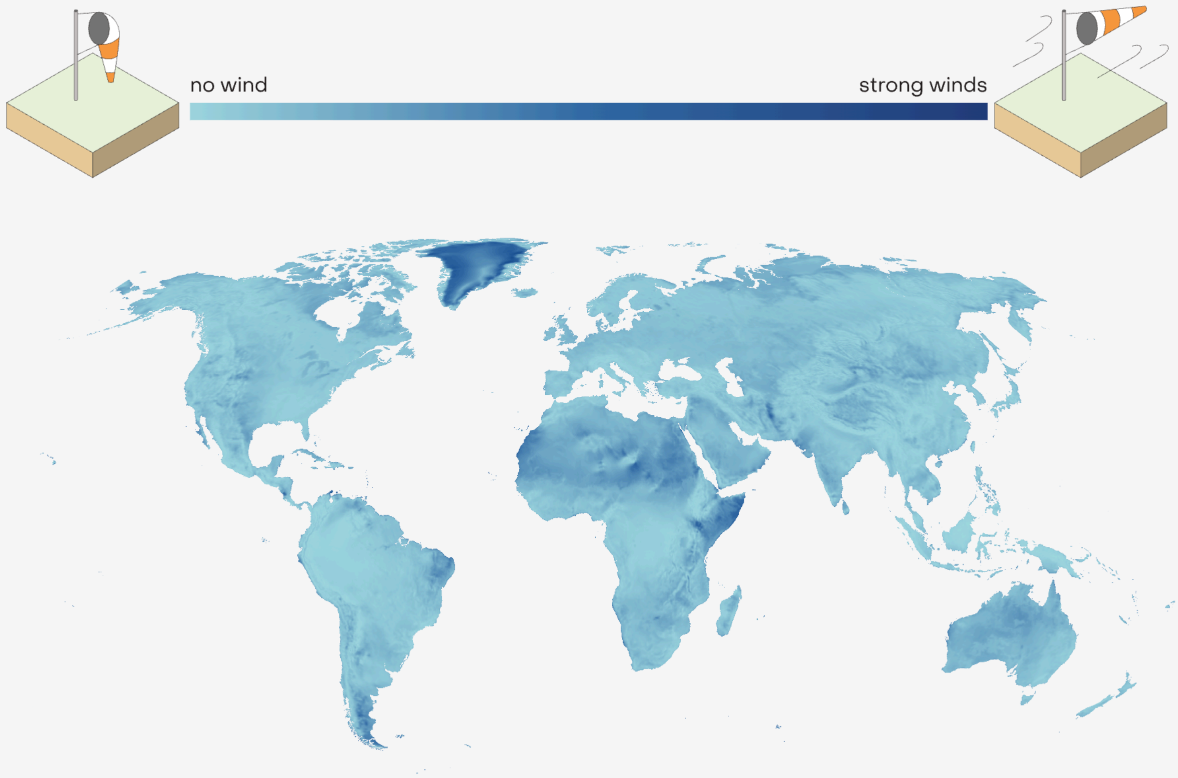
Dark ground surfaces, like forests, will not reflect enough light back towards the satellite sensor, possibly leading to higher uncertainty. As with low sun elevation, this might make it difficult to detect methane absorption. Snow-covered areas also appear mostly dark in the shortwave infrared wavelengths used to detect methane. This effect can be easily seen over tropical forests and snow-covered regions at high-latitudes. In contrast, arid regions will reflect abundant light and be favourable for methane sensing.

Inland and ocean water surfaces are excluded in our study, because, in most cases, they are too dark to be used for methane retrievals. Note that new techniques are being developed to adjust the viewing angle of the sensor to enhance reflected sunlight off the water (sun glint). This technique can offer significant insight e.g. for offshore oil and gas production, but is not part of this report. For some instruments, a surface that is too bright also poses a challenge, as the large amount of light could blind the sensor; since this is uncommon, the effect will not be accounted for in our study.

Wind speed

Wind disperses methane plumes, making them harder to detect

After methane is emitted in the atmosphere, winds will carry it away from the source, forming a methane plume. High wind speeds can cause a plume to be diluted faster over a wider area, reducing methane concentration at each location, making it harder to be detected.



Source: Based on ERA5-Land data.

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Strong winds can quickly disperse methane far from its source, reducing local concentrations and thus making it harder for a satellite to distinguish the plume from background methane concentration. While a certain amount of wind is needed for plume formation and thus plume quantification, in general, higher wind speeds are associated with [higher detection thresholds](#).

In regions with persistent strong winds, like in southern Argentina, satellites will only be able to detect larger plumes compared with regions with milder wind conditions.

Wind conditions will have a greater impact on high-resolution plume-imaging satellites, as methane plumes will be quickly dispersed by strong winds. Coarse resolution satellites, aiming to map methane over wider regions, will be less affected by wind conditions.

Our methodology

These five environmental factors, and their change over the course of a year, have been studied to explore the favourability of locations for methane observations. First, the effect of each environmental factor for each month is studied individually. Specifically, we apply thresholds to each of the five factors to define if the conditions at that particular time and location are 'favourable', 'moderate', or 'difficult' for observations (see the supporting material for a detailed description of the thresholds and input datasets used). Secondly, we calculate the combined impact of all parameters for each month. If any input falls into the 'difficult' category, the month will be classified as difficult. Similarly, if any input is categorised as 'moderate' but none as 'difficult', the final score will be 'moderate'. To achieve a 'favourable' score, all inputs must be in the 'favourable' category. The result is a monthly classification for each location worldwide.

As noted before, the assigned categories should be used only as rough indicators of areas where satellite observations of methane may be less available . Our analysis is conservative in the sense that we are identifying areas and times of the year where at least some satellite sensors are expected to be less able, or unable, to monitor methane. These categories do not, for example, capture how environmental conditions differently impact instruments designed for monitoring facility-scale emissions versus those intended to measure emissions over larger areas. In areas labelled as “moderate” or “difficult” to monitor, users need to be attentive, as some satellites that otherwise may be very useful for their use case may not perform as expected.

Next, we investigate the impact of these environmental factors on coal, oil, and gas extraction infrastructure, responsible for a substantial portion of anthropogenic methane emissions.

3. Challenging to monitor regions

Most regions can be well monitored by satellites, but some challenging regions remain

Seventy percent of fossil fuel extraction sites are in regions favourable for satellite observations during most months of the year, while 30% are in areas classified as 'moderate' or 'difficult' for observation. The number of such facilities varies significantly between countries.

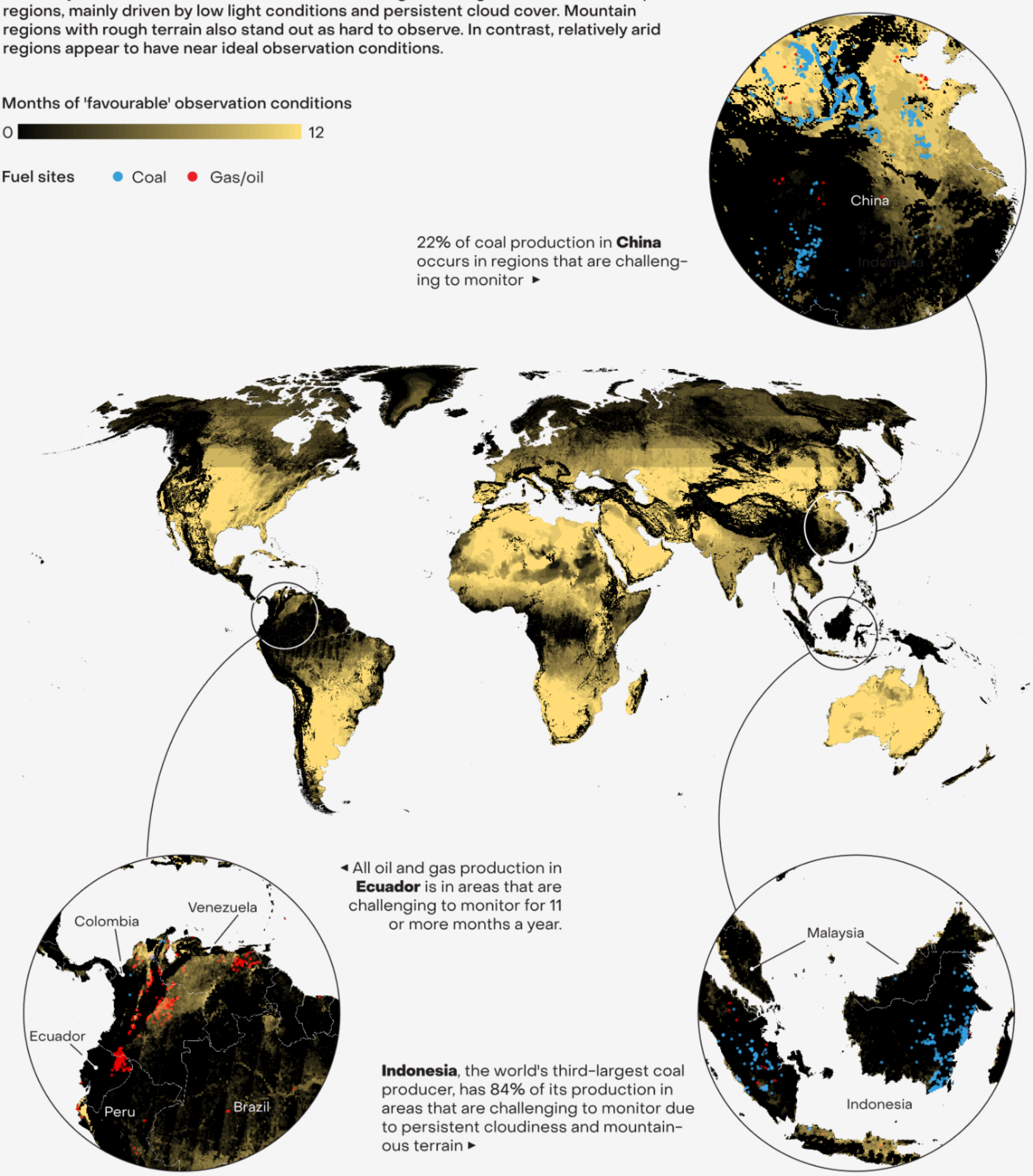
The environmental conditions affecting satellite monitoring around the world are far from homogeneous. Areas we classify as challenging - where conditions are ‘moderate’ or ‘difficult’ for at least 6 months per year - are located primarily in tropical regions, mainly driven by persistent cloud cover, and high latitudes, that face the added challenge of low light conditions during winter. Mountainous regions with rough terrain in east Asia, western America, and Europe are also hard to observe, mainly for area-mapping satellites.

In contrast, relatively arid regions in north Africa, central Asia, Australia, and the southern US appear to have near ideal observation conditions throughout the year. Not surprisingly, many of the initial satellite studies that inform our understanding of methane emissions are focused on these relatively arid regions.

Based on production data from the GEM's Global Coal Mine Tracker (GCMT), our analysis shows that 30% of coal production occurs in regions that are challenging to observe. For onshore oil and gas, data from the GEM's Global Oil and Gas Extraction Tracker suggests that 29% of global production is situated in challenging-to-monitor regions.

Combined effect of environmental factors prevent satellites from effectively monitoring methane emissions in some parts of the world

Our analysis reveals a number of hard to observe regions at high latitudes and in tropical regions, mainly driven by low light conditions and persistent cloud cover. Mountain regions with rough terrain also stand out as hard to observe. In contrast, relatively arid regions appear to have near ideal observation conditions.



An interactive map showing the methane detection category of each fossil fuel asset, as it varies every month, can be explored online.

Detection difficulty score for methane retrieval by satellite

Methane detection categories

Difficult Moderate Favourable

Source: The geography factor: How environmental conditions shape methane monitoring from space, Ember & Clear Air Task Force, Basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community · Location Data: Coal mine, oil, and gas site locations sourced from the Global Coal Mine Tracker (Global Energy Monitor, April 2024 Release) and the Global Oil and Gas Extraction Tracker (Global Energy Monitor, March 2024 Release)

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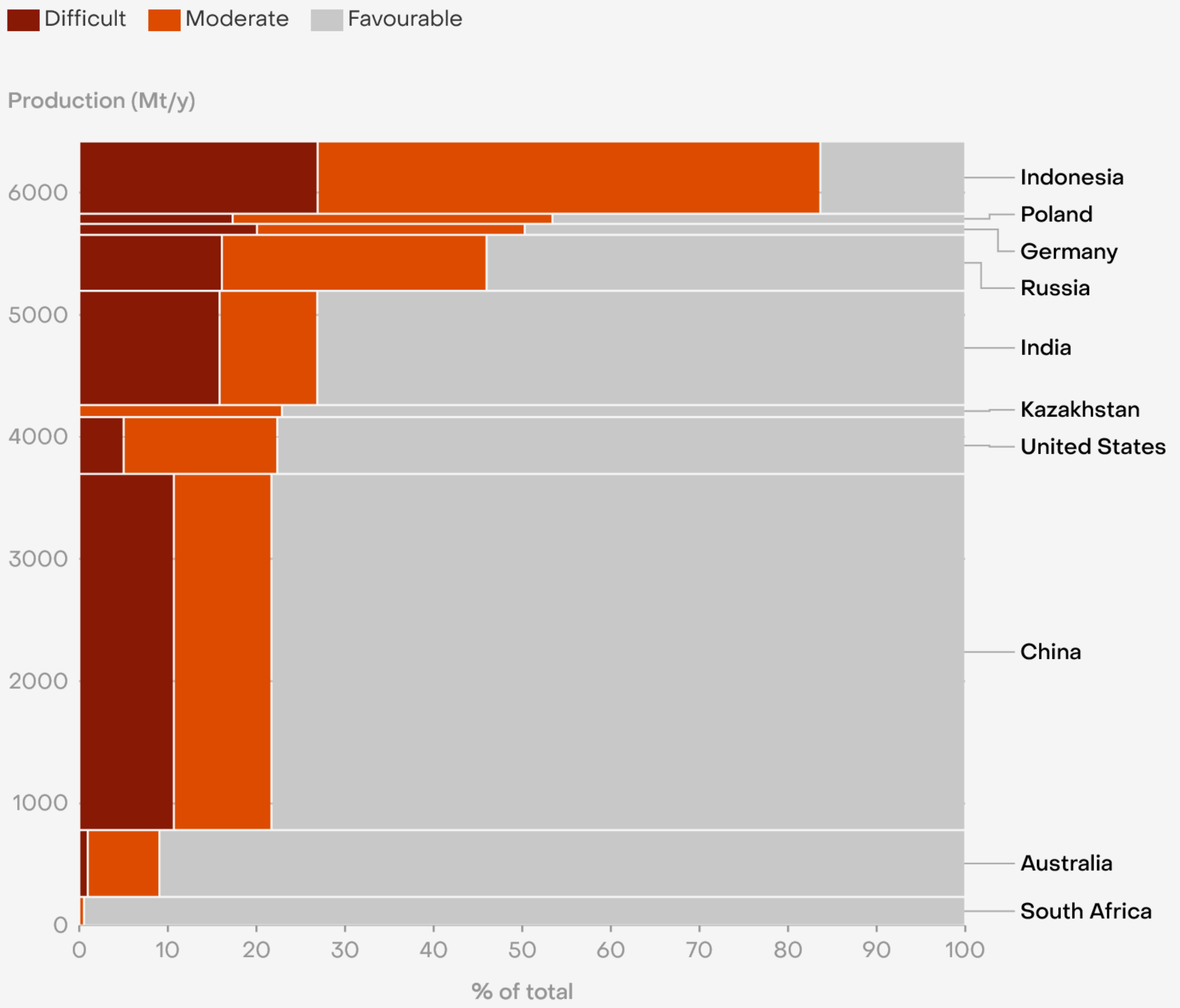
Country-level differences in the ease of satellite monitoring of coal production

An analysis of the top 10 coal producing countries reveals that conditions for satellite-based methane monitoring are nearly ideal in South Africa, where 99% of production occurs under favourable conditions, and in Australia, where 91% of

coal production takes place in favourable regions. In contrast, the majority of coal production in regions with challenging-to-monitor conditions are concentrated in parts of China, Indonesia, India, Russia, and the United States.
Challenging-to-monitor is defined as having 6 months or more with either a 'difficult' or a 'moderate' category.

All the top ten coal producers have some coal mines in locations that are challenging for methane monitoring by satellite

Top ten coal producers ranked by the percentage of their production located in regions where satellites find methane detection hard.



China

22% of China's coal production, amounting to 633 million tonnes annually, is found in challenging-to-monitor regions. Many of the mines are located in southwestern China, where cloud cover and rugged terrain create challenging conditions for methane monitoring, especially for area-monitoring satellites.

Indonesia

Remarkably, Indonesia, the world's third-largest coal producer, has 84% of coal production located in challenging-to-monitor regions. This amounts to 496 million tonnes of coal production per year that may go unmonitored. Most coal mines are clustered on the islands of Sumatra and Kalimantan where challenging conditions are caused by persistent cloudiness and mountainous terrain.

India

27% of the coal production in India, which is 251 million tonnes annually, is located in regions that are challenging to monitor for a few months of the year. This is caused by cloudiness during the monsoon season between the months of July-August which might impact satellite monitoring.

Russia

In Russia 46% of coal production, amounting to 211 million tonnes annually, is in challenge to monitor regions. Methane monitoring by satellite may be challenging due to seasonal low sun elevation and cloudiness.

United States

In the United States 22% of the country's coal production is in challenging-to-monitor regions, which amounts to 104 million tonnes per year. In the Western Interior Basin coal mining region, challenging conditions are caused by the rugged terrain of the Rocky Mountain ranges. In the Appalachian Basin, conditions are challenging due to a mixture of mountainous terrain (Appalachian mountains), intermittent cloud cover and dark surfaces.

Other coal mining regions that are challenging-to-monitor

There are other clusters of regions with coal mines in challenging locations. One such cluster is found in the western Balkans—specifically in Bosnia and Herzegovina, Serbia, and North Macedonia. These mines are located in the Dinaric Alps, where mountainous terrain might make methane monitoring by satellite challenging for area flux mappers.

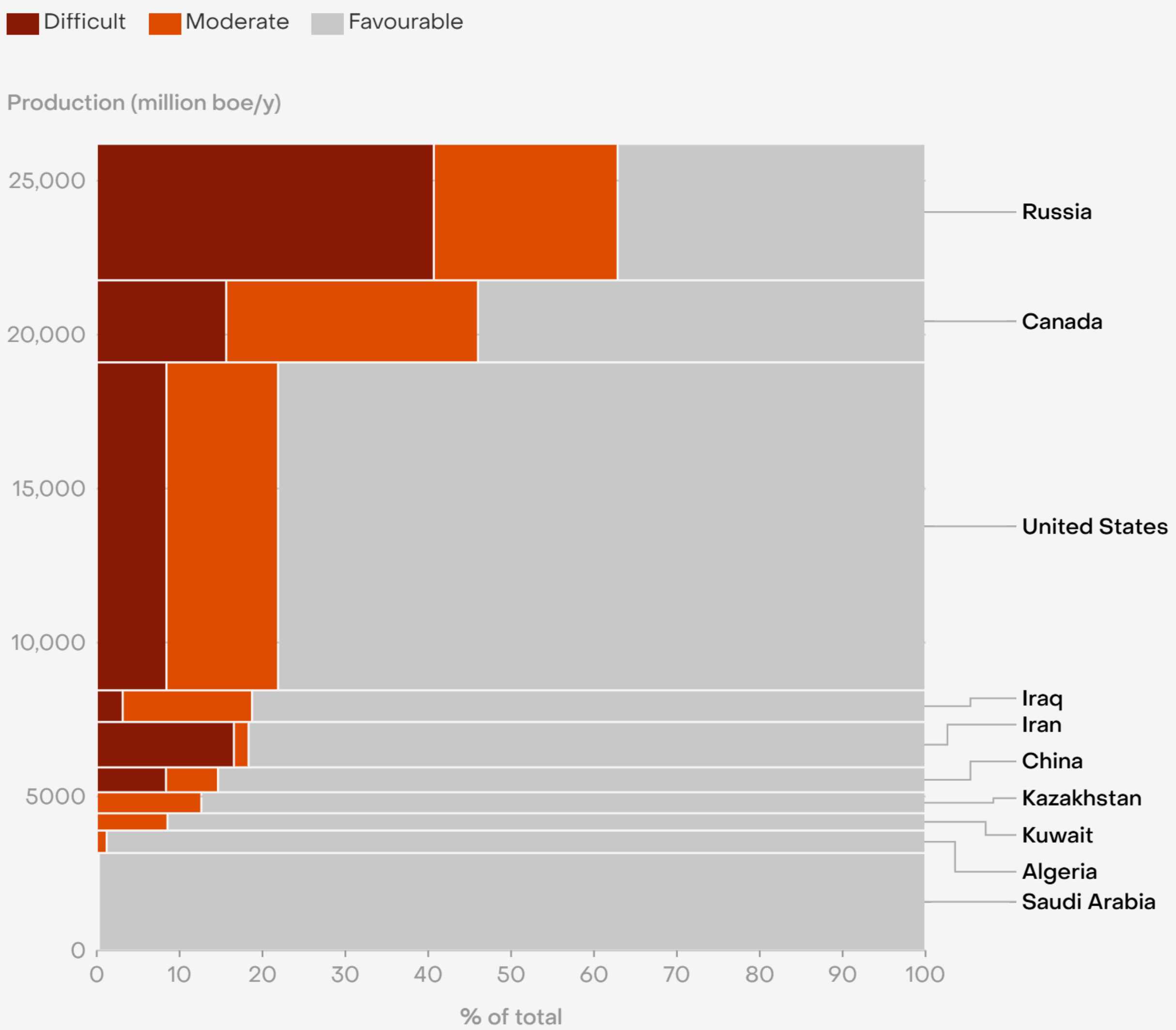
Country-level differences in the ease of satellite monitoring of oil and gas production

An analysis of the 10 top oil and gas producing countries reveals that conditions for satellite-based methane monitoring are nearly ideal in Saudi Arabia, where 100% of production occurs under favourable conditions, and in Algeria, where 99% of production takes place in favourable regions.

The majority of oil and gas production in challenging-to-monitor regions are concentrated in parts of Russia, Canada and the United States.

Many oil and gas extraction sites are in locations that are challenging for methane detection by satellite

Top ten oil and gas producers ranked by the percentage of their production located in regions where methane detection by satellites is hard



Source: Oil and gas production comes from the Global Oil and Gas Extraction Tracker, Global Energy Monitor, March 2024 Release.

Russia

In Russia, 62% of the country's oil and gas production is in challenging-to-monitor regions. The majority of hard-to-monitor oil and gas sites in Russia are clustered in the Western Siberian Basin, which is Russia's largest oil and gas-producing region, with substantial hydrocarbon reserves. Monitoring these sites is challenging for several months every year due to low sun elevation in winter, frequent cloud cover, and intermittent dark surfaces.

United States

In the United States, 22% of total production occurs in regions that are challenging to monitor. These extraction sites are distributed across several areas. The first cluster is located in Alaska, spanning the North Slope and the Gulf of Alaska. These sites are situated at latitudes above 59.7°N and monitoring conditions are greatly impacted by the lack of sunlight. The second cluster is in the Appalachian Basin, where monitoring is complicated by a combination of intermittent cloud cover and dark surfaces, which can interfere with satellite observations. Additionally, there are smaller clusters, such as in the Ventura Basin, north of Los Angeles. In this area, the rugged terrain of the Transverse Ranges may pose challenges for satellites with coarse spatial resolution.

Canada

In Canada, 46% of the oil and gas is produced in challenging-to-monitor regions. These are found along the eastern flank of the Rocky Mountains where rugged terrain makes monitoring challenging, mainly for coarse resolution satellite sensors. To the east of the Rocky mountains, in the Alberta Basin, conditions are challenging due to a mix of low sun elevation, cloud cover and sporadic periods when the surface is dark.

Iran and Iraq

Both Iran and Iraq have 19% of oil and gas production in regions that can be challenging-to-monitor. In Iran these production sites are located within the Zagros Fold Belt, a major area for oil and gas production. The rugged terrain of the Zagros Mountains poses significant challenges for satellite monitoring due to its complex topography, while other factors are favourable for methane observation. As a result, satellite sensors with high spatial resolution can effectively monitor these oil and gas sites, while those with a coarse resolution will struggle to monitor methane emissions.

In parts of Iraq, production is challenging-to-monitor in between June and August due to the Shamal winds, a strong, seasonal northwesterly wind.

Other oil and gas producing regions that are challenging-to-monitor

Several countries in Latin America have large parts of their oil and gas production located in challenging-to-monitor regions. For example, 70% of Colombia's production might be hard to monitor with satellites. This production happens in the Putumayo-Orient-Maranon Basin along the border with Ecuador, where persistent cloud cover hinders monitoring efforts, and the Upper, Middle, and Lower Magdalena Valley Basins, where monitoring is complicated by the surrounding Andes Mountains. Nearly all oil and gas production (98%) in Ecuador is in challenging-to-monitor regions. Ecuador's extraction sites are clustered in the Orient Basin, part of the Amazon region, located directly at the equator. As with Colombian sites, due to the tropical rainforest climate, satellite retrieval can be inhibited by persistent cloud cover all year around.

Case Studies

The factors that make methane retrieval challenging vary depending on the location of the facility. These case studies are selected to highlight how different combinations of environmental factors impact a satellite's ability to monitor methane emission from facilities around the world.

Tabang Project Coal Mines, Indonesia

Tabang Project Coal Mines, located in East Kalimantan, is a collection of coal mines spanning an area of 30km^2. Sub-bituminous coal is mined at the site. It is the 7th largest methane emitting coal mine in Indonesia according to the Global Energy Monitor. Methane retrieval is persistently challenging all year (11 moderate and 1 difficult month) due to multiple factors.

The site is cloudy for 9 months of the year. The mine is located in a mountainous region and this will limit observations, especially from satellites with coarse spatial resolution that are more strongly affected by terrain roughness. In the limited cases where satellites can find cloud-free conditions to observe the ground, the surface appears dark in the shortwave infrared wavelengths used by the satellite, so it is possible that only strong plumes will be detected.

Challenging observation conditions at Tabang Project Coal Mine, Indonesia

Rough terrain, dark surfaces, and persistent cloud cover in Indonesia's Tabang coal mine may make satellite methane observations challenging throughout the year

Environmental factors
Number of months when methane monitoring is difficult and moderate

Cloud cover 9/12
J F M A M J J A S O N D

Wind speed 0/12
J F M A M J J A S O N D

Terrain roughness 12/12
J F M A M J J A S O N D

Sun elevation 0/12
J F M A M J J A S O N D

Surface brightness 7/12
J F M A M J J A S O N D

Combined effect **12/12**
J F M A M J J A S O N D

Shanxi Qincheng coal mine, China

The Shanxi Qincheng underground coal mine, located in China's primary coal-producing region of Shanxi Province, extracts anthracite coal primarily for electricity generation. With a depth of 446 m, the mine is methane-intensive due to its deep structure. Methane retrieval can be challenging all year around (12 months with moderate category) mainly due to the terrain roughness of the Taihang Mountains, which may limit the usefulness of area mapping satellites. There is intermittent cloudiness and the surface is dark during August and September.

Challenging observation conditions at Shanxi Qincheng Coal Mine, China

Rough terrain, along with periods of dark surfaces and cloud cover, might make satellite methane observations challenging year-round at China's Shanxi Qincheng coal mine

Environmental factors

Number of months when methane monitoring is difficult and moderate

Cloud cover 3/12
J F M A M J J A S O N D

Wind speed 0/12
J F M A M J J A S O N D

Terrain roughness 12/12
J F M A M J J A S O N D

Sun elevation 0/12
J F M A M J J A S O N D

Surface brightness 2/12
J F M A M J J A S O N D

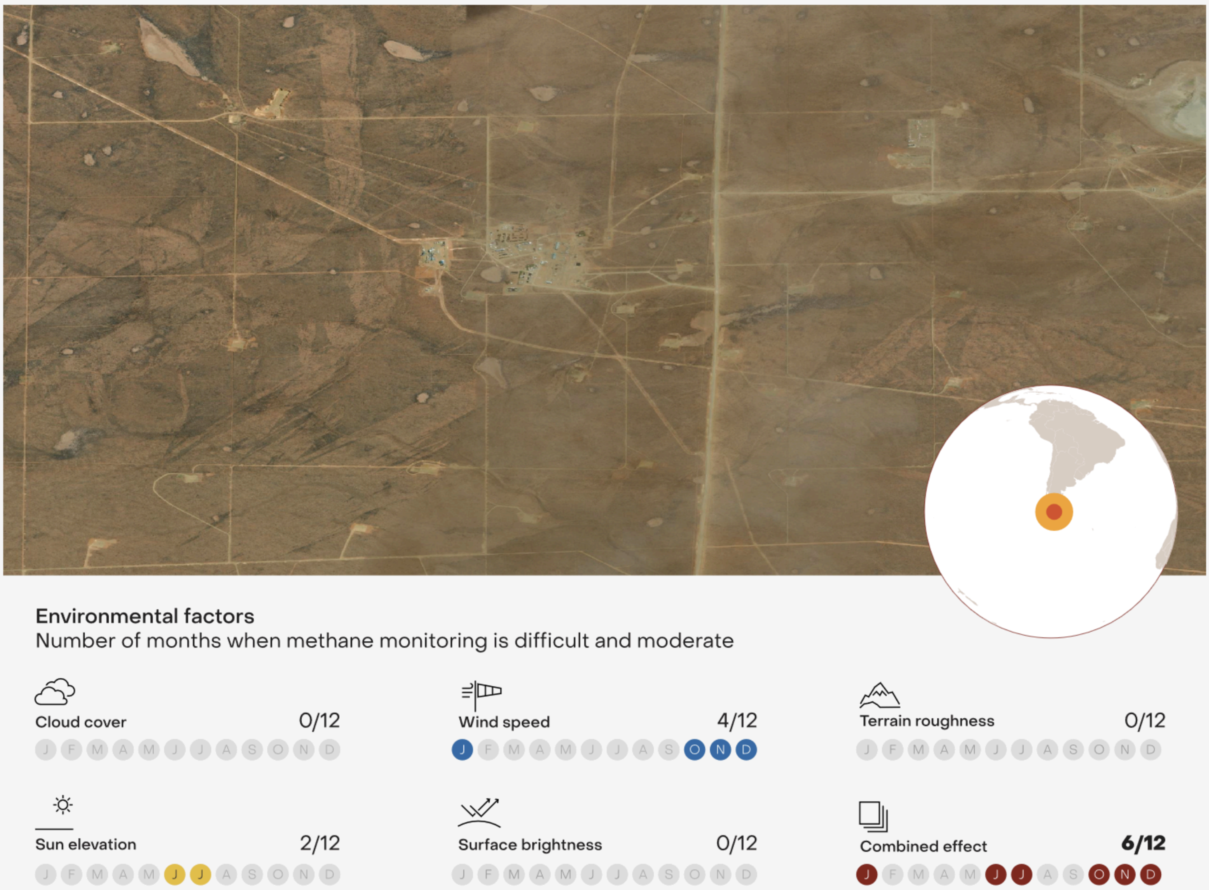
Combined effect **12/12**
J F M A M J J A S O N D

Campo Indio Oeste gas field, Argentina

Campo Indio Oeste is a gas extraction site located in the southern province of Santa Cruz, Argentina and its observation conditions are typical of the southern part of South America. Methane retrieval may be challenging for half the year (6 months with moderate category). The site is windy, with monthly average wind speeds exceeding 4 metres per second between October and January, which would disperse methane plumes making them challenging to detect. Methane monitoring is also hindered during the winter months (June–July) when the sun elevation is low.

Challenging observation conditions at Campo Indio Oeste Gas Field, Argentina

Low sun elevation in the winter and high wind speeds in the summer might make satellite methane observations challenging for half the year.



Athabasca Oil Sands, Canada

The Athabasca Oil Sands in Alberta in Canada are large deposits of bitumen and are one of the largest sources of unconventional oil in the world. The region may be challenging for methane retrieval for half the year (2 difficult and 4 moderate months). In the winter (November-February) the sun elevation is low in the sky meaning very little light reaches the surface and, consequently, any satellite sensor. The surface is dark during the winter (November - January) due to snow cover which absorbs shortwave radiation. This absorption means little light is reflected back to the sensor. June is also a cloudy month which may impact methane monitoring by satellite.

Challenging observation conditions at Athabasca Oil Sands, Canada

Low sun elevation and low surface brightness in the winter might make satellite methane observations challenging for half the year

Environmental factors
Number of months when methane monitoring is difficult and moderate

Cloud cover 1/12
J F M A M J J A S O N D

Wind speed 0/12
J F M A M J J A S O N D

Terrain roughness 0/12
J F M A M J J A S O N D

Sun elevation 4/12
J F M A M J J A S O N D

Surface brightness 4/12
J F M A M J J A S O N D

Combined effect **6/12**
J F M A M J J A S O N D

Designing observing strategies that take local conditions into account

A mixture of technologies needs to be considered when developing a strategy for methane emissions monitoring. Near-ground measurements, with sensors on aircrafts, drones, ground vehicles, or static locations, may be needed to identify emission sources and empower mitigation action.

Robust observation systems are needed to enable methane mitigation goals to be met. Spaceborne instruments are set to form the backbone of these global methane-monitoring observing systems thanks to their ability to detect large individual emission events and to assess regional emissions across large regions of the globe.

New satellites, such as MethaneSAT and Tanager-1, expand the current set of monitoring instruments and offer high spatial resolution, providing greater opportunities to measure methane emissions, including in cloudy regions. Additionally, scheduling satellite observations during times of the year when environmental conditions are favourable would enhance data coverage, to the extent that that is feasible. However, some regions will be more challenging to monitor than others due to environmental conditions - and relying on satellites alone may not be adequate for certain purposes in some regions.

To most effectively monitor methane emissions, a multi-tiered observing system is required. This is a system that uses different types of measurements to understand emissions as required by specific environmental conditions and user needs. This is analogous to a weather observing system, where satellite observations are combined with radar, ground station measurements and weather balloons to create the data needed for weather forecast models and long-term monitoring of climate trends. For instance, continuous monitoring by ground stations can measure air temperature in the arctic where satellite observations are limited. In contrast, satellites can infer air temperature over the ocean, where there are no ground-based stations.

A universal design for a multi-tier observing system is unlikely to suit all scenarios due to diverse environments, methane source variability, and technology constraints. Local users will need to adapt measurement technologies to their specific conditions, needs, and resources. Where favourable observing conditions are rare, like in Ecuador or Indonesia, satellites will be less likely to effectively monitor large emissions events or inform validation of the methane emission inventories. In these cases, robust systems will need to be developed to take up these tasks. Making such systems feasible with available resources, including in developing countries, is a critical task for researchers, policymakers, and donors.

Alternative methane measurements technologies

A number of alternative technologies are being used to complement satellite methane monitors. These technologies are based on sensors mounted on aircraft, drones, ground vehicles or fixed locations. Used either individually or in combination, these systems offer a detailed view of methane emissions, filling in for the spatial and/or temporal scale that satellite systems are missing. Being near the source of the emissions, they can frequently detect much smaller emissions and help locate the specific source, helping guide mitigation. There is a rapid pace of research and investment to transform such individual technologies into robust monitoring systems and make such technologies more readily available.

No single technology will be the silver bullet, able to effectively measure methane at all of the spatial and temporal scales required to support mitigation. Each technology gives only a partial view of the invisible methane world, and a combination of them, integrated in a multi-tier observing system, will be required. Moreover, all sensors can also be affected by environmental factors such as wind, cloud cover, and light availability. For instance, some passive ground-based sensors which rely on ambient light are similarly affected by low-light conditions as satellite sensors are. In contrast, active sensors, which generate their own light source, remain unaffected by natural light conditions (as do some systems which do not utilize light absorption to detect methane). Further research is needed to assess how various alternative measurement approaches respond to environmental challenges. To develop an effective methane monitoring strategy, it is essential to understand the limitations of both satellite and alternative technologies.

As this report has shown, the exact mixture of technologies that will make up this system needs to be geographically specific, taking into account the emission characteristics and local environmental conditions. In some regions, satellite data alone may be adequate for regular monitoring of large emission events and top-down emission estimates. However, in other areas, additional technologies—potentially combined with satellite observations—will be required.

Looking beyond specific technologies

Building effective multi-tier observing systems entails much more than just deploying sensors: it requires coordinated efforts and support. With external support where appropriate, local stakeholders need to build the capacity to develop, evaluate, and adapt measurement technologies in their specific settings, and they need the resources to do so.

Practitioners in different regions facing similar challenges should be connected to exchange best practices and lessons learned, to allow user-led innovations to spread. And international efforts to develop testing protocols and facilities should be rapidly developed, to foster consistency and trust on produced data.

To keep within its climate goals, the world needs to reduce fossil-related methane emissions by 75% by 2030. Satellites will have a key role in this effort, monitoring the progress of well-understood mitigation steps but also highlighting new opportunities for action. With little time, knowledge must be shared freely and efficiently so that all stakeholders can maximise their impact in this collective fight.

Methodology

This is a technical description of the method and inputs used to derive the detection categorisation.

Five gridded datasets are combined to create a score with three categories; favourable, moderate and difficult for methane detection. The scoring system is designed flexibly to be run on any spatial resolution or timestep. For the purposes of this study, each dataset is interpolated onto a consistent spatial and temporal grid ($0.1^\circ \times 0.1^\circ$, which is approximately 10 km resolution at the equator, and a monthly timestep). The spatial grid was chosen to be the same as the ERA5-land grid.

For each input dataset, the conditions in each grid cell are labelled as favourable, moderate or difficult, based on the thresholds defined in the table below.

A combined category for each grid cell / month is assigned as follows:

- Favourable : All inputs must have favourable categories.
- Moderate: One or more inputs must have a moderate category.
- Difficult: One or more inputs must have a difficult category.

The result is a detection category for every month, for every 0.1 degree pixel globally.

Input datasets and thresholds used to calculate the difficulty categories.

Input data	Source data	Favourable	Moderate	Difficult
Elevation variability	GMTED2010	$\sigma_z < 80$ m	$80 \leq \sigma_z \leq 100$	$\sigma_z > 100$ m
Solar zenith angle	Modelled	$\theta < 70°$	$70° \leq \theta \leq 75°$	$\theta > 75°$
Cloud cover	Cloud Score+	$c > 0.3$	$0.2 \leq c \leq 0.3$	$c < 0.2$
Albedo	Sentinel-2	$\alpha > 0.06$	$0.02 \leq \alpha \leq 0.06$	$\alpha < 0.02$
Wind speed	ERA5 land	$w < 4$ ms^{-1}	$4 \leq w \leq 10$	$w > 10$ ms^{-1}

Elevation variability

Mountainous regions are identified using the variability in elevation from the GMTED2010 digital elevation model. The standard deviation of the elevation within a 0.1-degree grid box is derived from 30 arcsecond data. Standard deviations > 100m are classified as difficult. Values between 80m and 100m are classified as moderate and less than 80m are favourable. These thresholds are the same as those used to apply quality flags in the TROPOMI retrieval algorithm.

Solar zenith angle

Solar zenith angle is modelled using the day of the year and latitude. Monthly values are calculated as the mean of the maximum daily values. Solar zenith angles greater than 75° are classified as difficult, between 70° and 75° are moderate and less than 70° are favourable. These thresholds are taken from the quality flags applied to the TROPOMI retrieval algorithm.

Cloud Cover

We identify areas too cloudy for methane retrieval using the Cloud Score+ product, available on Google Earth Engine. The product has been derived using Sentinel-2 imagery and machine learning to identify the similarity between cloudy and clear sky images, and contains two cloud scores. Here, the so-called cs band is used, where values of 0 represent "cloudy" skies and 1 represents "clear" skies. Monthly mean Cloud Score + data were extracted for the years 2020-2023. A monthly average is calculated over these years to account for interannual variability in cloudiness.

The CloudScore+ developers provide a recommended threshold of 0.65 to distinguish between clear and cloudy days, however this threshold is only valid for the raw 10m daily data. A new threshold is needed when the data is aggregated onto the 0.1 degree spatial resolution and a monthly time step. The parameter tuning section below describes how the favourable threshold was empirically selected. The tuned cloud cover threshold for 'favourable' conditions was estimated to be greater than 0.3. The 'difficult' threshold was defined as ≤ 0.2. Judgement was used when selecting this threshold to ensure that countries had a distribution of oil, gas and coal production in both the 'moderate' and 'difficult' categories.

Albedo

Surface albedo in the shortwave infrared, where methane sensing takes place, was estimated from Sentinel-2 using band 12, centred around 2190 nm. The data is masked to remove inland water and ocean using the MODIS land classification map. The albedo was cloud masked using the Cloud Score+ product described above. Monthly average albedos are calculated using Google Earth Engine and aggregated from 10 m to 0.1° x 0.1° resolution. Monthly data is output for the years 2020-2023. A monthly average is calculated to account for interannual variability in albedo and reduce the impact of cloud cover on the data coverage. The parameter tuning section below describes how the threshold for favourable detection was selected. The empirically tuned albedo threshold for 'favourable' conditions was estimated to be greater than 0.06. The ‘difficult’ threshold is defined with albedos ≤ 0.02. This value was selected because it is associated with the low-quality data in the TROPOMI retrieval algorithm.

Wind speed

We use monthly mean zonal (u) and meridional (v) 10 metre wind speeds for the years 2020-2023 from the ERA5-Land dataset, available on the Copernicus Climate Data Store. Wind speed is calculated from the components and a monthly climatology is calculated. Wind speeds below 4m/s are labelled as favourable, between 4-10 m/s are labelled as moderate, and greater than 10m/s are labelled as difficult. The parameter tuning section below describes how the ‘favourable’ threshold was selected. For wind speed, 'difficult' was defined as exceeding a threshold of 10 m/s. This threshold was loosely informed by publications indicating that the probability of detection is lower at higher wind speeds. These studies showed reduced probability of detection up to 8 m/s, so we opted for 10 m/s to err on the side of caution. This is a semi-quantitative approach, as the threshold may vary depending on emission rates and there is no clear definition of the ‘moderate’ and ‘difficult’ categories.

Threshold tuning

To establish favourable thresholds for cloud cover, wind speed, and albedo, we tuned these parameters using 2,962 methane plume observations from TROPOMI, detected by Kayrros and IMEO. We explored a range of plausible threshold values—wind speed (1–14 m/s), cloud cover (0.25–0.6), and albedo (0.025–0.3)—and generated 500 different combinations using Latin hypercube sampling. For each combination, we checked how often TROPOMI observations happened in favourable locations and months. We defined the best set as the one that found observations in favourable conditions in about 85% of the cases.

Note that only the 'favorable' categories were tuned, as it is straightforward to define whether an observation exists or not. The threshold separating 'moderate' and 'difficult' categories was not tuned in this way because it is unclear how to do so precisely. Instead, we set those thresholds based on our judgement for each parameter, as described above.

Limitations of the method and future work

There are no universal thresholds that apply to all satellites, and individual sensors may be better at detecting methane than others in some environmental conditions. For instance, sensors with a high spatial resolution (e.g., GHGSat, EMIT, CarbonMapper) are able to detect methane in some mountainous regions where an area flux mapper (TROPOMI) would find this challenging. Moreover, for most parameters there exist no clear physical limits where the sensor stops detecting methane, but rather a gradual degradation of its expected performance. Threshold tuning was performed only on a limited dataset, based on one sensor, and including only positive detections. Therefore, all provided thresholds should be treated as rough guides and not as hard physical limits for satellite performance.

Another limitation is that the detection categories are based on monthly data, whereas satellite observations represent a single, instantaneous overpass. This simplification is due to the practicalities of managing large datasets. However, using monthly data may obscure the variability present in daily observations

Not all factors that impact methane retrieval are included in this study. For instance, high aerosol load could be of particular importance over arid and semi-arid regions but has not been taken into account. Ground albedo variability will also impact methane retrieval, especially for multi-spectral sensors, making it difficult to distinguish methane plumes from ground artefacts; this has also not been considered in this study.

Location fossil fuel assets

The locations of fossil fuel extraction sites are taken from the Global Energy Monitor (GEM) Global Coal Mine Tracker (GCMT) and Global Oil and Gas Extraction Tracker (GOGET). Monthly 'difficult', 'moderate' and 'favourable' categories are calculated for the nearest latitude and longitudes for 3,778 operational coal mines and 4,703 operational oil and gas upstream assets. Only onshore oil and gas exploration sites are included.

Fossil fuel production data

Coal production data is sourced from the recently released September 2024 supplement to the Global Energy Monitor's Coal Mine Tracker. This supplement provides historical production figures for operational coal mines worldwide with capacities exceeding 1 million tonnes per year, covering the years 2017 to 2023. For the analysis, the production values from the most recent year available for each coal mine is used.

Oil and gas production data comes from the Global Oil and Gas Extraction Tracker (GOGET).

The data includes extraction sites that have production of 1 million barrels of oil per year or more and or reserves of 25 million barrels of oil. To estimate the combined oil and gas production, gas output is converted into barrels of oil equivalent per year. Similar to coal, the production data for the most recent available year is used in the analysis.

Production in 'difficult', 'moderate' and 'favourable' categories is calculated by multiplying the GEM production by the proportion of the year classified with each category. It is important to note that the GEM dataset does not include production information for all listed assets, resulting in some missing data. However, we chose this dataset because it is openly accessible.

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Photo

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