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A Metrics Framework for GHG Monitoring

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Abstract

Reducing net anthropogenic emissions of greenhouse gases (GHGs) to zero is key to combating climate change. The United Nations Environment Programme estimates that to limit global temperatures to 1.5°C above pre-industrial levels, net GHG emissions must be reduced by 45% from current levels by 2030. Tracking of global progress toward emissions reduction goals requires a combination of observational and modeling techniques to estimate the GHG concentration in the atmosphere, as well as fluxes around GHG sources and sinks. In this paper, the elements of a systems framework to derive verification metrics that can serve as a basis for international and industrial dialog and technical exchange were presented. The present state of GHG monitoring efforts and considerations in designing greenhouse gas information systems (GHGISs) on various scales were surveyed. Additionally, design, modeling and simulation techniques, as well as illustrative examples of GHGISs were identified. Configurations that combine airborne, space-based, and terrestrial platforms and distributed low-cost terrestrial sensors in an Internet-of-Things (IoT) network show considerable promise considering recent technological trends. A foundation for future system architecting efforts was presented by identifying the steps for defining the requirements of a GHGIS and assessing the types of instrument platform, processing algorithm, and data transmission architecture development that would enable the required performance. Future work will involve identifying a prototypical GHGIS system architecting problem and performing the detailed steps of architecting the system.

Keywords: greenhouse gases, earth observation, remote sensing, monitoring, system architecting

1. Introduction

Reducing net anthropogenic emissions of GHGs to zero is key in combating climate change. The United Nations Environment Programme estimates that to limit global temperatures to 1.5°C above pre-industrial levels, net GHG emissions must be reduced by 45% from current levels by 2030, and for 2°C, net GHG emissions must be reduced by 30% by 2030 [1]. As a part of the Paris Agreement, 192 countries and the European Union have made commitments to reduce their GHG emissions. Various non-state actors like cities and corporations have also pledged to reduce GHG emissions, such as in the UN's "Race to Zero" Initiative. In the recent COP27 conference, the need for greater ambition among the parties was reaffirmed [2].

Tracking of global progress toward emissions reduction goals will require a combination of observational and modeling techniques to estimate the GHG concentration in the atmosphere, as well as fluxes around GHG sources and sinks.

In this paper, we describe the core elements of a systems framework for deriving verification performance metrics that can serve as a basis for international and industrial dialog and technical exchange. The systems framework is an analytical framework for designing an information system that would monitor and verify GHG emissions changes by countries and discrete actors. The information products so obtained would feed a variety of applications, such as monitoring pledge compliances and decision support for country and discrete actors.

Our goal is to build a foundation for future system architecting of various versions of GHGISs for a range of possible scenarios, and monitoring and reporting schemes. A GHGIS is a combination of sensing platforms (space-based, airborne, and terrestrial, which may be remote or in situ), data transmission and processing systems, models, calibration, and validation & verification processes for producing information products to support decision-making. The concept of GHGIS has been explored in [3] and [4].

In light of our goal stated above, we:

- Surveyed of the current state of monitoring and reporting, which are the building blocks of a GHGIS, both existing and planned.
- Outlined specific potential scenarios and use cases of a GHGIS. For each scenario, we identified design considerations for the foundation of a future system architecting effort.

- Identified the main gaps and prospective areas for research and development. We described relevant technological and computational challenges, high-potential areas for research, and identified the most tractable problem statements among the options.

2. Background

2.1 Current state of GHG monitoring

A variety of sensors measuring atmospheric composition on all types of platforms are currently operational. The government-funded space-based and airborne platforms are primarily designed for scientific and research purposes, which make them suitable for only a subset of monitoring scenarios [3], as will be explored in the GHGIS Application Scenarios section. Space-based instruments often measure background concentrations, that is, essentially the net effect of all sources and sinks combined. This then requires assimilation into chemical transport models to provide information on the spatial and temporal distribution of fluxes (referred to as the 'top-down' approach).

Parties to the Paris Agreement take annual National Inventory Reports (NIRs), or National Communications for developing countries, as part of their commitment to the UN. Most countries who produce NIRs base their inputs on 'bottom-up' measurements, for example, inventories produced by direct emissions measurements taken at various sources, combined with estimates from economic activity, such as fuel purchased and electricity consumed, and demographic data. Only the UK, Switzerland, and Australia combine 'top-down' and 'bottom-up' measurements in the development of NIRs [4, 5]. The approaches followed by these countries will be explored further in Appendix A.

In general, reconciling source attribution of GHG emissions estimated by 'top-down' versus 'bottom-up' approaches is a significant challenge [4, 6], since the discrepancy between the results of the two estimation approaches suggests flaws in our current understanding.

Researchers [4] have explored the benefits of combining atmospheric observations from multiple platform types to better constrain sources and sinks, as well as to decrease uncertainty and redress under-reporting of emissions.

Lastly, several initiatives such as ClimateTrace, Anomaly Hot-spots of Agricultural Production (ASAP), and The Early Warning eXplore (EWX) aggregate measurements from multiple sources and apply machine learning techniques to create integrated data products for decision support [7, 8].

2.2 Types of data products

The types of data products that may be required from a GHGIS can be categorized as follows:

- **Quantities measured or estimated:** Common quantities of interest are gas concentrations, total column density of gases, and fluxes around sources and sinks. For the source and sink fluxes, the sources of interest may be point sources or distributed, and stationary or mobile.
- **Chemical compounds:** The GHGs of interest to monitor are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, nitrogen oxides (NOx), and sulphur oxides (SOx).
- **Sensor location/platform:** Sensors may be located near the source of interest (i.e., in a power plant or other facility), or on terrestrial, mobile, airborne, or space-based platforms.
- **Sensor type:** Common sensor types are visible or infrared imaging, interferometry, and in situ sampling.

2.3 Types of estimation problems

For many applications, emissions data products are generated using modeling and measurements. The main data products of interest are fluxes from specific sources and sinks.

As nations track their progress toward their emissions goals, independent measurements of emissions are required to verify their inventories of GHG emissions, especially in regions with fewer resources for monitoring. In situ and space-based measurements provide valuable information at local and broad scales, respectively. The most common GHG quantities available through space-based measurement are total column densities of gases, which is the integrated sum of the trace gas concentration from the top of the atmosphere to the surface.

Source attribution is the process of identifying where, geographically, and from which sectors/facilities GHGs originate. Source attribution can be achieved by inverting atmospheric transport models using observations. Human activities disrupt the Earth's carbon cycle, despite contributing only about 5% of fluxes. Therefore, even the most important emissions sources generate a comparatively small observational signal in the global flux budget. This poses a challenge for assessing the impact of anthropogenic sources on observed changes in the earth system as it is difficult to differentiate these sources from larger biogenic signals.

Often, GHGs can be attributed to a particular location where multiple sources are collocated. It is frequently of interest to distinguish between various anthropogenic and natural sources (and sinks), since emission reduction goals apply only to the former [3]. Source apportionment is the process of assigning fluxes to each collocated source, which, in model inversions, requires a priori knowledge about some or all these sources. Apportionment by source type can also be achieved by measuring relative concentrations of carbon isotopes which have different abundances depending on source type [9].

Additionally, hyperspectral imaging (HSI) sensors such as Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) [10], Mid-infrared Airborne Hyperspectral Imager (MAHI) [11], and Mako [12] can perform plume detection and source identification. Image processing and machine learning techniques may be combined to detect the presence and characteristics of specific types of sources [13, 14].

2.4 Performance metrics

Characterizing the spatial distribution of sources and monitoring their change on various time scales are both critical to address emissions reductions and to predict how emissions may change. Thus, observational network requirements need to be defined for the GHGIS. The measurements required in a GHGIS can be evaluated by the following performance metrics:

- **Earth coverage and spatial resolution:** These metrics refer to the area of the Earth and vertical levels of the atmosphere that can be observed. Spatial resolution determines the level of differentiation that can be made between collocated sources. For space-based sensor platforms (and airborne to a lesser extent), Earth coverage and spatial resolution are affected by the platform orbit/flight path and the sensor design. The performance of in situ sensors depends on the location with respect to sources (such as whether to locate sensors upwind or downwind of specific sources).
- **Temporal coverage and resolution:** These metrics are defined by the ability to capture variability on different timescales and the sampling frequency and revisit time of a given location. The revisit time is primarily affected by the platform chosen, while the sampling is affected by the platform and sensor type, as well as the wavelength of the measured radiation. For example, passive sensors operating in the ultraviolet (UV), visible, and near-infrared spectrums can only take measurements in daylight. Additionally, for space-based sensors, the orbit properties may limit the time coverage.
- **Measurement precision and accuracy:** These metrics define the allowable level of measurement uncertainty to meet the regulatory goals of the system. Precision refers to the consistency of measurements across the entire system. The GHGIS must have a method for quantifying errors to ensure confidence in the results. Accuracy refers to the ability to capture the value of the observed quantity without the influence of systemic bias. Accuracy is a function of the sensitivity and specificity of the instrument, which can vary with environmental conditions. A GHGIS must be designed to minimize uncertainty in all measurements where its goals are relevant, such as capturing diurnal emissions without systematic differences between measurements made at day and night. In addition, any emissions estimates that rely on models and/or inventories must have their uncertainties well defined and considered when designing the GHGIS. Calibration and validation can occur for individual components of the GHGIS, such as for specific instrumentation, as well as for the integrated system. In cases where multiple gases are measured by the same instrument, the gas with higher precision, accuracy, and sensitivity can be used to improve estimates of co-emitted gases.
- **Measurement stability:** Measurement stability refers to the precision and accuracy of the rate of change of the measurements. The requirements for this metric depend on whether an application requires the measurement trends over time, such as for intermediate goals for emissions reductions. Continuous calibration and validation can be implemented to improve measurement stability.

2.5 Documented challenges and opportunities in GHG monitoring

- **Difficulty of reconciling ‘top-down’ and ‘bottom-up’ approaches:** Several researchers [3, 5, 6, 15] have documented the need for reconciliation of ‘top-down’ and ‘bottom-up’ approaches to GHG emissions estimation since they often do not agree. The authors of [4] and [5] highlight the advantages of combining the approaches, using the top-down measurements as a constraint in the estimation problem.
- **Attribution requires fine spatial and temporal resolution:** The authors of [3] and [6] discuss the need for fine spatial and temporal resolution in measurement data for source attribution. Data of the required resolution for some of the applications discussed in this paper may not be available with current monitoring infrastructure.
- **The ability to monitor the diurnal variability of various emissions sources is a current gap:** For example, certain point sources have the flexibility to choose the diurnal profile of their GHG emissions; if the observational platforms chosen can only measure during the day (as with SWIR/NIR remote sensing instruments), operators of individual facilities may choose to bypass

monitoring by shifting their emissions to nighttime. This tactic can be defeated with the use of Thermal Infrared (TIR) sensing methods that rely solely on scene self-emission and can thus provide full diurnal coverage.

- **Other model inputs, such as a priori source data, may be a limiting factor:** In [16] (box 3.5) the need for and challenges associated with accurately quantifying carbon stocks and biomass are discussed, as well as the potential benefit of combining airborne and space-based sensing. The authors of [9] discuss the need for isotopic discrimination in source apportionment, while the authors of [17] discuss the benefit of combining in situ measurements with space-based measurements.
  Overall, the need for a multi-platform GHGIS is clearly agreed upon by the field experts.
- **Untapped opportunities in mitigating non-CO_2 GHG and CO_2 emissions from land use changes:** The authors of [4] suggest that model inversion techniques are valuable for estimating non-CO_2 GHG fluxes and CO_2 fluxes associated with land use changes and forestry (LULUCF), where other robust techniques are not available. The authors of [5] emphasize the importance of mitigating CH_4 emissions, which has not been invested in as much as CO_2, and yet can be relatively cost effective and quick to provide benefits. The authors of [18] highlight the potential of remote sensing in mitigating CH_4 emissions, pointing to the demonstration of leak detection using publicly available satellite data by the data analytics company Kayrros, with even more potential as higher sensitivities and resolutions of data become available.
- The authors of [3] and [19] bring to our attention that halocarbons emissions are underreported, and discuss the need for improved monitoring methods to prevent large discrepancies.

3. GHGIS application scenarios

In this section, we examine three categories of scenarios where a GHGIS may be applied. In all categories, the goal is source attribution and apportionment to specific sources for some or all GHGs. We selected a subset of these scenarios, based on feasibility, for analysis in subsequent sections.

3.1 Global treaty verification

This is the scenario that was analyzed in [3] and is the most stringent of all the scenarios, since source attribution must be made precisely down to a granular level to distinguish anthropogenic sources from natural ones. In this scenario, the data products are inputs to the enforcement of a treaty, in that penalties or incentives are quantitatively dependent on the data.

To maintain cooperation and trust between the parties to the treaty, results of monitoring must be agreed upon by the parties. Feasibility considerations include the high spatial and temporal resolution needed for such granular source attribution, the ability for the monitored to replicate results using technology available to them, and that data products need to be unassailable in their interpretation since parties being monitored are incentivized to interpret results in their favor.

This scenario is likely to be too challenging to design a GHGIS for with current technology, since the technology availability among monitored parties is highly variable, accessibility for airborne and in situ sensing may be an issue, and producing data products that can be agreed upon by all parties is a challenge.

3.2 Local regulation

This scenario is similar to the first but restricted to a hypothetical cooperative territory where monitoring access is guaranteed, and local authorities have willingly adopted a monitoring-based regulation scheme. The territory under consideration may be on a country-, state-, or city-wide scale.

Here, one can apply a nested transportation model that uses the global concentrations as boundary conditions and applies high spatial and temporal resolution monitoring and atmospheric transport models to perform granular source attribution and apportionment.

This scenario is likely to be too challenging to design a GHGIS for in practice, since the issues from the global treaty verification scenario remain, other than availability of technology and access. However, this scenario, with a hypothetical territory that meets the conditions described above, may be worth analyzing as a bounding case for performance of the GHGIS.

3.3 Informational (global or local)

In this scenario, source attribution is performed for research, decision support for local officials, and public awareness and education, rather than for regulation. Within a territory of interest, technology availability, cooperation, and access may vary. The quality requirements for data products can be relaxed in this scenario. Data quality may vary by region.

A variety of system architecting problem statements may fall into this category, depending on the type of data to be produced. Feasibility depends on the required performance. In subsequent sections, a generic problem statement of this type will be analyzed.

Some considerations when analyzing the specific system architecting problems are:

- Technical feasibility: phenomenology, sensitivity of sensors to phenomena of interest.
- Operational feasibility: practical considerations like platform, power draw, bus type needed (CubeSat or full-size, whether specialized satellite is needed), launch options (such as if piggyback is possible), and orbit type (GEO for single area to stare at or LEO for greater Earth coverage).
- Other: Cost, maintenance, big data considerations, etc.

The informational GHGIS scenario is likely feasible for many problem statements, and we will discuss illustrative examples in Appendix A.

4. Building blocks of a GHGIS

A GHGIS is composed of sensing platforms (space-based, airborne, and terrestrial, which may be remote or in situ), data transmission and processing systems, models, and calibration/validation & verification processes. The authors in [3], [7], and [4] discuss how systems that are currently operational can be leveraged in building a GHGIS. In this section, we survey the systems that could be the building blocks of a GHGIS.

4.1 Space-based platforms

In [7], the authors identify 34 Earth Observation (EO) spacecraft having GHG monitoring capabilities, of which 17 were in orbit at time of writing (2021), namely (instrument names in brackets) SciSat-1 (ACE), FengYun-3D (GAS), Gaofen-5 (GMI), TanSat (ACGS), Sentinel-5P (TROPOMI), Metop-A/B/C (IASI), PRISMA(HYC), GOSAT (TANSO-FTS), GOSAT-2 (TANSOFTS2), Aqua (AIRS), Suomi NPP (CrlS), OCO-2, OCO-3, GHGSat-D, GHGSat-C1 and GHGSat-C2, and Aurora. Another 16 spacecraft with GHG monitoring capabilities were in development in 2021.

4.2 Airborne platforms

In [3], the authors note several airborne in situ monitoring programs by US government agencies, including:

- **NASA programs:** Global Atmospheric Sampling Program (GASP), Global Tropospheric Experiment (GTE) Expeditions, CITE Expeditions, ABLE Expeditions, PEM-WEST Expeditions, TRACE-A and TRACE-P Expeditions,
- **NOAA programs:** The Carbon Cycle Greenhouse Gases aircraft program, Indianapolis Flux Experiment (INFLUX), Mid-Continent Intensive (MCI), US Coast Guard Collaboration: Alaska (ACG), Indianapolis Urban Plume Study, Sacramento Urban Plume Study, Martha's Vineyard Tower Project, AirCore Atmospheric Sampling System,
- **National Center for Atmospheric Research (NCAR) programs:** HIAPER Pole-to-Pole Observations (HIPPO) in collaboration with NOAA, Naval Research Laboratory (NRL) Military Support Division (MSD), and DOE-SC Atmospheric Science Program (ASP).

Additional programs of note are the Atmospheric Tomography Mission (ATom), ASPECT (Airborne Spectral Photometric Environmental Collection Technology), and CarbonMapper.

4.3 Terrestrial platforms

The authors of [4] describe the existing air pollution monitoring infrastructure which may be leveraged for GHG monitoring, though not sufficient for all purposes. The authors of [20] describe the air pollution monitoring infrastructure in Europe consisting of a heterogeneous network of ground-based air quality measurement stations.

4.4 Models and aggregators

The authors of [7] and [8] identify data systems that aggregate and analyze satellite data for decision support, including Anomaly Hot-spots of Agricultural Production (ASAP), the Early Warning eXplore (EWX), Global Agricultural and Disaster Assessment System (GADAS), the FAO Agricultural Stress Index System (ASIS), GLAM (the Global Agricultural Monitoring System), the WFP-VAM (World Food Programme Vulnerability Analysis and Monitoring), and Climate Trace. Other aggregate models of note are CarbonMapper, En-ROADS, and the Open Earth Foundation's OpenClimate.

4.5 Organizations

Organizations engaging in GHGIS-related research and development include JPL, Sandia, Los Alamos, Lawrence Livermore national labs (all of which had researchers who participated in writing [3]), the World Meteorological Organization, which produced [4], National Institutes of Standards and Technology (NIST), International Methane Emissions Observatory (IMEO), NASA, NOAA, NCAR, DOE, NRL, and the company ClimateTrace, which produced [7]. Several academic institutions also conduct research in this area.

Additionally, numerous stakeholder organizations such as state and local governments, city networks, and advocacy groups may be natural partners for efforts in setting up GHGIS [4].

5. Problem statement for a GHGIS system architecture

In designing a GHGIS for source attribution, the problem can be defined by specifying:

1. the chemical compounds to be measured,
2. the territory in which to characterize sources and sinks,
3. how sources are to be partitioned (into natural and anthropogenic totals, by sector, or down to the facility level),
4. source characteristics (distributed or point, stationary or mobile) and their associated metrics.
5. the performance requirements on the data product.

A GHGIS can be defined by its functional requirements and the performance metrics it is designed to.

A problem statement when architecting a GHGIS can be specified in this form: "To attribute emissions of [specified GHG] to sources [of specified characteristics] within [specified territory] with [specified precision and accuracy of attribution]."

This statement is derived from the goals and interests of the organizations developing the GHGIS.

6. Methods and techniques for GHGIS architecting

The need and sophistication of data to be produced can be understood in terms of "tiers," as described by the authors of [4]: at the national level as ranging from a first rough estimate to more detailed attribution, and at the city level as ranging from "identifying major emitters and anomaly detection" to "processing understanding of emissions and tracking of mitigation impacts". A corresponding concept of GHGIS can be identified for each tier.

From the requirements, the number and types of sensing platforms can be identified. The authors of [3] and [4] discuss the process of Observation Systems Simulation Experiment (OSSE) that can be used in designing the network of platforms needed. The performance requirements are used in decisions on orbits for space-based sensors and trajectories for airborne and mobile terrestrial sensors, as well as in the design of the sensor instruments.

Lastly, methods and models for sensor fusion and source attribution problems, calibration, and validation & verification can be designed. The authors of [21] describe an approach taken by the EPA in augmenting regulation air quality sensors with a network of low-cost sensors and show that improved performance can be achieved through sensor calibration techniques. Similar approaches to GHG monitoring have been proposed in [22]. In [23] and [24], the authors describe Internet of Things approaches to sensor fusion and demonstrate the feasibility and considerable potential of these approaches for improving GHGIS spatial resolution and ability to characterize variable sources.

Study of recent experimental initiatives with GHGIS-like attributes may be a valuable exercise when architecting the system. We discuss a few illustrative examples in Appendix A.

7. Steps to architect a GHGIS

From the problem statement, a GHGIS can be architected in the following steps:

1. Collect all available a priori knowledge of sources and sinks in a specified territory.
2. Calculate metrics of scales of variability (e.g., spatial and temporal) that characterize the monitored sources under study.
3. From the metrics that characterize the sources under study, estimate the temporal resolution and coverage and measurement stability requirements of the GHGIS.
4. From the a priori geographical distribution of sources and sinks, estimate the Earth coverage and temporal/spatial resolutions of the GHGIS needed to distinguish sources with the required characteristics.
5. From the a priori knowledge of sources and sinks, required source characteristics and the required precision and accuracy for attribution, estimate the measurement precision and accuracy requirements of the GHGIS components. OSSE can be employed here.
6. Identify all existing and planned measurement platforms of the required GHG available for the territory, including space-based, airborne, and terrestrial platforms whose data is expected to be available during the mission life of the GHGIS. Compile the performance metrics of all available platforms.
7. Identify the gaps between available platforms and the measurement performance requirements.
8. Identify performance improvements that can be made by development of data assimilation schemes that integrate data on different grids and of varying errors/uncertainties, and improved methods of intercalibration of data. These efforts would leverage existing efforts operating on smaller scales, such as the NASA Open-Source Science Initiative.
9. Identify possibilities for additional measurement platforms to add to the GHGIS to close the performance gaps.

10. Scope the GHGIS development process by selecting measurement platforms and processing schemes to develop to close the performance gaps.
11. Design the data transmission, processing, and distribution architecture, as well as a scheme for assimilating new observations as they come online.
12. Decide whether to make the architecture static or dynamic; if dynamic, design plans for updating architectures to include new methods and technologies as they are available.

Once the overall architecture is finalized, detailed system engineering can begin for each component system, and this is outside the scope of this work.

8. Research Directions

Efforts in developing GHGIS are enabled by previous and current research and development in the areas of:

- remote and in situ sensing technology,
- algorithms for sensor data processing, calibration and validation, and fusion,
- airborne, terrestrial, and space-based platform technology,
- algorithms for path planning, guidance, navigation, and control of platforms,
- computational and modeling methods in atmospheric science.

Specifically, the following trends hold significant potential for advancing GHGIS development:

- the trend toward large constellations of Earth observation spacecraft, which employ SmallSat technology, collaboration with commercial entities, and economies of scale in their production,
- the use of machine learning and big data in processing large volumes of sensor data [25],
- the development of inexpensive, miniaturized sensors for both remote and in situ sensing of GHG [26], and
- the development of distributed processing algorithms for cross-calibration of sensors, to condition data [27].

These trends enable a GHGIS to include and leverage a variety of sensors in an IoT architecture, potentially combining high-quality and expensive sensors and platforms with inexpensive and distributed sensors deployed to improve spatial resolution, coverage, and other performance metrics. The performance of a GHGIS may be enhanced through suitable signal conditioning using algorithms capable of handing the large volumes of data produced.

9. Conclusion and future work

We have surveyed the state of GHG monitoring efforts and considerations in designing GHGIS systems on various scales. Overall, the need for a multi-platform GHGIS is clearly agreed upon by the field experts. In recent years, several experimental initiatives have demonstrated the feasibility and performance advantages of combining atmospheric modeling and multi-platform sensing.

Configurations that combine airborne, space-based, and terrestrial platforms and distributed low-cost terrestrial sensors in an IoT network show considerable promise considering recent technological trends.

We have described the foundation for future system architecting efforts by identifying the steps for defining the requirements of a GHGIS system and assessing the types of platform, processing algorithm, and data transmission architecture development that would enable the required performance.

Future work will involve identifying a prototypical system architecting problem of particular interest and performing the detailed steps of architecting the system.

Additionally, continued R&D in the areas of large constellations of space-based platforms, miniaturized sensors for remote and in situ sensing, machine learning and big data for sensor data processing, and algorithms for cross-calibration of sensors will be enablers for advancement in GHGIS.

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Appendix A (Case Studies of GHGIS-like Initiatives)

Here, we discuss examples of recent initiatives that use multi-platform sensing and numerical modeling at a local scale for characterizing GHG fluxes. Deeper study of these initiatives will be beneficial for future GHGIS architecting efforts.

A.1 National Inventory Reports

A.1.1 United Kingdom

Annex A.6 of the UK NIR [28] describes the modeling approach used to verify bottom-up estimates. A Lagrangian dispersion model called NAME was used with GHG measurement data from a network of measurement towers (including one at Mace Head in Ireland) as well as data shared by European facilities.

A.1.2 Switzerland

Annex 5 of Switzerland's NIR [29] describes a similar verification approach to the UK's. Bottom-up inventories of HFC and SF6 are verified against observations at the high-Alpine station Jungfraujoch, which are filtered by a set of model-based criteria to select for air masses that are affected by Swiss emissions.

For CH_4 and N_2O, data from a GHG observing network in Switzerland, part of the CarboCount-CH SNF-Sinergia project, is used in a sensitivity-based model to create a verification test.

In both of the above cases, a weather model called COSMO is used.

A.1.2 Australia

The Australian NIR [30] describes inverse modeling approaches used in identifying methane plumes using data from flux towers in the Surat Basin, as well is in verifying emissions of HFCs and SF_6. These latter two gases are considered well-suited to the inverse modeling approach: HFCs since they have no natural sources, and SF_6 because it has no sinks, simplifying the models. The inverse model used, called InTEM, is described in Appendix 4.A of [30].

A.2 National Institute of Standards and Technology testbeds

In the US, NIST is implementing urban testbeds for developing measurement tools for source identification in cities. Two of them, INFLUX [31] and Northeast Corridor Urban Test Bed [32] each combine modeling approaches with aircraft and tower-based measurements. In INFLUX, the modeling results are compared with bottom-up inventories. The Northeast Corridor Urban Test Bed uses meteorological data in developing atmospheric dispersion models. A third testbed, the The Los Angeles Megacity Carbon Project [33], uses data from a 14-node network of rooftop and tower-based in situ sensors and calibration techniques to produce CO_2, CH_4 and carbon monoxide measurements.

A.3 Studies and experiments

A.3.1 Natural gas leak in Aliso Canyon

The Los Angeles Department of Public Health led an effort to monitor and analyze the impact of methane fluxes from a 2015 natural gas leak in Aliso Canyon. The report [34] describes a modeling approach that combines portable Sensor Network for Air Quality (SNAQ) sensor data with meteorological and citizen science data. A dispersion model was used for source identification as well as assessing health risks to residents from exposure to the gases and particulate matter from the leak.

A.3.2 Air pollution in the Mojave Desert

A 2015 NASA experiment to study air pollution in the Mojave Desert, described in [35], is an interesting application of multi-platform sensing of multiple chemical compounds. The experiment measured methane and other GHG, as well as ozone. A combination of air transport modeling, space-based observation (from the GOSAT-COMEX experiment and MODIS), two types of airborne sensing (Cloud Physics LIDAR on NASA Earth Research-2 high altitude plane and the AlphaJet Atmospheric Experiment fighter jet) and terrestrial mobile sensing (AutoMObile greenhouse Gas Surveyor) were used in source identification.

A.3.3 Coal-fired plants in western Germany

A 2018 study of CO_2 and CH_4 emissions from a region in Germany containing coal-fired power plants [36] combined an inverse Gaussian plume model with airborne in situ measurements (the aircraft METAIR-DIMO) and airborne remote sensing measurements (MAMAP on a University of Berlin aircraft). For calculating background concentrations of CO_2 and CH_4, another model called SECM, built on space-based measurements, was used. The modeling results were found to be in agreement with bottom-up estimates of the power plant emissions.

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