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# Satellite-Based Monitoring of Atmospheric Greenhouse Gases: A Real-Time Observation

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## Abstract

To enhance our understanding of the sources and sinks of greenhouse gases (GHGs), particularly carbon dioxide and methane, it is vital to monitor their atmospheric concentrations in near real time and at high spatial resolution. This study proposes a novel approach involving a constellation of miniature satellites equipped with compact spectrometers possessing nanometer-scale spectral resolution. Climate change, one of the most pressing global challenges, exerts profound impacts across environmental, social, and economic domains. Effective monitoring and assessment are therefore essential to inform policy decisions and mitigate its consequences. Remote sensing technology has emerged as an indispensable tool in climate change research, offering the ability to observe, evaluate, and predict environmental changes on a global scale. By utilizing satellite imagery, aerial surveys, and other sensing methods, scientists and policymakers can collect robust datasets, monitor long-term climate trends, and make evidence-based decisions. The integration of miniaturized satellite spectrometers represents a significant advancement in the effort to improve the timeliness and accuracy of GHG monitoring.

**Keywords**: Monitoring; Greenhouse Gases; Satellite; Remote Sensing; Climate Change

## Introduction

Tracking the levels of greenhouse gasses in the atmosphere One of the biggest problems of the twenty-first century is climate change (Shearman, Smith, J.W. 2007 and Ripple, W.J., Wolf, Newsome, T.M, Barnard, Moomaw, W.R 2020). Rising sea levels, melting glaciers and ice sheets, decreasing sea ice, rising global temperatures, and more frequent and intense heat waves are only a few of its repercussions that are becoming more and more obvious (Javadinejad, Dara, and Jafary 2020). According to Siddik, Islam, Zaman, and Hasan (2021), the concentration of greenhouse gases (GHGs) in the atmosphere has increased at an unprecedented rate due to rising anthropogenic emissions, especially from burning fossil fuels, resulting in an imbalanced Earth's Radiation Budget (ERB) and increased trapping of terrestrial infrared radiation. This threatens the entire biosphere and has far-reaching effects on the climate system, most notably the global warming of the Earth's surface.

Global and thorough measurements of the Earth's primary climatic variables are required in light of the fast changing climate in order to research the complex dynamics of the climate and determine the degree of human influence on the climate system. This information is crucial for developing mitigation and adaptation plans that work and lead us to a more sustainable future. 55 Essential Climate Variables (ECVs) are identified by the Global Climate Observing System (GCOS) as needing close monitoring (Zemp et al 2022). The concentrations of carbon dioxide (CO2) and methane (CH4) in the atmospheric columns are undoubtedly important ECVs, and their worldwide monitoring from space is crucial because human emissions of these gases are mostly to blame for global warming (Friedlingstein 2021 and Saunois 2000 et al). One example is the European Space Agency Climate Change Initiative (ESA CCI), which focuses on CO2 and CH4 measurements for climate change monitoring and study. Using satellite observations and other sources, it seeks to offer thorough and precise information on the amounts of various GHGs in the atmosphere.

To resolve the dynamics and cycles of GHGs in the atmosphere, monitoring of the two essential GHGs, CO2 and CH4, must be carried out on a variety of spatiotemporal scales. For example, in order to define and comprehend the worldwide distributions and trends of greenhouse gases, we require observations with global coverage. However, in order to identify and quantify their local sources and sinks, we also need high spatial resolution observations, ideally down to a few kilometers. Furthermore, in order to resolve the significant diurnal fluctuations in significant GHG sources, we also require measurements at quite high temporal resolutions. Continuous real-time measurements on diurnal timescales over the entire world should be our ultimate goal. Based on this viewpoint, satellites are essential instruments. The kind of satellite and orbit most suited for GHG monitoring is one of the problems. Low Earth Orbit (LEO) satellites may make observations at better spatial resolutions over the entire planet, including the Polar Regions, because they are significantly closer to the Earth's surface than Geostationary Orbit (GEO) satellites. However, LEO satellites have a much smaller field of vision than GEO satellites, do not continually observe the same area, and usually have lengthy revisit periods (the interval between a satellite's observations of the same scene). A trailing satellite constellation is one technique to get around these LEO satellite constraints. The short-term fluctuation in the CO2 and CH4 distributions worldwide is somewhat resolved by this configuration, which allows for an overall shorter revisit period (the amount of time that passes between observations of the same scene but this time by separate train satellites).

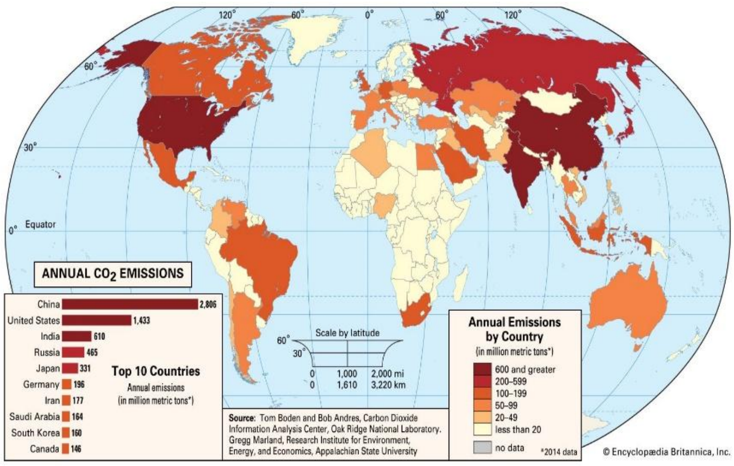
A Small Sat constellation is a desirable alternative to cut expenses and installation timeframes. In fact, the ongoing measurements of the Earth Energy Imbalance (EEI) under the scope of the Uvsq-Sat (Meftah 2020) and Inspire-Sat 7 (Meftah et al 2022) missions have already demonstrated the value of SmallSat constellations in the monitoring of ECVs. Uvsq-SatNG Meftah et al is an innovative SmallSat designed to demonstrate the feasibility of measuring carbon dioxide and methane, with accuracies tending towards those of large satellite missions. The Uvsq-SatNG mission is led by the Laboratoire Atmospheres, Observations Spatiales (LATMOS), a French laboratory specialized in climate and Earth atmosphere sciences. The launch of Uvsq-SatNG is planned in 2025. This mission is viewed as a pathfinder in the near-real-time monitoring of GHGs with a SmallSat constellation. CO2 and CH4 measurements will be performed with a small and compact spectrometer (Meftah et al). The miniaturization of such an optical instrument has led to some compromises, especially concerning the spectral resolution of the spectrometer, which is approximately ∼5 nm. The light source of the Uvsq-SatNG spectrometer is the solar spectrum backscattered upwards in the 1200–2000nm wavelength range. The Uvsq-SatNG spectrometer, with its linear complementary metal oxide semiconductor (CMOS) sensor containing 256 pixels, is designed to capture Earth observational scenes with a ground footprint diameter close to 5 km thanks to its 0.15° narrow field of view. Uvsq-SatNG also includes a high-definition camera.

**The GIS and Remote Sensing Evolution**

A geographic information system (GIS) is a computer –assisted system for handling spatial information. GIS software can be considered as a collection of software programs to acquire, store, analyze, and display information. The input data can be maps, charts, spreadsheets, or pictures (Robert Sanderson, 2010). GIS was born when the virtues of classical map are wedded to the power of computers. It originated in the early 1960s from two independently functioning organizations; the Harvard laboratory for computer Graphics (HLCG) and the Canadian Geographic information system (CGIS). HLCG was set up in 1965. It was to develop automated procedures capable of using line printer to create maps quickly and cheaply. It produced the mapping package SYMAP (Synagraphic mapping system) that could generate a variety of maps including chrolopleths and isolines (Tasneem Abbasi and S.A.Abbasi, 2010). The Canadian Geographic information system (CGIS) is commonly acknowledged as being the first time GIS. The Canadian Government was planning the Canadian land inventory (CLI) to map the land capability of settled canada. By the end of the 1960s this idea had been turned into a working system that held maps and associated attribute information for the whole canada (Tasneem Abbasi and S.A.Abbasi, 2010).The 1970s saw increase in the processing power of the computers. This coupled with increasing awareness of the environmental issues, spurred the growth of GIS, with developments spreading to private software companies in North America and Europe. In the 1980s Arc Info was launched. It was the first GIS software package that was to become the industry standard for the next decades. The Environmental Systems Research Institute (ESRI) developed the software. MapInfo from the Map Info Corporation was the first popular software program that could also digitize photographs.

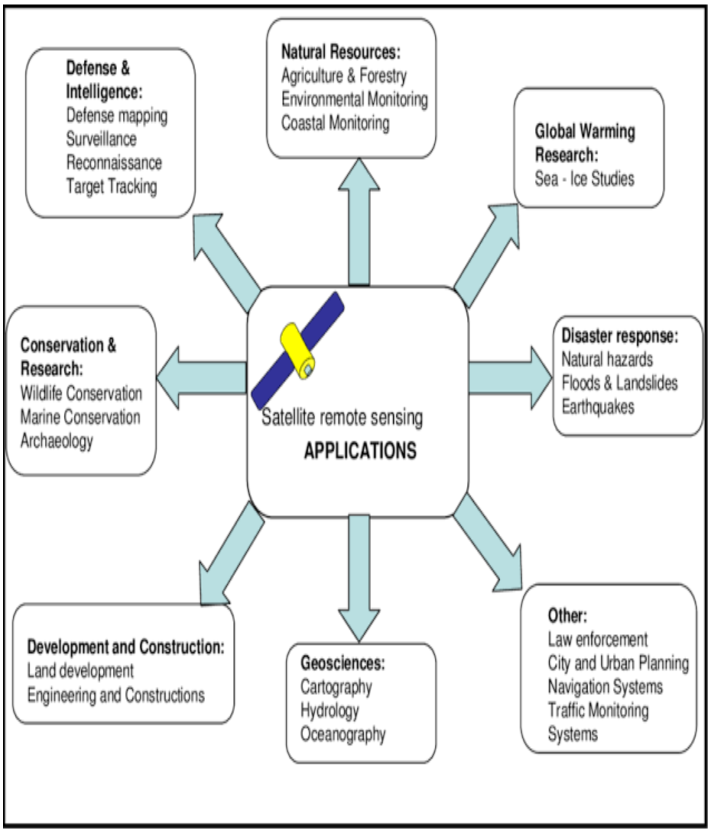
**GIS Remote Sensing in Mapping the Distribution of Greenhouse Gases**

Carbon dioxide (CO2) and Methane (CH4) are the two major important anthropogenic greenhouse gases and contribute to global warming. Satellite measurements of vertical columns or column averaged mixing ratios of CO2 and CH4 have the potential to improve this situation. This is because satellites produce large amounts of data which cover the entire Earth in short time periods. The first satellite instrument which provides this type of information is Scanning Imaging Absorption spectrometer for Atmospheric cartography (SCIAMACHY) on board the European environmental satellite (ENVISAT). This is because SCIAMACHY measures spectra of reflected solar radiation in the near-infrared spectral region in nadir (down looking) observation mode. These measurements are sensitive to greenhouse gas concentration changes at all atmospheric altitude levels including the lowest layer of the atmosphere where the sourced sink signals are largest (Michael Buchwitz, 2008). At the Institute of Environmental Physics/Remote sensing (iup/ife) of the university of Bremen, located in Northern Germany, a retrieval algorithm called WFM-DOAS has been developed to retrieve information on greenhouse gas columns from the spectra measurements of the SCIAMACHY instrument. Recently, three years of data (2003-2005) have been processed using WFM-DOAS. For each month a global map has been produced which displays the spatial distribution of the corresponding greenhouse gas during this month. These maps have been combined to an animation to show how the greenhouse gas distributions are changing with time. The satellite data have been filtered using a number of criteria in order to make sure that only good measurements are considered. The greenhouse gas distributions are shown as column-average volume mixing ratios (VMRs) also called column-averaged dry air mole fractions. The units are ppm (parts per million) for CO2 and ppb (parts per billion) for CH4 (Micheal Buchwitz, 2008).



**Key Applications of Remote Sensing**

Limon J. (2024). Applications of remote sensing in climate change monitoring include the following: Heat islands and monitoring temperatures: Global temperature increases are among the most obvious signs of climate change. Technology for remote sensing is crucial for monitoring temperature variations across several locations. Satellites equipped with thermal infrared sensors are able to record changes in surface temperature, giving researchers the ability to track both local temperature changes, such urban heat islands, and global warming trends. Remote sensing helps to understand how climate change is affecting local and regional climates by providing crucial information on temperature anomalies through the analysis of these temperature patterns across time.




*Monitoring greenhouse gas emissions*: Greenhouse Gases (GHGs), such as Carbon dioxide (CO2), Methane (CH4) and Nitrous oxide (N2O), are major contributors to climate change. Remote sensing enables the monitoring of these gases through satellite-based instruments that measure their concentration in the atmosphere. For example, NASA's OCO-2 (Orbiting Carbon Observatory) satellite provides high-resolution measurements of CO2 levels, helping to track carbon emissions at both global and regional scales. Additionally, remote sensing aids in detecting methane leaks from natural gas infrastructure, contributing to more accurate emission inventories and improved climate change assessments. Carbon sequestration and vegetation: By removing CO2 from the atmosphere, vegetation serves as a natural carbon sink and contributes significantly to carbon sequestration. Scientists can track changes in land usage, vegetation cover, and health using remote sensing technologies like multispectral and hyperspectral imagery. Remote sensing aids in measuring variations in the potential for carbon storage over time by examining vegetation indices, such as the Normalized Difference Vegetation Index (NDVI). This information is crucial for monitoring the effects of land degradation and deforestation as well as for comprehending how forests, grasslands, and other ecosystems contribute to climate change mitigation. Sea level rise and coastal erosion: As a direct result of global warming, rising sea levels pose serious threats to ecosystems and coastal communities. Data from remote sensing technologies is extremely useful for tracking changes in sea level and coastal erosion. Satellites like NASA's ICESat-2 and the European Space Agency's CryoSat-2 track changes in the earth's surface height, including variations in sea level. Furthermore, data from remote sensing aids in tracking changes in coastal habitats, including wetlands, coral reefs, and mangroves, which are especially susceptible to climate-related temperature changes and sea level rise. Extreme weather occurrences: Hurricanes, floods, droughts, and wildfires are among the extreme weather events that are becoming more frequent and intense due to climate change. Remote sensing technology plays a key role in tracking these events, providing real-time data for assessing their impacts and guiding emergency response efforts. For example, satellites with radar and optical sensors are used to monitor rainfall, soil moisture and flood extents, enabling scientists to track and predict flooding events. Similarly, remote sensing is crucial for monitoring wildfire activity by detecting changes in vegetation and assessing fire damage.

**Relevance of GHG Observations and Scientific Requirements**

Of a Few Space Missions the rise in atmospheric GHG levels primarily caused by human activities has been identified as the principal factor behind the observed increase in Earth's surface temperature. In 2023, set to be the warmest year on record, the global temperature increase reached 1.4 °C compared to pre-industrial era, breaking climate records. Predictions suggest that in 2024, it could exceed the 1.5 °C warming threshold for the first time—beyond the warming limit outlined by the Intergovernmental Panel on Climate Change (IPCC). An unexpectedly powerful El Niño phenomenon, which alters wind patterns that disperse warm waters throughout the Pacific Ocean and causes a brief warming of the atmosphere, may be partly to blame for this escalation. Depending on how severe it is and how it affects temperatures, this El Niño climate phase could have a much greater impact on global warming. The continuous rise in temperature linked to rising GHGs is exacerbated by this phenomena. As the primary cause of climate change, carbon dioxide is a major greenhouse gas that is mostly produced by human activity. Its concentration in the atmosphere has risen from a pre-industrial level of approximately 280 parts per million (ppm) to over 420ppm in 2024. This rise is attributed to sources including deforestation, changes in land use, cement manufacturing, and notably the combustion of fossil fuels. The latter became the predominant source of emissions around the 1950s and currently accounts for over 87% of total emissions. Atmospheric methane is the second largest contributor to climate change and consists of a diverse mix of overlapping sources and sinks, so it is difficult to quantify emissions by source type. Its concentration in the atmosphere has risen from a pre-industrial level of approximately~720 parts per billion (ppb) to over 1900ppb in 2024. Since 2007, globally averaged atmospheric methane concentration has been increasing at an accelerating rate. The annual increases in 2020 and 2021 (15 and 18ppb, respectively) are the largest since systematic record began in 1983. Causes are still being investigated and analysis indicates that the largest contribution to the renewed increase in methane since 2007 comes from biogenic sources, such as wetlands or rice paddies. Quantifying CO2 and CH4 variations and anthropogenic emissions is critical for understanding the current and future impact of human activities on climate change. It is also vital to track global emissions across the entire planet, not just in mid-latitude regions. Monitoring at the poles is particularly important due to the significant climate changes occurring there. For instance, the melting of Arctic ice releases substantial amounts of methane previously trapped within the ice. Additionally, it is necessary to measure GHG emissions as comprehensively as possible across the globe at different geographic scales. Depending on the spatial resolution, it is feasible to monitor GHG sources and sinks on larger regional scales, such as for national GHG assessments, in megacities, or even at point sources smaller than a few kilometers. The deployment of space-based instruments is indispensable for global GHGs monitoring, providing the breadth of coverage required to accurately track these emissions worldwide. ESA CCI recommends space-based instruments to achieve a 1ppm absolute accuracy in measuring the CO2 total column, with a precision of 1ppm and a stability per decade of 2ppm. Meeting these requirements enables near-real-time sink determination with a spatial resolution of 5km and a revisit time of 3 h.

Regarding CH4 total column measurements, the recommended requirements include 2ppb absolute accuracy, 5ppb precision, 2ppb stability per decade, 10km spatial resolution, and a revisit time of 3 h. Numerous space based missions were deployed with the primary objective of measuring the atmospheric columns of greenhouse gases These missions aim to gather comprehensive data on the concentration and distribution of GHGs like CO2 and CH4 in the Earth's atmosphere.

**New Development in the Area of GHG Emission**

The Twin Anthropogenic Greenhouse gas Observers (TANGO) is an upcoming satellite mission scheduled to launch in 2027 as part of the European Space Agency's (ESA) SCOUT program (Landgraf et al., 2024). The mission consists of two CubeSat95 satellites: TANGO-Carbon, which focuses on measuring CO2 and CH4, and TANGO-Nitro, which measures NO2 emissions, both targeting point source emitters such as power plants, industrial sites, and oil and gas production facilities. The temporal co registration between CO2/CH4 and NO2 measurements is designed to be less than 60 seconds, enabling synchronized observations of co-located emissions from the same sources. TANGO-Carbon will measure sunlight reflected by the Earth and its atmosphere in the 1.6μm spectral range (15901675nm) with aspectral resolution of 0.45nm and spectral sampling of 0.15100 nm. The push broom spectrometer is designed to achieve a signal-to-noise ratio of 270 at the spectral continuum of a reference scene with a solar zenith angle (SZA) of 70°, a viewing zenith angle (VZA) of 0°, and a Lambertian surface albedo of 0.15 (Lref = 3.16 × 1012 photons/(sr cm2 nm s)). This capability enables the detection of CO2 sources larger than 2 Mt/year and CH4 sources larger than 5 kt/year. TANGO-Nitro will use the visible spectral range (400–500 nm band) to assist in plume detection. The satellite's narrow swath width of 30 km and ground pixel resolution of approximately 300 meters make it suitable105 for detecting localized emission sources. TANGO uses two agile Cube Sat satellites, to be launched into a low-Earth, sun synchronous orbit at approximately 500km altitude. The satellites' agility allows them to dynamically adjust their observation strategy—through roll, pitch, andYaw maneuvers—enabling them to prioritize and scan high-emission targets, enhancing their versatility compared to more static satellites. Additionally, TANGO will operate in a late-morning orbit, with an equatorial crossing time of approximately 10:30, as assumed in this study. In our simulations, the TANGO-Carbon orbital parameters and 110 detection limits are used as a proxy for the targeting satellites to evaluate their capabilities in measuring point source targets of CO2 and CH4 and determining how many of these sources can be detected under various scenarios.

## Conclusion

Remote sensing technology is playing an important role in the monitoring and assessment of climate change. By providing large-scale, accurate and timely data on a wide range of climate indicators, remote sensing enhances our understanding of the Earth's changing climate system. While challenges remain in data accuracy and integration, the continued advancement of remote sensing technology, coupled with emerging data analysis techniques, with high potential for improving climate change monitoring and informing global mitigation and adaptation strategies. As climate change continues to pose significant threats to ecosystems and human societies, remote sensing will remain a fundamental tool for a sustainable future.

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